Hans U. Fuchs · Federico Corni

Primary Physical Science Education

An Imaginative Approach to Encounters with Nature

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To Dario and Magnus

& to Gigliola

Preface

This is a textbook on *Primary Physical Science Education* (PPSE) for student teachers of kindergarten and primary school levels. The term *primary* is used here in a dual sense. It means *early* in the sense of education addressed to children when they build their primary understanding of the world. It also refers to the understanding of concepts of physical science that may rightly be called *primary*, i.e., the concepts that form the roots of scientific thought. These elements of understanding are important not only for children but for everyone, at any age, for a meaningful approach to aspects of physical reality.

In this book, we create a narrative account of how *Primary Forces of Nature* (FoN) such as *Wind*, *Rain*, *Fire*, *Light*, and *Heat* and *Cold* are understood (Fuchs et al., 2019; Fuchs, Corni, & Dumont, 2021; see References); and we outline an equally imaginative approach to the handful of *Basic* FoN (Fluids, Electricity & Magnetism, Heat, Chemicals, Gravitation, and Rotational and Linear Motion) that populate macroscopic physics (Fuchs, 2010[1996], 2015; Fuchs, d'Anna, & Corni, 2022). In it, we show how children and their teachers can start their encounters with nature by engaging with what are colloquially called the *elements*. These encounters will let young children connect to and converse with nature in a manner that is the prerogative of youth during their phase of mythic consciousness, before the cognitive tools of literacy have become dominant (Egan, 1997).

Analysis of human experience of nature (Dewey, 1925) can set us free from a belief that we need to take a scientific approach to nature education for children. Children should not be taught science per se, which, for young learners, often comes as a watered-down version of „true" science. We believe that, in contrast, we should ask how people in general and children in particular experience and interact with nature, and how they communicate about it with their teachers and their peers. The point of origin of our approach to nature pedagogy is the child or, even more radically, the *nature-child relationship*, rather than science. Science will emerge dialectically from the interaction of mythic experience and a scientific attitude that becomes available to learners during their adolescence.

If high-quality direct (physical) experience of nature and artifacts is fostered and joined with narrative experience made possible by stories of Forces of Nature and other imaginative forms of participatory sense-making (De Jaegher & Di Paolo, 2007; Hutto, 2007), the foundations for later understanding of science will be laid. In a nutshell, by emphasizing the role of imagination for our understanding, we are putting human nature back into the scientific exploration of the world around us. Where certain practices of science and philosophy—at least since René Descartes—have undoubtedly alienated us from nature, we want to build upon an approach to physical systems and processes that can help bridge the divide that was created between humans and nature.

Two volumes. The book is divided into two volumes. The first of these, *Primary Physical Science Education: An Imaginative Approach to Encounters with Nature*, outlines a primary form of engaging with physical processes. This will be particularly suited for children during kindergarten and the first few years of primary school (Corni, 2013, Corni & Fuchs, 2020, 2021; Fuchs, Corni, & Pahl, 2021). In Chapter 1, we introduce readers to early, mythic forms of consciousness and culture, and to Kieran Egan's scheme of recapitulation of cultural forms of understanding that make use of cognitive tools of mythic, romantic, and philosophical phases of development (Egan, 1988, 1990, 1997). The first chapter clarifies the role of imagination and cognitive tools such as metaphor, story, and visual art, and charts a course towards the very first encounters with Forces of Nature. Moreover, we briefly describe important differences between mythic and scientific attitudes toward engagements with physical processes and then show in what sense modern macroscopic physics is a collection of theories of Forces of Nature.

In Chapter 2, we introduce *Primary Forces* and explain how experiencing them leads to imaginative forms of communication and understanding. Stories included here and in later chapters demonstrate how *narrative experiencing* of Forces can arise. Chapters 3 and 4 serve a somewhat more formal description of the imaginative structures underlying the *Basic Forces* of *Fluids* (represented by Water and Air), *Gravity*, and *Heat*. Importantly, the discussion of interactions between these Forces leads to the notions of power and energy.

Visual metaphors and mimetic (embodied) plays, introduced in Chapter 5, will help teachers deal with Forces productively at various levels. *Process Diagrams* allow us to imaginatively represent our qualitative, yet formally and scientifically compelling, understanding of the interaction of Forces in chains of processes. Such diagrams resemble storyboards used in designing *Forces-of-Nature Theater* performances suitable for learners in primary school. Finally, in Chapter 6, we sketch an example of how different forms of experience and expression—physical, narrative, and mimetic—can be brought together for creating a unified imaginative approach to nature studies for young learners that is not yet scientific but can lay the foundations for later scientific engagement with physical systems and processes.

In Volume 2, *Primary Physical Science Education: Experiencing Forces of Nature in Natural and Technical Systems*, we continue the description of (1) the Basic FoN with chapters on *Electricity* and *Magnetism*, *Substances*, and linear and rotational *Motion*, and (2) imaginative education centered on schematic, metaphorical, analogical, and narrative uses of oral and written language (there, we briefly introduce important elements of modern cognitive linguistics and narratology). Moreover, several of the topics in physical science will be used to demonstrate how, with the help of simple-to-use software, dynamical models of physical systems and processes can be created—these models and their simulations represent a scientific analog to story-worlds and storytelling (Fuchs, 2015). We shall conclude Volume 2 in a manner paralleling the final chapter of Volume 1; however, in Volume 2, we shall choose examples of nature pedagogy that make a gentle move towards scientific forms of engaging with nature and machines.

Studying real life complex systems. Engaging with FoN allows us to account for the role of physical phenomena in our natural environment. When outlining properties and functions of Forces, we make physics part of the study of real-life systems—we involve it in fields such as earth and environmental science, physiology, astronomy, and energy engineering. Examples include the role of sunlight for our planet, the production of wind, the global cycle of electricity and the role of thunderstorms, global cycles of water and carbon, the blood circulatory system and water transport in trees, and our planet's place in the solar system and the universe. Moreover, we show how Forces are active in technical artifacts, particularly in renewable energy systems.

And finally, the form of presentation is meant to demonstrate to teachers how elements of our understanding of the Forces around us can be gently nurtured in learners, starting with a mythic approach to encounters with physical phenomena and, during the later years of primary school, by joining the cognitive tools of beginning literacy with those of scientific practices such as experimenting, measuring, and simple calculating; collecting, categorizing, graphing, and mapping; and, generally, organizing and documenting. Formal and theoretical forms of understanding must be left to middle and high school.

Winterthur and Bressanone, 2023

Hans Fuchs and Federico Corni

Notes and Materials

We present issues relating to physical and cognitive sciences that are important for teachers who want to take a look at physical phenomena from an imaginative and narrative perspective. The book is not a manual of day-to-day teaching. Nevertheless, the approach taken here suggests pedagogical and didactic ideas and activities. In the first volume, we present a number of stories of Forces of Nature suitable for teaching, and in Chapter 6, we outline a concrete example of early nature pedagogy where we discuss design principles for stories and Forces-of-Nature Theater performances. In the second volume, we shall develop cases that show how children's minds can be nurtured to evolve from mythic understanding of Forces towards scientific forms of collecting, creating, and organizing knowledge of important processes in natural and technical systems.

A note for instructors of student teachers. As instructors of student teachers and in-service teachers, we have made it our goal to explore the roots of human engagement with physical phenomena. For us, trying to become aware, and encouraging our students to become aware, of the origin of abstract elements of thought arising in the experience of Forces of Nature, has been truly revealing. Putting oneself in the shoes of children—to the extent that this is possible—is worth the effort: we are rewarded with an understanding of the origin of concepts in physical science, and we can discover physics from a new perspective.

The references listed here will hopefully help instructors to embark on this journey. See, in particular, Corni (2013), Corni & Fuchs (2020, 2021), Fuchs et al. (2019), Fuchs, Corni, & Pahl (2021). For the science of Forces of Nature, see Fuchs (2010[1996]) and Job & Rüffler (2016). For a wide-ranging coverage of topics for physics courses at middle and high school levels, see Herrmann (1990-2021).

Above all, we should mention Kieran Egan's work on the philosophy of primary education that can be of profound help if we wish to see the issues of science and children's learning with new eyes (Egan, 1988, 1990, 1997).

Additional materials on the science of Forces of Nature. There are three books on the subject of physics and one on chemistry that take the perspective of what we have called Forces of Nature. Two of these are for middle and high school, the third and fourth are for university level courses.

The first of these is the *Karlsruhe Physics Course KPK* (*Karlsruhe Physikkurs, KPK*) by F. Herrmann (1990-2021) and co-workers (see References at the end of the book). In several volumes for middle and high school (available in several languages, including German, English, Italian, and French), it covers a wide range of classical and modern topics in physics using language and imagery that is similar to (but slightly more formal than) what we do in this book. The form of presentation makes the *KPK* eminently readable, and eminently useful as a companion text to our course.

The second (Borer et al., 2010) presents a very short outline, suitable for high school, of the basic phenomena of classical physics. It includes an introduction to how to create dynamical models of physical systems and processes employing system dynamics modeling software with graphical user interfaces that make use of visual metaphoric building blocks.

The third of these (Fuchs, 2010[1996]) is devoted to a modern theory of the dynamics of thermal systems and processes; it includes a short introduction to other fields of classical physics using the perspective of Forces of Nature and their interactions, and develops the generalized approach to the energy principle how we apply it here. Finally, the book on chemistry by Job & Rüffler (2016) develops a theory of chemical processes from a unifying perspective by making use of chemical potential and amount of substance as primitives—a form that parallels that of a science of Forces of Nature.

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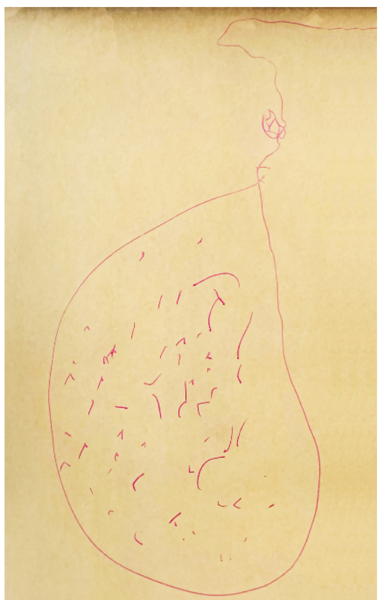
Contents

Chapter 1

Myth, Imagination, and Science



„Dangerous Ener-Gee" by DL
(3 years 10 months)

There is an old, basic cultural form of understanding of the world around us, which has been called *myth*, *mythic consciousness*, or *mythic culture*. In concrete form, myth comes to us as stories, often as tales of human and natural *Forces*.[1] This culture or consciousness has much to do with our direct *experience* of the world as expressed in *oral language*.

Mythic consciousness relates reality to *imaginative figures* that populate our mind. In their early years, as their orality develops, children are expected to display forms of mythic meaning-making that include a number of important *cognitive tools* such as basic schematizing abstraction, metaphor, analogy, and story-telling. These tools, and our experience of natural Forces, will find their way into more formal approaches to understanding nature that develop later in life.

H. U. Fuchs, F. Corni, *Primary Physical Science Education*,
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In this book, we develop an account of how meaning of our encounters with nature and qualitative understanding of physical science[2] arise from combining the direct experience of causal *Forces* with imaginative forms of human expression such as storytelling and mimesis. We write this from two perspectives: *mythic consciousness*[3] and modern *continuum physics*.[4] This may sound rather strange—ancient mythic culture and modern physics do not seem to mesh. We shall see, however, that there is an interesting connection between the two that may very well help us explore how the understanding of physical processes grows in a child.

Cognitive tools of mythic culture

The children we are considering here will be between 3 to 4 and 9 to 11 years old. There is good reason for believing that, as they develop, young children are part of a culture that has important elements in common with mythical societies that first evolved some tens of thousands of years ago; not the least of these elements is oral language and the *cognitive tools* that come with mythic understanding in general and *orality* in particular.

Naturally, this text is not for children but for their teachers and for anyone else interested in what myth and imagination might have to do with our modern physical science and its applications to engineering, medicine, earth science, astronomy, and environmental science; nor is this a book that spells out in detail what teachers should do in their day to day work in kindergarten and primary school.

However, taking a look at physical phenomena from a mythic and generally imaginative perspective lets us present and explain aspects of physical science in a manner that directly suggests pedagogical and didactic ideas and activities. Simply put, we want to help readers navigate some of the natural scientific and cognitive issues that emerge when they join children in exploring nature in imaginative ways. Let us briefly contrast traditional with imaginative approaches to early science education and sketch what our job will be.

The tradition in physical science education. Primary level educators are charged with—among many other things—introducing children to science, starting at an early age, maybe as early as kindergarten. This task has typically taken the following form:

1. We accept science for how it presents itself and is presented to us in school and the media. Simply put, science is a given.[5]

2. Scientists or science educators select some topics from the body of a particular science that (a) typify the science, (b) can be simplified to fit with early education, and (c) should, if possible, be an element of a child's immediate physical environment. In physical science for kids, rainbows, buoyancy, the law of the lever, simple electrical circuits, and mechanical forces lead the hit parade of topics; energy has lately become an important theme as well.

3. We transform a chosen topic to what is deemed acceptable to a given level in our educational system; what is acceptable is decided on the basis of prevailing developmental and educational models.

4. We commonly try to be aware of the „fact" that children harbor „wrong" and „misguided" theories and conceptions of things and processes, and we want to apply the best methods for overcoming such misconceptions and faulty theories.[6]

Of late, it has become fashionable to center (early) science education around the „scientific method." While this is an important development and certainly influences pedagogy—it shifts our focus a little bit away from information and „bare" knowledge toward active involvement with a theme—this does not, in general, impact scientists' and teachers' attitudes toward the status of science, scientific knowledge, and children's developing but basically „lacking" cognitive abilities.

In all, this is a purely top-down approach to early science education: we go from natural science to the child. We accept science as is, with its forms, methods, and products, and take into account the limitations of the child's capacities as an „unfinished" or „immature" adult.[7]

Note, moreover, that in such an approach, physics, as an important modern cultural product, is given a dominant position. Nature, in contrast, takes the backseat: it is reduced to a source of examples for the science; it is the object rather than the subject in the science-nature relationship. And the child becomes the recipient of wisdom stored in the science.

Engaging imaginatively with nature. In this book, we would like to reverse the direction of flow of the typical argument: we start from nature and the child, or, more radically, from the *child-nature relationship* that will include, in very important ways, joint activity with caregivers. This relationship is marked and characterized by encounters with *Forces* such as *Wind*, *Rain*, *Light*, *Fire*, *Water*, *Heat*, *Electricity*, *Food*, and many others, and by how the encounters are spoken and generally communicated about. We want to explore

- how a child encounters and interacts with nature, and what this has to do with mythic consciousness;
- how experiencing natural Forces might lead to imaginative structures that help children understand their experience;
- how accepting children as „complete mythic beings" rather than „incomplete adults" helps them and us develop meaningful encounters with nature;

Children as mythic beings

- how a child learns to communicate with others about these encounters through stories of natural Forces;
- if imaginative understanding of natural phenomena might serve a child as the basis of later scientific understanding; and if so, how this is possible;
- what kind of educational program might follow from developing an imaginative approach to encounters with nature.

Looked at from the perspective of how children (jointly with their caregivers) encounter and interact with natural Forces, and what this means for the growth of their understanding, science (especially macroscopic physical science) and science education can be re-imagined. First, every science has a *mythic core*; it will be important to understand what this core is, and what forms of thought it makes available to us in a particular science. Second, as we already said above, there are strong indications that children are members of a culture that has important aspects in common with oral mythic cultures of past and present. Not the least of these aspects are *schematizing/abstracting* and *imaginative mental activity* that are vivid and powerful in children of this „mythic culture."

Abstraction and imaginative mental activity

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This lays out the program for the introductory chapter. We shall briefly describe how immediate experiencing of the world in general and of nature in particular creates a mythic mind that grows with the development of oral language; how this mythic mind creates the notion of *Forces* active in nature, and what this has to do with imagination; in sum, we shall outline a model of how child and caregiver *jointly experience, and interact with, nature* (Section 1.1). We shall sketch how mythic culture developed as part of human evolution (Section 1.2), and present reasons for believing that children's minds are characterized by mythic awareness, even in today's cultures. Specifically, we want to list some of the cognitive tools of mythic understanding that are used to suffuse the child-nature relationship with meaning (Section 1.3).

Joint action in and with nature

Naturally, the child's development does not stop with myth. We should be interested as well in what it takes to go beyond mythic culture so that scientific forms of exploring nature can develop upon the understanding myth provides us with (Section 1.4). To argue this issue, we shall make use of Kieran Egan's model of cultural recapitulation of *mythic*, *romantic*, and *philosophic* (formal, theoretic) forms of understanding and briefly trace cognitive tools of later stages of personal and mental development (Egan, 1988, 1990, 1997); chief among these are tools of *literacy*, which will help children and adults to enter upon a journey towards aspects of physical science. Importantly, however, the roots of this development will have been laid in the imaginative structures that grow earlier in mythic life.

Recapitulation of cultural forms of understanding

Finally, we shall sketch elements of the formal scientific basis of our approach (i.e., continuum physics), briefly review what we mean by *Primary Physical Science Education* and explain how the two are related (Section 1.5). Supporting our approach must include a discussion of two separate but related issues any presentation of physical science will have to face. The first of these issues is which meaning we want to associate with the concept of *Force*—given the fact that our embodied understanding of *Force* is rather different from, and much more encompassing than, what is traditionally called *force* in physics. The second is related to the philosophical stance[8] one wishes to take regarding how physics explains its subject; the decision made has wide-ranging consequences for how physics presents itself and which topics are deemed important for lay audiences.

Continuum physics and Primary Science Education

Debating two issues: What is Force? and... What is physics?

Having made and explained our choices, we can concentrate upon telling the tale of encounters with natural Forces and how experience of such Forces can be developed into a more formal approach to physical science. This will be our task in the following chapters and in the subsequent volume.

1.1 Experience, Myth, and Imagination

Myth is said to be most directly about reality—a form of awareness evolving from immediate experience and meaning-making. It is a symbolic form in which we integrate object and phenomenon with feeling and idea. Myth or, rather, mythic consciousness endows things with qualities or characteristics, and this endowment is taken literally, i.e., as real. A new unity (a perceptual unit or gestalt) evolves in which objects and activities are given „personalistic" character—in some sense, they are „animated."

Mythic consciousness

We shall explore what this means by first studying a concrete example of myth, a mythic tale about *Wind*. The story can help us understand what is particular about mythic awareness of nature, and in what sense this awareness is imaginative or makes use of tools of imagination. Most importantly, our analysis leads us to a central imaginative figure created in mythic experience of nature, which we call *Force of Nature* (FoN).[9] After briefly describing the meaning of FoN, we shall outline fundamental properties of myth and then discuss a model of unified direct and narrative experience of nature in joint action of child and caregiver. The historical development of myth and oral language—their origin in the cultural evolution of humanity—will be the subject of Section 1.2.

Wind in ancient cultures

Among objects and activities in nature, *Wind*[10] easily presents us with one of the most direct examples of what can be experienced. Wind is very easily perceived and made sense of: we have all been exposed to situations that present themselves as *windy* or *wind-still*. In our mind, we recognize Wind, there is no mistaking it for anything else—it is a figure, a perceptual unit that forms easily and unmistakably.

If we go back to the origins of human cultures, we see how important *Wind* has been ever since humans have developed their power of imagination. Wind has served as one of the most important, immediate, and primitive experiences to talk about our origins and about our relationship with nature. Wind let Egyptians and Babylonians understand how the world began and has been sustained ever since (in Chapter 2, p.64, we shall present a story of the beginnings of the world with Wind as one of its characters). In their cosmologies, Egyptians and Babylonians tell us that Wind separated the Sky from the Earth, and keeps doing so; by doing this, it sets up an „original tension" that keeps life going on the surface of Earth.[11]

Wind in ancient myths

Tales of *Wind spirits* in North American indigenous mythology give us an impression of the relationship between nature and humans, and they show how language is used to express experience of Forces. There is a story that is titled *Why We Need Wind* (or *Koluskap and the Wind Eagle*). Koluskap is a central character, a culture hero, of a number of native peoples. As R. M. Leavitt put it, Koluskap „made the world habitable for human beings and taught them their place in it."[12] In many translations or told directly in modern English versions, the Wind Eagle is given a name: *Wocawson*. However, „The wind's name, *Wocawson* is not a noun, but a verb, meaning *'it is windy.'* Likewise, other elements—such as Rain, Snow, Sunshine, Cold, Heat—are also expressed as verbs, continuing actions or processes rather than independent things [...], allowing speakers the possibility of interacting with them and affecting them, just as Koluskap did."[13]

Verbs characterize Forces as actions

Interacting with Forces

Why We Need Wind

The story[14] tells about Koluskap who wanted to go duck hunting in the bay where he and his grandmother lived. He went out on his canoe but was constantly pushed back ashore by the strong Wind blowing incessantly. He finally went to find Wocawson up on the mountain and asked him to stop flapping his wings to make Wind. Wocawson refused; so Koluskap caught him and threw him in a crevice where he got stuck and could not move any longer. Koluskap went back to the shore, went out hunting but soon was bothered immensely by the foul smell of the air and foam on the water that would not go away. So he went back up to the mountain, freed Wocawson, and they agreed for the Wind to blow only at certain times. Here are excerpts of a modern rendering of the story—*Gluscabi*[15] *and the Wind Eagle*—from the Abenaki tribe:[16]

> *[Gluscabi tried to paddle out into the bay but failed...] But again the Wind came and blew him back to shore. Four times he tried to paddle out into the bay and four times he failed. He was not happy.*

[Going to find the Wind...] He walked across the fields and through the woods and the Wind blew hard. He walked through the valleys and into the hills and the Wind blew harder still. He came to the foothills [...] and the Wind still blew harder. Now the foothills were becoming mountains and the Wind was very strong. Soon there were no longer any trees and the Wind was very, very strong. The Wind was so strong that it blew off Gluscabi moccasins. [...] Now the Wind was so strong that it blew off all his hair, but Gluscabi still kept walking, facing the Wind. [...] on the peak ahead of him, he could see a great bird slowly flapping its wings. It was Wuchowsen, the Wind Eagle.

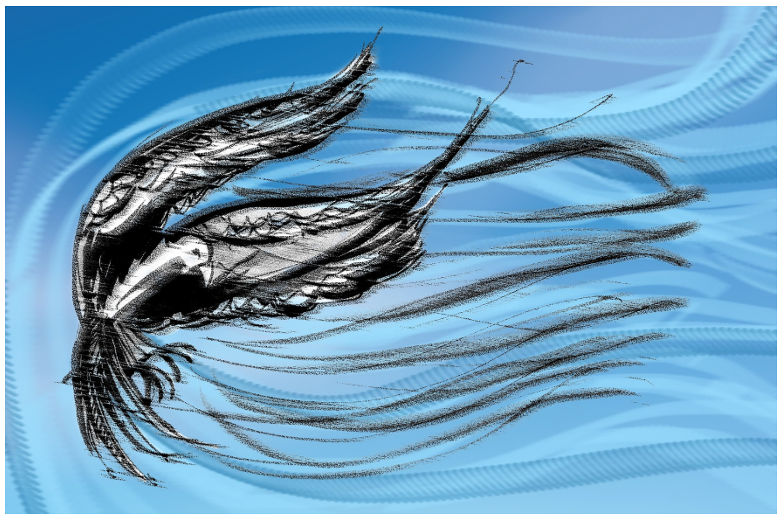

Figure 1.1: *Wocawson, the Wind Eagle (artwork by M. Guidetti).*

[After meeting the Wind and arguing...] "Now Grandfather," Gluscabi said, picking the Wind Eagle up, "I will take you to a better place." He began to walk toward the other peak, but as he walked he came to a place where there was a large crevice, and as he steps over it he let go of the carrying strap and the Wind Eagle slid down into the crevice, upside down, and was stuck.

[Back at the bay...] "Now," Gluscabi said, "It is time to hunt some ducks."

[After being out on the water...] "Grandmother," he said, "What is wrong? The air is hot and still and it is making me sweat and it is hard to breathe. The water is dirty and covered with foam. I cannot hunt ducks at all like this." "Gluscabi," she said, "What have you done now?" And Gluscabi answered just as every child in the world answers when asked that question, "Oh, nothing," he said. "Gluscabi," said Grandmother Woodchuck again, "Tell me what you have done." Then Gluscabi told her about going to visit the Wind Eagle and what he had done to stop the Wind.

[Back up on the mountain...] "Oh, Gluscabi," said the Wind Eagle, "a very ugly naked man with no hair told me that he would take me to

> *the other peak so that I could do a better job of making the Wind blow. He tied my wings and picked me up, but as he stepped over this crevice he dropped me in and I am stuck. And I am not comfortable here at all." [...] Then Gluscabi climbed down into the crevice. He pulled the Wind Eagle free and placed him back on his mountain and untied his wings.*
>
> *[...] Gluscabi said, "It is good that the Wind should blow sometimes and other times it is good that it should be still." The Wind Eagle looked at Gluscabi and then nodded his head. [...] So it is that sometimes there is Wind and sometimes it is still to this very day. And so the story goes.*

Wind as a Force of Nature (FoN)

In the story of Koluskap and Wocawson, Wind is characterized in a manner we will encounter again and again as we study other Forces—we will learn to understand what makes Wind a member of the family of Forces of Nature.

Characteristics of Wind—Meaning-making in myth. First of all, we perceive the *polarity* of windy ↔ wind-still, which creates our experience of *intensity* of Wind. Actually, it does even more: experience of intensities and or tensions, i.e., differences of intensities, is basic for any organism. From this spring other aspects of experience; we might even say that the experience of a polarity is the source of our experience of Forces of Nature (Chapter 2, Section 2.2).

Polarity for Wind

In the story, *intensity* of Wind is indicated by the progression of *blowing hard* or *being strong „... and the Wind blew hard. [...] and the Wind blew harder still. [...] and the Wind still blew harder. [...] and the Wind was very strong. [...] and the Wind was very, very strong."* This is a linguistic rendering of the *degrees of intensity of Wind*, which helps us make sense of felt *tensions* as well (see the introduction to polarities, intensities, and tensions evident in our immediate—mythic—experience of nature in Section 2.2).

Intensity of Wind

Second, the story makes very clear that Wind is a *powerful* phenomenon. The power of Wind shows itself in passages where we hear about what the Wind is doing or causing: „*But again the Wind came and blew him back to shore"* or „*Now the Wind was so strong that it blew off all his hair..."*. Indeed, the experience of power pervades the entire story and its messages.

Power of Wind

There is a third fundamental feature of Wind—its *size*: Wind can be „bigger" or „smaller." This does not come out so clearly in the story, but we know that it is important to Wind: in a hurricane, Wind extends over hundreds or thousands of kilometers; the „size" of a tornado may be just a few dozens of meters. What we see here is the (spatial) *extension* of Wind. Extension is implied in the story—we get a feeling for it as we read about the long journey from the ocean to the mountain top during which Koluskap is subject to strong Winds; and when we hear about the size of Wocawson's wings that make the Wind. This is how we measure extension: the extension of Wind is proportional to the size of an area exposed to Wind; the bigger the area, the „more Wind" we can catch. The area is the cross section of an object—a person, a building, sails of a ship, the blades of a wind turbine—facing the Wind.

„Size" of Wind

Extension of Wind

In *Why We Need Wind*, the characteristic of extension or size or quantity („How much wind is there?) appears to us in the form of the body of Wocawson. When the Wind Eagle is large, with its wings spread wide, there is a lot of Wind; if he is small, tied up and stuck in the crevice, there is no Wind. Through its embodiment, Wocawson tells us about the fact that Wind can be big or small.

Wind is fierce or gentle, big or small—a more or less powerful entity

Wind is experienced as an agent. Wocawson lets an image of Wind as a (more or less) *powerful agentive entity* or *being* (an *agent*)[17] arise in our mind. Wind is either big or small, and fierce or gentle, and therefore more or less powerful. The imagery arising here is a simple example of what myth can be about: it gives us personalistic access to our experience of nature. To mythic experience, the perceptual unit arising in consciousness is as real as the direct (pure) physical activity of wind alone (i.e., Wind as purely physical or material). The character we call *Wind* is the synthesis of the pure (physical) activity and the image(s) it gives rise to in our embodied mind.

Wind is a being

Does calling Wind an agent mean that we give human characteristics to Wind? Remember that what we call the *Wind Eagle* in modern renderings of the story in English, is, first of all, a verb (Wocawson → it is windy) describing an activity and not a person. Still, in mythic experience, Wocawson (Wind) becomes a character we can interact and communicate with; such experience is accepted as true—Wind, as experienced by a mythic mind, is truly a *being*, an *agent*, but not human.

Natural language and mythic experience

When we speak about Wind, we can use natural everyday language without having to anthropomorphize the agent, and still get the full (mythic) experience of the phenomenon. Natural oral language has all the tools we need for this task: it is rich in basic human schematic abstractions, metaphors, and analogies which are the building blocks of imaginative accounts of our experience. When integrated in a story, these elements make *narrative experience* possible that interacts with direct physical experience and so makes rich experience of Forces possible (see Fig.1.3 for a model of the interaction of myth, language, and narrative).

Forces are agents experienced in causal interactions

Forces of Nature as created in mythic experience. In summary, we can say that *Wind* is experienced as an agent having *intrinsic characteristics of intensity*, *extension* (*size*), and *power*. Causal interactions (such as when Wind interacts in the environment and with us) lead to images of agents which we call *Forces*. Importantly, the images are in us, but they are taken for real, for existing out there—this is a typically mythical form of awareness. Without going into detail at this point—we will do this at length in later chapters—it should be clear that *Rain*, *Light*, *Fire*, *Water*, *Heat* and *Cold*, *Electricity* and *Magnetism*, *Gravity*, *Motion*, *Food* and *Medicine*, and many more, belong to the family of *Forces* of which *Wind* is a member (see Chapter 2 for a first encounter with this family).

Myth

We shall now extend and deepen our understanding of basic characteristics of myth by describing in more detail what mythic experience and consciousness are about. In doing this, we follow the analysis provided by A. F. Losev in his 1930 treatise *The Dialectics of Myth*.[18] According to Losev, myth is a personalistic symbolic rendering of immediate experience; it is real to the senses. Before we explain what this means, we shall briefly describe another example of mythic experience—that of color and sound.

Experiencing colors and sounds. Here is another example[19] that can inform us about myth and its centrality to meaning-making even today when we have „progressed" beyond primary forms of understanding. The example is about how we experience and understand colors and sound, how we speak about the experience, and how this is different from and yet basic to scientific understanding.

Most likely, we all have used expressions such as warm and cold colors; sharp and dull or heavy and light sounds. Red might appear as aggressive, green as calming, blue as cold, and different sounds have their own qualities. The point is that these expressions report true experience—we do not superficially embellish colors and sounds with some fancy qualities; colors *are* warm or cold, sounds *are* heavy or light. This is mythic experience.

Mythic experience of color and sound

In these examples of experience, senses of color (sight) and sound are fused with senses of hotness (or coldness), sharpness, and weight; new perceptual units are formed. Note that the characterizations are made in terms of qualities (rather than quantities or matter). The qualities belong to *polarities* such as hot ↔ cold or sharp ↔ dull, each of which creates a scale allowing for different „values" of a quality lined up between the poles; in the case of the hot ↔ cold polarity, degrees of „hotness" are anywhere between burning hot and freezing cold. We shall learn how the experience of polarities is central to a scientific analysis of Forces.[20]

Modern cognitive science recognizes the association of color or sound (and other perceptual phenomena) with qualities from other domains of experience as cases of *metaphoric projection* from one domain onto another (this is particularly true of Conceptual Metaphor Theory in cognitive linguistics; we shall describe metaphor and other cognitive tools in detail in Volume 2). This is an example of modern theoretic work based upon what, at its core, is mythology. A mythic mind perceives a unity, an equality, between sight (of color) and warmth; as we have said, colors *are* warm or cold or can have other characteristics. In cognitive linguistic research, we create an imbalance; knowledge of the domain of heat is projected onto the domain of (seeing) color. The two are not the same any longer as in myth—our modern mind tells us that green *feels as if* it were calming.

Metaphor

Three forms of expression. Losev discusses three different forms of expression in which we create particular relations between *two spheres of being*: an *outer* physical realm of *object* or *phenomenon*, and an *inner* mental realm of idea or image. The three forms of expression—*allegory*, *model*, and *symbol*—are distinguished by the type of balance or imbalance they create between inner and outer realms.[21] In an allegory, the outer world is „weightier" than the inner one. In a model, the relation is reversed. But in a symbol, there is perfect balance between physical phenomenon and idea or image—the two are equal. Let us see what this means for our understanding of myth.

Connecting inner and outer spheres of being in allegory, model, and symbol

Balance in symbol

Myth is neither allegory nor model. To characterize myth, it is also important to say what it is not. A mythic story is not an allegory even though it may contain one. In a fable, we have animals speaking and presenting us with a message. Nobody takes the speaking animals for real; their task is to point to the message. Wocawson is clearly different from such animals: he (or she or it) *is* Wind, a character we interact with, and this experience is real for a mythic mind.

Neither is myth a (formal) model in the sense of a schema or blueprint pointing to a particular real object, such as when the drawing or plan of a house allows an architect to have the house built. Wocawson is not a model of wind, Wocawson *is* Wind. All of this points to the reality of Wind in mythic consciousness. Our mind creates a synthesis of phenomenon and image, forming a new reality.

Myth is a symbol. The clear feeling of a new unity of two separate things arising in mythic awareness is a further indication that a myth is neither an allegory nor a model—it is a *symbol*. Allegory and model are „unbalanced" relations; in an allegory, idea follows from phenomenon (such as talking animals in a fable), and in a model (such as a blueprint for a machine), object follows from idea. In a symbol, however, the two sides, phenomenon and image, are united as a new reality; in other words, one stands for the other, they are in balance, they are equals. Wind *is* the agent as described and perceived in *Why We need Wind*; it *is* a character we can communicate with.

Symbol vs. representation

Symbol or representation?

Myth as a *symbol* is a relationship between—a paring of—two realms or spheres of being: an outer (physical, material) and an inner (ideal, imagistic); the former may be an object, phenomenon, or event, the latter could be called its meaning.

In myth, the two parts of the pair are on equal levels, and such a pair is a new reality (its former parts have become identical, they have been fused or synthesized in what philosophers call a dialectical move). At least this is the feeling we get from mythical consciousness.

Modern ways of thinking often give us the impression that a thought or idea is *about* an object or event (it is directed at or points at the latter). Expressed differently, the thought is said to be a *representation* of the „thing out there." This argument puts a great distance between the two realms of being; it creates an example of a duality, such as between thought and reality. Reality is often equated with matter, and thought with immateriality. This way of thinking and arguing is very „un-mythical."

Oral culture

As we shall see, language is a symbolic tool,[22] and the first full-fledged „natural" human language is spoken (oral) language. Therefore, it should not come as a surprise that *orality* will play a central role in our further investigation of myth and learning about nature; part of our task will be to study what form the understanding of nature takes in an oral culture.

Myth is not science

Myth is not science. Very importantly, myth is not science, not even „primitive" or proto-science. Science is different—it is a product of a different and culturally more recent consciousness. In science, we organize and categorize observations differently, we measure and calculate, we create formal models and theories, we ask different questions and have different goals. „In order to obtain even the most basic scientific generalization, one must observe and memorize a great deal, analyze and synthesize a great deal, and separate the essential from non-essential with great care. Science is exceedingly restless, painstaking, and fastidious in this sense. It strives to find an ideal numerical or mathematical regularity in the chaos and disarray of empirically indistinct and fluid facts—a regularity that [. . .] is [. . .] an ideal logical order [. . .]."[23] It is quite clear from a story such as *Why We Need Wind* that myth is not about what is central to science. Myth is about basic immediate understanding of the world around us, expressed through oral language and clad in images. It provides knowledge for living with nature and other humans in a pre-literate society. Myth and science may have the same phenomena in mind, but procedures and goals are different.

Science needs myth

Myth and science. If myth is not science—not even a precursor of it—how can it be relevant for science? First, it is clear that myth connects us to nature, and to the extent that being connected is relevant, myth will always be important. Second, it makes us conscious of Forces of Nature: „[. . .] science is not born of myth, and yet it can never exist apart from myth, which means that it is always suffused with mythology.”[24] Third, and most centrally important for the development of a scientific attitude, myth provides us with basic forms of rationality—with specific cognitive tools—that make formal scientific reasoning about, and the creation of theories of, Forces of Nature possible.

Myth and basic forms of rationality

Experiencing and communicating about Forces of Nature

We shall now describe a model of experiencing nature that rests upon two pillars: accepting nature as a partner, i.e., creating a *second-person relation* between child (or adult) and nature; and *participatory sense-making* when child and caregiver jointly experience nature. Regarding the former, establishing a second-person relation means that we call nature a *you* rather than a *he/she/it*. The second is characterized by child and caregiver communicating in natural oral language—and by possibly using other means of communication such as play-acting, drawing, singing, etc.—about their *joint experience*. Since direct or immediate experience of the natural world is an important element of this model, it may be called a modern rendering of mythic participation in the world.

Joint experience

A model of experience. The model is illustrated in Fig.1.2. The green boxes represent „objects” such as the physical world, a primary organism (say, a young child), a second organism (maybe a primary caregiver), cultural artifacts (such as written texts and materials for simple experiments). If the texts are stories, they can be read directly by a child having achieved some literacy; or it can be mediated indirectly by another human: a storyteller. Naturally, the primary caregiver can take the role of the storyteller.

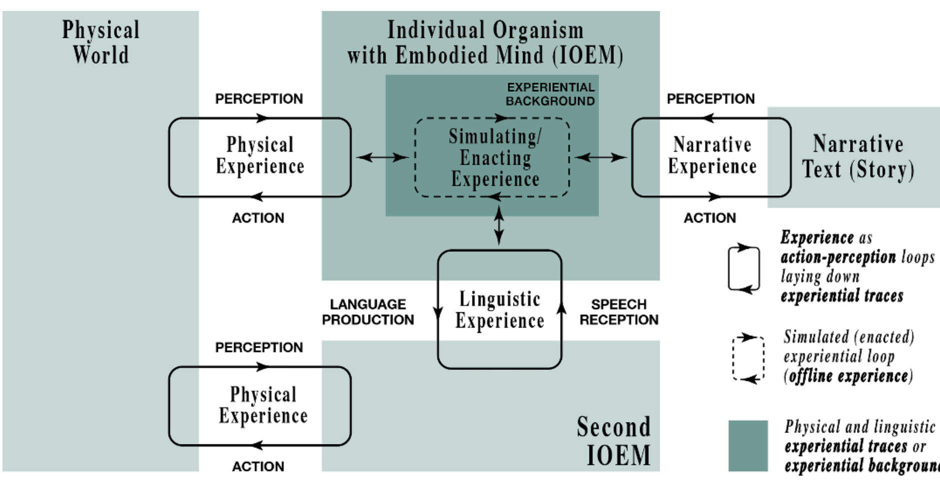

Figure 1.2: *A schematic rendering of a model of human experience. In its most extended or general form, experience is the result of the synthesis of several forms of interaction (feedback loops) between entities (boxes) in the world (physical world, persons, and artifacts). Only a selected few possible types of interaction are shown.*

A loop denotes the unified process of *action* and *perception*, i.e., an *interaction*. Its form calls attention to the nature of experience: it is the result of *feedback loops* such as those acting between a human and the natural world. Unfortunately, quite often, experience is taken in the restricted sense of perception alone—let’s call it impression of a person by the world—which is a one-way flow of information (which

Feedback loops of action and perception then is worked upon by a computational mind, just as what would happen in a computer). Often, we speak of sense impressions and treat them in the manner just described—as one-way flows of data. Naturally, there are also material objects flowing toward and into the human organism; natural scientists would add that this also includes energy. However, we are interested in what we usually call information: what we gather by sense-impressions.

In contrast, it should be clear that a living organism such as an animal or human acts upon the environment, not just the environment upon the organism. While we might do this in response to sense-impressions, the two, perception and action, are not normally seen as constituting a unity of experience—but in fact they do.[25]

Learning about Wind

Experiencing Wind and learning about it

Let us briefly outline what experiencing *Wind* could mean for early education. According to the model of experience just described, we need a child, nature (a windy day!), a teacher, some more children, and a storyteller. The only interactions or communications are those between child and nature, teacher and nature, teacher and child, between the child and his or her peers, and between the narrator of a story about *Wind* and the group of children. This limits the experiential interactions to *direct physical interactions* between humans and nature, and *oral narrative communication* between humans. In such a system, we believe, mythic awareness will arise. It can, if properly developed, support later more scientifically oriented explorations of the natural world.

Direct physical and narrative experience

If you are a teacher, take your young students out into nature and let them experience Wind. Speak with them about what they and you experience—in the widest sense of the word—and, at one point, tell them a story about Wind, maybe the one we have seen here or one you have written yourself. Make sure that you and the children speak about how intense Wind can be, how „big," i.e., spread out it can be, and how powerful it may be as experienced through what it does to them and you and the things around you. Use the simplest, clearest, everyday, non-scientific and non-formal language you can find. Observe mythic consciousness arising and be sensitive to how it may be strengthened and developed.

Experience is active/dynamical. In contrast to the limited view sketched above, we shall describe interactions between the participants in our model (natural world, child, caregiver, etc.) as feedback-loops, as closed loops of influencing and causing. Researchers working on some of the modern approaches of cognition and mind have demonstrated how, for example, visual perception and action—getting the body ready to visually perceive—form a unified whole that is best understood as feedback in a dynamical system.[26] In other words, an interaction between two entities is a „give and take;" *interaction is a form of communication* in a deep sense, not a one-way transfer of information. This applies not just to our interaction with nature but with all other entities as well. In particular, talking to each other is a feedback process of hearing (perceiving) and speaking (acting); even just hearing is an active loop of perception and action.

Experiencing as causal loop

If we consider the example of hearing and speaking, i.e., interaction through oral language, it becomes clear that there is more to the experience of (human) communication: something happens in our mind. If we are aware of it, it is clear that we are thinking (in a very general sense of the word) as a response to the loop of hearing and speaking (or simply orienting ourselves to the speaker—to get ready to listen). What happens in the process we call thinking can be described as an inner feedback loop of experiencing. Models have been developed that speak of *simulated experience*, such as the response one has to hearing or reading a story (see Volume 2 for a discussion of *narrative experientiality*[27]).

Enactive models of cognition. In enactive or embodied models of human cognition,[28] the mind is assumed to arise as a result of human-world interactions, where a person's world is made up by nature, other humans, and cultural artifacts. Forms of interaction can be action-perception loops between people and nature, orally linguistic with other people, literary with books, artistic (when we use paint and canvas, or our body in performances), or technical with machines and buildings. Importantly, in a human organism, these interactions are accompanied by (and they communicate with) inner simulated forms of experience.

In summary, we use the term *experience* in Dewey's (1925) sense, as the result of feedback in action-perception loops occurring between an organism and its physical, social, psychological, and cultural-linguistic environments. Alternatively, we might call *experience* the *unified action of perception and conception.*

Our model is one of mythical consciousness. In research on modern cognitive science, myth is rarely a theme. However, if we restrict our attention to the most direct or immediate experience of nature by a human, accompanied by communication with other humans in an oral society, the model presented in Fig.1.2 may offer a good image of mythic experience.

1.2 The Development of Myth and Orality

Some 40,000 to 50,000 years ago, and possibly earlier, modern humans started populating our planet. The designation *(early) modern* is referring to people who possessed fully developed (oral) language. They were anatomically modern and developed cultural features that went very much beyond what had come before. These humans and their culture(s) and societies seem to have developed over a time span that may have started 400,000 years ago, during the decline of what was the very long lasting (1.5 million years or so) culture of *Homo Erectus*. It is assumed that the mythic culture(s) of *early modern people* have survived up to today in some hunter-gatherer societies.

We are interested in the development of both orality and myth, and in the question of how they relate to each other. In order to understand this relation and the forms of consciousness they afford us even today, it may be helpful to briefly look further back to what has been termed *mimetic culture*, and forward to the *cultures of literacy*. This may give us a clearer impression of why and how myth and orality are important. How they are important for modern educational models will be explored in the following section.

Before myth: Episodic and mimetic cultures

Scholars exploring the history of the human species and our evolving mental powers typically divide the entire historical period from early hominids up to today into (more or less) distinct phases.[29] This development or, rather, evolution, is said to by *phylogenetic*, in contrast to the development of an individual from birth to death which is called *ontogenetic*.

Phases of human cognitive evolution

When discussing the human mind and forms of understanding, we can find models of a small number of such phases (Table 1.1) that can be called *episodic*, *mimetic*, *mythic*, *romantic*, and *theoretic* in phylogeny, and somatic, mythic, romantic, and philosophic in ontogeny.[30] Sometimes, scholars add very recent cultural developments on top of the list and speak of ironic or some post-X phases (post-industrial, post-modern…). Different researchers use different sub-divisions, but, very interestingly, they all seem to agree on a phase they call *mythic*, both for phylogenetic and ontogenetic developments. For education, the idea that, in ontogeny, we recapitulate cultural stages (Egan, 1997), will become important (see the rightmost column in Table 1.1, and Section 1.3). In the rest of the present section, we follow mostly Donald's (1991) description of the evolution of the human mind.

Mythic phase

Table 1.1: Phases of the human mind

Phylogeny (*)	**Age (†)**	**„Language"**	**External storage**	**Ontogeny (‡)**
Episodic	6 Ma	Reaction to events		Somatic (0-3)
Mimetic	2 Ma	Mimesis		
Mythic	100 ka	Oral language		Mythic (4-9)
Theoretic	10 ka	Early literacy	Stone, paper	Romantic (10-15)
	1 ka	(Formal) Literacy	Paper, film, HD, DVD, Cloud…	Philosophic (>15)

(*) M. Donald (1991). (†) Ma: million years; ka: thousand years. (‡) K. Egan (1997); age of an individual in years.

Different types of memory. Before we sketch aspects of the evolution of the human mind, it pays to briefly mention models of animal and human memory, since memory is an element of what allows an animal to function intelligently in its environment. A particular model of memory introduces three distinct types: *procedural*, *episodic*, and *semantic* memory.[31] Distinguishing between such memory systems will help us understand aspects of a model of human cognitive evolution.

Memory systems

Procedural memory

Procedural memory is hypothesized to be the earliest to have formed in birds and mammals. It serves the performance of physical procedures such as walking and grabbing and throwing objects. It is highly schematizing, i.e., abstracting, since it would not serve us well if we had to remember every step we ever took or every type of motion of the hand we ever performed. Note that the idea of abstracting from the details of physical procedures—which animals and we must obviously do—is not far from the notion of the formation of *embodied schemas* that result from recurring experience of the (physical, embodied) interaction between an organism and its environment. Embodied schemas, particularly in the form of image schemas, serve a foundational role in models of figurative understanding that have been developed in cognitive science in general and in cognitive linguistics in particular.[32] It seems that embodied schemas generalize the notion of procedural schemas to all results of learning having to do with our sensorimotor interactions with our physical environment (for example, see Section3.8).

Episodic memory, on the other hand, is believed to store episodes in relatively great detail, allowing us to have memories of things we have done and encountered. This is important in navigating a concrete physical environment and for functioning at a highly sophisticated level in social setting—being able to function physically would not be enough for social animals if we could not remember who we met the other day and what their and our roles are in a given society.

Episodic memory

Semantic memory, finally, is said to be unique to humans: it is a memory system for symbols, and only humans are believed to have a fully functioning symbolic mind. Symbols are physical objects or immaterial signs (including speech) that relate to an idea or meaning—remember what we explained about the meaning of symbolic activity in the context of myth (see p.9). Art, music, dance, and human natural language are all described as symbolic systems. Having a semantic memory means that we are capable of storing and retrieving symbols—this lies at the root of the human form of meaning-making.

Semantic memory

Episodic culture. The Great Apes are masters at episodic perception (event perception), recall, and corresponding understanding of a given situation.[33] This means that they are able to recognize meaningful episodes, store them in memory, and recall them for important purposes. Meaningful episodes for a primate might include a foraging trip where food was found, who wronged him or her, and generally, who is who in the group the individual is living in. All this is important for survival and cohesion of a group of primates. „Complex societies demand a tremendous memory capacity, and the type of memory that is important in social relationships is, above all, episodic memory. Episodic memory is little else than a storage system for event perceptions, and thus there is a close tie between episodic memory and the capacity for social event perception."[34]

Hominids and primates

Event perception

We can expect early hominids (whose ancestry goes back some 6 million years) to possess similar cognitive abilities. Importantly, all hominids, archaic humans, and modern humans (including us) still possess the ability of event perception and episodic recognition and recall—without these functions we would not survive day one. This leads to an important message: we still have fundamentally primitive (original, primary) abilities, and we need them; what we call „advanced" cognitive powers will have been built on top of older and simpler ones. New capacities do not replace older ones!

Event perception has not disappeared in us

Mimetic culture. About 2 million years ago, a group of humans evolved whose culture would survive for another 1.5 million years or so: *Homo Erectus* (*HE*). These archaic human groups developed a culture that is clearly distinct from what went before. Unlike primates and early hominids who basically stayed put in their environments, *HE* migrated out of Africa over large areas of the Eurasian continent. They developed tools and materials much more sophisticated than what their ancestors had. *HE* used fire (and probably cooked food) and engaged in seasonal hunting. Anatomical change included an increase of brain size to about 80% of today's humans.

Homo Erectus

On hard evidence from sophisticated tools and weapons—considering that there were no advanced and refined tools for producing these tools—we can hypothesize that *HE* needed social and cognitive skills that would allow for such tool manufacturing; this includes, importantly, skills for passing the mastery of toolmaking to the next generation and so maintaining the culture of *HE*. If we think of human cultural and cognitive evolution as adding layers upon existing abilities, it seems that what enabled the new culture is a new ability of re-presenting (modeling, enacting) episodic knowledge and memories. All of this had to happen without natural (spoken) human language (there is no evidence that language in this sense could have evolved before about 100,000 years ago).

We still possess the ability to (re-)enact what we might call direct experience without making use of language per se—this is called mime (mimetically enacting experience). We do this to a large degree and in a very refined manner in all the arts (drawing, sculpture, pantomime, dance, music, film, opera, and theater) and in technical apprenticeship. It is certainly true that having language greatly facilitates passing skills from one person to another but, fundamentally, language is not needed. Moreover, there are or were fully functional people who do not possess language: pre-linguistic children and deaf-mutes of the past (who did not receive education enabling them to develop a form of language). This tells us that there must be a cognitive layer between episodic culture and mythic understanding (where the latter depends upon our modern form of language).

People without language

Mimetic skill

Mimetic skill can be very sophisticated. It can create elements for enacting episodes that are part of our modern natural language as well. „Mimetic skill or mimesis rests on the ability to produce conscious, self-initiated, representational acts that are intentional but not linguistic.”[35] Note the reference to conscious and intentional acts. We can think of the importance of intentionality in how a pre-linguistic child detects the intentions of a parent in participatory sense-making. Apparently, other primates mostly lack this ability, at least in its sophisticated form.[36] A list of properties of mimetic acts can give us a feeling for what is involved: mimesis is intentional, generative, communicative, referential, auto-cueing, and allows for enacting an unlimited number of events. Being generative means that mime includes symbols that can be re-combined in different sequences for expressing different situations and intentions; auto-cueing refers to an individual being able to prompt himself or herself for mimetic acts and to recall how specific episodes were mimed before and by others. All this may have led to a cognitive ability we can call an early form of thinking. In sum, „Mime is intentional; its objective is the representation of an event.”[37]

Mimetic ability can explain some social sophistication that must have been in place with *HE*, such as representing social structure, coordinating group actions (such as hunting), simple pedagogy, including apprenticeship, and games. *HE* set itself apart from the other primates, and with mimesis, set the stage for the next phase of human cognitive evolution.[38]

Mythic Culture and Oral Language

The next stage in the evolution of our mind may have started a couple hundred thousand years ago but was not fully in place until about 40,000 to 50,000 years before present. We refer here to what has been unanimously called a mythic phase of human development. The humans emerging during the transition from mimesis to myth are what we now call modern humans (*Homo Sapiens Sapiens*).

Homo S. Sapiens

Indigenous societies

Judging from archeological records, especially those showing us the artistic achievements of modern humans (see p.18), and surviving mythic indigenous societies, social structures and oral language developed much more profoundly and earlier than technology. Toolmaking did not progress beyond *HE* levels as fast as social and cognitive inventions must have.[39] Therefore, looking to tool-making as the driving force in the development of the modern mind in general and language in particular, might be the wrong place for us to search. It seems more likely that a general trend towards greater, more intense, and longer lasting episodes of

Technology lagged behind linguistic skill conscious awareness, both in individuals and shared in social groups, must have been the force that led to change. In some mythical stories, we can interpret a recurring theme of moving toward the light and fear of falling back into the dark as an expression of the meaning and emotional power of becoming conscious.[40]

One of the most powerful examples of experience early modern humans may have become conscious of is the certainty of personal death. Becoming conscious of this, maybe through the practice of killing animals, may very well be a powerful reason for needing to understand our place in nature and society[41]—something myth is predestined to help us with. Myth originates as a response to emotional and psychological pressure that needed to be dealt with socially—it could not be dealt with in an isolated mind. Inevitably, myth creates a new form of understanding upon the existing mimetic mind.

There is much to learn from the studies of myth and mythic societies that have been undertaken to date—too much to deal with here. We shall discuss the importance of art for myth, and of myth for education, further below. At this point we just want to describe a model that may help us understand the co-evolution of mythical consciousness and oral language (see Fig.1.3), which will be a recurring theme in our subject of primary science education.

Co-evolution of myth, language, and narrative

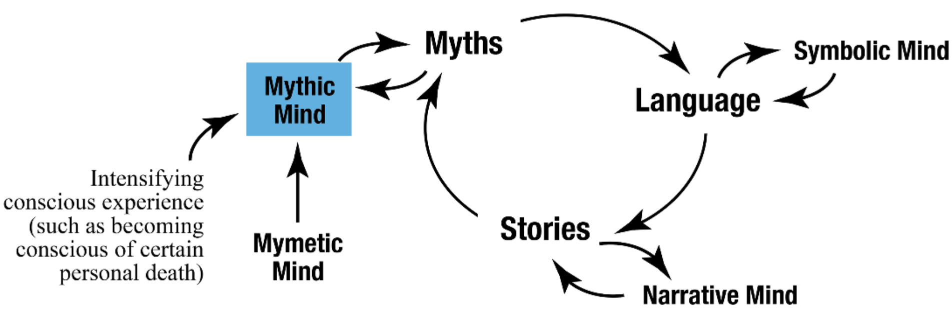

Figure 1.3: *A strongly simplified dynamical model of the development of myth (mythic consciousness, culture, and mythic stories). Myth, language, and narrative understanding depend upon each other equally for their development. The feedback cycle may have been initiated by the emotional need of late Homo Erectus or early modern humans for expressing intensifying (self-)awareness of their place in the world. Small cycles symbolize mutual development of consciousness and product (such as symbolic understanding and language skill).*

For myth(s) to develop, three capacities needed to be in place or, rather, to co-evolve: *mythic consciousness* or understanding, *symbolic understanding*, and the general *understanding of narrative* (a narrative mind). Let us take a look at language which is a symbolic form of human expression. On the surface, language consists of linguistic symbols—parts of words, words, utterances, and whole sentences. More fundamentally, these symbols consist of a physical part—the spoken and heard sound—and a meaning. These would be the units our semantic memory keeps for us to be retrieved upon cueing (when we hear or read a linguistic symbol). In other words, *language is symbolic in the same way myth is* (remember how we described the meaning of symbol above on p.9: a symbol unites two spheres of being, physical and ideal, in a new perceptual unit or gestalt).

Myth and language are both symbolic

Myth to language. Starting the model of co-evolution of myth, language, and narrative with myth (we can actually start at any point in a loop like the one seen in Fig.1.3), lets us hypothesize that myth drives language development. Mythic consciousness creates the need for expressing the particular mythic experience—the unified image arising from a phenomenon such as wind and the emotion, feeling, idea it give rise to, i.e., the character of *Wind*—in a different way, so one can re-present it to oneself, or maybe share it with others who have the same mythic experience. We can assume that the mythic symbol—*Wind*—will be modeled and expressed in terms of another symbol such as the linguistic symbol *wind*. The linguistic symbol is the object that is created by fusing the sound wɪnd (this is the phonetic rendering of the English word *wind*) with a meaning. This meaning could be borrowed from the meaning associated with the (mythic) experience. If it is, we have an explanation of how linguistic signs are understood: their meaning should coincide with a non-linguistic meaning created in experience: we understand something through language if the linguistic sign gives rise to the feeling and meaning of the original experience.

Mythic and linguistic symbol

Language to narrative. This brings us to the next point: experience is experience of something going on, an event. An event can be „microscopic," a very brief incident such as you noticing all of a sudden that there is wind (the awareness of wind popping up in your mind); it can be a „meso-scale" episode such as wind blowing a leaf along a street; or a large-scale phenomenon such as a storm hitting a beach, creating giant waves that destroys a town.[42] The human way of reporting and recording the event is to tell or recall a story. A story—the prototype of narrative—includes all of the following elements: (1) *events*; (2) (conscious) experiencing of events by *agents*; (3) *tension* for creating events; and (4) *reason or occasion for telling* by a narrator.[43] This short list already hints at a strategy for understanding Forces of Nature: tell stories about them!

Story for large-scale experience

Story: Elements

„Narrative skill is the basic driving force behind language use, particularly speech: the ability to describe and define events and objects lies at the heart of language acquisition."[44] Narrative in general and stories in particular tell of a narrative mind, a way of understanding the world around us with the help of narratives. Stories are more than the reporting and recording of an „atom" of experience („there is a leaf on the street"): they give form to a unified experience that includes the perception of agency and explanation of what is going on in terms of such agency; explicitly or implicitly, they are telling us about the meaning of the experience. Note, that „narrative imagination can be supported in a purely oral, or preliterate, tradition;"[45] we know this from indigenous hunter-gatherer societies that existed until just recently (or are still existing), and we know this from young children before they become fully literate.

Narrative to myth. This bring us back to myth and concludes the cycle we use as our model of how myth, language, and narrative co-evolved (Fig.1.3). Concrete myths are presented in story-form. We need a narrative mind in order to put mythical experience into proper linguistic form. In their totality, and if they are developed to a high degree, language, narrative, and myth are „the prototypical, fundamental, integrative mind tool. [They try] to integrate a variety of events in a temporal and causal framework. [They are] inherently a modeling device, whose primary level of representation is thematic"[46] rather than episodic.

Concrete myths are narratives

Mythic art: Abstraction and imagination

While oral language is a premier mythic cognitive tool, we should not forget all the other possibilities of human expression that must have shaped, and were shaped by, mythic culture as well: drawing, sculpting, acting and dancing, and making music. They all represent symbolic capacities that grew out of mimetic culture.

Art is symbolic

Of all these, the products of visual art have survived the tens of thousands of years since their invention (Fig.1.4).[47]

There is much controversy as to what meaning the various artifacts might have had for their creators and owners. If we do not want to impose our modern way of thinking and understanding upon these ancient artistic expressions, we have to admit that it is difficult to answer this question. A few things are certain, however. The art was produced at a time when oral language had developed to a very high standard (judging from oral cultures still existing today), and it was a part of mythic society (again judging from today's oral civilizations). One more thing we can say with certainty—and it is important for the theme of this chapter and the book as a whole—the art speaks of a mind capable of extraordinary feats of abstraction and imagination.

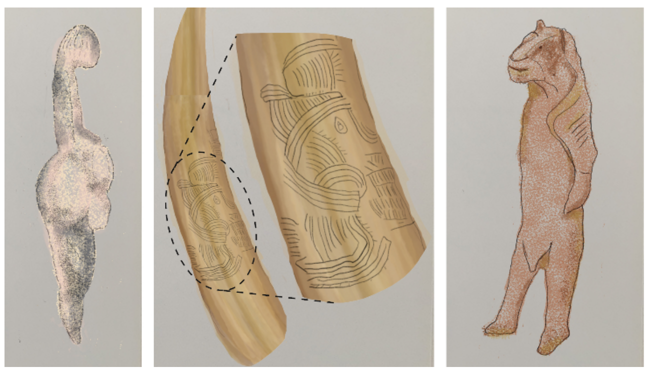

Figure 1.4: *Drawings of ice age art by RF (photographs of these objects can be found online or in Cook, 2013). Left: Female figure. Center: Abstract ornaments on a mammoth tusk. Right: Lion Man. The Lion Man is about 40,000 years old; both the female figure and the mammoth tusk engraved with geometric forms are roughly 25,000 years old.*

Ice age art is abstract and imaginative

Consider, the abstract rendering of a female figure (Fig.1.4, left). Here, a human body is composed of idealized geometric volumes as in a modern cubist panting. Simple schematic elements are used for representing a real object, a human body, in a highly abstract image. The engravings on a mammoth tusk (Fig.1.4, center) are schematically abstract in the same basic sense. Whether or not the image is purely ornamental or may be a kind of map, as has been suggested, of the area where the object was created, does not change our judgement that the art is highly abstract, a result of the schematizing action of the human mind (see p.23 below, and Fig.1.5).

Now, take a look at the statue of the Lion Man (Fig.1.4, right) discovered at the Hohlenstein-Stadel cave in Germany in 1939. Here, our focus is on the imaginative activity of the artist: whatever the meaning or use of the figure may have been, a being of this type does not exist in physical reality, but it may so quite easily in mythic reality. Artistic creation and enaction of beings that do not exist physically is one of the great powers of imagination that have shaped important aspects of understanding the world, starting at least with the mythic age.

Orality and Literacy: Development of writing

Let us add a very brief outline of the cognitive evolution that came after myth, the invention of linguistic symbolic enacting of experience, and the growth of literacy.

Apart from everything else that matters, literacy—writing systems for natural language, plus systems of formal languages that evolved from the former—may have been the most important tool added to the modern mind. It must be said and stressed: without literacy there would be no science. Remember what we said about myth: myth is not science, not even primitive or proto-science.

External storage of visual linguistic symbols

Writing systems depend upon the externalization of linguistic symbols. Writing systems enlist visual-graphical elements as signs for linguistic symbols and external storage systems for keeping records of „spoken language" that can be inspected again long after they were written down. Writing systems can be hieroglyphic, cuneiform, ideographic, or phonological (alphabetic).

Mathematics as formal language

The consequences of writing go far beyond us being able to record what we otherwise would simply have said out loud. Think of mathematics as one of the symbolic systems that heavily depends upon the use of visual-graphical signs and our ability to write. For the sciences, mathematics is the premiere formal language in our toolbox of languages.

It is difficult for us today to understand how writing systems have enabled a literary mind to evolve and what this means for our understanding of the world. Our thinking and understanding—our entire form of consciousness—have changed dramatically. One of the profound changes relates to the difficulty we have today if we want to understand mythic consciousness; this difficulty becomes obvious when we consider our „modern" attitude toward nature and try, as hard as we can, to put meaning into nature myths of native peoples—it is no easy undertaking, and success is by no means ensured.

Another sign of this profound shift can be seen in our heavy reliance upon dualistic thinking—one of its expressions is found in how we put a distance between self and other. Again, our relation to nature serves as an example: we feel that plants, animals, rivers, mountains, oceans, the atmosphere, and actually all the other things on this planet and beyond, are profoundly separate from us; everything is a pure object of study and exploitation. A mythic person's insistence that we can communicate with nature strikes us as quaint.

Memory in oral and literate societies

Homer and oral tradition

To get a feeling for what has changed, consider this: what was and is the role of memory in oral and literate cultures? In a purely oral society, there are no records of words; as soon as a word has been spoken, its physical trace has vanished. Remembering must take a form which is hard for us to fully appreciate today. Consider Homer's epics, the Iliad and Odyssey, that were born of myth and orality. How could a singer or storyteller remember all of the Iliad and Odyssey? Milman Parry studied the still living tradition of bards in the Balkans in the 1930s.[48] From what he learned, he became convinced that, first, Homer would have to be placed in the oral tradition, not the literary one and, second, that it would have been impossible to remember these epics by heart—as we understand learning, remembering, and reciting by heart today. Listen to what Robert Wood (1767, p.158) had to say on the meaning of memory in oral and literate societies:

> „[...] nor can we, in this age of Dictionaries, and other technical aids to memory, judge, what [the] use and powers [of the oral tradition] were, at a time, when all a man could know, was all he could remember. To which we may add, that, in a rude and unlettered state of society the memory is loaded with nothing that is either useless or unintelligible; whereas modern education employs us chiefly in getting by heart, while we are young, what we forget before we are old."

Poets and bards would use the overall arc of a story plus the power of rhythm and rhyme to produce the story and its verses anew every time they recited an epic for the public; in other words, a bard would improvise, in the best and deepest sense of the word. Being able to do this would have taken a lot of training of a type we no longer use.

1.3 Children's Oral Mythic World

Myth is the first „modern" form (modern in the sense of modern humans) of relating to nature that is still with us today.[49] We are not usually aware of this, particularly not in scientific approaches to the world around us; so, part of our goal for this book is to show how myth—even though it is not science or scientific in any sense of the word—helps us enter the world of scientific studies of nature.

We owe much of our knowledge of the importance and meaning of mythic culture for primary education to Kieran Egan,[50] a philosopher of education who suggested how specific *cognitive tools*[51] such as play, metaphor, story, sense of agency, tools of literacy (forms, lists, maps...), the search for authority and truth, and meta-narrative understanding, develop through ontogenetic phases of cognitive growth he calls *mythic*, *romantic*, and *philosophic* (Table 1.1) in a manner resembling cultural development. When children first enter and develop an oral culture, they are said to go through a phase of mythic consciousness. Only later would they become capable of using the tools we usually associate with a scientific attitude, practice, and understanding.

Cognitive tools

Mythic, romantic, and philosophic phases

If we apply Egan's idea to education, we might speak of a scheme of *recapitulation of cognitive cultural stages*.[52] After briefly touching upon this idea, we shall describe examples of early emergence of abstract and imaginative forms of understanding in young children. Finally, we list some of the cognitive tools of mythic culture we can identify in today's children. In general, we choose and emphasize aspects that refer most directly to our theme, to nature education.

Cultural evolution & Cultural Recapitulation

While there seems to be a relatively straightforward line of ontogenetic development from mimesis, to oral language, and to early and refined uses of literacy (especially influenced by print[53]), cognitive stages relating to this evolution do not follow a simple historical sequence. Take the example of romantic understanding which can be associated with at least three historical phases in European cultures. There is a first occurrence of „romance" in the historical writings of Herodotus who, after the oral history of early Homeric Greece wrote about the wonders of Egypt; his writings differ sharply from a modern analytical and intellectual approach to history (which, by the way, was already achieved by Thucydides shortly after Herodotus' writing in his analysis of the Peloponnesian war). We can again recognize a romantic attitude in the early Renaissance, which brought us a modern sense of space (rather than just an understanding of spatial relations); we can see this in Francisco Petrarch's description (1336) of himself climbing to the summit of Mont Ventoux and seeing the Rhone valley lying below.[54] And, naturally, there is the modern age of romanticism in the late 18th and early 19th centuries, where poets tried to give nature and science a new (old?) meaning after we have already had a phase of philosophic/theoretic development in Newton's physics and Descartes' philosophy.

Maybe the simplest way of characterizing cognitive cultural (not historical!) stages is in terms of forms of language use (Table 1.1, column 3). In a very crude form, directed by our focus on nature and science, we can associate myth with a sense of nature being populated by „animated" entities; romance denotes a form of enhanced awareness of a distance between self and world which makes it possible to see nature as consisting of a great number of wondrous and awe-inspiring „things" we might want to get to know; and philosophic understanding gives us a sense of the meaning of analysis and theory, of formal schemes and theoretic knowledge. Clearly, cognitive tools of early and „high" literacy take time to develop.

In sum, recapitulation of cognitive stages must mean something different than retracing either biological, psychological, or historical phases. In particular, we should not want to compare today's children to adults in past oral mythic societies. Neither do children have the experience of a long life nor are they part of a purely oral society—today, they are part of a culture that values and employs tools of literacy. Therefore, „[the] basis of the comparison [between past oral cultures and today's children], however, is neither knowledge content nor psychological development but techniques that are required by orality." „Orality entails a set of powerful and effective mental strategies [. . . that] should be conserved as foundations for more sophisticated forms of understanding."[55]

Repeating what we said before, children should not be treated as incomplete adults but as complete human beings in a phase where they develop (or are already in possession of) a certain set of mental tools. Among their most important abilities are powers of abstraction and imagination (see p.23).

Children and their learning. If we now turn to the question of how all of this relates to children and their learning, we first have to ask when is a child not a child any longer? If we are interested in primary science education, it probably makes sense to put the transition of where children become adolescents at an age of 11 to 12 years. Yet, this leaves us with a very long period indeed during which children develop in major ways. We will therefore, for our present purpose, choose an age range between about 3 or 4 to 8 or 9 years when, as has been pointed out by Egan, children go through a developmental phase he calls *mythic*.[56]

Children's mythic understanding

The mythic phase of children—a recapitulation of cognitive aspects of mythic culture in the history of human development—is characterized by the development of cognitive tools chiefly associated with oral language; to these we should add mime, art and music, rhyme and rhythm, games, and story.

Romantic culture

By age four, most children master much of spoken language. Then, by age 8-10, they will have acquired some facility with early literacy (in Egan's terminology, this is the beginning of *romantic* culture and understanding[57]). This move greatly changes the type of cognitive tools available to children, not to mention important changes in their psychological makeup that will occur soon after. Therefore, when we want to discuss how children encounter Forces of Nature, we need to consider the age of the children and the cognitive tools available to them.

The reader will have noticed that we assume phases to overlap and merge into one another. It would be wrong, for example, to assume that if we wish to develop mythic understanding and the cognitive tools related to it, we should refrain of developing literacy. Not only would this be impossible to do—in our school systems, children begin reading and writing rather early—it would also rob us of the opportunity to use some tools of literacy for working on mythic understanding. If stories are an important ingredient of the mythic phase, why should children not be taught to read them by themselves? The point is simply that the stories should be of a form that supports myth; in our view, this is particularly important if we create and use stories of Forces of Nature.

These issues will accompany us throughout our book and will come up prominently again and again. Different issues in *Primary Physical Science Education* and different ways of dealing with them will call for new perspectives for learners at different stages of development. Let us start with a couple of issues relating to the younger group of children. We shall discuss how steps toward science could be taken in Section 1.4.

Children and the power of abstraction and imagination

A first basic question that will concern us here is about how small children experience nature. We have claimed that body and mind provide us with experience of a perceptual unit we call Force of Nature (FoN), and that concrete Forces are understood in terms of schematic structures developing in us through recurring sensorimotor activity as we interact with the world around us (see, in particular, the sub-section starting on p.7). Can we recognize young children's minds in our description of how we understand Forces of Nature? After all, the description is made from the perspective of adults for other adults in literate societies.

A pertinent point in our discussion concerns the issue of *abstraction*. Depending upon which developmental psychologists and educators we listen to, we may be told that children and adolescents develop through stages called sensorimotor, pre-operational, concrete operational, and formal operational. This is sometimes abbreviated as saying that children are concrete thinkers who, much later in life, develop the ability of abstract thinking.[58] We shall take a different perspective in this book.

Abstracting as schematizing action of mind. Before we continue discussing the development of cognitive tools of young children, we should describe what we mean by abstraction. In fact, abstraction can be taken to mean quite a few different things (Fig.1.5). Sometimes, we say that *abstract* is what is *not concrete*, but then we need to explain what we mean by „concrete." Sometimes the distinction is made between physical and nonphysical, such as when we refer to a house or a tree as (physically) concrete and to justice or anger as (non-physically) abstract. In our view, it makes a lot more sense to keep the designations *physical* and *nonphysical* rather than *concrete* and *abstract* in order to make this distinction.

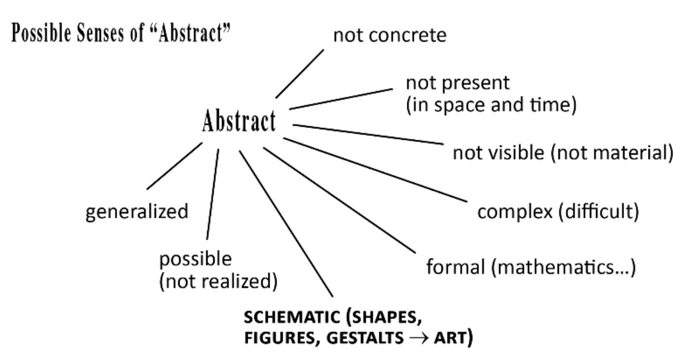

Figure 1.5: *Possible meanings of the words „abstract." There are some uses (such as for complex/difficult of formal as in mathematics) that should be rejected—they do not mean abstract in any sense. We prefer to use „abstract" in the sense of schematizing.*

There are other uses of the word abstract that do not make much sense. In everyday life, we quickly use the designation for things and situations that are complex and difficult or formal (as in mathematics and formal logic); see Fig.1.5. To the extent that mathematics is formal, it does not create or deal with abstractions per se—which does not mean that mathematics would be incapable of creating its own new abstractions.

However, as we shall discuss shortly, *abstract* may make sense if we use it for *not-concrete* in the opposition of *concrete – generalized*, i.e., if we mean a concrete specimen (which can include a „specimen" of justice or anger) as opposed to the abstract category made of all possible cases of buildings or instances of the perception of justice.

Abstracting as schematizing action

The verb *to abstract* stems from Latin (*abstrahere*) and means something like *drag away from*, *remove* (forcibly), *split*, *keep away from*, *exclude*. Its root, *trahere*, means *pull*, *draw*, or *drag*. This comes close to how we shall use the term here: it describes the power of the human mind to *schematize*, to create shapes, figures, or schematic images (which do not have to be visual at all) from concrete experience (Fig.1.5). Concrete experience—and this includes the experience of emotions and feelings that lead us to phenomena we are inclined to call purely abstract such as love or justice—is transformed through recurrent activity of body and mind into schemas which we are able to put before us in imagination, manipulate, and work with.

This sense of abstract does include its use for distinguishing between concrete and general (i.e., general in the sense of not concrete). However, it is best described by an example of schematizing action which we can see happening in Fig.1.5: if you look at it carefully, you may see an oval around the word *Abstract* at the center of the spatial arrangement of the terms and lines: the straight lines end at the periphery of a non-existing oval and so let the oval appear in our mind—it is *imagined*. This is an example of what is called (visual) gestalt perception. Importantly, gestalts do not have to be visual or graphic—they can be auditory or related to any of the other kinds of our senses.

Image schemas in early language

DL's language and stories. Here are some examples of early linguistic, narrative, and artistic development of a boy we had the privilege to observe. When DL was one and a half years old, he started speaking. Observations of the development of his language are quite revealing of how schematic structures become accessible early in life. Binary opposites and polarities became evident as soon as the first words emerged and were expressed as single terms: *up* for up ↔ down, *open* for open ↔ closed, *cold* for cold ↔ warm are among the most important examples.[59]

What appeared to be names for some objects actually denoted fairly large-scale experiential units: *coffee* stood for the action sequence consisting of being carried to the coffee machine, turning it on, opening the lever (for which the term *open* was used), inserting a capsule, closing the lever (when DL again uttered *open*), placing a cup, and pressing the button for the espresso; a second uttering of *coffee* called for his grandfather to sit on the couch and drink the coffee. The term *jacket* meant that he wanted his jacket, be carried downstairs to the terrace door, be lifted so he could insert the key and open the door (this sequence was called *key*), and then go outside.

Logical conjunctions came early as well: *not* was first, then came *and*; *or* actually took quite a bit longer, until DL was maybe three or even three and a half. Naturally, he had nouns for objects as well, but they did not seem to be particularly dominant in the totality of his use of language.

When DL was exactly four years old, rather than having a story told to him, he told his father a bedtime story about Baby Wolf:

Stories told by young children

> DL: *Eines Tages war dort ein Baby Wolf. Der hat so haauuu gemacht, und der ruft nach seiner Mama. Und dann bin ich angekommen zu dem Baby Wolf und habe ihm geholfen.*
>
> *Und dann bin ich in einen Abfluss rein gegangen, da bin ich hoch und runter, rechts und links, hoch, runter, rechts und links. Und dann bin ich bei der Wolf-Mama angekommen.*
>
> *Dann bin ich wieder hoch und runter, rechts und links, hoch, runter, rechts und links, gegangen. Dann sind wir rausgegangen aus dem Abfluss.*
>
> *Und dann bin ich wieder nach Hause gegangen.*
>
> Father: *Da hast Du eine gute Tat gemacht.*
>
> DL: *Und die war ganz klein...*
>
> Father: *Der Baby Wolf?*
>
> DL: *Nein, die Geschichte...*

[English translation: DL: One day there was a baby wolf. He made so haauuu, and he calls for his mama. And then I arrived at the baby wolf and helped him. And then I went into a drain, I went up and down, right and left, up, down, right and left. And then I arrived at the wolf-mama. Then I went up and down, right and left, up, down, right and left again. Then we went out of the drain. And then I went back home. Father: You did a good deed there. DL: And it was very small.... Father: The baby wolf? DL: No, the story...]

Polarities in stories

As a unit, the story is generated by a tension derived from a polarity (insecure ↔ secure, fearful ↔ consoled, or similar)—the little wolf is lost and fearful; DL is ready to help and reunites the little wolf with its mother. For DL, we might also postulate a polarity expressing his willingness to help (helpful ↔ unhelpful) which accompanies another feeling expressed by good ↔ bad. The structure of the story is conventional: there is a beginning where the tension is set up, a middle where the challenge is addressed, and a resolution at the end telling us that all is good again. In the story we find words using spatial schemas that help us develop a sense of what it meant for DL to search and find the little wolf, deliver it to its mother, and return home.

DL's drawings. When he started drawing, his productions were typical of those of children his age—scribblings[60] and non-figural colorful shapes. Before he approached his fourth birthday, he started representing ideas, objects, and experience in rather abstract schematic manner (Fig.1.6). After a prolonged period of being fascinated by volcanoes, he drew „Dangerous Ener-Gee," as he called it (Fig.1.6-1). Apart from this being a representation of an idea—not a material object—the drawing is highly schematic: there is a container with some stuff (dangerous energy) inside and flowing violently out at the top.

Abstract (image) schemas in early art

His monthlong activity of constructing bridges—which he would destroy to the song *London Bridge Is Falling Down*—led him to draw „Bridge Over Water," a highly abstract sketch of a concrete situation, on a blackboard (Fig.1.6-2). Finally, a little later, when he was around four and a half years old, he drew two electric towers (actually put underground below buildings; Fig.1.6-3) with cables between them.[61] About the drawing he said „in the middle is where the electricity acts."

A couple of months later he repeated the drawing but replaced the schematic figure at the center of the connecting power lines by a colorful (yellow-orange) and schematic rendering of a fire (inset Fig.1.6-3B). Ornaments developed and were used repeatedly for different objects and situations when he was about five to five and a half years old (Fig.1.6-4).

Schematizing action of mind at an early age

DL's activities provide evidence of the schematizing—abstracting—action of experience at an early age.[62] If we accept the model of embodied and enactive experience, it should not come as a surprise that the production and use of schematic structures, both in language and art, must start when the life of a person begins—abstraction in the sense of schematizing action of the mind happens early.[63] What we call rich concrete knowledge of the world around us takes time to develop—years of encountering and hearing and learning about lots of „stuff," and acquiring cognitive tools for dealing with all that „stuff," which, among other things, involves the use of literacy. Part of our job is trying to understand how the power of primary abstraction can be used by children for learning about forces of nature.

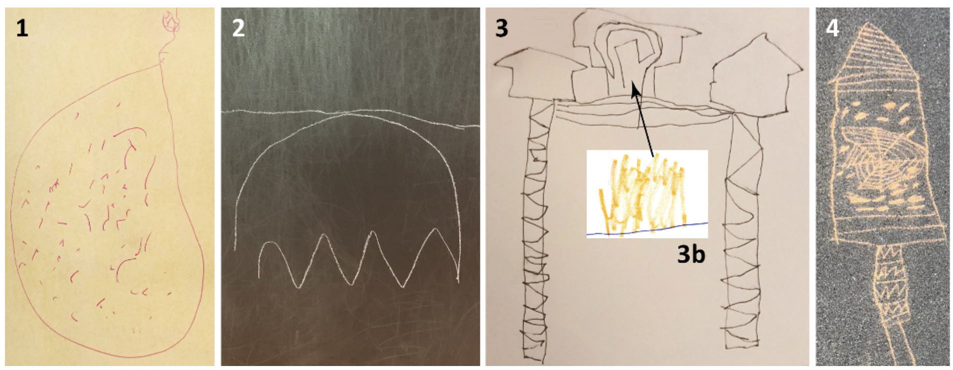

Figure 1.6: *Drawings by DL when he was between a little less than four years and four and a half years old. (1) „Dangerous Ener-Gee." (2) „Bridge Over Water." (3) „In the Middle Is Where the Electricity Acts." The names or descriptions of the drawings are those given to them by DL. (4) DL's street art: ornaments on a piece of firework.*

Cognitive tools of mythic understanding

We know what children—in the age range we have associated with the mythic phase (from 3 or 4 to 8 or 9)—are capable of and what they love to do. They play and invent games, they use mime and props for these games; they use simple materials such as cardboard boxes, strings, sticks, etc., for building something that may never have existed before; they sing and are able to memorize lyrics; they sing and talk to their stuffed animals, dolls, and other toys (when they are a little older, they also read to them); they might have imaginary friends and they „see" ghosts; they love to hear stories and are obviously able to invent simple ones themselves; they use abstract schemas in art; and they use metaphor and analogy[64] when they recount and explain events.

The stories they like to hear or the movies they love to watch are full of fantasy—the more, the better. The Disney *Ice Age* movies are a great example of what kind of stories and fantasy kids go for. They also love dinosaurs, but if we want to bore them out of their minds, we simply need to make them watch a typical „explanatory" tv show on dinosaurs that employs what we adults call „realism."[65]

All this tells us something about the mind and the abilities of children. They abstract from the direct flow of experience and think and act imaginatively; they have great episodic memory; they use sophisticated oral language and understand metaphor and analogy; and they are able to get deeply involved in stories and play where narrative experience is created (Fig.1.2).

A list of cognitive tools. Based upon such observations, Egan proposed a list of important *cognitive tools* of what he described as a child's mythic phase: *Story*; *metaphor*; *binary opposites*; *rhyme*, *rhythm*, and *pattern*; *jokes* and *humor*; *mental imagery*; *gossip*; *play*; and *mystery* (and, not to forget, embryonic forms of *literacy*).[66] The list is strongly influenced by what is available to us as a consequence of oral language use. Egan's general claim is that if we wish to go after the holy grail of modern education—literacy of various forms and formal reasoning—we need to create a solid foundation upon which a child can securely stand; this foundation can be found in the cognitive tools of a mythic phase.

Cognitive tools of myth (a list)

The list of cognitive tools contains elements that may be seen as belonging to different categories or, rather, abilities present in mythic culture. Moreover, it makes sense to add important abilities to this list, particularly those that involve a more active use of our body than will be needed by just employing spoken language. This allows us to create an overview as follows (Fig.1.7): some of the cognitive tools, such as rhythm and narrative experiencing and sense-making have to do with our ability to *experience* (in the very general sense of the word expressed in Fig.1.7); others, not mentioned explicitly in Egan's list but certainly implied, such as miming and speaking, are part of the category of *creating symbols*; still others, such as play, are part of a person's or a group of persons' *creations*.

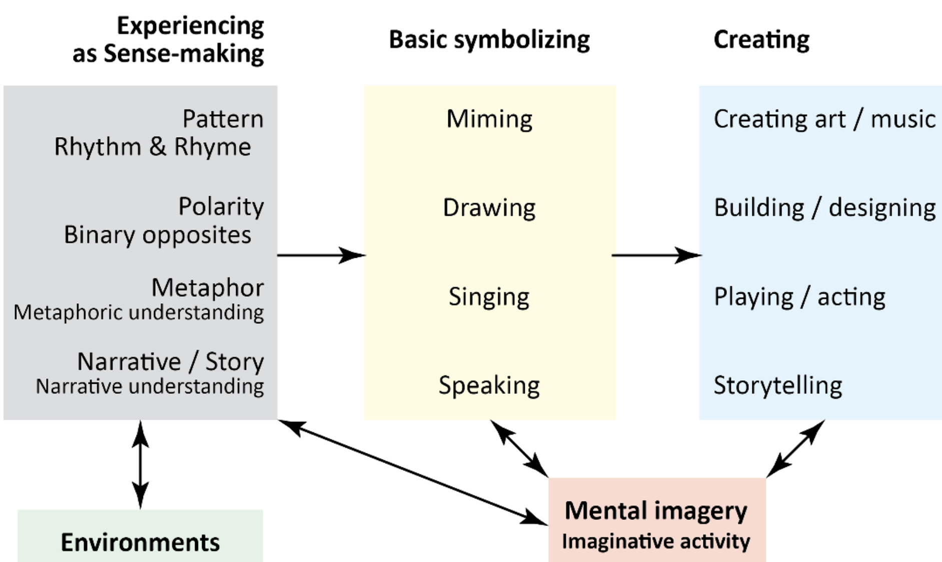

Figure 1.7: *A feedback model of cognitive (experiential, symbolizing, and „embodied" and „manipulative") tools ordered according to our abilities to experience (in the sense of sense-making), symbolize, create, and imagine. The ability to use mental imagery underlies which symbols we create and how we play, build, and tell stories, and, finally, how we experience.*

Experiencing as sense-making. Experiencing includes our ability to feel, use, and understand patterns we can see, hear, smell, taste, and perceive through direct touch. They include the sensation of temporal patterns, which is fundamentally important for our understanding of dynamical phenomena in which Forces of Nature (and other Forces) are involved.

In such patterns, we can discern differences—we can distinguish between feelings of differing intensities. More specifically, this may be the source of a prominent feature of mythic consciousness which we find expressed in much of children's activities, communication, and preferences as well: the sense of *polarity* or of *binary opposites*,[67] which are a special case of polarity (see below for a more detailed discussion of this point).

Children quite obviously understand and use metaphor, and the same is the case with narrative. Note that *metaphor* and *narrative*, listed as forms of experience and means of sense-making, do not refer to specific metaphoric expressions or particular stories—the terms describe our sense of, or sensibility for, seeing one thing in terms of another (in metaphor) and being sensitive to narrative experiential units that include certain specific forms, schemas, and patterns (such as events, agency and causation, and time).

Metaphor and story as part of experiencing

Basic symbolizing and Creating. The next two boxes in Fig.1.7 list two groups of cognitive tools that have to do with expressive acts. We have explicitly added *miming* (basic acting), *drawing*, *singing* (or, generally, using instruments), and *speaking* to the box in the middle; these are obviously implied in Egan's list, particularly speaking, but it makes sense to list them separately as tools to be used and nurtured during primary education. The abilities are among the ones that allow us to express ourselves symbolically.

Myth & imagination

Myth and imagination, imagination and myth

It is possible to interpret imagination and imaginative activity as a mental power that enables mythic consciousness. Myth relates two spheres of existence: the inner with the outer; the idea (image, shape, or figure) to the real object or phenomenon (which includes what is felt of body and emotions, such as joy, anger, pain, justice and injustice, clarity and confusion, etc.).

The role of imagination in the concrete creative activity of a person or group of persons is exactly this: it enables the purely physical of the activity to be related to its meaning. By presenting images of the real to consciousness, we create the symbols which are the essence of myth.

Therefore, educating the imagination is part of nurturing and forming the cognitive tools of myth (and other phases). Imagination is not just one of a number of cognitive tools—it is entwined with each of these tools.

Miming, drawing, singing, and speaking may be understood as basic *abilities* whereas art and music, crafts (building, designing), playing and acting, and storytelling clearly refer to what we see children do, often and over longer periods of time—these are the actual activities children create. Even though symbolic acts such as miming and speaking can appear spontaneously on their own, seemingly out of a larger context, they usually are integral parts of the creative activities listed in the box on the right in Fig.1.7.

Imagination and imaginative activity. Children demonstrate how creative they can be through their acts and products: the songs they sing, the objects they build, the games they play, and the stories they tell. These activities are imaginative in the sense that they create and use mental images.

Before we continue, three things need to be explained about mental *images*. First, they do not have to be visual—they can be auditory or olfactory or generally related to any of our senses (including that of temporal patterns). Second, mental imagery is visible not only in creative activity but also, and very importantly so, in symbolizing and experiencing. How we understand metaphor and narrative, or mime, draw, sing, and speak „speaks" of mental imagery, i.e., of structures of imagination. The symbols we create are imaginative in a fundamental embodied sense: we might say that enactive/embodied experience supplies our mind with schematic (abstract) images, which we then use to create symbols, which, in turn, are integrated in our activities. Finally, mental imagery (or, more generally, imaginative activity) feeds back to experiencing, symbolizing, and creating. This closes several cycles of the dynamical system sketched in Fig.1.7.

Experiencing at different scales

Third, imaginative activity, like experiencing, takes place at different scales: *small*, *medium*, or *large*; scales can be *temporal* (short to long), *spatial* (small to large), or *systemic* (simple to complex).[68] A mental image can be about a short incident, a medium-sized spatial scene, or a large-scale (long lasting and complex) event.

Meaning of and educating the imagination

The feedback model presented in Fig.1.7 can help us understand, at least to some extent, the meaning of *imagination* in general and *educating the imagination* in particular.[69] The most compact summary of Egan's model of educating children and adolescents might be this: we should focus upon nurturing and shaping students' power of imagination. In our model, imagination is that which mediates between the different groups of cognitive tools thereby enabling them in the first place. Think of a group of children playing and telling stories; this creative activity involves mental imagery. The structures of imagination present in this case will feed back to symbolizing abilities such as speaking and miming. If speaking, for example, is more than just the physical act of producing sound, we should assume that orality is nurtured not simply by „sounding a story," but rather, indirectly, through the images that arise in play and storytelling. We might say that the power of oral language as a symbolic activity grows out of, and feeds back to, the imaginative structures being symbolized (see Fig.1.3). Note that there is no arrow in Fig.1.7 that directly feeds back from creating to basic symbolizing—our mind passes through imaginative activity to complete the loop.

Imagination as part of a feedback loop

In the above model it appears simple to educate the imagination: make sure that mental imagery (in its broadest sense) becomes a conscious part of the activities used to train cognitive tools. We should not really have to say this but, sadly, science is the realm where imaginative activity is often viewed with suspicion. In this book, we hope to show how fundamentally imaginative any engagement with physical science must be, no matter how advanced a form it takes. The meaning of a Force of Nature, to use an example, is mythic and therefore imaginative, and so is our basic understanding of it.

Pattern, polarity, metaphor, and story

Of all the cognitive tools mentioned here, only four—pattern, polarity, metaphor, and story—shall be discussed in more detail because they play a particularly prominent and foundational role in the pedagogy of *Primary Physical Science*

Education that we are developing here. We deal with these four again in Volume 2 where we want to sketch what has been developed, over the last few decades, in cognitive science in general and in cognitive linguistics and narratology in particular. Here, we only say a few words relating the cognitive tools to the issue of mythic understanding and primary education.

The cognitive tools in this short list are forms of experiencing or sense-making (see the model in Fig.1.7). Naturally, pattern, polarity, metaphor, and story are observed in the symbolic and creative acts children and adults are capable of; this is where—rather than in experiencing itself—they find their expression for everyone to see. Nevertheless, the four represent a group of theoretical concepts that should make it possible for us to make transparent how we experience our encounters with nature in general and Forces of Nature in particular.

From pattern to polarity. Patterns appear allover in all forms of experience; when speaking or singing, they can be experienced as rhythm and rhyme, two forms of expression that help children make sense of and remember what has been said or sung. We get visual patterns when drawing or creating objects. In general, patterns speak of felt spatial and temporal differences and similarities and their repetition.

Discriminating degrees of a quality

Without the power of discriminating perceived values or degrees of the same quality—such as color, pitch and loudness of sound, temperature, sweetness, etc.—we would not have patterns. Moreover, the ability to discriminate, or to distinguish, gives us another basic sense—that of binary opposites and polarities. The term *binary opposites* is used for a perceptual pair that is felt to be in tension: good and bad, happy and sad, light and dark, hot and cold, etc. For immediate social, emotional, and physical sense-making, such pairs are important. They appear prominently in understanding of the world as well, which makes them important for education. Binary opposites are organizers of meaning and can be seen as entry points to knowledge: good and bad let characters (the Good and the Bad) arise in the mind and help a child to judge social situations; light and dark, and hot and cold, give us initial access to two primary Forces of Nature—Light and Heat. We recognize the fundamentally important role binary opposites play for children if we consider the stories they like that are driven by tensions between good and bad, heroic and timid, secure and insecure, and so on.

Binary opposites

Binary opposites are easily perceived as acting in children's early imaginative life. It appears to take longer, though, for a sense of degrees (or characters) to emerge that are intermediate between the two elements in a perceptual pair that is in tension. Are there story characters that are placed somewhere along the distance that separates the Good from the Bad, the Hero from the Coward, etc.? More importantly for our theme, what does it take to learn that there is a *continuum* between extremes of hot and cold or light and dark?

Polarity

This is where the concept of *polarity* comes in: in a polarity we have, in general, a continuum of different degrees of intensity between two poles given to a perceived quality. We are all familiar with the polarity called *hotness* which spans the distance between „hellishly" hot and „freaking" cold (which are taken as the poles of this polarity), and the words we have in our language for intensities that lie in between: burning hot, very hot, hot, warm, tepid, cold, very cold, freezing cold, and so on. It seems that, at least as far as knowledge of, and easy facility with, linguistic terms is concerned, education has an important role to play. Children will profit from an educational approach that places value upon learning words for different positions along the path that forms between the poles of a polarity.

Learning to understand the meaning of degrees of intensity associated with a polarity is a case of *mediating between the extremes* that may come to our attention first. Learning about such mediation through examples drawn from nature may very well be helpful for learning about ourselves, others, and social situations in general. Maybe, working on natural and social phenomena in an integrated educational approach where no strict distinction is drawn between the experience of hot and cold and that of good and bad will help children to mature emotionally and intellectually in tandem. We do not have to go far to see how to do this: remember the story *Why We Need Wind* in Section 1.1 where Koluskap and Wocawson negotiate (mediate) a value of the intensity of Wind that serves both of them. In turn, learning about social mediation may serve as an analogy to how a hot and a cold body brought in contact „negotiate" a intermediate value of temperature.

Mediating between extremes

Returning to binary opposites: we have said that the perceptual pair in a binary opposite is in tension. It will be very important for our educational scheme for physical science to nurture the understanding of a feeling of *tension* for two different values of intensity of a physical polarity such as hot ↔ cold, high ↔ low, light ↔ dark, fast ↔ slow, and, generally, tense ↔ relaxed. Such tensions will be understood as the causes for Forces of Nature to be or become active.

Tension as drive

Metaphor and story. We usually speak of a metaphor and a story, or metaphors and stories, by which we mean concrete (linguistic or visual) products. Examples of concrete metaphoric expressions are „he went over to the dark side," „my mood is up," and „the cold slowly crept into his bones." Concrete stories are *Why We Need Wind* (p.5) and *Baby Wolf* (p.25), and all the stories we have heard as children and still hear every day. As these are concrete creations, they belong in the box on the right in Fig.1.7.

Metaphors & stories as linguistic products

What we call *metaphor* and *story*, however, are powers of experiencing and sense-making—they are forms of understanding and thinking; more generally, they are examples of how we imagine, similar to *pattern* and *polarity*. *Metaphor* is said to be our ability to see one thing in terms of another (good as light, bad as dark; quality of feeling as being a vertical scale on which happy is up; or cold as a fluid capable of flowing and creeping). *Story*, on the other hand, is our narrative skill, our capacity to see events in complex settings caused by tensions and undergone by characters. We experience them as wholes we tell about in the form of stories that not only recount the events but create their meaning; in particular, they tell us how we should understand what happened and how we are supposed to feel about the whole affair the tale is about.

Metaphor & Story as mental powers

Metaphor must be a symbolic activity just like myth itself. Remember the basic principle of myth: it brings together, unites, two spheres of being; myth is a symbol where the two elements are equal partners: one points to the other and vice versa. Metaphor does this too: it combines what in modern cognitive linguistics are called two domains (Volume 2). A modern mind, though, will tell us that the two are not on equal footing: good is not light, happy is not up, and cold is not a fluid. However, for a mythic mind, no such distinction exists. Colors and sounds are experienced through other senses (p.8): red *is* warm, blue is cold, a sound *can be* heavy, and the feeling of being secure and comforted *is* warmth. Interestingly, modern research[70] shows that we interpret the relation in a metaphor literally upon direct, fast, and unconscious understanding, and that the domains are considered on unequal footing only upon conscious analysis. So, after all, cold *is* a fluid, temperature *goes up* when it gets warmer, and Wind *is* an entity we can communicate with—at least this is so for a mythic mind.

Metaphor as symbol

Children work with stories and metaphors, which tells us that they partake in the powers of metaphor and story. We do not have to assume that they are born with these capacities, nor do we need to think that they will understand metaphors and stories only if we explain them to them, i.e., if we teach them these powers. We can think of children as beings growing up in a mythic culture where they develop their abilities of wielding symbol, narrative, and myth according to the feedback model described in Fig.1.3. Certainly, the strength of the interactions in this cycle will go up if we find proper ways of educating young students' metaphoric and narrative skills, if we, as caregivers and educators know that metaphor and story are cognitive tools worth nurturing and making good use of.

Growing up in a mythic culture

Cognitive tools involved in experiencing Forces of Nature. Sensing spatial and temporal patterns, feeling tensions related to particular polarities, experiencing one thing in terms of another, and knowing that phenomena and the characters active in them are tied into a unit we can tell a tale about, are important elements of our meaningful encounters with Forces of Nature. These are not fuzzy, squishy, feeble „mythic" abilities alien to rationality; rather, they are the foundations of rationality: patterns and tensions are the start of sentient life, and metaphor and narrative have in them structures of rationality. They are foundational to scientific rationality as well.

Myth as foundation of rationality and science

In *Why We Need Wind* (p.5), there are temporal and spatial patterns (differences and repetitive occurrences) and, related to them, the tension of strong vs. calm Wind that drives the story; there is Koluskap's metaphoric movement up the hill as the Wind (Wocawson) gets stronger and stronger; there is Wocawson as a more or less powerful character, entity, or spirit who interacts with Koluskap; there is mediation of the intensity of Wind on the scale of stormy to calm; and we finally have the story as a whole that tells us about how Wind works and how we are to feel about the importance of Wind for nature and us. Tensions, Wind as an entity, power, and concrete courses of events tied together and explained through the story are all elements of rational understanding that are centrally important if we wish to create a scientific approach to causal phenomena.

◦ ◦ ◦ ◦ ◦

This concludes a very brief description of some of the elements of understanding and some of the cognitive tools available to children growing up in an oral world. We are well advised to nurture and work with these tools, not because they are scientific—they are not—but because they are foundational for understanding of life in general and our encounters with nature in particular; this makes them foundational for science as well. Emotion, metaphor, and story provide us with tools of rationality we would be lost without once we take steps towards scientific rationality.

1.4 Taking Steps Towards Physical Science

If children initially grow up with mythic consciousness, and if myth is not science, as we have said, then how do we help them develop some scientific practices and understanding? Part of the answer, in the scheme we borrow from Egan,[71] will surely have to do with forms of consciousness connected to new cognitive tools developing as children move toward adolescence.

Here, we will be very short and just briefly mention the cognitive tools of literacy and the important element of psychological development toward a sense of self as distinct and distant from others and the world, both of which we believe will have much to do with how more formal scientific attitudes, activities, and topics can be approached in later primary school.

In this section, we shall briefly touch upon the difference between science and myth, list tools of literacy useful for approaching science, and the meaning of a romantic sense of a reality „out there." We conclude the section by outlining an approach to early science education, and by presenting a short story of a storm for somewhat older learners.

What makes science different from myth?

When we consider modern practices and products of science and engineering, we realize that we are light-years away from how mythic people engaged, and still engage, with nature. In societies whose fate is entwined with science and technology, people by and large lack a sense of participation in the affairs of nature. Nature no longer is a partner we communicate with in any meaningful sense.

A new and different sense of realism

On the upside, by creating a distance between us and nature, we can analyze what is „out there" in great detail and depth, which fosters a *new sense of realism*. Remember what we, however sketchily, said about science (above on p.10): In science, we organize and categorize observations differently, we measure and calculate, we create formal models and complete theories. We experiment and measure, observe and write down; we collect, list, map, and put into diagrams what we see and measure. We experiment, analyze, and synthesize, and we bring great and powerful mathematical tools to bear upon all the data we amass.

Doing physics

Ways of doing physics as a professional science

In the past, physics was characterized by two major forms of practice: experiment and theory. A few decades ago, with the advent of computers, computational physics joined this very short list of fundamental ways of working in the science of physics.

The major practices can tell us, as spectators, a little bit about how physicists work, and what kind of tools they employ. Experimentalists build (new) equipment, run experiments with this equipment, measure and do a lot of data analysis. Theorists, on the other hand, create concepts and relations which they assemble into theoretical structures from which results are derived with the help of sophisticated mathematical tools.

Computational physicists write computer programs that represent models of complex systems for which results could never be derived by hand on a piece of paper—such systems and processes include stars and their lives, the dynamics of our atmosphere and oceans, and the interactions of myriads of subatomic particles in the great machines that have been built for their study.

These days, the borders between the three major methods are blurring. Theorist use computational models since they cannot simply derive results of theories on paper any longer. And computational physicists can use their models to run simulations that are a kind of virtual form of experimenting.

Tools of literacy

Here, we already find strong hints at what type of cognitive tools might have to be developed if we wish to enter the world of science (and technology). We need *tools of literacy*: we need to be able to write, graph, and map; and we need to be able to employ formal languages, particularly mathematics. Clearly, most of this by far surpasses, in quantity and formal sophistication, what children would be able to learn through the phase of primary education, and even through middle school. But we get a feeling for what type of cognitive tools we might want to develop together with our students.

In sum, there are at least two elements that distinguish mythic persons from those exposed to science: (1) a growing sense of distance, even a separation, between us and nature, i.e., a *new sense of realism*, and (2) a certain mastery of tools of *literacy*. Are the two related? This seems at least reasonable to assume: how we think has a lot to do with the „thinking tools" we have available; and, naturally, how we are led to think—growing up in a culture permeated by science and engineering—will push us in a certain direction, favoring certain cognitive tools over others.

Science starts with, and falls back upon, myth. Modern science gives us the impression that having acquired the two elements just described, i.e., having developed tools of literacy (plus what they entail for a formal theoretic culture) and a sense of distance between us and nature (making nature an object), will be sufficient for developing a science. Somehow, after these two elements are in place, science is assumed to pull itself up by its own bootstraps. However, this misses two important points: how do we create fundamental images (ideas) about what to expect „out there," and, once we have a science, how do we explain in very basic terms how the world „out there" works? This brings us back to myth: we still need mythic capacities if we want to create the foundations of an approach to a particular filed of science and make sense of how that science explains phenomena. Meaning-making, i.e., creating understanding, requires us to connect formal scientific results back to our mythic understanding of nature.

Grounding & explaining requires mythic images

Tools of literacy in emerging science and theoretic understanding

Simple „scientific" practice that might rightfully take place in later years of primary school, but more importantly, in middle school and in high school, tells us quite a lot about new tools required: we need to be able to write, list, map, sketch on paper, create diagrams, measure and calculate, and we need to be able to put it all together in writing, telling others what we have learned.

Let us not get into details concerning all these specific tools of literacy—this is not our place; we are not experts on how to teach children how to read and write and do arithmetic. We only want to point out that new tools are needed, and that their development quite obviously takes time. Suggesting that we „do science" starting in kindergarten will therefore miss the point (see the final discussion in this volume in Chapter 6). It will definitely miss the point if we have missed out on meaningfully fostering the cognitive tools of myth during the years leading up to when children have achieved a certain mastery of literacy.

Instead, let us just discuss the observation that the initial development of tools of literacy coincides with a number of changing „senses," „attitudes," and „habits" of children; Egan lists these as part of the category of cognitive tools of *romantic understanding*.[72] We can think of a growing interest in extremes, boundaries, and limits of experience; an association with heroes; a sense of wonder; development of hobbies and an urge to collect „stuff;" being able to change a topic and, importantly, a viewpoint; and, above all, a heightened sense of a reality „out there" (we shall come back to this last point in the following sub-section). In our cultures, some of these senses, attitudes, abilities, or tools of understanding will develop fairly early. Such change is driven, in part, by the wide-ranging availability of and exposure to visual media (photographs, picture books, and film), and by access to a great many technical toys. Media and toys can be made use of for a more scientific and formal engagement with physical processes.

It would be strange if the availability of all these tools did not change the way children think. It is this change we want to be aware of and sensitive to; it is this change that provides us with an opportunity to „do science" already in primary school classrooms. In turn, a well-crafted and gentle scientific approach to encounters with nature and machines can help the cognitive tools of the new romantic consciousness to develop more solidly. And, at the same time, we want to remain sensitive to mythic understanding of our encounters with nature.

A sense of reality „Out There," romantic realism, and theoretic culture

Here is a brief outline of what *romantic realism* is about: a strong sense of an independent outside reality that can be listed, mapped, measured, and experimented with; the concept of space: the abstraction of (empty, dark, infinite) space; and an interest in its beauty and rich detail.[73] The first and the second of these are intimately related, and we shall say a little more about them right below. At this point, let us state what is important about an interest in the outer world's beauty and, particularly, rich detail.

Rich detail of reality. People in a mythic society, and today's children for that matter, cannot and need not know every object in the world out there; having only oral language and its tools at one's disposal for listing and memorizing objects creates a heavy cognitive burden. One needs to be judicious about what one wants to know (harking back at the theme of our book, phenomena or Forces pertain to knowledge one would want to have). For example, when it comes to food, we need to know the difference between edible and inedible, and we need to know the most important foodstuffs in our environment. With literacy, however, it becomes possible to build a repository, a list, of every single plant and animal one is able to come across. Slightly older children can easily get engaged in such an activity: collecting everything of a certain kind that is fascinating (beautiful to one's mind) and wondering if there is more of it in the wide world.

Writing makes recording details of reality possible

This changes everything, and it may present us with a partial answer to how the sense of romantic realism arises. It is clear that, in the course of cultural development, its aspects grew in parallel with literacy, and it makes sense to claim at least some causal force on the part of the techniques of writing. Science is definitely a child of literacy and its techniques that include formal languages (e.g., mathematics), the printing press, and now, the Internet.[74] Without the tools of literacy we would not have the means of listing, mapping, measuring, and graphing the sheer infinite diversity of material reality; we would hardly have the means for experimenting in a manner that would go beyond what is needed for making tools and simple machines.

Causal Force of writing

Distance between us and nature and the abstraction of space. This, however, is only half the story. Another driving force, which interacts with the first, is psychological: it is the experience of self that grows as consciousness develops—

both historically and in the individual. This feeling of the independence and power of my own mind or my own soul—the self vis-a-vis an outside reality—is the result of an increasing distance between the self and its unconscious.[75] This distance is responsible for sensing the reality of the outside world and is reflected in the historically recent abstraction of infinite, empty space.[76]

Something important must have changed in the modern mind. Francisco Petrarch presents us with a beautiful example of how a romantic feeling for the reality of the outer world combines with a feeling for space as an entity. In his letter of 1336 to a philosophy professor he writes:[77]

> Today I ascended the highest mountain in this region, which, not without cause, they call the Windy Peak. Nothing but the desire to see its conspicuous height was the reason for this undertaking. [...]
>
> The day was long, the air was mild; this and vigorous minds, strong and supple bodies, and all the other conditions assisted us on our way. The only obstacle was the nature of the spot. We found an aged shepherd in the folds of the mountain who tried with many words to dissuade us from the ascent. He said he had been up to the highest summit in just such youthful fervor fifty years ago and had brought home nothing but regret and pains [...] While he was shouting these words at us, our desire increased just because of his warnings; for young people's minds do not give credence to advisers. [...]
>
> And now [...] listen also to what remains to be told. [...] At first I stood [at the summit] almost benumbed, overwhelmed by a gale such as I had never felt before and by the unusually open and wide view. I looked around me: clouds were gathering below my feet [...]. The Alps were frozen stiff and covered with snow [...]. They looked as if they were quite near me, though they are far, far away. [...]
>
> Then another thought took possession of my mind, leading it from the contemplation of space to that of time [...] I had better look around and see what I had intended to see in coming here. [...] The sun was already setting, and the shadow of the mountain was growing longer and longer. [...] I turned back and looked toward the west. [...] one could see most distinctly the mountains of the province of Lyons to the right and, to the left, the sea near Marseilles [...]. The Rhone River was directly under our eyes.
>
> I admired every detail, now relishing earthly enjoyment [...] I was completely satisfied with what I had seen of the mountain and turned my inner eye toward myself. From this hour nobody heard me say a word until we arrived at the bottom.

Romantic realism and the notion of abstract space

This is an important passage testifying to a new element of the modern mind: romantic realism and the abstract concept of space. Without this development we would not have modern science and we would not have—starting some 500 years after Petrarch—the overwhelming feeling that reality lies in the motion of little particles in empty space.

Theoretic culture. Then there is theoretic culture. Again, without literacy, we would not have the technical means for developing mathematical theories. Still, it seems we need psychological developments as well to create theoretic thinking. On the one hand, there are the tools for formal, logical thinking, on the other there is the growing sense of reality of the thinking self and the products of its thought. It seems that the development of the sense of self—whether by technological means including those of literacy or by natural development of the psyche—is a key to understanding the development of modern science beyond its mythic roots.

Products of thought are „objects" we can analyze

Microscopic model of matter and processes. Let us return to a brief remark made above: without a sense of space as an entity, we would not have little particles roaming through empty space; there would not be any microscopic models of matter and processes. We should therefore accept that, if we wish to develop a stable and meaningful understanding of this idea in young learners, we need to wait for the sense of space as an abstraction to have developed (and this might not happen much before adolescence has solidly set in). This means that we should refrain from trying to explain characteristics and activities of Forces of Nature with the help of microscopic models during the phase of primary science education. Here is an idea that has not yet been tested but might make a lot of sense: Start nurturing the feeling for the meaning of space by exposing (older) primary school and middle school children to the stars and the universe. Little particles can wait—in our case they can wait for Volume 2.

Sense of abstract space is a prerequisite for the idea of particles

Pedagogy of early science education

By now it should have become clear that we do not think that nature education for early years can be called a part of science proper—science education must await the growth of the romantic tools of understanding we have talked about above. However, there is reason for gently starting on a course, late(r) in primary school, that includes certain practices and themes we might call *scientific*. Not surprisingly, these activities will be tied in with tools of literacy.

A pedagogy of early science education should connect up, in a meaningful way, with activities developed for the earlier years. So far, we have suggested storytelling integrated with direct physical exposure to *Primary Forces of Nature* (such as Wind, Rain, Snow, Sunlight, Fire, Heat & Cold, Rivers, Thunderstorms, Plants, and Food) as activities. Naturally, simple artifacts can be built and used by young children to play with and expose to the „elements" to develop a deeper understanding of what Forces are and what they do.

Primary Forces of Nature

Physical science and tools of literacy. We would want to continue with such activities in our pedagogy for later years, but they can be adapted to new situations and supplemented by additional materials, tools, activities, and themes. Stories of Forces of Nature can be written that are more sophisticated and suggest ideas for understanding that do not yet make sense to younger children; the physical exposure to Forces can be enriched with more sophisticated observations (including recording and reporting); and media—books, TV, and the Internet—can be used to explore what other people can tell us about these Forces.

Recording, reporting, and using media

Let us just mention some simple structured observations and experiments performed with artifacts built by children and the technical toys available these days. During a rainstorm, older children can collect rain-water with a large funnel into a narrow container so they see how fast the amount of water rises. This can be recorded and possibly graphed (which, by the way, lets us introduce some simple calculations); they can build a water wheel, connect it to a toy generator and an LED light, and place the water wheel in a stream (if accessible); they can use a small photovoltaic panel, expose it to the Sun at different angles and record the voltage established (if simple and cheap multimeters are available); or they can

Collecting data, graphing and calculating record how a small amount of water heated by one or two or three candles warms up. Then, simple stories and Forces-of-Nature Theater performances (see Chapter 5) are invented to tell about the activities of the Forces that animate nature and machines.

Some general tools of romantic understanding. Activities like these are certain to help develop the tools of literacy; but what about the more general cognitive tools of romantic (and later philosophic or theoretic) understanding? What about the growing interest in extremes, boundaries, and limits of experience; development of hobbies and an urge to collect „stuff;" an association with heroes; a sense of wonder; being able to change a topic and, importantly, a viewpoint—and, not to forget, a heightened sense of a reality „out there?" Topics we associate with physical science do not relate equally to all of them, but there will certainly be opportunities to include some of them.

Exploring extremes and limits of experience

Exploring extremes, boundaries, and limits of experience will be rather easy to include in a physical science curriculum. Where are the hottest and coldest spots on Earth? Where is the hottest spot in the solar system or in the universe? What about highest and lowest points on Earth, and highest and lowest values of pressure? You get the idea: polarities that structure our experience of intensities and tensions are particularly useful in this regard. Naturally, size is important as well: what are the largest and smallest structures in the universe?

„Collecting" and listing as many Forces of Nature as possible

The growing urge to create (complete) collections of a realm of experience might be better served by biology and geology, but we can do something here as well: What about beginning to „collect," and then study and report about, as many Forces of Nature as we can come up with?

Forces as „heroes"

Heroes do not seem to be a particularly apt topic for physical science, but even here we can do some good work, particularly if we include „heroes" of science, engineering, and medicine in one or the other of our stories of Forces of Nature. Maybe, Forces can be „heroes" as well? Forces can certainly be helpers or destroyers—again, we are facing a polarity that could help us expand the range of stories of Forces of Nature we tell in our classrooms (Egan, 1986).

Wonder about mysterious and invisible Forces

A sense of wonder and even magic need not be strangers to science topics either. Magnetic phenomena can help us here (see the chapter on Electricity and Magnetism in Volume 2). Just playing with magnets can make us wonder about this mysterious and invisible Force that seems to involve not only small magnetic bodies but the entire Earth—we can make invisible Forces a theme involving Cold and Heat, Gravity, and maybe Electricity! The phenomena are well suited for some qualitative investigations. A simple example shows this: connect a number of identical (bar) magnets in series, North pole to South pole, to realize that the magnetic strength sits only at the ends of the sequence and is no greater than that of a single one of the magnets.

Critical thinking. Being able to change one's perspective is an important element of critical thinking. Here, physics seems to present us with a problem: often, at least in popular modern culture, physics is said to give us absolute (objective, true) knowledge. How could one want to change one's perspective on an issue of scientific truth, especially as a mere onlooker to, or consumer of, science? Naturally, we can use the history of science and point out how certain models and theories, upon later scrutiny, have turned out to be limited, flawed, or even wrong; however, such cases are usually presented as „yesterday, scientist thought that…" but „today we know that…" This does not really give us much of an opportunity for changing our mind.

Still, we believe that it is important for teachers to help students analyze issues of critical thinking, i.e., study questions regarding what it means to change one's perspective concerning a phenomenon. Our theme—experience, analysis, and interpretation of the characteristics and roles of Forces of Nature—presents us with at least a small number of examples where the need for changing one's perspective will become apparent.

Here are three interesting and pertinent cases. First, experiencing Forces of Nature—which are fundamentally immaterial—involves what cognitive scientists call *Figure-Ground Reversal*: we switch from seeing physical objects as foregrounded figures to „seeing" Forces as foregrounded (as figures) acting in or on these physical objects that will need to be moved to the (back-)ground in an imaginative act (see Chapter 5, p.255 and Section 5.6).

Figure-Ground Reversal

Second, learning to experience a complex Force such as a storm or a volcano as „made up of" a number of Basic Forces (such as Fluids, Heat, Motion. . .) is a worthwhile theme for a romantic curriculum. In fact, it lends itself to studying questions of how we create categories.

Analyzing a complex Force in terms of Basic Forces of Nature

Third, if and when discussing microscopic models, it is important to realize that such models constitute a different perspective rather than an underlying truth from which macroscopic models can be derived (put differently, macroscopic and microscopic models constitute distinct metaphoric realms, each constituting their own reality). It will be critical for teachers to understand such issues and know when, and if, to make their students aware, however gently, that we can indeed entertain different perspectives regarding the same phenomenon.

Explanation can involve distinct metaphoric realms

◦ ◦ ◦ ◦ ◦

This list can be extended at will. There are more important issues, though, than what we choose to do in particular. First, it will matter that we have created a secure mythic base upon which we can continue to build. Second, it will be important to make an effort at developing the *cognitive tools of literacy* as an integral part of our plan for physical science education. For the teachers, the challenge will be to understand our encounters with nature in general, and with Forces in particular, in mythic terms, and to contrast mythic with scientific understanding. This means, above all, that a teacher feels secure in his or her use of the tools of mythic understanding. These tools include a form of natural language use infused by proper acts of imagining without being twisted into unresolvable knots by pseudo-scientific talk that is all too common in our culture. What these „proper acts of imagining" are, will hopefully become clear in the following chapters.

Acts of imagining and using natural language

A „modern" story of a storm

To make the foregoing discussion a little more real and practical, let us conclude this section by presenting an outline of a story which is probably well suited for 10-11 year old children. Two sisters, Sarah and Robin, experience a hurricane that hit the North East of the United states (we are using hurricane Sandy[78] in 2012 as a backdrop for our story; characters, particular events, and locations are fictional). Such a story develops the gestalt of the Force of a Storm, it makes use of the concepts *size* (extension), *intensity*, *power*, and *temporal course* as the storm rages through the area, and it connects the overall phenomenon to *Basic Forces* such as Heat, Fluids (Water and Air), and Electricity.[79] Romantic and theoretic aspects are easily embedded and entwined with mythic understanding, and can be used to guide classroom activities geared towards developing these new senses. Here is the sketch of a story of *Hurricane Sandy*:

> *In the Fall of 2012, a tropical storm had formed over the Atlantic Ocean between Africa and the Americas. It would soon get its own name as a hurricane and change the life of many people along its track from Cuba all the way up to the coast of New York.*
>
> *Robin and Sarah heard their president say that "This is going to be a big storm. It's going to be a difficult storm." They have access to television and computers, they track the storm, map its path (Fig. 6), collect satellite images of its development and pictures of its impact. They do this during the days schools have been closed as they huddle in the living room, afraid that the storm will damage their home but still excited to be part of something so awesome. When the storm cuts their electricity, the backup power which their parents had installed recently kicks in. They keep busy discussing the relevance of factors such as size, intensity, and duration upon the devastation it causes and come up with semi-quantitative models.*
>
> *They hear that the storm's power is fed by the warm waters of the ocean and that the intensity of the storm decreases fast when it is over land. However, there it will meet with the very cold continental air of another storm which will lead to the development of extremely intensive rain and snowfall. They remember what their teacher had told them about Heat as an agent and how Heat can drive engines and create storms. All of this can be turned into a consideration of the power of Heat as the driving agent of the storm, and Wind and Water as Forces joining in the destruction caused by hurricane Sandy.*

We shall say more about how to create concrete stories of Forces in Chapter 6. This and the discussions of Forces in Chapters 2-4 should enable teachers to turn the sketch into a useful didactic tool.

1.5 PPSE and Physical Science

What do we mean by Force and Physics?

It is time to confront the issues we alluded to at the start of this chapter (p.4) and conduct the debate about what we mean by *Physics* in general and *Force* in particular. We need to answer these questions here for the simple reason that our approach to physical science is quite different from traditional ones. We shall see that there is no single clear-cut, objective "out-there-in-the-world" answer to these questions. How we answer them depends upon explicit choices that, in our case, are motivated by our goals of (a) creating nature pedagogy for young children by basing it upon the foundations of human understanding; (b) joining these foundations up with modern macroscopic physics; and (c) trying to put nature and us humans back on speaking terms again. These objectives, in their combination, are at odds with much of what is customarily assumed in the science, philosophy, and the teaching of physics—courses based upon such customs simply do not meet the goals we have set for *Primary Physical Science Education.*

Goals for PPSE

In this last section, we will first sketch a critical analysis of typical answers to the two questions raised. After this, we need to make a couple of constructive moves. We shall explain, as briefly and as simply as possible, what modern macroscopic physics is and how it is a science of Forces of Nature (starting on p.45). We shall conclude this chapter by outlining how modern macroscopic physics and what we know of human understanding allow us to create an imaginative approach to our experience of Forces of Nature (starting on p.50)—we do this by sketching how Light as a Force will be treated in PPSE.

Modern macroscopic physics as science of Forces of Nature

Debating the meaning of *Physics* and *Force*

The meaning of physics will depend upon whom it is for, which is related to how it is practiced, and for what reasons. Currently, as an end in itself, physics is involved mostly in studying light (for learning about the nature of information), particles colliding in huge machines built just for that purpose, and stars, galaxies, and the early universe. In all these fields, it is hoped that new surprising phenomena may be discovered requiring new fundamental theories, i.e., new explanations of "how the world ticks."

Much of physics, however, is in its applications: it is applied in the natural sciences, in engineering, and in medicine. And it is active in the business of explaining what has been done and learned in all these activities, and in teaching to young people what is known in this science. For our purpose, we are mostly interested in the last of these practices: explaining and teaching physics, especially to an audience of young people who will not necessarily become scientists or engineers themselves.

Physics: What it is assumed to be or mean in popular culture. According to the US Bureau of Labor Statistics, „Physicists explore the fundamental properties and laws that govern space, time, energy, and matter;"[80] and according to the Encyclopedia Britannica, „physics is the science of matter, motion, and energy."[81] It should therefore not come as a surprise that teaching physics to a general audience is guided by the wonders and mysteries of nature as presented to us by physicists active in „physics as an end in itself." After all, that's physics! Applications of it are fine, and teaching it is necessary, but that's not physics per se!

Physicists deal with space, time, energy, and matter

So, what is this physics, or rather, what is the explanation of the world it offers? Here is a caricature, albeit a common, widespread, and well accepted one, of the modern "self-image" of physics. The universe, nature, or whatever we are considering "out there," consists of "tangible" things which we call *matter*. Then there is *energy* that somehow "animates" lifeless matter. Matter consists of particles that, because of energy, are moving in empty, geometrically flat space and bump into each other, or they wiggle around in the materials they make up, again because of energy; this, among other things, explains heat. Finally, whatever is not "tangible" in its simple sense must be energy.

Reality is made of matter and energy

Matter is made of particles; their motion is the ultimate cause

From fundamental physics. . . Here is a more sophisticated version of this self-image. It derives its features from quantum physics and relativity (i.e., from modern fundamental physics) and their applications to light, particles, and the (early) universe. In addition to matter, which consists of particles, there exist *fields*. We probably have all heard of *gravitational* and *electromagnetic fields*, but there are two more: the *fields of weak and strong forces* which act at very small sub–atomic scales. All these fields are made up of particles, just like matter, but of a different kind from those of matter. Particles of matter are called *fermions*, those of fields are called *bosons*.

Matter and fields

Weak & strong forces

Fermions & bosons

Fields are conceptualized as the physical entities that „mediate" forces „acting between" matter particles. Force is understood here as mechanical force that is responsible for influencing the motion of (matter) particles. So, for instance, an

Fields mediate forces with the help of bosons

electromagnetic field will influence the motion of an electrically charged particle, say, an electron. A gravitational field will influence the motion of anything that has mass, be it an electron, an apple falling from a tree, or light moving near the Sun; and the strong force holds the quarks together that make up particles called hadrons of which protons and neutrons are examples. Since fields are made of particles (bosons) as well, the „mediation of forces" is interpreted as the *exchange of bosons* between particles. Electromagnetic „force" is mediated by *photons* (just like the photons of visible light); gravity is mediated by *gravitons*; *W-bosons* and *Z-bosons* mediate the weak force, and *gluons* are responsible for the strong force. In summary, there are *four fundamental forces* which are called *gravitational*, *electromagnetic*, *weak*, and *strong forces*.

Bosons

Four fundamental forces

. . . to modern fundamental physics. . . What we have presented here is an almost old-fashioned account of fundamental physics and the four fundamental forces. In the last few decades, the theory of electromagnetism has been unified with that of the weak force (similarly to how electricity and magnetism were unified as a single theory long time ago by James Clerk Maxwell), leading to what is a theory of the *electro-weak force*; and this has been unified with the strong force in so-called „*grand unification*." Physicists working in these fields are now busy trying to unify the „grand unified" force with gravitation.

Unifying the four forces

Relativity, quantum physics, and work on the unification of the four forces have radically changed our view of the naive self-image of physics—or, rather, of the imagery it has created, i.e., of flat space filled with well-formed particles of matter at well-defined positions moving along well-defined paths. Space, time, and motion (position, speed, etc.) are no longer what they are for us in classical physics. Matter is now an amalgam of different *fields*, while the fields are still fields—so the stuff of reality is made of fields. There are *no forces any longer*; in general relativity (the theory of gravitation), force is a consequence of the shape of space, so there is no gravitational force any longer. Force talk is replaced by talk of *interactions*. Finally, and worst of all, there are *no particles*—what we normally call particles are understood as the quanta („chunks" or „grains") of charge, spin, entropy, amount of substance, and energy, arising in interactions.[82]

Naive concepts have been radically changed

Fields are the stuff of reality

Interactions replace forces, and there are no more particles

. . . and back to a popular account of physics. In a more popular account of this model of nature („nature" as seen by physicists), deep confusion arises simply because the concepts (images!) needed for an understanding are rarely treated properly by the scientists telling us their story. Fields are mixed up with energy: haven't we all heard of energy fields? Quite likely, we have also heard the term force fields; so, is force energy, which is the same as fields, which are bosons? Moreover, we know, thanks to Einstein, that matter can be converted into energy, and vice versa.[83] Now, the confusion of what is what—matter, field, energy, and force—should be complete. Nevertheless, the deep-seated assumptions about what physics truly is makes it clear that what we need to teach are the topics of particles, fields, forces, energy, and the like—the earlier the better.

What are the fundamental concepts in modern fundamental physics? Which brings up the following question: Are space, time, energy, matter (as composed of particles), fields (which are also made of particles), and the four fundamental forces really all we need for describing nature? What about the fundamental concepts of (classical, relativistic, and quantum) physical theories such as spin, charge, momentum, and entropy, and electrical and gravitational potentials and temperature, etc., that are absolutely essential for any explanation of any physical system and process whatsoever, in all fields of physics, classical and quantum,

Fundamental concepts: Spin, charge, entropy, and a few more. . .

fundamental and applied? Are we to believe that they do not matter, or that they muddy our understanding of reality if we were to deal with them in (popular) accounts of physical science?

Actually, the answer to this question is simple: it is believed by many if not most physicists and, consequently, by the lay public, that the concepts that are offered as the building blocks of our fundamental understanding of nature—matter, field, energy, and force—will suffice for whatever else we have in mind: everything else, meaning all the other concepts of physical theories that regularly overwhelm us, can be derived from this „fundamental" image. At the moment, the standard answer physicists give us is that there are these four *Fundamental Forces* (gravitation, electromagnetism, weak and strong forces) whose properties and effects upon the entities of the universe can explain everything. And if we are patient enough, we shall, one day, have a single theory of everything!

Reducing everything to first principles and motion of little particles. As a simple example, take the notion that heat and temperature can be reduced to the wiggling of little particles—that, in essence, they *are* (the energy of) this wiggling motion. In conceptual change research, we are told that temperature is an emergent phenomenon and has to be treated as such. This sounds sophisticated but it is not; it contradicts everything we know from continuum thermodynamics and modern cognitive science: physics in general and thermodynamics in particular are not self-starters.[84] If we do not understand what we mean by temperature guided by phenomenology, i.e., by our embodied experience, physics is going nowhere. And so it is with much of the conceptual apparatus of physical theories: we construct it from basic schematization of experience, through metaphor, analogy, and narrative. And yes, once we have constructed *embodied concepts*[85] and formalized them, we are able to derive a lot of new stuff—that, indeed, is the business of much of theoretical physics.

Deriving what actually are basic concepts

Embodied concepts

Importantly, though, the claim that we are able, somehow, to derive everything based upon four fundamental forces (and little particles), goes much deeper than assuming that we can derive all the other concepts used in physical theories and models. The claim appears to imply that we can construct explanations of everything and anything from „first principles.," applied to the motion of particles. For instance, we might be led to believe that how a hurricane comes about (and where it is going to move), and how we should design a bridge, can be reduced to the principles of fundamental physics. Clearly, that cannot be the case—reductionism is not how explanation, prediction, and understanding work.

Deriving models from four fundamental forces

How does explanation work? This is a tough question that keeps philosophers and cognitive scientist and, actually, some physicists as well, up at night. We shall not expand on what scholars are debating in this important field of inquiry. We shall be very brief and sketch just a couple of points.

From everything we can learn these days, it has become quite clear how explanation in physics in all its manifestations does *not* work: it is not reductionist, at least not down to the last and least elementary particle! Even though we shall engage in a little bit of „reduction" ourselves when we show how complex Forces—such as oceans, glaciers, or volcanoes, or even just Wind—can be „reduced" to the acting of the *Basic Forces* of macroscopic physics (see p.45), it should be clear that this does not mean that we will be able to go „all the way down" to where modern quantum field theories and gravitation have led us and surely will still lead us, and then make our way back up again to trees, volcanoes, and entire planets and stars. Just claiming this does not make it become real.

Consider too, that, by performing this kind of reduction, we lose all sorts of aspects of a more complex system; a specific volcano is not simply some generic object where Heat, Gravity, Motion, and Magma (as a Substance) are active. We lose much of the beauty, terror, and utility of this object when we „reduce" it to a model of Basic Forces (not to speak of „reduction" to fundamental forces). On the other hand, why should we not produce such models if they help us in understanding aspects (but only aspects!) of volcanoes better?

Explanation at appropriate scales

Simply put, there always are appropriate ways of explaining in physical science. Models must fit the *level* or *scale* a system is situated at in the wider universe. Explanation is always happening at an appropriate level or, put differently, at the appropriate *spatial*, *temporal*, and *systemic scales.* Remember what we said about experiencing and imagining working at different scales (pages 18 and 29): the same is true of explaining. The three, *experiencing*, *imagining*, and *explaining* form a tightly integrated triad in whose space our forms of expression, our models and explanations, will have to move to be effective.

For the purpose of PPSE, we have decided to make use of the explanatory power of modern macroscopic physics, i.e., continuum physics and the physics of dynamical systems, joined with forms of explanation afforded to us by embodied cognition (pages 45-50). We feel that this is appropriate not only to nature pedagogy for small children but, importantly, to a natural science charged with helping us deal with our broken relationship with nature. What this means for our choices of topics and forms of explanation will be discussed below (starting on p.50).

Physics of Forces of Nature

Here is a concrete example of explaining and modeling at an appropriate level: water transport in a tree. We refer to a particular technical text on *Plant Physiology* by P. S. Nobel (2005). A glance inside the book shows very little microscopic physics—what is dealt with in technical form is mostly macroscopic physicochemistry. To be fair, there are always certain elements, typically of constitutive relations and parameters rather than basic assumptions, that have been motivated by microscopic models. However, the overall explanations of phenomena such as water transport are patently macroscopic. They deal with objects we can see and touch and phenomena that are neither too fast nor too slow. Put simply, the explanations are dynamical models motivated by the *physics of Forces of Nature*, as we use the term here.

What, then, is the meaning of Force? We need to come back to the question of what the term *force* might mean. The notion of *force*, as formally used by physicists, has appeared in our debate in the context of the four fundamental forces, before dissolving in the most modern elements of fundamental physics (see pages 41-43). Now, we do not need to go that far: *force*, as traditionally used in physics, is a concept we certainly want to deal with (the reader will have to wait for Volume 2, before we start using it). Most importantly, however, we need to make clear how the traditional usage of *force* we have inherited from Isaac Newton in 1687 (p.49), is different from how we use *Force* in *Forces of Nature.*

The concept of force in mechanics

Momentum transfer

In physics, the concept of *force* is a severely restricted notion reserved for an aspect of theories of (classical) mechanics where, *force* stands for the *rate of transfer of momentum* effected either by conduction or by radiation[86]—these are the only accepted meanings of *force* in mechanics. Momentum is transferred conductively when two material bodies touch (which also means that momentum goes through materials); in this case, we are dealing with so-called *surface forces.* When a body is interacting with a gravitational or electromagnetic field, momentum is transferred in a manner that is called radiative—it flows through the field; here, we are dealing with *volume* or *body forces*. Momentum can be transferred with a flowing fluid as well, but the momentum current associated with this process may *not* be called a force. In contrast to these uses of the term *force* in mechanics, in our imaginative approach to encounters with nature, *Force* refers to the gestalt, i.e., the unified phenomenon, we call *FoN*.

In case we are giving the reader the impression that we are, with our terminology regarding *Force*, returning to some prescientific past that will upset our understanding of modern science, let us go back very briefly to the most modern theories where *force* has disappeared. We have mentioned above that the concept of *force* as used in classical mechanics has been replaced by the notion of *interaction*. This is not simply a redefinition of the same concept, nor is it an innocent move: in its qualitative „feel," and in its embodied meaning, *interaction* reflects our mythic understanding of the notion of *Force*, before it was distilled down to a narrow concept in Newton's mechanics (p.49). *Interaction*, as used in quantum field theories, strongly resembles the notion of *causal interaction of Forces of Nature*, as we use this term (see p.76; Sections 3.1 and 3.3; the subsection starting on p.164; and much of Chapter 5). What we see here reflects the simple truth that *Force* is an eminently important element of our embodied conceptual apparatus, for both primary *and* formally scientific discourse. We would not even begin to be able to communicate about the world around us (including our social environment!), if we could not use the term and the embodied concept it refers to.

Imagery of interactions replaces that of forces in classical physics

Causal interaction of Forces of Nature

Finally, note that the word *force* is older than its appearance in Newton's mechanics (which was developed during the second half of the 17th century): it goes back to about 1300 (in English) and has roots in the probably still older vulgar Latin word *fortia* and the Latin word *fortis* (for strong, mighty, brave...). The meaning of the English (and German, Italian, etc.) *force* derives from Old French *force*, meaning „strength; courage, fortitude; violence, power, compulsion."[87] This has a lot in common with how we use the word in *Force of Nature*.

Origin and meaning of the word Force

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No matter how different our goals might be for *Primary Physical Science Education*, we should not lightly dismiss the power of the widely accepted self-image of physics—physics is a powerful part of contemporary culture; its self-image translates, at least to an important degree, into our own self-image: Who are we? What is reality? What is the world, and where is our place in it? The answer we give to the question of „What is Physics?" has far-reaching consequences. However, the task before us, as modern humans in the cultures we have built, on the planet we inhabit, is not one of choosing between physics in its self-image and a new relationship of humankind with nature: it is about both—on the one hand, continuing our search for new physics and, on the other, uniting the power of scientific practices with that of our mythic relationship with nature. Physics has a task, an obligation, that goes far beyond what is happening in the fields of modern fundamental physics. In this book, we have decided to make the dialectical move to explore what a unity of science and mythic understanding could lead to.

The scientific category of *Forces of Nature*

In a nutshell, macroscopic physical science is a collection of theories of phenomena that bear the marks of *Basic Forces of Nature*; moreover, these theories are fundamentally narrative and make use of figurative structures such as (image) schemas, metaphor, and analogy.[88]

Physics as science of Forces of Nature

Neither of these observations is commonly made in traditional presentations of physics. However, the practice of modern continuum physics and of the physics of dynamical systems[89] prepares us for an approach to physical systems and processes that is quite different from Newtonian physics on the one hand, and modern quantum field theories[90] on the other. Interestingly, despite its highly formal presentation, continuum physics retains a human-level appearance simply because it deals with human-level phenomena and uses for its formalism many of the fundamental abstractions our mythic mind makes available to us.

Moreover, philosophy and modern cognitive sciences employing models of an embodied and enactive mind suggest that our imaginative interpretation of macroscopic physics could very well tell us something new about the meaning, form, and uses of science. We believe that if we add the perspective of mythic consciousness—as a part of the evolution of the human mind—to the repertoire of cognitive science and philosophical approaches to science, we arrive at a view that allows for some continuity between primary (mythic) minds of children and primary aspects and concepts of the science of Forces of Nature.

A short list of Forces in physics

Basic and Primary Forces of Nature

The list of Basic Forces of Nature in continuum physics. In the physical science of non-relativistic macroscopic systems and processes, there is a relatively short list of basic physical and chemical phenomena that is said to cover what we can experience more or less directly in our interactions with nature. The list is made up of processes related to Fluids, Electricity and Magnetism, heat, chemical Substances, linear Motion, Rotation, and Gravity (see Table 1.2 below). We call the Forces in macroscopic physics *Basic Forces of Nature* so they can be distinguished from the much larger family of *Primary Forces of Nature* (see p.37, and p.61). Theories that have been created for these phenomena are—in broad strokes—structured just like experience structures Forces of Nature for us.

Example: A simple electric circuit

To see the figure of a FoN emerging, consider the following example of a simple electrical system composed of a battery, wires, and a small incandescent light bulb. In a battery that is not yet exhausted, the chemicals react, make energy available, and so, in turn, establish an electrical tension. If a closed path for electric charge to flow exists, the tension will force charge to flow through a wire to the bulb where it drops from the higher to the lower electrical level. As a consequence, the energy that was made available to electricity in the battery will be released (made available) for producing heat and light—the wire in the bulb gets very hot (a thermal tension is established), starts glowing, and the light produced carries away the heat together with the energy released. The charge, depleted of energy, returns to the battery through the second wire to be pumped to the higher electrical level once again.

Electricity as a Force of Nature

Let us focus just upon the electrical aspects. Electricity clearly appears as a Force having the same basic characteristics we see emerging in our experience of Wind in the story of Koluskap and Wocawson (p.5). Electric tensions appear on the scene (and there are chemical and thermal tensions as well). Obviously, there is an entity that flows. What is missing from this particular narrative is the fact that this entity could also be stored (there are no capacitors in this circuit that would make this obvious). Finally, electricity is a powerful agent: it causes the process that makes the light bulb work.

Basic characteristics of theories of macroscopic processes. The form of description is basically the same for all of the phenomena listed in Table 1.2. Even though the phenomena are in no way the same, and even though there are myriads of differences in appearance and detail, we can treat their basic aspects similarly—

imaginative acts make them analogous.[91] First of all, each phenomenon is governed by an intensive quantity—called *potential* in physics—whose differences are felt and imagined as *tensions*. These tensions drive processes and, in turn, are established by processes.

Potentials and tensions

Table 1.2: Basic Forces of Nature in macroscopic physics

Phenomenon	Potential & Tension	Fluidlike Quantity	
Fluids (*)	Pressure & pressure difference	Volume of fluid	P O W E R & E N E R G Y (†)
Electricity & Magnetism (○)	Electric potential & electric tension	Electric charge	
Heat	Temperature & temperature difference	Amount of heat (caloric thermal charge, entropy)	
Substances	Chemical potential & chemical tension	Amount of substance	
Linear Motion	Speed & speed difference	Quantity of motion (momentum)	
Rotation	Angular speed & difference of angular speed	Spin (angular momentum)	
Gravitation	Gravitational potential & difference of gravitational potential	Mass (gravitational mass or gravitational charge)	

(*) Fluids could be subsumed under substances (and pressure interpreted as an aspect of chemical potential); we shall not do this in general.
(○) Magnetism is one side of the coin called *electromagnetism* which is a formal theory that unifies what we would otherwise see as two different Forces of Nature. Experiments and theory that are at the root of this part of physical science were created in the 19th century.
(†) The concepts of power and energy are identical for all Forces of Nature. There are no „different forms" of energy, there is no energy conversion, or the like.

Second, in theories of Fluids, Electricity, Heat, Motion, and so on, a concept is needed that corresponds to a quantity describing an *amount of* ... (amount of fluid: volume; amount of electricity: charge; amount of heat: caloric or entropy; amount of linear motion: momentum; amount of rotational motion: spin; and amount of gravitation: gravitational mass). These quantities take the imagined form of fluids—we treat them *as if they were fluids*; that's why we call them *fluidlike*. Clearly, these fluidlike quantities are *extensive*, i.e., they are extended (or spread out) through space. Their basic properties are, with some exceptions, the same for electricity, heat, substances, motion, and so on.

Forces of Nature act as fluid entities

Extensive quantities

Being extended—or, expressed more formally, being *extensive*—amount of fluid, heat, electricity, etc., have a few basic characteristics: they can be stored in physical systems (in materials and fields) and they can all be transported in some

Storage, flow, and production

ways (all of them can be transported conductively and convectively, whereas only amount of heat (caloric, entropy), spin, and momentum can be transported by radiation). Moreover, amount of heat (caloric, entropy) can be produced in irreversible processes (but not destroyed), and amount of substance and volume of fluid can be both produced and destroyed. All this means that these extensive quantities satisfy *balance relations* appropriate to their character and concrete circumstances.

Laws of balance of extensive quantities

Macroscopic physical science

Macroscopic physical science

In the simplest forms of models, continuum physics treats physical systems as continuously spread out in space and processes acting continuously over time (a simpler subset of continuum physics is found in spatially uniform dynamical models; Fuchs, 2010[1996]). Continuum physics is the unified collection of theories of materials and fields in classical (non-quantum) physics. It treats physical objects as the scenes where a handful of Forces of Nature are at work.

Models based upon the theories of fluids, heat, electricity, motion, etc., found in continuum physics and the physics of uniform dynamical models play an important role in applied physics and engineering; in these fields, the models are often implemented as large scale finite-element computer codes.

Applications range from stellar evolution through atmospheric and ocean physics to the flow of fluids (around airplanes and vehicles), and thermal and mechanical structures (buildings and bridges). Finite-element models are used by physicists and engineers in designing even relatively small-scale systems found in medicine (such as implants) and energy engineering (such as solar cells).

Macroscopic physical science should be contrasted with microscopic models of behavior of physical systems. In microscopic models, at least in their „popular" form, it is assumed that little particles roam in basically empty space, and that their motion explains (all) the phenomena of physical nature we can perceive both directly and indirectly (aided by instruments).

Power and energy. Finally, macroscopic physics makes use of the notions of *power* and *energy* among its central concepts. Fluids, Electricity, Heat, Motion, and so on, are all more or less powerful, depending upon circumstances. They cause other phenomena, and they can be caused by other phenomena.

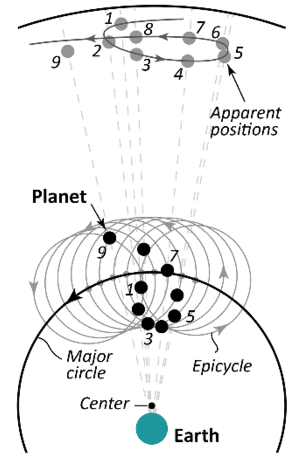
In physics, we introduce a measure, called *energy*, of how much is happening in an interaction between two phenomena (how much of a phenomenon is caused by a causing phenomenon); *power* is the measure of the rate of this causing. Both concepts take the same forms for all phenomena.[92] For example, the amount of water that can be pumped to a certain height with the help of an electrically driven water pump is determined by *the amount of energy made available by electricity* in the pump (multiplied by the efficiency of the coupling); this, in turn, is determined by how much electricity (how much charge) has flowed („dropped") from higher to lower electric potential. *Power* is the rate at which energy is made available in spontaneous processes and used in non-spontaneous phenomena. Again, the forms used to calculate the amount of energy made available and the power of a process are the same for all the phenomena discussed above. Energy and power are the same concepts in all realms of macroscopic physical science.

Energy and power take the same roles in every Force of Nature

Energy is quasi-fluidlike: it can be stored in physical systems (materials and field), and it can be transported; it is neither produced nor destroyed.[93] Therefore, amount of energy satisfies its own law of balance.

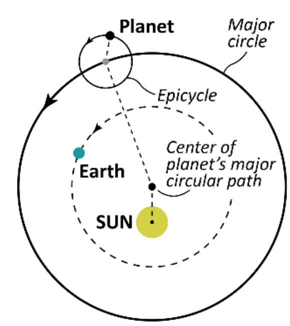
Balance of energy

Kepler's imagery of a Force of Nature, and Newton's notion of force. If modern macroscopic physics is a science of Forces of Nature, we should be able to find vestiges of our primary, mythic understanding of natural phenomena expressed in the works of the early masters of this science. Johannes Kepler (1571-1630) is a natural source for our search. In his „war on Mars," as he called his quest for understanding the motion of the planets, he was guided by his deeply held conviction that, how the planets moved, had to be *caused* by the Sun; he expressed this belief using the imagery of a causal Force emanating from the Sun.[94]



Ptolemy: Epicycle model of planetary motion

We need to understand how important this belief was and still is. Before his time, almost all models of the solar system were formulated as purely geometrical ideas; there was no physics involved, certainly not in the sense of a physics of Forces causing changes.[95] In the ancient Greek and Ptolemaic model of the universe and the solar system,[96] a planet moved at constant speed on a circular *epicycle* whose center moved uniformly on the periphery of a *major circle* around the Earth—circles were the only geometric forms accepted in ancient natural philosophy. The epicycle allowed for the possibility of a planet moving "backwards" in the sky for some time before resuming typical "forward" motion again. The center of the major circle had to be moved away from the center of the Earth—otherwise, one could not predict the changes of speed of motion of a planet on its path, as seen from the Earth.



Copernicus: Simplified version of model of planetary motion

This purely geometric approach was accepted by Nicolaus Copernicus (1473-1543). By putting the Sun in the center of the universe and letting the Earth and the planets move around it, he made an important step toward a modern view of the solar system. However, since he did not let go of the main assumptions of Greek astronomy that offered a purely geometrical explanation of planetary motion, he needed to resort to the same "tricks" as had Ptolemy: the center of the major circle of a planet had to be moved away from the center of the Sun. Moreover, in order to correct for smaller "irregularities" in the motion of the planets, Copernicus had to take recourse to the idea of epicycles as well.[97]

In Copernicus' model, the Sun was not the „motive" (causal) center of the solar system—it simply served as a „lamp." Contrast this with Kepler's image: The Sun is responsible for the motion of a planet, it is the causal center, the object from which a Force emanates and makes the planet move as it does.[98]

Kepler: The Sun is the causal center of the motion of the planets

We can now understand Newton's notion of *force* and how it appears in his equation of motion. If our desire is, like Newton's was, to produce a mathematical (i.e., formalized) description of motion, we could reason as follows. A *Force* (as in Force of Nature) is the causal agent influencing the motion of an object. We now call *force* the formal *quantitative* measure of what directly leads to a *change of motion* of the object. On the other hand, we measure motion by *amount* or *quantity of motion* (*quantitas motus*, in Newton's original Latin text: Def. II). Therefore, we can reason that what Newton called *force* will lead to a *change of quantity of motion*.[99] As we create a formal expression of our images, we set *force* and *change of motion* equal—here is Newton's formulation of this idea, named LEX II: *Mutationem motus proportionalem esse vi motrici impresse…* (2nd Law: That the change of motion is proportional to the motive force impressed upon it…).[100] Note that Newton wrote *motive force*, not just *force*. Very likely, he chose his words carefully because he must have been aware of the general meaning

Newton: Force as quantitative measure of change of motion

Newton's Second Law of Motion

of *motion*, handed down to us by the Greek philosophers, as any type of natural *change* rather than just change of location (which was called *local motion*).

Imagining how causal agents work

It all makes perfect sense from the perspective of a mythic understanding of Force; Newton's second law is motivated by imagining how causal agents work. What has happened in the formal rendering of this reasoning, though, is that the word *force* no longer applies to the perceptual unit we call *Motion*, with all its attributes of intensity (velocity), extension (quantity of motion), and power. The term *force* is now restricted to the formal measure of what causes a change of motion where change of motion is measured in terms of change of quantity of motion.

Newton's concept of force as transfer of momentum

Here is an imaginative depiction of this formalism: if quantity of motion is possessed by a moving body, its change is effected by giving the body some quantity of motion (or withdrawing some of it from the body). Therefore, *force* is seen as *transfer of quantity of motion* (i.e., of *momentum*; see Table 1.2). In short, what has happened in the creation of Newton's mathematical theory of motion is that the mythic figure of the Force of Motion, i.e., the causal agent in phenomena of motion, has faded into the background—*force* refers now to only an aspect of one of the aspects[101] of this figure. Still, if we are mindful of our experience, we will readily perceive a FoN called *Motion* at the root of mechanics.

PPSE—An imaginative scientific approach to Forces

Imagining interactions of Forces of Nature

We cannot separate what we propose to do for *Primary Physical Science Education* from our primary goals listed at the beginning of this section: (a) creating nature pedagogy for young children; (b) following what we can learn from modern macroscopic physics and the cognitive science of an embodied mind; and (c) trying to put nature and us humans back on speaking terms. These imply an additional set of objectives different from those of traditional physics courses: we want to nurture the tools of mythic consciousness and *imagination*; gently develop the cognitive tools that lead us on the road to a scientific approach to our encounters with nature; and treat physical phenomena as *causal interactions of Forces*. These points should be on our mind when we think of what to do for young learners.

But, we should ask, what does this mean for the teachers of these young students? We believe that the three goals (and their corollaries) outlined above can be framed as a single overarching objective for our book: We need to write a narrative about our encounters with Forces of Nature—using all the tools of imagination available to us—that encourages teachers to make the aims of experientially based primary science education their own.

The story of Forces & Imaginative Forms of expression

Making physical science a narrative about *Forces of Nature* constitutes a pivot toward primary forms of experiencing nature; remember that experiencing, in its widest sense, subsumes conceptualizing. The narrative we have in mind will *set out the story of Forces*, both Primary and Basic. Beyond that it needs to be a model for how to create and use *imaginative forms of physical and social interaction and expression* available to children that allow them to communicate about encounters with Forces of Nature and so create meaning and understanding. These forms of expression include figurative oral *language*, *storytelling*, *embodied simulations* and *Forces-of-Nature Theater* performances, and *visual arts* (see Fig.1.7). Importantly, these are the same forms of expression available to everyone who is not an expert in formal approaches to scientific knowledge.

Such a narrative will not only give teachers the tools for creating imaginative forms of nature pedagogy themselves; it will allow them to develop a deeper understanding of physical phenomena and important concepts of modern (macroscopic and microscopic) physics than can typically be obtained by traditional formal approaches to physical science. In case this should have been lost in all we have written so far, let us stress this point: We all need to „re-discover" the roots of our mythic or primary forms of experiencing if we wish to make meaning and develop understanding of our encounters with nature (and machines). As we have demonstrated in this section, a primary experiential approach to natural phenomena will not clash with important elements of modern science—indeed, it is a prerequisite for understanding physical systems and processes. If the teachers of young children learn to re-connect to their own mythic roots, they will be rewarded with a strong foundation for the modern aspects, uses, and meaning of science.

Myth as prerequisite for understanding

Concluding our *Debate about Physics and Forces*, we want to touch upon what all of this means practically for the science topics investigated in our book, and the way this is done. We shall discuss this by choosing the example of Light as a Force. Here are things we shall study, and things we do not or cannot cover.

Light as a Force of Nature. *Light* is, first of all, what every other Force of Nature is as well: it is a *character* we meet in our encounters with natural phenomena. It is an agent or a patient capable of interacting with other phenomena; it can cause other phenomena or be caused by them (pp.80-87; and Volume 2). *Causing and being caused* involves *power*, where power can be measured as the rate at which energy is exchanged in interactions of Forces.

This sets the scene and suggests what can primarily be done about Light. We certainly want to make sure Light has the fundamental properties of a Force, i.e., it must be characterized in terms of intensity, extension, and power. The first of these characteristics is quite certain: we derive our sense of Light from the perception of the polarity of light $\leftrightarrow$ dark; clearly, light can be intense or weak. Then, distinct from intensity, there can be more or less light in the sense that it can be more or less spread out, covering larger or smaller areas. Moreover, in our first encounters with Light, it becomes obvious that it is an activity very much like Wind, Rain, Fire, and Rivers (and, if they were not so slow, maybe we would have added glaciers to this list as well). As an activity, the Force of Light is a somewhat different member of the family of Forces which includes "things" like Water, Air, Heat & Cold, Electricity, and many more.

Intensity of Light

Extension of Light

Then we want to know how light is powerful and causes or "sets in motion" other phenomena; i.e., we want to study Light as an agent. This opens the door to phenomena where Light produces Heat at the surface of the Earth, thereby making the planet warm and driving the winds and the water cycle.

Power of Light

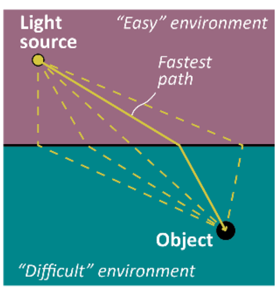
But Light can do much more than produce Heat: it is needed by plants as one of the three "ingredients" for producing food. This means we are able to understand Light as a phenomenon for which a "quantity of stuff" exists (p.95): this quantity is light-as-a-substance, which is delivered by Light as an activity—the longer the activity lasts, the more of this light-substance is delivered. Light-substance takes part in chemical reactions like all the other chemicals we know of—we simply need to remember that is is made of bosons rather than fermions (p.41). As a substance, Light drives the chemical process we have learned to make use of in solar cells. Similar to the case of photosynthesis in a leaf, the photovoltaic process caused by Light allows us to harvest the energy Light brings along. Studying Light as a FoN suggests that energy engineering as an important theme.

Light as Substance

We shall study the basic appearance of Light as a Force in Chapters 2 and 6, and the phenomena where Light produces Heat, or sugar in a leaf, or sets up an electrical tension causing Electricity to become active, in Volume 2; and we shall have a little something to say about phenomena where light is produced. Apart from this, just to suggest how the theme of Light and colors could be approached, we shall present a story for our youngest learners that can answer their question about why the sky is blue (p.84). Color is important for Light as a Force as well: after all, the color of light matters in photosynthesis and photovoltaics.

There is a lot more that could be said about Light. What about everything else we can associate with Light? With the colors it appears to be made out of; the colors it brings about in our world; the blue sky and rainbows; the activity of seeing? What about how light appears to travel in our environment, bouncing off surfaces and going through materials, moving as rays; the rings appearing around a lamp seen through a foggy window at night? And what about the study of Light in quantum physics and its use in modern information technology?

We shall be quiet about these phenomena, not for lack of interest, not because they would not be important. The reason is simple: We believe that Light as a Force should come first; and then there is only so much time, space, and ink to be spent on a subject such as ours. As part of the family of Forces, Light will allow us to develop ways of imaginative reasoning that are fundamental if we wish to study Light from additional angles. Just so that this does not remain an empty claim, let us suggest how we could deal imaginatively with the phenomenon of refraction of light.



Refraction of light

Refraction of light. We begin with a sketch that can be turned into a story of Light. Light is born in the Lamp, learns that there is an object it must illuminate, but the path to the object leads through two different environments, one easy to move through, the other harder. Given a general spatial arrangement, which path should Light take in order to arrive at the object as fast as possible?

The same situation can be turned into an embodied play, maybe outside where a parking lot borders on a grassy or otherwise uneven field. A number of kids acting as Light start at a „light source" along a few paths made of two segments, going first over the asphalt and then over the field, to the object to be „illuminated." The teacher can keep time for the children by clapping rhythmically. Children take one step every „clap" on asphalt, and only one step every two claps on the grassy field—let's see who arrives first.

Older children can construct the situation on paper and measure lengths of path segments and calculate how long it would take Light to move along a particular compound path, then graph the results and realize that there is a minimum time in the graphical curve generated in the exercise. And as always, the stories, plays, or exercises should be accompanied by opportunities to observe the refraction of light out there in nature and in artificial environments.

◦ ◦ ◦ ◦ ◦

Maybe we have convinced readers that our narrative about Forces of Nature will be worth their time and effort. Accepting that these Forces arise in mythic experience—as mythic or primary images we work on or „manipulate" imaginatively in our mind—prepares us for a new approach to physical phenomena suitable for the type of primary encounters children (and we) have with nature. So, let us begin the narrative about Forces we keep promising.

Notes

[1]Note the important distinction between *Forces of Nature* and the concept of *force* in mechanics: they are not the same! We shall discuss the issue of how to understand and use the term Force form different perspectives at the end of this chapter (Section 1.5).

[2]We, the authors, are physicist by training, and our book is about physical science. We shall not always put the qualifier „physical" in front of „science," but, in general, this is what we mean. We shall try and make clear if and when we mean natural sciences in general.

[3]We hope to make abundantly clear that *myth* is not what we often use the word for: expressions or stories that are not real, not true, possibly even lies. In everyday modern usage, we sometimes accuse someone of telling a myth, meaning that what has been said opposes reality and truth. Myth, as it is understood in anthropology, literary and historical studies, and cognitive science is about a phase in human history when a new form of consciousness and new cognitive tools evolved that made our ancestors into modern humans (Homo Sapiens Sapiens). Myth, as we shall see, is very much about reality as directly experienced.

[4]*Continuum physics* is a collection of macroscopic theories of Basic Forces of Nature—the Forces covered are Fluids, Electricity and Magnetism, Heat, Substances, Gravitation, and linear and rotational Motion. In the simplest forms of models, continuum physics treats physical systems as continuously spread out in space and processes acting continuously over time (which leads to initial value problems in partial differential equations; in theories of uniform dynamical models—which are a subset of continuum physics—we obtain systems of initial value problems in ordinary differential equations that are generally simpler to deal with; see Fuchs, 2010[1996]).

Importantly, continuum physics does not make use of the metaphoric web upon which microscopic („particle") models are based; rather, it arises from the metaphoric concepts underlying our understanding of Forces of Nature. Physicists have been successful in „reducing" macroscopic systems and processes to the handful of phenomena listed above (which we call *Basic Forces of Nature*).

[5]Physics is known as a formal science („formal" is typically mislabeled as „abstract"); moreover, it is assumed to be an objective representation of how nature „truly" is—if you want to know what reality is, how it works, and how it presents itself to us as truth, ask a physicist. There are popular renderings of this science where we try to present to a lay public the most recent findings and how they must be understood.

[6]Here we allude to issues in (science) education that may be labeled *Concept Learning* in general and *Conceptual Change* in particular. We shall have much more to say about this in Volume 2.

[7]This criticism of standard theories of cognitive development has been leveled by Kieran Egan (1988, 1997). His model of recapitulation of (or development through) cultural stages in ontogeny offers a clear alternative. In his model, imagination takes center stage, and we gain an understanding of the development of abstract forms of understanding by the youngest children that parallels what we know from second generation cognitive science (including cognitive linguistics and narratology; see Lakoff, 1987; Johnson, 1987; Varela et al., 1991; Lakoff & Johnson, 1999; Hampe, 2005; Caracciolo, 2014). We discuss some elements of abstraction and imagination developing in young children in this chapter; more will be said in Volume 2.

[8]Choices of ontology and epistemology (related to physics) to be made here are not simply, and definitely not a priori, philosophical—products of experience will matter fundamentally. We let ourselves be guided by what second generation cognitive science can tell us about how humans understand their interactions with their diverse environments (see Lakoff & Johnson, 1999), and by those theories of physics that will allow us to work on phenomena in our human-scale natural and technical environments that grant us forms of direct experience.

[9]We borrow the term *Forces of Nature* (abbreviated as FoN) from how it is used, colloquially and scientifically, for Forces such as Ice, Fire, Rivers, Wind, and Gravity that have shaped the

surface of the Earth and, in various forms, those of the other planets as well. Examples of how this term may be used are found at https://www.nationalgeographic.org/interactive/forces-nature/ (Forces of Nature: Explore the science behind earthquakes, volcanoes, tornadoes, and hurricanes...).

In the prestigious journal "Nature" we read: "Agriculture and excavations shape the landscape more than rivers and glaciers. ... Hooke called humans "geomorphic agents", comparing them to land-shaping Forces of Nature, such as rivers, glaciers, rain and wind." See Philip Ball: https://www.nature.com/news/2005/050307/full/news050307-2.html (visited on March 5, 2023).

[10]When we name a *Force of Nature* such as *Wind*, *Heat*, or *Water*, we shall normally capitalize the name (and print it in italics, if that is needed for clarity). The reason for this is simple: words such as „heat" or „water" are used in a number of different ways. *Heat* might denote the class of phenomena we might call thermal, or it may be used for the amount of heat thought to reside in bodies and flow in and out; it may even be used for describing the feeling of hotness. In the case of *Water*, we may have even more difficulty being clear: in the first place, water appears to us a a materiel substance; however, it may very well be experienced as a powerful agent—in this case, it takes the role of a *Force of Nature* that can be seen to have a number of aspects (not just that of being a material substance).

[11]In Egyptian myth, Wind separates Sky from Earth and then supports Sky above Earth (Fig.2.15). In the Babylonian epic of creation, we learn how Marduk was given the power of Wind to fight and conquer Tiamat (the primordial Sea); upon killing her, he split her „like a dried fish" and made one part into the Sky and the other into Earth. We shall use the Egyptian story in Chapter 2 (Section 2.4) for a discussion of the meaning of Wind and Air.

[12]Robert M. Leavitt (2011), p.49.

[13]Robert M. Leavitt (2011), p.49.

[14]A translation of an original version of the story—*Koluskap naka Wocawson: Koluskap and It-Is-Windy*—in Passamaquoddy by Lewis Mitchell is presented in Robert M. Leavitt (2011), p.55–57.

[15]Gluscabi is one of several spellings of Koluskap.

[16]„Why we need wind." http://www.angelfire.com/ia2/stories3/wind.html. Visited in March, 2020.

[17]The terms *agent* and its opposite, *patient*, are taken from cognitive linguistics. An agent is the active „being," a person or thing, in an interaction. A patient is the entity stuff is happening to.

[18]Losev (1930/2003) explains in what sense myth is a symbolic form of expression. See also E. Cassirer, 2020/1925.

[19]Losev (1930/2003), see his discussion of color and light, pp.43-50.

[20]For example, the polarity called *hotness* is the starting point of the construction of the concept of *temperature* in continuum thermodynamics.

[21]Losev (1930), p.38. „[...] expression can be a symbol. In contrast to a schema and an allegory, we find here a complete equilibrium between the 'internal' and the 'external', the 'idea' and the 'outer shape', the 'ideal' and the 'real'. There is nothing in the 'outer shape' that is not also to be found in the 'idea'. The 'idea' is by no means more 'universal' than the 'external image'; and the 'image' is not something 'particular' in relation to the idea. Rather than being mentally added as an abstract concept, the 'idea' is given in a concrete, sensuous, and visible way. At the same time, the 'image' itself speaks of an expressed 'idea', not of 'idea' merely as such; and the contemplation of the 'image' itself and purely 'perceivable' features suffices to comprehend the 'idea'. [...] In a symbol, on the other hand, the 'idea' contributes something new to the 'image' and the 'image' contributes something new to the 'idea'. The 'idea' is identified here not with a mere 'external shape' but with the identity of this 'shape and idea', and, similarly, the 'external image' is identified not with a mere abstract 'idea' but with the identity of the 'idea' and 'image'."

[22]Deacon (1997) has called humans the symbolic species. An important discussion of symbolic inventions in the development of the human species and mind can be found in Donald (1991). On a natural history of communication, see also Tomasello (2008).

[23]Losev (1930), p.13. Our analysis of myth presented so far is partly based upon Losev's „The Dialectics of Myth." We apply what he and other philosophers and literary scientists have told us about the nature of myth to the notion of Forces of Nature—and everything else this implies for the schematic/abstract, metaphoric, analogical, and narrative character of physics (Fuchs, 2006, 2015; Corni, 2013)—we have developed in our studies of macroscopic physical science (see Fuchs, 2010[1996]).

[24]Losev (1930), p.18, refers here to the (necessary) belief in flat, empty, dark, and boundless space for Newtonian mechanics; he calls this belief the foundational myth of this theory (and therefore of much of traditional approaches to classical physics). We, on the other hand, might call the experience of Forces of Nature the mythology upon which we base our approach to macroscopic physics.

[25]See J. J. Gibson (1979), A. Noë (2004), A. Chemero (2009).

[26]See A. Noë (2004) for a modern account, but also J. Dewey (1925) for his philosophy of experience.

[27]See M. Caracciolo (2014). On the general issue of understanding language as the result of embodied simulation, see B. K. Bergen (2012).

[28]Models that do not treat our mind as a computer but rather take our embodiment and our communication with the world around us as point of departure have been developed since the 1980s (or longer still, if we accept the work of pragmatist philosophers such as J. Dewey, 1925, and W. James, 1890 and 1911). See, in particular, Varela, Thompson, & Rosch (1991); A. Chemero (2009); M. Johnson (2007); Hutto & Myin (2013); and Di Paolo, Cuffari, & De Jaegher (2018).

[29]Scholars work on questions relating to biological, cultural, and mental development from perspectives as far ranging as biology, archeology, cognitive science, and cultural studies. See S. Mithen (1996), M. Donald (1991), J. Gebser (1986). Gebser's division into periods during which the human mind has been developing gives us archaic, magic, mythic, mental, and integral phases.

[30]The distinctions referred to here have been taken from M. Donald (1991) and K. Egan (1997).

[31]See E. Tulving, 1985, 1986; Duff et al. (2020).

[32]See M. Johnson (1987), and B. Hampe (2005).

[33]M. Donald (1991), Chapter 5.

[34]M. Donald (1991), p.157.

[35]M. Donald (1991), p.168.

[36]M. Tomasello (2014). Tomasello explains how the ability to plan as a group, in a social context, i.e., „putting their heads together," distinguishes modern humans from modern apes.

[37]M. Donald (1991), p.171.

[38]See the table presented in M. Donald (1991), p.198.

[39]M. Donald (1991), p.213. "Stone Age cultures demonstrate how far language development initially outstripped technology. Technology in these societies is primitive, while language in social contexts soars to great heights. [...] The use of language in tool technology, by contrast, is limited; most trades and skills are transmitted by apprenticeship, that is, by mimetic modeling. [...] The most elevated use of langue in tribal societies is in the area of mythic invention—in the construction of conceptual "models" of the human universe. [...] there are always myths of creation and death and stories that serve to encapsulate tribally held ideas of origin and world structure. Stories [...] of the tribe and its relationship to the world [...] abound. These uses were not late developments, after language had proven itself in concrete practical applications; they were among the first."

[40]In one of the oldest Egyptian myths, the *Devine* or *Heavenly Cow*, this fear of being pulled back into the dark while we wish to move toward the light is clearly expressed. In that story, it is snakes in the ground which have the power to pull us back into darkness. While it is possible that this story tells the experience of mythical minds developing further toward what we might call „modern" minds, after the development of literacy, we can still take it as a parallel to how „awakening" consciousness must have felt to early modern humans during the long period of the transition from mimetic to mythic culture. (K. Weber & R. Fuchs, private communication.)

[41]See G. Nixon (2010). Nixon, similar to other authors, sees myth driven by emotional need (following expanding consciousness) and leading us toward the discovery of the sacred.

[42]We take the term *scale* to apply to temporal, spatial, and systemic "size" or extent. An experience that is recognized as such and forms an experiential unit can be brief or long lasting, it can occupy small to large spaces, and it may involve a smaller or larger (or rather, simpler or more complex) system. See Fuchs, Dumont, & Corni (2023); in particular, see Figure 3.

[43]This is a slightly adapted version of a possible definition of story as given by D. Herman (2009); see Fuchs (2015).

[44]M. Donald (1991), p.257.

[45]M. Donald (1991), p.257-258. „Aboriginal hunter-gatherer cultures, in their possession of elaborate mythical accounts of reality and in their daily uses of language, show a predominantly

narrative mode of thinking. [...] The supreme product of the narrative mode, in smaller preliterate societies, is the myth."

[46]M. Donald (1991), p.215.

[47]The British Museum created an exhibition of Ice Age Art in early 2013 that has been documented in Jill Cook (2013).

[48]Milman Parry, in A. Parry ed. (1987).

[49]There is a feeling that myth already represents an age of „loss" resulting from a profound change of our relationship with nature—humans began sensing a distance between themselves and nature. Lévi-Bruhl (1985) expressed this by saying that myth constitutes an attempt to compensate for this loss.

[50]K. Egan (1988).

[51]K. Egan, 1997, 2005.

[52]K. Egan (1988), chapter 5.

[53]Walter Ong (1982)

[54]Petrarch (1336/1948).

[55]K. Egan (1988), pp.52-53.

[56]K. Egan (1988).

[57]Kieran Egan (1990).

[58]The four stages mentioned here have been developed from research by Jean Piaget. We fear that the typical treatment given to his model in schools misses much of what could be important to early education. If we say that—what, at the face of it, is certainly correct—children do not yet know about the world and concepts such as democracy or entropy, and that mathematics—which is commonly considered to be the epitome of abstractness—eludes them, we actually miss much of the rich emotional and mental life of young children.

[59]There is evidence that early humans used single terms to denote polarities. See Gabor Gyori and lren Hegedus (1993). See in particular Section 3 for a discussion of binary opposites / polarities.

[60]Drawings have long been recognized as an important form of expression of children's experience. There is an important collection, called the Rhoda Kellogg Child Art Collection, of early childhood „scribblings" that has been made available at the Zürcher Hochschule der Künste: https://www.early-pictures.ch/kellogg/en/. See also Maurer & Riboni (2010), Maurer et al. (2009; and 2013-2019).

[61]His concrete experiential background was twofold. First, where he lives, there is a major overland transmission line with lots of electric towers and cables visible. Second, his father took him past a small transformer station—a small house—without any cables leading in our out; his father told him that the cables had been buried below ground.

[62]There is a vast literature in the field of developmental psychology, some of which deals with exactly these kinds of questions. A good source for the issue of schematizing actions of mind in small children is Jean Mandler (2004).

[63]There is evidence that „an abstract to concrete progression may capture important features of how knowledge develops in the realm of biological thought and in many other areas of understanding as well." Simons & Keil (1995). See also further work by Frank Keil (2010). The work done especially by Frank Keil specializes our general observations about (schematizing) abstraction in important ways to science and science learning.

[64]See, in particular, the research on analogy by J. Atkins (2004).

[65]Young children love animated shows such as *Dinosaur Train* (beginning in 2008) or the longer stories of *The Land Before Time* (starting in 1988), but they lose interest very quickly if we let them watch the realistically rendered and narrated tv series called *Prehistoric Planet* (2022). We may learn from this that the abstract form of images used in animations easily wins, with children, over the realistic rendering of dinosaur life; equally, the story form where the animals speak wins over the explanatory narrative of a nature show by a long shot.

[66]K. Egan (2005), Chapter 1.

[67]Binary opposites have been described as a major tool of sense-making in oral societies by C. Lévi-Strauss (1966, 1969, 1978). This is one of the sources of its application by K. Egan (1988, 1997) in education.

[68]Fuchs et al. (2018); Fuchs, Dumont, & Corni (2023).

[69]Imagination is a hotly debated subject in philosophy and cognitive science. See Johnson (1987), Casey (2000), Caracciolo (2014), Kind (2016), Levy & Godfrey-Smith (2020).

[70]B. K. Bergen (2012)

[71]K. Egan (1990, 1997, 2005)

[72]K. Egan (1990, 1997, 2005)

[73]In the following, we make use of parts of H. U. Fuchs (2014a).

[74]Ong (1982); Donald (1991).

[75]Neumann, (1949/1954); Weber (2006).

[76]This may sound strange: don't we all „know" space? We do know spatial relations (up-down, front-back, near-far, in-out, path, etc.); without having formed these abstractions in early experiencing, we could not survive. However, being able to „see" empty, dark, cold space before our inner eye is indeed a modern achievement; there is no indication of space as an abstract notion (as an experiential unit) in, say, ancient Egyptian culture. Even to Greek scientists such as Aristotle it was anything but clear that empty space (void) could exist. See our discussion of early natural philosophy in Volume 2.

[77]F. Petrarch (1336/1948).

[78]On hurricane Sandy, see https://en.wikipedia.org/wiki/Hurricane_Sandy (visited on June 7, 2022).

[79]On thunderstorms in hurricanes, see https://www.nasa.gov/mission_pages/hurricanes/archives/2006/hurricane_lightning.html (visited on June 13,2022).

[80]US Bureau of Labor Statistics; https://www.bls.gov/ooh/life-physical-and-social-science/physicists-and-astronomers.htm.

[81]https://www.britannica.com/science/physics-science

[82]All of this is certainly much more intricate and sophisticated than presented here; for an eminently readable account, see Rovelli (2017).

[83]This popular form of interpreting Einstein's $E = mc^2$ is simply wrong. Energy and mass are properties of any physical system, and the two are equivalent. Particles that have mass have energy (according to their mass), and when they are converted into radiation (which is the only „conversion" that takes place), this radiation has the same energy and mass as the particles before. This also tells us that radiation is not energy! It *has* mass and energy (or more precisely, mass/energy, since the two are equivalent).

[84]On the development of the concept of temperature based upon the notion of hotness, see Truesdell (1984). On the experience of thermal phenomena, see Fuchs et al. (2022).

[85]On the origin and structure of embodied concepts in thermodynamics, see Fuchs, Dumont, & Corni (2023).

[86]*Conduction* and *radiation* are the technical terms for two of the three ways fluidlike quantities such as momentum and entropy (see p.47) can be transported; the third type of transport is called *convection*.

Conduction is a transport of a fluidlike quantity *through* a material. Usually, this transport takes place if there is a tension (i.e., difference of potentials) associated with the quantity; in the case of momentum, this would be a velocity difference. Interestingly, in typical models of mechanical situations, many of the conductive transports of momentum do not need such a tension—they take place in a manner that is best called „superconducting," as in the case of superconducting transports of electrical charge.

Radiative transport happens in the interaction of bodies and fields where both, bodies and field, occupy the same space at the same time. In this case, there are sources or sinks of momentum in a body: momentum enters or leaves a body at every point inside the body where a (gravitational or electromagnetic) field is present.

Convection is the name for the transport of momentum with a flowing fluid—since the fluid flows, it contains („has") momentum, and it obviously takes its momentum along with it. Importantly, *force* is defined only with respect to a body that keeps its integrity, i.e., where no matter can either enter or leave the body. Therefore, convective momentum currents are not a case of *force* in Newton's sense!

Conductive momentum currents measured at the surface of a body are called *surface forces* whereas the source rates of radiative momentum transfer are called *body* (or *volume*) *forces*. Convective momentum currents are called just that: *momentum currents*. A detailed explanation of these concepts of continuum mechanics is presented in Fuchs (2010, Chapter 3).

[87]https://www.etymonline.com/word/force. Visited on 10 June, 2022.

[88]H. U. Fuchs (2014b, 2015).

[89]C. A. Truesdell (1984), I. Müller (1985), and H. U. Fuchs (2010[1996]).

[90] C. Rovelli (2017).

[91] On the form and structure of analogy that governs the experience of different forces of nature, see Fuchs (2006), Fuchs, Dumont, & Corni (2023).

[92] This means that there is only a single concept called energy in physical science: there are no forms of energy, energy is not transformed; very importantly, there are no „forms" of energy stored in physical systems.

[93] Energy currents are not Galilei-invariant, in contrast to currents of charge, entropy (caloric), momentum, etc. Furthermore, it is not clear how to identify energy transfers in (classical) gravitational fields.

[94] See, for instance, C. Wilson (1972); A. Koestler (2017[1959]); O. Gingerich & J. R. Voelkel (2005). Wilson and Koestler give very readable accounts of how Kepler arrived at his laws (Koestler: Part Four, Chapter 6).

[95] Accepting geometric models as answers to the true nature of planetary motion goes back to Plato and his notion of the existence of an objective world of geometric ideal forms (of which the most ideal was the circle). However, we should not forget Aristotle who took a different view of reality in his natural science. There, change (processes, which were called motion) followed from natural causes such as the Four Elements finding their natural places in the universe if disturbed from them. Still, for astronomy, it took until Newton's mechanics for Forces to arrive center stage in a new physical science.

[96] Claudius Ptolemy (about 100-170 ce) worked out the details of what is now called the epicycle model of planetary motion in his Almagest, which would remain the foundational text for astronomy up until Kepler, Galilei, and Newton changed the face of physical science. Having an eccentric circle with an epicycle placed on it, and a planet moving on this epicycle, all at constant speed, is indeed a purely geometric model of planetary motion. If we wanted (but Ptolemy did not do this), we could add an epicycle on an epicycle, and again and again more of them, to attain any desired accuracy for predicting the apparent motion of a planet (this is a geometric version of Fourier analysis).

[97] See http://ircamera.as.arizona.edu/NatSci102/NatSci/text/copernicusmodel.htm; moreover, https://farside.ph.utexas.edu/books/Syntaxis/Almagest/node4.html (visited on March 7, 2023). Copernicus's epicycles were quite a bit smaller than those of Ptolemy, and they served a different (less important) purpose. In Ptolemy's model, the epicycles were fundamentally needed for explaining retrograde motion. Despite these geometric „tricks," Copernicus's model predicted something Ptolemy could not: with the Earth moving, the size of a loop a planet traces in the sky is a measure of its distance (this is the well-known parallactic effect where we view an object against a distant background from different positions). Therefore, for the first time in history, Copernicus could give an account of the (relative) distances of the planets, i.e., of the „proportions" of the solar system.

[98] Kepler clearly had this vision of a Force emanating from the Sun. However, he did not manage to formalize the idea and make it part of a new physics—this remained to be done by Newton. While all three laws of planetary motion formulated by Kepler are correct in modern non-relativistic mechanics, they are descriptive and not explanatory in the sense of the new physics created by Newton. Nevertheless, as explained by Wilson (1972) and Koestler (2017[1959]), Kepler needed his belief in order to weed out a number of physically impossible scenarios—this finally led him to formulate the laws we now know by his name.

[99] And, since quantity of motion of a body depends upon the speed of the body, changes of quantity of motion translate into changes of speed from which we can calculate how the body moves through space in the course of time.

[100] I. Newton (1687), Definitiones, p.2; and Leges Motus, p.12.

[101] The main aspect the term *force* is related to is *quantity of motion* (*momentum*); of this, *force* is the aspect of *flow* of quantity of motion—so, we have an aspect of an aspect.

Chapter 2

Encounters with Forces of Nature

Encountering Wind
(Photograph by ML, June 2021)

Within our rich flow of experience, we discriminate a perceptual unit called *Force of Nature*. We experience many diverse *natural Forces* such as *Wind*, *Rain*, *Light*, *Fire*, and *Lightning*; *Heat* and *Cold*, *Water* and *Air*; *Electricity* and *Magnetism*; *Motion* and *Gravity*; *Food*, *Fuels*, *Medicine*, and *Substances* in general; and many others. In this and the following chapters, we shall discuss how we, starting at an early age, experience such *Forces* and how we speak and generally communicate about them.

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When helping children learn about physical nature, we might want to consider first and above all how they and, for that matter, we all, encounter nature, and what arises from these encounters. Much can be learned if we take a fresh look at *experience as ongoing dynamical organism-environment couplings* and study how mind emerges when different forms of experience (e.g., physical and linguistic) interact. Central among these forms of experience are direct physical perception of nature and forms of communication among people about such experience. In this chapter, we begin the discussion of how this fresh look helps us with constructing *Primary Physical Science Education* (PPSE).

Experience

At the center of human experience of nature, we find an *abstraction*—an *experiential unit* or *perceptual gestalt*—we call *Force of Nature*, for which we can find many concrete examples in our cultures. Modern usage of the term *Force of Nature* (FoN) often refers to *planet shaping Forces*. The Sun, rocks from space, glaciers, rivers, oceans, volcanos, and hurricanes have visibly transformed the surface of the Earth. This reaches even deeper: Earth's crust is moved and worked over by the mantle below it, which shifts, lifts and swallows entire continents and makes them collide (Fig.2.1). Back on the surface, we now recognize life in general and human society in particular, as planetary Forces.

Force of Nature as experiential unit

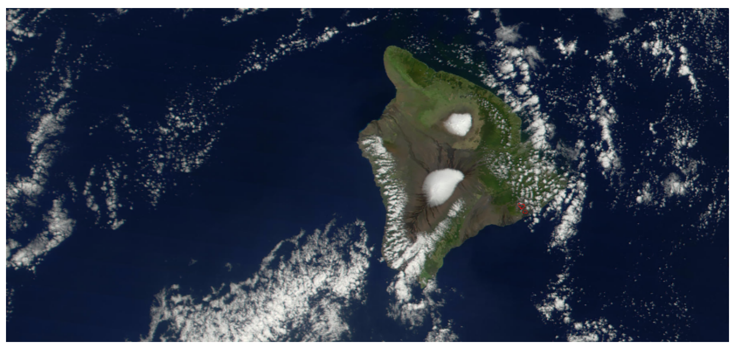


Figure 2.1: *The Island of Hawaii („Big Island") is a place where we can literally see and feel Forces of Nature at work. The two white puffs over Hawaii are snow on top of the volcanoes Mauna Kea (top) and Mauna Loa, the highest mountains on earth if we measure them from the bottom of the ocean. The Hawaiian islands are created by a hot spot in the Earth's mantle below the Pacific. (Image: NASA/MODIS Rapid Response Project.)*

We often see physical structures such as oceans, the atmosphere, volcanoes, glaciers, and rivers as Forces. There are other uses of the notion of FoN, though, that come closer to what we have in mind. Legends of North American native peoples tell of *nature spirits* such as *Sun*, *Rain*, *Wind*, *Lightning*, and many more.[1] Ancient Egyptian and Babylonian myths explain how Wind separated the Sky from the Earth and so helped shape and maintain the world we live in.[2] In modern science, we describe the history of our solar system and Earth; we tell stories of how *Gravity*, *Motion*, *Heat*, *Electricity*, and a multitude of *Substances* were at work in the creation of our Sun and Earth; how the Forces of Wind, Water, Ice, and Fire—and, finally, Life—shaped our planet's surface; and how the Sun's light and myriad substances made life possible here on our planet. These Forces should be categorized as either processes (such as Rain and Wind) or as having the character of real and imagined substances (Chemicals, Heat, Electricity, etc.) rather than structures or objects. Here, Forces of Nature appear as agents at work behind the scenes—they will be the characters of our story.

Main categories of Forces of Nature: Structures, processes, real and imagined substances

Primary Forces of Nature. Our understanding of nature—both in pre-scientific and in scientific forms—grows around elaborations of the abstraction of Forces of Nature as *agents* (Table 2.1). This is why we start this chapter by tracing origins of this abstraction in human experience, which involves the experience of *causation* and the perception of *polarities* as generators of the notion of *Force*. Next, we shall study a first group of physical Forces—Wind, Rain, Fire, Light, and Lightning—which we have associated with the category of processes, activities, or events. Interestingly, processes lead us quite directly to the other group of Forces, which is related to our experience of substances, both real and imagined—such as Air, Water, Heat or Cold, Light-as-Substance, Gravity, Food and Fuels, and Electricity. Among these are *invisible* Forces such as Gravity, Heat, and Electricity. All of the Forces mentioned here are experienced quite directly—they are what we call *Primary Forces of Nature*.[3]

Causation and polarities

Primary Forces of Nature

Basic Forces of Nature. In a major part of physical science—called *continuum physics*—theories of Forces of Nature have been created around a rather small category of Forces (Table 2.1, column on the right; see Chapter 1, pp.45-50). We can look upon the scientific category of Forces of Nature as born from the wish of finding a small number of *Basic Forces* acting behind the scenes of *Primary Forces* (Table 2.1, left column).[4] If we accept Fire as a Primary Force, science tells us that we can understand Fire as the result of Substance(s), Heat, and Light (as an electromagnetic phenomenon) interacting; and Wind will be understood as arising from the interaction of Sunlight, Heat, Fluid, Gravitation, and Motion.

Basic Forces of Nature

Table 2.1: Examples of *Forces of Nature*

Primary *Forces of Nature*	**Basic *Forces of Nature***
Wind & air	Fluids (water, air, . . .)
Rain & water	Heat
Fire & ice, heat & cold	Electricity & magnetism
(Sun-) Light	Substances
Thunderstorms & lightning	Gravitation
Food & fuels	Translational motion
Gravity & motion	Rotational motion

Formal science, however, will not be our immediate concern; we will approach it slowly and carefully in the later chapters of this book. Before we do this, we shall develop models of Primary Forces of Nature, discuss how we make sense of them, and how we communicate with and about them using natural language and other forms of expression.

Names for Forces of Nature. Looking at Forces of Nature in this manner lets characters or figures arise in imagination. For this reason, we should consider a word such as *Wind* not just as a noun used for a phenomenon but rather the *name* of an agent. This is why we have capitalized names for Forces in the previous paragraphs. We shall continue to do so if it is important to point out that we are giving a name to a gestalt in its totality rather than to an aspect of it.

Names rather than just nouns

Consider the term *heat*: do we mean the totality of thermal phenomena for which we have a name, *Heat*, or do we possibly speak about amount of *heat* which is like an invisible imaginative fluid that comes up in everyday language and science

Perceptual unit versus aspect

(Chapter 4)? Since the distinction is very important, we shall, when appropriate, follow the somewhat unusual custom (in English, at least) of capitalizing the name of the Force. However, if the meaning is clear from the context, we can forgo this formality.

2.1 Experiencing Forces

Causation and tensions

Complex living beings like us experience Forces and form an understanding of their meaning in at least two distinct ways: first as the result of an overall judgement of larger and longer lasting scenes where we can „see" agents acting in story-like settings, acting and interacting as things around us change; and second, through direct experience (feeling) of *tensions* created by differences of directly perceived intensities (such as hot and cold, light and dark, humid (or wet) and dry, fast and slow...). We shall discuss the second avenue to the notion of *Force* in the following Section 2.2.

Events and causings

We see things changing around us constantly—fruit ripening on a tree, temperature rising in the morning of a beautiful day, a cat moving from one of its favorite places to the next, a forest burning down, wind felling trees, heat making a steam-engine work. In continuous change, we identify chains of events such as when the Sun's light warms up the surface of the Earth, which lets water evaporate and air ascend, causing winds that transport vapor to places where it will rain, and the water feeds trees that produce fruit, which is eaten by animals and people who then are ready for any number of activities. In all these cases we are prone to see one event as the *cause* of the next, and so on.

Notice how we express our sense of Forces in everyday language. Here are just a few examples from nature, engineering, and our social environments; and let us not forget our psyche:

- On an electric contractor's website we read: „*We've said it before and we'll say it again: electricity is a force to be reckoned with, and reckoned with carefully.*"[5]
- In 1824, Sadi Carnot titled his book on thermodynamics *La puissance motrice du feu* (*The Motive Power of Heat*). In the introduction he gives a beautiful account of Heat as a Power or Force: „*To heat also are due the vast movements which take place on the earth. It causes the agitations of the atmosphere, the ascension of clouds, the fall of rain and of meteors, the currents of water which channel the surface of the globe, and of which man has thus far employed but a small portion. Even earthquakes and volcanic eruptions are the result of heat.*"[6]
- After the little boy has made a huge mess of his bedroom, his father says „*It's as if a tornado just hit.*" And his mother says admiringly „*He's a force of nature!*"
- Economists or business people, and journalists reporting about it, regularly speak of *Market Forces*: „In such a system, employers protect workers from many of the vagaries of market forces..."[7]
- Clearly, *anger* is a (psychological) Force—note our metaphoric rendering of anger as a heated fluid,[8] as when we say „*He made my blood boil,*" and „*She blew her top.*"

Our overwhelming inclination to „see" causes is one of the sources of our imagination of Forces (of Nature). We somehow believe that an event is a Force—or rather that there is a Force behind the event—that causes the next event and leads to change. If we tell a tale of a sequence of events, we are likely to use language suggesting that a Force is responsible for another; we do not just say, first A happened, then B, and the C. . . , but we want to give reasons for what we have experienced. Inventing Forces imagined as agents appears to be our way of introducing reasons: A Force is a powerful agent that can cause something new to happen.

Forces as causes

Reasons for events

Forces, effects, and causes

Causation

The phenomena we call *Forces* are associated with *effects*—they *cause* other phenomena to happen. This may very well be the first and most direct aspect we associate with Forces; it is one of the reasons why we experience and speak of *Forces* in the first place.

The perception of causes runs deep in all living beings—we need to be able to react to our environments. Humans have created an important concept from this experience: we call it *causation*.

2.2 Polarities—Tensions Create Forces

Apart from our experience of causation, where might our abstract sense of Forces of Nature stem from? If we study creation myths of bygone eras, we can learn something important for our modern understanding of Forces of Nature. Many myths tell us that the world started in an undifferentiated state—as the ancient Egyptians said, no two things existed[9] —from which a first difference arose spontaneously, and then many more. According to many creation myths, the first difference that arose was that of *light and dark*. Then others emerged such as *high and low*, *hot and cold*, and *humid (wet) and dry* (which was a defining difference for the Egyptians living along the Nile river, with desert on both sides, separating life from death).

When myth developed, the world was already a highly differentiated system with many differences apparent, making distinctions possible; indeed, the story of human understanding is one of a mind capable of discriminating objects—qualities, events, and physical things—in the continuous flow of experience.[10]

Discrimination and differences

Experiencing polarities and tensions

Organisms experience differences. Usually, these differences do not constitute a duality or dichotomy—meaning that only two extremes exist as we usually assume of differences such as alive and dead. If the difference is one of hot and cold or humid and dry, we know that there are myriads of possibilities existing between two extremes (such as freakishly cold and hellishly hot, or dripping wet and bone dry). The experience of such qualities is called a *polarity*. We can imagine two extreme values—the *poles*—with a line between them along which we can place all the different possible intermediate values (this is a *schematic scale*: Fig.2.2;

Polarity

Scale schema

Tension

see Volume 2 for more detail). An organism experiences differences of two values along the scale—such as warm and lukewarm, or somewhat humid and moderately dry—as a *tension*, as a cause of or a drive for change, for something happening in the world.

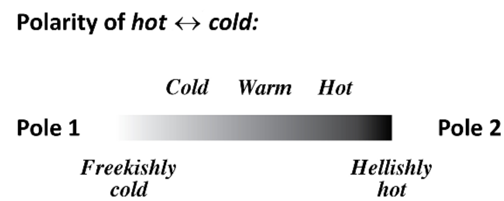


Figure 2.2: *A polarity (here: hot ↔ cold) is characterized by a scale schema—a path leading from one pole to the opposite one, showing changing degrees of intensity.*

When Heaven and Earth Were Created. According to one of their origin myths, for the Egyptians, the difference between earth and sky is one of the fundamental polarities set up early during the creation of the universe. The polarity was created by Wind going in between Earth and Sky. In their myth, we now have Shu (Wind) standing upon Geb (Earth) holding up Nut (Sky) and making sure it will not fall back down (Fig.2.3, left). We have an ur-tension which, as long as it exists, keeps life going. Here is a little story[11] written for young children that introduces a boy and a girl, Inpu and Tameri, who lived in a modest home in a village on the Nile (Fig.2.3, right), a long, long time ago...

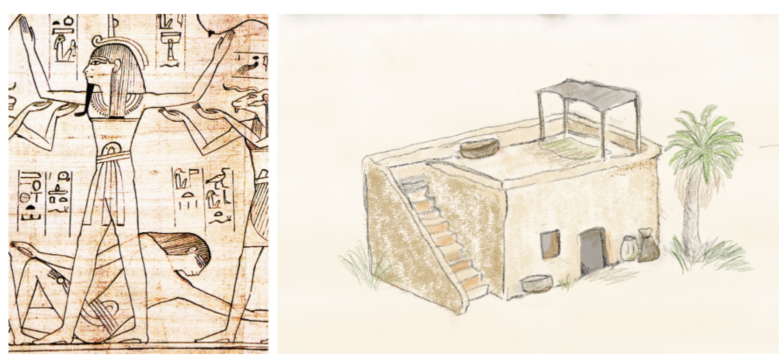


Figure 2.3: *Left: Earth, Sky, and Wind (detail from the Greenfield Papyrus, photographed by the British Museum; original artist unknown). Right: Inpu's home (RF).*

> *Long, long ago, a boy named Inpu lived in a village on the river Nile in Old Egypt. Inpu had just turned six years old when one morning, he started to feel unwell. He still helped his mother and his older sister Tameri to get ready for the day but then he became so tired that he just lay down in a corner of their simple home. He started feeling hotter and hotter and worse and worse. His mother came to him, felt his cheeks and said "Inpu, you are ill. You don't have to help in the field today. We will leave you here with Grandma. You can rest and get better."*
>
> *But Inpu did not feel better. His head and body felt hot to the touch, his body ached and his mouth was very dry. His grandma watched over*

him, brought him water to drink and a cool wet cloth for his forehead. His grandma sat next to his bed, held his hand, sang to him and told him stories. He usually loved hearing stories, but today it seemed as if he could hear them only from very far away. He was somewhere in a world between sleeping and waking.

As the day went on, the sun rose higher and it got warmer in their little house despite its thick mud walls. This did not help Inpu feel better. Inpu's grandma knew how she could help. As soon as the worst of the heat of the afternoon was over, she took the little boy up the stairs onto the flat roof of their home. She held him in her arms as they sat there looking over the river Nile to where the sun was setting. There was a nice breeze and it cooled the hot body of the child. Inpu loved this feeling, and he remembered a story his grandma and his parents had told him about the Wind. He wanted to hear it again and so he asked his grandma to tell him how the world came to be, and she did.

„Nothing existed in the very beginning. Everything was the same. It was not dark nor light, not warm nor cool, not beautiful nor ugly, not dry nor wet, not hard nor soft. There was no high or low, no day and no night. There was no waking and no sleeping. There was nothing, not even heaven or earth. There were no two separate things.

„Then, the first two things were created: heaven and earth. At first, they were together, the sky rested on the earth. But soon the new sky arched over the new earth creating up and down, high and low. And this is how day and night were born, and how waking and sleeping came into the world."

The boy listened to his grandmother's words and imagined what they meant. How did up and down come to be? He was too tired to get up from Grandma's arms but he could get a picture in his head how he stood and looked down at his feet touching the earth. He slowly raised his eyes up higher and higher, and in his mind he saw the stars of the night sky high above him. He could feel himself standing upright between heaven and earth. There was down and up, high and low.

Inpu loved the part of the story that was to come. He breathlessly asked how the sky could stay up and not fall down to earth. Grandma told him that the Wind came between heaven and earth and supported the sky from falling down onto earth. And as long as the Wind was holding them apart, life would go on between them. There had to be up and down, high and low for everything else to happen in this world.

Inpu had seen a picture of what his grandma was telling him when their family had gone to a nearby temple. He closed his eyes, listened to her words and vividly remembered the picture of Shu standing on Geb and supporting Nut—those were the names of gods the grownups used for the Wind, the Earth and the Sky.

It was now getting darker on the roof. Inpu's Grandma knew that the boy was some-times afraid of the dark, so she went on to tell him what happened after the world was born. "The new sky arched over the new earth, and for the first time the sun—the god Ra—could move across it. On the first evening, Ra went to the underworld in the west and crossed in a boat to where he could rise again in the east in the morning. Now

> *that earth and sky existed, day and night could exist as well. There had to be dark for there to be light," Grandma said. Remember, she said, "before the world was born, not even dark or light existed. But now we have both, and after the night, Ra will rise again."*
>
> *Inpu barely heard the last words of the story as he fell asleep. He could finally rest. When he woke up in the morning, he felt cool again, and as his grandma had promised him, after the dark of night, the sun came to rise up in the sky again.*

Note the polarities this little narrative speaks of and makes use of for moving the story along. The main polarity is that of healthy ↔ ill, but there are others: light ↔ dark, day ↔ night, awake ↔ asleep, hot ↔ cold, and, finally, up ↔ down or high ↔ low that define the difference between earth and sky. See Table 2.2 for examples of polarities, our modern nominalized terms, i.e., names, for them, and Forces that are created by them. The story presented here can be used to give children a feeling for tensions and Forces, and it allows us to discuss the meaning of polarity (as opposed to duality or dichotomy).

Table 2.2: Some polarities experienced in encountering nature

Polarity	Nomilnalized form	Force
Bright ↔ dark	Brightness	Light
Hot ↔ cold	Hotness	Heat
Windy ↔ wind-still	Windiness	Wind
Humid ↔ dry	Humidity	Water (in soil or air)
Healthy ↔ ill	Healthiness	Health
Tense ↔ relaxed	Pressure	Fluids
Concentrated ↔ diluted	Concentration	Chem. substance
Salty ↔ bland	Saltiness	Salt
Aggressive ↔ calm	Reactivity	Chem. substance
Fast ↔ slow	Speed	Motion
High ↔ low	Level/height	Gravity

Forces associated with polarities and felt tensions

The type of experience we have called *polarity* stands at the beginning of human experience—organisms feel differences of qualities as tensions. Think of it: even our knowledge of physical objects is the result of the experience of qualities whose differences we perceive. A rock is hard (hard ↔ soft), rough (rough ↔ smooth), heavy (heavy ↔ light), possibly has dull corners (sharp ↔ dull), and blocks our view of things behind it (opaque ↔ transparent); together, these and probably a few more qualities define the rock for us, at least in mythic experience.

Tensions as drives

As part of experience, if something is going on around us, if there is change, we note differences and feel tensions. Our mind seems ready to see this correlation as one of causation: differences cause change.[12] The specific cause of a change is presented to our mind by the type of polarity of which the tension is part. A fire makes the air very hot which allows for cold objects nearby to get hot as well; Sunflowers turn their faces into the light. Water flows by itself if there is a downhill slope, i.e., a level difference, and so on.

Experiencing polarities and communicating about them

Experience of polarities (and tensions) is basic for complex living beings, and humans have developed an important toolset for dealing with—and communicating about—such experience. Natural language features very prominently in this toolset, but it includes (older) mimetic forms of expression as well (remember our discussion of the development of mind in Chapter 1).

Experience and natural language. Note, first of all, how we speak about what is associated with a polarity: we use *adjectives* to denote what is best described as *degrees of* the feeling of an *intensity* associated with a given polarity. Consider this example for the polarity hot ↔ cold: we use an *ordered sequence of words*—burning hot, hot, warm, lukewarm, cool, cold, very cold, freezing cold—to speak about what seems to be the experience of an *ordered sequence of sensations* (Fig.2.2).

Adjectives for felt degrees of intensity

The agentive phenomena that are associated with or arise from particular polarities are the Forces of Nature we have referred to here. The examples of Forces associated with the polarities called *hotness*, *brightness*, and *pressure* are typically called Heat, Light, and Fluids, respectively (Table 2.2).

In summary, it makes sense to see the origin of our sense of Force in our experience of polarities and associated tensions and their causings. If we wonder if something could be considered a Force (of Nature), we can ask ourselves if we can identify a polarity that could be its origin. Since we experience hot ↔ cold and fast ↔ slow, there should be Forces by the names of *Heat* and *Motion* (Table 2.2).

Polarities and Forces

Polarities are perceptual units for which names have been invented. In nominalized form, we call the sequence going from hot to cold *hotness* (see Tab.2.2). The term summarizes a number of distinct sensations—different intensities—that are placed at different points along a line, like beads in a string (Fig.2.2). This allows us to speak of *degrees of hotness*, just like we can think in terms of degrees of pain, speed, brightness, or windiness. What we call a *tension* can now be understood as the *difference of degrees* of a particular polarity.

Polarity as a perceptual unit

Tension

Note, moreover, that if we make use of the abstraction of a polarity and name it as a whole—with names such as hotness, brightness, speed, etc.—the proper way to refer to characteristics of the polarity is again in terms of a sequence of adjectives, this time of a single sequence, namely that relating the polarity of high ↔ low. Degrees of intensity are either *high* or *low* (not big or small or the like!). And if we describe processes of changing intensities, we use the *verbs* of *moving up* or *down*! Speed is high or low, and it goes up or down; there are no other intuitively or imaginatively good ways of speaking about such perceptions than these. We use a *vertical scale schema* (see Volume 2 on *image schemas*).

Up ↔ down and vertical scale

Cognitive linguists have introduced us to the idea that behind this form of communication lies an experiential abstract *schema*, an *image schema* called *scale*. We will study the schematic structure of our understanding in much more detail in Volume 2; for now, simply note that we have well structured tools for communicating about our experience of polarities, degrees of intensity, and tensions. We should make good conscious use of them.

Image schema

Mimesis. Let us not forget even more basic forms we can make use of when expressing our experience of intensities and tensions (Chapter 1: sub-section starting on p.13). Since intensities and tensions (generally, qualities and their differences) are felt, our body will certainly be a medium through which we can express such feelings; indeed, this can happen even unconsciously, involuntarily. However, under voluntary control, using the body as an expressive medium will lead to interesting examples of pedagogy for dealing with Forces (see Chapter 5 for an introduction to mimetic—embodied—simulations and performances with which we can model the activities of Forces). In short, intensities and tensions can be expressed through bodily posture, facial expressions, and the use of hands (such as when we make fists and combine this with upper body posture—note what happens when Bruce Banner is set in rage and turns into the Hulk).

2.3 Wind, Rain, Fire, and Light

To begin our journey from how a child might encounter nature toward a first, however casual, appreciation of physical science, let us study a small group of primary Forces that easily arise in everyday experience: *Wind*, *Rain*, *Fire*, *Light*, and *Lightning*—they are the closest thing to mythic natural Forces. Even though they are not the basic Forces of physical science (Table 2.1), they help us with becoming aware of aspects of the gestalt of Force that need to be present in a more formal approach.

Gestalt of Force

In short, we experience these Forces as animated entities (spirits, characters, agents) that are more or less intense (aggressive ↔ relaxed, or whatever polarity is felt; Fig.2.4), small or large (i.e., more or less spread out in space; Fig.2.5), and more or less powerful (both Figs.2.4 and 2.5). We shall learn how these *basic aspects* recur with every Force we study and how they help us understand how Forces are active in nature and machines.

Figure 2.4: *Left: Gentle Wind blowing seeds off a flower (photo: ML). Center: Strong Wind (photo: Adobe Stock/tuaindeed). Right: Destructive Wind in a storm (Cyclone Pam, 14 March 2015: Graham Crumb/imagicity.com).*

Primary Forces of Nature. We call the examples listed here (and above on p.61) *Primary Forces of Nature*. They constitute a somewhat fuzzy category where the status of a member can be different from that of the others—like in a family.[13] They are primary because they appear to us early and, it seems, spontaneously in our life; and they are primary because they prepare the ground upon which we build conceptual understanding that can lead us toward understanding of Forces of Nature in physical science.

Fuzzy category and family resemblance

Here is the plan for this section: We shall explore some processes we commonly and easily come in contact with—Wind, Rain, Fire, Light, and Lightning in thunderstorms. We shall see in what sense they belong to the same family but how they are different from each other at the same time. In the following sections, we will see how these phenomena let us experience a second group of Primary Forces that have a quasi-material or fluidlike character and that bring us one step closer to how a modern mind deals with encounters with nature—*Water* and *Air*, *Heat* (and *Cold*), *Electricity*, and *Substances*.

Primary Forces with fluidlike character

How we experience *Wind*

In Chapter 1 (Section 1.1), we described and discussed the first of the primary Forces listed above: *Wind*. We stated that direct experience of nature has a mythic character—the experience unites feeling and idea, i.e., the appearance in imagination, with the pure physical phenomenon. Moreover, the example of the mythic tale „*Why We Need Wind*" helped us grasp what mythic consciousness and understanding might be all about. Here, we want to repeat and deepen the rather quick analysis performed on pages 7-8, and then extend it to Rain, Fire, Light, and Lightning.

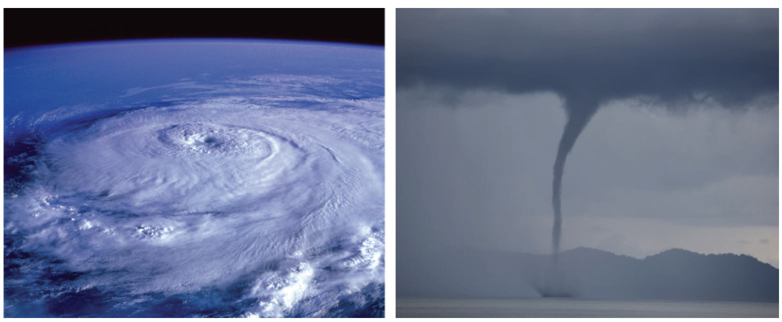


Figure 2.5: *Left: A giant hurricane seen from space; Wind in this storm stretches over a vast area (photo by Pixabay from Pexels). Right: In a tornado, (strong) Wind is limited to a narrow region (photo: Adobe Stock/narathip12).*

Direct experience of Wind. Taking children „out into the Wind" just a single time and making the effort to talk about the experience without getting into any formalities, may already be enough to let the feeling of Wind as a figure or character appear in their mind. Taking this example of communication further, maybe with the help of a story about Wind, will then be enough to gently point to the characteristics of Wind as a figure.

We all know that Wind can be gentle, strong, or even fierce (Fig.2.4). We may use these terms in order to characterize *degrees of windiness* (degrees of *intensity* of wind), something sailors are well acquainted with (see the discussion of the Beaufort scale in Chapter 3 (Section 3.2). Experiencing Wind on different days under different circumstances may be a great way of introducing children to how to express degrees of intensity of a particular experience.

Intensity of Wind

Second, even though this takes some practical effort, we can directly experience that Wind is *more or less spatially extended* (Wind can be „small" or „big;" Fig.2.5). If we want to do this ourselves, we may, under favorable conditions, run from one place to another to notice that the Wind cannot be felt everywhere. Alternatively, if we are on elevated ground, we may observe the spatial extension of Wind from how it does or does not move the branches of trees and bushes. Armed with modern tools for gathering information, somewhat older children may

Extension of Wind

very well be able to „experience" the extension of Wind in photographs (Fig.2.5) and reports. Indeed, narrative experience may be what is needed if we wish for children to develop a secure understanding of the extension of Wind.

Power of Wind

Finally, it is as simple to perceive the *power of Wind* as it is to feel its intensity. In fact, intensity is most often „derived" from the observation of how powerful Wind is. Where there is Wind, other things are bound to happen: we might feel a cooling effect on our skin and notice our hair move; leaves blown across a street, grass swaying back and forth in a field, and branches of trees moving; if we go sailing or windsurfing, we feel the power of Wind, and so on. Wind is an active, causal entity, a figure or character that makes other things happen.

The perceptions of power and intensity are so immediate and simple that they might be difficult to differentiate—power certainly grows with rising intensity. We shall come across other cases where intensity and power are so closely related in experience that we are hard pressed to clearly discriminate one from the other when asked to talk about a phenomenon. This points to a challenge for scientific understanding of Forces of Nature: we need to be able to discriminate intensity and power, otherwise we „amputate" an arm or a leg from the gestalt we want to describe. Therefore, one of the tasks of an approach to primary science education is finding ways to make the differentiation of a gestalt possible for young learners.

Intrinsic properties of Forces of Nature

Forces as agents are intense, big, and powerful

Experience leads to *abstractions* (mental *schemas* or imaginative *shapes*) of *intensity*, *extension* (or size), and *power*, respectively, that are used imaginatively in describing the appearance of more or less powerful figures or *agents*. These images apply to Rain, Fire, and Wind, and to all the other Forces as well.

One of the premier tasks of primary science education is finding ways of making learners aware of the distinction between intensity, extension, and power. This is something we do not always do consciously and properly in everyday life (simply because we do not need to!).

Mediating between the poles of a polarity. In Chapter 1 (Section 1.3) we pointed out that one of the powers of young minds is the ability to discern opposites such as good-bad, angry-calm, hot-cold, sweet-bland, etc. At first, such opposites are expressed very simply and crudely, possibly with just a single word, then two words for the extremes of what is actually a polarity; only much later, and very likely only as a result of focused learning, do children possess a rich arsenal of adjectives that allow them to linguistically express what they surely can feel much earlier: that there seems to be a continuum of degrees of the intensity felt in association with a phenomenon.

The story of *Why We Need Wind* teaches us about the importance of mediating, both practically and linguistically, between extremes of the polarity of windy $\leftrightarrow$ wind-still. Koluskap and Wocawson go through a process of mediating between the extremes of intensity of Wind (of constant strong Wind or no Wind) and finally arrive at a point representing a natural *balance*. Balance is another example of experience which is said to lead to an embodied schematic/abstract notion with

Balance

which we understand ourselves and the world around us—in science, the notion has evolved into the formal concept of *equilibrium*.

Equilibration of intensities

Balancing intensities, reducing tensions

Here is one more important message we can obtain from *Why We Need Wind*: mediation, i.e., reaching a balance, is achieved for degrees of intensity associated with a polarity. What is happening here is the reduction—to zero, in the end—of a tension.

Importantly, we reduce tensions, *not* differences of extensions or sizes or amounts! Mediation of sweetness of sugar water means balancing the sensation of how sweet the water is, not amounts of sugar: we need a lot more sugar in a large amount of water compared to a small amount of water if we wish to make both equally sweet.

Feedback and interaction between humans and nature. Moreover, the story reminds us of some old wisdom: what goes around comes around. In more formal modern terms, what we are told about is an example of a *feedback process*—a closed loop of influences. Koluskap experiences strong Wind that hinders his hunting, he goes to the source of the Wind to turn it off only to find that now the climate has become unbearable. As a reaction, he goes to the source again and „tunes" it in such a way that nature is served best.

Feedback

Feedback is a ubiquitous phenomenon in dynamical systems—indeed it is the process that leads to *intrinsic dynamics*[14] in the first place. Even though it is important, it is often as simple and harmless as when Wind blows, which might lead to lowering of the atmospheric pressure where the Wind comes from, which, in turn, leads to a weakening of the Wind, and so on, until the Wind has died down.

Intrinsic dynamics

Here is a less harmless example of feedback: It appears we humans are changing the atmosphere of our planet and, with it, the climate. As the Earth is getting warmer, ice at the poles of the planet melts, which makes the surface darker, leading to greater absorption of sunlight, causing still stronger warming, which then leads to more melting, and so on. The system composed of atmosphere (and other parts of the planet) and human society includes many types of feedbacks and is much more complex that the simple cup of coffee sitting on your desk and quietly cooling.

Wind or air? Here is a point we need to be aware of before we continue—our description of the experience of Wind may appear „unscientific" to the modern eye. Where is the air in our story, and where are the molecules the air is composed of? When encouraged to speak or think „scientifically," we modern humans immediately start speaking of air and air molecules.

Apart from the question of where this urge of talking about a material substance as the „real thing"—rather than communicating about direct experience—comes from, two points need to be made clear. First, Wind is not air, Wind is a phenomenon, a process, not a material. [To give an example, if we speak of solar wind—the flow of material ejected forcefully from the surface of our Sun and flowing through the solar system—we need to understand that it certainly is not air;

more importantly still, we need to understand what makes solar wind a type of Wind!] To recognize Wind as such is fundamental to human understanding of nature. We have seen what this means in our description of Wind: Wind is a Force of Nature, having fundamental characteristics of intension (and tensions), extension (size), and power!

Second, even if we were to focus upon air, and we will certainly do so a little later in the course of our story (see Section 2.4), talking about molecules will not help us understand air very much, definitely not if we wish to understand Air as a FoN. Importantly, there is strong psychological and pedagogical reason to believe that this talk will not help smaller children understand air in the least. Developing the imagination that leads us to a useful understanding of „particulate nature" of matter requires more mature minds trained in some cognitive tools small children neither have nor need (see Chapter 1, in particular, p.35).

Getting to know *Rain*

Next, we shall take a look at the phenomenon of Rain (Fig.2.6). Again, as with Wind, we would like to get to know rain as such—what makes it a member of the family of Forces of Nature?

Figure 2.6: *How rain may appear (left: Adobe Stock/Paylessimages; center: Adobe Stock/Mihail; right: Adobe Stock/sergejson).*

A story of Rain. Let us begin with a story[15] that tells about an experience of Rain. We do not choose a narrative for listing or describing scientific aspects of the phenomenon of Rain for direct consumption or formal learning. Rather, it is presented here to give you, the reader, an opportunity for creating your personal simulated experience[16] of the physical phenomenon. After all, we do not expect you to sit outside in the Rain reading this text. Apart from allowing for such an experience, the story can serve as an example of stories of Forces of Nature suitable for children in a pedagogy where direct physical experience is combined with narrative experience.

> *"Elliot needs to get out," their mother called from the basement of their farmhouse. The kids knew it was their turn to take the dog on his morning walk. The sun was already burning bright as Sean and his older sister Frances finally got up from their games to take Elliot into the fields.*
>
> *Their farm was up on a hill overlooking the valley. Summer had not yet started, but it had not rained in what felt like an eternity—it had*

been terribly dry all this time. The soil in the fields was hard as rock. The valley looked brown, and the river that usually glistened in the sun was lying there like a washed-out ribbon. Frances and Sean looked up into the sky hoping to see some clouds that would promise rain. They actually loved the hot dry weather, but they had heard their parents talking about how bad this early drought was going to be for their fields and their animals.

As they ran through the pasture with Elliot way ahead of them, Frances felt some wind that she knew couldn't just be because she was running. The wind felt warm but not as warm as she thought it should be. She looked up over the valley and saw towering clouds in the distance beyond the valley. "Look, Sean," she exclaimed, "we're going to have rain!" They ran back to the farmhouse to tell their parents.

That afternoon, the sky changed; there was no more sun. The wind had moved the clouds from far over to their hill and their farm. Sean and Frances took Elliot out again to experience the changing weather. They already could see rain falling over a large part of the valley. The wind blew in their faces, made their t-shirts billow and let Frances' hair fly. Then they felt the rain as it slowly moved over their hill and fields and farm: gently first, then stronger and stronger. It first felt like a gentle pat on their faces and hands, then it became very noticeable as it fell dense and hard. Soon it poured. Their shirts and pants got soaked, and the first puddles filled on the dry fields. The rain came down so hard that the ground could not take the water up fast enough. The water cut narrow channels into the dry soil and it started to flow off down the hill. From the direction of their barn, they heard the loud sound of rain pouring on the roof.

Frances loved getting wet and cooling off in the rain—Sean and Elliot had already sought shelter. She stood there looking over the valley, and she could see the rain coming down, creating dense curtains in some directions and lighter ones over other parts. The rain did not fall evenly on the land, it left some areas untouched, but the river would certainly grow stronger again and bring much needed water to all of the valley. Their farm was helped by the rain, too, and plants, animals, and people could breathe a sigh of relief. And then, slowly, the rain became weaker, gentler, before it stopped altogether.

Reflecting upon the story. This little narrative has a typical story-structure. A scene is created at the beginning, a problem is raised, a tension is made to be felt. Here, the tension is created by the *opposition* or *polarity* „not-rainy/dry" versus „rainy/wet." The felt tension or problem moves the story along; it is eased in the course of the story and, finally, it is resolved. There are *protagonists* or *agents*: Wind, Clouds, Rain, Water, the River, and, more in the background as „*sufferers*," Soil, Plants, Animals, and People. It is never expressed directly, not in so many words, but we get the feeling that there is another actor, maybe the one who created the problem in the first place: the Sun. Frances, Sean, and Elliot are *observers* rather than agents or „receivers" or „sufferers."

Tension

Agents

In the story, we hear certain things about the main character, Rain, and about those that are part of all the activities and interact with Rain. Clouds „bring" Rain, Rain „brings" Water for fields and River. The Rain is felt or observed to be

Intensity, extension, and power of rain

intense or gentle (Fig.2.6, left and center), it can pour or drizzle, come down in „dense curtains" or in „thin strands;" and it can cover the entire land or only part of it (Fig.2.6, right). The Rain makes the soil and the children and dog wet, and the roof under which Sean and Elliot have sought shelter, blocks the Rain.

Temporal course

Restoring balance

The story does not say this in so many words, but it is clear that the rain begins and ends, its intensity, extension, and power change in the course of time. And finally, the Rain „releases" the land, plants, animals, and people from their suffering; it restores a proper balance.

Organizing experience

Expressing meaning

Opening up experience

What the story does for us. Notice how a story allows us to recount and present rich and vivid details of actual physical processes and activity—details we notice, remember, and know. At the same time, it is a vehicle for *organizing* these memories and the *knowledge* that is part of our experience. Above all, a story lets us tell how things *feel* and what they *mean*; and it lets us have a new kind of experience—*narrative experience.*

Physical experience can be rich in detail—if we are ready for and „tuned into" an encounter with nature. No single experience of rain will be exactly the same as one you will have in a few days from the time you read this story; and it will not be the same as an encounter someone else had or will have.

Discriminating „objects" in the flow of experience

The flow of experience. So, what are we to do with this richness and endless variety that may very well leave us bewildered? Actually, experience is never quite like this: perception is a process undergone by an organism that „picks out" or discriminates parts or „chunks" in the flow of activity of life that allows for some „orderly" forms of experience. Without this, life would really be „just one damn thing after another;" but, as we well know, it is not. We are able to discern or see „objects" of different kinds (emotions, feelings, qualities, material objects, events happening before or after others, etc.) in the flow of experience, store them, put them in order and relation, and make sense of them.

Forces and change

Forces of Nature teach us about change, but also about structure

Phenomena, processes, and activities bring change, and it is change that makes us think of Forces. When we study Forces, we focus upon *dynamics* rather than just structure; we need to understand Forces if we want to better understand the causes of change.

Still, we should never underestimate the importance of *structure*, how things are built and what they are made out of. Change caused by Forces brings forth structures, and structures make it possible for Forces to act in particular ways. So, even if this is not our main concern, now and then we want to know how certain things are built.

This is not unlike in a novel where people act in a city—the structure of the city constrains them; at the same time, people bring forth structures in the city.

Part of what we want to do in this chapter is point out elements of experience that recur so frequently that they become tools for understanding what we experience. It turns out that, if we are attentive to direct experience or to stories we tell about such experience, we recognize recurring features we associate with phenomena in a way and to an extent that they characterize these phenomena for us—we say that a phenomenon *is* like this or that, or that it *has* this or that *property*. These features and properties are then the subject of our knowledge; they may even become the subject of science. If we learn about these features and characteristics, we will be able to recognize them again and again in different instances of the same phenomenon and, importantly, even in phenomena of a totally different kind. Let us see *what is characteristic of Rain* and ask how this compares to the experience of Wind.

Experiencing Rain as a Force. Imagine now that you are up on the hill with kids and dog. When you reflect upon how we experience rain, the *effects* of this phenomenon might come to mind first: we get wet, country roads get muddy, the soil of dry fields is made moist again, streams and rivers swell, plains flood, and water reservoirs are filled.

Effects of rain

Intrinsic properties of Rain. Effects of a phenomenon are important—they may be the prime reason why we call phenomena such as Rain or Wind *Forces*. However, foregrounding the effects distracts from other basic properties of Rain itself. What is *intrinsic* about the phenomenon we call Rain? What is it we can *notice* about Rain most directly and most generally? Clearly, Rain can be strong or weak, i.e., more or less *intense*. We can see this, and we can hear it too. We can see how hard Rain is coming down; it can pour or drizzle; it can pound loudly or patter softly on surfaces.

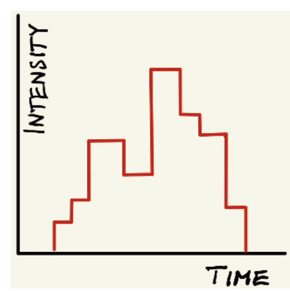
Intensity of rain

Clearly, at any moment, the *intensity* of Rain can vary from point to point across the land. But there is more. Rain can be strongly localized, affecting only a small area; or it can cover large swaths of land. In other words, Rain can be spatially limited or *extended*, covering smaller or larger areas at a given moment.

Spatial extension

Temporal course of a process. There is a different sense of extension associated with a process or *activity* such as Rain: this is *temporal extension*. An event of Rain can be short or long, it can last for just a brief moment or for an extended period. Temporal extension is an important aspect of Forces of Nature that present themselves to us as processes such as Wind, Rain, Fire, Light, a Storm, or a River. A River is no longer a River when the water is not flowing. However, there are *Forces of Nature* such as *Food* or *Water* where temporal extension does not have the same basic meaning: they are still *Forces of Nature* when they are „just there;" one of their characteristics is *quantity* or *amount*, and a quantity of Food can just lie there, be stored in some area, and still be experienced as a *Force*.

Temporal extension



Relation between characteristics. Now, let us think about how the characteristics of Rain we have considered, i.e., *effect*, *intensity*, and *extension*, relate to each other. Everyday experience suggests that the magnitude of the effect must be related to both intensity and extension. Imagine a large dried-out landscape and ask yourself what is responsible for how much of the ground is made how moist. Obviously, if the Rain covers only a small area, the effect upon the landscape will be limited. If the Rain is more extended, the effect will be greater. As to intensity, if the Rain is more intense, the effect will be greater as well. In other words, intensity and extension together determine the magnitude of the effect.

Magnitude of effect

There is yet another way we speak about the magnitude of the effect of a Force such as Rain: we say that Rain is (more or less) *powerful*. If the impact is strong, rain is powerful; and if the effect is small, rain is weak. The aspects we have just collected here are the *intrinsic properties of Rain*—*intensity*, *extension*, and *power*. They are the same we have identified in our discussion of Wind as a Force of Nature.

Power of rain

Chains of processes

It is time to contemplate some part of common experience: Forces of Nature do not appear one at a time, separate and separated from each other. They form chains, and chains can split and form different (parallel or concurrent) paths. This tells us that we must look for how Forces link up in such chains, how they *interact*.

Power of a Force related to tension and extension

Relation of power to extension and tension

Experience tells us that the power of a Force of Nature must be related to both its extension (its size) and its tension. So far, this seems to be the case for Wind and Rain. Increasingly intense wind and Rain means greater power.

It is clear that, if Wind is equally intense everywhere it is active, double the „amount of Wind," i.e., double the area over which it acts, makes it twice as powerful. What is less clear, is how the power of Wind depends upon its tension—however, it is certain, that it depends upon the tension, i.e., the measure of how much the intensity drops across an object affected by Wind.

Power and effect

Agent & Patient

Note that power and effect need not be the same. Power measures the „force" of an *agent*, effect measures the consequences for a *patient* (a patient is the recipient or „sufferer" of the power of the agent). In everyday life, we hardly ever distinguish between power and effect; still, for physical science, the distinction will prove to be important.

Where does Rain come from? Rain has effects, it causes other phenomena to happen. There are things coming after Rain, caused by Rain. But what is before Rain? Where does Rain come from? We do not want to answer this question in any detail—explain how water vapor is transported into the atmosphere, condenses, and falls back to the ground as rain, snow, or hail—but rather use the question to point out what we all know—namely, that *Rain is caused* by antecedent phenomena or Forces. There are Forces that lead to the occurrence of Rain. In other words, *a Force is a part of a chain of processes.*

Chains of interacting Forces

Chains of processes. Let us use the example of Wind to briefly raise this important issue: Forces *interact*. We can see this in the case of Wind if we ask where Wind comes from and what it leads to. Wind can be seen to start with heat produced by the light of the sun, which lets heated air rise in the gravitational field at the surface of our planet, creating the motion we perceive as Wind (Section 4.6). Then, Wind can cause a number of things such as moving a sailing ship. So, here is a chain of interactions of Forces of Nature:

Sun's Light → Heat → hot air helped by Gravity
→ ***Wind***
→ moving a sailing ship.

Agents and patients

We see here very clearly that Wind as a Force of Nature is *both caused and causing*. In cognitive science, we often speak of the roles of *agent* and *patient*—agents cause something to happen, patients are „at the receiving end" of what an agent does, their activities are caused by the agent.

Interactions between two Forces of Nature form something like the building blocks of dynamics in nature. This means we will have to study how such interactions are described and modeled. What is it about Forces of Nature that lets us describe and understand how one Force „causes" or „drives" another, how it „brings it to life," so to speak? We shall see that an imaginative way of speaking about interactions is in terms of agents representing Forces „meeting" in certain places where they interact (see, in particular, Chapter 5, for a description of how imagining leads us to a possible answer).

Forces interact in chains of processes

Forces and chains of processes

Wind and rain are caused by some phenomena, and they cause other things to happen. This means that we see Wind or Rain as Forces of Nature embedded between other Forces. There are Forces that lead to Wind or Rain, and there are Forces set „in motion" by Wind or Rain. Forces *form chains* and *interact*!

When two Forces interact, we have one that appears to cause the other. The first of these we call *agent* whereas the second is called *patient*. Importantly, in an interaction, an agent gives a patient *energy*—this is how we will introduce the energy concept that is one of the important ideas of physical science.

Energy

The abstract meaning of *Force of Nature* (FoN)

At the end of the section where we introduced *Wind* (see p.71), we warned the reader not to fall into what we modern people do so easily and effortlessly—namely, *foreground matter*. We have been told to believe in matter as the ultimate physical reality and that, if we want to be „scientific," we need to talk about matter (its properties and activities) above all else.

Foregrounding matter

If we want to recognize *Wind* as such, i.e., as the Force of Nature called *Wind*, this modern urge creates a challenge—we need to resist this impulse and refrain from speaking about air as soon as we hear the word *Wind* (see also p.92). We need to take a deep breath, sit back and let Wind impact our perception directly. Though Air will become important as a Force of Nature in its own right, it is a distraction to recognizing the abstract nature of *Wind*. It would simply be too bad if we never allowed ourselves to learn about this abstraction—*Wind as Wind*. Not only is the notion of *Wind* we have developed correct, what we have discussed on the previous pages is fundamentally important to our quest for understanding our experience of nature and building bridges to modern science!

Wind as Wind

The case of Rain may be even more difficult for our modern mind. While we need to make a certain effort to actually „see" and accept Air as a reality, Water as a phenomenon behind or related to *Rain* is too hard to keep hidden from awareness. Still, we need to make this effort and learn about the abstract aspects of Rain as a gestalt or perceptual unit. Think about it like this: what makes the rain of methane and other hydrocarbons on Saturn's moon Titan *Rain*?[17] Obviously, it does not „consist" of water. What makes sand raining down in a sandstorm *Rain*? If we let our imagination do its work, it should not be too difficult to come up with an understanding of what makes rain here on Earth a case of *Rain*.

Water „in" Rain

Rain as gestalt

Rain and raindrops. There is something about rain that raises another quite disturbing issue: rain can appear as drops. It does not always do so: it can be a fine mist or so dense that drops are hard to identify. Still, we see many descriptions of rain, and especially stories written for small children, where drops are foregrounded and made the representatives of the „true material nature" of rain.[18] Sadly, this often leads to misunderstandings: drops are mistaken for „particles" and molecules, and water is confused with vapor, and the like.[19]

No drops in water...

Whatever interesting stuff we can learn from drops—such as the importance of surface tension, or their random appearance in gentle rain (see Volume 2)—should never lead us to say that „there are drops of water" in a glass of water or in a lake; this simply does not make any sense. Accepting that there are no drops in water, but that we can „pull" a drop from the surface of a body of water with our finger,[20] can tell us a lot about modern physical science which centers around the idea that things are made of particles. It turns out that particles appear only when we or an instrument interact with physical objects; otherwise, particles do not exist.[21] All of this, however, should not keep us from experiencing Rain in its most basic and fundamental form as a Force of Nature.

Fire as a powerful agent

Speaking about fire

Even though few of us may have directly experienced a forest fire, we probably have all read enough about them to imagine Fire as a Force of Nature. A forest fire destroys a forest, it consumes the wood of trees and bushes; as terrible as this is, it may actually make space for new life. It may have been caused/made/created by Lightning, and aided/enabled by a lack of Humidity. It moves, jumps, grows, shrinks; eventually it will die. It gets more intense/fierce/aggressive, or less so. It roars or just crackles, and it lights up the night sky. It can be fought, hindered, opposed, confined, resisted; maybe it could even have been prevented...

Fire as an agent or character in events

What we see here are the great many aspects of a phenomenon such as fire and how we are able to express our experience linguistically. When we hear stories of fires that use the imagery conjured up by the words used in the previous paragraph, we see a character or agent emerging before our „inner eye." We have said this before about Wind and Rain, but no phenomenon seems to be as forceful as fire to drive home this point: our imagination has a bias for creating the feeling of powerful figures as part of our experience of nature.

Fire as helper or destroyer

Fire can be more than the destroyer it is in a forest fire. In the engines that have made the industrial age possible and that still power much of today's technological society, fires are burning. Fire drives steam engines in fossil power plants, gas turbines, combustion engines in cars, or the engines powering modern airplanes. We speak of a nuclear fire burning at the center of our Sun—the fire that sustains life. So, if we are looking for a polarity describing aspects of our understanding of Fire, we may express it as destroyer ↔ sustainer of life.

Polarity for fire

Basic characteristics of Fire as a Force. Fire is not even remotely similar to Wind or Rain; still, our mind picks out certain abstract features of Fire that are the same as those we have identified for the other two Forces of Nature we have discussed. First of all, just as Rain can be pouring or drizzling or anything in between, a fire can be raging or burning slowly as embers or, again, anything in between. There are at least a couple of possibilities for naming a polarity we perceive underlying Fire and giving us a sense of different degrees of intensity:

aggressive ↔ peaceful

raging $\leftrightarrow$ calm

The fire in one forest fire can be more or less aggressive or raging at different locations, giving us a sense of a tension. Obviously, the characteristic described here is the *intensity* of Fire (Fig.2.7): Fire can be more or less intense, just like Rain or Wind.

Intensity of fire

In analogy to Rain and Wind, Fire can be seen to have a second basic property: it can be small or large. Again, just as we have seen in the case of Rain, it can extend over small or large areas: Fire has an *extent* in addition to being more or less intense (Fig.2.7). At any moment in time, a fire has a certain *size* or *extension*. Moreover, the intensity of Fire will in general be different from point to point across the area where it burns.

Extension or size of fire

It certainly does not come as a surprise that we associate the aspect of *power* with fire as well—a fire can be very powerful indeed, but it can also be weak. Just as rain, fire affects things, it has effects, it is the *cause* of things that come after it. It consumes the forest it burns; it makes a room warm, boils water, cooks food; it can give us light; and when we burn fuels in engines, it makes them run. And as with Wind and Rain, *intensity* and *size* (extension) combined tell us how powerful a Fire is. Consider a forest fire. How much of the forest is consumed, and how fast this happens, depends upon both the size or extent of the fire and upon how violently it burns, how intense it is.

The power of fire

Where does fire come from? We have said that rain „comes from," or rather is caused by, other phenomena. Rain is part of a continuous cycle of events on Earth; it is embedded in a chain of processes. It is true, though, that in a particular location, Rain can appear and disappear. Let us see what this observation means for our understanding of Forces of Nature.

With Fire, appearing and disappearing are even more evident. There is no continuous „cycle of fire" going on all the time. Fire appears and it dies. It appears out of nowhere, its extension is zero before it starts. Its extension changes during its life, and then its size will go back down to zero when it dies. In the case of Fire, processes of „birth" and „death" are even more conspicuous than in the case of Rain.

Creation and destruction

Figure 2.7: *Left: A forest fire as an example of a raging fire covering a large area (photo: Adobe Stock/MyPhotoBuddy). Center: An almost extinguished fire covering a large area, burning slowly (photo: Adobe Stock/jon manjeot). Right: A small fire burning strongly (photo: PL).*

A phenomenon such as Fire teaches us a number of interesting things about human thought. We think about beginnings and endings, about change, and about Forces and causes. These are elements of thought that go before science, but they are basic building blocks of science.

Fire as a complex phenomenon. When we let our encounters with Fire, Rain, and Wind create their immediate acts of experience—when we recognize them as Forces of Nature—we often only scratch the surface of these phenomena. Let us use the example of Fire to see how much complexity lies beyond the immediate abstractions, and what kind of questions might arise if we dig a little deeper.

Forces are not permanently active

A Force such as Fire can arise or die

Phenomena such as Fire, Rain, and Wind can tell us something about an important form of thought: At least some Forces are not permanently active, which makes us think that they can arise and die away. Fire, Rain, and Wind make us aware that the way we think about processes of life is not totally alien to our experience of physical nature.

Whether or not anything „survives" if a Force is not active is not quite clear—maybe it is just dormant. We shall have to take a closer look at the nature of Forces to answer this question.

Dynamics is temporal change caused by Forces

No matter what our answer might be, more than any other processes, *birth* and *death* remind us of *temporal change*—nature is dynamical. Dynamical processes are the norm, not the exception. To learn about nature means to learn about change and what we see as the causes of change.

Fire is not easy to grasp—literally and figuratively speaking! What, actually, is a fire? Is a fire the process of consumption of fuel, or is it the cause of this consumption? Is a fire the collection of flames, and what are these flames? We shall see that following the path of science by investigating a small group in the larger family of *Basic Forces of Nature* (remember the list on the right in Table 2.1) will help us give satisfactory answers to the questions asked. From the perspective of these Basic Forces, Fire can be understood as the complex phenomenon that starts as a chemical reaction (the combustion of a fuel), leads to the production of heat that makes the air so hot that it produces visible light (these are the flames). The flames (the hot air, or the heat in the hot air) can then trigger combustion in more fuel and so let a fire eat its way through a forest, just to give an example.

Fire as a producer of heat

This short discussion demonstrates that by experiencing Wind, Rain, and Fire, we have found a starting point for imaginative understanding and interesting and important questions that can lead us further in our investigations of how we encounter nature.

Light as a Force of Nature

Our world is filled with light and dark, things can be bright or dim. If our vision is not impaired, light $\leftrightarrow$ dark is one of the most easily experienced polarities from which a sense of the phenomenon grows. Indeed, the experience is so basic and emotionally powerful that it has served as one of the first elements of creation myths told all over the world. A recurring theme is that in parallel with the creation of other differences such as water and land or earth and sky, the separation of light and dark was instrumental in setting up the world as we know it.

Power of light

Like all the other Forces of Nature, Light can be the cause of many other processes. Apart from making things bright, the Sun's light makes our surroundings warm, and it can even be concentrated to make steam in a solar tower for driving a steam turbine (Fig.2.8, left); moreover, light is part of the „ingredients" used in creating new substances in a leaf from light, water, and air (Fig.2.8, center); and it can make electricity flow when it shines upon a solar cell (a photovoltaic cell; Fig.2.8, right). Clearly, Light can be powerful.

Figure 2.8: *The power of light. Left: Concentrated sunlight produced heat for a solar tower power plant (photo: Adobe Stock/Bob). Center: Light is part of photosynthesis and the processes that create an apple (photo: Adobe Stock/ZoomTeam). Right: A child's drawing of light driving a photovoltaic cell (the cell powers a little motor at bottom left; drawing made by a 4th grade student as part of the FCHgo Horizon 2020 EU Project).*

The Sun's light has determined much of the development of our planet, including life. How plants make use of Light is fundamental for much of life. The Sun's light also powers physical processes such as winds and ocean currents (see Chapter 4). Its (very slight) variations over the last tens of thousands of years has influenced how much of the planet's surface has been covered with snow and ice.

Brightness as intensity

If we step back for a moment from what we believe Light can do and consider how we notice it in the first place, we come across an old acquaintance: we perceive differences in *brightness* (Fig.2.9). Brightness is one of these immediately perceived polarities like hot and cold, humid and dry, or fast and slow.

We can conceptualize this experience by introducing another polarity, this time that of dark $\leftrightarrow$ light. Brightness spans a range or scale from (absolutely) dark to (extremely) light or bright, and everything in between. Again, this tells us that the phenomenon of Light is characterized by *degrees of intensity* (Fig.2.9). Remember that intensity is one of the basic characteristics of a Force of Nature—we have come across this before when we studied Rain, Wind, and Fire.

What, then, would be the *extension* of light? Can we experience light as being extended? Take a look at the first two photographs in Fig.2.10. The scenes visible in these pictures suggest that light streams or flows through space. We have all heard or used expressions such as „After I opened the curtains, the light flooded the room."

The images and the words we use let us see an aspect of Light that is quite similar to what we know of Rain and Wind. The larger the area rain falls upon, the „more rain" we have, the more extended the *activity* of rain is at a given moment. We „catch" more wind with a larger sail, and we do the same with light if we

Spatial extension of activities

have a larger window in our apartment or larger solar collectors on the roof of the building: we „catch" more light. The same is true of a tree that has more leaves: it intercepts more of the light streaming through the tree. Light „falls upon" a surface, just as rain does.

Figure 2.9: *Light and dark. Left: Bright sunlight casts dark shadows. Second from left: Sunlight dimmed by fog (photo: PL). Second from right and right: Lamps turned up high and turned down (reflected on a metal table).*

Extension of light

Therefore, knowing that light can illuminate smaller or larger areas, seeing that it can be more or less extended, it makes sense to use this knowledge and introduce the concept of the *extension* of light. To give an example that is fundamental for our planet, the „amount of light" received by the Earth from the Sun is proportional to the cross section of the planet.

Figure 2.10: *Sunlight flows through space. Left: Sunlight streaming across a field (photo: PL). Center: Sunlight flowing through a tree (photo: PL). Right: The Sun's rays represented as arms with hands in an Egyptian mural (photo: Richard Mortel from Riyadh, Saudi Arabia).*

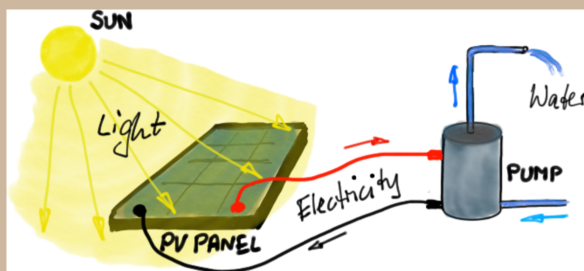
The two figures on the right in Fig.2.9 demonstrate this notion of extension as well. Consider the circle illuminated by a single lamp. If we have two or three lamps instead, we have „more" light; the area that is lit (at a fixed level of brightness) is bigger for two and bigger again for three lamps.

Both the notions of extension and power of the Sun's light are captured in an ancient Egyptian depiction of the Sun (Fig.2.10, right). Rays emanate from the Sun's disk, showing how light flows from the Sun to our planet; and there are hands at the ends of these rays presenting us with an image of what light has to offer to us.

Harnessing the power of the Sun's light

Harnessing the power of light

Here is an example of how people have learned to use the light of the Sun for a particular technical purpose. We can pump water using the Sun's light by employing a solar photovoltaic panel and an electric water pump (a pump that is driven by electricity)—naturally, the Sun is part of this system as well (see the figure below and Table2.3).



This can be described quite vividly with the help of the notion of Forces of Nature. *Sunlight* falls upon solar cells and, because it is a powerful Force, it can cause electricity to flow. It sets up an electric tension which forces electricity through a wire toward the pump and then lets it flow back to the cells through another wire. It appears that *Electricity* is a FoN in its own right.

The light has made electricity powerful. In the pump, it uses its power to pump water: it raises the intensity of water, i.e., its pressure, and it makes it flow through the pump and into a reservoir lying in a higher place. Clearly, this description makes *Water* another of the Forces of Nature.

Here is an interesting aspect of the system that makes it possible to pump water with the help of the Sun's light: we can think of a system as a combination of material *elements* (objects or devices) and *Forces of Nature*: Forces are at work in these elements as if on the stage of a theater.

Table 2.3: Systems: Objects/devices and Forces

Forces of nature	**Objects**
Light	Sun
Electricity	PV panel
Water	Pump

How powerful is the Sun's light? First, it matters how intense the Sun's light falling upon the solar panel is at a given moment (date, time, weather, and orientation of the solar panel are important here). Second, it matters how big the solar panel is. Together, these two factors determine the power of the Sun's light in the system shown in the figure above.

Temporal extension

Naturally, as in the case of Rain and Wind, we can make out a temporal extension of the process of Light—Light can last for short or long durations, and it is born

Collecting light

Understanding amounts of...

and it dies. The longer Light shines, the more of it we can „collect." This image—light can be collected—is an important aspect of our next steps in the exploration of Forces of Nature where we investigate our images and embodied understanding of *quantities* or *amounts* of light, water, air, heat, and the like (see our discussion of Forces of Nature starting with Section 2.4).

Top: Spectrum of sunlight from edge of glass railing on stone floor Bottom: Rainbow

Light and color. Experiencing Light presents us with the perfect opportunity of addressing aspects of Forces that are more specific than the basic ones we have discussed so far (i.e., intensity, extension, and power)—it is clear that a Force is more than its three basic characteristics. In the case of Light, this is the aspect of *color*. The aspect of color does not appear to point to Light as a Force, as a causal agent. Color—of Light itself and the colors (sun)light brings out in the objects around us—appears as a secondary feature, almost just a detail, of the experience of Light. However, if we realize that the particular color of Light falling upon a leaf or a solar cell matters for the functioning of either one of them, we realize that *color is important for the power of Light* as well.

Even though color is a property that emerges from the interaction of Light, objects, and us as experiencing beings,[22] let us assume that color is an objective feature of Light, particularly of sunlight. Sunlight is seen by humans as light-yellow, almost white; at least, the Sun presents itself in this color to us. When sunlight passes through transparent objects having non-parallel surfaces, such as raindrops or glass prisms, the light appears „split" into different colors. We see a band of colors—in the sky as a rainbow, or on a surface where the light falls—aptly called the colors of the rainbow. Instead of saying that sunlight is split into light of various colors, we can say that sunlight „consists" of, or is a mixture of, different types of light having different colors. These rainbow colored „components" in the light of the Sun have far reaching consequences, among them the color of the sky on a sunny day, and how leaves and solar cells react to sunlight.

Why the Sky Is Blue. Before we say just a little more about (sun)light, colors, and teaching, let us tell a story[23] that may answer, to young children, the question often asked about why the sky is blue.

> *It was the time shortly after the world had come into being. The Wind had separated the sky from the earth, and the Sun had just started to shine. The sky arched high over the young earth. On the earth, there were animals, among them Red Fox, Blue Jay the Bird, and Black Bear. The three had been friends since the beginning of time. Insects buzzed around, and there were some plants and flowers that struggled to grow so they could cover the earth and make it beautiful and provide food for the animals. Red Fox and Black Bear often looked up to the sky wondering how high it could possibly be. They were a little envious of Blue Jay because he alone could fly up into the sky.*
>
> *The Sun was still new and a little unsure at its job of giving the earth its light. So, it made a decision to put all its power into creating the most beautiful and perfect green color it could think of. The Sun said to itself: "Green makes me feel calm, so this must be good for the animals and plants on earth and in the sky." During the day, green light poured over the earth, bathing everything in its green glow. The Sun was a strong green disk in the sky, and the sky was just a tiny bit green as well. This was because some of the green rays of light coming from the Sun gently bounced around in the stuff the sky is made of, going here and there, making the sky shine a little bit in a pale green light.*

For a long time, the animals were pretty content; the green sky made them feel calm. Red Fox, Blue Jay the Bird, and Black Bear met from time to time to talk. They felt a certain kinship because all three of them were black. Black Bear sometimes wondered why his friends were called Red Fox and Blue Jay considering that they were black just like he was. But he quickly forgot about this—it did not seem to matter. Other animals looked pretty similar, mostly black or some washed out dark gray. Only the snakes and the lizards were different shades of green.

Plants were green too, but not their flowers. Flowers looked dull, many of them black and some of them some shade of green. The insects were pretty unhappy with this situation— they had the hardest time making out the flowers on the few plants that already existed on earth.

The plants had the hardest time growing right. Somehow, they could not digest the green light very well and this made them feel weak—green light just did not seem to be the right type of food for them. And with that they could not produce all the food they wanted to make available to the many different animals living on earth.

The three friends, too, started to become worried that they would not have enough food. One day, as they met for an urgent conference, Blue Jay said: "I wonder if green light is really good for us and the plants. When I see the bees buzzing around angrily, working hard to even see the flowers, maybe the light is not good for them and us." Red Fox and Black Bear nodded. Maybe, they could ask the Sun to change the color of its light.

No sooner said than done! Since Blue Jay the Bird could fly high up, he got the job of telling the Sun of their demand. The Sun thought about it for some time and then decided that, indeed, it could use its power to create some new light. Red seemed to be a good choice and so the Sun changed its light to the most beautiful and perfect red color it could think of.

On earth and in the sky, strange things happened. Even though it was bright on earth as usual, the sky became dark, almost as dark as during the night. Only the intensely bright red disk of the Sun could be seen. Maybe, red light would just go through the sky without bouncing around? Maybe that was the reason for this strange situation. . .

The plants were thankful, though. They could digest this new red light much more easily than what the Sun had sent them earlier. They thanked the Sun by growing wildly, creating more food for the animals than they could ever eat. And the insects were happy too: leaves now appeared black, but there were lots of red flowers which the insects could easily see.

The first time the three friends met, after the Sun had made red light, something happened that would change their relationship. Blue Jay and Black Bear stared at Red Fox: Red Fox had changed! He looked RED! Startled and unsure, Black Bear asked: "Am I red too?" And Blue Jay asked: "Am I red too?" Red Fox looked at them not really understanding their questions: "Why, no, you are black as always!"

> *As happy as the friends were that they now had more and better food, the new situation irritated Blue Jay and Black Bear. Red Fox felt unsure about himself too: would the other two still be his friends? The red light shining all over the earth did not help—it made all animals feel irritable, even a little aggressive. Looking at all the black leaves, Red Fox said: "I'm going to be sick!"*
>
> *Something had to change! Despite feeling unsure about each other, they got together and decided that Blue Jay should fly up again in the sky and ask the Sun to come up with a new color. The Sun became a little irritated and did not feel like starting all over again. So, it decided to simply create green and red light at the same time and put them together. Bringing green and red light together created a golden yellow light. So now, there was this golden disk in the sky during the day, and the sky itself turned a light green, maybe just a little paler than how it had been when the Sun had made only green light.*
>
> *Now, there were yellow and red flowers, the leaves of plants were green again, Red Fox was red, but Black Bear and Blue Jay were still black. Especially Blue Jay did not like this and decided all on his own that he would fly up again as high as he could and tell the Sun in no uncertain terms that he wanted something else. The Sun, exasperated, said in a cold tone: "I'll see what I can do!"*
>
> *The Sun remembered that it had never tried to create blue light. So, it decided to do this, but remembering that a single light like green or red had not worked well before, it simply mixed the new blue light together with red and green. The Sun was quite impressed with itself: it was now a gleaming and glowing hot white! That would show the animals on earth who had been complaining about wrong colors all this time! Now, color was gone from the light! They should really be happy with WHITE and stop grumbling and protesting!*
>
> *What happened now seemed a miracle! Blue light happily bounced back and forth, going here and there, in the stuff the sky was made out of. It did so much more easily than green light had done, so the sky turned a beautiful strong BLUE! The white rays coming from the Sun, after losing some of their blue part, became a soft yellow. Squinting into the Sun (which they should not have done!!), Red Fox, Blue Jay, and Black Bear saw the yellow Sun and thought it was beautiful. In the new light, leaves were green, flowers were red and yellow and blue. Red Fox was RED. And, finally, Blue Jay was BLUE! He was so happy and flew high up into the sky as fast as he could, flying the craziest paths he could think of.*
>
> *Only Black Bear was still black, but he had a friendly calm way about him that let him accept that this was right. After all, his name was BLACK Bear! Now we know how Red Fox, Blue Jay the Bird, and Black Bear got their names, and why the sky is blue.*

The story follows a mythical form—a form we still use in stories for children. The world has just come into being, and animals guide us through experiencing it. The explanation for the glow of the sky (not the air!) makes its appearance almost incidentally. In the narrative, we are introduced to what we (or the animals!) can see, and that may motivate us to start exploring light and colors.[24]

Even though its power is not the main focus of the story, we still encounter Light as a character. It is created by the Sun, flows, bounces around in the sky, creates the colorful appearance of animals, plants, and the sky, and „has" itself a color that may or may not be powerful in a useful way for the plants.

Thunderstorms: Lightning and thunder

Let us consider one more Force that appears to us as an activity—*Thunderstorms*. There are few processes in nature more awe inspiring—and more easily discernible in the flow of experience—than such storms. To our senses, the confluence of dark, towering clouds, strong wind, torrential rain, deafening thunder, and the sudden flashes of lightning bolts (Fig.2.11) lets us experience nature in one of its magnificent forms, putting Forces center stage. Thunderstorms let us perceive two Forces we have not yet met: *Thunder* and *Lightning*.

Figure 2.11: *Left: Clouds before a thunderstorm. Center: Thunderstorm and lightning over water (photo: Adobe Stock/denis_333). Right: Thunderstorm and rain (Adobe Stock/Mikhail Ulyannikov).*

Thunder. The central polarity of the experience of *Thunder* is loud ↔ quiet, which makes thunder an example of *Sound*. There may be other polarities used to describe different aspects of the perception of sound: Thunder can come as a short, sharp clap or it can be drawn out rolling and rumbling. Then there is an aspect of spatial and temporal extension: there might be a lot of thunder, happening in quick succession coming from various locations and directions, or it might come only at long drawn out intervals, and from only one place. Maybe, sound is not perceived as physically powerful so directly; if we think about it, Thunder—if it does not damage our hearing—is more likely a Force that heightens our emotion.

Polarity for sound

Thunder sets off emotion

Lightning. Like thunder, *lightning* is definitely a phenomenon that gets our imagination going. Witness the many stories that, through the ages, have been told about thunderstorms, their force, and their origin.[25]

We can describe lightning in thunderstorms as being more or less *intense* if we consider how it lights up the sky, if we use a measure of brightens (bright ↔ faint). For a primary encounter with lightning, though, a different measure of intensity may be more direct and more important. Through lightning arises a feeling that there exists a fundamental *imbalance* in nature—between the sky or the clouds and the Earth—a tension that must be released. We are easily led to associate this feeling of a natural imbalance or tension with emotional imbalances or tensions: the sky, the clouds, are angry, and a thunderstorm is where such tensions are released.[26]

Intensity

Imbalance and tension

Extension

Just as we saw in the case of thunder, an impression of *extension* may be associated with lightning; maybe not so much with a single lightning bolt, but more easily with the „size" of the thunderstorm, i.e., the „size" of the space which is lit up by lightning bolts streaking across the sky. And again, there is a temporal aspect to the activity of lightning in the course of a thunderstorm.

Lightning causes fire

Lightning is definitely *powerful*. We learn very early in life, both through direct and social experience, to be wary of lightning—it is dangerous. One of the signs of its power is related to the fact that lightning can set off fires. It is very likely that humans learned to „take" and then domesticate fire from blazes caused by lightning (unless they got it from volcanoes; cf. the Prometheus myth).

Interactions of several forces

Thunderstorms as complex interactions of different Forces. In thunderstorms, several different Forces of Nature—the Sun's light, Substances (Water and Air), Heat, Gravity, Motion, and Electricity—„join forces" to produce what we perceive. Combined, the Forces create a new natural Force, *Thunderstorm*, with all the usual aspects of size, intensity, and power. Studying thunderstorms may be an emotionally satisfying example for learning about Forces and their interactions. Moreover, the example teaches us that the category of Forces of Nature is rich and varied. There are members of this family of Forces that are as complex as volcanoes, glaciers, oceans currents, and hurricanes, or as simple and basic as Water and Heat. In all cases, however, a Force is experienced as a perceptual unit, a gestalt or figure on its own, before we enlist our imagination in communicating about aspects of the gestalt.

2.4 Rain and Water, Wind and Air

Being vs. Activity

We shall now take a step in the direction of a new and relatively small group in the family of Forces of Nature—those we associate with *being* rather than with *activity* (Fig.2.12). Activities have this fundamental aspect of a temporal course: an activity is „born" and it „dies," and between these moments it *runs a course*. We might say that, without being active, a Force such as *Wind* or *Rain* or *Fire* simply does not exist.

Figure 2.12: *Left: Inflated and deflated balloons (high and low air pressure). Center: Deep lake in Kärnten. Right: Shallow puddle in a field (photo: PL).*

This is in stark contrast to what are called *Air*, *Water*, *Heat* and *Cold*, *Light-as-Substance*, and *Electricity*. We can confine some air to a container such as a balloon (Fig.2.12, left) or a cylinder in a heat engine, we can see water collected in a lake or a puddle (Fig.2.12, center and right), and we can put a hot stone inside a well insulating container and so „lock up" heat inside.

Collecting stuff

In these examples we can imagine air, water, and heat to *exist*, to simply *be there*, *without having to be active*. And we can *collect* water and other liquids, air and other gases, just as we can collect electricity and light—just as we collect all sorts of *stuff* in everyday life.

Powerful agents

Naturally, for them to be experienced as Forces, as being powerful, they will have to become active (Fig.2.13). Nevertheless, if we accept *Air*, *Water*, and *Heat* as Forces, they are a kind of visible or invisible figure or agent that can exist in a location and wait for its time to come.

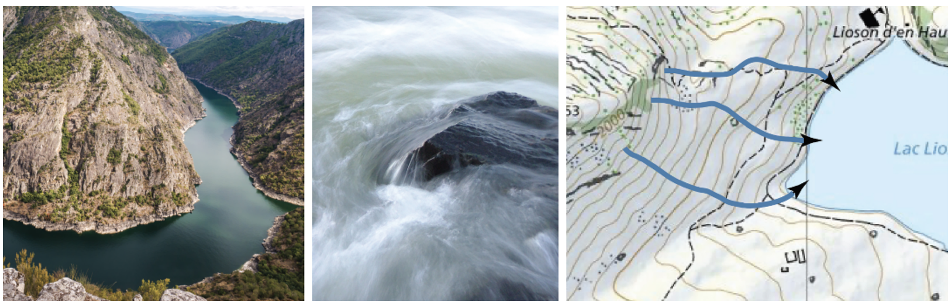


Figure 2.13: *Water is powerful—it is a shaper of landscapes (left; photo: Adobe Stock/photohampster) and beaches (center; photo: The_Power_of_Water_-_Flickr_-_JoshuaDavisPhotography). Water flows along the steepest gradient in a landscape; gradient lines are perpendicular to level contour lines in a map (right; ©swisstopo).*

Shifting our perspective

We shall now describe, rather briefly and preliminarily, the roles *water*, *air*, *light-as-substance*, and *electricity* can play in physical systems; much more will have to be said about these Forces in the remainder of the book. These examples will move us closer to the list of phenomena studied in macroscopic physical science. In Section 2.5, the examples are used to argue that we are performing an important *shift of perspective* to *new polarities* and a *new measure of extension*. We shall conclude the chapter by discussing one of the new Forces which appear to our mind as „invisibles"—namely, *Cold* (Section 2.6).

New polarities and extensions for *Water* and *Air*

Turning to *Water* and *Air* after discussing *Rain* and *Wind*, is no accident. The former are so closely related to the latter that this begs the question whether or not we are now dealing with the same Forces once again.

New polarities for air and water

Pressure

Polarities and tensions. The answer to this question is a clear no: we are definitely dealing with new Forces of Nature. One way of contrasting *Wind* and *Rain* with *Air* and *Water* as Forces is made possible by the emergence of *new polarities*. A truly new polarity signals a different Force; remember that we argued that *polarities create Forces* (Section 2.2). Whereas we associate windy ↔ wind-still and rainy ↔ dry with *Wind* and *Rain*, respectively, we use tense ↔ relaxed and deep ↔ shallow with the experience of *Air* and *Water* as Forces. The sense of tense ↔ relaxed, i.e., of *pressure*, can arise from our experience of blowing up balloons, and deep ↔ shallow is perceived when we see a body of water lying before us, such as a lake or a puddle in the field (Fig.2.12).

Extension as amount of some „stuff”

Extension found in amounts of „stuff.” The experience of *extension* of water and air is quite straight forward: there are *amounts* of water and air (Fig.2.14). After all, water and air are experienced as substances or some „stuff” for which a measure of amount is quite natural. One thing we need to accept if we want to recognize *Air* and *Water* as Forces distinct from *Wind* and *Rain*, is a shift of perspective from spatial extension, i.e., geometric *size*, to *amount* (of stuff).[27]

Figure 2.14: *Water collects in tanks (left) and flows in rivers (second from left); it drives water wheels (A. Baumann), and it can be pumped (right; photo: unknown author).*

Hydraulic and pneumatic Forces

Water and air as fluid Forces of Nature. All this points to *Air* and *Water* being their own new kinds of Forces—they cannot be subsumed under *Wind* and *Rain*. They are fluids having their special intensities (polarities and tensions) and extension (amounts of fluid). If we take this particular perspective, if we study how air and water create phenomena and are powerful as fluids, we call the phenomena *pneumatic* and *hydraulic*, respectively. In other words, *Air* and *Water* are pneumatic and hydraulic Forces of Nature.

Water and *Gravity*

There is an oddity or inconsistency in the description of air and water given above: we call both Air and Water *fluid Forces of Nature*, but we associate them with different polarities—tense ↔ relaxed for the former, and deep ↔ shallow for the latter. If they both belong to the group of fluid Forces, shouldn't they be characterized by the same polarity? Indeed, when we study phenomena called *hydraulic*, i.e., processes undergone by liquids such as water, oil, or blood, in more depth (Chapter 3), we shall see that these liquids are characterized by the polarity tense ↔ relaxed whose degrees we call *pressure*. Pressure as intensity applies equally to liquids and gases.

Gravity as a Force of Nature

Vertical level as gravitational tension

So why did we introduce the polarity deep ↔ shallow—or, equivalently, since water stands high in a deep lake and low in a shallow puddle, high ↔ low—for water? This has to do with the fact that water (and all the other fluids) can be experienced as still another Force, namely, *Gravity*,[28] and for that Force, high ↔ low is the proper polarity. In other words, the proper measure of *tension of Gravity* is the *vertical level* above ground.

What seems to cause this possible confusion—Water as a hydraulic and a gravitational Force of Nature—is the simple fact that it can appear to us as a number of different figures or agents: water can be *fluid* (creating hydraulic phenomena), *wet/humid* or *dry* (appearing as a chemical in soil and air, or in plants and animal bodies), chemically *active/aggressive* or *passive/mild* (as a participant in chemical reactions), *fast* (leading to phenomena we call motion), and *hot* (being the source of *Heat* as a Force of Nature). It seems that when we think of water as an example of matter, all we see is a facade behind which the Forces of Nature we are interested in seem to hide.

The many faces of water

What's the* matter *with water?

We have become accustomed to seeing water primarily as an example of matter. However, as material entities, water and all the other material things[29] are nothing but „playgrounds" for the Forces of Nature we are interested in. In experience, water presents itself to us in myriad ways, each way hinting at the existence of a particular Force of Nature. Here is a list of qualities we can associate with water. Water can be...

stressed/relaxed

high/low above ground

moving fast/slowly

whirling fast/slowly

chemically active/passive

making things humid/dry and moist/dry

hot/cold

salty/bland (fresh)

Water as ground rather than a figure

Each of these qualities is part of a polarity that may make a Force of Nature arise in our mind. Here, water as a material thing is not one of the Forces arising in our encounters with nature. Like the material parts of an electric motor, a pump, or a solar cell (see Table 2.3 on p.83), water can serve as the ground upon which the figures we call *Forces of Nature* act and interact (see Chapter 5 for visual ways of dealing with this).

Horizontal flow of water and blood

In order to recognize that the hydraulic nature of liquids is not tied to vertical level, it helps to briefly mention a fluid phenomenon different from water being stacked in containers or lakes, or flowing downhill or being pumped uphill. Consider blood being pumped by the heart and flowing through the body of an animal lying down. Effectively, then, blood will be flowing horizontally; the driving force for its *flow* is the *pressure difference*, i.e., the *hydraulic tension*, set up by the heart. In the case of air, we experience changing pressure quite easily because air can be compressed without much effort; since we cannot really compress liquids very much, it is harder to perceive pressure changes, and therefore pressure, in these fluids; still, water and blood are characterized by the polarity tense $\leftrightarrow$ relaxed just as air is; in other words, pressure measures their intensity.

For the moment, though, it is enough to note that the Forces of *Fluids* and *Gravity* are so tightly joined in a material such as water that we can, in a first approach, forget that height (level above ground) is not the same as pressure. In this chapter, we shall describe the activities of water as if vertical level and pressure could be used for the same purpose. We shall come back to this important observation and to the question of *Fluids* and *Gravity* in Chapter 3.

Water as a Hydraulic *Force of Nature*

For now, we want to concentrate upon what might appear most directly in experience: water is a liquid material (some liquid „stuff”). It flows, drips, trickles, leaks; it fills any container of any shape. It is collected in storage elements, can flow, can drive machinery, and can be pumped (Fig.2.14). As such, water is a member of the class scientists call *fluids*. The processes made directly possible by water in this existential form are called *hydraulic*.

Hydraulic process

Naturally, there is a second character water presents us with quite naturally and directly in everyday life: We drink water and we use it for cooking and cleaning. Here, water appears as a *chemical agent* of great importance. However, let us limit our discussion to water as a fluid (hydraulic) figure for now.

Hydraulic phenomena. How is water a hydraulic (or fluid) Force of Nature? Water is collected in reservoirs big and small and flows in rivers, through hoses, and down the window during rain; we let it rush through pipes from artificial lakes in the mountains down into the valleys for driving turbines and generators in hydroelectric power plants. We pump it for various applications in agriculture, industry, and households, and we store it for later use (Fig.2.14). And it can be used for running hydraulic machines such as hydraulic computers that were built before electronic computers became the standard.[30] If we take such phenomena as characteristic of water, we treat it as a *hydraulic Force of Nature*, i.e., as a fluid in its most direct sense.

Letting water flow

Pumping and storing water

Water flows in rivers and through pipes. When it flows „by itself,” it always flows downhill, from high to low, but we can make it go the other way. We can carry it uphill or use any kind of pump to pump it uphill; plants can „draw” it up from soil and pump it to their highest parts.[31] And naturally, when it flows, water can „force” other things to move such as the rotor of a turbine used in a power plant, sand at the beach, and stones in a riverbed. The last examples tell us how, over time, Water can be a FoN in the truest sense of the word: it is a *shaper of landscapes* at the surface of our planet (Fig.2.13, left and center).

Downhill flow

Water must be pumped uphill

In these phenomena, we recognize the same three fundamental characteristics we have already identified in Forces that are experienced as activities (Rain, Wind, Fire, Light, and Lightning): Water can be *powerful* (Fig.2.13, left and center), there is a measure of *intensity* associated with it, which we relate, most easily and directly, to the polarity high ↔ low since water always flows downhill (Fig.2.13, right) if left to itself, and we can have more or less of it—there is a *quantity* or an *amount* of water. And all these measures are different from those for Rain.

Power of water

Intensity and amount of water

Wind and *Air*

What we have said about the relation between Rain and Water applies to Wind and Air as well. The issue is even more interesting and pressing from a cognitive perspective. How do humans experience Wind? As moving air? There are reasons to doubt this, and not only because we cannot „see” air. Even if we could, there still would be reasons to believe that *Wind* is primary in our encounters with physical nature and that learning about *air* is an altogether different matter.

Do we perceive Wind or air?[32] Which can be used to tell stories? Which is related directly to emotion? Which should we learn about in school—at least at first? Here are a couple of arguments that tell us that we should definitely start with Wind. First, if we study ancient sources ranging from texts written and stories told by Egyptians, Babylonians, Maoris, or the native peoples of North America, we always find that *Wind* is one of the important phenomena used and told about in myths (Fig.2.15). There simply are no "air myths."

Stories of Wind, but no „air-myths"

This last point needs some explaining. In our modern culture, we are quick to think of air—and the motion of air as the reason for wind—so that we do not recognize the primacy of Wind as a Force (a unified perception) any longer. It does not seem to matter that we do not have any simple direct means for perceiving air and, conversely, that we readily perceive Wind. It seems that we modern humans are dissociated from the natural world in a profound manner, and the issue of Wind versus air is a case in point.

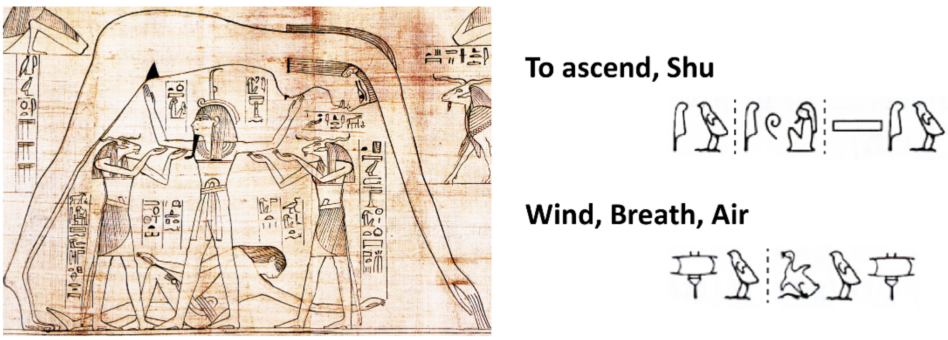


Figure 2.15: *Left: Shu (Wind, standing) separates Earth (Geb, reclining) from Sky (Nut, arching); detail from the Greenfield Papyrus (photographed by the British Museum; original artist unknown). Right: Different versions of hieroglyphic writing of „to ascend" and „Shu" (note the feather) and what we, today, differentiate as wind, breath, and air (note the billowing sail).*

As a consequence, translations of ancient Egyptian texts speaking of wind (or breath) mostly show a "modern" bias. What should be interpreted as the description of a phenomenon or *action*—blowing of wind or the act of breathing—is *nominalized* and called *air*. Some say this is supported by the Egyptians themselves who, as we explain today, introduced *gods to personify phenomena*. Shu, who is "air personified" in modern interpretation, separates heaven and earth (Fig.2.15, drawing on the left).

Nominalization and personification

Our modern ambivalence about wind and air is exemplified by translations in which we distinguish between wind and air, but the Egyptians did not. Two things can be noted about what is expressed in ancient Egyptian language. First, the word pronounced *shu* is both a verb—meaning to ascend (to the sky)—and the mythic idea, i.e., the spirit, associated with the phenomenon (what we today call the „god"[33] Shu); see upper line of hieroglyphs on the right of Fig.2.15. The feather in the word *shu* symbolizes something carried up by the Wind. Shu stood for the cool northern winds and the breath of life; he was invoked to give Wind to the sails of boats. Second, there is no difference between what we today discriminate as wind, breath, and air as seen in the hieroglyphs on the lower right of Fig.2.15. The symbol for wind and air used in Egyptian is the billowing sail that certainly identifies the action of Wind and not the presence of a substance, air.

At any rate, it is not necessary to think of Shu as a person or substance that intervenes between heaven and earth. Rather, it makes more sense to think of Shu as the *agentive character* of the gestalt (i.e., the perceptual unit) of the phenomenon everyone calls *Wind*. Equally, in translations of Babylonian cosmology, it is the

Wind experienced as an agent

Wind, not air, that moves between two disks and separates them so they become Earth and Sky.

Air as fluid Force of Nature. Let us now turn to the question of how we can distinguish between Wind and Air as Forces of Nature. As with Water, the difference is one of polarity (with its experience of intensity and tension) and extension. Wind and Air are both powerful, so the difference does not lie there.

Amount of air

Just like Water, Air is a fluid. It is a gas, not a liquid, but that does not affect the basic phenomena that makes air fluid. Air „exists" as a material „stuff," just like water; the atmosphere is made of it, and we can collect it in containers. Simply put, we can identify a quantity or an *amount of air*—there can be more or less of it. Furthermore, air can *flow*. It can flow by itself (and so drive other processes such as the turning of the wings or blades of a windmill), or it can be forced to flow by a fan.

Four Elements in Greek science

Earth, Water, Air, and Fire—Things or activities?

There is a famous case of early scientific reasoning: Aristotle's theory of *Four Elements—Earth*, *Water*, *Air*, and *Fire*—derived from Empedocles' idea of the *Four Roots* (for which Empedocles uses the names of four gods: Hera, Idoneus, Nestis, and Zeus) from which everything in nature derives.

The standard interpretation is that Greek philosophers assumed the world to consist of these four elements (with a *Fifth Element—Quintessence*—making up the world beyond the Moon). If we ask for the meaning of the ancient words—γῆ, ὕδωρ, ἀήρ, and πῦρ—a somewhat more nuanced picture emerges. For γῆ we find meanings ranging from solid and land to earth; meanings for ὕδωρ are rain, rainwater, sweat, or water; ἀήρ means (morning) mist, wind, space (volume), blue or gray (the color of the sky), or air; finally, meanings found for πῦρ encompass fire, lightning, or a fever.[34]

The feeling we are given today is that the elements were considered material constituents of the world, even though fire might be more like an activity. However, if we go back to Empedocles' *Roots* and their identification as gods, and if we accept that what we call the Ancient Egyptians' gods would be better understood as Forces of Nature, we might be inclined to look upon the *Four Elements* as typical examples of our sense of Force of Nature.[35]

In summary, if we disregard the fact that air can be compressed easily and water cannot, we have a high degree of similarity between the two fluids. Therefore, we can call air and other gases *hydraulic* Forces of Nature (or, if we prefer, *pneumatic* Forces), or simply examples of the *Force of Fluid*.

The polarity of Air as an aspect of the Force of Fluid. In the case of Water as a fluid FoN, we identified level (or vertical height) as the relevant intensity. Even though air is a fluid as well, vertical height somehow does not seem to be appropriate as the measure of intensity of air. Air easily flows horizontally as we know from the winds on the surface of Earth.

But what would be an appropriate polarity? Direct experience, such as when we blow up a balloon or let the air rush out of it again, lets us feel a degree of tension or relaxation of air. We tense air when we compress it, and we let it relax when we allow it to expand. So, the polarity we are looking for may be said to be tense/stressed ↔ relaxed. The term used when we nominalize the experience related to this polarity is *pressure*. When we let air flow from one balloon into another as in Fig.3.10, we see that a *pressure difference* is the driving force; therefore, *pressure* is the intensity of Air. In Chapter 3, we shall learn that pressure applies as the intensity of all fluids, including water. The polarity high ↔ low will consequently be said to belong to Gravity, not to Fluid.

Pressure as intensity of air

Light-as-Substance

What about light? Light presents us with a dual nature as well. First, there is the primary experience of light and dark, of light streaming through the world and flooding it or, alternatively, of darkness spreading; in other words, light is an activity.

Second, light brings something with it, or is made out of something, which plants need to grow and live. We call it *light* as well, but when we think about it, it appears to have a different character. It is more like a substance that, in the leaves of plants, combines with water and air to produce new substances from which the plants grow and whose seeds and fruits animals and people eat. We could speak of *light-as-substance* so we can distinguish it from *light-as-activity*.

In this description, Light is again a Force of Nature, this time a chemical Force: there can be more or less of it (there is an *amount of light*), it has different intensities or qualities, and it is more or less powerful. However, as a chemical Force, it is more like Water and Air and Heat than Rain or Wind or Fire: as we said, it is a kind of chemical (see the chapter on substances in Volume 2).

Amount of light as „substance"

Note that we are saying that light is (more or less) powerful, like any other Force of Nature: it can cause other things to happen, it can incite other Forces to become powerful. Being powerful usually means, in modern language, that the phenomenon has *energy*, is associated with energy. It does *not* mean, in any way, that the phenomenon *is* energy! Light brings energy, but *it is not energy*!

Light is not energy

Lightning as electrical

Today, we are accustomed to thinking of lightning as an electric phenomenon or simply *as* electricity. If we take this last step—*lightning as electricity*—electricity is imagined as *a kind of fluid* that can be in materials making them electrified, and can flow through materials. In the early days of the investigation of electric phenomena (late in the 18th century), researchers spoke of *electric fire* or *electric fluid* (Fig.2.16). In science, we call it *electric charge*.

Electric fire, fluid, or charge

Saying that Lightning *is* Electricity is similar to insisting that Rain *is* Water or Wind *is* Air. We have criticized this attitude, not so much for being wrong but for not being faithful enough to direct experience.[36] There is no harm in naming „electricity" as being behind lightning, but it is important that we let nature have its direct—and emotional—impact upon experience. There is enough in lightning and thunderstorms for a child to learn about before electricity becomes a subject of exploration.

Showing that lightning is an electrical phenomenon is not that simple; and above all, it is *dangerous*. We would somehow have to „catch lightning" and then show that the phenomena we know from simple experiments with electricity can be induced in the laboratory. Benjamin Franklin described such experiments in a newspaper article in 1752:[37]

> „*As soon as any of the Thunder Clouds come over the Kite, the pointed Wire will draw the Electric Fire from them, and the Kite, with all the Twine, will be electrified, and the loose Filaments of the Twine will stand out every Way, and be attracted by an approaching Finger. And when the Rain has wet the Kite and Twine, so that it can conduct the Electric Fire freely, you will find it stream out plentifully from the Key on the Approach of your Knuckle. At this Key the Phial may be charg'd; and from Electric Fire thus obtain'd, Spirits may be kindled, and all the other Electric Experiments be perform'd, which are usually done by the Help of a rubbed Glass Globe or Tube; and thereby the Sameness of the Electric Matter with that of Lightning compleatly demonstrated.*"

The phial mentioned in the newspaper article is a Leyden jar (see the chapter on electricity in Volume 2), a „container" that can collect and store the electric fluid or electric charge. Franklin was convinced that lightning was of electric nature and he mentioned many analogies between electricity and lightning, as we can read in his notes. Experiments with lightning were performed by using lightning rods on buildings and directing their „fire" into a laboratory where the electric nature of lightning could be ascertained. In one such experiment, Georg Wilhelm Richmann was killed in Saint Petersburg in August 1753.

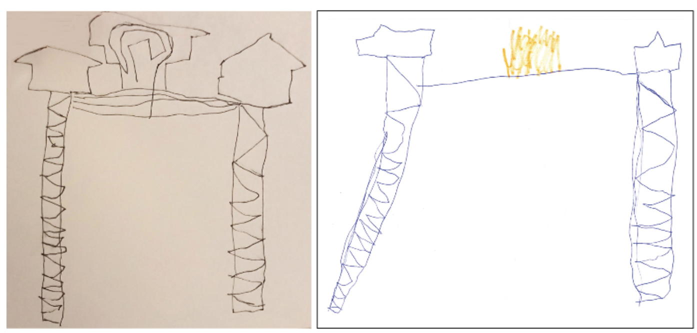


Figure 2.16: *Drawings by DL when he was about four and a half years old. They are drawings of what he thought electric towers placed underground would look like. Of the drawing on the left he said „In the Middle Is Where the Electricity Acts." On the right, electricity acting is represented as fire.*

From activity to substance, once again. Once again, we encounter what we call a Force of Nature as activity—*Lightning*—with another force—*Electricity*—hiding behind it. We have discussed this issue at some length in the cases of Rain and Water, and Wind and Air. Lightning is just another example of an activity in nature where we are confronted with the appearance of something „*fluidlike*" on the scene (see Table 2.4 further below). This new fluid is *amount of electricity* or *electric charge*. Identifying such *fluidlike quantities* and associating them with their own intensities and aspect of power is one of the hallmarks of the modern science of Forces of Nature (see Volume 2).

Fluidlike quantities

2.5 Shifting Our Perspective

In the previous section, we have taken a step towards recognizing a new group within the family of Forces of Nature. Forces in this group have aspects derived from our experience of fluid matter that exists in space and can flow—their extension is described in terms of amount, such as amount of water or air, rather than spatial and temporal extension. These Forces will open the door to those that are explored in macroscopic physical science, such as Fluids, Heat, and Electricity.

Moreover, the description of Water and Air as (fluid) Forces of Nature has taught us an important lesson—they are in no way the same Forces as Rain and Wind. We can understand the distinction most clearly and most easily by considering what the appropriate measures of *intensity* (and tension) and *extension* must be in each case. We shall now describe the differences in experience as one of shifting our perspective.

Wind or Air?

Wind or Air, Rain or Water, Fire or Heat?

Wind and Air, Rain and Water, Fire and Heat appear inseparable, maybe even identical. However, we should be more circumspect and discriminating here. There is clearly a difference in the experience of Wind and Air, Rain and Water, or Fire and Heat. Water and Air should be considered materials having their own characters, and Heat is one of these invisible and imponderable "substances" that cause our scientific thinking so much trouble.

A possible way of dealing with this challenge is to say that water accompanies rain, air accompanies wind, light-as-substance flows with Light, and heat accompanies (or is produced by) Fire.

Activities as bringers or producers of „stuff"

Forces as activities

Collecting „stuff"

Wind and Rain are *not* the same Forces as Air and Water. We see new Forces emerging from the old if we consider the old—Wind, Rain, Fire, Light, and Lightning[38]—as *activities* that (when experienced over an extended period of time) let us collect some „stuff" we should call *amount of air*, *amount of water*, *amount of heat*, *amount of light-as-substance*, and *amount of electric*ity, respectively.

This constitutes the first shift of perspective. The amounts of „stuff" give rise to the experience of new Forces we call Air, Water, Heat, Light, and Electricity, respectively. The new Forces are intimately associated with the „stuff" they arise from—indeed so intimately that fluidlike figures emerge in our mind for air, water, heat, light, and electricity which we take for the new Forces of Nature.[39]

Substances and Quasi-Substances

The fluidlike figures or gestalts are imagined as *material* (in the case of water and air) or as *quasi-material* (in the case of heat, light, and electricity). The latter quasi-substances are of a special *figurative* or *metaphorical* kind, which we shall initially describe very briefly in Section 2.6. Much more will be said about them in the rest of this book.

Fluid substance as schema in metaphors

We shall see that what imagining does in these cases is to project our experience of fluids such as water, oil, blood, and even sand—from which we derive, among others, the abstract schema of FLUIDLIKE SUBSTANCE—upon Forces of Nature we call *Heat*, *Light*, *Electricity*, and *Motion*.[40]

Transporters and producers

Put differently, we can consider the activities as bringing or producing some „stuff" which we notice when we let them act over some period of time. Wind, rain, light, and lightning are *flows* or *transports* of these different kinds of „stuff" whereas fire is the *producer* of heat.

Compressing activity into a new experience

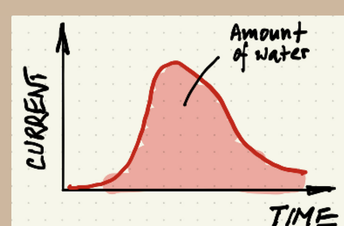
Summing over time—creating a new sense of extension. This distinction between, for example, Rain and Water, emerges if we *integrate* our experience of Rain over an extended period of time, if we *compress* what happens over time into a new experience. At an instant, Rain is simply Rain, but if we allow our mind to sum over our sense impressions, if we aid our experience by collecting „Rain" in a bucket, we can see Water emerging. And the longer we wait, as our perception of the level of water in the bucket goes from shallow to deep, the more water will have been collected.

From rain to amount of water

From activity to amount of fluid: The case of rain and water

We have seen the extension of Rain, Wind, Fire and Light related to the area over which a Force is active. There is "more" Rain if it is spread over a larger area, and the same is true of the other Forces just mentioned.

When we see rain „as" water or wind „as" air, we need to take a different perspective: the *amounts* of water or air "delivered" by rain or wind, respectively, depends upon *how long* we are exposed to wind or rain. In other words, the aspect of quantity of water related to rain is obtained by "summing" rain over time—in practice, we can do this by setting up a container of given area (say, one square meter) and measuring how the level of water rises in it (photo on the left). This container serves as a rain gauge: it measures how much water has been "delivered" by the rain (for an area of one square meter).



(Photo on the left: Adobe Stock/sutichak) What one does is this: One determines the *current* of water from *how fast the level rises* in the container; this value is multiplied with the area over which rain has been falling with this intensity. If we have this data, we can draw it in a diagram as a curve (see diagram on the right: Water current as a function of time). The area in the diagram between the curve and the time axis gives us the amount of water delivered in a period of time.

The same process of „collecting" different kinds of „stuff" by letting processes operate over time applies as well to the other activities we have discussed so far: Wind, Fire, Light, and Lightning. Collecting the fluidlike quantities called air, *Collecting fluid quantities*

heat, light-as-substance, and the electric fluid basically works the same way, but it can be difficult in practice to do the collecting. It's easy in the case of heat if we put a pot of water over the fire. It is easy, in some sense, with light: solar collectors and leaves constantly „collect" the Sun's light (the problem with collecting light is that it disappears immediately as it is collected). With electricity, it is different, though: bodies cannot store much of the electric fluid before losing it again.

Shifting our perspective

From activity to substance, from extension to amount

Our mind is quite flexible in taking different perspectives or viewpoints. We do not notice or think about this—it just happens. One of the important ways our mind works is by shifting from using *spatial schemas* to adopting *object* or *substance schemas*, and vice-versa, and then applying them in metaphors when expressing experience.

When we deal with Primary Forces of nature, this happens quite readily. We perceive rain and bring the tools of thought to bear we have talked about—*intensity*, *spatial and temporal extension*, *power*—and then immediately „see" water behind the phenomenon for which we use schemas related to OBJECT or (FLUID) SUBSTANCE, plus the associated polarities with their intensities and tensions, i.e., differences of intensities (see Table 2.4).

Table 2.4: Two groups in the family of *Forces of Nature*

Force as activity	Force having a „fluidlike" character	Intensity belonging to fluid substance
Rain	Water	Height/Level
Wind	Air	Pressure
Fire & ice	Heat & Cold	Hotness & coldness
Light	Light-as-Substance	Light potential (*)
Lightning	Electricity	Electric potential (*)

(*) *Potential* is a generic term used in physical science for what we have called *intensity*. Like intensity, potential is imagined as a *level* that can be *high* or *low*. In Chapter 3, and again in Chapter 5, we shall learn more about the meaning of potential.

Air is all around us, but how do we collect it from Wind? „Catching" Wind, storing it—and so creating an experience of amount of air—is not so easy; we can use a bag made of airtight material, let the Wind „blow it up," and then close it. Such an activity may serve as imagery for how we collect air in our lungs and expel it again. Usually, however, if we need to store air, we take it directly from the atmosphere with the help of machinery.

Collecting electric fluid, finally, works and it is done with so-called capacitors, but the quantities of electric fluid so collected are minute. Sizable amounts of the electric fluid, however, are accumulated in thunder clouds and at the surface of the Earth (all of this is the result of the activity that leads to thunderstorms).

New polarities, new Forces...

Here is the second aspect of our shift of perspective. As we have already made clear, Wind and Rain and the other *activities as Forces of Nature* are contrasted with Air and Water and the Forces that have a fluidlike aspect (Light, Electricity, and Heat) with the help of a set of new polarities that create new Forces for us (remember what we said in Section 2.2). We have already discussed these polarities for Air and Water; they may be termed tense ↔ relaxed and deep ↔ shallow, respectively (see p.89).

Heat presents us with perceptions of hot ↔ cold, something we are all very familiar with; this easily makes heat one of the important Primary Forces. Electricity, on the other hand, is quite „hidden" as a Force (if we disregard its many uses in our modern technically influenced societies). Neither can we see the „stuff" that creates its fluidlike aspect, nor is it quite clear and straight forward how we might perceive its intensity or the tensions it creates. However, if we let our imaginings be guided by the description of the feeling of a special kind of heightened tension before and during a thunderstorm (see p.87), we might be inclined to simply use high tension ↔ low tension as the polarity not only of thunderstorms and lightning but of electricity as well; we shall see later in our exploration of electricity as a FoN that this choice is indeed quite appropriate (Volume 2).

Light-as-substance is a little harder to grasp; a proper polarity isn't light ↔ dark (this one is reserved for light-as-activity) but has to do with the nature of light as a special kind of chemical (see Volume 2).

2.6 Invisible Fluids as Forces—The Case of Cold

The examples presented in Sections 2.4 and 2.5 confront us with a shift of perspective from Forces of Nature that are *activities* (such as Wind and Fire) to what appear to us as *fluidlike characters* having extensions called amounts of water, air, light, and electricity. Among the group of *„fluidlike" Forces* there are some that are clearly invisibles and untouchables—they do not appear as material fluids such as water, but our imagining endows them with a fluidlike figure. Examples of such Forces are *Heat* (and *Cold*), *Electricity*, *Gravity*, and *Motion*.

„Fluidlike" Forces

In this section, we move towards making visible what exists in imagination only by describing Cold as a Force of Nature. In the following chapters, we shall have a lot more to say about Forces appearing as „invisible" agents.

Snow, *Ice*, and *Cold*

Let us describe a character, or figure, we call *Cold* that appears to be active in objects we experience as being cold, such as snow, ice, cold air, and cold water. We see how imagining creates this figure which certainly does not exist in any material, ponderable, visible, and touchable form. It emerges from our direct experience of the polarity of cold ↔ hot, which is one of the most primary of human sensations. It will become clear that the perception of the polarity of *coldness* (or hotness) is not enough for our mind—somehow, we come up with an invisible figure which we hold responsible for what we see happening around us (Chapter 4).

Coldness as polarity

A Winter Story—Cold as a Force of Nature. Here is a little story of a town in winter where *Cold* is the protagonist.[41] Witness the language that is used to bring

Cold and its properties to life without actually personifying the Force of Nature we might call *Cold*.

> *A small town called Little Hollow lay in a hollow surrounded by a high plain. People had settled in that place because small streams collected on the plain and flowed down into the hollow and through their town as a nice gentle river. This the people of Little Hollow liked a lot. But there was something they liked a lot less: Winters in Little Hollow were harsh.*
>
> *As the last of the warmth of late Fall left the plain surrounding Little Hollow, cold found its way into the area and spread out. Because the plain was so wide, the cold of winter had to spread pretty thinly, so it was not all that cold up there. Moreover, even in the midst of winter, the Sun managed to send some warming rays onto the plain. The snow that fell on the plane was not so cold either, but it was plenty, and the people of Little Hollow loved to go up to the plain for cross country skiing. The little kids went there to build beautiful snowmen.*
>
> *But in Little Hollow, things were different. The cold of winter knew a good place where it could do its job much more easily of making everything and everybody cold. It could flow into the hollow where the town had been built. It could collect there, and it knew it would not be driven out so easily by a little bit of wind as could happen on the plain. And the Sun could not reach the town that easily, also because of fog that often lay over Little Hollow and made everything gray. More and more cold could collect in Little Hollow, and it got colder and colder as the winter grew stronger. The temperature fell and fell.*

Figure 2.17: *Little Hollow (artwork by An Pei). Fireplace (photo: PL).*

> *The people of Little Hollow cursed winter and its cold. They knew that the cold would find its way into their homes like a hungry animal if they were not careful to close windows and doors. The cold could even sneak in through tiny cracks between walls and windows, so the people in Little Hollow had learned to build their homes well and put in strong wood burning stoves.*
>
> *At times when much cold had collected in the town, when it had become terribly cold and the temperature was very, very low, the fires in the furnaces had to work very hard to fight the cold that had made its way*

> *inside. The people in their homes made sure that fires roared in the stoves and that the heat they produced would balance the cold. But it was an almost impossible fight: the cold loved to go to where it was warmer, and it would eventually get what it wanted. Once inside a home it made the warmth pale and weak.*
>
> *For the children of Little Hollow, the cold of winter was not so bad. They dressed warmly so they could keep their body heat in, and they played hard when they were outside. But even for them, the thick cold of winter had mischief in mind. It went into the snow lying on the ground to make it very cold as well and this made the snow drier and harder to work with. The children could not form snowballs, and it was much more difficult to build snowmen. They had to wait until winter had grown somewhat tired, and the cold was slowly driven out of Little Hollow. When there was less cold and the temperature was a little higher, the snow became warmer and much more fun to play with.*
>
> *When that happened the cold of winter knew its time had come. The warmth of early Spring would grow stronger and drive the cold out of the hollow. The cold knew it had to accept its defeat, but it also knew very well it would be back...*

Cold as a character

Analogy

Analyzing the Winter Story. First, note that this story brings *Cold* to life as a character, as an agent. Still, there is no direct form of personification. *Cold* is not pictured as an animal or human figure, except for in that brief statement „*... the cold would find its way into their homes like a hungry animal...*" This is actually a deliberate *analogy* which appears briefly linguistically and as an image in our mind, just to disappear again. The use of the word „*like*" signals explicitly that this is not the case—*Cold* is not an animal.

Story-world and story

Still, *Cold* is clearly a powerful character that acts in the world created by the story and interacts with other characters, both physical and human. That we see *Cold* as an agent is not just the result of particular expressions (such as those collected on the right in Table 2.5) but of the story as a whole. The story sets the stage and lets events come to life as they unfold over time—it creates a dynamical world in which *Cold* makes its mark as a powerful yet invisible agent or character.

Metaphors as projections

Source and target

Let us use this story to demonstrate how understanding of phenomena as Forces of Nature works: our mind makes use of certain basic figures or abstract shapes which are then *projected* onto the desired phenomenon—the products of such projections are called *metaphors*. Metaphors are created by projecting knowledge of a so-called *source domain* onto a *target domain* for which adequate understanding might still be lacking (see Volume 2 for background on metaphor).

Metaphor is an example of *figurative thought*, a tool we make use of in much of our communication of experience.[42] We shall study figurative language and thought in quite some detail in Volume 2, so we become adept at identifying figurative aspects not only in everyday communication but in physical science as well.

At this point, we want to present just a single example of how a small group of general abstract schemas are projected onto our experience of cold and so create the metaphor COLD IS A FLUID SUBSTANCE, among many others (Table 2.6). First, and most generally, we project our understanding of *fluid* (as an abstract schema) onto *Cold* itself. Then there are further schemas that are related to and illuminate aspects of the schema of fluid, such as *amount* or quantity, *containment* (fluids are contained in containers), *flow*, or *obstruction* of flows. Our understanding represented by these schemas is generic—learned and abstracted from experience with fluids—and can now be used to create understanding of a new experience.

Table 2.5: Metaphors and metaphoric expressions of cold

METAPHOR	LINGUISTIC METAPHORIC EXPRESSION
(DEGREE OF) COLD IS A VERTICAL SCALE (DEGREE OF) COLD FORMS A THERMAL LANDSCAPE	The cold loved to go where it was warmer... And it got colder and colder as the winter grew stronger. The temperature fell and fell. When it had become terribly cold and the temperature was very, very low...
COLD IS A FLUID SUBSTANCE COLD IS A MOVING OBJECT	The cold found its way into the area and spread out. It could flow into the hollow... it could collect there... The cold could even sneak in through tiny cracks between walls and windows... ...fight the cold that had made its way inside.
COLD IS A POWERFUL AGENT COLD IS A MOVING FORCE	The cold of winter knew a good place where it could do its job of making everything and everybody cold... The fires in the furnaces had to work very hard to fight the cold. Spring would grow stronger and drive the cold out of the hollow.

Metaphoric expressions

Metaphors—as concrete linguistic expressions—constitute much of the language of the story that signals how we are supposed to feel about what has been said as we read or hear the narrative, thereby learning to understand what has been said. When we analyze cases where schemas we have come to know before are used to speak metaphorically about *Cold*, we can identify three groups of expressions. This tells us that we make use of three basic metaphors: (DEGREE OF) COLD IS A VERTICAL SCALE, COLD IS A FLUID SUBSTANCE, and COLD IS A POWERFUL AGENT. There are additional or alternative forms used for naming the metaphors: COLD IS A THERMAL LANDSCAPE, COLD IS A MOVING OBJECT, and COLD IS A MOVING FORCE.[43] Examples of expressions that fit these metaphors are given in Table 2.5.

Summary 1: Cold as a powerful invisible fluidlike character. How do the story and the metaphors in the story present *Cold* to us? As we can learn from the story, it lets *Cold* appear as an invisible entity that possesses a few basic characteristics we have come to know from having studied other Forces. In our imagination, this invisible entity is visualized as an agent that is spread out and flows like fog or water. In this shape, it can be seen to be more or less concentrated which means we can imagine the agent being more or less cold itself—as a gestalt it exhibits different degrees of coldness expressed as different levels of tension. And, of course, it is (more or less) powerful, i.e., it causes other things to happen such as when it changes the properties of snow or when it makes homes cold.

Cold flows and accumulates

Its quantitative (or extensive) aspect is quite important and visually powerful. Our natural language suggests that *Cold* appears to us as a kind of fluid. It can accumulate in things when it flows into them, but it can also flow out again. It spreads out in nature, it „sneaks" through materials, and so on. So, if we want to begin to understand Cold, we should learn to literally „see" how it collects in materials and how it flows through materials, as it makes all the things in nature more or less cold.

Table 2.6: The COLD IS A FLUID SUBSTANCE metaphor

Source (Fluid substance)		Target (Cold)
Fluid	→	Cold
Amount of fluid	→	Amount of cold
Containment of fluid	→	Cold in materials
Flow/transport	→	Flow of cold
Obstructing a flow	→	Insulating against the flow of cold

Summary 2: Cold moves in a metaphoric landscape. The amount of cold is only one if its fundamental characteristics. The one that is actually felt—*coldness* with its degrees—is just as important for our figurative understanding of the phenomenon of *Cold*. It appears that we speak of coldness as a *vertical scale*—degree of coldness (or its alter ego, temperature as degree of hotness) rises or drops, goes up or down, is higher or lower at a point in space at a given moment in time.

Vertical scale

From the viewpoint of imagining, there is still more to it: when we say that cold flows from points where it is very cold to points where it is warmer, a *landscape of coldness* arises in our mind. Degrees of coldness are simply measures of level or height in this metaphoric landscape.

Landscape of coldness

And then there are still more invisible agents...

Let the foregoing discussion serve as a blueprint for the path we are going to follow when we investigate other Forces such as *Heat*, *Electricity*, *Gravity*, and *Motion*. It turns out that learning to see agents representing invisible Forces is a powerful tool for understanding and communicating about our encounters with these Forces.

In all these cases—which actually represent a good part of the list of Forces studied in macroscopic physical science—our experience leads to the perception of gestalts that can be analyzed similarly to how we have done this for *Cold*. Certainly, the world of Forces of Nature is richly diverse—and we will learn about many differences and special cases—but Heat, Electricity, Gravity, and Motion all exhibit *intensities*, and we give each of them an aspect of *amount* that can be visualized as the amount of a fluid (Table 2.7), just as we have done in the case of *Cold*. Moreover, they are all more or less *powerful* Forces that interact with others to create the chains of events we observe in nature, machines, and our body.

As intuitive as all of this may sound, there are obstacles we need to remove or overcome in our continued studies of Forces. The most important and durable of these is our bias about seeing matter or materiality as the hallmark of „reality." We shall need to overcome this bias and learn to sharpen the tools that let us imagine Forces as immaterial agents active in a material world. While we might be ready to do this for Forces such as *Heat* and *Electricity*, we will have a much

Immaterial agents in a material world

harder time with motion or chemical processes which, superficially, present themselves as the change of position of pieces of matter, or as the transformation of matter, respectively. Learning to visualize immaterial, invisible, imponderable, untouchable agents behind the scenes of what we take to be „real" will prove to be quite a challenge, but one worth facing head-on.

Table 2.7: Invisible Forces, intensities, and amounts

Force	**Intensity**	**Fluidlike amount**
Heat	Temperature	Quantity of heat (caloric)
Electricity	Electric potential (*)	Charge (quantity of electricity)
Gravity	Gravitational potential (*)	Mass (gravitational charge)
Motion	Speed	Momentum (quantity of motion)

(*) *Potential* is a generic term used in physical science for what we have called *intensity*. The imaginative rendering of this term is described in detail in Chapter 5 (Section 5.4).

◦ ◦ ◦ ◦ ◦

Forces of nature come in many different forms—some are conspicuous, others are more discrete; some are *activities*, others appear to us more like some *stuff*. We experience all of them quite similarly, at least from the perspective of how our mind forms perceptual units. The gestalts we call *Forces of Nature* are all associated with *polarities* and related *intensities* and *tensions*; they all are *extended* in a general sense—either *spatially and temporally* or in the form of *amounts of stuff*; and, last but not least, they are all more or less *powerful*.

General sense of extension

In its totality, a Force presents us with images of a *powerful agent* that *interacts* with other Forces. A first Force drives a second; it causes the second one to become active in turn. All this activity is imagined as *stories* unfolding in nature and in human made artifacts and infrastructure. Stories of Forces of Nature have the typical structure of tales and myths that are repositories of powerful *figurative language* such as metaphor and metonymy, and analogical structures based upon them.

While experience of Forces starts with felt intensities and tensions, interaction may well be the feature that leads us to imagine phenomena as Forces in the first place—when they interact, Forces present themselves as powerful. The *experience of power* will be instrumental in forming an important idea which pervades many aspects of the physical sciences—namely, the notion of *energy*.

Notes

[1]See http://www.native-languages.org/nature-spirits.htm. A particularly interesting myth is the story „Why we need wind." http://www.angelfire.com/ia2/stories3/wind.html. Visited in March, 2020.

[2]In Egyptian mythology, basic Forces—Forces of our psyche, social and cultural Forces, and Forces of Nature—are personified. We find *Shu* for Wind and *Tefnut* for Moisture, or *Geb* for Earth and *Nut* for Sky; each of the pairs actually represents a particular type of unit which later become what we might call *polarity*. At some point in the development of the world, Shu (Wind) enters between Geb (Earth) and Nut (Sky) and so separates them. This establishes one of the central polarities, a tension between Earth and Sky. See, for example, Sproul B. C. (1979): *Primal Myths. Creation Myths Around the World.*

[3]We should be cautious with this statement when it comes to *electricity* and *motion*. If it were not for our technical culture, we would not know much about electricity (which also means that we would not know what to look for and experience). Motion is a challenge in a different way: we see bodies moving, but this is only the surface of the phenomenon. Below it are two invisible Forces characterized by speed and momentum and angular speed and spin in linear and rotational motion, respectively. How to learn to „see" momentum and spin in place of the material bodies themselves has vexed physics education for decades if not for centuries.

[4]Remember that we have to distinguish *Basic Forces* from the physicists' *fundamental forces* which are quite a different type of concepts in physical theory. See Section 1.5.

[5](https://www.guardelectric.com/offers. Visited on Jan. 1, 2021.)

[6]Sadi Carnot (1824), p.3.

[7](https://hbr.org/2017/03/inequality-isnt-just-due-to-market-forces-its-caused-by-decisions-the-boss-makes-too. Visited on Jan. 1, 2021.)

[8]See Lakoff & Kövecses (1987).

[9]This is a difficult notion for modern people. We often hear that light was created first which gives us the impression that before that the world must have been dark. However, the idea is that light and dark were created together; dark did not exist independently.

[10]J. Dewey, 1925.

[11]R. Fuchs and H. Fuchs (2010-2023). The authors have created a small number of short stories with the express purpose of introducing certain Forces of Nature or aspects thereof. These stories have since been used in school for didactic investigations or simply for enriching some traditional teaching in kindergarten and primary school.

[12]A curriculum called *Energy and Change* was created in 1992-1995 by Richard Boohan and Jon Ogborn (Boohan & Ogborn, 1992-1995). The central idea of their approach is that change is caused by differences, for example, differences in temperature or in concentration.

[13]Maybe you expected this to be called a *category* rather than a *family*. The problem with *category* is that, in classical cognitive science and formal logic, membership in a category is determined by necessary and sufficient conditions. No such conditions can be found unequivocally in the case of *Forces of Nature*. This is actually true for many if not most *natural categories* as has been established in the newer cognitive sciences (see Rosch, 1973; Rosch et al., 1976; Rosch & Lloyd, 1978; and for a discussion in cognitive linguistics, see Lakoff, 1987). Therefore, we use Wittgenstein's (1953) term *family resemblance* when suggesting that a phenomenon should be considered a member of a certain category (*family*).

[14]There is always a chance of extrinsic dynamics—when the environment forces a system to behave in a certain way. Intrinsic dynamics means that there is a (dynamical) structure of the system itself that leads to dynamical behavior, i.e., to change over time.

[15]This story is one of a series of narratives of Forces of Nature created as part of the project *Primary Physical Science Education*. They serve as examples for materials useful for an imaginative approach to physical science in primary education. The stories have been used for student teacher education, and some of them have found their way directly into primary school classrooms. See Corni (2013), Beccari (2016), Fuchs R. & Fuchs H. U. (2020).

[16]Marco Caracciolo (2014) has described in detail how stories create what he calls *narrative experience*. Narrative experience results from a mental simulation that can give us emotions and feelings similar to those that arise in the experience of the actual events told in a story, and so lead to similar knowledge and understanding.

[17]Climate of Titan (Wikipedia: https://en.wikipedia.org/wiki/Climate_of_Titan; , viewed on Jan. 5. 2021)

[18]How do we avoid focussing upon drops right away and learn to recognize the aspects, particularly intensity and extension, of rain that make it a Force of Nature? Maybe elements of the story presented above may help. If we consider the phase where the kids observe the Rain moving over the valley from the hill where the farm is located. From that vantage point, the phenomenon of the rainstorm can be seen in full—as a gestalt—in its spatial extension, in its temporal course, and in its changing intensity. Drops will definitely not be visible from such a distance, so we are free to focus upon the large-scale basic aspects of Rain as a Force of Nature.

[19]Here is an example that is full of misconceptions: L. Timm „The Story of a Little Rain Drop" (https://www.youtube.com/watch?v=_TwKDuozJC4, viewed on Jan. 5. 2021)

[20]Take a glass full of water and gently touch the water surface with the tip of your finger. Then slowly pull your finger up. Your will see that a little bit of water is „stretching" upward and, finally, a drop of water will cling to the tip of your finger (see Volume 2 for a discussion of cohesion, adhesion, and surface tension, and photographs of the process just described).

[21]See A. Hobson (2013), and C. Rovelli (2017).

[22]We all say that the sky is blue (and that the grass is green, and the Sun is yellow). It would be wrong, however, to take this as objectively true—the sky (the air?) does not have a color. Neither does the light that comes to us through the atmosphere; scientifically speaking, light is electromagnetic radiation having different wavelengths, but it is not „colorful" in itself. It is correct, though, to say that we see the sky as blue; in its interaction with the environment, our organism with its perceptual apparatus and nervous system (brain) lets it appear blue. Our organism creates the color sensation: color is an embodied concept. Philosophers have debated this issue for centuries, and many would still try to take an objectivist („dis-embodied") stance in this regard. However, in the light of modern cognitive science, this does not make sense. On philosophy and cognitive science of light, see Lakoff (1987); Lakoff & Johnson (1999, pp.23-26, 105-106); Giere (2006, pp.17-40).

[23]R. Fuchs & H. Fuchs (2010-2023). In a lab session with student teachers at the Free University of Bolzano, the question came up, how would a teacher react if a child asked why the sky is blue...? If we want something more than a „definition"—if you want more than „it's due to the scattering of the blue part of the spectrum of the Sun's light in the atmosphere..."—then we might come up with trying a story that does justice to children's imagination.

[24]Such an exploration can, and should, take different forms depending upon the age of students—we can certainly start in kindergarten with some of the aspects, and then continue with light and color through primary school. There are two major themes involved here: the first has to do with sunlight seemingly consisting of light of different colors; the second applies to the colors taken by objects in different lights. It should be simple to explore the apparent colors of differently colored objects (as they appear in normal daylight) using lights and simple colored filters in a dark room. We can even find software for notepads that lets us simulate different situations of lighting (see „Light and Color" by Tinybop at tinybop.com).

[25]Again, North American mythology abounds with stories of thunderstorms and thunder and lightning.

[26]The former tension—that of differences of brightness—is actually associated with consequences of lightning. The latter, this feeling of a basic imbalance in nature, will lead us in the direction of a new Force—Electricity, which, today, we see as the Force behind lightning.

[27]Naturally, a fluid has a spatial extension as well. Amounts of fluids occupy certain volumes of space, they flow in and out of these spaces, and they may be created and destroyed inside. However, it makes sense to focus upon amount rather than spatial extension associated with amount when speaking of the extensive aspect of Forces having a fluidlike aspect.

[28]We should note that what physicists call the *Force of gravitation* and our *Gravity as a Force of Nature* do not point to the same thing. In physics, *force of gravitation* refers to the Newtonian (i.e., mechanical) force caused by gravitation. By *Gravity as a Force of Nature*, on the other

hand, we mean the perceptual unit presented to us by gravitation—we mean a *Force of Nature* in the sense described in this chapter and in this book.

[29]Actually, we have to add non-material entities to this list, namely, what physicists call fields such as gravitational and electromagnetic fields. They are real physical entities just like the things we call matter. Fields are „playgrounds" for Forces just like standard material objects.

[30]In 1949, William Phillips built a hydraulic computer for studying the British economy (see M. Morgan, 2012).

[31]Or do trees „suck" water up their trunks all the way to the leaves? The experience of sucking in air or water through a straw is a strong primary perception and deserves investigating and discussing with young learners. The uptake of water in plants with subsequent evaporation provides for an interesting backdrop, especially for children.

[32]The following lines and Fig.2.15 are adapted from Fuchs & Cervi (2015).

[33]There is good reason to assume that what we today call the Egyptian gods were no such thing, at least not in any modern sense. Much rather, we can assume that, originally, these „characters" represented the personification, in a mythic sense, of Forces of Nature. These „gods" were part of nature and humanity. Only very slowly, over hundreds and thousands of years, did a sense of gods in a more modern sense arise. In the Egyptian myth of the *Heavenly Cow*, a new feeling or experience seems to have been expressed for the first time: „The gods are no longer with us"—the gods moved „up" and away from Earth.

[34]Descriptions of etymology and meanings can be found at en.wiktionary.org/wiki/γῆ, en.wiktionary.org/wiki/ὕδωρ, en.wiktionary.org/wiki/ἀήρ, and en.wiktionary.org/wiki/πῦρ. Note some of the roots in Proto-Indo-European and Proto-Hellenic languages.

[35]See, for instance, Catherine Rowett (2016).

[36]Moreover, there is quite a distance between experiencing lightning and demonstrating that it is electrical. Some of this distance is covered in Volume 2 in the chapter on electricity where we recount aspects of the history of research into electrical phenomena.

[37]Benjamin Franklin: *The Pennsylvania Gazette*. October 19, 1752.

[38]We could add a number of Forces to this list of activities, such as rivers, lava flows, ocean currents, earthquakes, and glaciers (the latter, if we can take the „long view" that shows that glaciers flow and carve landscapes).

[39]There is a linguistic and conceptual dilemma that easily leads to misunderstandings. What we have listed as *amounts of* air, heat, electricity (etc.) is often just called air, heat, electricity (etc.), and assumed to be some kind of „stuff" being characterized by an amount. In other words, we confuse phenomenon and its extensive aspect (amount). If the *distinction between* phenomenon, i.e., *Force of Nature*, and its *extensive aspect* is a sensitive matter, we shall try to be consistent and use the words such as *Electricity*, *Heat*, and *Motion* for the former, and speak of *amount of electricity*, *amount of heat*, and *amount of motion* if we mean the latter.

[40]The transfer of schematic images is ubiquitous in physics. When studying phenomena such as earthquakes—whose spread through the Earth is an example of the propagation of sound—we are confronted with an interesting case of schematism and metaphor. We use an image of *quantity of motion* being carried or flowing through the Earth; *quantity of motion* is the term Isaak Newton used in his theory of motion to describe what motion is all about „behind the veil" of appearances.

[41]Fuchs H. U. (2011).

[42]This is the modern interpretation of (conceptual) metaphor which is different from how a mythic mind interprets the relation between two realms (which here are called source and target domains). Remember what we said about myth and metaphor on p.31 (Section 1.3).

[43]In conceptual metaphor theory, two of these metaphors are commonly named ... MOVING OBJECT and ... MOVING FORCE (Lakoff & Johnson, 1980, 1999). Our terminology is adapted to our theme, i.e., Forces of Nature.

Chapter 3

Wind, Water, and Gravity

„Untitled" by DL (3 years 6 months)

Wind, *Water*, and *Gravity* are among the great shapers of the surface of our planet. We easily experience *Wind* and *Water* as *Forces* that have been fundamentally important for the development of both nature and human industrial culture, and we can see them interacting with *Gravity* when they flow vertically upon the surface of Earth. In this chapter, we are going to study these Forces in order to explain what happens when they interact. This will bring us closer to an understanding of the notion of *power* and how to quantify it.

H. U. Fuchs, F. Corni, *Primary Physical Science Education*,
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Wind, *Water*, and *Gravity* create an easily experienced group of *interacting Forces* that have been fundamentally important for the development of both our planet and industrial human culture (see the wind and water mills in Fig.3.1). Wind makes windmills work that pump water for drainage and irrigation. When water and air flow, they shape landscapes, and we make use of their power in industrial processes. Indeed, it is the interplay between different Forces that lets us recognize the meaning of *power* most directly and easily. We shall discuss this from an imaginative angle in the first section and then turn to formalizing the idea in Section 3.6.

Figure 3.1: *Wind and Water drive important processes in our technical culture. Left: Water making a mill wheel spin (photo A. Baumann). Center: An old farm windmill is used for pumping water (photo by Myburgh Roux from Pexels). Right: Waterfall in Manoa Valley on Oahu (Hawaii) suggests the power of water made to fall by gravity.*

Polarities for water and gravity

Afterwards, we study intensity and extension of the Forces of *Wind* and *Water* and how to quantify these properties (Section 3.2). At first, intensity, especially of water, will pose a challenge since we have two different polarities as generators of *Water* as a *Force of Nature* (FoN): high ↔ low and tense ↔ relaxed. We resolve this problem by recognizing *Gravity* as a third Force that appears on the scene whenever air and water *flow vertically*, up or down, on the surface of the Earth (see Sections 3.3 and 3.4). In other words, we shall accept high ↔ low as the generator of *Gravity* and tense ↔ relaxed as that of *Fluid*.

Waterfall as Archetype

When the Forces of Gravity and Fluids interact, many important phenomena arise that have shaped and still shape our natural environments. Among these phenomena are *waterfalls* (Fig.3.1, right) that are centrally important for our scientific imagination. If we accept waterfalls as archetypical physical processes, we can learn how to quantify the power of Forces of Nature (Section 3.6).[1]

Experience of fluids creating abstractions

The theme of this chapter is fundamental in the sense that it demonstrates how our experience of fluids such as water, blood, or oil leads to the creation of embodied schematic abstractions with which we understand much of what is to follow in the course of our study of Forces of Nature. For this reason, we summarize the chapter by presenting a brief outline of these fundamental schemas in Section 3.8.

What do all fluid materials have in common as hydraulic Forces? We want to get to know water and air as prototypes of the FoN we call *Fluid*. Before we start our work, it is important to understand that all the different fluid materials—liquids such as water, oil, and blood, and gases such as air—share the same basic schematic aspects of *intensity* (and *tension*) and *extension* (i.e., *amount of fluid*) that makes them members of the family of *Fluid*. We shall see that these aspects are *pressure* (and *pressure difference*) and *volume of fluid*, respectively. Moreover, all fluid materials must be powerful in the same basic sense we associate with *Fluid*, i.e., when they flow and make other things happen.

Fluids encompass liquids and gases

Fluids are liquids and gases. If we do not need more detail, the differences between liquids and gases are simply these: the density of gases is low, that of liquids is high; and gases can be compressed quite easily, liquids cannot be compressed very much. Compressing is understood as reducing the volume of a body of fluid; relaxing means letting the volume get bigger.[2] So, the fact that liquids are hard to compress means that changes of volume are small, even under quite high pressure. Still, this does not mean that water could not be in a *tense or relaxed state*. The pressure of water, and that of other liquids, can change as easily as that of air and other gases.

Pressure as tense or relaxed state

Compressibility

Compressibility —measuring how easy it is to compress a fluid—makes gases more interesting but also more complicated to work with; Forces such as Heat and Motion interact with a gas in ways they do not with a liquid. As long as we deal with incompressible liquids, we are confronting one of the simplest examples of physical and technical phenomena.

There are many different liquids—water, vegetable oils and crude oil, blood, alcohol, gasoline, liquid soaps, honey and Ketchup, and, if we want to go to extremes, even hot lava—and they all share certain characteristics that makes them members of the class of *hydraulic Forces of Nature*.

3.1 Letting Wind and Water Interact

In science and engineering, studying the interactions of Forces has led to the question of how the *power* of a Force of Nature relates to *tension* on the one hand, and *extension* (spatial size or amount) on the other. We have hinted at the importance of Forces interacting in chains of processes, and how that may shed light upon the power of Forces, in Chapter 2 on pages 76 - 77. We shall now create an imaginative pictorial form of thinking about such interactions.

Our experience in this regard is pretty clear: whenever a phenomenon is more intense, and whenever the imagined agent representing the Force is „bigger," i.e., if its spatial extension is bigger or there is more of it present, the process is more powerful. Let us now use the interaction of wind and water in windmills used for pumping water in order to create an image of power.

Pumping *Water* with *Wind*

Windmills have been used for a very long time for pumping water—the history of wind-driven water pumps in Holland (Fig.3.2) and on farms in the United States (Fig.3.1, center) attests to this. Obviously, wind is powerful in the sense a person or an animal is when operating a mechanical water pump. In Holland, canals have been built for draining the low-lying parts of the land (see Fig.3.2, left and center); the canals themselves lie a little higher than this land, so water needs to be pumped from a lower to a higher point. For accomplishing this, windmill-powered pumps have been placed along such a canal—see the three windmills indicated in the satellite photo on the left in Fig.3.2.

Let us now consider a windmill such as one depicted in Claude Monet's painting (Fig.3.2, center) or the wind turbine on the right in Fig.3.2. The *area* spanned by the sails or the blades of these windmills define *how much wind* will be caught—it defines the extension of the wind blowing that is powering the water pump. For a given mill, it is a constant. Naturally, if we could make it bigger, more wind would be caught, and the power of the wind would be greater.

Figure 3.2: *Left: Windmills along a canal in Kinderdijk, Holland (satellite photo: Google Maps), pumping water from low lying land into higher up canals. Center: Windmills along a canal (painting by Claude Monet, 1871). Right: Modern wind turbine.*

The second factor that determines the power of wind for a given windmill is its *intensity*—the higher the intensity, the greater the power. However, we have to be more careful here: the wind will still blow behind the sails of a windmill or the blades of a wind turbine. Naturally, the intensity of the wind will be lower after it has caused the mill to work. What counts for how powerful the interaction of the wind and the windmill will be is the difference of the intensities before and after—it is what we have called the *tension*, i.e., the difference of intensities at two different points along the path of the wind.

Figuratively speaking, in the interaction with a mill, Wind is flowing from a point of high to a point of low intensity—it is flowing *downhill* (Fig.3.3, left) This is very much like what we have discussed in the case of spontaneous flow of water down a hillside (Fig.2.13, right). Therefore, by imagining, we can depict what is happening here as a given „quantity" of wind (defined by the area covered by the sails of the windmill) *flowing down* a *metaphorical level difference from high intensity to low intensity* as depicted in Fig.3.3.

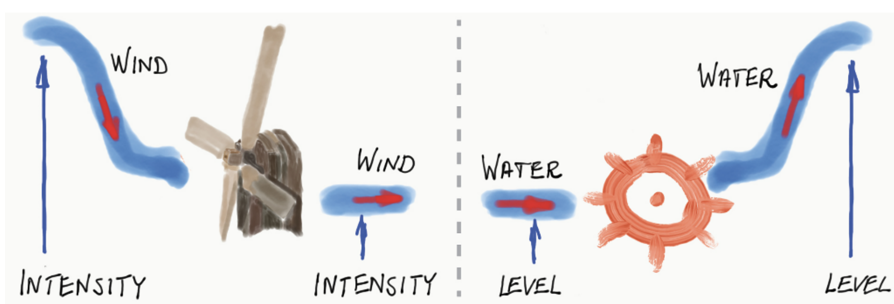


Figure 3.3: *Left: Schematic and symbolic rendering of wind interacting with the sails of the Windmill—figuratively speaking, the interaction makes the wind flow downhill. Right: Schematic and symbolic rendering of the pumping of water, i.e., its forced uphill flow; the wheel symbolizes the pumping mechanism.*

In response to the downhill flow of wind, water will be pumped and therefore flow *uphill* (Fig.3.3, right). To make all of this possible, engineers have invented intricate mechanisms that mediate between Wind and Water; however, as we focus upon the Forces of Nature acting here, the mechanism recedes into the background—we do not consider it, at least not in any detail.[3] It is important to imagine the Forces interacting—they need to be like characters on a stage, experienced as vividly as if we were in a theater.

Level: Schematic and metaphoric

Experience of „level" is concrete, schematic, and used metaphorically

The imaginative rendering of intensities and tensions obviously relies upon the schema of LEVEL or HEIGHT—*Wind*, when driving a wind mill, goes from a high to a low level of intensity even though, from a spatial perspective, it flows horizontally.

The concrete experience of LEVEL as vertical height above ground is so ubiquitous that it leads, through schematization, to the abstract notion of vertical level. The schema of VERTICAL LEVEL is applied to all sorts of phenomena: LEVEL for status in society, LEVEL for intensity of heat (temperature), etc.

For this reason, it is important to be clear how we use the word *level*: do we mean concrete height above ground, or are we using it metaphorically?

Power explains relation of *Forces* in interactions

There are two rather different ways of answering the question of how water can be pumped by wind. One is by saying that the mechanism (windmill plus water pump) makes it possible for the water to be forced uphill. The other focusses upon Wind and Water and their interaction; here the answer is that Wind is powerful and so causes Water to flow uphill, against its natural tendency, and become powerful in turn. Expressed differently, a powerful *Wind* can *empower Water* by lifting it (Fig.3.4).

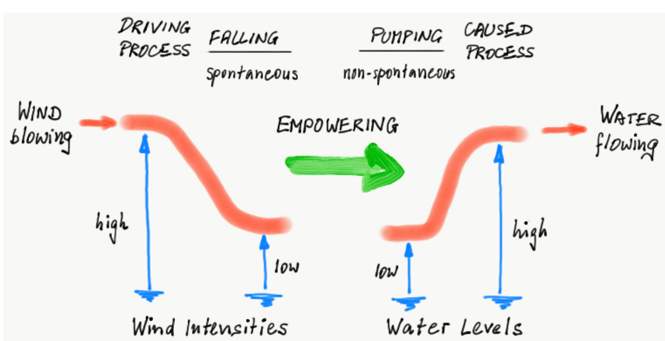


Figure 3.4: *Schematic rendering of the interaction of wind and water: Wind goes from high to low intensity, i.e., it becomes less powerful. In turn, Water goes from a low to a high level—it becomes empowered. The green arrow going from the agent to the patient symbolizes the still purely qualitative notion of power and empowering.*

We need the notion of *power* in order to explain how *Wind* can force (pump) *Water* in the first place and, secondly, how much water can be pumped. Qualitatively

Relaxing and tensing

speaking, by going from high to low intensity when flowing across the sails of the windmill, *Wind relaxes* and becomes less powerful. Since *Water* does the opposite, it *tenses up* and becomes more powerful. Clearly, water pumped to a higher level on Earth can cause other processes to happen—it has tensed up and become powerful.

Power establishes an exchange rate between Forces interacting

Current

In sum, it feels as if the wind has „given" some of its power to the water. If we quantify the notion of power, we have something like an „exchange rate" between *Wind* and *Water* or, more generally, between any two *Forces* interacting. *Power* lets us state how much of *Wind* activates how much of the Force of *Water*. Since the power of *Wind* driving the windmill depends upon both the „quantity of wind" flowing, i.e., the strength of this flow, and the tension across the sails of the mill, we can say that these two factors combined will let us find out how high a *current* of water can be pumped (remember that we use *current* as the formal equivalent of *flow*; see p.98).

Flow & Current

Flowing, flow, and current

So far, we have used the word *flow* almost exclusively as the verb, *to flow*. Very rarely has it been used as a noun, *the flow* (as in the sense of something is flowing—*the flow of some „stuff"*). When we used it in the latter nominalized sense, we did so almost exclusively when speaking about experience; we talked about *the flow of experience* rather than a „physical" flow.

Strength of flow

This will change now: more and more often we shall talk about *the flow* of water, air, heat, electricity, and other quantities. There are two important senses of this: one is colloquial, when we want to suggest the phenomenon of flowing as a figure or gestalt we call *the flow*; the second refers to how much of some „stuff" is flowing past a measuring point per second—this is a numerical measure of a flow. There is a way of making the distinction clearer: we could use the term *strength of flow* of some „stuff" when we refer to *flow* in the second sense, but often we will just use the short term: *the flow* of X...

Current as Strength of flow

There is a different noun that can be used in place of *flow*: this is *current* (note that there is no verb form for this). Again, it can be used in two ways: colloquially as in ocean currents, currents of air, money currents, etc., suggesting the phenomenon of flow; or as the formal concept of *strength of flow*.

Wrong usage of „current" as amount of electricity

Careless use of language in the field of electricity has led to a confusing (and conceptually and imaginatively wrong) way of using the word *current* as amount of electricity, i.e., as a term for some electrical „stuff" that flows (Volume 2). We can read expressions in scientific texts, such as „current flow," i.e., current of current or flow of flow which is obviously meaningless. The situation in German is even worse and more confusing: German speakers use *current* as a substitute for electrical energy. [Linguistically put, *current* is used as a mass noun instead of what it really is: a count noun derived from a (Latin) verb.]

Waterfall as archetype

In Section 3.6, we shall take the step toward quantifying the power of processes by showing how it is calculated in the case of waterfalls. This will serve as the *archetypical* form of how the power of a process is calculated—it will serve us well in the description of other *Forces* and their interactions that produce the many phenomena we encounter in nature and in machines. Let us anticipate the simple result: the power of a waterfall is calculated by determining the product of the current of water and the height of its fall.[4]

Interaction of Forces as a transaction. Let us consider an analogy: maybe we can look at the interaction between two Forces of Nature as an economic transaction. One aspect of such a transaction is the transfer of money from one agent to another. The first brings money to the table, the second receives it—money is *exchanged* (for some goods).[5] The first is powerful in the sense of having and bringing money, the second will become powerful by obtaining it and carrying it away, maybe for a subsequent transaction. So, here, the notion of power—of being powerful—is a quality behind which we recognize a „thing"—money.

So it is in physical interactions. The agent is powerful and will make the patient more powerful as a consequence of interacting. Power is a quality, not really something that is transferred—even though we often say that we give, hand, or transfer power to someone. Physical science actually has a concept for a quantity we imagine being exchanged—this is what is called *energy*. So, to begin the description of the concept of energy (see Section 3.7), we might say that energy is something that an agent brings to an interaction with a patient, hands it over in the interaction and so lets the patient become a powerful agent in turn. We will revisit this image in the following chapters on physical Forces and extend it importantly and imaginatively in Chapter 5.

Energy is exchanged in interactions

3.2 Quantifying Aspects of Wind and Water

After taking a more careful look at extension and intensity of wind, it will be time to create a more formal descriptions of the basic aspects of fluid „stuff," i.e., liquids such as water, oil, and blood, and gases such as air. Fluids are basic and central to our experience of nature. Not only are fluids and their behavior easily experienced, our experience of the phenomena they create provides us with the most basic and important schematic (abstract) elements of imagination and thought (Section 3.8). It is no exaggeration to say that spatial and temporal experience together with that of fluids constitute much of what makes our figurative understanding of the world around us possible (see also Chapter 2 and 4, and Volume 2).

Extension of wind

Remember that wind is an activity whose extension is measured in terms of spatial size. Spatial size is easy to measure in principle—we are dealing here with length or distance, area, and volume—but which spatial extension are we to choose in the case of wind? Should we choose a horizontal area on the ground over which wind blows? After all, at any one moment, wind may blow all the way from the Atlantic across France and Belgium into Germany (Fig.3.5). Or should we choose a line, the front, along which wind is felt?

Extension as spatial size

What makes most sense is to choose what we experience if we try to „catch" wind: we expose ourselves or some objects in such a way that the wind „hits" it perpendicularly. In other words, we choose a vertical surface, like a wall or any real or imagined upright surface, over which wind is active: people, trees, buildings, and windmills experience wind as active on their vertical surfaces if the wind blows horizontally. The extension of wind will then be measured as the surface area over

Extension is area perpendicular to wind which it is active—this may be the sails of a sailing ship or the rotors of a field of wind turbines (Fig.3.6).

Obviously, if we imagine a rectangular vertical surface, it extends along a line on the ground and vertically up to a certain height. If we need to quantify this surface, give a number, we obviously also need a unit to go with it. So, the extension of wind may be said to be so and so many square meters or square kilometers.

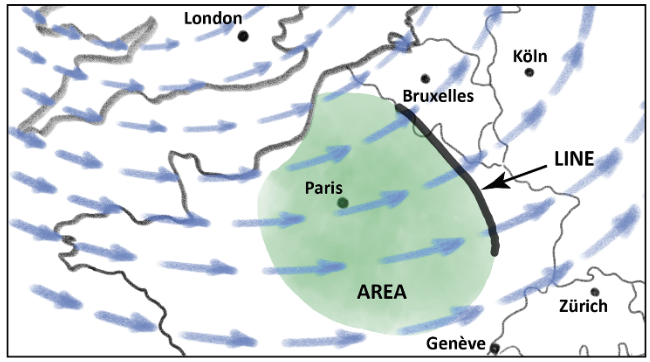


Figure 3.5: *Sketch of a map of a part of Europe showing an example of the flow of Wind represented by arrows. Superimposed we see an arbitrary area on the ground „covered" by wind, plus a line or front of a certain length along which wind is blowing (the line should be chosen so that it is perpendicular to the local direction of wind).*

But what about the fact that a storm may cause damage over a (more or less) horizontal area on the ground over which it moved? Woods may have been flattened and buildings destroyed. Seen from above, the destruction covers an area on the ground. What we see here is simple the result of the flow of wind over an area, something that happens over time; it is the result of the activity of wind which, over time, stretches over an area on the ground.

Figure 3.6: *Exposing sails and blades of wind turbines to the wind. Left: Sailing ship in the Zuiderzee (Holland). Right: A field of wind turbines at the shore of the Zuiderzee.*

Quantifying the intensity of wind

„Quantifying" the intensity of wind qualitatively, i.e., with the help of words instead of measurements and numbers, is what we all do when we make use of our sense of a polarity. The intensity or strength of wind can be felt directly with its impact upon our body which creates in us the sense of the *polarity* windy ↔ wind-still. We use words such as calm, fresh, strong, and stormy in order to describe what we mean (see Fig.3.7, left).

Intensity of wind as vertical scale

If we superimpose our sense of high ↔ low (or up ↔ down) upon the polarity, we can create a vertical scale of intensity or strength of wind with degrees for which we can introduce numbers if we like (see Fig.3.7, right). A scale that introduces numbered degrees is the famous *Beaufort* scale. The scale was created in 1805 by Francis Beaufort when he was a young sailor on a British navy ship. It reflects how intensely wind is seen to affect a ship. It is semi-quantitative in that it does not use our direct sense of intensity of wind; rather, it is created upon the observation of impact of wind upon the sails of a ship or the wave height of the ocean.

Introducing such a vertical scale is typical for qualitative reporting of degrees of intensities such as how warm, sweet, bright, or loud a perception appears to us. Wether or not we use numbers for the „degrees" on such a scale does not really matter. If we do not have an instrument but only our bodily perception, the reporting remains qualitative or semi-quantitative.

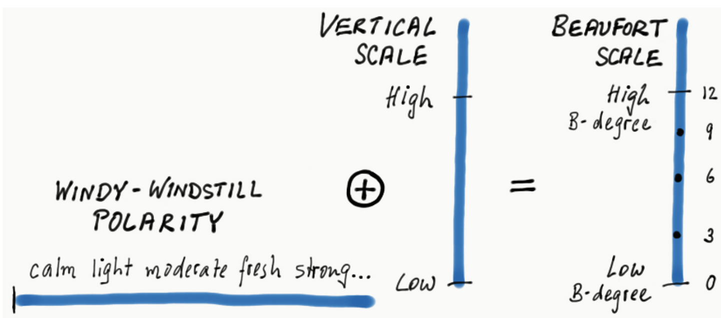


Figure 3.7: *Left: The polarity* windy ↔ neutral *with words marking its range; note that the polarity has a lowest „value" equal to zero or wind-still. Center: A vertical scale from low to high. Right: A semi-quantitative scale, the Beaufort scale, with values denoting degrees of strength of wind (B-degree).*

Later, when wind speeds could be measured, it was possible to relate Beaufort's qualitative classification to actual numbers on a different scale (Fig.3.8). Naturally, doing this is not an objective affair, simply because one of the „measurements" is based upon partly subjective observations. What we see here is based upon some choice so as to get a „clean" relationship that can be represented mathematically—the modern result of this is shown as a graph of *Beaufort* degrees as a function of wind speed on the right in Fig.3.8.

The graph shows something interesting, which we will encounter again when we study how „sweet" sugar water appears to us (see Volume 2): the sensation of „sweetness," i.e., a degree on the „sweetness scale," which spans the polarity of sweet ↔ neutral experienced when drinking sugar water, grows more slowly with added sugar if the water is already sweet: at a high degree of sweetness we have to add a lot of sugar if we want to go up a „degree on the sweetness-scale;" at lower degree of sweetness, less additional sugar is needed. Interestingly, our perception of loudness, heaviness, and brightness follows the same rule. And again, pretty much the same happens here with the felt or observed intensity of wind and its relation to wind speed (see the increasing horizontal distance for each higher degree on the Beaufort scale in the diagram on the right in Fig.3.8).

Wind speed / m/s	Beaufort "Degrees"	Qualitative description
0.5	1	Light air
1.6	2	Light breeze
3.4	3	Gentle breeze
5.5	4	Moderate breeze
8	5	Fresh breeze
10.8	6	Strong breeze
13.9	7	High wind
17.2	8	Fresh gale
20.8	9	Strong gale
24.5	10	Storm
28.5	11	Violent storm
32.7	12	Hurricane force

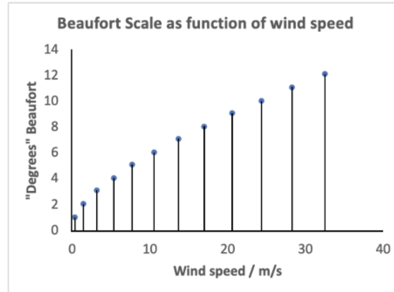


Figure 3.8: *Modern relation between wind speed and the degrees on the Beaufort scale. Note that the perception of the intensity of wind does not grow linearly with wind speed. To „feel" an added degree, the speed must go up more the stronger the wind is.*

Wind as flowing air

All this is quite useful, certainly for practical applications in everyday life—wind- and kite-surfers are quite happy with reporting intensity of wind in the Beaufort scale. However, if we want to study applications in science and engineering, if we are interested in atmospheric science or using wind for powering some of our machinery, we would like to introduce more precisely reproducible forms of quantification.

Extension and intensity of moving air. This approach brings up the modern concept that is not so readily perceived in primary experience—the notion of *air*; remember *shifting from wind to air*, discussed in Sections 2.4 and 2.5. Today, we are accustomed to interpreting wind as moving air. So, if we want to introduce a formal version of the *extension* or size of wind, we turn to the idea of quantity of air flowing toward us or any other object. We choose an *area* facing the wind and ask how much air flows through this area per time (Fig.3.9). If we measure quantity of air by its *volume*, then the flow of air is measured as *volume flow* (telling us how many cubic meters of air flow through the area per second; formally, this is called the *volume current* of air), and this volume flow can be taken as a formal measure of the extension of wind („how much" wind there is).

Quantity of wind as volume flow of air

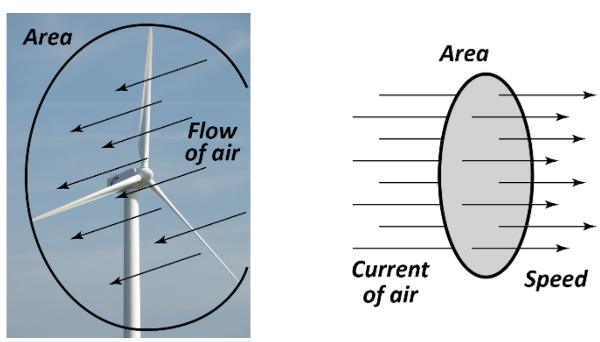


Figure 3.9: *Quantifying both extension and intensity of wind by considering it as a flow of air (left). All we need for doing this is the definition of an area through which air flows and then measuring the speed of flow of the air (right).*

From the foregoing discussion of the Beaufort scale, we already have an idea of what to choose as an easily quantifiable measure of the *intensity* of wind: the *speed of flow of air*. If we accept this choice, we get a direct relationship between extension (volume current of air) and intensity of wind (speed of flow of air):

Speed as intensity

$$\textit{Volume flow of air} = \textit{Area} \text{ multiplied by } \textit{Speed of flow of air} \tag{3.1}$$

In other words, the extension of air flowing equals the product of area and intensity of flow of air. This is a result which should make us stop and think. It looks as if, in order to quantify wind, we only need one independent measure, namely, the speed of air (and, yes, area, but area has nothing to do with air per se). Something is missing here: extension and intensity should definitely be two independent measures of wind, also when we interpret wind as moving air.

This puzzle arises because we have chosen only spatial and temporal measures for both quantities: area (perpendicular to the flow of air) and speed (which combines our experience of spatial extension, i.e., distance, and time). It seems we need a different measure of *amount of air* and therefore also of magnitude of flow of air. The problem is solved if we take what, in everyday life, we call the *weight* of air. In physical science, this is the *mass of air* measured in kilograms.

Mass of air

Wind as Motion

Wind seen from the perspective of Motion as a Force of Nature

The title of this subsection already gives it away: *Wind as moving air*—we obviously can understand *Wind* as a mechanical phenomenon, one that properly belongs to the science of motion (see Volume 2). Introducing *speed* as the measure of intensity of wind shows that the Force to work with is *Motion*: fast ↔ slow is the proper *polarity* of this phenomenon. Moreover, *Wind* interpreted as an example of *Motion* requires us to learn more about the concept of *amount of motion*[6] as the extension of *Motion* as a *Force of Nature*.

We need to take this viewpoint if we want to move toward a quantifying science. The approach underlying our discussion of *Primary Forces of Nature* in Chapter 2, remains qualitative but foundational.

Mass of air is not so easily determined, simply because air is so light. Here, we only sketch what is involved—it takes more work to make everything precise. What we need is knowledge of the *density* of air, which tells us how much of it (in the sense of mass) is in a given volume. Since volume is easy to measure, knowing the density we get the mass of a chosen volume of air:

$$\textit{Mass of air} = \textit{Density} \text{ multiplied by } \textit{Volume of air} \tag{3.2}$$

The density of air changes with temperature and pressure, quantities which again are measured easily, at least in principle (we shall hear a lot more about pressure of air and other fluids in the remainder of this chapter; see the description starting on p.123). Knowing these, we can determine the density of air and therefore the mass of a given volume of air. This, in turn, allows us to calculate the *mass flow* of air, and this is finally the measure of extension of wind which we need:

Mass flow

$$\textit{Mass flow of air} = \textit{Density} \text{ multiplied by } \textit{Volume flow of air} \tag{3.3}$$

We shall see later how the measures of *Wind*—extension (mass flow) and intensity (speed)—are related to what we are often interested in: the *power* of wind driving a windmill or a wind turbine. It is related to (1) how far the speed of the air drops as it flows across a wind turbine (i.e., to the tension) and (2) to the extension, i.e., the *current of mass* of air (but remember the Box on p.121).

Densities

There are different types of density

Density: degree of crowding

The move from *Wind* to air, from activity to some „stuff," has introduced us to the idea of *density*. The simplest way to understand density is developing the image of *crowding* or *packing*: more or fewer people can crowd into a room, more or less of different types of stuff can be packed into a space (if the stuff can be compressed). Obviously, there is a polarity we can describe by crowded ↔ uncrowded or packed ↔ empty, and density is the scale of this polarity.

As a quantitative measure of this „crowding" or „packing," we take how much „stuff" (or whatever else) we have in the space relative to size of that space; in other words, we take the *ratio of amount to volume* of that space.

Mass density

Take *weight* (or, rather, *mass*; see Section 3.3) as the measure of amount such as air; then, the density is the ratio of mass to volume. This is the standard way of using the term *density*, in the sense of *mass density*.

Density as concentration

There are a good number of other types of density. We can dissolve more or less sugar or salt in a volume of water; we can have more or less heat in a given amount of water or a stone of given volume; and we can have more or less of quantity of motion (momentum) in a moving body. The first of these examples—dissolved substances—is described as *concentration*. In other words, a useful new way of looking at the different types of density is calling them by the name of *concentration*. So, *mass density* would be *concentration of mass*, density of heat in a material is *concentration of heat*, and density of dissolved substances is simply *concentration*.

Some typical numbers. Modern offshore wind turbines have blade lengths, and therefore, radii of the area of the turbine, ranging from 50 to 80 m. Let us consider the smaller value and calculate some numbers for wind mass flows. The area covered by a turbine having 50 m blades is about 8000 m^2. The range of wind speeds for which such turbines work properly is roughly between 3-5 m/s and 20-25 m/s (according to Fig.3.8, the high value corresponds to a storm at which point turbines need to be turned off). Since the density of air is, on average, a little above 1.2 kg/m^3, we get mass flow rates for such a turbine ranging from about 30,000 kg/s to 240,000 kg/s.

Wind turbines work most efficiently if they are designed in such a way as to make the wind speed drop by two thirds (and not all the way to zero!). Moreover, they are working best at wind speeds of about 15 m/s (5 m/s behind the turbine). The power of interaction between wind and turbine will then be about 10 MW for the size chosen here. Naturally, the power of the electric process driven by wind will be noticeably smaller, maybe 3-5 MW at optimal wind speed. This would allow us to power some 500,000 LED bulbs or 200 concurrently used car battery charging stations having a power of 20 kW each.

Intensity of *Fluid* in hydraulic phenomena

We have been moving from Wind to Air and will now go on to the FoN called *Fluid*. In this and the next subsection, we shall study what we should accept as measures of *intensity* and *amount* of fluids such as air and water.

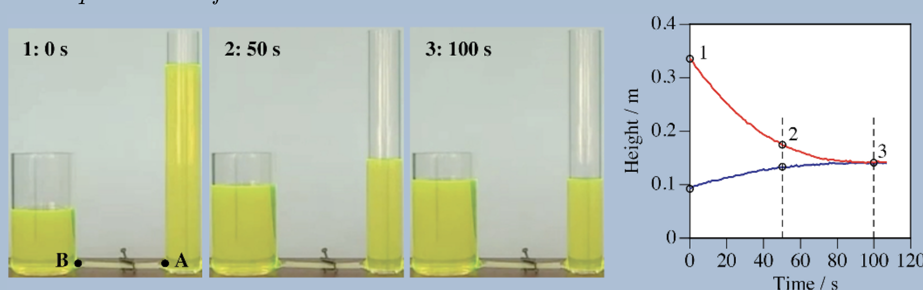
We begin with the search for intensity while keeping in mind that of the many ways these substances can be powerful (see the Box on p.91) we are interested only in the one we experience as hydraulic. This still can leave at least three measures on the table: those related to tense/stressed ↔ relaxed, high ↔ low, and fast ↔ slow. We reject the last of these since it lets *Motion* arise as a *Force of Nature*. This leaves the first and the second. Since they are strongly related, especially in our experience of water, we need to make clear which one it is that belongs to *Fluid* as a *Force of Nature*.

Height does not express the intensity of fluids. When we first recognized Water as a a *hydraulic agent* (Section 2.4), we accepted high ↔ low as the generating polarity. However, as we have said before in Chapter 2 (see Table 2.2 and Section 2.4), high ↔ low should be understood as the generator of the *Force of Nature* we call *Gravity*. Therefore, we need to look elsewhere for the defining polarity for *Fluids* such as *Water* and *Air*.

Equilibration

Equilibration happens for intensities—not amounts

The example of communicating balloons presents us with a common and very important phenomenon: intensity typically reaches the same value in elements that communicate after the processes made possible through their being connected have run their course. We say that the intensities have *equilibrated* or that *equilibrium of intensities* has been established.



In the photographs and the diagram of the figure above we can see very clearly that water levels (interpreted as intensities) and not amounts of water, equilibrate if we connect two water tanks having different cross section.

A few examples might convince us that height above the surface of the Earth does not work as intensity of *Fluid*. In our body, it is not gravity that drives blood flow, even though gravity may very well be involved if we are standing upright. We know that the heart takes the function of driving the flow. It serves as a *pump that raises the pressure of the blood* so it can be forced through arteries, capillaries, and veins. If we are lying horizontally, we can accept the role of pressure as the intensive quantity in blood-flow quite easily (see the Box on p.124).

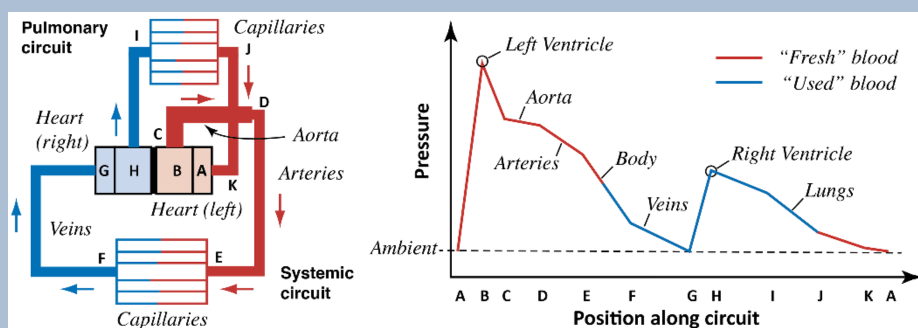
Pumps raise the pressure of fluids

The same role is played by water pumps for irrigation if water source and fields lie (at roughly) the same height. Imagine a long horizontal pipe carrying water from source to fields. If we did not have a pump, the water would simply lie there in the pipe without moving. To make the water flow in a sustained manner, the pump will need to set up a pressure difference simply to overcome fluid friction. A fluid sticks to the wall of a pipe, and different elements of the fluid stick to other elements—this is what makes fluids more or less *viscous* (honey much more so than olive oil, and olive oil much more so than water).

Blood circulation

Our blood circulatory system: A hydraulic perspective

In mammals such as us humans, blood flows in a closed circuit consisting of different types of „pipes" with two „pumps" built in (figure on the left). The pumps are needed for raising the pressure of the blood; as the blood flows through the different „pipes," its pressure gradually goes down (diagram on the right).



We can begin the description of the flow of blood in the atrium of the left part of the heart (point A in the figure on the right). There, the pressure of the fluid is roughly as low as that in the body exposed to ambient air (in other words, it is roughly 1 bar). The blood is let into the left ventricle of the heart (B), and there, its pressure is raised to its highest point in the body (in an adult human, that would be a little less than 1.2 bar).

When the pressure at B is higher than in the aorta (C), the blood flows into and through the aorta—along the way, the pressure goes down somewhat. It continues to go down as the blood flows through arteries and then smaller and smaller vessels to the capillaries of every part of the body (D-E). After it has reached these parts, it is collected again in the veins (F), still flowing from points of higher to points of lower pressure.

The fluid reaches the atrium of the right part of the heart (G) at low ambient pressure. The right ventricle of the heart (H) raises the pressure once again, not quite as high as in the left ventricle, though. From there, the blood flows through the lungs and back to the left atrium. Along the path from H to A, the pressure drops back to the ambient value.

As a third example, we take two possibly different balloons and connect them with the help of a short pipe (with a valve built in). We blow up the first of the balloons as much as we can and the second one only a little bit (see Fig.3.10). In this example of communicating balloons it is equally clear that vertical level does not play a role. When we open the valve in the pipe, the air flows effectively along a horizontal from the balloon where the pressure is higher to the balloon where the pressure is lower (see the data of pressure of the air inside the balloons taken during the experiment in the diagram on the right of Fig.3.10); it does so until the pressure is the same in both—we say that the pressure of the air has *equilibrated*. Balloons teach us in a physically accessible manner what might be meant by the term pressure—the air is under pressure because of the taut rubber membrane of the balloon that keeps the air compressed.

Equilibrating pressure

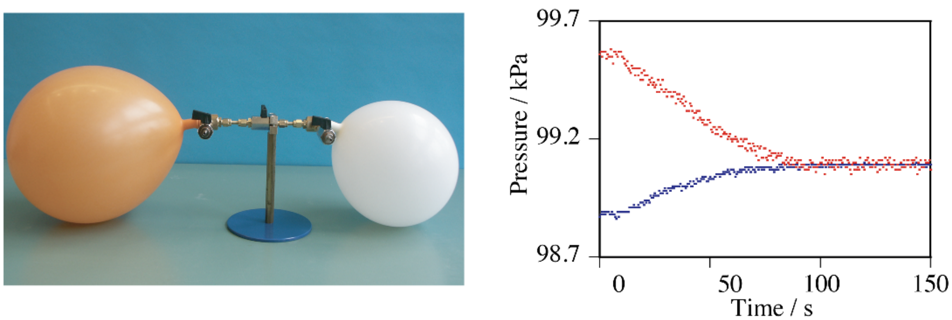


Figure 3.10: *Left: Two communicating balloons. Right: Pressure of air (which, in this example, has nothing to do with vertical level) equilibrates: after opening the valve in the pipe between the balloons, air flows as long as there is a pressure difference.*

Experiencing pressure. It is becoming clear now that *pressure* is the notion we need to understand as the proper measure of *fluid intensity*. We know physical pressure from touch and being touched. The experience forms a *polarity* which we express through strong ↔ weak or hard ↔ soft—we press hard, and we are touched softly. In the case of fluids, there is a certain difficulty, though, because fluids such as air often surround us completely. We are not really aware of the pressure of the air upon us, and if it changes, we do not necessarily notice the effect. If we dive in a lake or ascend or descend in an airplane, we may feel this as a strange sensation in our ears but we can adjust to the new situation (to higher or lower pressure) quite quickly and then are left with no direct sense of the pressure of either water or air upon our body.

Therefore, the phenomenology of pressure needs to be explored with some care. The examples of blowing up toy balloons, feeling the growing strength of the air wanting to get out of the balloon, feeling the growing tension in our lungs when blowing, and imaginatively putting ourselves „in the shoes" of the air inside are still some of the most direct forms of experience we may have of pressure related to fluids (Fig.3.11). We may also let go of a toy balloon we just blew up and observe it careening through the air; alternatively, we do this with a toy balloon car—the car is driven across the floor by the air being pressed out of the balloon; we credit the observed motion to the air being violently pressed out of the balloon (Fig.3.11, center).

Feeling pressure in toy balloons

We could also fill such a balloon with water, grab it with both hands and force the water out of the balloon by compressing it quickly and strongly. This is basically what the muscle of our heart does with blood (see the description of the blood circulatory system in the Box on p.124). Alternatively, we can call upon experience with water spraying from garden hoses (Fig.3.11, right); a pump or whatever may be used to make the water flow in our garden or household will establish a pressure difference that lets water shoot out of hoses and faucets.

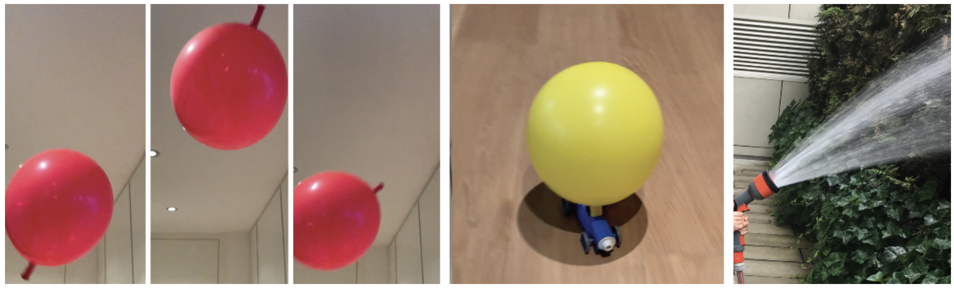


Figure 3.11: *Left: A toy balloon careening through the air (as it loses its air). Center: A toy balloon drives a toy car across the floor. Right: Water is forced out of a garden hose by the pressure established by a pump.*

Bounded polarity, bounded scale

There is a lowest value for pressure. There is something quite remarkable about our experience of pressure: the *polarity* of stressed ↔ relaxed or, rather, the *scale* associated with it, is *bounded* on one side. It is clear that the pressure can go to zero but not below—lower than „completely relaxed" on the scale spanned by the polarity does not make sense. We can imagine taking more and more air out of a vessel and so lowering the pressure of the remaining fluid more and more. In the end, if there is no air left, we should expect the pressure to have approached a value of zero.

On the other hand, if we go in the other direction, it is not clear if there is a limit to the degree of being stressed. If we think that the pressure of water in the deepest oceans must be incredibly high (namely, 1000 times as high as the pressure of our atmosphere at sea level), we can go to the center of the Earth where it is about 3000 times higher still. And at the center of the Sun, the pressure will be higher by another factor of almost 100,000, and that's not the place in the universe with the highest pressure imaginable.

Absolute zero value of pressure

In physics, we say that *pressure* is a scale that has an *absolute zero point*, it cannot go lower. On the other side of the polarity, it is not clear how high pressure can go—certainly very high if we believe the models created by astronomers of very exotic places in the universe.

Pressure of air at sea level. We are immersed in a sea of air, and we do not feel this, unless it changes. There are people sensitive to such changes, especially in some areas where warm, dry winds coming over mountains can noticeably affect their well-being. However, this experience is not interpreted as one of air pressure—we are quite insensitive to the pressure of a fluid surrounding us completely. In underwater habitats located several tens of meters below the surface of an ocean, the pressure of the air for the researchers living there is the same as that of the water outside. For every ten meters, the pressure rises by one *atmosphere*—the pressure of the air measured in the atmosphere at sea level. The people working in such a habitat do not notice the strongly raised pressure, at least not once they get acclimatized.

Pressure unit

Still, the pressure of the air surrounding us is not zero. It is roughly 100,000 standard units (called Pascal, abbreviated by Pa) at sea level. It is true that this value changes a little (maybe by as much as a few percent) as weather changes, but the 100,000 Pa have been taken as a standard and given its own unit called bar: 1 bar = 100,000 Pa (see p.159). Inside a very strong hurricane, the pressure of the air may be as low as 0.92 bar. For comparison, if the pressure of air is 1 bar at sea level, it will be 0.92 bar at about 700 m above sea level (Fig.3.21).

Since our life plays out in this sea of air, differences of values of pressure relative to surrounding air pressure are of more concern in everyday and technical situations and applications. To give an important example, the pressure inside our body is pretty much the same as that of the surrounding air—values relating to surroundings are usually called *ambient values*.

Ambient pressure

Bounded and unbounded scales

Bounded and unbounded polarities and scales

The pressure polarity is by no means the only one that is bounded on one side—meaning we would assign a value of zero to the degrees on a scale associated with such a polarity. *Brightness* and *loudness* appear to be other examples; *windiness* (as in windy ↔ wind-still), *raininess* (as in rainy ↔ dry), *saltiness*, and *humidity* come to mind. An important example in this class is *hotness* (as in hot ↔ cold), which we shall learn about in some detail in Chapter 4.

We know unbounded polarities from social and psychological phenomena; good ↔ bad and just ↔ unjust are examples of this kind. If some situation is very bad, we can certainly imagine one that is worse, and the same would hold for very good and still better. Interestingly, there are four important *unbounded intensity scales* in physical science as well: gravitational potential for *Gravity*, electric potential for *Electricity*, and velocity and rotational velocity for linear and rotational *Motion*, respectively.

Unbounded scales in physical phenomena

When we are told during a health check that our upper and lower values of blood pressure are 120 mmHg and 80 mmHg, respectively, this is the pressure above ambient pressure, i.e., *relative* to ambient. The unit for pressure abbreviated by mmHg is called *millimeter mercury column*. The relation with standard units is this: 1 mmHg = 133 Pa = 0.00133 bar. This means that the relative pressure of blood in the aorta—i.e., its tension relative to ambient outside the aorta—changes rhythmically from 0.11 bar to 0.16 bar, and it does so roughly once to twice a second. The aorta, by the way, is near where blood pressure is measured (remember what we said about our blood flow system above).

In technical applications, it is quite standard to refer pressure to ambient, meaning that we report *excess pressure* or *underpressure* depending upon the pressure of a fluid being above or below the value of ambient pressure. Underpressure is *negative pressure measured relative to ambient pressure.* This means that it is quite normal to work with negative values of pressure if it is clear that they are reported relative to some arbitrarily chosen value such as ambient pressure.

Excess pressure

Negative pressure

We shall have quite a bit more to say about fluid intensity, i.e., pressure later in this chapter (Section 3.4). The fluids of interest to us—such as the air of our atmosphere or water in vertical tanks and in artificial lakes in the mountains—often interact with gravity. which leads to change of pressure in the vertical direction. Among many other things, liquids can be used for building simple pressure measuring devices (see Fig.3.20); the now old-fashioned mercury blood pressure gauge at doctors' offices make use of this effect.

Intensity and tension

What matters—intensity or its difference (tension)?

Intensity is one of the three basic characteristics of any Force of Nature. From this concept, we can derive the idea of *difference of intensity*, which we have associated with our embodied knowledge of *tension*. But, we may ask: Is tension really a derived quantity rather than a primary one? Shouldn't we derive the notion of intensity from tension?

The answer depends upon what polarity we consider. If the polarity—or, rather, the scale introduced with it—is one-sided, i.e., if it has an *absolute zero point* as is the case with pressure, temperature (Chapter 4), and chemical potential (Volume 2), we should prefer to say that intensity (i.e., potential) is primary. It matters for air at what *absolute pressure* it is at a given moment, and the same is true of the absolute temperature of a material or the chemical potential of a chemical substance.

Still, even in these cases, tensions have a central role to play: power of a process and spontaneous („downhill") flow, to name just two important examples, depend upon differences of potentials at two points.

If, however, the intensity is „open-ended" at both poles of a polarity such as in phenomena of *Gravity* (Section 3.3), *Electricity*, and *Motion*, all that matters are tensions, i.e., differences of intensities. There are no absolute zero points of the scales of gravitational potential, electric potential, and velocity. Therefore, a value of potential is irrelevant for the state of a system—we arbitrarily assign zero levels; therefore, values associated with a potential at a point are meaningless by themselves.

Storage and flow of water—The concept of amount of fluid

Fluid storage

Water and air, and all the other fluids, can be *stored*, i.e., contained, in storage elements, and they can flow into and out of elements and through conduits. These phenomena raise the question of how much fluid is involved in a concrete situation or process. In other words, we need to decide upon a measure of *amount of fluid* if we want to make progress in our understanding of hydraulic processes.

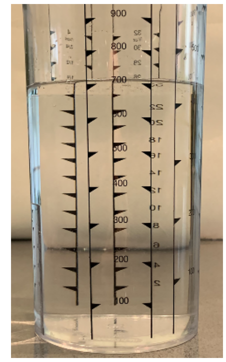
Amount of fluid

There are different ways one can specify amount of water (or amount of fluid in general), which reflect the different abstract (in the sense of schematic) characters water as a material substance presents to us. Water can appear as a hydraulic, gravitational, or chemical agent (as discussed in Section 2.4), and each provides us with a different measure of amount: *volume* for hydraulic phenomena, *gravitational charge* for gravity (gravitational *mass*, see below in Section 3.3), and *amount of substance* for chemical processes (Volume 2).

Volume, mass, and amount of substance

Volume of fluid. Volume of fluid—especially in the case of water—is an easy measure to obtain and grasp, and what is meant by it is visually accessible—we can see volumes of water! This is quite important conceptually because it presents us with an example of a physically accessible image of *amount of a fluidlike quantity*. Most fluidlike quantities in physical science are invisible; this is the case of electric charge, amount of heat (caloric), momentum, and spin (angular momentum). In those cases, we put a heavy burden on the activity of imagining—it is the only way our mind can create the concepts of amounts of those quantities.

We might add mass and amount of chemical substance to the list of invisibles, even though they are accessible to physical experience, but only indirectly. We access gravitational mass through weight, and amount of substance through weight (mass) and accounting for weight in chemical reactions.



Amount of substance presents us with an intricate story. If there was only a single chemical substance in the world, it would be easy: we could use the indirect measures via volume or mass to quantify amount of substance. If the substance were salt, we could call a handful of it one unit of amount of substance, and two handfuls two units, and so on. However, there are countless chemical substances, and to find the amount of substance for each requires us to study their activities in chemical processes; only then can we relate amount of substance of a new chemical to that of already known substances (see Volume 2).

Volume, mass, and amount of substance

Converting measures of amount

The three measures of amount of fluid—volume, (gravitational) mass, and amount of substance—can be converted into one another if needed. Volume and mass are related by what is called density:

$$Mass = Density \cdot Volume$$

Different types of density

Since this makes density equal to mass per volume, the „common" density is mass density. Since there are many different measures of density—such as density of amount of heat (density of caloric), density of electric charge, density of amount of substance, etc.—it is important to be clear which density we are speaking about. Since the standard units of mass and volume are kg and m^3, respectively, the standard unit of mass density is kg/m^3 (on units, see p.159).

Unit of density

Molar mass

Then, there is a common relation between mass and amount of substance, which introduces the concept of molar mass (Volume 2):

$$Mass = Molar\,mass \cdot Amount\,of\,substance$$

Speaking casually, we can say that the molar mass (of well defined chemical compounds and their mixtures) tells us how much a unit chemical amount of substance weighs. The standard unit of amount of substance is mol; therefore, the unit of molar mass is kg/mol.

Current of volume of fluid. Fluids can flow—this is their main activity, hydraulically speaking, i.e., if we look at fluids as *hydraulic Forces of Nature*. It is important, therefore, that we introduce the idea, and the measure, of a flow of amount of fluid. Technically speaking, since amount is measured as volume, we need an understanding of what is called *volume current*.

Transport by constant current

As we know from everyday experience—in the household, our work environment, and nature—currents of water can be weak or strong. This can be a trickle from a faucet, the strong flow from a firehose, or the roar from a giant waterfall. If we know the strength of a current, we can calculate how much water flows past a point over the course of a period of time. If the current is *steady* (i.e., *constant*), we simply multiply the strength of the current by the length of time it flows:

$$\textit{Transported amount} = \textit{Current} * \textit{Period of time} \tag{3.4}$$

Integrating a variable current

Summing a current over time. If the current is *variable*, the procedure of calculating the transported amount is more cumbersome. In mathematics, the procedure is called *integrating the current over time.* If we work graphically, we can obtain the answer by figuring out the area under the current plotted as a curve in a current-time diagram. However, there is an extremely simple physical way of doing this (Fig.3.12): we hold a container under a variable flow and wait for the prescribed period of time; the amount of water collected is simply the amount that was transported by the particular current. The assembly of a container with a single flow into it can be called an *integrator of the current.*

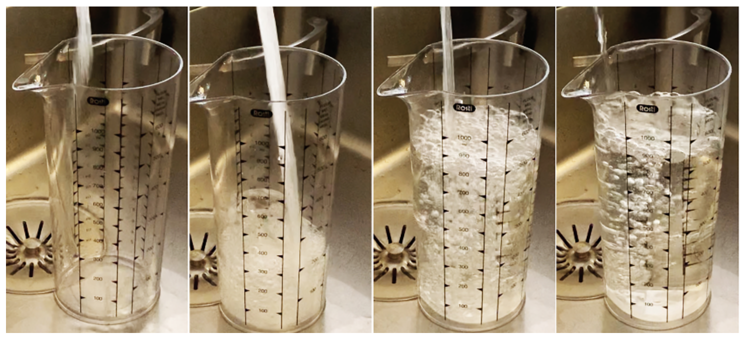


Figure 3.12: *Letting a variable water current flow into a container. The container collects the water and so acts as an integrator of the current.*

We can use the procedure of collecting water for determining a changing current as well (see the Box on p.131). What we need to do in this case is to record the amount of water collected over the course of time—we need to see how the amount grows as time passes. We can then choose a short time interval and read how much water has been added to the container from the change of level of water. If we divide this small added amount by the short time span it took to be added, we get the average value of the strength of the current for the chosen period. We repeat this for many time intervals and so obtain information about how the current changes over time. What we do here is the inverse operation of integrating a current; it is called *differentiation* or *taking the derivative* of the information given by the volume of fluid as a function of time. This is the procedure used for measuring the intensity of rain as a function of time.

Inverse operation: differentiation

Some typical numbers for fluid flows. We already reported some values of (mass) flows of air toward a large wind turbine. To get a feeling for typical flows in liquid flow systems, let us collect some information. If we fill a one-liter container from the faucet in the kitchen in 5 seconds, we have a (volume) flow of 0.2 L/s (liters per second) or 12 L/min (liters per minute). The typical average blood flow in a resting adult human will be around 6 L/min, and the maximum output of the left ventricle into the aorta will be about 600 mL/s (milli-liters per second).

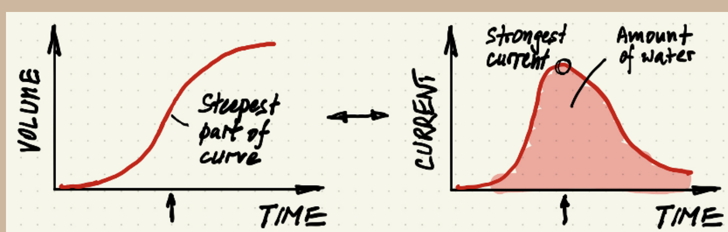
In what is called heavy rain, we get between 1 and 5 cm of rain per hour; this translates as follows: for one square meter of ground, we get between 10 L/h and 50 L/h, and for a stretch of land measuring one square kilometer the flow of rain is 10-50 million liters per hour (or roughly 3000 to 15000 L/s). Globally, rainfall has an average strength of about 16 million cubic meters per second.

In the hydroelectric power plant of Nendaz in Switzerland, rated at 400 MW electric power, the flow of water from the lake 1000 m above the power station is about 45 m^3/s (or 45,000 kg/s). The volume flow of the Mississippi River into the Gulf of Mexico is roughly equal to 17,000 m^3/s. The mass flow of the light streaming from the surface of our Sun is about $4.2 \cdot 10^9$ kg/s (4.2 billion kg/s; light—a non-material fluid—is „heavy," therefore, we can calculate the mass of light from Einstein's $E = mc^2$).[7]

From speed of rise of volume to current

Determining flow from change of volume of fluid

Here is an example of how the strength of flow of water can be measured. Take a graduated cylinder (a glass cylinder having markings for volume of liquid poured into it) and let water flow into it with an unknown strength of flow—this may be from a faucet whose valve setting you change in the course of time. The level has to be recorded as a function of time and the numbers have to be entered into a *Volume-Time* diagram. The resulting curve might look like the one on the left in the figure below.



The flow or current of water is obtained as follows. Qualitatively, it is clear that the water level and/or volume of water in the graduated cylinder rises fast when the flow is strong and slowly when the flow is weak. So, we need to determine how fast the curve in the diagram rises at different points.

This is done by zooming into the curve at a chosen point and—imagining standing at that point—determining its direction in the diagram. The direction so determined is the slope of the line which tells us how fast the curve is rising (or falling). The idea is analogous to going along a winding road and determining its direction at every possible point.

The results tell us how strong the current is at a given moment. The numbers are then transferred into the *Current-Time* diagram on the right.

Amount and flow of fluids, and hydraulic tension

Now that we have become acquainted with amount, flow, and tension of the Force we call *Fluid*, we can ask how these measures are related—it is clear that they must be related in a given case. First, if we put more air in a balloon or more water in a tank, the pressure difference between the fluid and the environment goes up (see Section 3.4 for a more detailed investigation of this phenomenon); second, if we have a greater tension, there will be a stronger flow (if we do not prevent the flow by enclosing the fluid in sealed containers or setting up other barriers such as water dams). We are interested here in the second phenomenon.

Take a closer look at the results of the observations reported in Fig.3.10 (for air flowing from one balloon into another) and in the Box on p.123 (for water flowing from one tank into another). The temporal patterns—the run of pressure and level as functions of time—suggest what we just said: the higher the fluid tension, the stronger the current of fluid. The example of the flow of water in a system composed of communicating tanks is quite revealing. We see that the water levels change faster when the level difference is higher. The level difference stands for hydraulic tension, whereas the speed of change of levels suggests the strength of flow of water through the pipe—and it is clear that the higher the tension, the stronger the flow. Indeed, when the tension has vanished, the flow has stopped (on relations between tension and flow, see Section 3.5).

Tension-Flow relation

Flows are caused by tensions, and they are related to them

Experiencing directly that flows of water and air need tensions, i.e., pressure differences, and that higher tensions create stronger flows, is fundamentally important—it represents the archetypical case of flow-tension relations. We shall encounter other cases of tension-flow relations in totally different phenomena such as *Heat*, *Electricity*, and *Substances* (see Chapter 4 and Volume 2).

Given a certain pressure difference, it is by no means certain that a flow of water or air will always be the same. Quite the contrary: the strength of flow, i.e., the current of water or of air established with a certain tension will depend strongly upon circumstances. Take the pipe connecting the two tanks in the photograph on p.123: this pipe can let the water flow more or less easily or, put in inverse but equivalent terms, it can resist the flow more or less strongly.

Conductance & Resistance

This has led to the formulation of the concepts of *conductance*—as the measure of *how easy* it is for a fluid to flow—or *resistance*—as the measure of *how hard* it is for a fluid to flow, given a certain tension. For a given pressure difference, the flow will be stronger for greater conductance and weaker for greater resistance.

3.3 Water and Gravity Interacting

Water is primary in our experience, and it confronts us with a great many qualities. We have listed a number of such qualities in Section 2.4 (in the Box on p.91). Each of these hints at a different *Force of Nature* making itself felt through a substance such as water. In this section, we want to investigate what it means for water to be *heavy*. Expressed simply, apart from being a chemical substance and a hydraulic fluid, water is a mediator of *Gravity*[8] as a *Force of Nature*, which can be studied by considering how it interacts with fluids.

Gravity as a Force of Nature

Before we clarify the character of *Gravity*, we shall have a look at our sense of heavy and light—interestingly, it can muddle our sense of what this new *Force of Nature* is all about.

Experiencing things as heavy or light

We have used the term *Gravity* quite a few times already, dropping the name here and there, but we never stopped and thought about it. We acted as if everyone surely knew what was meant by it. It turns out, however, that recognizing *Gravity* as a *Force of Nature* takes more than direct perception; it takes quite a bit of talking and thinking about it imaginatively.

Light ↔ heavy

This may strike us as strange since gravity makes things heavy and we perceive the polarity heavy ↔ light very directly and easily. A name for this polarity could be *heaviness*.[9] Things in the world around us are heavy—very heavy or not so heavy or quite light. And *heaviness* makes them fall. However, flames and balloons rising in the air, and styrofoam balls falling more slowly than equally sized steel balls, muddle an apparently simple question—how heavy is a particular object? To make things worse, a ball made of wood can be said to be heavy—it falls in air—but it rises if submerge in water (Fig.3.13).

Heaviness

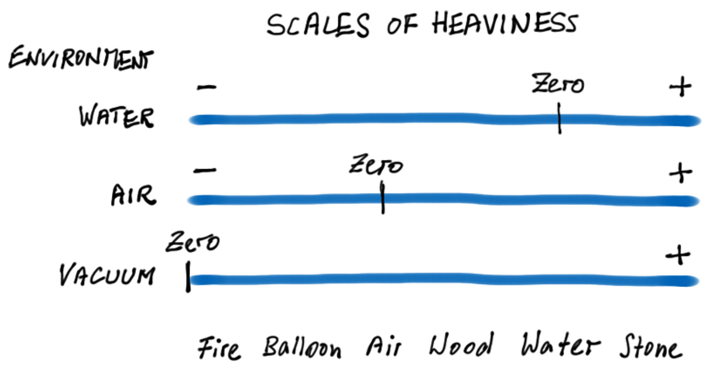


Figure 3.13: *Scales of perceived heaviness appear to be relative to the environment bodies or materials are in. A value of zero indicates that the material floats in its environment. For positive values, a body sinks, for negative ones it rises.*

Relative degrees of heaviness

So, maybe, *degrees of heaviness*, i.e., values on the scale characterizing the heavy ↔ light polarity, are *relative*—relative to the environment we find ourselves in (see Fig.3.13). We could introduce scales that give us degrees of heaviness that allow for both positive and negative values, where the value of zero is different for air and water as environments. Objects with positive degrees of heaviness would fall, those with negative values would rise, and those with a value equal to zero would float. By the way, this raises the interesting question if the heaviness scale would have no negative values if there were no environment such as air or water in which objects would fall or rise (which, by the way, would make all objects fall!). No environment—no fluid such as air or water in which things exist here on Earth—would be what we call *vacuum*.[10]

Flames and balloons

Flames and helium balloons have a negative value on the scale created for air, and balls made of wood or steel will have a positive heaviness (Fig.3.13). On the scale appropriate for water, wood has a negative value whereas steel balls have a positive value. But what about ships made of steel? Their degree of heaviness is negative on the scale for water, which is not easy to square with our sense of what is meant by heavy or light! It seems the phenomena having to do with weight and our sense of heaviness are not understood as easily as we might have wished.

Falling and rising

We shall take a first brief look at falling, floating, and rising things, and give a first answer to what might be behind these appearances, when we have a better grasp of gravity and fluids and their interaction. This will also lead to a better understanding of how our everyday sense of heaviness refers to a couple of different aspects of substances (see below on p.160). Moreover, since the phenomena described here are often said to belong to the realm of *Motion*, we shall take up this challenge once more from a complementary perspective in Volume 2.

Falling, floating, and rising. . .

What would children say about falling, floating, and rising objects?

The reader probably knows the formal answer to what it is that lets objects fall, float, or rise—if the weight of the displaced fluid is less than the weight of the object displacing the fluid, the object will fall (if it is not suspended or supported in some other way); if the weights are equal, the object will float, and if the weight of the displaced fluid is greater, the object will rise.

The description of the phenomenon of heaviness raises a few interesting questions for practitioners of primary education. Should we introduce children to the polarity heavy ↔ light with its seeming paradoxes? Given that the paradoxes are traditionally resolved in a theory of motion, should we aim at using „proper physics" and especially mechanics from the start? How old should children be for this start? And, after all, what would be the Force of Nature associated with the polarity heavy ↔ light?

Buoyancy

On p.160, we can see how the phenomenon—which is called *buoyancy*—can be explained from the viewpoint of the interaction of fluids and gravity.

Experiencing gravity

Heavy ↔ light polarity is not directly useful

It turns out that the question of heaviness or weight is not the right place to start our inquiry into *Gravity*. Differences of *heaviness* (i.e., the difference of weight of different bodies) is not the tension we need in order to recognize the role of *Gravity* and its interaction with other Forces. For a proper tension, we need *a difference of a gravitational quality in the same body* in analogy to when the same stone can be warmer or colder, faster or slower, etc.

Waterfalls and polarities for gravity. Waterfalls (Fig.3.1, right) are a good place to look for a new polarity—they are archetypes of gravitational phenomena, they demonstrate what *Gravity* is all about. After all, it is gravity that makes water flow from a high to low place.

Sense of gravity is related to up ↔ down or to high ↔ low

We see now where this is going. *Gravity* is what gives us a sense of *high* and *low*; *without Gravity there would be no up or down*! Indeed, we could turn the tables and say that our sense of *Gravity* may well arise in our direct and ubiquitous experience of *up* and *down*, *high* and *low*, i.e., of *verticality*. So, the polarity, or the polarities, we are looking for could be up ↔ down and high ↔ low, rather than heavy ↔ light. A name for the new polarities could be *vertical level*.

Vertical level

Gravitational tension

If we accept *verticality* as the generating polarity for our sense of gravity, we can introduce a proper measure of *gravitational tension*: *difference of height* or *level difference* which can be determined rather easily. As always, a difference of intensities is felt as a *tension*.

As we shall shortly see on p.137, this is deceptively easy, too easy indeed. The difference of height measured in meters or whatever unit serves us best is only one of two factors responsible for giving us the proper gravitational tension. We shall see that we also need to know where we are in the universe if we want to quantify intensities of gravity and their differences.

When we used high ↔ low for characterizing intensities of water at the surface of the Earth, specifically when contained in tanks and lakes, we realized that this could not be the end of the story. The same is true for heavy ↔ light for Gravity. Sometimes we have to critically reflect upon experience if we want to create understanding that goes beyond isolated phenomena. As a result of our reflecting we can now say that we have a better understanding of the roles of high ↔ low and tense ↔ relaxed and, additionally, of heavy ↔ light.

Children, gravity, and the sense of up ↔ down

Children's sense of up ↔ down as related to gravity

If up ↔ down or high ↔ low are the proper polarities for generating a sense of gravity, do children understand this? Can they learn to appreciate the importance of the schema of VERTICALITY and how it relates to gravity?

Verticality

It seems this should not bee too difficult if we perform an embodied simulation where we *climb* a staircase, either short or long, and relate the experience to the feeling of getting tired. Together with a qualitative understanding of *effort* as a stand-in for *energy used*, it should become clear that changing one's vertical level is somehow related to an invisible FoN we call *Gravity.*

Effort and energy

Alternatively, sliding down a long and steep hill, maybe in winter on snow—and noticing how steep the hill is—can help us understand the notion of steep or gentle *slope*, i.e., *gravitational gradient.* Visualizing landscapes can be most helpful in this respect (see the map in Fig.2.13, right).

Gravitational gradient

A measure of amount of *Gravity*

A polarity with related intensity and tension is only the first of the three fundamental characteristics of a Force of Nature. The second is a measure of extension which, in the case of gravity, takes the form of *amount of a fluidlike quantity.* The third is power (Section 3.6).

What kind of experience could lead us to *amount of gravity*? Again, let us turn to waterfalls (Fig.3.1, right). If height serves as a measure of tension, surely amount of water falling through this height must somehow be linked to *amount of gravity.* We know that more of the fluidlike quantity of a FoN makes that Force more powerful. More water flowing in a waterfall makes the phenomenon—which is caused by gravity—more powerful. After all, water is heavy.

Meaning of mass

Three meanings of the term „mass"

Stuff massed in an area or volume

The basic or original meaning of mass can be made clear through its everyday use as in a *mass of dirt on the floor*, a *mass of money in my pocket*, or a *mass of people in the stadium*. In other words, *mass* stands for an amount of something that clings together, or large quantities that have a *mass-like* or fluidlike character and are *massed* in a certain space.

This sounds as if we could say *mass of electricity*, *mass of water*, *mass of motion*, *mass of light*, etc. for what we have called amount of electricity, water, motion, or light. However, if we tried to say *mass of mass*, we should realize that the word *mass* is used rather differently in physics.

Gravitational mass

Inertial mass

Actually, there are two distinct uses of *mass* in physics. The first is for how we are using it here: *mass* or *gravitational mass* is the quantity we should call *gravitational charge*, the property of bodies that lets them be heavy (such as at the surface of the Earth). The second is for *inertial mass* which is a measure of how hard it is to accelerate a body (say, by pushing it).

To sum up, mass in physics is an abstract, schematic concept; it should never be confused with the things themselves. But since our mind concentrates so quickly upon matter as that which is real, and all things have the property of mass, we are too often drawn to give the name *mass* to stuff or material or matter.

Simply put, more stuff such as water means a greater amount of gravity. Since „quantity of gravity" is so directly tied to stuff, or material, or „matter," we quickly associate it with amount of matter, amount of something we can see and touch. However, that leads us astray—amount of gravity is as abstract or schematic as amount of electricity which is called *electric charge* (see Chapter 2, p.95, and Volume 2). It would therefore be sensible to call the concept we are trying to establish *gravitational charge*. The meaning is simple: gravitational charge is the property of materials that lets them be heavy, just as electric charge means that which lets things be electric.

Gravitational charge

Mass of a body as gravitational charge

The technical term for the quantity we should call gravitational charge is *gravitational mass* or simply *mass*. It is the *extensive property of things that leads to the phenomenon of gravity*, i.e. it is the fluidlike quantity of *Gravity*.

Since mass lets things be heavy, we should be able to determine the mass of an object through its weight. We can now say more clearly—but still in simple everyday terms—what we mean by weight: it is what a typical kitchen or bathroom scale, or a truck scale at a weigh station measures, when we place whatever it is on it. Assuming that we do not have to deal with the problem of surrounding gases or liquids making the bodies apparently lighter, the idea is simple: twice as much mass (twice the gravitational charge) should be twice as heavy and so show twice the weight. When we buy two kilograms of apples at the market, its gravitational charge is twice that of one kilogram of apples. We call the measure used *weight*, but it actually is what physicists call *mass*.

Weight or mass?

Degrees for amounts

The scale schema applied to amount

We can tell now why there is a problem with the polarity heavy ↔ light: it is related to the *amount of gravity* rather than to its intensity! That's an interesting cognitive phenomenon—degrees, measured along a scale, can be associated with amounts as well. We can see this phenomenon arising in the ubiquitous metaphor MORE IS UP (for which „his mass is low" and „her savings just went up" are examples). Saying „more weight" or „higher weight" is both possible.

Intensity and tension of *Gravity*

Intensity of gravity depends on height

What makes a gravitational situation—which we may consider consisting of a certain body or amount of fluid here on Earth—more or less intense? We have given a first—partial—answer: simply by being higher or less high above the surface of our planet! And obviously, the higher up materials are to be found on Earth, the higher their gravitational intensity will be.

Gravitational intensity is measured, first of all, by height or level above ground (Fig.3.14, left). We might assume, at least for simplicity's sake, that the intensity rises linearly with height above ground, i.e.

$$\textit{Gravitational intensity} \sim \textit{Height above ground.}$$

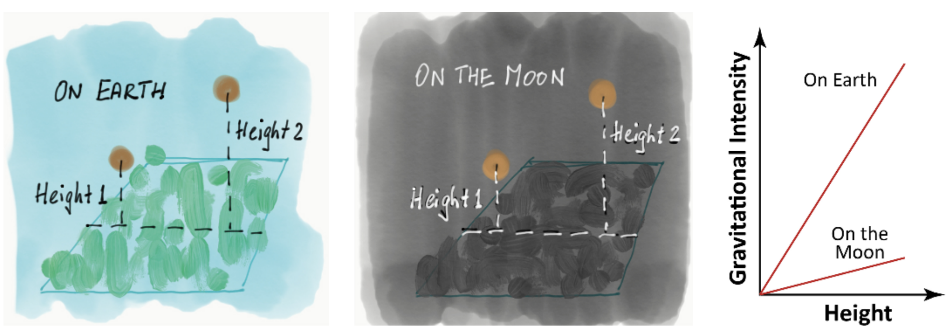


Figure 3.14: *The gravitational intensity of a situation—such as a certain stone at a certain height above ground—depends upon two factors. The first is the height (level) above ground; the second factor depends upon where we are, at the surface of the Earth or on the Moon or somewhere totally different in the universe.*

The symbol $\sim$ denotes proportionality: we are claiming that the intensity is proportional to the level (above ground). This is not unreasonable. It seems that as we climb up vertically, twice the distance will require twice the effort; and climbing 100 m from ground or from already higher up does not make a difference.

But this is not all. If we were to transport a typical everyday situation here on Earth—a certain stone positioned at different heights above ground—directly to the Moon, the gravitational situation would not be the same (Fig.3.14, center). What is different is this: as we climb a certain distance, the change of gravitational intensity will be greater here on Earth than on the Moon. It is simply harder to climb the same distance—or lift a body the same distance—here on Earth than at the surface of the Moon. Put differently, the intensity of gravity rises faster here than on the Moon, and how much faster it rises has to do with how much „stronger" gravity is here than there (gravity is about 6 times stronger here than on the surface of the Moon; Fig.3.14, right).

Intensity vs. strength

Distinguishing between intensity and strength

The terms intensity and strength give rise to different feelings and images. Still, the two are typically related in situations to a degree that it is not easy to distinguish between them. There are many situations when the two can be confused and need to be kept apart through conscious effort: in strong medicine, we have a case of intensity; if we speak of an intense reaction, we actually have a case of a strong (violent) reaction.

If we are careful, we should use the term *intensity* only for the aspect of intensity of a Force (of Nature). As such, it is related to the image of level and the feeling of tension (where tension is measured as difference of two degrees of intensity at two different locations in physical systems).

Strength, on the other hand, can be used for a number of different aspects of physical systems and processes. Flows or currents of fluidlike quantities can be strong or weak, and so can be fields such as the gravitational field (p.138).

Strength of gravity

If we introduce the factor by how much the intensity of gravity goes up as we go up one meter, and call this factor *strength of gravity*, we can write:

$$\begin{aligned} &\textit{Difference of gravitational intensity} = \\ &\quad \textit{Strength of gravity} * \textit{Difference of height above ground}. \end{aligned} \tag{3.5}$$

On Earth, this factor, the strength of gravity, has a value of 10 in standard units; on the moon it is about 1.7 standard units (on units, see p.159).[11] We have to go quite high, maybe a hundred or several hundred kilometers, to notice much of a change of these number for a given astronomical body. If the factor introduced here is constant, we have a simple relation between intensity of gravity and height above ground where we stand:

$$\textit{Gravitational intensity} = \textit{Strength of gravity} * \textit{Height above ground}. \tag{3.6}$$

Gravitational potential

In physics, the *intensity of gravity* is called *gravitational potential*. The term *potential* carries a similar meaning in science as in everyday life—it denotes the feeling we get of a situation where something exists in possibility, but the possibility is dormant or latent; the possible outcome suggested by the situation has not yet been actualized. We shall take a closer look at the notion of potential, which is quite general and important in the sciences, in Chapter 5, Section 5.4.

The gravitational field

When Isaac Newton first proposed a mathematical model of gravity during the second half of the 17th century, he was ridiculed for his assumption that gravity could work directly (and without delay) at great distances without any material mediating its effect. He basically proposed that gravity would exert a *mechanical influence* upon apples falling from a tree and our Moon moving around the Earth alike, and that this influence needed no mediating substance.

No mediating material for gravity

Even here on Earth it is clear that gravity works at a distance. If we assume the Earth to be responsible for heaviness and falling, what makes an apple heavy and lets it fall cannot be caused by the tree or the air surrounding the apple. The Earth does what it does here directly and at whatever short or long distance. So, how does gravity function? Does its influence, and with it its power, simply jump through empty space to whatever object is waiting there to be affected?

Action at a distance

Fields as physical objects. In the course of time, a different answer took shape. Electricity and magnetism seem to have a similar problem—they work directly at a distance as well. In this case, however, after about 1820, Michael Faraday created the image of immaterial—but still physically very real!—entities filling or pervading space; these entities, which Faraday called electric and magnetic *fields*, mediate the effect of electricity and magnetism between material bodies. Later, around 1860, James Clerk Maxwell created a mathematical theory of a unified (combined) *electromagnetic field*. Electric and magnetic influences and power emanating from charged or magnetized bodies travel through this field at the speed of light and so influence other such bodies. The transfer of influence happens in wavelike manner—not unlike waves in water; this is why we speak of *electromagnetic waves*—such as visible light—traveling through the electromagnetic field.

Fields are physically real

The gravitational field. This imagery has been transferred to gravity as well. Through Albert Einstein's work, the idea of a *gravitational field* took complete hold. Objects create this field around them, and the field pervades all of space (actually, in Einstein's General Theory of Relativity, space *is* this field—but let us not try to wrap our minds around this idea, at least not for the moment). In 1916, Einstein showed that in his model of gravity, gravitational influence travels in wavelike manner through the gravitational field at the speed of light. These gravitational waves will show up as, generally, almost undetectable distortions of space (and time). The first time gravitational waves were measured directly here on Earth was in 2015-16—the event detected is said to have originated 1.3 billion years ago when two black holes merged violently and so „bent space out of shape." The ripples of this cataclysmic event travelled through the universe—through the gravitational field—for 1.3 billion years before they arrived here.[12]

Gravitational fields extend through space

In summary, the gravitational field is in some way a physical object (like all other objects), but also different in that it is not like standard matter. It is like all other objects in the universe in that it is extended in space and possesses and transports quantities of motion (momentum and spin; see Volume 2) and energy. As it is invisible, it gives us the impression of Gravity being a ghostlike Force acting directly at a distance, however long or short.

Gravitational fields are physical objects

Visualizing the gravitational field—Potential and strength. We can chart the gravitational field of a body such as Earth with the help of its potential (see Fig.3.15a). Since the distance from the surface of the body creating the field matters for value of the potential, we can visualize the potential of the field almost as if it were a landscape with highs and lows. Naturally, a single body such as the Earth creates a simple „landscape"—a single depression. The closer we are to the Earth, the lower the potential.

Potentials create metaphorical landscapes with highs and lows

An impression of this „depression" can be given if we sketch the values of the potential—which go up as we go up—as a curve whose distance from the dashed center line in Fig.3.15a indicates the numerical measure of the potential. If we do this as a pseudo-three-dimensional sketch, we obtain the picture of something like a funnel, narrow at the bottom and widening as we climb higher.

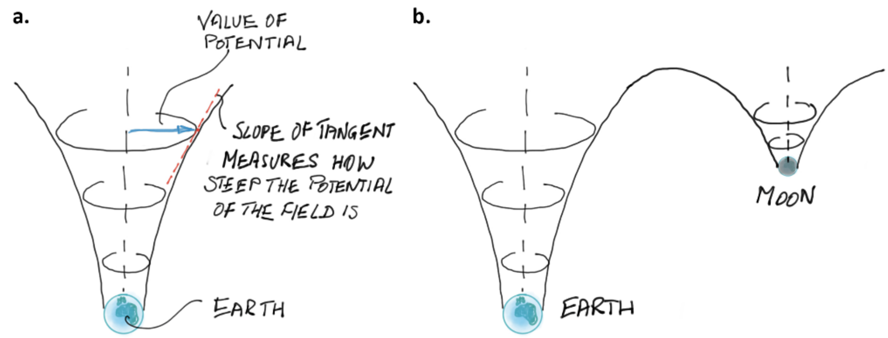


Figure 3.15: *Visualization of the potential of the gravitational field of the Earth (a) and of Earth and Moon combined (b). Plotting the potential as a function of distance from the center of the astronomical body in rotational symmetry creates the image of a „funnel" we could „fall into." The slope of the surface of this funnel (indicated by the red dashed tangent in figure a), measured at an arbitrary point, is equal to the strength of the gravitational field at that point (the steeper, the stronger). This means, among other things, that there is a point between Earth and Moon where the strength of their combined fields equals zero; this is where the combined potential has its maximum value.*

If we are careful not to over-interpret this simple image, we can read a number of useful things from it. The „funnel" is not an object in real space, it is a depiction of the intensity of the field, i.e., the potential, in an abstract space of potential-versus-distance (from the center of the planet). Still, it gives us the correct feeling of a place we could „fall into" and which it would be hard to „climb out of." Furthermore, and this is important both imaginatively and formally, the slope of the curve that measures the values of potential is *indicative of the strength of the field*! In the drawing in Fig.3.15, the curve becomes less steep if we go further from the Earth, telling us that the field is getting weaker—and that makes a lot of sense! (See the box on p.141.)

For a simple case of what this means, and how we can use our feeling for gravity to make sense of this, imagine yourself climbing vertically up from the surface of a planet. How hard this is, depends upon what we call the strength of the gravitational field. If this strength is great, climbing is hard, and this tells us that the gravitational potential should go up fast with every meter we go up. If, in contrast, the field at the surface of the planet—maybe we are on Mars—is weaker, the potential of the field will go up less per vertical meter. This imaginative observation has been used in physics to define the strength of the gravitational field as the measure of how fast (per meter gained) the potential rises as we move up. Remember that such a measure—how fast a quantity changes with distance—has been called a *gradient*, a slope (remember how we introduced this notion in Chapter 2, Fig.2.13). Therefore, *the strength of the gravitational field at a point in space equals the gradient of its potential at that point.*

Strength of gravity equals gradient of gravitational potential

At the surface of the Earth, the gradient—the change per vertical distance—of the potential equals almost precisely 10 J/(kg·m) in standard units (for some units, see Table 3.1).[13] Put differently, the potential rises by 10 standard units for every meter higher up. For our Moon, this value is about 1.7, for Mars it is about 3.7.

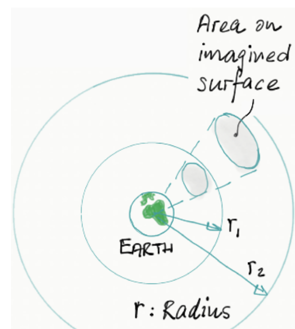
Strength of field at surface of Earth

Note that these values hold at or near the surface of these astronomical bodies. The farther we go from the (surface of the) astronomical body, the weaker the field becomes, which means that the potential rises more slowly as we go farther up and away. It turns out that the strength of the field decreases by a factor of four if we move to a distance of two times the radius of the body from its center (where we are one radius up from the surface). If we move up to where satellites are in geostationary orbit[14] around the Earth, which is about 6.6 Earth radii from the center of Earth, the strength of the field is only $1/43$ of that at the surface.

The gravitational field of spherically symmetric bodies

Strength of gravitational field

Around the time of Newton, some researchers suggested that the strength of gravity should diminish as the inverse square with distance from the center of the Earth—and, presumably also of other astronomical bodies such as Moon, Sun and the planets. This idea derived from an image of Gravity as a kind of Force „emanating" from these bodies almost like a fluid, maybe like light. Kepler created such an image when he assumed that the Sun was not simply the geometrical center of our solar system but actually the mover of the planets.



So, if we imagined some „stuff," maybe in analogy to light, emanating from the Earth, and if the amount of this stuff stayed constant, it would have to spread over larger and larger areas as it flows away from the Earth. In fact, the same „amount" would have to flow through increasingly large imagined surfaces whose areas grow as the square of their radii (i.e., the distances from the center of the Earth). This is why the density of this imagined flow (the amount flowing divided by the surface area) diminishes as the square of the distance from the center of the Earth:

$$Densityofflow \sim 1/r^2$$

In physics, type of flow is actually called flux (here: gravitational flux), and the flux density is defined as the strength of the gravitational field. Using the word flux means that, in physics, we follow the images that were created long ago before a mathematical form of all of this existed. Newton took this idea and showed in his mathematical model of motion that this assumption led to the proper form of planetary motion (he so derived Kepler's laws; see Volume 2). Moreover, he proved that the strength of the field of a spherically symmetric distribution of matter was the same as that of a point with all the matter concentrated in it.

Imaginings in physical science

The strength of the gravitational field will decrease as the square of the distance from the center of an astronomical body if the value of the gravitational potential is assumed to decrease inversely with distance:[15]

$$Gravitationalpotential \sim 1/r$$

This is the form of the potential as a function of distance we have sketched in Fig.3.15.

So far, we may have created the impression that astronomical objects—large bodies such as Earth or Moon—create a gravitational field to which all other smaller objects (apples, people, and astronauts) are passively subjected. This is not the

Every object creates its field

case. Every single body, every collection of physical stuff (and that includes fields as well!) produces a gravitational field. So, two apples hanging on their tree each have a gravitational field, and as a consequence of this, they attract each other—if alone in the universe and left to themselves, they would fall towards each other.

If this is true for two apples, it must be true for Earth and Moon as well (see Fig.3.15b). Each of these bodies has—creates—its gravitational field, and these fields overlap, producing values of potential indicated in the drawing on the right in Fig.3.15. As a consequence, they fall towards each other. Fortunately, both move just fast enough in a direction perpendicular to the line joining them, and so they „fall around each other," keeping their distance as they revolve around their common center of mass.

Gravitational potential is relative

No zero level for gravitational potential

Gravitational potential is relative. This means there is no absolute value of gravitational potential—only differences of gravitational potential, i.e., gravitational tensions, matter. A zero point is always chosen arbitrarily.

Put differently, for a body placed in a gravitational field, it does not matter what value of potential we assign to that location. The only thing that matters is how the potential changes, i.e., how high the gradient of the potential is.

The weight of objects. We are now in a position to explain what is meant by weight of an object, at least under the simple circumstances where it rests at the surface of the Earth. Remember we have to remove the influence of fluids around bodies upon their apparent weight—we have to consider „true" rather than „apparent" weight (maybe we simply imagine having no air or water at the surface of the Earth where we measure the weight of the object).

Now, the weight of an object depends upon two factors. First, if we could double the object, it would have twice its mass and also twice its weight. This presupposes that we are at the same location in the universe. So, the second factor must be „locational," depending upon the gravitational field where the object happens to be. To be precise, the second factor is the strength of the gravitational field where the object is located. Therefore, we can calculate weights by

$$\textit{Weight of object} = \textit{Strength of gravity} * \textit{Mass of object}. \tag{3.7}$$

Here at the surface of our planet, 2 kg of apples weigh 20 J·kg/(kg·m) = 20 N (the strangely complicated form of the unit after the first number is identical to the unit of mechanical force, called Newton (N) in honor of Isaac Newton; indeed, weight is an example of what physicists call mechanical force; see Section 1.5).

Being weightless and the phenomenon of „artificial" Gravity. The weight of an object can change without altering anything about the object or its location in the universe. Carousels and roller coasters tell the story. Moreover, it is quite well known that one will be weightless when in a spacecraft moving around the Earth; and one will be a lot heavier when riding a rocket into space.

Just to dispel a common misconception, the astronauts are not weightless because the strength of gravity of our planet is gone at the altitudes where they fly. The

International Space Station flies at a distance of 400 km from the surface of the Earth; this is very little (about 6 percent) of the Earth's radius. At that distance, the strength of the gravitational field established by Earth is still 90% of what it is at the surface. So, that simply does not explain why one would be weightless in the ISS.

Obviously, there is a lot more to the story of weight then we have told. Here we leave the phenomenon of changing weight unresolved; the story will be picked up again in Volume 2.

3.4 Fluids „Stacked" in the Gravitational Field

If we want to further explore the experience of pressure, we can call upon what we know about water „stacked" vertically in open, tall vessels—anything from an artificial lake to an aquarium to a bottle will do (see Figures 3.16 and 3.17).

Figure 3.16: *Water stacked vertically in vessels. Left: An artificial lake in the Alps (Grand Dixence dam)—water is delivered at high pressure to a hydroelectric power station almost two kilometers below. Center: Water tanks are raised high in order to raise the pressure of water at the tap. Right: Water in a bottle flows with different strengths from different depths.*

Gravity makes fluids „heavy;" therefore, their pressure goes up the deeper down we are in such a fluid. This applies to water in a bottle, a tall tank, a lake or the ocean, and, importantly, the atmosphere; air pressure is highest at sea level and it goes down as we go up. Pressure and fluid tension (i.e., pressure difference) of a fluid „stacked" vertically in the gravitational field are related to gravitational tension (difference of gravitational potential).

We can support this experience by imagining how we would feel if we were in the place of water inside a tall tank, near the bottom. We know that gravity makes water heavy. If we are the layer of water closest to the bottom, and if we imagine successively more layers of water being piled on top of us, these layers will press more and more strongly upon us. The imagined sense of pressure—including its change with depth—can be simulated, and therefore experienced, in an embodied performance (we shall describe a first example of an *Embodied Simulation* that lets us experience tensions in Section 3.4).

Letting the *Forces* of *Gravity* and *Fluid* interact

The explanation makes use of the following image: there are two Forces interacting—*Gravity*, because water is a gravitational material, and *Fluid*, through water being a hydraulic fluid. Remember what we said about the role of the material we call *water*: it is just an easily perceived „front" for the actual Forces that act through it (see the Box on p.91). What we should be concentrating upon are Gravity and Fluid as abstract agents. Imagine going vertically downward in a body of water. The intensity of the gravity of water—its gravitational potential—drops; water as a material that exhibits gravitational characteristics by virtue of its mass becomes less potentially powerful. However, in doing so, Gravity raises the potential of water as a Fluid; what we notice is that the pressure of the water goes up.

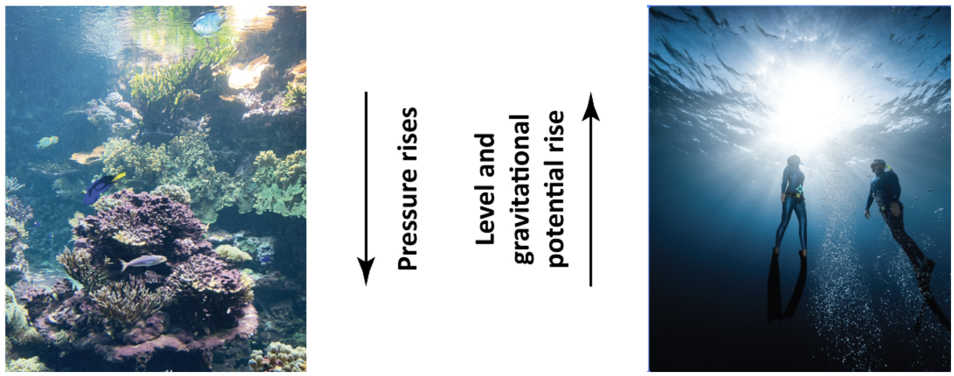


Figure 3.17: *In an aquarium tank at the zoo or in the ocean, the pressure of water rises as we go down. Level and gravitational potential, on the other hand, go up as we go up (photograph on the right: Adobe Stock/Dudarev Mikhail).*

Ambiguous meaning of power

Power: Active or not?

Our everyday embodied understanding of *power* is a little fuzzy or ambiguous. Do we mean that an agent is powerful even if she/he/it is not active, does not actively cause another agent to become powerful? Or should we reserve the term *power* for how it is used in physics where it denotes an active interaction where „something," i.e., energy, is exchanged?

For the purpose of physical science, we shall speak of power only in the latter sense. However, we are aware of our embodied forms of understanding, where an agent under tension is felt to be powerful without acting. So, for these situations, we choose to speak of agents being „potentially powerful."

Hydrostatic equilibrium

Notice that the water does not flow in the situation we have discussed—it is at rest in its reservoir or container. Gravity and Fluid as Forces of Nature are *balanced*, they are in *equilibrium* (in physics and engineering, this is called *hydrostatic equilibrium*). There is no flow and therefore no active power: gravity and fluid are only „potentially powerful" rather than actively powerful.

Observing pressure as a function of depth. Because it is such an everyday and practically important phenomenon, and because it tells of the coupling of gravity and fluids as Forces of Nature, we shall take a brief look at how the pressure of a liquid changes with depth from its surface.

If we measure the pressure of a liquid as a function of depth from its surface, we see that it goes up linearly (Fig.3.18). Pressure starts with a value equal to air pressure at the surface of the liquid. It is important to note that the rate at which pressure goes up as a function of depth does not depend upon size and shape of the vessel that holds the liquid (Fig.3.18, diagram on the left). The rate at which pressure changes as a function of depth is called pressure gradient (remember our description of the meaning of gradient in Section 2.4, and the discussion of gradient of gravitational potential in the present chapter, p.140).

Pressure of fluid rises with depth

The pressure gradient depends upon the density of the fluid (Fig.3.18, diagram on the right)—the greater the density the higher the pressure gradient. The observations reported here are useful for measuring pressure at the bottom of a column of liquid: we can use data from the diagrams in Fig.3.18 and take the height of the column in order to ascertain the pressure of the fluid at the bottom (or rather, we can use the column height as a measure of the pressure difference it sets up).

Pressure gradient

Pressure and depth in liquids

Pressure as a function of depth in liquids: Pressure gradient

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The data reported in Fig.3.18 lets us do some calculations that will be suggestive of how the pressure gradient of liquids depends upon the type of liquid (actually, its density) and where we are on Earth.

In the diagram on the left in Fig.3.18, we can measure the gradient by the slope of the single straight line. Since the line is straight, its slope is the same everywhere—the pressure gradient in water is constant. The actual value is very close to 4.0 kPa/0.40 m = 10,000 Pa/m. Since we can assume the strength of the gravitational field and the density of water to be factors that determine the gradient, the number can suggest to us the following. We know that the density of water equals 1000 kg/m^3; the strength of gravity, on the other hand, equals 10 J/(kg·m). If we multiply the two figures, we get the gradient: 1000 kg/m^3 · 10 J/(kg·m) = 10,000 J/m^4. Since the unit of pressure can also be written as Pa = J/m^3, we have 10,000 Pa/m which is the measured gradient. Therefore, we can assume that

$$\textit{Pressure gradient} = \textit{Density} \cdot \textit{Strength of gravity}$$

If we accept this, we can use the data in the diagram on the right in Fig.3.18 for determining the densities of the liquids. The gradients are about 12,000 Pa/m, 9,000 Pa/m, and 7,500 Pa/m for glycerine, olive oil, and alcohol, respectively. Therefore, the densities of these liquids are about 120%, 90%, and 75% of that of water.

Since the pressure gradient is constant, we can calculate the pressure difference in a liquid for a given difference of height (or depth) by multiplying the gradient by the height difference:

$$\textit{Pressure difference} = \textit{Density} \cdot \textit{Strength of gravity} \cdot \textit{Height difference}$$

The fact that the pressure gradient is constant in a liquid is due to the fact that a liquid is almost incompressible which makes its density constant! From this relation we get a value of pressure at the deepest point of the oceans, which is about 10 km, of 10^8 Pa = 1000 bar.

Pressure gradient and the size and shape of containers. There is an important point about the change of pressure with depth in a fluid we have not yet discussed: we may be confused by the fact that pressure rises at always the same rate as we go down in a fluid no matter how large the fluid body is or what shape it has. If pressure in water „stacked" in a container is a result of gravity, i.e., of weight, should the pressure not rise faster if the body of water is bigger, since bigger means higher weight?

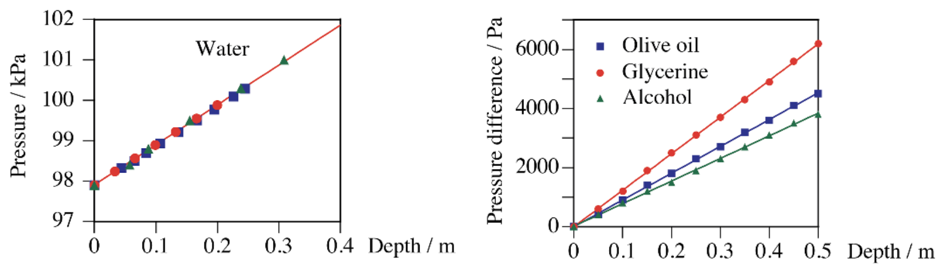


Figure 3.18: *In a liquid at rest in vessels of any size and shape, the pressure of the liquid rises linearly as a function of depth. Left: Data for water in different containers (the value of pressure at the surface is air pressure at the place where the measurements were performed). Right: The pressure gradient depends upon the density of the liquid.*

When we think about it, it is clear that how fast the pressure of water rises with depth in water (or any other fluid) cannot depend upon size or shape of a container in which we „stack" water. If (lateral) size and shape mattered, the pressure would rise differently for divers in the local lake or in an ocean—but it is all the same where we go diving. Moreover, we see this observation ascertained by the data shown in the diagram on the left in Fig.3.18: pressure was measured in water in several containers having different diameters.

There is still another observation (which does not require taking any data) proving to us that the pressure gradient in a fluid at the surface of the Earth does not depend upon size and shape of a container (Fig.3.19).

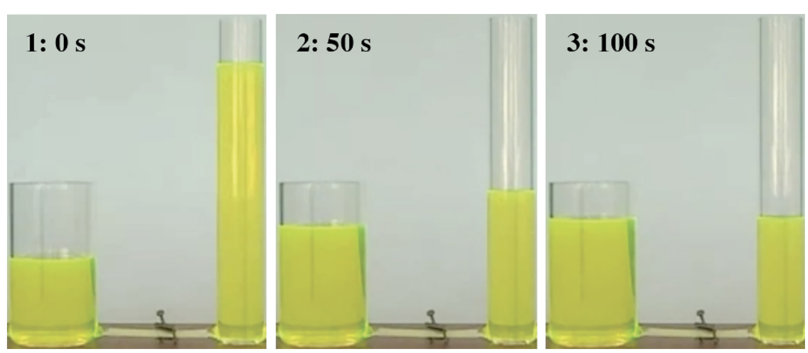


Figure 3.19: *Two communicating vessels: water flows from one of them through a hose into the other. Water levels are shown at three different moments (points 1, 2, and 3). When the process stops, the water levels have reached equal heights.*

Level difference makes water flow

If we connect two water tanks having different diameters (and possibly different shapes as well, like different plastic drinking bottles) by a hose at their bases and fill one or the other with water, water will flow as long as there is a *level difference* between the water columns in the two vessels. No matter the size and shape of the vessels, in equilibrium, where the hydraulic tensions of the water columns must be equal, the heights of the columns will also be equal! This proves that the hydraulic tensions (the vertical pressure difference from top to bottom) of the water in both tanks seen in Fig.3.19 must be the same, irrespective of the size of the containers.

Pascal's barrel

It is said that Blaise Pascal was able to make a barrel full of wine break with just another glass of wine. He is told to have inserted a thin and long vertical pipe into the lid of a closed and full barrel, then climbed up on a high latter to the top of the pipe which he filled with just a small amount of wine. Since the pressure of the liquid rises with height—and not with amount!—it became high enough in the barrel to make it explode.

Columns of liquids for measuring pressure

Barometer

The effect of pressure differences of vertical columns of liquids was often used to measure the pressure of fluids. We bring a liquid column in a vertical pipe—however thin—in contact with a fluid whose pressure we wish to measure. This is how, even today, blood pressure is determined, and it is how, historically, air pressure was measured. In 1643, Evangelista Torricelli is reported to have used a barometer of his design to achieve this feat (Fig.3.20). The barometer consists of a shallow open container having a relatively large diameter. Some liquid—preferably a very dense one!—is filled into the container. Then, the same liquid is filled into a thin glass tube closed at one end, and the tube is placed with the open end into the liquid in the container.

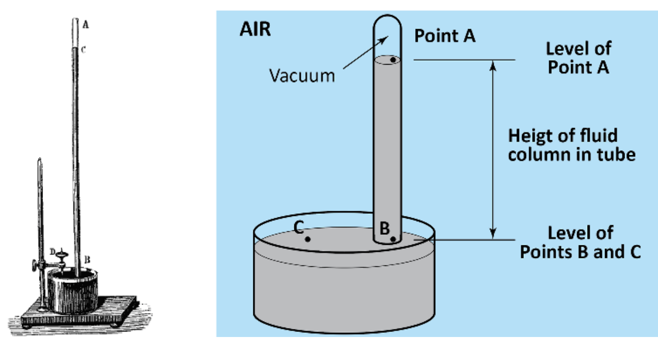


Figure 3.20: *Left: A sketch of an old-fashioned barometer as designed by Torricelli. Right: Drawing explaining how the barometer functions. If we use mercury as the liquid, the height of the mercury column in the glass tube will be less than a meter. With water, the barometer would have to be 10 m high. Above Point A, there is no air.*

If the tube is high enough, the liquid in it will flow out a little bit, leaving a near vacuum at the top where the tube is closed. Assuming that the liquid does not flow further, we have a case of two communicating tanks—the open container and the glass tube—with a liquid at rest in both.

The pressure of the liquid will be the same at points B and C since they are in the same body of fluid at the same height. On the other hand, the pressure of the liquid will be nearly zero since we have a near vacuum in the glass tube above the liquid. Having a pressure of 0 Pa at A, the pressure difference of the liquid column in the glass tube will be equal to the pressure at B, and therefore, equal to the pressure at C. Now, at C the pressure of the liquid is equal to the pressure of

Hydraulic tension of fluid column

the air. Therefore, the hydraulic tension of the fluid column in the tube is equal to air pressure—that's how a barometer of Torricelli's type works.

If we use Torricelli's barometer at sea level at standard atmospheric pressure with mercury as the liquid, the height of mercury column will be about 76 cm, which gives us a value of 1.013 bar for this standard atmospheric pressure. If we had used water as the liquid instead, the barometer would need to be a little more than 10 m high!

Pressure of air in our atmosphere

Our atmosphere is a complex system where pressure changes laterally across the surface of the planet, with altitude, and, naturally, over time as well. We have said that as weather changes, the pressure of the air at a location typically changes by a few percent only. However, if we go up from the surface, changes become much greater.

All the knowledge about Earth systems in general and our atmosphere in particular, which we now take almost for granted, was extremely uncertain less than 400 years ago. Torricelli had built the barometer around 1643, which allowed air pressure to be measured. One therefore could have an impression of an actual value at the location where it was used, but it was not clear at all if the pressure would change with altitude. In 1648, two Frenchmen, Blaise Pascal and Florin Perier, hiked up the Puy de Dome with an altitude of 1460 m above sea level. They took a Torricelli barometer with them and reported that readings changed—lower pressure at higher altitude. Almost 150 years later, in 1787, Horace Benedict de Saussure climbed to the top of Mont Blanc at about 4800 m. He recorded pressure and temperature as he went up, reporting that temperature dropped by a steady 0.7°C for every 100 m. Pressure changes were not steady: the higher he went, the more slowly pressure dropped (Fig.3.21).

Air pressure drops with altitude

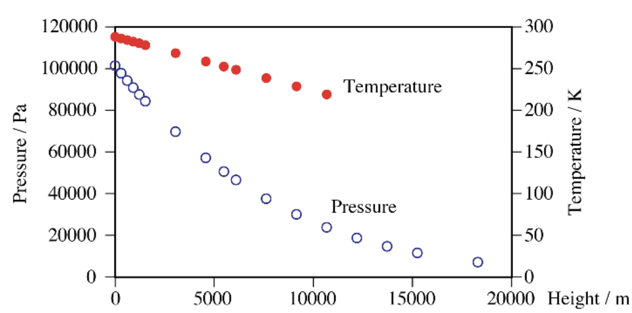


Figure 3.21: *Pressure and temperature of the air in our atmosphere as functions of height above sea level. The values are for a „standard" atmosphere, since the real values change with time and location, but they provide a fair impression of real conditions. Units are standard units, Pascal (Pa) for pressure and Kelvin (K) for temperature.*

We have seen that pressure rises linearly with depth in a liquid. We can now understand why the gradient of pressure diminishes as we go up from the ground in our atmosphere: the air gets „thinner," i.e., its density goes down with altitude. The constant gradient in a liquid is the result of constant density.

What the first investigators saw in their numbers added to a fast changing view of the Earth and the universe. The dropping pressure showed that, at some altitude, the pressure would be equal to zero, meaning that this would be the top of the atmosphere and the end of air. Beyond that, there had to be vacuum, something that was supposed to be impossible to exist if one accepted the opinion of Aristotle, the natural philosopher of greatest influence coming out of antiquity. In Aristotle's natural philosophy, the sphere below the moon was filled with air (and fire atop air); past this sphere, Sun, planets, and stars reigned (all of these heavenly bodies were made of the *Fifth Element—Quintessence*). There was no room for vacuum in this cosmology, and it was likely assumed that the air had the same properties everywhere where we could find it.

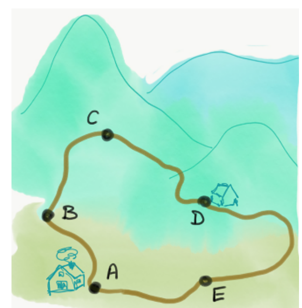
Aristotle's disbelief in void

Pressure is a level—metaphorically speaking

More than anything else, our experience with water in lakes, reservoirs, and vessels of any size and shape here at the surface of our planet should convince us that we see pressure as a kind of vertical level (see the examples in Fig.3.16, 3.19, and 3.20). We use aspects of our understanding of *vertical level* when we *speak* (and write) about pressure in fluids (see Table 3.3 in Section 3.8).

Hydraulic landscape in communicating tanks. If pressure is a vertical level, if the pressure of a fluid goes up or down, slowly or fast, this sounds very much like we, or the fluid, are moving in a hilly landscape—a *hydraulic landscape*. The particular image is an important example of a projection created by the metaphor PRESSURE IS A VERTICAL SCALE (see Table 3.3). This case of imagining is indeed a powerful tool of our mind that can help us greatly in coming to terms with all the different potentials we are confronted with in physical science. We have seen a form of visualization of an imagined space with highs and lows created before when we discussed gravity and its potential (see, in particular, Fig.3.15).

Hydraulic landscape



Let us return to the example of two communicating water tanks (Fig.3.19, and below in Fig.3.22, left) and consider what kind of hydraulic landscape it presents us with. After everything we discussed, the details emerging here should be pretty simple to put together. In a preliminary step, we need to imagine a path we want to follow through the water in the system—we shall take the one represented by the dashed line on the left in Fig.3.22.

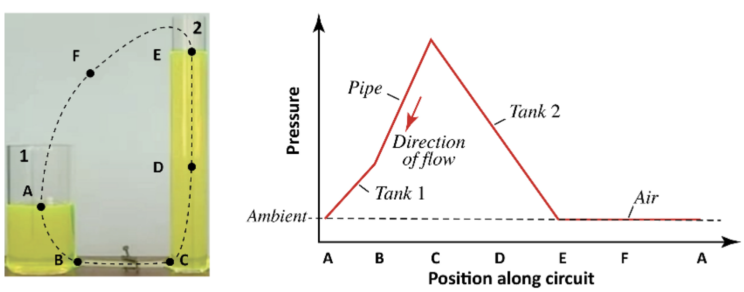


Figure 3.22: *Left: Two communicating containers with water undergoing a dynamical process (the water is flowing, so the photograph depicts a moment in the dynamical process). A closed loop (imagined path through the system) has been drawn over the photograph. Right: Values of pressure of water in a pressure-position diagram, along the closed loop. At A, E, and F, the pressure equals air pressure.*

There are two things quite certain after what we have learned about pressure gradients in vertical columns of water: the pressure of the water rises from A to B and from E to C in the two tanks. At A and at E, water is at the same pressure as the air (ambient pressure). So, as we construct the pressure landscape in a pressure-position diagram (Fig.3.22, right), we can start with ambient values of pressure at A and E and draw straight lines up to the proper values of pressure at B and at C. Clearly, the pressure at C must be higher than at B.

This leaves a gap between B and C. However, it is clear that if the pipe between C and B is open (and the water running), the pressure must change smoothly from C to B (or vice-versa). Since the pressure at C is higher, we have a downhill slope from C to B which indicates that water should flow through the pipe from C to B—this is what we know to happen in this system; in the photograph on the left in Fig.3.22, the water is flowing from right to left (if the hose is not clamped shut). What we can now conclude with certainty is that when a fluid flows through a conduit, even horizontally, its pressure goes down in the direction of flow. There is a *pressure gradient in horizontal flow* of water through a conduit.

Horizontal pressure gradient

Moving along closed paths. The imagery created here suggests an interesting logical consequence for pressure differences (tensions) along an imaginary closed path through a fluid in a hydraulic system. As we move from A to B to C, etc., and back again to A along the loop, we end up at the hydraulic level where we started. This means that, if we sum up all the different pressure differences we might consider along the path, we get a value of zero (to be certain, to arrive at this result, we need to count going „downhill" as a negative value).

The rule we have just established is well known from examples of electric circuits which we will study in the chapter on electricity in Volume 2. There, it is called *Kirchhoff's Second Rule* of electric circuits, sometimes also called the *Loop Rule.* By the way, having the same rule in hydraulics and in electricity is an important example of analogical reciprocity—if we understand the rule in one of the realms of nature, we can hope to understand it in the other one as well.

Kirchhoff's Loop Rule

3.5 Fluid Flow and Hydraulic Tension

Water flows spontaneously downhill, both literally and figuratively speaking. Literally, when it is high in the gravitational field, when Gravity is the Force of Nature behind its behavior; and figuratively, when water is behaving as a hydraulic agent. In the latter case, there needs to be a hydraulic tension, i.e., a pressure difference for water to flow through a conduit such as a pipe.

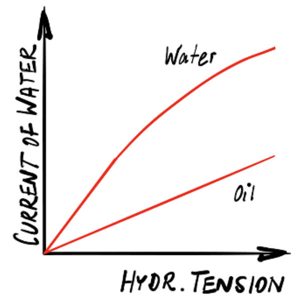
The relation between tension and flow

For what we call spontaneous flow of a hydraulic agent such as water, there needs to be a pressure difference—actually, a pressure drop—in the direction of flow. Water flows horizontally—when Gravity does not play a role—if it is pushed from behind, i.e., if the pressure behind water in a pipe is higher than in front of it. This is what we have observed in the example visualized in Fig.3.22: water flows through the horizontal pipe seen in the photograph on the left, from C to B. Figuratively speaking, water flows downhill in a hydraulic landscape (see p.149). Levels in this metaphoric landscape are shown in the diagram on the right in Fig.3.22.

Our everyday experience tells us that the flow of water through a given conduit is higher, the higher the pressure difference. We notice this when water flows from a faucet or a garden hose, and we see this in the more controlled environment of the experiment visualized in the Box on p.123. In the latter example, changing levels of water in the two tanks indicate that the flow is stronger when the level difference is higher—which corresponds to a higher pressure difference along the horizontal pipe.

Flow of water and oil through pipes—Flow-Tension relation

Flow-Tension relation



From the interpretation of observations of cooling and heating—such as seen in the data of the experiments presented in Figs.3.10 and the Box on p.123—we can construct a hydraulic tension - current of fluid relation. When the pressure difference is zero, so will be the current; and the higher the tension, the stronger the current. The simplest possible relation, expressed formally, is one of proportionality. If we use the symbol I_V for the strength of the current of volume of fluid, and $\triangle p = p_{high} - p_{low}$ for the hydraulic tension, we can express the idea as follows:

$$I_V = G_V \triangle p \tag{3.8}$$

Conductance

The factor of proportionality G_V—called *hydraulic conductance*—tells us how easy it is for a fluid to flow through the given conduit such as a pipe. If we represent Eq.(3.8) graphically, we get a straight line whose slope is the value of G_S. The notion of conductance is the inverse of *resistance:*

Resistance

$$R_V = 1/G_V \tag{3.9}$$

R_V is the symbol for hydraulic resistance. We introduce the *hydraulic resistance* of a conduit if we wish to express the notion of how hard is is for a fluid to flow through this conduit.

The conductance depends upon how viscous the fluid is, and how long and wide the pipe is through which the fluid will be flowing; it will be smaller for greater viscosity of the fluid, greater for larger cross section of the pipe, and smaller for greater length of the pipe).

The relation constructed here typically holds when a highly viscous fluid such as oil flows through a pipe. This works as well for water, which is not very viscous, but only if the flow is rather weak. At a certain threshold, the way water flows, changes from laminar to turbulent. As soon as this happens, the current will increase at a steadily decreasing rate as a function of tension—we get a curve rising more slowly as the tension gets higher.

If water is allowed to flow through a conduit—if there is no blockage—the current of water is stronger for higher hydraulic tension along it. How the relation works out precisely, needs to be investigated and measured (see the Box on p.151). There are simple cases of flows when the current grows proportionally with pressure difference. This happens for viscous liquids such as oil flowing through a pipe; for water, this is the case if the flow is weak which makes the liquid flow slowly and orderly (the flow is then called *laminar*). However, as soon as the flow becomes faster, it becomes disorderly (we call this type of flow *turbulent*), and the flow-pressure-difference relation becomes more complicated.

Naturally, there is another factor influencing the strength of the flow of a particular fluid: the point is how easily the liquid finds its way through the conduit such as a pipe. The conduit opposes the flow more or less strongly; if it does this strongly, we say that it sets up a high fluid resistance, and if it does this weakly, we speak of low fluid resistance.

Embodied Simulations—Feeling and understanding tension and flow

We have been saying that our understanding of how we encounter nature is strongly influenced by our bodily experience. What happens to our organism as we experience nature is instrumental in forming abstract figures with which we construct and express our understanding. Intensities and their differences, i.e., tensions, are most likely the first and most basic embodied schematic forms shaped by our encounters with our environments. We now want to suggest how we can use our body for creating a form of simulated experience that helps us become aware of what might otherwise remain unexplored.

Using our body for creating a simulated experience

Containment and tension. How can we simulate the experience of physical tension and associate this experience with pressure of a fluid such as water collected in a tank? As an example, consider the pressure of water as a function of depth in a tall container—see the sketch on the right in Fig.3.23. We imagine a number of layers of water in the tank and represent each layer by a person. We know that, going downward in the liquid, the pressure of the water will rise for successive layers.

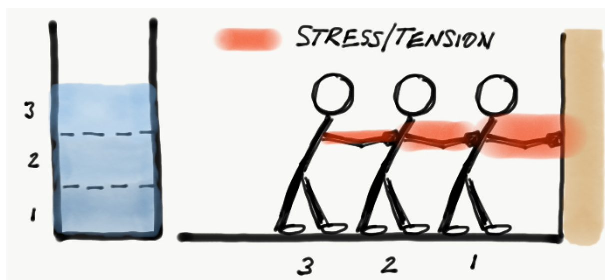


Figure 3.23: *Left: Water „stacked" in a tall tank—different layers are identified, and each layer is represented by a person. Right: Persons representing layers of water stand in line, leaning against each other and against the wall.*

We let the persons representing the layers of water stand in a line (Fig.3.23, right). The person in front faces a wall and leans against it, arms outstretched, with the hands touching the wall. We know from everyday experience that we feel the arms being stressed mechanically (this is a case of compressional stress); the stress will be greater if we lean at a greater angle—gravity makes this so as a consequence of our weight.

Gravity creates tension in water

Now, we let the other persons representing consecutive layers of water lean against the person in front of them, roughly at the same angle, again with arms stretched forward. In the end, the arms of all the participants will be stressed (tensed). If we ask the participants, we should get a report of consecutively increasing stress, from left to right (Fig.3.23), with the person leaning against the wall feeling the greatest stress.

The stress felt in the arms simulates water pressure of successive layers and its cause quite faithfully. By leaning forward, the arms of the participants are stressed compressively as a consequence of gravity, which is quite the same in the case of water in the tank. We now have a physically embodied representation of what it must feel if we were in the place of the water in the tank; we understand the gradual rise in tension (with depth) and the fact that the pressure of the fluid should be highest at the bottom of the tank.

Tension and flow. We can continue the game of an *Embodied Simulation* (ES) and ask what should happen if the water container in Fig.3.23 had a hole or, better still, a hose attached to the bottom. We now add people to the chain simulating the rising pressure in the tank (Fig.3.23, right) who represent water in the pipe (Fig.3.24). For the moment, let the pipe be closed: the flow of water will be blocked (this can be simulated by an additional person pushing back against the chain of people).

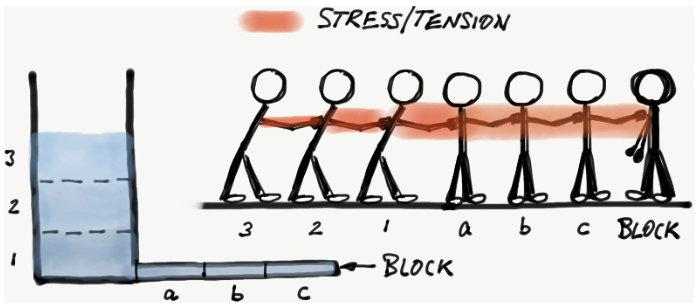


Figure 3.24: *Water in a tank having a horizontal pipe fitted at the bottom. A chain of people represent water in the tank (1-3) and in the pipe (a-c).*

Since the pipe is horizontal, there should not be any added effect of gravity upon the water resting in the pipe. For this reason, we let the persons simulating the water there stand upright. Interestingly, if the simulation is performed correctly, persons a-c (Fig.3.24) should all feel the same tension in their arms, and this tension should be equal to the tension is the arms of the person representing the lowest layer of water in the tank. Indeed, this is what measurement of pressure of the water along the pipe will show in a laboratory setting.

Embodiment

Concepts are embodied

It is important to realize that we do not only rely upon linguistic interaction when communicating and forming concepts. ES and other forms of physical play and interaction may help us understand that concepts in a science such as physics are embodied—we do not have to accept them as purely formal constructs for which no deeper meaning and understanding is available.

What should happen now if we suddenly opened the pipe? This part is very difficult to perform adequately, but we can imagine fairly easily what should happen under ideal circumstances. For the following, imagine that persons a-c could slide fairly easily across the floor (while staying upright) whereas persons 1-3 could continue to push with their feet against the floor. When the person blocking the chain suddenly moves away, the tension in the arm of person c immediately drops to zero, and she begins to move. As a consequence, the tension in the arms of b is lowered, and so is that in the arms of person a (tension for a will still be higher than that for b). This change of tension happens very quickly as a-c are slowly pushed across the floor.

Apart from what is already difficult to perform, more trouble lies ahead if we really want to physically simulate the complete process. Person 1 in the tank would have to „convert" into a person representing water in the pipe, and person c leaves the game, etc. Let us not try this but simply imagine—and then reason about— what experience can teach us.

A number of things can be said about the water in the pipe: first, its pressure drops from the point where the pipe meets the tank to where it opens to the environment; at the outlet, its pressure is that of the ambient whereas, at the bottom of the tank, it is equal to the highest pressure of water in the tank. Overall, we conclude that the pressure difference (tension) of the water along the pipe equals the pressure difference of the water standing in the tank (measured from top to bottom).

Furthermore, and this is quite important, the change of pressure of the water in the pipe happens very quickly, much faster than the water will flow. This suggests something that will otherwise need sophisticated equipment and reasoning to demonstrate: the signal that travels from right to left through the horizontal pipe (see Fig.3.24) moves at the speed of sound in water (about 1500 m every second!) whereas the water moves very slowly. Establishing a pressure landscape (see p.149) in a hydraulic system happens extremely fast whereas the processes constituted by flow are happening much more slowly.

Finally, there should be direct experiential feedback to us concerning the relation between tension and strength of flow of for the water in the pipe. As we have just said, the pressure difference along the water in the pipe equals that established by the water in the tank. It should be quite clear that if this tension is high, the flow of water through the pipe should be strong, and if this tension goes down, the flow decreases. Second, at any given tension, the ease (or the difficulty) with which persons a-c slide across the floor will be instrumental in establishing the strength of the flow. This is what we have summarized in the Box on p.132.

3.6 The Power of a Waterfall

Waterfalls suggest the power of Gravity

Like no other phenomenon, waterfalls let us experience the power of *Gravity* as a *Force of Nature* (Fig.3.25, left). They exhibit, for all of us to experience in physical immediacy and clarity, the basic characteristics of *Gravity* we have been observing and constructing. We can visualize gravitational tension in the height of a waterfall, and the extensive aspect is presented to us in the form of the magnitude of the flow of water (we shall see later how it is quantified in terms of the flow of mass of water).

And no other phenomenon suggests to us so transparently that *power* depends upon the other two basic aspects we see embodied in a waterfall: height of fall and magnitude of flow of water. Through their immediacy, beauty, and power, waterfalls serve as archetypes of processes involving *Forces of Nature*—we shall make use of this power of suggestion again and again as we study these *Forces*.

At the end of Section 3.1, we suggested that the notion of power serves to quantify the interaction between *Forces* as a transaction: the agent brings something to the table which the patient will receive and possibly use in a subsequent interaction. We have used the analogy of an economic transaction—with money being passed from the agent to the patient—for understanding better how we might quantify power.

In physical science, what is being passed from agent to patient in natural interactions is called *energy* (Section 3.7). Now, we shall disregard the interaction of an agent with a patient and focus solely upon the agent and its power. For this reason, we have changed the visual symbol for *empowering* in the schematic diagram of an interaction in Fig.3.4 to a short arrow representing the agent's part of it: the agent brings energy to the table, so the green arrow in the schematic diagram in the middle of Fig.3.25 denotes this „bringing to the table" of energy. For the moment, we simply disregard what will happen with what the agent passes on to one or more patients.

Empowering

Agents provide energy to patients

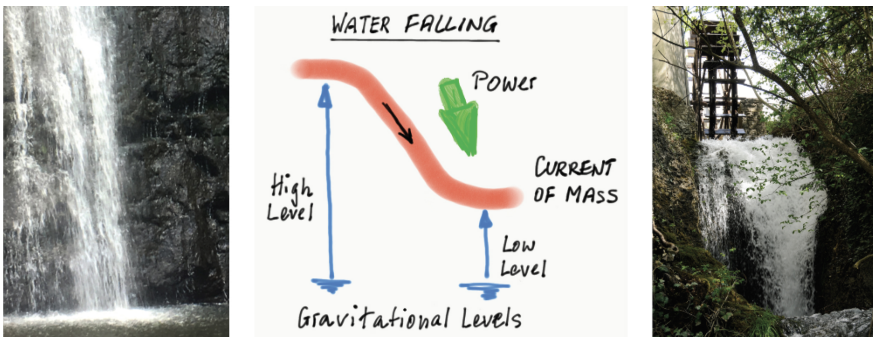


Figure 3.25: *Left: Waterfall, Manoa Valley, Honolulu. Center: A waterfall in abstraction. In its simplest form, a waterfall is characterized by three factors:* HEIGHT *of fall (level difference or tension),* FLOW OF FLUID *(strength of flow or current of imagined fluidlike quantity), and* POWER*. Here, the green arrow symbolizes the part of „empowering" related to water falling (see Fig.3.4). Right: Waterfall and mill wheel (photo A. Baumann).*

Constructing a formal expression for the power of *Gravity*

We can never be sure if a phenomenon can be rendered formal and quantitative, but we can always try to make it so. This is one of the methods of science: see if we can come up with aspects of a phenomenon that can be turned into concepts that could possibly be made quantitative, and then use our imagination to create a sensible relation between such concepts. Finally, we check if what we have produced can be used under various circumstances for different applications (this suggesting, constructing, and then using of suggested relations is called *modeling* and *simulation*[16]).

Modeling and simulation

Imagine you are standing next to a waterfall. What are the most basic, intrinsic, and schematic aspects of an abstract waterfall (Fig.3.25)? One way of coming up with an answer to what matters here is trying to think about what aspects could be changed about the waterfall for it to make a difference. Or, maybe more easily, try to imagine different waterfalls and ask how they are distinguished at the most basic level.

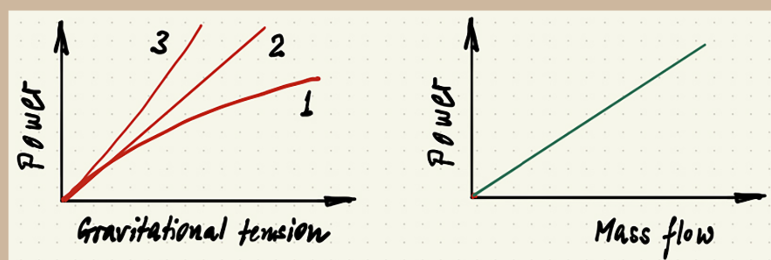
It seems that we could do this in a number of ways: (1) change the height of the waterfall; (2) change the strength of the flow of the liquid falling down; (3) split the flow into two parallel ones; and (4) let the water fall down in a couple of steps instead of a single one. We could also have (5) a liquid methane-fall on (6) Titan, Saturn's biggest moon if we wanted to change the fluid and the strength of the gravitational field at the location of the waterfall. Maybe, we can come up with even more possibilities for changing aspects of a waterfall.

Constructing a formal relation

Constructing a formal quantifiable relation

Let us assume that we want to create a formal relation for a quantity (power) which we say must depend upon two other quantities (gravitational tension and flow of mass). Having said this, the next question is *how* the first is dependent on the latter two.

Since we want to work formally, we shall introduce formal symbols for the quantities we are going to use: $\mathcal{P}$ for power, $\triangle\varphi_G$ for gravitational tension, and I_m for flow (current of mass), respectively.



Step 1: How does the power depend upon gravitational tension? A tool that helps us contemplate this question is a Power-Tension diagram (see above on the left). Three typical possibilities are sketched qualitatively. Case 1 means that the power grows less fast for higher fall. Case 2 is for proportionality. Case 3 means that the power grows faster with higher fall. In either case, we will now have to create a formal relation for the case we find most sensible. If we choose Case 2, the relation between power and tension is written like this:

$$\mathcal{P} \sim \triangle\varphi_G \tag{3.10}$$

The symbol $\sim$ denotes „is proportional to." Doubling the gravitational tension leads to double the power.

Step 2: How does the power depend upon the current of mass? Here, logic dictates that the relation must be that of proportionality:

$$\mathcal{P} \sim I_m \tag{3.11}$$

Step 3: Combine the assumptions. What kind of simple mathematical operation is logical in this case? Addition and subtraction are impossible: quantities of different type cannot be added. Also, if either $\triangle\varphi_G$ or I_m is zero, the power must be zero as well, and that is not possible if the two quantities were added or subtracted. Division does not make sense either. Multiplication remains the only possibility. Power is proportional to the product of the two quantities it depends upon. To get the actual equation, we need a factor of proportionality to complete an equation for power.

Since this is the first instance of ever introducing a relation for power, we are at liberty to set $a = 1$. This is exactly what has been done in physics. Therefore, we have

$$\mathcal{P} = \triangle\varphi_G \, I_m \tag{3.12}$$

Factors (3) and (4) do not really bring up anything new: we could simply consider each part a unit of a waterfall—a waterfall on its own—for which we again ask the same questions. This leaves the first two and the last two of the factors or circumstances mentioned.

Clearly, location matters for gravity as a FoN. The strength of the gravitational field (see Section 3.3) on Titan is about one seventh that at the surface of the Earth. Keeping everything else the same, a waterfall on Titan would only be one seventh as powerful as on Earth.

The substance a „water"-fall is made of presents us with an interesting point: substance does not matter for gravity. As long as we use *gravitational charge* (*mass*) as the measure of amount of gravity, nothing specifically chemical matters. Naturally, if we were to use volume as the measure for amount of fluid, the situation would be different. Liquid methane will have a density roughly half of that of water—therefore, we need double the volume of methane flowing compared to when water flows to have the same gravitational effect. In summary, we use the strength of *flow of mass* (also called *current of mass*) of the liquid when calculating the power of a fall of a fluid.[17]

Flow of mass

This leaves just one factor: *height of fall* (Fig.3.25). Actually, height of fall or difference of height combines with strength of the gravitational field to give us *gravitational tension*, the *difference of the gravitational potential* at the top and at the bottom of the fall (seen the subsection on p.137). If the height difference is not too great, the gravitational tension is obtained simply by multiplying level difference and strength of the gravitational field at the location of the waterfall.

Gravitational tension

We have now sorted out the factors that we believe matter for determining the power of a waterfall: flow (current) of mass and gravitational tension. However, the work of imagination is not yet done—we still need to construct a relation for power from the factors that influence it. We have chosen to assume that only two factors matter. Can we imagine how each of them, taken separately, will quantitatively influence the power of a waterfall?

The first factor, strength of flow, is easy to deal with. If we have two identical waterfalls side by side, their flow is twice that of a single fall. Moreover, their power must be double that of a single waterfall. Double the flow, double the power (or half the flow, half the power): this kind of relation is called *proportionality*. Therefore, the power of a waterfall is proportional to the strength of the flow.

Proportionality

What about the gravitational tension of a waterfall? Here, we need to remember what we mean by potential: it is the aspect of a Force of Nature that makes it potentially powerful. In other words, the image of potential created by experience relates it directly to power. For this reason, we make power proportional to potential difference, i.e., to the tension associated with the Force. The power of a waterfall is proportional to its gravitational tension.

What we need to complete the relation is knowledge how to combine two factors that each make themselves felt in terms of proportionality. Mathematics teaches us how to do this—we simply multiply both factors:

$$\textit{Power of waterfall} = \textit{Gravitational tension} * \textit{Current of mass of liquid}. \quad (3.13)$$

We can see that this should work if we consider an example such as what happens if we double the tension (by effectively doubling the height of fall) and, concurrently, the flow of mass. Obviously, the power must grow fourfold. This is the same result we get from the equation above.

How good is the relation for power of a waterfall? There are at least three different aspects to this question: Have all possible factors that can make a noticeable difference been included? Have all these factors been combined correctly? How do we measure the power of a waterfall independently? The last of these questions is fundamental because, without it, the first two questions cannot be satisfactorily answered either.

Without determining the power of a waterfall independently, the relation we have built is simply a definition—it has no intrinsic meaning or value. We can measure the two factors and multiply the two numbers, but so what? „Power of a waterfall" would just be the name for—simply a definition of—the product of the two factors we have included in the relation, and that would be it; there would be no further meaning to this product.

What this tells us is this: we need to know what we mean by *power* in the first place. We have taken *power* to be the measure of how strongly a *Force of Nature* empowers another *Force* (see Fig.3.4). In other words, our formal expression of the power of a waterfall makes true sense only if it is useful for telling us how powerful a process driven by the waterfall has become. This means that we need to extend the concept of *power* from agents to patients—we need to transfer the formal expression we constructed for the power of a process of *falling* of water to caused processes such as the *lifting* of water; we need to assume that the same formula holds for patients as well.

Going from falling to lifting

One way of expressing this task is this: we need to understand *interaction as transaction* (p.117). In physical science, this has been made possible by the invention of the concept of energy as a measure of how much an agent hands to a patient in an interaction. We shall discuss what is behind this idea in some detail further below in Section 3.7.

Table 3.1: Some quantities, symbols, and units

Name of Quantity	Symbol	Unit	Symbol
Height, level	h	Meter	m
Level difference	$\triangle h$	Meter	m
Time	t	Second	s
Mass	m	Kilogram	kg
Mass current	I_m		kg/s
Gravitational potential	φ_G		J/kg
Grav. potential difference	$\triangle\varphi_G$		J/kg
Strength of gravity	g		J/(kg·m)
Energy	E	Joule	J
Power and energy current	$\mathcal{P}$, I_E	Watt	W = J/s
Volume	V	Cubic meter	m^3
Density	ρ		kg/m^3

A few numbers for illustration. We know the strength of the gravitational field at the surface of the Earth: it equals 10 J/(kg·m). This lets us quantify the gravitational power of waterfalls or other flows of water from a higher to a lower location. Let us construct a first numerical measure by letting water fall at a rate of 1 kg/s through a level difference of 1 meter; the power of this gravitational process is 10 J/(kg·m) · 1.0 m · 1.0 kg/s = 10 J/s = 10 W (under ideal circumstances, this would power a fairly bright LED light). If we need to get a feeling for what 1 W might correspond to, we could make the current of water falling through a 1 m level difference equal to 100 grams per second.

Units for energy and power

W is shorthand for Watt (named after James Watt), which is the name of the standard SI unit for power; see Table 3.1 for some important quantities and units of physical science. The way units are constructed and assigned tells us that the unit W is identical to J/s, where J is shorthand for Joule (named after James Prescott Joule), which we use to denote the standard SI unit of energy. What all of this tells us is that energy is related to power in the sense we have suggested before: power tells us how „fast" energy is handed from agent to patient; remember what we said about power and energy at the start of this chapter.

Units and how to deal with them

Units of physical quantities

When physical quantities (such as pressure, temperature, speed, amount of heat, power, etc., are given numerical values, these values need to be accompanied by a proper unit: is a length or distance given in centimeters or inches, or in kilometers or miles? Without a proper unit, a number is meaningless.

SI-system

Standard units

Since it is possible to apply different units to the same physical quantity (Pascal or bar or mmHg for pressure), it is important to create a standard unit system. Physics uses the SI-system (French: *Système International d'unités*) which assigns a *standard unit* to every physical quantity. When we stay within this system, we can be sure that the result of a calculation returns the value of the new quantity again in standard units. Example: When we calculate the energy exchanged from power (by multiplying power by period of time), and if we use W (Watt) and s (second) as units of power and time, respectively, the amount of energy calculated will be given in standard units, i.e., in J (Joule).

Non-standard units

There are some widely used non-standard units, particularly in the US (where *non-standard* units are used for length, volume, weight, and temperature), but also depending upon the field people are working in (mmHg and bar for pressure are still standard in medicine and meteorology, respectively, kWh is standard for amounts of energy, especially in electrical applications). If we encounter such non-standard units and need to perform calculations, it pays off to first convert the values given to standard SI units.

Here are a few more examples. The flow of water (rather, the flow of mass) of the Niagara Falls is about 5.5 million kilograms per second on average. The height of fall equals 50 meters. As a consequence, the gravitational potential difference (the gravitational tension) equals 10 J/(kg·m) · 50 m which is 500 J/kg. If we multiply this by $5.5 \cdot 10^6$ kilograms per second, we obtain a value of $2.75 \cdot 10^9$ W. Expressed in words, the average gravitational power of the Niagara Falls is a little less than 3 billion Watt or 3 GigaWatt (3 GW).

As a further example, imagine we could collect rainwater on the roof of a house 10 m high, covering a surface area of 100 square meters. The rain is moderately strong, 1.0 cm per hour, as reported by the weather service. As it rains, we let the water run down through a drain. The current of mass in this case is 1000 kg/h = 0.28 kg/s (1 cm of rain means 10 kg of water per square meter). The gravitational tension equals 10 J/(kg·m) · 10 m which is 100 J/kg. So, the gravitational power equals 100 J/kg · 0.28 kg/s = 28 W.

To create an impression of what these numbers mean—and here we see the importance of relating a *Force of Nature* to other *Forces* through their power—imagine we could set up a perfect chain of couplings of *Forces* from falling water to lighting some LED light bulbs. This means that we imagine water falling in a gravitational process leading directly, and ideally, to the production of light (we will describe means of understanding and dealing with chains of processes in much more detail in Chapter 5 where we introduce visual and mimetic representations of such chains). In the case of rain described here, we could keep two or three such bulbs burning as long as it rains as described; the Niagara Falls, in contrast, could power 200 to 300 million such bulbs continuously.

Rising flames and balloons

Let us return to observations we made when we described *Gravity*. We started with our experience of the polarity heavy ↔ light (Fig.3.13). There, we noted the phenomenon of objects sinking, rising (such as flames and balloons), or floating in surrounding fluids, and reported on the difficulty of making clear what might be meant by a measure of *heaviness*. Not only is the sense of heaviness as it arises from everyday experience influenced by the fluid (such as air or water) a body finds itself in, but we also speak about two different measures of heaviness, and both are somehow related to what makes things heavy. In everyday life, we might say two obviously contradictory things: (1) Water is lighter than steel, and (2) a big bucket full of water is heavier than a small steel ball. So, which is it?

Olive oil in water. In order to notice the contradiction and deal with it, we need to do two things. We need to observe carefully so we can distinguish different situations and cases, and we need to clarify words we want to use when we communicate about our experience. So, let us start with observing. In Fig.3.26, we see pictures of a drop of olive oil rising in a glass of water—the pictures have been taken from a video of the process.

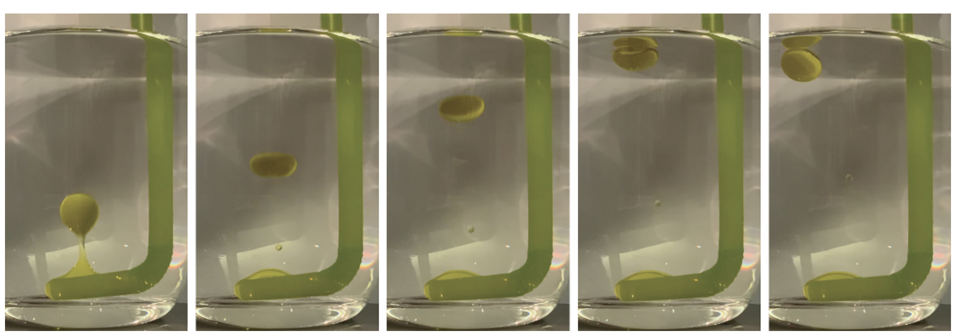


Figure 3.26: *A drop of olive oil is rising in a glass of water. The oil is introduced at the bottom of the glass through a straw.*

We would normally conclude the observation by saying that olive oil is lighter than water. If we had instead introduced a drop of maple syrup at the top of the water, the syrup would find its way to the bottom of the glass: maple syrup is heavier than water.

In a second set of observations, we could notice that if we filled the same glass once with water and then with olive oil, the glass with olive oil would be lighter on a scale: its weight is noticeably lower. For maple syrup, we would observe the opposite: the glass filled with syrup is heavier on a scale, i.e., its weight is greater than the glass with water. Since the volume of liquid is the same in all three cases (water, olive oil, and maple syrup), we have a situation where different liquids are „packed" more or less densely. We conclude that maple syrup is denser than water, and water is denser than olive oil (densities of some materials have been listed in Table 3.2).

Table 3.2: Density of some materials (typically at 20°C)

Material	Density / kg/m^3	Material	Density / kg/m^3
Air (sea level)	1.22	*Glass*	1900
Wood (pine)	420-640	*Concrete*	2200-2400
Alcohol	790	*Granite*	2650-2750
Olive oil	910	*Earth (planet)*	5500
Ice	917	*Steel*	7750-8050
Water	1000	*Copper*	8960
Glycerine	1250	*Mercury*	13690

Density. This is what we need in order to understand sinking, floating, or rising of an object—be it a solid, liquid, or gaseous material—in a fluid environment. A body made of a material that is less dense than the material of the surrounding fluid will rise (that is the situation we have in the case of Fig.3.26). If the body is made of denser material, it will sink, and if the density is equal, the body will neither rise nor sink, it will float. Imagine a blob of water in a glass of water; in other words, in your mind, visualize a certain amount of water inside the water. This blob of water will neither rise nor sink (if the layers of water are still). We have a „neutral" situation.

Relative density

This finally explains the idea of different scales of heaviness for different materials in different environments, which we introduced in Fig.3.13. What we called heaviness there is best understood as *difference of density of material and fluid environment*. All materials are denser than vacuum, so all will be heavy and fall in a gravitational field in vacuum (such as on the Moon[18]). In water, however, bodies made of certain materials will rise instead—if they are made of materials that are less dense than water. The value of „zero heaviness" indicated on the scales in Fig.3.13 indicates the „neutral" situation just mentioned.

Buoyancy—A case of Forces of Nature interacting. We can understand the dynamics of sinking or rising from the viewpoint of how *Forces of Nature* interact. Take the example of the drop of olive oil rising in water (Fig.3.26). If the drop were falling, we would know what to say: gravity causes this to happen. But what if the drop moves upward? This is certainly a case of non-spontaneous rising of a liquid, as if it were pumped. The question is if we can understand what is doing the pumping or raising.

What we have here is a case of *Gravity* interacting with *Gravity* (Fig.3.27), with the materials (water and olive oil) being the intermediary. Imagine, for easier mental visualization, the drop of oil being quite big. If the oil is near the bottom in the glass, we have lots of „light" oil below and a lot of „heavier" water above—the center of gravity of the water will be relatively high up. Once the oil has moved up, the situation is reversed: „light" oil above a lot of „heavier" water below—the center of gravity of water will have moved down while the drop of oil has moved up. So, we can say that gravity, mediated by water falling down, empowers the body of oil to rise, which is a gravitational process as well—this is like a *gravitational transformer*.[19]

Gravitational transformer

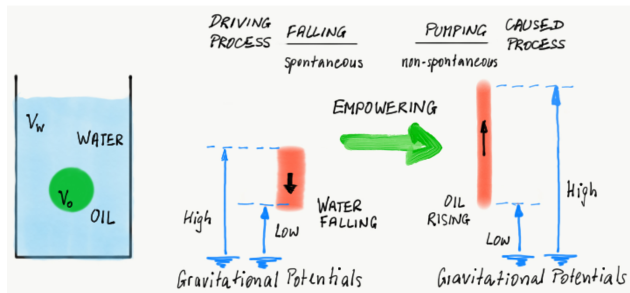


Figure 3.27: *Falling water pumps olive oil. As the body submerged in water rises, i.e., as its center of gravity goes up, the center of gravity of water goes down. Since the density of water is greater, the power of falling is greater than the power of lifting—the power is great enough for making the oil move and producing heat as a result of friction.*

A diagram can make clear what this means: Water flows from higher to lower gravitational potential whereas oil flows from lower to higher potential. A gravitational process drives another gravitational process (Fig.3.27).

It turns out that the changes of height, and therefore the changes of gravitational potentials, of water and oil are in inverse proportion to their volumes. If the volume of water takes 10 parts and the oil volume is one part, the change of the gravitational potential of oil will be 10 times that of the water. Now, since the density of water is greater than that of oil, the mass of water going down is more than 10 times greater than that of oil, therefore over-compensating the smaller change of gravitational potential. As a result, the power of water falling is greater than the power of the oil rising. This means that Gravity as the Force driving buoyancy, is more than powerful enough to force the oil up and drive a couple of additional processes. These processes are *Motion* and *Heat*: both the drop of oil and the surrounding fluid are first set in motion, and as soon as they move, there is friction that will lead to the production of *heat*. Once motion is steady, only the production of heat is caused by the excess power of water „falling."

3.7 The Role of Energy in Physical Processes

So far, our story of how we experience processes in nature and machines has not used the concept of energy much. This may surprise readers accustomed to standard presentations of physical science and engineering where we are given the impression that energy is the all commanding concept, the one idea that explains how nature behaves and why.

The truth is, we can learn much about the natural world around us without placing this concept center stage. This does not mean that the idea behind the term *energy* is not important. After all, we have needed the notion of *power* without which we would not have been able to tell our story, and we know that power and energy are deeply entwined. It is time now to study this relation in some detail in order to get prepared for using it in the context of Heat, Electricity, Substances, and Motion (see Chapter 4 and Volume 2). In Chapter 5, we shall construct visual metaphors for understanding the role of energy in physical processes.

An analogy for the relation between energy and power

Let us return to what was said when we described interactions between *Forces* as economic transactions (see Section 3.1, p.117): money is passed between agents in an economic transaction, and this is not unlike passing „something" between natural agents when they interact; we have called this „something" *energy*.

This analogy between energy and money is made even more meaningful if we search for an idea in economics that could be related to power. In macro-economics, there is a concept of *velocity of money* which, roughly, describes the rate of interactions in an economy as measured by the rate at which money is used, i.e., passed around and flowing through the economy.[20] Indeed, money, by itself, i.e., how much there is, is not all that important—if it is not used, if it is not passed around, the economy is at a standstill. If we compare power in physical processes to velocity of money in economics, we get a deeper understanding of what power is all about, and how it relates to energy. Power is the „velocity of energy," the rate at which it is „passed around" from agent to agent in physical interactions.

Velocity of money

If *velocity of money* is the basic notion for a living economy, in what sense is the concept of *money* important? First, we associate money stored—the amount of money in someone's bank account—with the wealth of a person; this is the meaning of *money* as *potential economic power* of that person. A second possible meaning of *money* is the quantity of money passed in a particular transaction. It is used in the sense of (a) how much has been accomplished in a transaction or (b) how much of a change has been incurred—change of amount of money in accounts of the agents involved. Importantly, using amounts of money as part of financial reporting does not say anything about dynamics, about how fast things happen and how strongly economic agents interact.

Velocity of money versus Money

The same is true for energy. By itself, amount of energy can describe (1) how much energy is stored in a storage element (how „rich" that element is in terms of energy), and (2) how much has happened in the course of a physical process and what this may mean in terms amount of energy exchanged, energy transferred, and the change of amount of energy in storage elements involved in the process. As in economics, amount of energy does not describe processes dynamically—it tells us how much has happened from an energy accounting perspective.

Comparing energy to money conveys an important additional message: just as money only carries meaning by accompanying an economic transaction, without constituting the transaction itself, so energy accompanies an interaction but does not constitute the interaction. Physical processes are determined by the Forces of Nature at play, by the tensions and the fluidlike quantities flowing, being produced and stored, and interacting. Energy tells only a small part of a given story.

Postscript on analogy. There is an aspect about money and economic transactions that could confuse us and make it more difficult for us to understand money as an analog of energy. In an economic transaction, goods and services flow in one direction and money in the other: I provide you with a service or some goods and you give me money.

What comes closer to energy is the value of goods and services which flows in the same direction as what is exchanged. We could have used value as an analogue to energy; however, it is simply more vivid to focus on money in order to make the point about energy and power. At any rate, an analogy always only goes so far—analogy is not identity; it is one of the mental tools available to us that helps us see one thing in the light of another and so learn something new about a domain we might otherwise not easily understand.

Energy made available, transferred, and stored

Before we can make use of energy accounting in a more meaningful and quantitative way, we need to formalize the basic ideas underlying the energy principle. These ideas are a condensed version of the eight points we made in Section 5.3. They can be summarized as follows: energy can be exchanged (made available and used) in the interaction of agents, it can be transferred, it can be stored, and it is conserved (i.e., it can neither be produced nor destroyed).

Properties of energy

Formal assumptions made about energy

In our discussion of the notion of *energy* we have made a number of assumptions that, together, describe what we mean by it in formal terms:

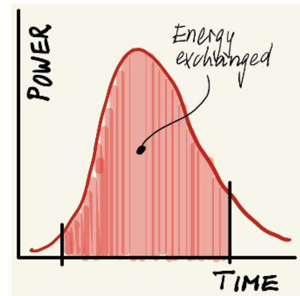
1. *Exchange*: Energy is *made available* and *used* in interactions of Forces of Nature. This happens as fluidlike quantities either relax or tense up.
2. *Transmission* or *transfer*: Energy is carried by fluidlike quantities to and away from places where interactions take place.
3. *Storage*: Energy can be *stored* in physical objects (materials and fields).
4. *Conservation*: The total amount of energy in nature always stays the same. Energy can neither be created nor destroyed.

Power and energy exchanged. We have formalized the relation between the tension present in an interaction, the flow of the fluidlike quantity, and power on a few occasions (see Section 3.6 and Eq.(3.13) for the power of a waterfall; and Section 4.4 and Eq.(4.3) for the power of heat). What we have seen can be summarized in the simple relation

$$Power = Tension * Flow. \tag{3.14}$$

Moreover, we have presented numerical examples of power, both of water and heat, so we could get acquainted with some numbers that might come up in everyday life, usually when technical devices and power plants are discussed. To give an example, when 1 kg of water falls through a height of 1 meter, the power of this process here on Earth is almost precisely 10 W. Since different *Forces* can be coupled in various different ways, fixing the power of one process numerically allows us to determine the power of other phenomena as well. Expressing coupling with the help of power and energy allows physicists to consistently fix units of all the other quantities important in quantitative science.

We now turn to the question of how amounts of energy exchanged in an interaction are determined if we know the power of the process. Since power is to energy exchanged as a current of water is to amount of water transported, we can apply the mathematical method of summing (integrating) power over time—the method has been explained vividly and graphically in Section 3.2 (starting on p.130), specifically in the Box on p.131. If the power of a process is constant, we simply multiply this constant number by the length of period of time over which the process is active:



$$Energy\ exchanged = Power * Period\ of\ time.$$

So, if the 1 m high waterfall having a flow of mass of 1 kg/s is active for one hour, the falling water has made a quantity of $10 \cdot 3600$ W·s $= 3.6 \cdot 10^4$ J available. Joule (J) is the name of the standard unit of energy. The units of power and energy are simply related: J = W·s (see Table 3.1).

Units of energy: kWh versus Joule

Here is another example of practical everyday importance. If we had an electric heater working at a power of 1000 W (which is also called 1 kilowatt = 1 kW) and let it operate for one hour, the energy made available for producing heat equals 1000 W · 1 h = 1 kWh (one kilowatt-hour; h stands for hour); this is the same as 1000 W · 3600 s $= 3.6 \cdot 10^6$ J. In other words, the often used energy unit called kilowatt-hour equals 3.6 million Joule. The 1 m high waterfall would have to work for 100 hours in order to make this much energy available.

If the power of a process varies over time, we simply sketch its values as a function of time in a diagram and determine the area between the curve obtained and the time axis for the period of time of interest (cf. Box on p.131).

Energy flow and energy transferred. The next point for us to consider is energy transfer, i.e., when energy is carried by energy carriers (such as visualized in Figs.(5.15)-(5.24), or if it is transported convectively or radiatively, i.e., stored in and flowing with fluids or light.

Energy transferred by energy carriers is characterized by the fact that the carrier—heat, water under pressure, electric charge, amount of motion, etc.—is flowing conductively, i.e., driven by a gradient of its associated potential. Note that this is not the case in convection or radiation. Energy transported in hot water is not flowing because the water is hot but because it is driven by a pump, i.e., by a pressure difference. However, if we have a conductive flow of the carrier, heat flows at a certain temperature, air or water at a certain pressure, electric charge at a certain electric potential, and amount of motion at a certain speed. If this is the case, there is a simple relation between the strength of the energy current, the carrier current, and the potential:

$$Energy\ current = Potential * Flow\ of\ carrier. \tag{3.15}$$

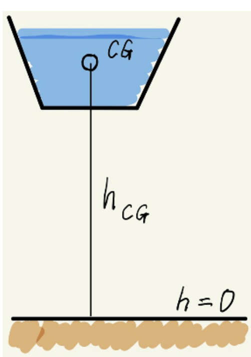
This form is necessary if we want to recover our basic equation (3.14) for how to calculate the power of a process. Imagine water flowing at a height h_1 toward a waterfall where it will fall to a lower height h_2. If we accept Eq.(3.15), the energy current associated with the current of mass I_m flowing at the higher level will be

$g\,h_1 I_m$. The water flowing away at the lower level will carry an energy current equal to $g\,h_2 I_m$. The rate at which energy is made available in the fall of water, i.e., the power of the waterfall, should be equal to the difference of these two values, $(g\,h_1 - g\,h_2)\,I_m$; this corresponds to the expected result. As in the case of power and energy made available, we can calculate amounts of energy transferred from energy currents if we sum the current over time. The mathematical procedure is exactly the same as the one described for power.

Here is the first of two examples that show why knowing energy currents and amounts of energy transferred can be of interest. Consider heating a building. Engineers and architects can calculate the strength of the energy current carried by heat out of a building in winter. The current of heat depends upon the temperature difference between inside and outside and the number that specifies how easy it is for heat to flow through the roof, walls, and windows of the building. One then predicts the energy current for changing temperature differences over the course of the heating period, adds it up over the period and finds how much energy is typically lost from the building into the environment.

This is important to know since one wants to understand what kind of heating the building should have, i.e., how strong the heating needs to be, and how much fuel is needed during winter—if we assume the heating to be done by burning fuel. The amount of energy that can be made available by burning fuels depends upon the particular type of fuel at hand. One kilogram of heating oil contains about $45{\cdot}10^6$ J $=$ 12.5 kWh energy that can be made available upon burning. Fuels are commonly rated according to how much energy they can make available, and this allows us to know how much fuel we will need.

Amount of energy stored. The second example concerns how much energy can be stored with water in an artificial lake in the mountains high above a power station in the valley. The answer to this question is important if we want to know how much energy can be supplied to customers. The result can be expressed in fairly simple terms: the amount of energy that can be made available by draining the full lake equals the height h_{CG} of the center of gravity of the water relative to the power station, multiplied by the strength of gravity (see Eq.(3.6)), multiplied by the mass of the water. The mass of water is obtained from the volume of the lake, and this is calculated on the basis of the shape of the terrain (this information also yields the level of the center of gravity).



Take the artificial lake Lac de Dix in the Swiss Alps. It has a maximum volume of about 400 million cubic meters, and the center of gravity is more than 1700 m above several power stations powered by the water of this lake. Therefore, this amount of water corresponds to roughly $7{\cdot}10^{15}$ J of energy stored, which is equivalent to $1.9{\cdot}10^9$ kWh. If 10 kWh of energy delivered by electricity costs one Swiss Franc, this amounts to a lot of money!

Deriving formulas for energy stored

Calculating the energy stored with water in a lake sounds easy, but the question we should ask is how such a simple formula is derived—how do we know that this is how to calculate the energy stored? The answer goes like this: we calculate the energy current carried by the water on the basis of its pressure at the level of the hydroelectric power station. If we accept Eq.(3.15), this current equals the pressure of the water multiplied by the current of volume of water. This energy current is calculated for every moment during draining, i.e., as the water level changes, and then summed over time until the reservoir is empty.

This is pretty much the approach taken by physicists when they derive expressions for how much energy is stored in various physical objects, including how much energy is in a battery, in water at a certain temperature, in a body moving at a certain speed, or in a certain amount of solar light. If the conditions relevant for Eq.(3.15) apply, i.e., if the process of flow of a fluidlike quantity carrying energy is conductive, one can derive (changes of) amounts of energy stored in all sorts of storage elements.

Accounting for amounts of energy

The business of accounting for energy can be quite important. There are two realms where energy accounting is commonly used: one is science, the other is energy technology and related economics. In science, it may be convenient to use before-and-after types of reporting on the change of the energy of physical systems rather than following the temporal course of a process—indeed, there are fields of physical science such as quantum physics where this is the only possible approach to modeling. In energy engineering and economics, we are interested in how energy required for running our technical devices is transported and made available, and how much this will cost the customer.

Energy accounting in physical science. Not surprisingly, accounting in finance works by comparing states of accounts before and after some activity. After all, we cannot see money moving through the economy (unless we observe someone handing bills or coins to someone else)—we only have direct access to amounts of money in accounts, i.e., in „storage elements" for money.

This situation is fairly similar to many applications in physics where accounting for amounts of energy is done. This requires us to quantify amounts of energy stored in physical elements. Since energy in storage cannot be seen, we need to be able to develop expressions for energy stored in terms of other quantities. This is what we have described above for the case of water in an artificial lake high above a power station. Another example arises when blood from the left ventricle of the heart fills the aorta. We do not „see" the amount of energy stored in the aorta increase—all we can ascertain are changing values of volume of blood and blood pressure; changes of energy stored with blood in the aorta will be expressed with the help of these variables.

Vertical toss of a ball

Here is an example of energy accounting that leads to answering a question often asked in school science: How high will a ball will fly if we throw it up vertically, given the initial speed (Fig.3.28, left)? The idea behind answering this question is the following: a moving body contains a quantity of motion (resulting in a certain speed) and a certain amount of energy (Volume 2)—the amount of energy stored in the moving body is determined by quantity of motion and speed. As the body climbs vertically in the gravitational field (Section 3.3) and slows down, the energy of the field[21] increases whereas the energy of the body due to motion decreases. If nothing else disturbs the balance, the energy lost by the ball equals the energy gained by the field; when the ball stops, all its energy has gone to the field. Since we know how the energy of the field depends upon the mass of the body and its height in the field—remember the case of water in an artificial lake—we can find how high the ball will rise. Naturally, air resists the motion and so disturbs the perfect balance, but if we are allowed to neglect this effect, applying energy accounting lets us find out how high the ball will fly.

We can even calculate the speed of the ball at every point along its vertical path. What we do not find, however, is when the ball will be at a given point, and when it will have arrived at its highest point. In other words, we cannot really answer the question of how the ball moves—all temporal information is lost. For instance, the James Webb space telescope was recently launched into space toward a particular point far away from the Earth where it will be „parked." Energy analysis of the type discussed here can tell us quickly how fast the rocket needs to be (after acceleration) for the telescope to make it to that point. We will not be able to say, however, how long it will take the object to get there—a day, a week, a month, or several months?

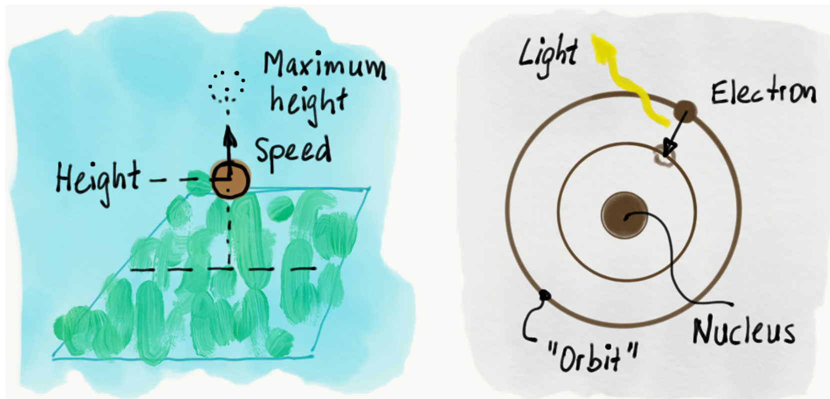


Figure 3.28: *Left: Vertical toss of a ball. We can calculate the speed of the ball for every height we wish and find the maximum height reached. Right: Classical (non-quantum) imagery of a „quantum jump" of an electron from a higher to a lower „level." After the „jump," the atom will be in a state having less energy. The energy is carried away with a quantum of light that is produced. Note the difference in size of the physical objects: the ratio of sizes is more than* $10{\cdot}10^{10}$.

Energy accounting in quantum physics

This before-and-after form of accounting is very important in quantum physics. All we usually do there is calculate changes of state of a quantum system such as an atom. We say, for instance, that the electron of a hydrogen atom makes a „quantum jump" from one quantum state to another such state which is accompanied by a certain change of amount of energy of the system (see Fig.3.28, right). We will never know how the electron got from „here" to „there" and certainly not how fast. In fact, there is no information about motion, there is not even a proper „here" or „there;" all we are able to calculate is this „change of state" which is characterized by the change of certain variables such as energy. This is quite curious: time does not seem to play a role in certain fields of physical science; quantum physics and traditional thermodynamics are two of these. This is in stark contrast to how we think about processes and change in nature from the viewpoint of *Forces of Nature*, as we have done.

When time does not seem to matter

Energy is one of these variables. So, when a hydrogen atom jumps from a „higher" to a „lower" state, its energy is diminished by a certain amount. In response, a quantum of light carrying this exact same amount of energy is emitted by the atom. The energy per quantum of light determines its color, and by observing the light we can find out what has happened to the atom.

Energy accounting in energy engineering and economics. Few people are likely to be very interested in the questions of how physicists deal with the concept of energy. It is one of the many quantities in physics that allow for certain questions to be answered that might be more exciting—what we find out about how nature works is interesting also for lay people but the role of energy in it is secondary.

This is quite different when it comes to our everyday use of technical appliances—running machines and whole factories; lighting and heating homes; growing, cooking and cooling food; using transportation, and more. This has traditionally been the business of engineers whose job it is to design and build efficient devices; but recently it has become clear that we should all be concerned with energy matters in our daily life. The reason for this is not so much energy itself but what consequences we incur by making it available, transporting it, and using it. The message is simple and clear: energy is a quantity used for accounting what, or rather how much we do, and what we do has material consequences—there is no such thing as „pure" energy we could handle and use without actually changing things physically in our environments.

Burning fossil fuels

When the use of fossil fuels for making energy available became important for our everyday activities, some 200 years ago, humanity started on a path that is profoundly changing the chemistry of our atmosphere—and not just that. Burning fossil fuels creates and releases carbon dioxide and other gases that had been taken out of the atmosphere hundreds of millions of years ago. These gases, mixed into the air of the atmosphere, make it harder for heat to leave the planet (Section 4.6). As a consequence of increasing the resistance the air puts up to the flow of heat from the Earth into outer space, the temperature at the surface of the planet is rising. The reason is simple: whatever heat is produced needs to get out again or the planet will boil in no time; and if the obstacle for heat to get out is greater, the drive for flowing must get higher.

Energy is a commodity

There are many other material consequences of our actions that we need to be aware of. Even though energy per se does not matter—what matters from a physical perspective are material objects and fields—it proves to be a powerful accounting tool for at least some of our activities. This is why it plays an important role in certain fields of economics where energy is treated as a *commodity*, just like all the other commodities that are made, traded, used, and discarded. And just like for any other commodity, there is an amount associated with it that lets us count how much we have, need, and use. This is very likely the most important aspect of the concept of energy for us in everyday life. We should become conversant, at least to some extent, in how much energy is required for certain types of lighting, heating, computing, moving about, and producing, processing, and consuming food. It matters that we should not be rattled by Joules and Kilo-Watt-hours, or by calories and barrels of oil equivalent, etc. Above all, we should definitely understand the difference between energy and power and know that the former is measured in Joules and Kilo-Watt-hours and the latter in Watt, kilo-Watt, Mega-Watt, Giga-Watt, and Tera-Watt, just to mention some of the basic and derived units.

Distinguishing between the units for power and energy

The global rate of human energy use. Global energy use (Fig.3.29) is best described by the rate at which this happens which can be understood as the strength of its flow, as in power or energy current. What we get in modern times are huge numbers, almost 200 thousand Tera-Watt-Hours, in one year, where Tera stands for a million million. In terms of „throughput" or energy current, that converts to 20 TW (Tera-Watt). If a single large electric power station is rated at a power of 1 GW (Giga-Watt), and if we had all our energy delivered electrically, it would take 20,000 such power plants running continuously to supply our current energy needs.

We could compare this energy flow to the source rate of energy from solar radiation here on Earth (the rate at which energy brought to us by the Sun's light is absorbed by our planet), which equals 120,000 TW (see Section 4.6 on how to determine this number). In other words, this rate is 6000 times bigger that the throughput of our technical civilization. Our energy use over the last 200 yers is shown as a percentage of the source rate of energy from solar radiation in Fig.3.29.

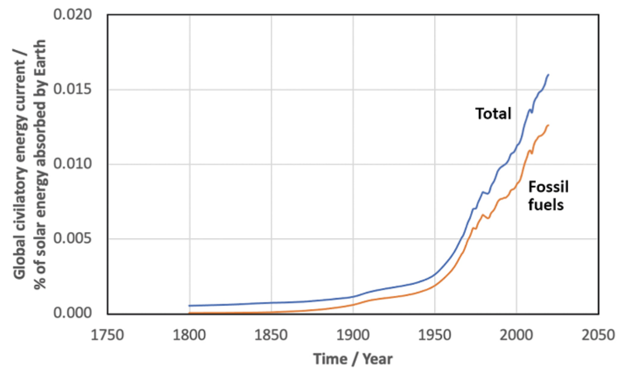


Figure 3.29: *Global energy flow over the last 200 years. The value given on the vertical axis is in percent of the energy of solar radiation constantly absorbed by our planet. Data supplied by Our World in Data: Energy Production and Consumption; visited on December 30, 2021.*

Energy use in agriculture

Another interesting number is the energy supplied to all 7700 million people on Earth through food. If we take the average requirement of a person as stipulated by the UN, we get a rate of 0.67 TW, which is about 30 times smaller than the global technical energy use. Apparently, the agricultural sector (including food processing) uses about a third of our technical energy flow, about 7 TW. In other words, as far as energy for food is concerned, the „agri-food sector" is only about 10% efficient. Note that this is not „biological" efficiency, i.e., energy efficiency of plant life. Energy stored in food is energy made available to us by nature directly—by plants and animals we consume; we do not „eat" the energy used to run agriculture. In other words, a flow of 7 TW is needed to „harvest" a flow presented to us by nature having a magnitude of about 0.7 TW.

We read that about 13% of global land surface is used for growing plant food (total agricultural land, including mostly pastures, amounts to less than 40% of land area). 13% of land area equals less than 4% of the surface of the planet which collects energy from the Sun at a rate of about 4,500 TW (if we assume agriculturally useful land to receive the average of sunlight of different areas on the planet). The energy that ends up in food consumed by humans is therefore about 0.015% of the solar energy current that falls on agricultural land. By the time the planet supports a highly developed biological species like us humans, only a small fraction of the energy supplied by the Sun can be used directly for food. This should be compared to the efficiency of plants which varies between less than 1% and maybe 3% (this last number is for sugar cane[22]).

3.8 Experiencing Fluids Creates Schemas

This chapter has given us insight into fluids and gravity, and into some aspects of how to formalize images, if only very cautiously, we have been developing throughout this and the previous chapter. However, this chapter is fundamental in a sense that goes beyond the particular subject treated. Phenomena having to do with fluids in general, and with water in particular, are experientially foundational—they give rise to the basic *schematic abstractions* we need for understanding and communicating about our encounters with nature.

Schematic abstractions

Before we take this issue up again in much more detail in Volume 2, we want to simply list some of these abstractions and show how they are used in metaphors. The reason is simply that we want to be prepared for what we should observe when we describe how Forces are experienced. We will make use of these schematic forms again and again in the following chapters introducing us to still other Basic Forces of Nature such as Heat, Electricity and Magnetism, Substances, and Motion.

Schematic images arising in the experience of water. If we limit our view to water as a fluid and coupled to Gravity, we are still presented with a rich experiential scene. It is important that we realize that the experience made possible by fluids is a result of our embodied encounters that need not be consciously processed. This is similar to much of what arises in the rest of our sensorimotor interactions with our environments that provide us with *spatial and temporal abstractions*—we understand space and spatial relations such as *front* and *back*, *left* and *right*, *near* and *far*, without having to reason about them. We know the meaning of *path* along which we can travel, and we understand what it means to move *slowly* or *fast*. Gravity gives us humans with our upright posture this ubiquitous sense of *up* and *down*, *steep* and *gentle*, and we certainly understand the feeling and meaning of *balance*.[23]

Spatial & temporal abstractions

Moreover, our experience of processes lets us understand quite intuitively what is meant by *causing*, *forcing*, and *making*; *letting*, *enabling*, and *permitting*; *hindering*, *obstructing*, and *blocking*. These are all schematic abstractions arising from our embodied interactions without which we would never understand the world around us. Just think about how frequently we use such terms when we speak about everyday experience.[24]

Now, add to all these schemas those that must arise from our experience of encounters with fluids in general and water in particular. We obviously borrow a lot of schematic understanding from our experience with fluids: *intensity* and *tension*; *substance* (stuff) and its *amount*, *containment*, *in* and *out* (of containers); *flow* and (spontaneous) *downhill flow*, and necessity for *pumping water uphill*; and, finally, we internalize *level* and *level difference*, *potential*, and *power*.

Using schemas in metaphoric projections. Consider how schemas such as these appear in our thinking and speaking *figuratively* about water, and what they mean for our understanding of the concepts we formed. We shall discuss only one example of such usage which appears when we *project* schemas of *verticality* (up-down and level, moving up or down, moving fast or slowly, returning to the same level, etc.) onto the experiential domain we call *pressure*.[25] Simply go back to some of the previous descriptions or find expressions you would use yourself when incorporating the term *pressure* in expressions concerning fluids.

Figurative thought

We will say things like „the pressure is (very) high," „air pressure has gone down lately," „as I am hiking up to the mountain top, air pressure goes down," „the pressure has changed," „the pressure is changing only very slowly," „pressure differences are very low in this case," „all that sugar on the berries has created a high osmotic pressure gradient„" „blood pressure has returned to the same level," and „in a shock wave, there is a steep pressure gradient."

This kind of *projection* leads to what we call a *metaphor*. An important example of concrete experience that is given abstract form in body and mind is that of

Metaphoric projection

Pressure as vertical level

verticality. When we project what we know in the *domain of verticality*—aided by the experience that gives us the SCALE schema—onto the experiential domain of *pressure*, we get the PRESSURE IS A VERTICAL LEVEL metaphor (see Table 3.3).[26] If a metaphor is the projection of schematic structure from a *source* (here: VERTICAL LEVEL) to a *target* (here: PRESSURE), then we can make the metaphor „visible" through showing concrete cases of projecting elements from vertical scale to pressure.[27] Just take the example where our feeling for and knowledge of moving up or down at a certain speed is projected onto how fast the pressure of a fluid changes. Lastly, what we do here is relate two polarities, verticality and fluid intensity, to each other.

Table 3.3: The PRESSURE IS A VERTICAL LEVEL metaphor

Source (vertical scale)		Target (pressure)
Level	→	Pressure
Level	→	Hydraulic potential
Highest/lowest point	→	Highest/lowest pressure
Moving up/down	→	Pressure rises/falls
Speed of moving up/down	→	Rate of change of pressure
Level difference	→	Pressure difference
Level difference as tension	→	Hydraulic tension
Landscape	→	Pressure landscape
Slope/gradient	→	Pressure gradient

In the case of water or other liquids in simple hydraulic systems, and air in the atmosphere, our body, and balloons, we most likely „derive" the notion of *pressure* from observations and the logic of how we experience *Forces of Nature*—such as when we study water in communicating tanks (Fig.3.19). We know from all sorts of experience that intensities and tensions are elements of understanding phenomena, and so we project basic schemas derived from sensorimotor activity onto the perception of fluid systems as well.

There is an interesting metaphoric phenomenon that shows how important our experience of *Forces of Nature* can be for the understanding of our social and psychological lives. Our knowledge of *pressure* provides such an example as when we speak of social or psychological pressure or tension: „Pressure at my job has risen lately" and „all that tension between them has become unbearable."

Clearly, this works the other way around as well: the experience of social and psychological pressure and tension is well suited to help us create meaning for our physical (natural) experience of fluids under tension. Experience of *Heat* is another example which is related metaphorically to *Anger*; we shall see this exploited in a story presented in Chapter 4 (p.188).

Notes

[1]This idea was used by Sadi Carnot in 1824 (Carnot, 1824) when he compared the operation of *Heat* in steam engines to that of water falling through a height difference (Chapter 4).

[2]Liquids are compressible as well, but not very easily. Here, we shall treat liquids as incompressible which means that the volume of a given amount of liquid cannot be changed.

[3]The mechanism is obviously important; without it, the Forces cannot interact in the manner envisioned. And it is important when we are interested in the efficiency of the interaction. However, we are not focusing upon such aspects at this point.

[4]Scientists and engineers acquainted with the power of waterfalls and wind turbines will note that the simple form that holds for waterfalls does not hold for a windmill. The reason for this is that wind will be understood, for the purpose of an energy analysis of wind turbines, as the convective transport of momentum. The simple expression for the power of a waterfall applies to the (differential) power of the (conductive) momentum flow through the material structure of the wind turbine as the result of a (small) drop of speed of the wind. Integrating this archetypical form of the power relation over the speed of the wind as it changes from a high to a low value will deliver the proper expression of the power of wind driving the turbine.

[5]In colloquial terms, and in economic transactions, *exchange* usually means that you give something to someone and receive something in return. In physical science, interactions are typically described by using imagery of *transfer* of some physical quantity from an agent to a patient; in other words, we imagine a one-way transfer of some „stuff." However, when this happens, the agent is affected as well—it experiences a *loss* of whatever it passes to the patient and reacts accordingly. Speaking of interactions as involving an *exchange* is quite common in modern physics; for example, electromagnetic interaction is understood as the exchange of photons (light), i.e., the transfer of light from one charged particle to another interacting with the former (photons are called the *exchange particles* of electromagnetic interactions). Therefore, the term *exchange* suits our case where energy is passed from an agent to a patient.

[6]Amount of motion is Newton's quantitas motus („Quantitas motus est mensura ejusdem orta ex Velocitate et quantitate Materiæ conjunctim," Newton, 1687, p.2), our modern concept of *momentum.* In a wind generator, the momentum brought by moving air—this is a convective flow of momentum—interacts with rotational momentum (spin) which, in turn, interacts with electricity.

[7]There is a flow of „normal" matter from the Sun—as a result of what is called the solar wind. The current of mass is estimated to be about $1.5 \cdot 10^9$kg/s.

[8]In physics, we might prefer to use the term *gravitation* for both the phenomenon and the theories used to describe it. Here, we shall continue using the word *Gravity* since it appears to appeal more directly to everyday informal usage. Moreover, by using the name *Gravity*, we want to point to the perceptual unit presenting itself to us rather than, say, just the mechanical force of gravitation.

[9]As we shall see shortly, *heaviness* can be confusing as it seems to depend strongly upon easily changing circumstances. Moreover, as we shall discuss further below, heaviness is often felt as relating to what physicists call *density* of a material. This raises the question why we do not directly introduce the concept of *weight* which seems to be better defined. However, this is not really so, as we can see if we note phenomena such as *weightlessness* (in a spacecraft circling the Earth or, closer to home, of a freely falling body) or *apparent weight* (which is related to the phenomenon of buoyancy of bodies submerged in fluids such as air or water).

[10]What we have introduced here as heaviness cannot be the weight of a given body, at least not in general. The feeling for heaviness is closer to the density of a material (see p.160).

[11]As to units of physical quantities, we first have to settle on the system of units we want to use. As is „standard" in physics, we use the SI-system (Système Internationale). In this system,

we can then choose *standard* units or, what is quite common, multiples or fractions (by factors of 10, 100, or 1000) thereof. In the SI-system of units, there are *basic* units for quantities that are chosen as basic such as time, length, mass, and temperature. Standard units of these are s (second), m (meter), kg (kilogram), and K (Kelvin), respectively. Bar and mmHg for pressure are not in the SI system, neither are inch and mile for length, and neither are hour or week for time. Multiples or fractions of a standard unit such as m (meter) can be cm (centimeter), mm (millimeter), nm (nanometer), or km (kilometer). So, the standard unit of strength of gravity is J/(kg·m) (Joule per kilogram and meter), which is the same as N/kg (Newton per kilogram), which is the same as m/s^2 (meter per second squared). In other words, it is a derived unit, i.e., derived from the basic standard units of the SI-system of units.

[12]Information on gravitational waves can be found at https://en.wikipedia.org/wiki/Gravitational_wave. Their detection and the instruments used in this endeavor are described at https://en.wikipedia.org/wiki/First_observation_of_gravitational_waves. The LIGO gravitational wave detector laboratory has its website at https://en.wikipedia.org/wiki/Gravitational_wave. NASA has webpages dedicated to gravitational waves: https://spaceplace.nasa.gov/gravitational-waves/en/ (sites visited on September 17, 2022).

[13]We make an effort to work in standard SI-units whenever possible, or convert non-standard units into standard ones whenever a calculation is attempted. Standard units for distance or length is meter (m). The unit for mass is kilogram (kg), and the unit for energy is Joule (J). Additional important units are second (s) for time, Watt (W) for power, cubic meter (m^3) for volume, Pascal (Pa) for pressure, Volt (V) for electric tension, Ampère (A) for strength of current of electric charge, Kelvin (K) for temperature, mole for amount of substance, and Newton (N) for mechanical force. There are many more.

[14]If a satellite is on a geostationary (or geosynchronous) orbit around our planet, it takes 24 hours (actually, 23 hours and 56 minutes) for one complete revolution. As a consequence, the satellite seems to stay above the exact same location seen from Earth. For this to work, however, the plane of the orbit must be the same as the plane of Earth's equator.

[15]In traditional physics courses, where motion is treated before all the other subjects, it is customary to introduce the potential after the concept of strength of the gravitational field (i.e., gravitational flux density). We prefer to discuss intensity (potential) and tension (potential difference) before we introduce the notion of field strength (as the measure of how fast the intensity changes as we climb). We think that a child can appreciate the height of a waterfall as a fundamental aspect of gravity before being able to deal with strength of gravity.

[16]Modeling is constituted by the step of selecting relations (equations), and simulation is the step of solving the model equations.

[17]Using the term fluid instead of liquid is no accident here. Vertical flow of air is subject to gravity just as much as is the flow of water. Indeed, we can have powerful „air-falls" in so-called downbursts, when wind comes down vertically onto the land. One can sometimes observe trees being felled by a storm in a radial pattern starting from a point. See the report in a Swiss newspaper on July 14, 2021: https://www.tagesanzeiger.ch/es-war-eine-gewaltige-druckwelle-ich-hatte-angst-374054358144.

[18]We can find videos on the Internet of astronauts dropping a hammer and a feather at the surface of the Moon.

[19]A transformer, such as an electromagnetic transformer or a mechanical gear box, „transforms" tensions, i.e., potential differences. Forces of the same type interact in a way that the tension of the agent will be different from that of the patient by some factor. If the coupling is ideal, what stays constant is the power of agent and patient.

[20]For a description of this concept, see the website of the Federal Reserve Bank in St. Louis; specifically, see https://fred.stlouisfed.org/series/M2V (visited on December 27, 2021).

[21]The somewhat vague expression „energy of the field" actually expresses the following idea. The physical situation is defined by the geometric configuration of the Earth and the body (i.e., the body's distance from the center of the Earth) and the configuration of the gravitational field created by Earth and body. The amount of energy stored in this situation depends upon, and is found in, this configuration. This is what is traditionally call *potential energy* of a body in a gravitational field. Importantly, the energy is *not* found in the body!

[22]https://www.britannica.com/science/photosynthesis/Energy-efficiency-of-photosynthesis. Visited on December 30, 2021

[23]Many of these schemas have been identified as *image schemas* in cognitive linguistics. See Johnson (1987); Hampe (2005).

[24]The schemas mentioned here were among the earliest introduced in cognitive linguistics—they form a group called *force schemas* (see Talmy, 2000).

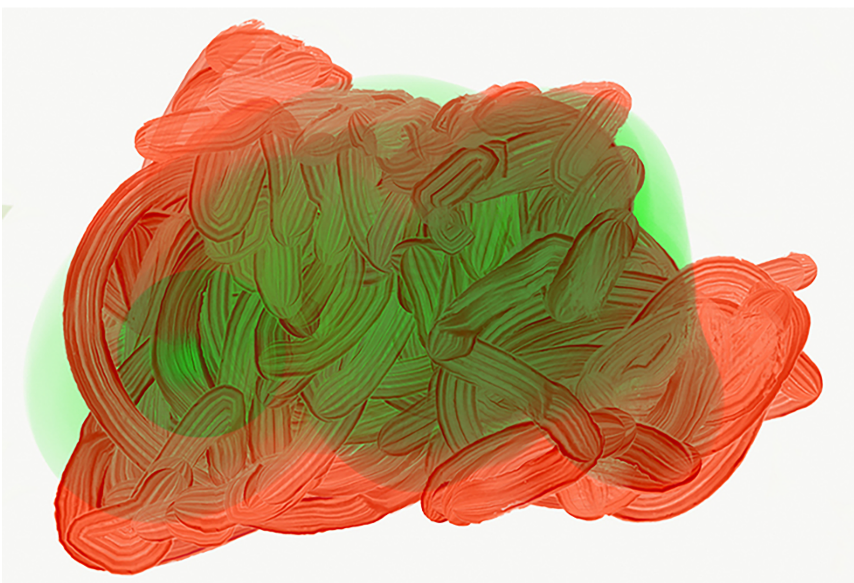
[25]What we are observing here are projections of understanding from one domain onto another that lead to so-called *conceptual metaphors*. Conceptual metaphor was introduced by Lakoff and Johnson (1980) and has since played an important role in cognitive linguistics. In recent years, it has found its way into studies in science education (Amin, 2009; Amin et al., 2015).

[26]The particular form of presentation of a conceptual metaphor has been taken from Lakoff and Johnson (1999).

[27]Metaphors that arise from projecting schemas and other simple domains onto other experiential domains, are examples of *Primary Metaphors* (Grady, 2005); PRESSURE IS A VERTICAL LEVEL is an example; others are SIMILARITY IS CLOSENESS, HAPPY IS UP. Projecting complex domains onto other domains results in various types of conceptual metaphors (Lakoff & Johnson, 1980); examples are HEAT IS A FLUID and A THEORY IS A BUILDING (in the latter cases, we can usually identify simpler sub-metaphors that create a metaphoric web). See Volume 2 for an in-depth description of metaphor.

Chapter 4

Heat as a Force of Nature



„Lava under Rocks" by ML (4 years 8 months)

Here on Earth, nature comes to life with the „fire" of the Sun—when the Sun's light is received, *heat* is created to which, as Sadi Carnot said, „*we must attribute the great movements which attract our attention here on Earth; it is to heat that we owe the agitations of the atmosphere, the rise of clouds, the fall of rain and other meteors, the currents of water which channel the surface of the globe, and of which man has thus far employed but a small portion. Even earthquakes and volcanic eruptions are the result of heat.*"[1]

H. U. Fuchs, F. Corni, *Primary Physical Science Education*,
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Sadi Carnot wrote these lines quite a while ago, in 1824. They make clear that he treated *Heat* as a *Force of Natur*e (FoN), very much like we do in our book. Moreover, in the first lines of his essay, he explained that we could draw on its *power*, and that this could be done through heat engines:[2]

> *"No one is unaware that heat can be the cause of movement, that it even has a great motive power: the steam engines, nowadays so widespread, are a proof that speaks to all eyes.*
>
> *„It is to heat that we must attribute the great movements which attract our attention here on Earth; it is to heat that we owe the agitations of the atmosphere, the rise of clouds, the fall of rain and other meteors, the currents of water which channel the surface of the globe, and of which man has thus far employed but a small portion. Even earthquakes and volcanic eruptions are the result of heat.*
>
> *„It is from this immense reservoir that we can draw the moving force necessary for our needs; nature, by offering us fuel everywhere, has given us the faculty, at all times and in all places, of giving birth to heat and to the power which results from it. To develop this power, to appropriate it to our use, such is the object of heat engines."*

Carnot's objective was to find out how *Heat* actually works in heat engines of any type, and how one could determine what their maximum power would be—back then, steam engines were extremely inefficient. To this end, he created a powerful analogy between heat acting in heat engines and water working in a waterfall—it is the most important example in the history of physics that suggests waterfalls as an archetypical natural process.

The form of explanation arising here, if we accept Carnot's imaginative step, will accompany us throughout the rest of the book. In the following paragraphs, we shall briefly outline what we need to deal with in this chapter on *Heat*.

Hotness & temperature

Heat and temperature. Long before Carnot's time, it was clear that one needed to distinguish between *intensities* and *amounts* of *heat* (Sections 4.1 and 4.3); we know how important the distinction between intensity and extension is for our understanding of *Forces of Nature* (Chapter 2). *Temperature* was introduced as a degree on the scale of *hotness*, i.e., the scale associated with the hot $\leftrightarrow$ cold polarity, and researchers introduced various methods for measuring it.

Extension of Heat

For the *extension* of *Heat*, which was variously called *heat*, *quantity* or *amount* of *heat*, or *caloric*, Carnot and his contemporaries used the most basic image we all come up with as a matter of narrative imagining: (amount of) *heat* is an *invisible fluidlike quantity* we visualize as being contained in bodies where it makes them warm (Section 4.1) and possibly melts or vaporizes them (Section 4.3), and flowing in and out in *acts* of *heating* and *cooling*.

This imagery—the imaginative acts leading up to it—is quite clear and natural. Children create or pick it up quite readily (see p.187), and adults use it. Nevertheless, it has rattled scientist and has led to an endless debate over whether or not we should be allowed to identify *heat* with the extensive quantity of *Heat*. In traditional thermodynamics, the notion of the extensive quantity was effectively banished when, around 1850, scientists began to identify *Heat* with energy. This step has been singularly destructive for our images of thermal phenomena.

Therefore, our answer is clear: we should definitely identify amount of *heat* with the extensive quantity of the gestalt of *Heat*! Just like every other *Force of Nature*, *Heat* has an *extensive aspect*. The most natural step we can take is to call the extensive quantity of Heat *amount of heat* (or simply *heat*). To be clear, this creates an element of linguistic—and therefore also semantic—difficulty which we already mentioned in Chapter 2 (p.61): the same word, *heat*, is used for denoting both the gestalt (the *Force of Nature*) as well as its extensive aspect.[3]

Heat and amount of heat

In order to be as clear as possible, we shall capitalize the word, *Heat*, when we mean the gestalt, and write *heat* (possibly in italics) when we need to be clear that the extensive aspect, i.e., *amount of heat*, is meant.

The extensive quantity of heat

Heat-as-substance—heat, amount of heat, caloric, or entropy—or how to use words

Caloric

In the initial phases of the science of heat, the *amount of heat*, i.e., the extensive thermal quantity, was called *heat*, *quantity of heat*, or *caloric*. The last of these terms, *caloric*, derives from the Latin *calor* (the German word for this is, very aptly, *Wärmestoff—heat substance*). When Carnot used it, he typically applied it (i.e., *calorique* in French) in place of *heat* (*chaleur*) or *quantity of heat* (*quantité de chaleur*) when he wanted to be somewhat more formal or suggest its fluidlike character.

About 25 years after Carnot, the *Extensive Quantity of Heat* was lost from physics because *heat* was, from then on, said to be (a form of) *energy*.[4] What we got from this is a *Force of Nature* with one leg—heat-as-substance—sawed off and substituted for by something that does not fit.[5]

Entropy

About 15 years after the inception of what came to be known as *Mechanical Theory of Heat*, Rudolf Clausius[6] formally derived a „new" quantity for which he coined the artificial name *entropy*.[7]

Entropy as caloric (amount of heat)

The word does not really mean anything from the viewpoint of natural language use; this reflects the fact that Clausius did not understand what he had constructed in formal mathematical terms—it turns out that *entropy* bears all the marks of an extended concept of *caloric*.[8] So, now, in addition to *heat*, *quantity* or *amount* of *heat*, *thermal charge*, *heat-as-substance*, or *caloric*, we could also use *entropy* in order to denote what every child knows: that there is *heat* in bodies that is responsible for making them warm.

Since *entropy* is a word that does not make sense, not to children, not to laypersons, and quite likely not to scientists either,[9] we shall not use it in this text except when explaining something to physicists and chemists.

(Amount of) heat can be produced

The production of heat. Before and during the period of Carnot's work, researchers assumed that *heat* could be neither produced nor destroyed—there would always be a fixed total amount of it in nature. The reason for this was that many of them associated concrete material properties[10] with this elusive fluid. One of our challenges will be to accept that *heat* can be *produced*; at any rate, this is what we do in our everyday ways of speaking about thermal phenomena (see the discussion beginning on p.201).

Distinguishing between temperature and heat. It seems to be easy enough to distinguish between temperature and *heat*; however, in everyday communication, and in less than careful scientific exchanges, we do not always make the distinction clear. For this reason, we shall extend our first encounter with *Embodied Simulations* (see Chapter 3, p.152) to the case of temperature (as a measure of hotness) and amount of *heat*.[11]

Heat falling from high to low temperature

The Power of Heat. That *Heat* can be powerful was generally accepted. Carnot was the first to suggest a way the *Power of Heat* could be investigated: armed with an image of *heat* falling from a point of high temperature (in the furnace of a heat engine) to a point of low temperature (in the cooler), he could derive an expression for the power of heat in analogy to that for the power of a waterfall (see Section 4.4, and our discussion in Section 3.6 in Chapter 3). The waterfall-image has helped us before, and it will now be instrumental for making progress in the physics of *Forces of Nature*. Importantly, getting a clear view of the power of heat will help us resolve the problem of production of *heat* which eluded researchers during Carnot's time.[12]

Carnot's words, which are quoted above, hint at the wide-ranging influence and importance of *Heat*. Its power is the source of much of what happens in nature: winds, the great movements of water, including evaporation and clouds, rain (and we would say storms in general and thunderstorms in particular), the currents of water which include ocean circulation, volcanoes, and more. This raises the interesting question of where (most of) the *heat* at the surface of our planet comes from—as we shall see, it is the power of Sunlight that drives the production of *heat* in the materials that swallow this light (see Section 4.6).

The Sun's light produces much heat here on Earth

Heat in technical culture and in the planetary environment. *Heat* has played, and still plays, and outsize role in our technical culture. It stood at the beginning of the rapid development of industrialization. We do not have to recount here what it has brought us both in benefits and in drawbacks. Nevertheless, there is an important issue we want to address: applying the power of *Heat* in machines that run on fossil fuels presents us with a challenge of truly global proportions. It has become very clear in recent decades that we are in the midst of warming our planet in ways that are unsustainable. However, if we turn our eyes to the role of *Heat* in our planetary environment (Section 4.6), we might see help on the horizon (Fig.4.1): since our planet produces much more *heat* than we would ever need for heating our homes, cooking our meals, processing materials, and running machines, we do not need to burn non-regenerative fuels!

Figure 4.1: *Left: From the Sun's light to electricity (photo: PL). Right: Solar thermal power plant (Andasol Solar thermal power station in Andalusia, Spain): parabolic trough mirrors concentrate the Sun's light upon a pipe carrying a synthetic oil which is heated to about 400°C. The heat of the hot oil then powers a thermal power plant; the thermal power plant can be seen at the center of the field. See also Fig.2.8 (left).*

4.1 Experiencing Hotness and Heat

Let us begin the story of how we all, and children in particular, experience *hot* and *cold*, and how the notion of *heat* might arise. The former experience is direct for a sentient being, the latter is, as we shall see, basic in imagined experience. On this journey, we will encounter the polarity hot ↔ cold (which we nominalize by calling it *hotness*); thermometers and temperature; an experiential gestalt having an extensive aspect we call *heat*; *heat* flowing; and *heat* being pumped by refrigerators and heat pumps. Along the way, we shall investigate our reasons for believing that *heat* can be produced but not destroyed. This should give us a workable sense of *hotness* and *amount of heat*.

The sensation of warm and cold

Thermal phenomena are experienced as primary: we have a basic sense of *hot* and *cold* that is with us from the very start of our life and helps us orient ourselves to our surroundings. As we have emphasized before, hot and cold form another of the basic *polarities* that create our sense of *Forces of Nature* (Section 2.2). In the case of hot ↔ cold, we come to recognize *Heat* as a *Force*.

Children speaking about hot and cold. When ML had just turned five years old, he told us he had an idea for our book: „Heat makes things warm—write about this!" Apart from the appearance of the word *heat*, to which we will return later (in the sub-section starting on p.186), it is clear that children know the sensation of *hotness* and can name examples such as cold, cool, lukewarm, warm, hot, etc. (see the graphical visualization in Fig.4.2). Experience and communication combine here in an important and fruitful manner.

Figure 4.2: *Visual rendering of the hot ↔ cold polarity for which we use the term hotness. Words for hotness form an ordered sequence. We can understand polarities as schematic abstractions (as Image Schemas, see Volume 2).*

Experience of hot and cold and the words for it come even earlier. When ML's brother, DL, was about 20 months old, he started using the word *cold*. Occasionally, he also used it for cases where we would use *warm* instead—it seemed as if he had only one word for the polarity of hot ↔ cold (see also p.24). This reminded us of all those instances when DL applied only a single term to some polarities or binary opposites: prominently *up* for up ↔ down and *open* for open ↔ close(d). It appears that in our (physical) experience, opposites and polarities arise as *perceptual units* (gestalts) before they are analyzed (see Volume 2).

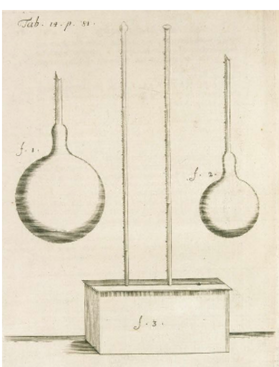
Polarities as perceptual units

Does Cold give rise to a truly independent experience? Sensations of hot and cold seem to be treated as independent of each other in our embodied experience of thermal phenomena. Notwithstanding the example of DL's use of the word *cold* for what seems to include the sensation of *warm* and *hot*,[13] there is some evidence that the experience of hot ↔ cold is different from that of, say, fast ↔ slow, bright ↔ dim, high ↔ low, or loud ↔ quiet (and of up ↔ down and open ↔ close(d) as used by DL). The latter polarities all suggest a single *Force* each: *Motion*, *Light*, *Gravity*, or *Sound*, respectively. *Slow* does not hint at a Force different from the one we associate with *fast*—it's all motion; and the same seems to be true for the other three examples; dark simply means the absence of light, and quiet is the absence of sound. We can get to know *Sound* as a *Force of Nature* without ever having to learn about a different Force called *Not-Sound*.

The *Winter Story* discussed in Chapter 2 (Section 2.6) suggests that there are reasons for treating *Cold* as a Force independent of *Heat*—at least when we are dealing with primary experience and learning.[14] We do not do this when creating a science of thermal phenomena, but the experience of *Cold* appears to be so strong that it might lead to its own gestalt. Maybe, in the case of experiencing what we now subsume under the heading of *thermal phenomena*, two polarities arise, i.e., *hotness* and *coldness*, where each has one pole identified with the degree of hotness/coldness that applies to our body. To the extent that experiencing hotness is tied to our body it is not surprising that its degree of hotness should serve as the level from which other intensities are judged; in other words, it is the tension between hotness levels of body and object that counts.

Accademia del Cimento

Cold in the history of thermal physics. About 350 years ago, a group of *Experimenters at the Accademia del Cimento* in Florence studied the *Force of Cold* in quite some detail. In particular, they wondered if they could find out about *Cold* and its power if they experimented with the freezing of various liquids, which they knew would change their volumes. They put a liquid in a glass bulb having a very long and thin neck and stuck that bulb in a tub with a very cold mixture of ice and salt.[15] They then recorded the times of changes of level of the liquid in the neck (as we do in thermometers built in a similar fashion). Note that, by observing how fast changes occur, they treated the actions of *Cold* upon the volume of liquids as a matter of dynamics.[16]



Magalotti (p.cxxxxviii)

The Experimenters had notions of *cold* and of *intensity* of cold/heat: „... that where the cold works there in its mines with its proper materials, it comes to condition the purest waters to achieve such a temperament, that it also forms them into very hard rocks of crystals, ...;"[17] our term *temperature* has been derived from *temperament* (*tempera* in Old Italian). In their descriptions, they treated *cold* as if it were a substance different from *heat* but then speculated about it: „Around then there have been various speculations at all times by the thinkers about the reason for the chill, whether this really arose from a proper and real substance of the cold ... or whether the cold was nothing more than a total deprivation, and expulsion of heat."[18]

Joseph Black on cold and heat

Even if we say today that everything is clear on the subject of *Heat* and *Cold*, the issue did not resolve itself easily and quickly. Around the middle of the 18th century, the Scottish chemist Joseph Black discussed whether we should consider *cold* as separate from *heat*: „[...] let us examine what we mean by this quality of coldness. We mean a quality, or condition, by which the ice produces a disagreeable sensation in the hand which touches it; to which sensation we give the name of cold, and consider it as contrary to heat, and to be as much a reality. So far, we are right. The sensation of cold in our organs is no doubt as real a feeling as the sensation of heat. But if we thence conclude that it must be produced by an active or positive cause, an emanation from the ice into our organs, or in any other way than by a diminution of heat, we form a hasty judgment."[19]

He then dismissed the notion of *cold* as a Force of its own as imaginary. The main reason given calls upon a simple everyday experiment with cold water we all can perform. We know that if we have two containers of water, one very cold and one just cool to the touch, and if we keep a hand in the very cold water for a while and then quickly switch it to the cool bath, it will feel rather warm to us. This simply confirms that the experience of hotness or coldness is relative to the thermal state of our body; there is nothing absolute about it. Black concludes from this that „We are therefore under the necessity of concluding from these facts, that our sensations of heat and cold do not depend on two different active causes, or positive qualities, in those bodies which excite these sensations, but upon certain differences of heat between those bodies and our organs."[20]

Sensation of cold and hot is relative

Choosing Heat over Cold

Experience and the choice of hotness over coldness

It is clear that the perception of the level of coldness/hotness refers to our body. Roughly speaking, what is colder than our body (mostly our skin where we experience how warm or cold an external body is) is called cold, what is warmer is called warm. Still, there is only a single polarity associated with the sense of coldness or hotness (Fig.4.2).

A single hot-cold polarity

We probably can understand now why, when we expand our knowledge of thermal phenomena into the realm of science, we only need one of the notions, either *Heat* or *Cold*. And it does make sense that heat was chosen. Degrees of hotness go up when it gets warmer; that makes sense; degrees of coldness go up when it gets colder; that makes less sense (even though it is correct to say this).[21]

Ever since, it has ben clear that *Cold* can be treated as the absence of *Heat* and that, in order to form a science of thermal phenomena, we only need one of them—scientists have chosen *Heat* as the *Force of Nature* to work with even though it would be possible to choose *Cold* in its place (and *coldness* for the intensity of *Cold*).

Hotness is basic in physical science as well. Accepting *hotness* as something that arises in experience is important in modern scientific approaches to macroscopic physics as well. It is worth listening to Ernst Mach who, in 1896, wrote a book about the physics of thermal phenomena from a historical-critical viewpoint. As far as we know, he is the first person who emphasized the importance of the notion of *hotness* and how it differs from the concept of *temperature*. This is what he wrote about our experience of *hotness*:[22]

Mach on hotness

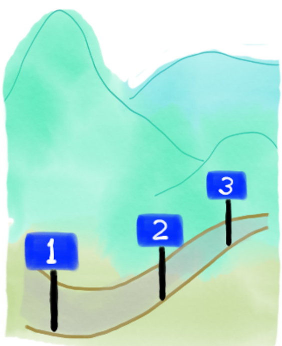
> [p.3] *1. Among the sensations by which, through the conditions that excite them, we perceive the bodies around us, the sensations of hotness form a special sequence (cold, cool, tepid, warm, hot) or a special class of mutually related elements. [...] The essence of this physical behavior connected with the characteristic of sensations of hotness (the totality of these reactions) we call its hotness.*
>
> [p.43] *5. The sensations of hotness, like thermoscopic volumes, form a simple series, a simple continuous manifold; [...].*

Hotness as an ordered line

More than any other description of the origin of scientific notions known to us, these lines by a well-known physicist and philosopher show the phenomenological origin of important concepts in physics. We rarely hear as clearly how concepts of physics are based upon our experience of interactions with nature.

The scale of hotness and the construction of temperature

If we accept the notion of *hotness*, i.e., the intensity of Heat, as foundational, as arising in us as a result of our encounters with nature, we have to ask how we can construct an understanding of *temperature* based upon such experience. Mach had the following to say about the concept of *temperature*:[23]



Temperature as a coordinate along the path of hotness

> [p.56-57] *22. According to what has been said so far, the temperature is nothing but the characterization, the marking of the hotness by a number. This temperature number has only the property of an inventory number, by means of which one can recognize the same hotness and, if necessary, find and restore it. At the same time, this number indicates the order in which the designated hotnesses follow each other, and between which other hotnesses a given hotness lies. [...]*[24]
>
> [p.57] *23. The temperature concept is a level concept like the height of a heavy body, the speed of a moving body, the electric and the magnetic potentials, and the chemical difference.*[25]

If we combine the hot ↔ cold polarity with the VERTICAL SCALE schema (for details on schemas, see Volume 2), we obtain the structure for our understanding of *hotness* (or *coldness*, if we so desire) as a vertical scale and *temperature* as marks on this scale (see Fig.4.3).

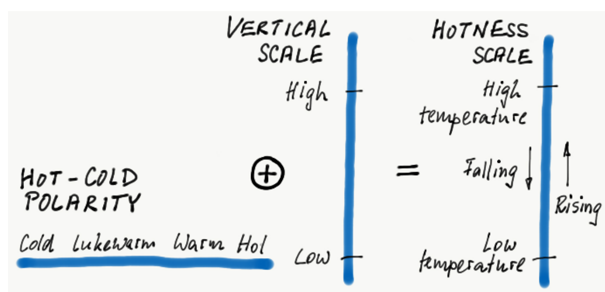


Figure 4.3: *If we combine the schema of the hot-cold polarity with the vertical scale schema, we obtain the hotness scale. Temperature values are locations (marks, coordinates)on this scale. Temperatures are high or low, they rise or fall.*

In order to complete the discussion of our experience of degrees of hotness (temperature), we could create a table outlining the kind of projections that constitute the metaphor TEMPERATURE IS A VERTICAL SCALE. In Table 3.3, all we need to do is replace the words *pressure* by *temperature* and *hydraulic* by *thermal*, and we have a description of how imagination deals with the sensation of hotness.

Measuring temperature and constructing scales. Temperature is the mark of hotness (of how warm a physical object is), so any property of an object that changes with hotness can, in principle, be used for introducing temperature scales and measuring temperature. Examples of such properties are the volume of liquids, electric resistance of electrical conductors, electric tension of thermocouples, pressure of gases, or the quality of the light emitted by warm surfaces.

Expanding liquids. Even though they are becoming less common in everyday life, the original instruments for measuring temperature are still with us: thermometers that use liquids such as mercury that expand as they get warmer (Fig.4.4, left).

Such thermometers were used for introducing the first temperature scales of which the most common are the *Celsius* and the *Fahrenheit* scales. A scale is introduced by establishing two fixed points of hotness—freezing and boiling of water for the Celsius scale—and then the distance between them is divided into a number of equal intervals—in the case of the Celsius scale: 100 degrees.

Celsius and Fahrenheit scales

Gas thermometer. Gas thermometers, where we measure the pressure of a gas in a container of fixed volume as the temperature changes, have played an enormous role in the science of heat. It is found that as the temperature of the gas changes, its pressure changes in proportion with the change of temperature. Put differently, the pressure follows a straight line in a pressure-temperature diagram (Fig.4.4, right). Naturally, we already need to have established an initial procedure for measuring temperatures such as with a mercury thermometer, before we can find out about the behavior of gases such as air.

The gas thermometer shows a peculiar feature. For a given gas and given amount in a container, the straight line established through measurements indicates that the pressure of the gas would become zero at some point (if the behavior of the gas were to continue down to that point as observed). Zero pressure would suggest that the temperature of this material has reached its lowest possible point!

Gas thermometer suggesting a lowest possible temperature

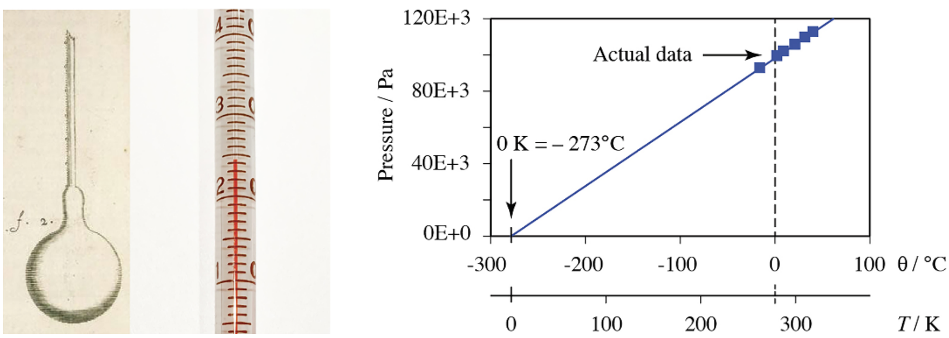


Figure 4.4: *Left: Part of a thermometer using an expanding liquid. Right; Pressure of a fixed amount of air kept in a fixed volume, as a function of (Celsius) temperature.*

How not to understand temperature

Losing sight of our experience of hotness

Quite commonly, in physics courses, we are introduced to the concept of temperature without the benefit of learning about its embodied origin, i.e., about *hotness* and how it is understood metaphorically. Indeed, we are usually given the impression that temperature is determined by the energy of the random motion of the „little particles" making up matter—its simple and basic meaning of a numerical mark of how warm a material is, is lost from view.

In other words, by using microscopic models, the impression is given that temperature is a derived concept—but it is not! Temperature, or rather *hotness*, is primary in experience and fundamental in conceptualization. We need this experience for creating our understanding of thermal phenomena.

That alone does not prove much; however, no matter what type of gas is used (air, oxygen, hydrogen, helium, neon. . .), we will always find that the pressure of the gas should vanish at exactly the same low temperature: –273°C. This is remarkable but still no proof that we have found the lowest possible temperature for all circumstances. Importantly, though, no material and no procedure has ever demonstrated a temperature lower than the suggested –273°C. This is a very strong indication that hotness scales have an absolute lowest possible point—this is commonly called *absolute zero*.

Absolute zero of temperature

We can now construct temperature scales that start with a value of zero at that lowest point of hotness. The one used in the sciences is the Kelvin scale where values change at the same rate as in the Celsius scale; therefore, a temperature difference of 1 K equals a temperature difference of 1°C (K is the abbreviation for Kelvin). Therefore, in the Kelvin scale, temperature values are always higher by 273 than in the Celsius scale.

Kelvin scale

Table 4.1: Some values of temperature (in Kelvin)

Substance or process	***T* / K**
Cosmic background radiation	2.7
Boiling point of helium	4.22
Boiling point of nitrogen	77.4
Freezing point of water	273
Mild summer day in central Europe	300
Melting point of beeswax	335
Boiling point of water (at a pressure of 1 atm)	373
Melting point of copper	1358
Surface of Sun	5780
Earth's core	6150
Center of Sun	$15 \cdot 10^6$

Imaginative experience of a fluidlike *Quantity of Heat*

Recognizing the aspect of intensity of the *Force of Nature* we call *Heat* is direct and simple—notwithstanding all the practical difficulties one might have with measuring temperature and the theoretical challenge of coming up with an absolute scale that would be independent of substances used for measuring. We have a primary sense of *hot* and *cold*. Getting a clear handle on *amount of heat*, on the other hand, is less than easy for the simple reason that *heat* is invisible. Nevertheless, an imaginative understanding of an *amount of heat* is as important as is knowing about *hotness*.

Our experience of fluids seems to be perfectly reversed. It is more difficult to clarify the notion of pressure than it is to understand extension, size, or amount of fluids. Water and other liquids that we can handle directly, prominently present the *extensive aspect* of *Fluid* as a FoN to our senses.

So, what do we do? We take indirect experience or, rather, an imaginative transformation of direct experience as our cue for how to construct the concept of *amount of heat*, which we often just call *heat*.[26] And we shall make frequent use of analogical reasoning: there is so much similarity in how our mind deals with

Amount of heat

different Forces of Nature that we can apply images from fluids or electricity to help us with this new concept.

Analogy

Direct experience suggesting the concept of amount of heat (or cold). Imagine you are standing in a cold stream with your bare feet. If you stay in the water long enough, you will feel "something creeping up" from your feet into your legs making them ache. Or peel 10 kg of carrots that just came out of cold storage—your hands and arms will get numb and hurt.

It is not only that parts of your legs and arms get gradually colder, the parts lower down before the ones higher up. Our mind readily creates the image of a "something creeping up" which we call *cold*. A similar situation is experienced if we stick a long metal spoon in hot tea: something, which we call *heat* quickly "flows up" along the neck of the spoon. We have a similar experience when feeling cold inside our body and being given something hot to eat or drink. Finally, remember the *Winter Story* where *cold* found its way through walls and windows and cracks between walls and windows (Section 2.6).

Think about it: we would be at a great loss if we could not describe such situations in terms of heat (and sometimes cold) flowing in, out, and through bodies; residing in these bodies; and being produced in a fire and some other processes. If, instead, all we could do is speak about the temperature changing locally and in the course of time, our narrations would become more than just awkward. Simply imagine what it would be like if our mind did not provide us with an image of an invisible entity that flows into and out of bodies and, when it is inside them, makes them warm (or cold in the case of cold).

Children pick up on the notions of *heat* or *cold* quite readily. Before he turned five, ML got into the habit of drinking hot camomile tea. On several occasions he commented that „I love hot tea because it gives me heat for the next day." During an exchange on why cooked carrots had gotten cold, he would say that „heat is now out of the carrots."

Creating images of (amount of) heat in mind

Imagining heat

It is quite clear that we cannot see or smell or literally touch and grab heat. The examples of experience of thermal phenomena and our response to them makes clear that we create images of some „thermal stuff" in our mind. We need it to speak of the phenomena in a manner that makes sense, and for this we need *heat*—in particular, we would never be able to apply imagery of agency and causation without the notion of an *amount of heat*—we could never answer the question *Why* something happened!

An investigation of kindergarten students indicates that speaking of *heat* in this imaginative form might be triggered by conversations or narrative experience.[27] The students played with hot stones which they put in cold water, observing that the water got warmer. Children who were asked directly after the activity why this happened usually just said that hot stones make cold water warmer—effectively re-describing what was observed. On the other hand, children who were told the *Winter Story* after the activity would, when subsequently asked, describe that *heat went* from the stones into the water. Remember, the story is about *Cold* and its activities, such as when it finds its way into homes through walls and windows, and makes the insides colder. Prompted by the imaginative presentation of *Cold*, children gave an actual explanation in terms of agency.

The story of Spike, the Angry Little Dragon. Here is a story introducing children to *Heat* and its characteristics.[28] It draws upon a particular imaginative structure—our sensation of how *Anger* is related to *Heat*, and the possibility of creating a parallel understanding of both a natural and a psychological Force through metaphors.[29]

Artwork by M. Rosi

> *A long time ago there was a small dragon called Spike. He lived with his father and mother on top of a high mountain. He spent most of his time in the air flying, and he observed the world from above. Spike was a happy dragon.*
>
> *But he had not yet met Anger and Heat. Anger and Heat were two small spirits, almost identical, always together and always ready to quarrel. They spent their time getting into and out of things and people. The difference was that Anger was angry and Heat was warm. Anger was red while Heat was yellow.*
>
> *One summer afternoon, Spike was happily flying in the sky, when he saw some children playing in a pool. He liked water too and thought this might be a nice opportunity to play with the children. But he remembered that his mother and father always warned him to stay away from children because they were afraid of dragons.*
>
> *Then Anger and Heat suddenly entered his body. He didn't know this at first, but he soon felt it. And very clearly! Spike immediately felt angry and hot. His face got very angry and frightful, and his mouth began spitting smoke. Spike looked at himself in a cloud … he had angry eyes, angry mouth, angry eyebrows, angry cheeks. His cheeks also felt very hot. Indeed, Spike's whole body was hot. Anger and Heat were in Spike's head. Spike was angry, angry, very angry. He was also hot, hot, very hot. And he felt sick because he couldn't control all that rage and all that heat inside his body. He absolutely wanted to drive the small phantoms out of his body because then he would have felt well.*
>
> *While flying and flapping the wings and spitting smoke, he approached the swimming pool with the children playing. The children were so happy, and he really wanted to play with them. Suddenly, he lost his balance and fell into the pool, just next to the children.*
>
> *But the children were brave and were not afraid of dragons. They made friends with Spike and wanted to play with him. Spike was amazed and was very happy to play with them and felt their love. Anger and Heat, meanwhile, had left Spike's body and had gone off to quarrel somewhere else. Spike was calm again and played with the kids.*

We shall accept the imagery of some "thermal stuff" in the sense described in these examples as the third primary aspect of the experience of thermal phenomena, aside from intensity and power. Clearly, if there is some "stuff," there is more or less of it, depending upon circumstances and time. This tells us that we associate an extensive aspect with thermal phenomena. The most fitting linguistic term that can and should be used to name this "stuff" will obviously be *heat* or, if we want to be a little more formal, *amount* or *quantity of heat*.

Joseph Black on distinguishing between heat and hotness. Let us take a look at an activity of heating water we can all perform in a simple manner and record and report qualitatively. It is modeled on the type of observations and interpretations Joseph Black used to make clear that we need to distinguish between hotness and heat (this happened in the second half of the 18th century).

Consider a certain amount of cool water in an insulated pot (Fig.4.5a). We heat this amount of water with a single candle for a certain period (which we call a unit of time). The water becomes somewhat warmer. Then we redo the whole thing, but we let the candle burn longer, maybe twice as long as before; the water becomes hot (Fig.4.5b). Finally, we start again and heat the water with two candles but only for a single unit of time (Fig.4.5c); the water will have become as hot as in the second case.

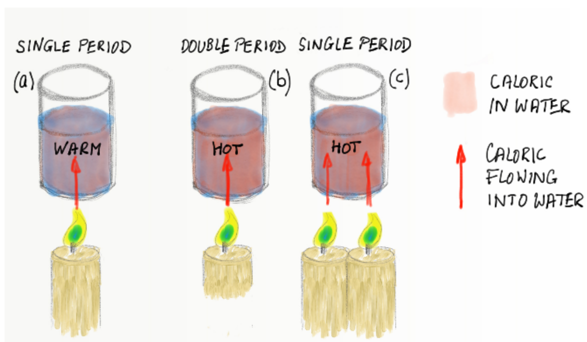


Figure 4.5: *Heating the same amount of water (in an insulated pot) with candles. (a) Heating for a unit period with one candle—the water gets warm. (b) Heating for twice the time with one candle—the water becomes hot. (c) Heating for a unit of time with two candles—the water becomes as hot as in (b).*

Since a burning candle represents an activity, and letting it burn longer or letting two candles burn represents more of the same or a stronger activity, imagination suggests that we are transferring something to the water. The Experimenters of the Accademia del Cimento put it like this: „. . . where fire, dissolved in very fast sparks, goes through the thickest crevices of stones and metals,. . . "[30]

Moreover, since more of that stuff makes the water warmer compared to having less of it, our mind creates the image of whatever has been transferred as now being in the water, and it is responsible for making it warm. Obviously, the *heat* produced by the candles heats the water—we now interpret *heating* the water as *letting heat flow into* the water. The same candle will produce twice as much *heat* when burning two time units, and two identical candles will also produce twice as much *heat* when burning as long as a single candle.

We can use the example of heating water in a somewhat different form. We again take the same amount of water as before, again in an insulated pot. We heat it as in case (a) in Fig.4.5; it will become warm as before (see Fig.4.6a). Now, we double the amount of water and heat it for the same unit period but with two candles (Fig.4.6b): double the amount of water will become as warm as the water in case (a). Clearly, we have communicated twice the quantity of *heat* to double the amount of water, and it makes sense independently of knowing this that—if we assume that *heat* is in the water—double the amount of water should store twice as much *heat* at the same temperature. So, whereas the hotness of the two bodies of water in (a) and (b) is the same, the amount of *heat* in them is different—amount of *heat* and degree of *hotness* cannot possibly be the same concepts.

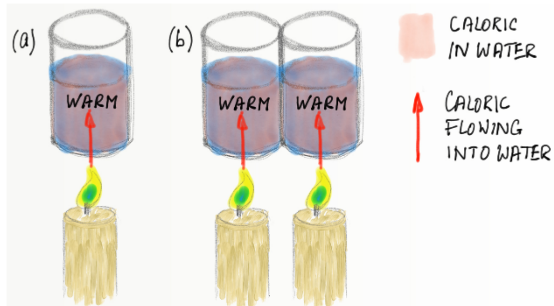


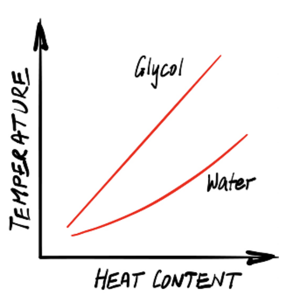
Figure 4.6: *Heating an amount of water and then twice as much to the same temperature—it takes twice the heating, twice as much heat will have been communicated to double the amount of water.*

Black (1803, p.78) put the example into these words: „If, for example, we have one pound of water in one vessel, and two pounds in another, and these two quantities of water are equally hot, as examined by the thermometer, it is evident, that the two pounds must contain twice the *quantity* of heat that is contained in one pound."

Heat capacity

Black used the observations and his interpretation to suggest that *double* the amount of water had twice the *heat capacity*. Note that, as used by Black and ever since in thermal physics, capacity does not denote how much of something a container can maximally store—this is how we usually use the word *capacity*. A truck has a certain capacity for carrying a particular load, a drinking glass has a certain capacity for water or milk, etc.

Specific heat or warming factor



Heat capacity (capacity for amount of heat) and warming factor

---

Heat capacity denotes how much *heat* is needed for a given body to make that body one degree warmer. Expressed formally, the capacity C_S is the factor relating change of temperature $\triangle T$ to change of heat content $\triangle S$ (S is the standard symbol for heat content, i.e., for entropy):

$$\triangle S = C_S \triangle T \tag{4.1}$$

Note that C_S is *not* a measure of the maximum amount of *heat* that can be put in a body. Actually, it makes better sense to refer heat capacity to unit amount of a given substance: this quantity is called specific heat. If the specific heat is high, it is hard to heat a body; if it is low, it is easy.

Warming factor

We can introduce a measure that reflects this observation better: we call the rise of temperature that can be achieved with one unit of *heat* the *warming factor* of a material. So, since it is easier to raise the temperature of rock than that of water with a given amount of *heat*, the warming factor of rock is higher. The warming factor so defined is the inverse of the specific heat of a material.

This is not how *capacity* is used in thermal physics where *capacity* denotes a kind of „size" of the storage element in the sense that to obtain the same change of temperature, more or less *heat* is needed. For instance, 10 liters of water need twice as much *heat* for raising the temperature by 1°C than 5 liters do.

Distinguishing between hotness and heat

How difficult can it be to distinguish between hotness and heat?

Joseph Black (1728-1799) is credited with having made clear once and for all that one has to distinguish between *intensity* and *extension* of *Heat*, i.e., between *temperature* and *(amount of) heat*. Writers before his time were not very clear on this point even though we may take their writings as evidence that they felt and knew the difference. The *Experimenters* at the *Accademia del Cimento* had a very peculiar way of dealing with what should be temperature. In their experiments on *Cold*, they stuck a second bulb with long neck filled with alcohol side by side with the experimental bulb and fluid in the ice-salt mixture. They called this second device the *thermometer*—it is indeed a thermometer in the modern sense for the ice-salt mixture but not for the experimental liquid in the other bulb.

When we ask if laypersons understand this distinction, we get decidedly mixed results. We usually do not distinguish fluently and consciously between temperature and heat in everyday life, at least judging from our linguistic expressions; we often use what amounts to inconsistent language. Scientists and engineers do this as well if there is no need for being precise. Remember what Joseph Black wrote about how the sensation of hot and cold is relative to the hand in the experiment with water of different temperatures: „[...] sensations [...] depend [...] upon certain differences of heat between those bodies and our organs." He knew full well that it is the difference of the intensity of heat, and not heat, that is the cause; still, he used this form of ambiguous language.

On the other hand, children have distinct ways of speaking of intensity (*cold*, *tepid* or *lukewarm*, *warm*, *hot*..., and *temperature*) and amount of heat (simply called *heat*; remember ML's expression that „heat makes things warm"). What should we conclude from this?

Learning that heat is the energy of the random motion of the „little particles" definitely does not help. If temperature is derived from this random motion as well (see the Box on p.185), the confusion is certain to be complete—maybe this is the deeper reason for the inability of many learners to clearly distinguish between intensity and amount of heat.

These observations are one of the reasons why we put much emphasis upon describing the basic aspects of *Forces of Nature* in imaginative ways—maybe a narrative approach to our encounters with dynamical processes will help children (and everyone else as well) to be, at the same time, more fluid and more precise when it comes to speaking about such matters.

Apart from telling us how much *heat* we need for making water warmer and helping us see more clearly that we need to distinguish between heat and hotness, Black's example does not tell us much. However, if applied to bodies made of different materials, the notion of *capacity* is quite informative. If we refer capacity to unit quantity of a material—quite often we use 1 kg—we will be informed by measurements that water, rock, and mercury have quite different *heat* capacities. If referred to unit mass (1 kg), the capacity is called *specific* capacity.

To give an example, the specific capacity of dolomite rock, sandstone, and soil is between 1/4th and 1/5th of that of water, and that of mercury is smaller by another factor of 7. It takes a lot less *heat* to heat 1 kg of mercury by 1°C than it takes to do the same for water. As Black put it, „The quicksilver, therefore, may be said to have less capacity for the matter of heat" (Black, 1803, p.82).

Why does land warm up faster on a sunny day than a lake? On a beach, the dry land can get pretty hot on a summer day whereas the water stays fairly cool. The difference can be striking: the water might not even get perceptively warmer whereas the temperature of dry sand on the beach can easily go up to 50°C or higher. Why is this?

Interestingly, land reflects more sunlight than the water of a deep lake or the ocean,[31] so we might wonder why it isn't the other way round—hot water and cool land? The reason we are usually given is that water has a higher heat capacity than land—more heat is needed to raise the temperature of water than that of sand or rock. However, values of heat capacity such as the ones reported above only make sense if we are given the mass of the substance that is being heated, namely one kilogram. Per kilogram, water indeed needs more heat than sand or rock, but that is not what counts. We need to know how much of the material of the land and how much of the water of a lake or the ocean gets heated. In order to give a sensible answer to this, one more assumption needs to be made: we need to look at the same size surface on land and in the water, say, one square meter.

So, let us consider one square meter, either of land or of water, and ask how deep down the heat of the day—produced by absorbing sunlight during the day—can reach; only then can we talk about „how much" stuff is being heated in these two environments. What sets the land and water apart is this: on land, light is absorbed by the thinnest of layers imaginable, and the heat generated has a fairly hard time traveling downward (see Table 4.2); in contrast, the Sun's light travels deep down in water, many meters in fact. As a result, the amount of material that gets heated is very small on land, and very big in the water. This outweighs the difference in heat capacity per mass (specific heat) between water and rock, sand, or soil by many times. Effectively, what we are confronted with is that a thin layer of land is heated versus a very deep layer in the water.[32]

Embodied Simulation of thermal tension

In Chapter 3, in the subsection on p.152, we presented the idea of an *Embodied Simulation* that helps us understand, in a most direct physical manner, the notion of fluid tension, i.e., pressure, We shall briefly do the same here for how one might create an embodied understanding of *thermal tension* and how it relates to quantities of heat.

Imagine „packing" *heat* into a body of water; better still, imagine that you and a number of your friends are *heat*, i.e., put yourself in the place of heat in a body of water and ask yourself what you will feel.[33] Clearly, if we accept the image of heat, i.e., the extensive *quantity of heat*, being like a fluid, packing more and more of it into a certain material will make it denser and denser. In other words, heat gets more and more „crowded" inside the water. If we represent heat, we obviously need to model the increasing amount by an increasing number of people inside an area on the floor (the area represents a body of water being heated; see Fig.4.7). If everyone stretches out their arms and touches someone else, the more densely we are packed, the stronger will be the pressure or (mechanical) stress felt in our arms as we have less and less space to ourselves. The tension felt by the actors “crowding into the body of water” is an embodiment of temperature.[34]

It is possible to simulate the effect of the size of the body containing heat, i.e., of what Black termed its heat capacity. Assume we have a number of people inside the area representing the body of water. Now, all of a sudden, enlarge the area on the floor representing the amount of water. It is clear what happens: the people present inside have more space, tension and temperature will drop.[35] This also means that, in order to keep the tension up, we need more *heat*: we need more people inside the larger body of water. Practically, if we add cold water to the already heated water, we need to start heating again—we need to have more people enter the enlarged area.

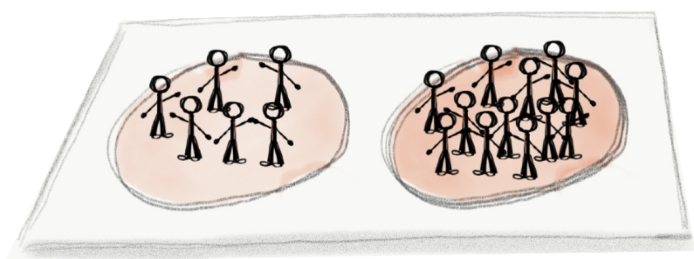


Figure 4.7: *A body of water—symbolized as the pink area on the floor—collects more and more heat. Heat is represented by persons—the more heat there is in the water, the more persons crowd into the area representing the water. This raises the felt tension such as in the persons' outstretched arms pressing against other persons.*

So, we feel tensed, and we are tenser the more there are of us.[36] This gives us the feeling of wanting „to get out” of the space so we can relax, and the desire to get out will be stronger the higher the density of people, i.e., the higher the tension. It is like a case of pressure: *heat* is „under pressure,” and it will find its way out of the heated body of water, however slowly or fast.

More fluidlike stuff in the same space often means higher tension

4.2 Storing Heat, Letting It Flow, and Producing It

Hotness is felt, (amount of) *heat* is imagined—this is what we learn from the previous discussion of thermal phenomena. We shall now take a closer look at the idea of amount of heat, its storage, its transport—in spontaneous flow, forced by pumping, and carried by fluids and light—and, particularly, its production.

An experiment suggesting the concept of *amount of heat*

Direct physical experience can be found not only in spontaneous everyday activities, it can also be gained in experiments where we create simplified environments and control circumstances. We shall study a few such experiments where we explain the properties and actions of heat by appealing to what we know about how water acts in analogous fluid mechanisms.

Here is a simple experiment that is analogous to the example of the two communicating water containers which we saw in Fig.3.19. We stick a cold solid copper cylinder into hot water inside a well-insulated container (Fig.4.8, left). There are electronic thermometers inside the copper cylinder and the water that record temperatures as functions of time (diagram on the right of Fig.4.8). What we see happening with the *temperatures* of copper and water is clearly reminiscent of what happened to the *water levels* in the box on p.123.

Just as in the case of communicating water containers, we can apply our imagination to the phenomenon of two bodies in thermal contact. However, in contrast to the case of fluids in Fig.3.19, all we can perceive happening here is the change of temperatures. There is no way we can see what would be equivalent to water in the hydraulic system—we can neither see nor hear, nor smell, nor weigh (quantities of) *heat*. Yet, our mind, our imagination, tells us that there must be something more than just the sensation of different degrees of hotness. Note how our capacity for analogical reasoning helps us in this task.

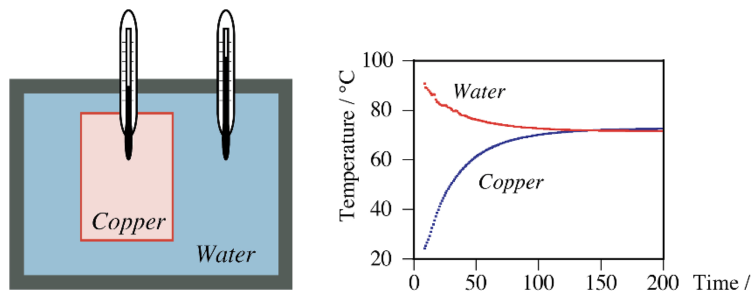


Figure 4.8: *Left: A cold solid cylinder made of copper—with an electronic thermometer stuck in the middle—is placed in hot water inside a well-insulated container. Right: Temperature datasets for copper and water showing the phenomenon of equilibration.*

Thermal tension makes heat flow

We use the analogy with communicating water tanks to suggest that *heat flows*. Moreover, we learn from using this analogy that *heat* flows from the hotter to the cooler body, and it flows as long as there is a *temperature difference*. In other words, we are now justified in calling a temperature difference a *thermal tension*, and we hold this tension responsible for the *flow of heat*—without such a tension, heat will not flow through materials.

Heat flowing through materials

Heat flows, it flows through materials, and a temperature gradient is needed for this to happen; this much is clear from everyday experience imaginatively extended to include the image of *heat* resembling a fluid. Accepting this imagery has helped us in interpreting the result of the experiment of thermal equilibration shown above in Fig.4.8. We now take a look at a second experiment including numerical data showing change over time.

Diffusion of heat. A sophisticated experiment supports the image of *heat* flowing through materials due to thermal tensions. In Fig.4.9 (left), we see a number of slabs, ten of them actually, of iron put together to form a long thermal conductor. Each of the slabs has a borehole that can fit a stainless steel temperature probe. Two of these slabs (S2 and S3) have been heated to a high temperature in boiling water, dried, and placed back into the row of otherwise cold slabs (Fig.4.9, center). The diagram on the right of Fig.4.9 depicts the temperatures of some of the slabs as functions of time—this shows how the cold slabs become warmer one by one, at the expense of the hot ones, indicating how *heat* diffuses through the conductor (diffusion is also called *conduction*; we shall have more to say about this right below).

Diffusion of heat

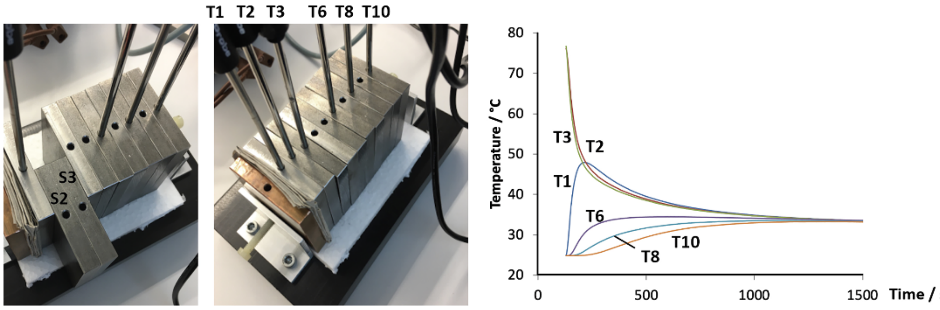


Figure 4.9: *Left: Ten slabs of iron in a row form a long metal bar. Center: Several of the slabs have been fitted with thermometers (the vertical thin steel rods). Slabs 2 and 3 have been heated to high temperature and inserted into the row. Right: Temperatures of slabs 1, 2, 3, 6, 8, and 10 as functions of time.*

Observe, in particular, how it takes time for the temperature to rise after the row of slabs has been put in touch with the hot ones (S2 and S3): it takes longer—there is a longer delay—for slabs far away from S3. The temperature of S1 rises quickly because it is in immediate touch with S2. What we see here strengthens our feeling that some „stuff" that makes bodies warm must be flowing through the row that gives rise to the observation of changing temperatures.

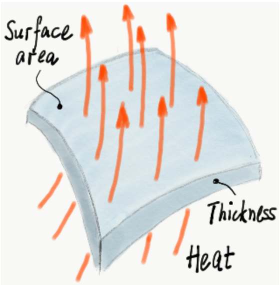
How easily do materials let heat pass? It is also clear, that different materials let heat pass more easily than others (Table 4.2). There is indeed a huge range in how easily heat is conducted through different materials. With the notable exception of diamond, the best conductors are metals. Stone, soil, and living tissue are somewhere in between, and wood, paper, and rubber are very bad conductors—we would therefore call them (thermal) insulators. Using a more or less thick layer of such insulating material can often make it so difficult for the heat of a hot body to escape into a cooler environment that it stays hot for a very long time.

Thermal insulators

Table 4.2: Conductivities (relative to copper) of some materials (at 20°C)

Material	Conductivity (relative)	Material	Conductivity (relative)
Diamond	5.2	*Sandstone*	0.0045
Copper	1	*Clay (moist)*	0.0045
Aluminum	0.50	*Glass*	0.0022
Bronze	0.28	*Tissue (muscle)*	0.0015
Iron	0.20	*Wood (oak)*	0.0004
Steel	0.11	*Paper*	0.00013
Granite	0.0076	*Styrofoam*	0.00008

Insulating bodies from losing heat is one thing; the other is making as much *heat* as possible go where we need it—this is the domain of what is called *heat transfer* in engineering. Here the question is how to make it as easy as possible for *heat* to flow assuming there is a given temperature difference.



To make it easy for heat to flow, we should choose a layer of highly conducting material that is as thin as possible and has a surface as large as possible. The point of high conductivity (Table 4.2) is clear, and so should be the question of thickness of the material: if heat has a shorter distance to travel for given thermal tension, the flow is less restricted. The point concerning the size, i.e., the surface area, of the conducting material is easy to understand as well. Simply imagine two heat conducting layers with the same material and thickness and temperature difference in the direction of flow. Two such slabs next to each other obviously let twice as much heat through than a single one would. Clearly, floor heating makes it easier for heat to spread into a room than small radiators at the walls ever could.

Letting heat flow or blocking it

Making it easy or hard for heat to flow

Once we have an image of heat as a fluidlike quantity, it is easy to understand what the everyday issues concerning the transport of heat are. First of all, unless heat is carried by a fluid, we need a temperature difference for it to flow—the higher the *tension*, the stronger the current.

Thermal tension

Second, the path along which heat flows—the materials the path is made out of—plays an important role: the nature of the path determines how easily heat is let through, or how strongly the flow is opposed. *Letting* or *helping* is expressed in terms of a so-called *conductance*: the higher the conductance, the stronger the current. *Opposition* or *obstruction* is measured in terms of a *resistance* (which is the inverse of the conductance): the higher the resistance, the weaker the flow for a given tension.

Conductance
Resistance

Why metal feels cold to the touch and wood does not. There is an interesting phenomenon whose meaning needs to be clarified if we want to understand our direct bodily experience of hotness: two objects, one made of wood and the other of metal, that have been lying in the same relatively cool environment for a long time and have attained the same temperature as the air in the environment. Nevertheless, they feel differently warm to the touch—the metal object usually feels noticeably cooler. So why does our direct bodily sensation give us different temperature „readings?"

Given that our finger is the same when we touch the objects, and given that we touch them in the same manner, maybe the phenomenon has something to do with the fact that wood and metal let heat pass through them rather differently, the former much less easily than the latter. Moreover, they let heat pass differently than the air that normally surrounds our finger. So let us first consider the situation where the finger is exposed to the air; in this case, the air touching the skin provides a relatively strong insulating effect leaving the outermost layers of the finger at a comfortable temperature, maybe 30°C, while the temperature of the air further away is maybe 20°C cool. Remember that the interior of our body is around 37°C warm which means that we have a certain *current of heat* flowing from the finger into the air.

Current of heat

When we touch a metal object, we replace the insulating air with a highly conductive material—the resistance to the flow of heat out of the finger drops, the outer parts of the finger will lose heat faster than before and their temperature will drop—the metal object will feel cold because the temperature receptors in the finger sense the lowered degree of hotness. On the other hand, if the object is made of wood or plastic, the flow of heat out of the finger may be even weaker than if we do not touch anything, giving us the impression of a warm object.

A flow-tension relation for conduction of heat

When heat flows through materials—a transport we call either conduction or diffusion of heat—there exists a simple relation between the thermal tension necessary for this flow to occur and the strength of the current of heat. We shall see that ideas already introduced when we studied the flow of water through pipes (Chapter 3) will help us in the case of heat as well.

Take a close look at the diagram on the right in Fig.4.8 (and compare the curves to those found in Fig.3.10 and in the Box on p.123, which were obtained for the flow of air and water). Obviously, from the shape of the two temperature curves we conclude that the temperature changes faster the higher the temperature difference (i.e, the thermal tension). The temperatures of copper and water tell us something about the amount of heat in these bodies—the higher the temperature, the more heat is in a body. Therefore, when the temperature changes fast, so does the amount of heat; when the temperature changes slowly, so does the amount of heat. Finally, there is no more change of amount of heat in either one of the two bodies when the temperatures have stopped changing.

Conduction of heat—Flow-Tension relation

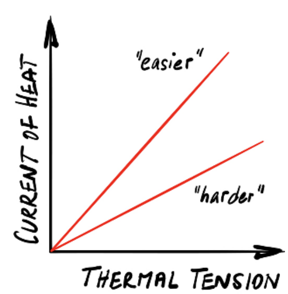
From the interpretation of observations of cooling and heating—such as seen in the data of the experiments presented in Figs.4.8 and 4.9—we can construct a thermal tension - current of heat relation. When the temperature difference is zero, the current will be zero as well; and the higher the tension, the stronger the current. The simplest possible relation, expressed formally, is one of proportionality. If we use the symbol I_S for the strength of the current of heat, and $\triangle T = T_{high} - T_{low}$ for the thermal tension, we can express the idea as follows:

$$I_S = G_S \triangle T \qquad (4.2)$$

The factor of proportionality G_S—called *thermal conductance*—tells us how easy it is for heat to flow through the given material. If we represent Eq.(4.2) graphically, the greater the value of G_S, the steeper the straight line will be. The notion of conductance is the inverse of *resistance*—we introduce the *thermal resistance* of a body if we wish to express the notion of how hard is is for heat to flow through this body.

The conductance depends upon the conductivity of the material and how long and wide the body is through which heat will be flowing; it will be greater for greater conductivity of the material, greater for greater cross section of the path, and smaller for longer distance to be traversed by heat.

Flow-Tension relation



Conductance

Resistance

Moreover, when the amount of heat in a body decreases (as in the case of water in the experiment in Fig.4.8), it must be losing heat—in our case, it is the heat that flows into the copper block and is stored there, so the temperature of copper goes up as a consequence. Furthermore, when the amount of heat of the bodies changes fast, the flow from one to the other must be strong: the faster the change, the stronger the flow! In summary, after assembling all the steps in this argument, we conclude that the flow of heat will be strongest when the thermal tension is highest, and the lower the temperature difference, the weaker the current of heat will be. Finally, the current will be zero if the tension is zero.[37]

The relation between strength of a current of heat and thermal tension driving it, as expressed in Eq.(4.2), is used very generally in thermal engineering and in architecture. If architects design a building, they use known values of conductances (or resistances) of building elements such as walls and windows and so know beforehand the heating requirements for different climates. Note that the expression is analogous to what we have seen for flows of water or other fluids in simple hydraulic settings (Chapter 3, Sections 3.2 and 3.4). This is another example of how analogical reasoning can guide us in our study of *Forces of Nature*.

Two more ways of transporting heat

Convection and radiation

The transfer of *heat* is a fundamentally important phenomenon in our natural and technical environments, and it can be quite intricate and lead to complex phenomena. The reason for this is that heat can be transported with the help of *fluids* and *light* in addition to just flowing through materials driven by a temperature gradient. The first of these mechanisms is called *convection*, the second is called *radiation* of heat.

Tensions for heat transfer

Different tensions for different modes of heat transfer

We have stressed several times already that the fluidlike quantity associated with a Force of Nature needs a tension if it is to flow from one place to another. If the tension is the one associated with the Force—such as a pressure difference with a Fluid as a Force, a gravitational potential difference with Gravity, or a temperature difference with Heat as a Force—we have a case of conductive flow.

If, however, the transfer is convective, i.e., if heat is carried by a material fluid, the tension responsible for this process is the tension that makes the fluid flow: In other words, the tension for convective heat transfer is a pressure difference.

Here are a few examples of convective and radiative transfer of heat. If air could stay absolutely still, it would be a great insulator. This means, areas of our planet are heated or cooled most effectively by winds—when hot or cold air flows into a region. Air stores heat, and when the air flows it takes this heat with it. Another example of planetary importance is the transport of heat with warm water in the oceans—take the Gulf Stream that carries warm water from the Gulf of Mexico to the North West of Europe (specifically, Ireland, Britain, Iceland, and Norway) thereby heating an area of the planet that lies fairly far north and would otherwise be quite a bit colder. Then there is the convective rolling motion of the thick mantle of the Earth (about 3000 km thick) that helps carry heat from the core of the planet to its surface (see Section 4.6). Finally, there are all the technical applications of convective heat transfer such as the flow of heat carried by water from a furnace in a home to the various rooms.

Radiation is equally of local and global importance. If we sit by a fire, we get heated by radiation: light is a medium that carries heat and passes through the air to where we sit (the air is hardly „touched" by the light, meaning that the heat carried by light does not actually flow through the air by conduction). Furthermore, radiation of heat is most important on an astronomical scale: our Sun could not get rid of all the heat that is produced in its interior if it were not for the light carrying it away into space. The same is true for the cooling of our planet; if the Earth could not radiate away all the heat it receives from the Sun plus all that is produced here (see Section 4.6)—if the outflow was effectively stopped—the planet would burn up in days or weeks!

Pumping *heat*

Pumping (forcing) heat „uphill"

If we are allowed to create an image of *heat* as a kind of fluid—which, so far, has worked very well—does this mean that *heat* can also be pumped? Liquids such as water spontaneously flow „downhill," but we can force them „uphill" with the help of pumps. We, or pumps, simply have to work for this to happen.

Refrigerators are heat pumps

Forcing heat uphill. It turns out that the same is true of *heat*. There are two important applications where we would want to pump *heat*. First, we might want to create a cold space in our usually warm environment: this is what a refrigerator does. *Heat* continually keeps flowing from the environment into the cold space inside the refrigerator, which then needs to be pumped up back to environmental temperature. A pit dug in a field with a continuous inflow of water is analogous to the situation of a refrigerator (see left part of Fig.4.10).

In other words, even though we do not have the most direct type of access to the notion of *heat*, our mind helps us. In fact, imagination is so strong that we can literally „see" heat flowing from body to body or being held inside materials. The case is analogous to electric phenomena (Volume 2): no eye has ever seen a quantity of electricity (electric charge), no scale has ever weighed electric charge, yet we speak of electricity being contained in materials and flowing through wires or, in the case of lightning, through air.

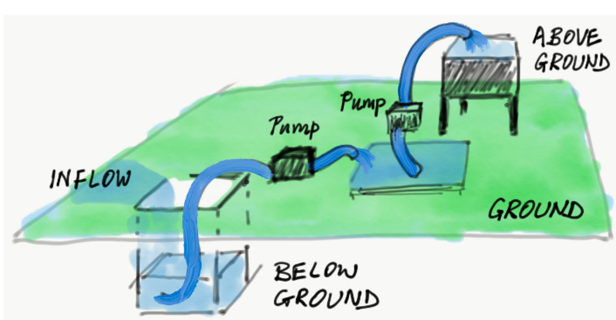


Figure 4.10: *An analogy, in pictures, between pumping water and pumping heat in refrigerator and heat pump applications. Left: Pumping water out of a pit in order to keep the water level as low as possible. Right: Filling a water tank with water from ground level. The situations are analogous to those of a refrigerator and a heat pump, respectively.*

Spontaneously, heat flows „downhill”

Just as water flows downhill by itself, and electric charge flows from points that are at higher electric potential to points where the potential is lower, *heat* spontaneously flows from places that are hot to places that are colder. This is what we learn from myriad everyday examples of thermal phenomena. Naturally, we can block *heat* from flowing but that does not negate the basic observation.

Pumping heat for heating

The second type of use of a heat pump is for heating. An hydraulic equivalent of this would be a tank or lake above the field, which is our ground level (see right part of Fig.4.10). In order to fill this tank or lake, water needs to be pumped up from ground level to the higher level. In the case of a heat pump, we take *heat* from the environment and use it to heat a body of water to higher temperature.

Heat pumps for space heating

Saving the planet with heat pumps!?!

In colder climates, we need to heat our homes, and the easiest way of doing this seems to be by burning some fuel. We know that this hurts the planet, so, taking heat from where it already is—the environment—and pumping it into our homes seems a good solution.

This is fundamentally true. However, heat pumps are powered electrically, and if the electricity is powered in thermal power plants that burn fossil fuels, literally nothing is gained.

So, heat pumps need to be powered by Forces that do not add CO_2 and methane to the environment. We can use solar electric power plants. On the other hand, we could heat our homes directly with solar thermal collectors—but then, the Sun does not shine much during winter, leaving us between a rock and a hard place.

Whatever we do, we need to somehow save the „summer sun” for winter. And this calls for a lot of ingenuity on the part of engineers.

Thermoelectric heat pumps. There are various types of mechanisms that pump *heat*, such as those we have in our refrigerators. Another type of heat pump is made of *thermoelectric materials* where electricity is used to pump *heat* (Fig.4.11), similarly to how electricity can be used to drive an electric water pump.[38]

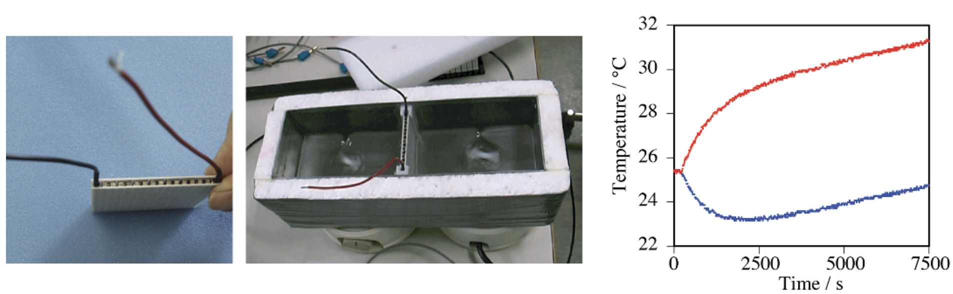


Figure 4.11: *Left: A thermoelectric element called a Peltier device. Center: The same thermoelectric element between two bodies of water in a well insulated container. Right: Temperatures of the two bodies of water as functions of time when the thermoelectric element is operated electrically.*

In the experiment shown in Fig.4.11, we make a Peltier device—a thermoelectric device that can be used both as a heat pump and as a heat engine—into a thin wall separating two quantities of water inside a thermally insulated container (Fig.4.11, center).

We pour the same amounts of water at equal temperatures into the two compartments, put an insulated lid over the container, fit two thermometers into the two compartments, and connect the wires of the Peltier device to a battery or electric generator. Over time, we see one of the bodies of water becoming cold while the other one gets warm (Fig.4.11, right).

If we use a Peltier device between the fingers of our hand and operate it, we notice that one side becomes cold and the other side becomes hot very quickly. When the device is between two equally warm bodies of water, heat flows from the water on the cold side toward the device, and from the hot side into the water on the other side. Inside the thin device, *heat* is pumped from the low to the high temperature side. Over time, the water on the cold side becomes colder, and the water on the warm side is made continuously warmer.

Heat is not energy

Let us not confuse quantities of heat with energy!

Every day, in schools, at universities, in engineering firms, in the media, and on the street we are told that *heat* is energy. Now consider heat pumps that need to be powered, i.e., they need energy for operation: if a heat pump pumps *heat*, and if *heat* is energy, then an energy pump pumps energy. This simply does not make any sense, certainly not in basic imaginative acts. If anything, heat pumps teach us that we should *not* imagine *heat* to be (a form of) energy but the subtle *fluidlike quantity* Sadi Carnot called *heat*, *amount of heat*, or *caloric*.

Energy, which we introduced in Section 3.7 and will explore in more detail in Chapter 5, has an altogether different role to play and should never be confused with the extensive quantities associated with every Force of Nature!

Remember that the vessel with the two bodies of water and the Peltier device is thermally insulated. There will hardly be any flow of heat going from the container to the environment, and vice-versa. In other words, what we see happening with the temperatures must be the result of transport of heat in the vessel. Simply put, heat has been pumped from one side to the other side, from cold to hot. *Heat behaves like a fluid.*

There is something in the measured temperatures—see the diagram on the right in Fig.4.11—that should make us pause, however. Why does the cold water not get colder forever? After about 2000 s, it is actually getting warmer! Has the pumping stopped? The warm water continues getting warmer but at the same rate as the cold water. Again, has the pumping stopped? What is going on in this container with water and a Peltier device?

Heat can be produced, but not destroyed

The answer to this question is simple yet possibly disturbing—in fact, it has caused great confusion in the history of the science of heat, and it continues to do so today as we try to understand thermodynamics. If heat is „like” a fluid, there should always be the same quantity in nature, at least so the reasoning goes. The calorists of their time often associated images of materiality with the quantity they called *heat* or *caloric* and, with razor-sharp logic, deduced from this that (quantities of) heat could neither be produced nor destroyed. However, experience tells us that

Heat is produced

heat is produced—fire, electricity, mechanical friction, and several other processes produce *heat* (Fig.4.12). Invariably, there is more of it in nature and in machines after processes have run their course. But then, *heat* cannot be a fluid, can it?

Figure 4.12: *Left: Producing heat in a fire. Second from left: Producing heat electrically for melting a piece of ice. Right: Friction produces heat (the photographs show a wooden drill bit drilling into a wooden board).*

Actually, for a mythic mind, this does not constitute an insurmountable problem (Chapter 1): the Force we call *Heat* is a ghostlike thing, an agent or character, very much like the character of *Cold* we encountered in the *Winter Story* in Section 2.6. A character can be born (be produced); as we shall see below, the question is rather if it can also die (be destroyed).

The problem we have with *heat* is not one of imagination, it is one of belief created by certain modern ways of thinking. Scientists generally believe that what science

Mind as mirror

comes up with *reflects* nature faithfully and quite directly.[39] We can be wrong about something, but eventually, science gets it right. If we say that *heat* is a *fluid*,

Literal thought

it *is* a fluid—what we say must be taken to be exactly so; it must be meant *literally*. However, we have seen again and again that our mind works imaginatively. When we say that *heat* resides inside materials, flows, and can be pumped, we assume

Metaphoric thought

a mythic mind that works *metaphorically* by projecting schemas (figures, shapes) upon new experience; in imagination, we add one more basic property to heat: *heat can be produced*!

Heat produced in a Peltier device. How does this explain the behavior of temperatures in the pumping of heat in the experiment of Fig.4.11? There are two different phenomena having to do with basic properties of heat which need to be kept apart. Consider, first, why the *difference* of temperatures of the two bodies of waters goes up at the beginning only and then stops going higher. All along, we have assumed that heat flows from a hot to a cold body if they are in contact. The two bodies of water are indirectly in contact: they are separated by the Peltier device which, like all normal materials, lets heat through. Therefore, as the temperature difference between the two amounts of water goes up, a spontaneous flow of heat from hot to cold is getting stronger; this flow is in the direction opposite to the direction of pumping. There will come the point when equally much heat flows back toward the colder water as can be pumped by the Peltier device. The temperature difference will not change any longer!

Now to the second effect: what makes the average temperature go up all the time? We know that when electricity flows through wires and other conducting materials, *heat* is produced. The Peltier device is an object through which we make electric charge flow, so heat will be produced in it. This means that more heat arrives in the warm water than is removed from the cold water, making the warm water get warmer faster than the cold water gets cold—exactly what we observe. Moreover, the total amount of heat in the two bodies of water will increase, making the average temperature of the two amounts of water go up—again exactly what we observe.

In summary, if *heat* had not been produced, the two temperatures would have changed symmetrically with respect to the initial value, and both would have become steady (unchanging) after some time—the curves would become straight and horizontal. In other words, the mark of the production of *heat* is seen most easily in the steadily rising temperatures after about 2500 seconds.

Irreversibility. If we accept the notion of *creation* of *heat*, should we also imagine that *heat* can be *destroyed*? The answer is *no*, we do not have to, and we should not. We cannot prove this, but simple experience suggests that heat is not destroyed—it can only be moved elsewhere. If we rub our hands, they get warm because *heat* has been produced. When the hands cool down again, *heat* does not disappear—it flows away from the hands into the environment.

Heat cannot be destroyed

There is something we really have to wrap our mind around. Even though experience and imagination tell us that heat can be produced but not destroyed, we—or the scientists who study thermal phenomena—usually have a hard time accepting this idea. What we can do is let our imagination play and see where production of heat without destruction leads us. We simply have to find out if the inherent logic of our images lets us produce stories of *Heat* that work out.

Naturally, there are observations we can call upon to bolster the idea of heat having this strange property. As we shall see in in the chapter on electricity in Volume 2, amount of electricity is always the same in nature; electric charge can only be moved around—that is what experience suggested to researchers at the time of Benjamin Franklin (remember Benjamin Franklin's description of the properties of what he called *electric fire* or *electric fluid*; see p.96), and the suggestion has held up it promise up until today. On the other hand, apples get produced and eaten—they are „born" and they „die." *Heat*, in contrast, is supposed to be this strangely one-sided fluid—we can produce it, but we can never again truly get rid of it; all we can do is let it go somewhere else.

Producing heat cannot be undone

Consider, for a moment, an electric drill (Fig.4.13, left). Even if we have never built one or taken it apart, we have an idea of its operation. Electricity drives rotational motion and at the same time *heat* is *produced* by the motor. Now consider a dynamo (Fig.4.13, right). A dynamo is an electric generator which is driven by rotational motion. So, a dynamo reverses the electrical and rotational operations of an electric drill: rotation drives electricity. However, it also *produces heat.* Heat (caloric) is *always produced* in parallel to the main process caused by the causing agent. Symbolically, the two cases can be represented as follows:

$$\begin{array}{rccc} & & \Rsh & Heat \\ Drill: & Electricity & \rightarrow & Rotation \end{array}$$

$$\begin{array}{rccc} & & \Rsh & Heat \\ Dynamo: & Rotation & \rightarrow & Electricity \end{array}$$

This means that there is *an operation in nature that is never reversed: the production of heat.* For this reason, one says that the production of heat is *irreversible.*

Producing heat is irreversible

Processes that produce heat

Even if we accept this, there is still the question why *heat* is produced in the first place when, for example, electricity powers rotation in an electric motor or drill. The reason for this is that there are a few fundamental *heat* producing processes such as fire or mechanical friction (Fig.4.12). A list of processes that create heat (caloric) is given in Table 4.3.

Figure 4.13: *Left: Electric drill. Right: Bicycle dynamo (photo: Adobe Stock/Philip-image).*

Heating up the Earth and the universe? Here's a question worth pondering: if *heat*, once produced, can never be destroyed, won't the Earth, or maybe the universe as a whole, continue to heat up and eventually „burn?"

Consider our planet. As sunlight is absorbed, vast amounts of heat are produced (Section 4.6). Still, the Earth does not get hotter because of this: the amounts of heat produced on the surface (and in the interior) of our planet are emitted into outer space by thermal radiation. As a consequence, if nothing else were changing, the surface of the planet would stay at a constant temperature. The phenomenon that is currently warming the planet—called global warming—is the result of chemical alteration of the air. With more carbon dioxide and other trace gases in the atmosphere, radiation carrying away heat has a harder time getting out to space. A slightly raised temperature can remedy this—virtually all the heat from the Sun plus what is produced here will find its way out again.[40]

Table 4.3: Heat producing processes

Fire	Mechanical friction (rubbing)
Chemical reactions (many of them)	Friction in fluid flow
Electricity flowing through conductors	Chemicals diffusing through materials
Absorption and emission of light (in general: radiation)	Heat flowing through materials
Mixing substances	Mixing warm and cold fluids

The universe expands and gets colder

So, the example of Earth does not pose a problem to the rule that *heat* can be produced but not destroyed. But what of the universe as a whole? With all the heat produced by all the stars, surely the universe will get hotter and hotter. Actually, the opposite is the case. Even though the amount of heat increases all the time, the universe cools down because it is expanding. This is analogous to when we let an amount of air expand: the air gets colder, not because it loses or destroys heat, but because the heat contained in it will be stored in a larger space. With a lower density of heat (amount of heat per volume), the temperature will be lower as well. (This observation will be instrumental when we study how the Sun's light produces the winds here on Earth; see Section 4.6.)

Is heat hot?

Does heat have a certain temperature?

Materials containing heat are more or less warm—normally, we associate values of temperature with materials and not with heat itself. Still, given our image of heat as a fluidlike quantity, we may ask if we should not think of *heat* having a certain degree of hotness?

We are free to do so: we can think of heat being either hot or cold. Indeed, from an imaginative standpoint, it makes sense to associate a value of temperature with the heat contained in a body. This is very much like imagining water being tense or relaxed (being at high or low pressure). Furthermore, it corresponds to the imagery developed with the help of the Embodied Simulation presented in Fig.4.7: actors represent the fluidlike quantity we call heat, and their felt physical tension corresponds to temperature. We can imagine heat as a fluid gestalt or figure and associate an intensity with it—we can imagine this figure to be more or less tense (under thermal tension).

Quantity of *heat* in imagination

Fluid metaphor for amount of heat

Let us summarize how we have created the image of *quantity of heat*. When we speak about *heat*, we make use of well-known schemas that derive from experience with water and other fluids. *Heat* is inside bodies, it flows, it can be pumped, it flows downhill, and when it does so, it can drive engines (Section 216). Moreover, as we just said, we can imagine *heat* to be under higher or lower tension—*heat* is hot or cold, it is at a certain temperature. Clearly, our mind is creating a metaphor that might be named the HEAT IS A FLUID QUANTITY METAPHOR (Table 4.4).

It is true that we say *heat* can be produced, and in contrast to many other cases (such as electricity, where we often say that it is produced), we have reason to believe that the image makes sense here. We need the image of *heat* being produced in processes such as fires, rubbing, letting electricity flow through wires, and several other phenomena. Moreover, we even need to add the assumption that *heat* cannot be destroyed once it has been produced.

In fact, material fluids such as water and oil are not permanent either. This is so because fluids are not just fluid—they are chemicals too—we know that they can be produced or destroyed. Water can be destroyed chemically when we pass electricity thought it (Volume 2), and it can be produced. Nature works like this too: oil is produced in olives that grow on trees, and, once consumed, olive oil will be destroyed. In other words, our experience with material (chemical) fluids adds the case of *production* and *destruction* to the properties of the abstract FLUID SUBSTANCE schema.

There is nothing illogical about the rules of human imagination that allow for something fluidlike to be produced! Using the abstract schemas that experience

Figure of fluid substance

with real fluids gives us does not mean that the gestalt or figure of FLUID—the entirety of FLUID schemas—faithfully reflects something physically real occurring in a particular case. The *figure* of FLUID SUBSTANCE is just that: a powerful imaginative structure, a *tool to think with.*

Table 4.4: The **HEAT IS A FLUID QUANTITY** metaphor

Source (fluid substance)		Target (heat)
Fluid	→	Heat
Amount of fluid	→	Amount of heat
Containment of fluid	→	Heat in materials
Flow/transport	→	Flow/current of heat
Obstructing a flow	→	Thermally insulating
Creation/destruction	→	Production of heat
Pumping	→	Pumping heat
Fluid power	→	Power of heat
Tension (pressure) of fluid	→	Thermal tension (temperature) of heat
Agency of fluid quantity	→	Heat as agent/patient

4.3 Ice, Water, and Steam—The Role of Heat

Ice, water, and steam present us with an extraordinarily rich array of phenomena that are important in both the non-living and the living world. Ice and water have profoundly shaped our physical environment. Think of glaciers, of alternating ice ages and warm periods, and the importance of ice at the poles of our planet. Steam, or vapor, in the atmosphere is part of the water cycle, and without it we would not have rain. And without the ability of trees to evaporate a lot of water, we could not have naturally cooling environments during a hot Summer day.

Apart from that, what is happening with ice, water, and steam, how they arise and how they are powerful agents in our physical environment, creates much wonder and interest, particularly for children. Therefore, it is important to study these substances, their relation, and their relation to heat.

One quick comment before we study simple aspects of these phenomena: we will learn that changes from ice to water to steam, or vice-versa, are actually chemical processes. From the viewpoint of substances as *Forces of Nature*, ice, water, and steam are different materials (even though they are made of the same microscopic constituents, i.e., molecules; we shall learn more about this in Volume 2). So, what does *Heat* have to do with these changes? Well, as we shall see, changes of heat stored in the materials accompanies such changes. Indeed, what happens with heat is an important element of these chemical phenomena.

Ice, water, and *heat*

It turns out that ice, water, and steam are not only interesting in themselves, they allow us to understand *heat* and *temperature* more profoundly. When water turns to ice (or ice to water), the heat content, i.e., the quantity of heat possessed by them, changes, but temperature does not. The same is true for when water turns into steam and steam into water. When we have only steam to work with, another interesting thing may happen: we can change its temperature without changing its heat content. These phenomena make it amply clear, that *heat* and *temperature* cannot be the same concepts.

Melting ice. Consider this simple quantitative experiment we can easily perform in the kitchen (Fig.4.14). All we need is a container, some ice (ice cubes or crushed ice), and a meat thermometer. We put the ice in the container, maybe add a few drops of water, and stir, possibly directly with the thermometer. The instrument will quickly show a temperature of 0°C.

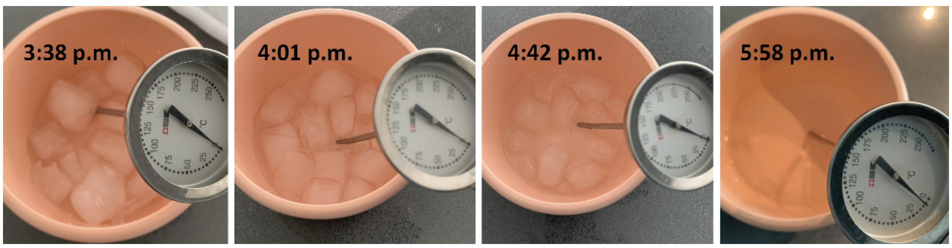


Figure 4.14: *Melting ice in warm environment. All the while, the mixture of ice and water stays at the same temperature of 0°C. Only after the last bit of ice has melted, does the water begin to warm up (the last temperature reading is a little above 0°C).*

Ice melts at constant temperature

We keep stirring and reading the thermometer. As more and more of the ice turns into water, the meat thermometer keeps showing the same temperature: 0°C. It does so until all the ice is gone and there is only water—then, at last, will the temperature reading go up.

Phase change

So, what does this mean, except for the obvious, namely, that the amount of ice is decreasing, the amount of water is increasing, and water and ice are colder than the kitchen? There are two important points and a conclusion about the relation between heat and temperature. First, and most obviously, the temperature of the mixture of ice and water does not change as long as there still is a mixture of the two. We usually call the period during which ice becomes less and water becomes more (or vice-versa during freezing) a period of *phase change*—one considers ice and water and steam (or vapor) three different *phases* of stuff that is made of the same chemical substance (having the same molecules, H_2O).

The observation that the temperature does not change may strike us as unexpected if we have never seen this to be the case. After all, a cold drink gets warmer as it just sits there in the kitchen. So, what is the matter with heat during the melting of ice? If we accept that in the case of the drink, heat flows into the liquid from the warm kitchen—making the amount of heat in the drink increase and making it warmer—maybe, for some strange reason, heat flowing into the ice-water mixture does not do what we expect it to do: it does not make the mixture warmer!

[On purely logical grounds, there seems to be one other possibility: *heat* disappears in the ice-water mixture. There are two possibilities for this to happen: one, it flows out right after flowing in, and two, it is destroyed. Now, neither case is acceptable. First, the kitchen is too warm, heat cannot flow out of the cold mixture. Second, we have just argued before in Section 4.1 that heat can only be produced but not destroyed. So, we need to accept that the amount of heat in the ice-water mixture is *increasing* whereas the temperature stays *constant*!]

Freezing water. Let us be clear that the same phenomenon—constant temperature during phase change—is also observed when water is freezing. The data shown in Fig.4.15 (left) stems from an experiment where we have a little bit of warm water in a test tube which is stuck into a mixture of crushed ice and a lot of salt in a larger container—this mixture gets very cold, about − 20°C. With electronic thermometers in the water and in the ice-salt mixture, we record temperatures as functions of time.

Heat leaves water when it freezes

There is a brief period during which the initially warm water gets colder—heat flows out and the temperature drops as expected. When the water has reached a temperature of 0°C, freezing begins and the temperature stays constant. Finally, the temperature drops again in a way reminiscent of what happened at the beginning when the warm water was getting colder. The phase change is complete, we now have only ice in the test tube and its temperature goes down, first quickly and then ever more slowly until the ice is as cold as the ice-salt mixture. This is the result of the amount of heat in the ice decreasing because heat keeps flowing out into the very cold environment.

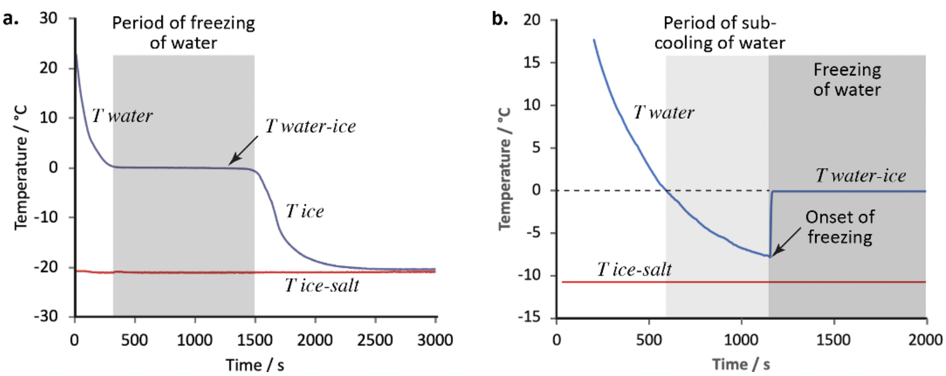


Figure 4.15: *Left: Freezing of a few grams of water in a test tube inserted into a very cold ice-salt mixture. The temperature of water and ice in the test tube is recorded as a function of time. Right: Temperature of 20 g of water in a small plastic bottle stuck in an ice-salt mixture at –11°C; here, sub-cooling occurs before the onset of freezing at about 1150 s, which still happens at 0°C.*

Our interpretation of what is happening during the period when the water freezes is the mirror image of what we just said about melting of ice. It would be very strange indeed if, during the period of constant temperature, heat was not flowing out of the freezing water in the test tube; after all, heat flows out of the water and out of the ice before and after the phase change. Accepting that heat indeed does flow out during freezing, we conclude that the amount of heat in the freezing water decreases whereas the temperature stays constant.

Note that, in the experiment reported here, the time for complete freezing to occur is much longer than it takes for the amount of water to be cooled from 20°C to 0°C (about 1200 s versus 300 s). This suggests that a lot more *heat* comes out of the freezing mixture than out of the cooling water. Indeed, melting ice takes quite a lot of heat, and when water freezes, quite a lot comes out of it. This is important both for our natural environment—for weather and climate, and therefore, also for life—and in technical applications.

Sub-cooling water. There is an interesting phenomenon that again shows that freezing is more than just a thermal phenomenon: still water left undisturbed in a cold environment can cool to a temperature below 0°C without freezing (see the data in the diagram on the right in Fig.4.15, up to about 1150 s). When this happens, freezing starts suddenly in a part of the sub-cooled water. This would normally release heat to the environment. Here, the heat „released" because of freezing of some of the water is kept by the body of freezing water thereby making its temperature jump back up to 0°C, the temperature at which, as should have been expected, „normal" freezing of the rest of the water continues.

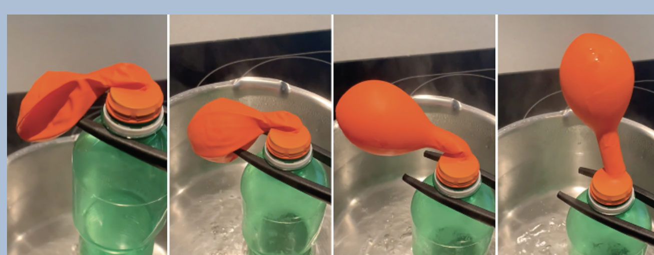
Effects of Heat

Heat can do more than just change the temperature of an object

We expect the fluidlike quantity we call *heat* to affect the temperature of a given object: more heat stored means higher temperature. However, this is not the only characteristic of a material heat can change.

Isothermal heating

We know that heat makes air expand (see the balloon attached to the neck of a bottle submersed in boiling water). If the body of air we consider is part of the atmosphere, heating it happens at constant pressure and, as a result, the air both gets warmer and expands. However, if the air expands rapidly enough upon heating (as might be the case in machinery with cylinders and pistons) it is possible for its temperature to stay constant; when this happens, we have a process scientists call *isothermal expansion*; as in the case of phase change, isothermal conditions do not mean that heating or cooling do not take place—the *heat content* of a body can still change!



Another phenomenon related to heating is change of the magnetic properties of a material.[41] If a piece of iron is made very hot, it loses its magnetic property. Again, changing how magnetic a material is can take place by heating (or cooling) at constant temperature, just like melting of ice or expansion of air. In summary, we can change certain properties of materials by adding (or withdrawing) heat without changing their temperature.

Latent heat and the distinction between heat and temperature. What we have just observed, described, and interpreted lets us distinguish between *heat*, i.e., the extensive quantity of thermal processes, and *temperature*, the intensive quantity, quite clearly. If the *heat content* of a material changes during phase change and the temperature stays constant, *amount of heat* and *temperature* are not related and simply cannot be the same concept. There is no way we should ever confuse *heat* and *temperature* again.

Heat cannot be temperature

In our defense, what is happening in phase change appears quite strange, at least at first. As we have said, and as we all know, heat makes things warm and lack of heat makes the same things cold. Apparently, we need to accept that this is not the only effect heat can have—it can also change the chemical nature of materials (such as when the material changes its phase), destroy the magnetism of a magnetic material, or simply let a body of air expand (see the Box on p.209)—all without changing the temperature of the objects.

Latent heat
Sensible heat

So, heat does not necessarily do what we expect it to do! It is as if it were hiding its „true" nature. Because of this, Joseph Black called the *quantities of heat* that appear to be „hiding" *latent heat.* In contrast, he and his successors in thermal science called the *amount of heat* that leads to temperature changes *sensible heat*—i.e., *heat* that makes itself felt to the senses as we expect it to do. Therefore, it is important to understand that the notion of *latent heat* applies not only to *heat* in phase changes but also in all the other possible changes, particularly in the expansion of air at constant temperature (see Section 4.6, p.241).

Joseph Black seems to be the one who coined the term *latent heat.*[42] He only applied it to phase change, particularly freezing and melting. Here is an excerpt from his writings that nicely shows how we can use natural language in order to speak about these phenomena:

> [p.129-130] *This experiment shews, that when water is cooled in a state of perfect rest, in a small vessel, it is disposed to retain this concealed heat, which I have been used to call its latent heat, a little more strongly than in ordinary circumstances. In common circumstances, the water retains the whole of this heat, until it be cooled to the 32d degree of Fahrenheit, or a very little lower. If, in ordinary circumstances, we attempt to make it colder, we may perhaps succeed in making it still colder by one degree or two, but no more, for then the latent heat begins to be extricated from a small part of the water, and to appear in the form of sensible heat, that small portion of the water which loses it, assuming consequently the form of ice.*

What Black describes here is the sub-cooling of water (Black spoke of *over-cooled* water). He used the term *latent heat* for *heat* stored in a material without making itself felt through its thermal intensity, i.e., its temperature. When *heat* is „felt" in the ordinary sense, it is called *sensible.* Researchers from Black onward until well into the 19th century talked about converting *latent heat* into *sensible heat* and vice-versa. Let us be clear that there are no different „forms" of *heat*—there is only the one extensive thermal quantity we call *heat*, which can simply have different effects.

Different substances require different amounts of heat

Let us return very briefly to the point raised at the beginning: phase changes are chemical processes, and ice, water, and steam (or vapor) are different chemicals. What we have just learned tells us that water is a substance that has a greater *requirement* for *heat* than does ice at the same temperature. To give an example, for water (as a sub-cooled liquid) to exist at –5°C, the substance needs to contain a lot more heat than if it were ice at –5°C.

Water, steam, and *heat*

When we boil water at a temperature near 100°C—this is the boiling temperature of water if we are not too high above sea level—it disappears, and in its place, *steam* appears (Fig.4.16). Disappearing water can be observed at much lower temperatures as well—in this case we say that *vapor* is formed (Fig.4.17).

Boiling. Boiling is easy to observe; the temperature and the decreasing weight of the water can easily be recorded during a process of vaporization. In the diagram in Fig.4.16 (right), we see how temperature and mass („weight") behave as we heat water with an electric immersion heater in an open beaker, then vaporize it for about 6 minutes, and finally turn the heater off and let the water cool. As far as the temperature is concerned, the most important observation for us at this point is that it stays constant during boiling when steam is formed.

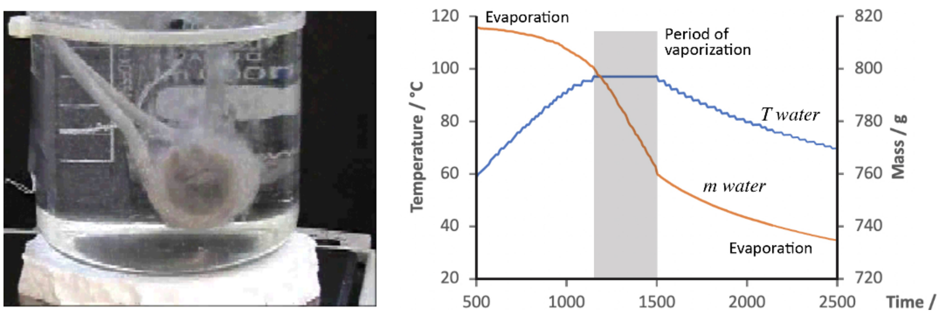


Figure 4.16: *Left: Electric heating, vaporizing, and subsequent cooling of water in an open beaker (the beaker sits on a scale). Right: Data of water temperature and mass („weight") of water as functions of time. Notice that boiling (vaporization) happened at a temperature a couple of degrees below 100°C because the experiment was performed in the hills above Zurich at an altitude of roughly 500 m above sea level.*

Boiling happens at constant temperature

Quite obviously, the electric heater supplies *heat* to the water the entire time until it is turned off at time 1500 s. So, as in the case of melting of ice, the *heat content* of water and steam increases whereas the temperature does not change—once again, we have an *isothermal process*. There is more heat, but it does not make itself felt by raising the temperature of the materials involved. In Black's way of expressing this fact, the *heat* supplied becomes *latent*, not sensible.

Steam contains more heat than water

In the case of boiling water, we can be quite sure what happens with the *heat* supplied: it does not stay in the water, it goes into the steam. Steam is a substance with a greater requirement for *heat* than water at the same temperature. Indeed, one kilogram of steam (at 100°C) contains a lot more *heat* than one kilogram of water (at 100°C). This is why burning our skin with steam can be so much more dangerous than if we got burned by the equally hot water: upon condensing on our skin, steam quickly deposits much more heat than the water could (by cooling maybe a few degrees upon contact with our skin).

Evaporating water

Evaporation. Recording the weight of the water demonstrates some interesting behavior. The mass of the water decreases quite fast during vaporization: vapor is produced at a high rate. However, the mass of water decreases as well, though much more gently, before and after boiling. Clearly, water disappears not just when it is properly boiling; it can also *evaporate*. Moreover, the phase after boiling, after 1500 s when the electric heater was turned off (see the diagram in Fig.4.16), demonstrates that evaporation is *not* a consequence of direct heating (as we might have surmised from the loss of water during active heating before boiling).

The impressive photograph of water vapor rising above a lake on a cool Fall morning (Fig.4.17) shows that water disappears and vapor is formed even though the water is fairly cool. So, what is the driving force for this phenomenon? We might get fooled by the picture of the Sun and its rays in the photograph on the left: it is not heat per se that drives evaporation of water. We usually think that water that is warmer than the surrounding air will evaporate. We see this to be the case in the diagram in Fig.4.16, and we can assume that the water of the lake in Fig.4.17 is warmer than the air on this Fall morning, but the difference is very small (about 10°C for the water and 8 degrees for the air). Still, what makes the lake evaporate is not the Force of *Heat*.

Figure 4.17: *Vapor rising over Lago Maggiore (Ticino, Switzerland) on a cool, and dry Fall morning (photos: PL).*

If we observe a body of water more carefully and with simple instruments, we can see that water must be evaporating for a different reason. In Fig.4.18, we have temperature and mass data for water in an open container on a kitchen scale. The temperature was measured with the help of a meat thermometer. In the beginning, the water was very hot, higher than 90°C, and we had a little more than 1 kg of it. The temperature of the air in the kitchen was a constant 25.0°C.

Hot water evaporates quite quickly. In the experiment, the rate of loss of mass of water was almost 4 grams per minute. As the temperature of the water neared the temperature in the kitchen, the rate had decreased 60-fold. What followed is remarkable: the water gets to be cooler than the environment (the temperature eventually reaches a steady state), and the mass of the water keeps decreasing. In other words, even though the water was colder than the air, it kept evaporating!

Finding out what is going on, both with the water and heat, is not that difficult. We could repeat the measurements outside on a rainy day. Naturally, we want to make sure that it does not rain into the container of hot and cooling water. What we will observe is that the temperature of the water eventually reaches and stays at that of the environment, and evaporation stops (the mass of the water in the container will not decrease any longer). What is different from the case of doing this in the kitchen is simply that the air is saturated with vapor—it cannot take up more of it. In the case of the measurement shown in Fig.4.18 the air was relatively dry (it was late winter, the heating was still on and the humidity in the apartment was barely above 40%). Therefore, we might assume that evaporation is driven by differences of humidity, and not by temperature differences.

We can assume the same to be true for the air above Lago Maggiore. The motion of vapor blown by the wind across the lake suggests that replacing humid air by fresh, dry air makes the air ready to receive new vapor. We do not have data of the humidity of the air on that day, but we can safely assume that it was relatively dry. Therefore, the scene suggests that it is the difference of „degree of wetness" between the water of the lake and the relatively dry air that is the driving force of water evaporating from the surface of the lake.

What is the role of heat in the case of evaporation from water that is cooler than the environment? The explanation goes as follows. Vapor contains more *heat* than water at the same temperature. Therefore, vapor, that is formed because of the difference of humidity between water and air, requires *heat* which can only come from the environment where it forms, i.e., from the water. That is why the temperature of the water drops below that of the environment (therefore, the temperature difference cannot be the driving force!). As the water gets colder, it will receive *heat* from the environment as it passes through the container wall; eventually, this goes on at the same rate as heat is passed to the vapor that is formed. When this is the case, the temperature of the water will remain steady. This is what we observe in the data of the diagram on the right in Fig.4.18.

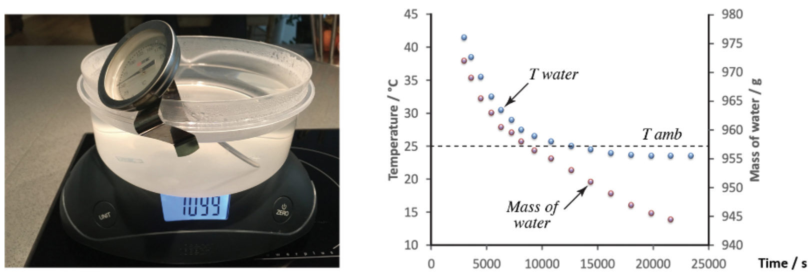


Figure 4.18: *About a kilogram of hot water is cooling and evaporating in an open container. The temperature in the kitchen is constant at 25.0°C. The water eventually gets to be colder than the kitchen and keeps evaporating.*

Evaporative cooling. Note that the temperature of the water should drop further if the container is well insulated against the flow of heat, making it harder for the heat which is lost because of evaporation to be replenished. What we have here is a case of *evaporative cooling*. The most direct experience we can have of this is when we are wet from taking a swim and now the water on our skin evaporates into the dry air around us; and if there is wind, the effect will be even stronger, simply because vapor is removed efficiently from around us, and new vapor is formed at a higher rate. By the way, this is also how trees are efficient at cooling their environments on a hot summer day. Observe the difference of sitting under a tree or under an umbrella on a hot and sunny day!

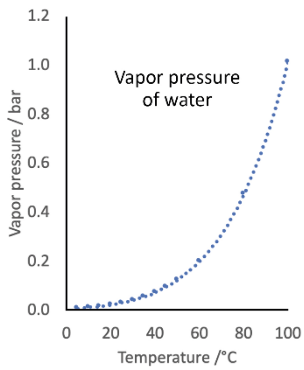
Evaporative cooling

Boiling and freezing points

The temperature at which water freezes is called its *freezing point*, and the temperature at which water boils is its *boiling point*. As we have already seen in a couple of examples, temperatures of freezing and boiling points sensitively depend upon circumstances.

We all may have heard or even seen that salt is used to melt ice on the streets in winter. What is happening there is that salt lowers the freezing point of water. As we have witnessed when we used crushed ice and a lot of salt in order to produce a very cold mixture (Fig.4.15), this effect can be very noticeable. By the way, sea water, which is salty, freezes at about −2°C. Fresh water, however, freezes at 0°C (notwithstanding the phenomenon of sub-cooling), pretty much independently of where on Earth we let this happen.

This is not the case with boiling where it matters crucially where we are on the planet, i.e., how high above sea level we are when we boil water. In the example seen in Fig.4.16, boiling took place at 97°C; the reason for this is that the air pressure where we did the experiment is lower than at sea level—depending upon the weather, maybe 5% lower. If we lower the air pressure even further—maybe by going up higher into the mountains—water boils at an even lower temperature. At an altitude of 4200 m above sea level—which is at the summit of Mauna Kea, one of the two high volcanoes on the island of Hawaii—air pressure is down to roughly 60% of 1 bar and water boils at about 86°C.



We can understand this behavior if we make clear to ourselves what happens when water boils on a stove. At the boiling point, tiny amounts of water inside the pot turn into steam and so form bubbles that will rise to the surface and so create the more or less violent motion we know from water boiling. Now, if the pressure of the air, and therefore of the water in the pot, is lower, it is much easier for a bubble of steam to form—water will boil at a lower temperature.

Scientists summarize this observation by saying that water has a certain *vapor pressure* which strongly depends upon temperature. To use a couple of examples, at 20°C, vapor pressure (of water) is about 2% of 1 bar; at 50°C it is 12%, at 80°C it is 47%, and at 100°C it is 100% of 1 bar. This simply means that, at 50% standard air pressure, we need to make water 80°C hot for it to start forming steam bubbles spontaneously and in a sustained manner.

At sea level, water needs to be 100°C hot for this to occur. And if we boil water in a pressure cooker where the steam is confined to a fixed volume—which allows for the pressure of steam and water to go up considerably—boiling takes place at correspondingly higher temperatures (if the pressure is allowed to go to about 2 atm, the temperature of water and steam in the cooker will be about 120°C).

Boiling means that bubbles of steam (vapor) form inside the body of water. Remember that water will evaporate from the surface of a puddle or lake at much lower temperatures if the air above it is relatively dry. As we have said before, this is a „chemical" process; we can now formulate more precisely why this happens: if there is a difference in vapor pressure of the vapor right at the surface of a body of water and a little further away in (relatively) dry air, vapor will form and migrate away from the body of water to where conditions are „dryer." The higher the temperature of the water, the higher is the pressure of its vapor at its surface, and the more easily it is for water (vapor) to escape into the air—again, only if the air is not already „dripping wet."

Humid air

All this should help us understand important phenomena related to humid air: why warmer air can take up more water vapor, why clouds form in the sky, and why dew appears on a patch of grass early on a summer morning.

Take the first of these phenomena. The story told by how vapor pressure depends upon temperature suggests that the tendency of water to „move out of its (liquid) state" and „into the state" of being vapor is stronger the higher the temperature. Conversely, the higher the temperature, the lower the tendency of vapor to condense and form water will be. Warm air can therefore take more water vapor (say, per kilogram or cubic meter of air) than cool air before the vapor „wants to revert to" the state of liquid water.

This explains the formation of clouds—which are condensed water droplets—and dew. As humid air moves up in the atmosphere, it expands and gets colder (we shall discuss this important process in some detail in Section 4.6). Therefore, the tendency of vapor to form liquid water increases and so it does not hold all its vapor any longer—the cooler air becomes „dripping wet" and clouds arise. Scientists say that the air has become *saturated*, and if there is even more vapor than saturated air can take, the excess vapor condenses. Finally, if the drops being formed are big enough, they will fall: it will rain.

Clouds form

Dew forms on summer mornings if the air is humid enough. During the day and evening, the air is still warm enough to hold its vapor. But when the air over a field gets cool enough, the air becomes over saturated and whatever vapor the air cannot hold any longer will condense; drops of water will form on grass.

Dew on grass

We might wonder why streets typically do not get wet from dew. The reason is simple: streets stay pretty warm whereas a thin leaf of grass exposed to the cool air quickly gets cold enough to allow for vapor to condense and liquid water to settle on its surface.

Dew point and wet bulb temperature

Dew point and wet bulb temperature

In meteorology and engineering, two measures are introduced that help us specify the humidity of air. The first of these is the *dew point*, which is the temperature at which vapor in air will condense. To give some examples, if the „normal" air temperature is 20°C and the reported dew point is 20°C as well, the air must be „dripping wet," i.e., it is probably raining. At the moment of writing this, our weather app tells us that the air temperature is 22°C and the dew point is 14°C; this means that the air is too warm for condensation to take place, which at the same time means that the humidity is lower than 100%—indeed, according to the app, the humidity is 62%. The example is a case of the general rule that the dew point will always be equal to or lower than the normal air temperature.

The normal air temperature is called *dry bulb temperature*. If we wrap a wet cloth around the bulb of a thermometer (such as those shown in Fig.4.4) and blow air across it, the temperature reading will normally go down and then stabilize at a lower point than standard air temperature—the reading is called *wet bulb temperature* and it tells us how cool a body can get if we let water evaporate from its surface. The phenomenon is called *evaporative cooling* and is a method for making things cool in a hot (and relatively dry) environment.

The reason for the lower wet bulb temperature in steady state evaporation is this. The evaporating water draws heat from the thermometer, making it cooler; on the other hand, heat will flow from the environment—which is now warmer—into the thermometer. At some point, the two flows of heat will be balanced and the temperature reading will have become steady. Obviously, if the humidity of air is 100%, evaporation cannot take place and the wet bulb temperature will be equal to normal air temperature (dry bulb temperature). The wet bulb temperature will always be between air temperature and the dew point.

Steam responding to *heat*

Water and ice change their temperature in response to heating and cooling, and that's it. Since steam is a gas, it reacts in a more complicated manner, and this is important for both natural and technical processes. First, we can confine an amount of steam to a fixed volume in a vessel with rigid walls. In this case its response to *heat* is the same as that of ice and water: it gets warmer and colder upon heating and cooling, respectively. If the steam is not confined, though, both volume and temperature—and therefore pressure as well—change in general. Finally, under special circumstances, the volume can change whereas the temperature stays constant—this is again one of the cases where heat does not do what we normally expect it to do.

Isothermal expansion and compression

Volume change without heating/cooling

There is one more process that deserves particular attention: gases can be compressed or expanded without heating or cooling taking place. What happens to the temperature of the gas, and why it happens, will be discussed when we treat the case of air responding to heat in Section 4.6.

◦ ◦ ◦ ◦ ◦

After all this discussion about heat and temperature, we might wonder how to quantify *amounts of heat*. Even if we are not scientists, measuring temperatures is something we do routinely in everyday life; and, as we have said, we have a direct sense of hotness. Quantities of heat, in the sense of the extensive quantity of Heat as a Force of Nature, are more difficult to nail down quantitatively, though. We shall see that we can do this more easily if we know how to quantify the power of Heat. Power relates Heat to other Forces, and if we manage to quantify other Forces that couple with thermal ones, we can then come back and calculate amounts of heat involved in concrete phenomena. We shall begin this work in the following section on the *Motive Power of Heat*.

4.4 The Motive Power of Fire

Waterfall image of thermal process

It is time for us to turn our attention to the third of the basic characteristics of Heat, namely its power. We shall make use of Carnot's analogy between *Heat* and *Water* which suggested to him the imagery of *heat* „falling" through a temperature difference from the furnace to a cooler when doing its work in a heat engine (Fig.4.19). If we accept this form of thinking, we can immediately write down how the power of *heat* flowing from a point where the temperature is high to one where it is lower should be calculated.

This will allow us to arrive at some important results very quickly. In particular, we will be able to discuss the processes of pumping and producing heat from the viewpoint of their relation to power. This will allow us to understand, among other things, why thermal power plants have a relatively low efficiency, and why pumping heat for heating purposes is preferable to producing it in a fire. Moreover, we can finally show how to calculate *amounts of heat* and so get a better understanding of this invisible quantity.[43]

A very brief history of heat engines

The history of the invention and early use of steam engines provides us with an opportunity to discuss how one FoN influences, i.e., drives or „causes" another one. More than one hundred years before Sadi Carnot's theory of heat engines, steam power started to come of age, though very slowly and inefficiently at first. Shortly before 1700, Thomas Savery built a steam driven water pump which he called

„miner's friend" because it was supposed to be used for pumping water out of coal mines. As the story goes, the first steam-water-pumps were so inefficient that more coal was used for powering them than could be obtained by mining. This is probably not quite the case, but early steam engines were indeed extremely inefficient. Importantly, for industrialized society, engineers did not give up on the idea even though, initially, it worked out very poorly.

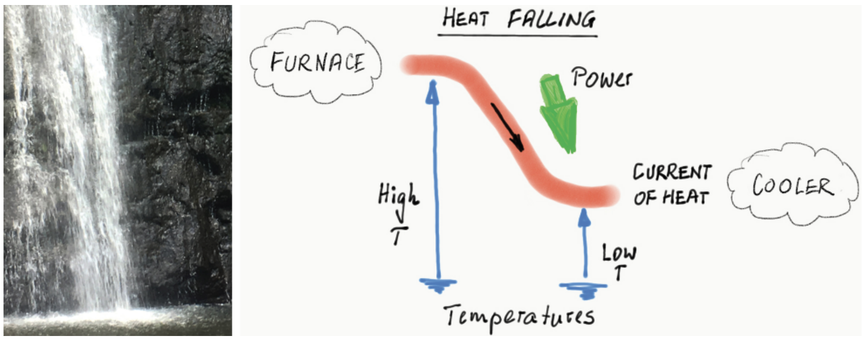


Figure 4.19: *Left: A waterfall in Manoa Valley, Honolulu. Water falling through a certain height suggests a view of heat operating that relies on the metaphoric projection of basic schemas of tension and flow relating to power (center). Right: Schematic (abstract) representation of the experiential elements in a waterfall, projected onto Heat. A fluid (generally: a fluidlike quantity) is falling through a level difference (potential difference), creating the „potential" for driving another process (see also Figs.3.4 and 3.25).*

A few years later, Thomas Newcomen improved upon the early designs with his atmospheric condensing heat engine driving a water pump (Fig.4.20), creating the first commercially successful heat engine.[44] The heat engine part consisted of a furnace, a boiler for producing steam, a „power" cylinder where the steam did its work and was then condensed with a spray of cold water and removed before fresh steam was admitted.

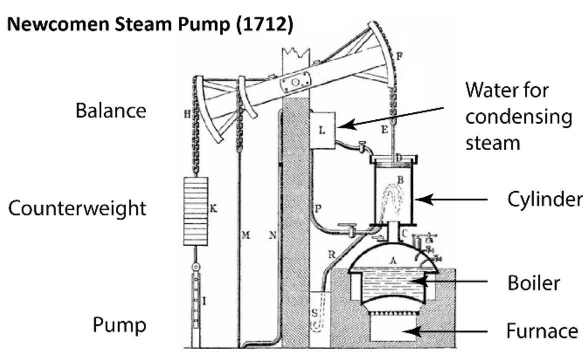


Figure 4.20: *Steam engine built by T. Newcomen. Notice the furnace and the cooler (implemented with the help of water for condensing the steam) which serve as the hot and the cold places between which heat flows and so does its work of powering the engine (which was used to drive a water pump for draining a mine).*

Still, as James Watt was to realize some 50 years later, the design was inefficient because the steam was condensed inside the „power" cylinder which would cool the cylinder walls as well. For every stroke of the engine, the cylinder needed to be heated again, so a lot of heat was wasted. Watt therefore added a „condensing" cylinder (simply called a condenser): after pushing the piston up, the hot steam was transferred to the condenser and condensed there. The Watt engine was first built in 1765.

After that, steam power and, more generally, heat power took off and „powered" the industrial revolution. It effectively replaced wind power and, at least to some degree, water power. Steam engines were put on rails; huge Diesel engines were installed on ships; internal combustion engines were to revolutionize private transportation with their use in cars; jet engines let us fly around the globe; large scale steam turbines now power the electric generators of thermal (fossil fuel, nuclear, or solar) power plants; finally, high efficiency gas turbines have come of age in electric power plants.

The need for hot and cold places. What the history of these inventions and their development tells us most vividly is the fact that, as Carnot put it, it is not enough to have *Heat*, we also need to procure *Cold* at the same time:

> *According to this principle, the production of heat alone is not sufficient to give birth to the impelling power: it is necessary that there should also be cold; without it, the heat would be useless.*[45]

Knowing this first hand let him imagine the functioning of a heat engine as the result of the „fall" of heat from hot to cold. Take a look at the drawing of the Newcomen engine (Fig.4.20): there is a fire and a boiler where steam is produced, which goes into the cylinder with movable piston, pushing the piston up. Moreover, there is a supply of cold water that is used to condense the steam and let the piston come back down and so move the lever of the engine and power the pump—without this step nothing much would happen. Here is how Carnot described the operation of a steam engine:

> *What happens in fact in a steam-engine actually in motion? The caloric developed in the furnace by the effect of the combustion traverses the walls of the boiler, produces steam, and in some way incorporates itself with it. The latter carrying it away, takes it first into the cylinder, where it performs some function, and from thence into the condenser, where it is liquefied by contact with the cold water which it encounters there. Then, as a final result, the cold water of the condenser takes possession of the caloric developed by the combustion. It is heated by the intervention of the steam as if it had been placed directly over the furnace. The steam is here only a means of transporting the caloric. It fills the same office as in the heating of baths by steam, except that in this case its motion is rendered useful.*[46]

Carnot's suggestion for how to express the *Power of Heat*

We have already read Sadi Carnot's writings about Heat as a Force of Nature—heat is powerful (p.178). But how does it do this? Again, it was Sadi Carnot who taught us a certain way of looking at Forces of Nature. If *heat* or *caloric*, as he called it, has fluidlike properties, it might work analogously to how water works. Water does its work by falling down, such as in a waterfall. Here are Carnot's words describing how he thought one could understand the operation of steam engines:[47]

> *According to established principles at the present time, we can compare with sufficient accuracy the motive power of heat to that of a fall of water . . . . The motive power of a fall of water depends on its height and on the quantity of the liquid; the motive power of heat depends also on the quantity of caloric used, and on what may be termed, on what in fact we will call, the height of its fall, that is to say, the difference of temperature of the bodies between which the exchange of caloric is made.*

We can take Carnot's analogy as a blueprint for a general understanding the power of Forces of Nature: a Force is powerful just as water is in a waterfall. A waterfall is the *archetype* of a physical process as it drives other processes—we speak of the *waterfall image* of physical processes.

Waterfall image

The notion of the power of a waterfall (p.154) was known to Carnot. He therefore had something to fall back upon, something that allows for analogical transfer. If we do the same with what we formulated in Eq.(3.13), we should assume the power of Heat to be given by

Analogy

$$Power\ of\ Heat = Temperature\ difference * Flow\ of\ heat. \tag{4.3}$$

So, whenever *heat* flows from a point of higher to a point of lower temperature, it makes its power felt: it will bring about other processes that will become powerful in its place.

The form of the relation is exactly the same as the one for the gravitational power of a waterfall; it can always be brought into the generic form of

$$Power = Tension * Flow. \tag{4.4}$$

Remember that we experience potential differences, i.e., differences of intensities, as tensions: we have encountered various tensions such as hydraulic (pressure difference), gravitational (difference of gravitational potential), and now thermal tensions (temperature difference). The generic result presented in Eq.(4.4) works perfectly in physical science.[48] It helps us relate different Forces of Nature to each other: the idea is that in their interaction, power plays a role. Having an idea about how to express the power of a Force should help us learn how to describe and quantify interactions.

Power of a generic process

Heat and *Water* interacting in heat driven water pumps

Our way of looking at Forces of Nature and their power makes it possible for us to discuss the idea of pumping water with the help of a steam engine (or generally, a heat engine) without having to go into technical details (Fig.4.21). From a purely schematic viewpoint, what is happening is this: *heat* is falling down, thereby lifting water from a lower to a higher level. Expressed even more schematically: Heat as an agent drives a gravitational process.

We have used this way of describing the interaction of two Forces before in Section 3.1 (see Fig.3.4)—we apply the imagery of an agent *empowering* a patient (Fig.4.21). *Power* is the notion that allows us to quantify this idea: if, indeed, the only thing happening is a first Force (agent) driving a second Force (patient), we shall say that the power of the agent equals the power of the patient:

$$Power\ of\ Agent = Power\ of\ Patient \tag{4.5}$$

or, applied to our case,

$$\begin{aligned} &\textit{Temperature difference} * \textit{Flow of heat} = \\ &\qquad \textit{Gravitational tension} * \textit{Flow of mass of water}. \end{aligned} \tag{4.6}$$

Ideal interaction

It is important to realize that this is a case that does not arise in reality. It represents an idealized situation; we would say that the interaction between agent and patient is *ideal*. We shall investigate real-life situations in thermal engines further below after discussing two more fundamental cases of the relation between heat and (thermal) power: *pumping heat* and *producing heat*.

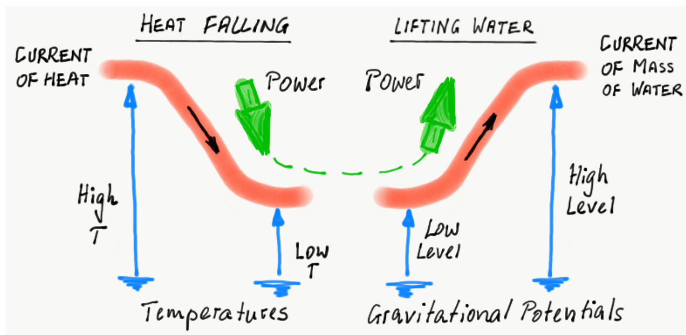


Figure 4.21: *A process where heat falls from high to low temperature pumps another fluidlike quantity from low to high potential. Shown here is a case of ideal coupling of agent (Heat) and patient (which can be Water, Motion, or Electricity)—we assume that the power of the agent equals the power required for „empowering" the patient.*

Heat pumps pump *heat*

We have described the case of pumping heat starting above on p.199. Now, we are in a position to formulate the relation between power and the raising of heat from a cold space to a warm space (Fig.4.22). Just as when we raise water in the gravitational field (Fig.4.21), we need a driving agent that will empower heat to go in the direction it does not spontaneously go, i.e., from cold to hot. Applying the form of power of an agent to that of a patient, we have

$$\begin{aligned} &\textit{Power required for pumping heat} = \\ &\qquad \textit{Thermal tension} * \textit{Flow of heat being pumped}. \end{aligned} \tag{4.7}$$

There are different ways of empowering heat to flow uphill. The most common heat pumps are used in refrigerators, followed by air-conditioning units and, more recently, heat pumps for heating purposes. Most of these make use of a refrigerant fluid that is evaporated by heat taken from the cold space; the vapor then goes to a radiator that radiates the heat into the warm space; finally, the vapor is condensed and returns to the cold space.

Stirling engine

What we have here is basically a heat engine running in reverse. Indeed, one of the most efficient heat pumps is made of a Stirling engine, a heat engine that is heated from the outside and always keeps air or another gas as the working agent enclosed in the engine (in other words, the working agent does not constantly have to be supplied to, and then removed from, the engine as it needs to be in internal combustion engines). Running the Stirling engine in reverse gives us a refrigerator. Another device that works both ways, as a heat engine and as a refrigerator/heat-pump, is made of thermoelectric materials that couple the Forces of *Heat* and *Electricity* directly (Fig.4.11).

Thermoelectricity

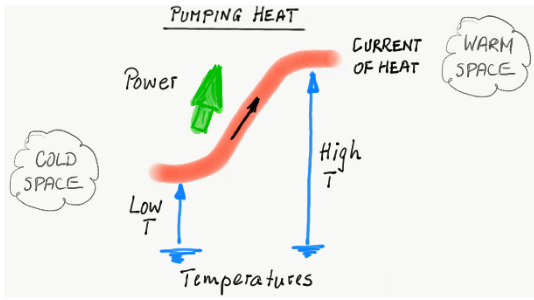


Figure 4.22: *Principle of operation of a heat pump: Heat pumps pump heat. Heat goes from a cold space (lower temperature) to a warm space (higher temperature). This requires some other process to raise heat and empower it in turn.*

Power of the process that produces *heat*

Let us conclude the discussion of the basic aspects of the power of a thermal process with an example that is particularly important to our understanding of thermal phenomena: the power of the act of producing *heat*. Apart from learning how to quantify the power of this phenomenon, we shall learn something important about the hotness scale: it is bounded at the lower end—temperature has a lowest possible value (which is given a value of 0 on the Kelvin scale; see Fig.4.4).

Production of heat must be driven

We need to be aware that the production of heat is a non-spontaneous (driven, caused) process. This means two things (Fig.4.23). First, we still need a spontaneous (driving, causing) process for heat (caloric) to be produced. Second, producing heat means that a tension, i.e., a temperature difference, is set up; remember, causing a process means creating a tension.

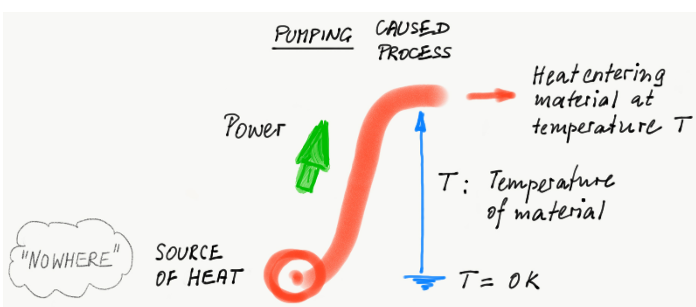


Figure 4.23: *Creating heat is equivalent to pumping it from absolute zero.*

The issue of processes causing the production of heat has been dealt with (Table 4.3). Chemical reactions, and in particular, combustion of fuels; mechanical friction; absorption of the Sun's light; and electricity flowing through conducting materials are archetypal heat producing processes. All of this means that the heat producing processes listed in Table 4.3 are powerful spontaneous (driving, causing) phenomena.

We conclude that these processes do two entwined things: they create heat and establish a thermal tension, i.e., a temperature difference. If producing heat is, apart from its special meaning, a caused process like any other, we already know how to calculate its power:

$$\begin{aligned} &\textit{Power required for creating heat} = \\ &\qquad \textit{Thermal tension} * \textit{Rate at which heat is produced}. \end{aligned} \tag{4.8}$$

We can express the idea of what heat producing processes do in still different words: *they produce heat at a specific temperature.* Consider using an electric water heater, a so-called immersion heater. You immerse the heating coils in some water at a given temperature and turn the electricity on. Heat is produced and enters the water at its current temperature. This suggests the idea that the heat has been produced at the temperature of the water.

Producing heat is like pumping it from absolute zero

The power of the process of producing heat

Producing heat is a non-spontaneous (driven, forced, caused...) process which means that it can be considered analogous to the pumping of fluidlike quantities.

We can create the following image for the production of heat: heat is created at absolute zero temperature and then pumped to the temperature at which it makes its appearance in nature. We can use the diagram on the right in Fig.4.22, set *Low T* (Potential 1) to zero, and obtain Fig.4.23.

Saying that heat is produced at a specific temperature, and knowing at the same time that what matters in a process is the associated temperature difference, brings up an interesting result: if the temperature at which heat is produced is a temperature difference at the same time, there has to be a fundamental level with respect to which all temperatures are measured. The temperature of this level of hotness is given a value of zero degrees. Therefore, the thermal tension used to calculate the power of the process of producing heat is simply the temperature at which heat has been produced (Fig.4.23). Consequently:

$$\begin{aligned} &\textit{Power required for creating heat} = \\ &\qquad \textit{Temperature} * \textit{Rate at which heat is produced}. \end{aligned} \tag{4.9}$$

Temperature has a point of absolute zero

In summary, apart from having learned how to express what the power needs to be when we produce heat, we now know that values of temperature need to be absolute! Imagine the hotness scale did not have a fundamental level to which we assign a temperature of zero degrees. We would then be free to assign any value of temperature to a given situation—the temperature would not be fixed. And this would mean that the power of irreversible processes would not be fixed either; it would be arbitrary.

4.5 Power and Efficiency of Thermal Processes

So far, we have collected the three basic forms of the relation between amount of heat, temperature (or temperature differences), and power: (1) the power of a fall of heat, (2) the power required for lifting (pumping) heat, and (3) the power required when heat is produced. Combining this knowledge will allow us to answer questions concerning the efficiency of thermal and other processes.

Production and absolute levels

Processes of production and destruction require absolute potentials

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The observation that heat can be produced—*heat* is what physicists call a *non-conserved* quantity—and that hotness has an absolute zero level are intimately connected. If temperature were not absolute, the power of the process of producing heat would be indeterminate.

The same is true of the production and destruction of substances—the chemical potential is absolute—and of the production and destruction of volume of fluid (expansion and compression)—the pressure is an absolute level.

Conversely, electric charge, which cannot be created or destroyed, does not have an absolute potential—we are free to choose whatever zero level of the electric potential we wish. The same holds for gravitational mass and its potential. And again, this also holds for quantity of motion and its potential (speed).[49]

The idea of efficiency of an interaction

When two Forces interact—wind pumping water, falling water driving an electric generator, heat powering a heat engine, electricity pumping heat—we use *power* to measure how powerful the agent is, and again when we measure how much the patient is empowered (Fig.4.21). When the two measures are equal, we say that the interaction is progressing *ideally*: all the power of the agent is there just to empower the patient, and nothing else will be caused. From the perspective of a transaction (p.117), everything the agent has to offer is taken up by the patient. We have said now and then that what is being passed from agent to patient is called energy; so, we can say that in an ideal interaction the patient receives 100% of the energy made available by the agent. In other words, the efficiency of an *ideal* interaction is said to be 100% or 1 (calculated as a ratio).

Real (non-ideal) interactions. However, almost always, interactions between an agent and a patient are not ideal: a second patient makes its entrance—*heat* is produced. This second caused process requires to be empowered just like the first one. Therefore, the process we are interested in, the one we say is primarily caused, shares the power of the agent with production of heat (Fig.4.24). We then introduce the measure of efficiency of the interaction by asking what fraction of the power of the agent is reserved for the primary caused process:

$$\begin{aligned}&\textit{Efficiency of interaction} = \\ &\qquad \textit{Power of primary process} / \textit{Power of agent}.\end{aligned} \tag{4.10}$$

Since patient 1 and patient 2 share the power of the agent, we can write this in a different form as follows:

$$\begin{aligned}&\textit{Efficiency of interaction} = \\ &\qquad (\textit{Power A—Power P2}) / \textit{Power A}.\end{aligned} \tag{4.11}$$

Some typical efficiencies. This is always less than one (less than 100%). To give some examples, the efficiency of the interaction of the fall of water in a hydro-electric power plant and the process of driving (pumping) electricity is typically greater than 0.8 (80%) in a well designed power plant. A well built electric motor can have an efficiency greater than 0.9 (90%). The efficiency of a nuclear power plant is around 0.6 (60%), and the efficiency of photovoltaic cells (solar cells) is between 0.1 and 0.2 (10-20%) in everyday applications.

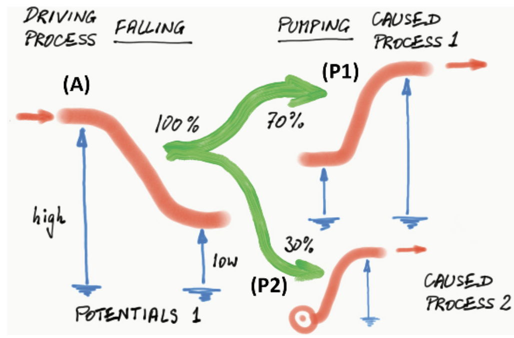


Figure 4.24: *An agent (A) drives two processes (P1 and P2) that share the power of the agent. Typically, the second caused process (P2) is heat production—interactions between Forces are almost always irreversible (i.e., heat producing interactions).*

Coming back to Carnot's quest of finding the limit of the motive power of heat engines, we can now express it in terms of the idea of efficiency. Given that heat engines of his time were indeed very inefficient—much more inefficient than the 60% of one of today's nuclear power plants—he wanted to explore how high the efficiency could go. Actually, he never used the term efficiency—he only spoke of maximum motive power by which he meant that power would not be „lost," wasted, or squandered. Simply put, if none of the power of Heat were wasted, the efficiency of a heat engine would be equal to 1. We shall see shortly what it is, mainly, that leads to „loss" of power in heat engines.

Conduction of heat—heat diffusing through materials

Thermal tension is driving diffusion of heat

Heat flows downhill by itself. Downhill means from points of higher to points of lower temperature—there needs to be a thermal gradient, a downhill slope in a thermal landscape, for this to happen (Fig.4.25). When heat flows through our physical environment in this manner, driven by its own tension, we say that it *diffuses* through the materials that make up the environment. Another commonly used term is *conduction*: heat flows through materials conductively from where it is warm to where it is colder.

In a stone, in the earth, in the wall of a building, or in the parts of an engine, heat flows in whatever direction the temperature drops. This is very much like rainwater streaming down a hill, finding its way wherever there is a downhill slope. Naturally, some materials let heat pass more easily than others: copper, and metals in general, are very good conductors for heat. Stone and soil are less good in this respect, and there are materials that make it very hard for heat to diffuse through them. These are the materials we use as thermal insulators, such as when we want to prevent the heat inside a building from escaping in winter.

The power of diffusive transports of heat. When heat diffuses through a solid material, very little else is happening in general: there are no chemical or electric phenomena caused by this, and as far as motion is concerned, not much goes on either. Solids and liquids expand a little bit, and in liquids and gases here at the surface of our planet, so-called convective flows can set in (see Section 4.6 for some important and beautiful examples). However, if we restrict our attention to solids conducting heat, very little exciting stuff goes on; in fact, we might think that nothing at all will be caused by the flow of heat.

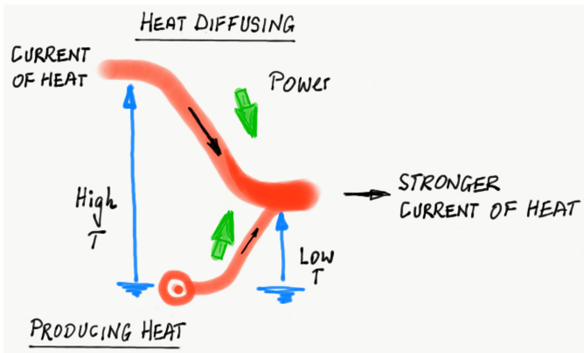


Figure 4.25: *Diffusion of heat produces more heat.*

This is actually not so: heat is flowing from points that are higher in a thermal landscape to points that are lower. Carnot's idea of a fall of heat applies here as well: whenever heat flows through a temperature difference, there is the possibility of „motive power," i.e., the possibility of driving some other process. And indeed, there is always something that can happen even if nothing is apparent: *heat* can be produced! This is exactly the case in diffusion of heat: *conductive heat transfer is irreversible*, meaning that heat is produced (Fig.4.25).

Diffusion of heat produces heat

The notion of loss of power. If there is a temperature difference, Heat is always potentially powerful. And if it indeed flows, it makes its power felt; however, in the case of conduction all that happens is that more heat is produced: the flow of heat at the lower temperature will be stronger than at the higher temperature where it originates. As far as „motive power" is concerned, the power of Heat is squandered, wasted, lost. Nothing we are interested in, such as making use of its power in heat engines, takes place. This is what Carnot meant when he said that if this happened, the phenomenon should be considered a „true loss:"

„Loss" of power

> *Since every re-establishment of equilibrium in the caloric may be the cause of the production of motive power, every re-establishment of equilibrium which shall be accomplished without production of this power should be considered as an actual loss.*[50]

By „re-establishment of equilibrium in the caloric," Carnot meant fall of caloric (*heat*) through a temperature difference. We can understand now why diffusion (conduction) of heat through materials has been added to the list of irreversible (heat producing) processes in Table 4.3. We can now also say how great the „loss of power" is in the conduction of heat: as always, when heat falls from a higher to a lower temperature, it is equal to what could potentially have caused a different process to occur.[51]

The main limiting factor of the efficiency of heat engines

Why are heat engines (relatively) inefficient (remember the 60% efficiency reported for typical thermal power plants)? Why is it impossible to achieve ideal coupling (interaction) between *Heat* and, say, *Motion*? The general reason is simply that whenever heat is produced, this requires the power of a driving process, and heat is produced in a multitude of processes (see Table 4.3).

Heat transfer limits efficiency

It turns out, however, that in thermal power plants, the main culprit is the transfer of heat from the furnace (or the nuclear reactor) to the steam turbine and from there through the cooler into the environment (all other processes in the steam turbine and on to the generator can be designed with rather high efficiency). Heat will not flow without a temperature difference, so a temperature difference is required both at the high and low temperature ends of the fall of heat through the power plant (Fig.4.26, left).

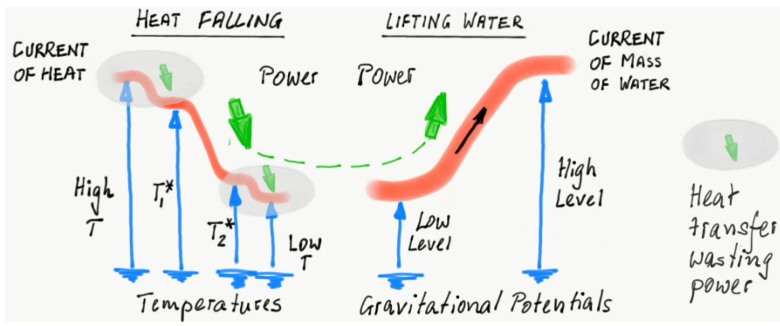


Figure 4.26: *In a real heat engine, heat needs to be transferred (conductively) which takes a temperature difference which causes nothing but production of heat (not shown). From the viewpoint of power, some of the power of heat is „wasted."*

Therefore, if *T_high* is the temperature in the furnace and *T_low* is the temperature of the environment where the heat flowing through the engine finally ends up, the power of the flow of heat will be (*T_high* – *T_low*) * *Flow of heat*. However, the power of the caused process—typically, this is rotation of the axle of the steam turbine driving the electric generator—will be considerably smaller simply because the real driving temperature difference is much lower ($T_1^* - T_2^*$, as in 4.26, left). As Carnot would have said, the temperature differences required for the transport of heat into and out of the steam turbine lead to „true loss" of some of the power of heat produced in the furnace.

A different, indirect, measure of thermal efficiency. Readers acquainted with thermal power plants and their reported efficiencies may have wondered about the 60% figure we wrote about above. If we ask the engineers at such power plants, they will tell us a much lower number, maybe slightly above 30%.

Power of heat vs. power of producing heat in the furnace

The reason for this is that the efficiency is calculated on a different basis: two different measures of power are used for calculating it. Compared to the natural definition we have given in Fig.4.24—where we compare the power that actually drives the desired process to that of the fall of heat from *T_high* to *T_low*—physicists and engineers most often compare the power that actually drives the desired process to the power of production of heat in the furnace or the reactor.

In Fig.4.27, we can see what this means. In a particular nuclear power plant, say Leibstadt in Switzerland, the upper operating temperature *T_high* is around

300°C which is about 600 K. Therefore, in the reactor, the heat that is produced requires a (nuclear) power equivalent to pumping it from 0 K to 600 K (see the diagram on the left in Fig.4.27). In this power plant, the power of the nuclear reaction is typically around 3 GW (Giga Watt = 10^9 Watt).

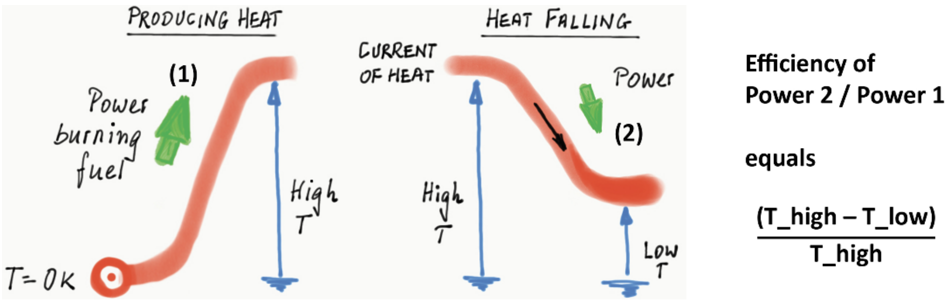


Figure 4.27: *The power of producing heat in a furnace driving a heat engine is much larger than the power of the heat falling in the heat engine. The formal result for the ratio of power 2 to power 1 is shown on the right. This is commonly called the ideal Carnot efficiency (even though we cannot find anything like it in Carnot's work).*

The heat that is produced in the reactor, subsequently falls from the high 600 K to the lower 300 K, i.e., the temperature of the environment. What is important here is that it cannot possibly fall any lower except when it is radiated into outer space—but that cannot possibly help the designers of the power plant. Therefore, the power of the heat falling from 600 K to 300 K is only half of the power of the nuclear process, i.e., about 1.5 GW. Now, as we have just discussed with the help of Fig.4.26, in a power plant of the type discussed here, about 40% of the power of falling heat is wasted, leaving the 60% we have talked about for powering electricity. However, this is now only about 30% of the power of the nuclear processes going on in the reactor.

Natural measure of efficiency

Which of the two measures of efficiency should we use? Well, that depends upon what we want to understand. The measure of efficiency based upon Fig.4.24 is the *natural* one used in all cases of processes and engines except thermal engines running on heat which is produced. It directly compares the power of the agent with how strongly the patient of interest is empowered. In other words, it directly measures the efficiency of the interaction of agent and patient. Clearly, we can extend the practice of defining efficiency as it is common in all fields of physics and engineering to thermal engines as well.

In contrast, the comparison of the power of the heat producing process to the measure of empowering of the desired process is indirect. Its disadvantage is that it gives engineers a bad reputation. „What, only 30% efficiency? Can't they do better than that?" The point is, once we have accepted that we will produce heat, we have already incurred a „loss" that will make itself felt further down the line. Using about 60% of the power of heat falling through the heat engine is about the best that can be achieved, and it certainly looks a lot better (and more reasonable) than 30%.

No combustion in batteries and fuel cells

What the low indirect measure of efficiency does tell us, however, is that we should not burn fuels and produce heat but let them undergo chemical processes that couple directly to what we desire, such as empowering *Electricity*. Now, such processes exist: this is what batteries and fuel cells are made for. We shall turn to this issue and study batteries and fuel cells in Volume 2.

Why we should pump rather than produce heat

We have discussed heat pumps and the question of heating with heat pumps before (starting on p.199) and suggested that it should make a lot of sense to take *heat* for heating from where it already exists rather than producing it in a fire. We are now in a position to make clear why this is so, and we can even give a quantitative measure of the possible gain.

We have images for both pumping and producing heat. Pumping it means lifting it from a certain temperature (usually that of the environment) to a higher one (usually the temperature of hot water used for both space heating and domestic warm water). In contrast, producing heat at the required temperature is equivalent to pumping it much higher, namely from absolute zero (Fig.4.28).

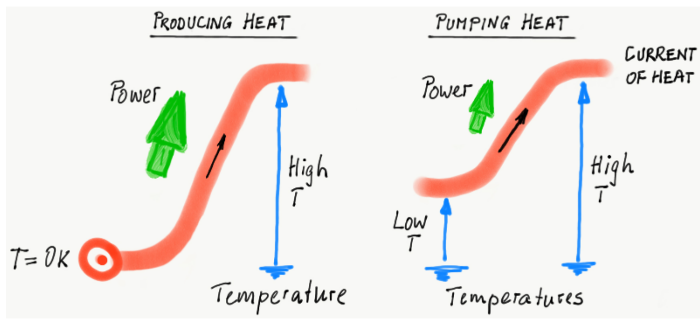


Figure 4.28: *Why it is better to heat with heat that is taken from the environment.*

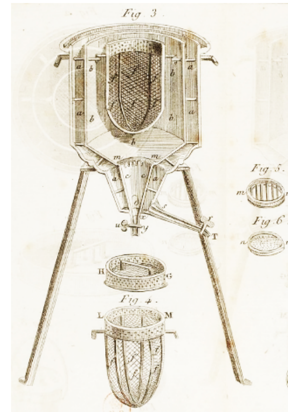
Clearly, the height of lift is smaller in the case of pumping heat. If, say, we take heat from the environment in winter at 0°C (about 270 K) and pump it in order to heat 60°C water (about 330 K), the height of lift is 60 K; for a fire or electric heating, on the other hand, the height of lift is 330 K—more than five times higher! Put differently, the power requirement for pumping is more than five times smaller. If we combine what we have expressed in Equations (4.7) and (4.9), we can directly write the formal result underlying the example: the power of pumping heat is smaller than the power of producing it by a factor of $(T_{high} - T_{low})/T_{high}$.

This numerical example applies to an ideal heat pump where the power of the agent—usually Electricity—equals the power required for pumping heat. In real life, the efficiency of a heat pump is less than 1, resulting in a power requirement for a heat pump that is about 3 to 4 times less than that for heating by burning fuels. However, if the electricity driving the heat pump is powered in a thermal power plant, and if the efficiency of this plant is about 30%, nothing much is gained as we have already warned in the Box on p.200. We could just as well burn the fuel in our own homes and so directly heat the house and whatever hot water we need. Certainly, if the electricity has been powered by the Sun's light, this all looks different and certainly a lot better for the planet's climate.

Measuring *amounts of heat*

Unit of heat

Measuring *amounts of heat* has posed a certain challenge in the history of the science of Heat. At first, this seems easy: melting ice takes place at fixed temperature of 0°C or 273 K (if we disregard what happens if we add salt or other dissolvable stuff); therefore, we could use melting a certain quantity of ice as a standard. For instance, we could say that whatever leads to melting of 1 g of ice has led to the addition of 1 unit of heat to the ice-water mixture. This comes close to the unit that is used in science: melting 0.8 g of ice takes one unit of heat. We shall give the unit of heat the name Carnot (Ct) which is the same as W·s/K.[52]



Lavoisier, 1789: Ice calorimeter (Pl. VI)

The practice of calorimetry. This is what was done early in thermal science. So-called *ice calorimeters* were the instruments used to determine amounts of heat by Lavoisier and Laplace, at the time. This was shortly before Carnot developed his thermodynamics. For example, one could bring a certain quantity of hot water with a temperature T_1 in contact with ice in such a calorimeter. Waiting for a while did two things: the temperature of the water dropped to a lower value T_2, and a certain quantity of ice was melted. Therefore, one knew how much heat had been communicated to the ice. Assuming that the heat came from the water, one could conclude how many units of heat the quantity of water needed for its temperature to change from T_2 to T_1. In principle, one could do this with all sorts of substances and determine the changes of their *heat contents* when they underwent certain thermal changes such as changes of temperature.

This was tried with gases as well since knowing about their thermal properties was important for the nascent science of thermodynamics—gases such as steam were used to operate heat engines. However, since gases have very small heat capacities, the smallest amount of heat could make big changes in their temperature, so the measurements were inconclusive.

That was the idea, but, as we know, something does not work out as expected: when we bring a warm substance into contact with ice, heat flows conductively from the warmer to the cooler body. As a consequence, more heat is produced and adds to the amount that comes out of the cooling body. Therefore, the usual form of calorimetry does not work well for us.

Measuring amounts of heat in electric heating. Fortunately, the phenomenon that causes such trouble for calorimetry, i.e., the production of heat, will help us solve the problem and find ways of measuring amounts of heat. Our idea about how to understand the coupling of processes leads to a solution. We know the power required for producing heat at a certain rate—the necessary idea is expressed in Eq.(4.9). If we manage to determine the power of a process producing heat and measure the temperature at which this happens, we know how much heat is produced every second (see Table 4.5 for some interesting values[53]).

So, this is what we can do in a concrete case: we heat water with an electric heater (as in Fig.4.16, but in a very well insulated container), continuously measure the temperature of the water, and determine the electric power at the same time. For the moment, let us accept that we know how to perform this last step—we shall discuss this in detail in Chapter 5.

Knowing the power of the agent, which is equal to the required power of producing heat, and knowing the temperature of the water, we can calculate the rate of production of heat for every moment of the process of heating. Then we use the same procedure we have applied when we wanted to determine how much water has been delivered by a given current (see p.130)—we interpret the production rate of heat as a flow and sum it up over a period of time to get the amount of heat produced in that time span. This finally allows us to relate the (change of) heat in the water to its (change of) temperature.

Using the coupling of thermal processes with other phenomena and applying the notion of power of processes allows us to quantify amounts of heat. We can start with water, as described, move on to other liquids and substances, and finally return to the standard practice of calorimetry where new materials are brought in thermal contact with substances whose thermal behavior has been quantified. As long as we know how to calculate amounts of heat produced when heat is transferred, we can always find what we need to know.

Table 4.5: Quantities of *heat* (rough values in Ct)

Heat produced by an electric heater at a power of 300 W at 27°C	1
Heat necessary for melting 1 g of ice	1
Heat added in heating 1 g of water from room temperature to boiling	1
Heat needed for vaporizing 1 g of water	6
Heat added when heating 1 m^3 of air by 10°C (at constant pressure)	40
Heat produced by an electric water heater in one minute	100
Heat produced when a fast traveling car brakes	10^3
Heat produced by a human body in one day	$2 \cdot 10^4$
Heat produced at room temperature by burning 1 kg of coal	10^5
Heat produced by 2 m^2 of a solar water heater on a sunny day	10^5
Heat needed for heating an apartment on a winter day	10^6
Heat produced by all human activity in one second	$5 \cdot 10^{10}$
Heat produced on Earth in one second (from absorbing sunlight)	$4 \cdot 10^{14}$
Heat lost by the Sun in one second	$8 \cdot 10^{23}$

Heat of ice, water, and steam. Ice, water, and steam play such an important role in nature and machines that it is worth taking a look at what quantification of heat can tell us about the heat of these substances and the changes of phase from ice to water and from water to steam (Fig.4.29).

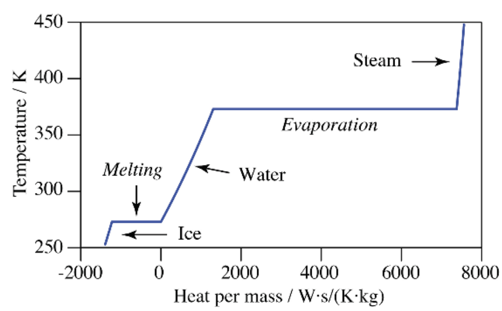


Figure 4.29: *Experimental data showing the relation between temperature and heat per mass for ice, water, and steam, including phase changes (horizontal lines).*

What we need to understand when engineers report values of heat stored in different materials, they usually do not care about absolute values—they start at some point, at some temperature, set the value of heat stored equal to zero at that point and then refer everything else to this reference point. This is what we have done for ice, water, and steam in Fig.4.29: we have arbitrarily set the value of heat stored in one kilogram of water at 0°C equal to zero.

If we now begin our description with a kilogram of ice at about –20°C, we give its heat a value of about –1400 Ct. It will take fairly little heat, less than 200 Ct, to warm the ice to 0°C. Then it takes about 1220 Ct to transform ice into water. In order to bring this water to a boil at 100°C, we need about 1300 units of heat. Another addition of a little more than 6000 Ct accompanies the process of evaporation—so we are at a heat content of about 7300 Ct for steam at 100°C (and a pressure of 1 bar) relative to water at 0°C. Finally, it takes only about a quarter as much heat to raise the temperature of steam by 1 degree than it takes for water—steam is easily warmed, more easily than ice, and ice is warmed more easily than water. All of this we can read from the curve in Fig.4.29.

4.6 Winds, Volcanoes, and Continental Drift

„[I]t is to heat that we owe the agitations of the atmosphere, the rise of clouds, the fall of rain and other meteors, the currents of water which channel the surface of the globe, and of which man has thus far employed but a small portion. Even earthquakes and volcanic eruptions are the result of heat." We started the chapter with these words from Carnot's book, and we want to end it by studying two examples of these great movements that are caused by *Heat*: the winds in our atmosphere and continental drift.

In order to prepare the scene for these examples of large-scale natural phenomena, we need to first study where the heat comes from that drives these motions. In the case of the atmosphere, sunlight stands at the beginning of a chain of processes that eventually leads to many important phenomena at the surface of our planet—vast amounts of heat are produced when sunlight is absorbed at the surface of our planet; part of this heat goes into causing the winds which are part of convective „rolls" created in the atmosphere (see Fig.4.30).

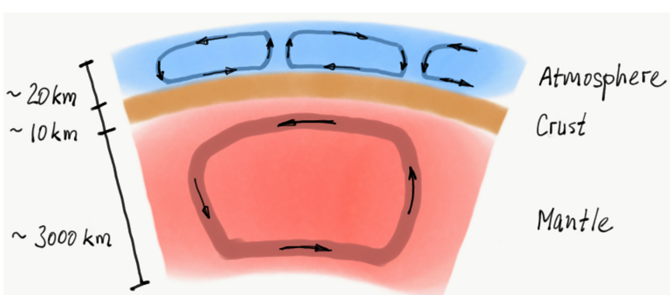


Figure 4.30: *Layering of the Earth (not to scale!). In the mantle and the atmosphere, convective flows transfer heat upward. Convection in the mantle makes the crust drift very slowly across the surface of the planet. Convection in the atmosphere creates the patterns of winds.*

Continental drift, on the other hand, is driven by slow convective movement of the thick mantle of the Earth (Fig.4.30), which, in turn is caused by the heat from the interior of the Earth. Radioactive decay of some elements making up our planet produce „fresh" heat, but there is also a lot of heat left over from when the Earth was formed that has not yet made it to the surface and into outer space.

Sun and Earth: Sizes and distance

We first need to get oriented a little bit with regard to Sun and Earth—how big and how far apart are they, how much light is created at the surface of the Sun and then pouring out into the solar system? And in the case of the Earth, how big and „substantial" are the atmosphere, the crust, and the mantle of our planet, and what is the power of radioactive processes and the flow of „ancient" (primordial) heat in the interior of the Earth?

The Earth: Surface temperature: 300 K *Radius:* 6400 km

Earth and Sun. Astronomy and earth science present us with some extremely fascinating and important aspects, also for primary education. These themes would be leading us too far afield for now, though, so all we can do is describe just a tiny bit of the knowledge we have of the Earth and its place in the solar system. Our planet is a spherical „rock" having a radius of roughly 6400 km and a mass of about $6{\cdot}10^{24}$ kg (see Fig.4.31). Its density changes from about 2 times that of water (surface layers) to 13 times that (at the center) with an average of 5.5 times the density of water. Temperatures are a little below 300 K on average at the surface to higher than 6000 K at the center.

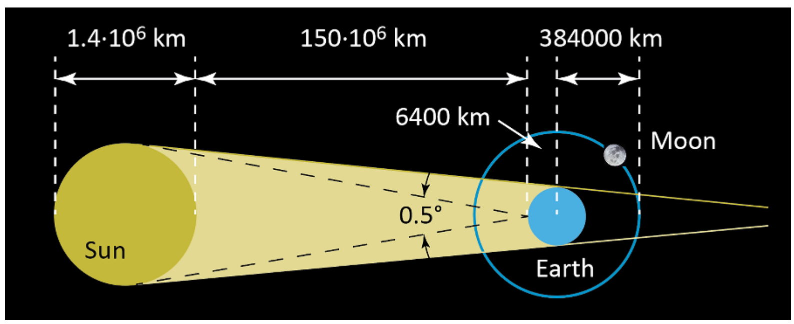


Figure 4.31: *Dimensions of the Sun and the Earth's and Moon's orbits (not to scale). The Sun is 100 times as big as the Earth, the size of the Moon's orbit is 1/400th of the Sun-Earth distance.*

The nearest heavenly neighbor of Earth is our Moon. It orbits the Earth at a distance of about 60 Earth radii (Fig.4.31). Its diameter is a quarter of that of the Earth, and its mass is 1/80th of that of the Earth. It is rocky like the Earth but a little „lighter;" its average density is roughly 3.5 times that of water.

Our Sun: Surface temperature: 5800 K *Radius:* 700,000 km *Distance:* $150{\cdot}10^6$ km

This may give us a little bit of a feel of our nearest neighborhood, even though these numbers are already pretty big. But we have to go 400 times farther than the Moon to arrive at the Sun, 150 million kilometers from here. Since the Moon is pretty much the same size in the sky as is the Sun—all seen from here—the Sun must be 400 times as large as the Moon which makes it 100 times as large as the Earth: the Sun's radius is about 700,000 km (Fig.4.31).

Having a radius a little more than a hundred times the radius of the Earth makes the Sun more than a million times as voluminous than our planet. The mass of the Sun is „only" 330,000 times that of the Earth which mean that its density is much lower than that of the Earth, about 1.4 times that of water. This indicates that the Sun is not a „rock" but made of gas that will be pretty dense and extremely hot, about 15 million Kelvin, at the center. At the surface, the temperature is a little below 6000 K.

Hearing about these numbers is one thing, understanding how they could be measured is another. Today, we have all sorts of tools for getting at these values, and determining them precisely. Historically, however, this was a different matter, and the story of how astronomers found out about our solar system and then the universe as a whole would fill many books. Measurements of the size of the Earth go back to the ancient Greeks. Eratosthenes travelled south from Alexandria to Syene (what today is Aswan) in Egypt and determined the distance between the two cities. Based upon how high the Sun appeared in the sky in both cities at the same time, and assuming that the Earth was indeed a sphere, he could derive the size of this sphere. Assuming that Eratosthenes used the length of the running track of the stadium in Athens as the unit of distance, he got a value of about 40,000 km for the Earth's circumference—very close to today's measurements.

Greek astronomers also found the distance of the Moon from how long it takes the Moon to move through the Earth's shadow during a lunar eclipse. Their value, 60 Earth radii, is pretty accurate by modern standards. A usefully accurate determination of the distance of the Sun, however, had to wait until about 1800: the Sun is roughly 400 times as far from us as the Moon is. Now, knowing how far away the Sun and the Moon are and seeing how large they appear in the sky—this is close to 0.5° for each—allows us to calculate their sizes using just a little bit of geometry.

How much sunlight is there?

The geometric values—basically the sizes of and the distance between Earth and Sun—are central for the following important determination: How much light comes from the Sun, and what is its property at the surface of the Sun and when it arrives at the position of the Earth? The answers start with how strong the Sun's light is here on our planet. First, to understand the following numbers, we need to know that scientists and solar energy engineers quantify the strength of sunlight (and other types of light) by specifying how much energy the light carries per second and per square meter of a surface it falls upon; this is called the *energy current density* of (sun)light (for more on energy and energy currents, see Chapter 3, Section 3.7).

Energy current density

Assume we have a clear sky, no clouds reflecting sunlight back into space. Still, on its way through the air, part of the light is swallowed and a good part is scattered in all directions—leading to the blue appearance of the sky. Depending upon how high the Sun is in the sky, the length of the path through the air that sunlight has to traverse is different—the higher the elevation of the Sun (measured as an angle), the shorter the path, the higher the percentage of light that makes it through (Fig.4.32, right).

If we know how „thick" the air is as a function of height, we can use the change of measured intensity of light as an indication of how much is absorbed and scattered by the atmosphere. Using this plus measurements of the intensity of sunlight at the Earth's surface, we get the value of how bright sunlight will be outside the atmosphere. This important value—which today can be measured much more accurately with the help of satellites—equals 1370 W/m^2 for a surface oriented perpendicularly to the Sun's rays. Scientists and engineers call this the *Solar Constant*.

Solar constant: Energy current density of sunlight at Earth's distance: 1370 W/m^2

This still leaves the question of how one can measure the flow of energy carried by sunlight. Like so many other things in the sciences and engineering, it is measured by its effect, i.e., by the coupling of light as a Force with some other Force. The most direct coupling leads to heat production when light is absorbed. Knowing the properties of the material that absorbs the light and how warm it gets, one can calculate how much energy is made available (and how much heat is created). Instruments such as pyranometers (Fig.4.32, left) use this effect.

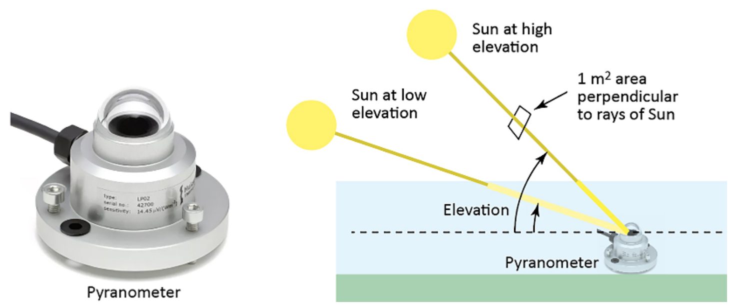


Figure 4.32: *Left: An instrument (called a pyranometer) used to measure the intensity of sunlight. The small black circle under the glass dome becomes heated by sunlight, and its temperature is an indication of the strength of the light. Right: The Sun's light must travel different distances through the Earth's atmosphere to reach us—the length of this path depends upon the elevation of the Sun in the sky.*

The current of energy carried by sunlight at the Earth's distance. The total amount of energy made available by sunlight absorbed at our planet's surface is calculated as follows (Fig.4.33). The energy current of sunlight striking and area of 1 square meter perpendicular to the flow of light equals 1370 $\mathrm{W/m^2}$ (outside the atmosphere). If we consider the geometry of the situation, we see that the total current intersected by the planet depends upon this number and the cross-sectional area of the planet.

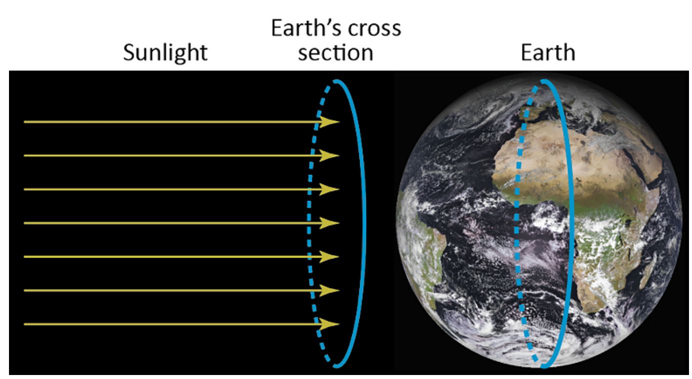


Figure 4.33: *The current of light intercepted by the Earth is determined by the cross section of the planet; this is a tiny fraction of the light emitted by the Sun. The energy current per square meter equals 1370 W (Image of Earth: EUMETSAT [2021]).*

Energy flow from Sun to Earth: 176,000 TW

30% of sunlight is reflected back to space

The radius of the Earth is 6400 km, which then makes the total energy current carried by sunlight and falling upon the cross section of the Earth equal to $1.76{\cdot}10^{17}$ W. Of this, 70% is absorbed, and 30% is reflected back into space, mostly by clouds and snow cover, without affecting the planet. This makes the rate of absorption of energy equal to $1.23{\cdot}10^{17}$ W, and, according to Eq.(4.9), the rate of production of heat is $1.23{\cdot}10^{17}$ W / 300 K = $4.1{\cdot}10^{14}$ W/K (see also p.237).

Heat created when sunlight is absorbed

The Sun's light makes us warm. So, it carries with it a lot of *heat*, right? Actually, no, it does not; the Sun's light carries a lot of energy but contains only a relatively small amount of heat—this has to do with the very high temperature of this light (the temperature of the light is almost 6000 K, the same as the temperature of the surface of the Sun, which is 20 times the average temperature of the surface of the Earth, i.e., 300 K). What warms us is the heat produced in our environment and our skin when sunlight is absorbed. Heat is generated with the help of the energy made available by sunlight "swallowed" by objects here on Earth. The same is true for our planet as a whole, simply at a much larger scale.

Here is how we know how hot the surface of the Sun is. Take a look at the drawing showing the geometry of the Sun-Earth system (Fig.4.34). The figure suggests how light leaving the surface of the Sun „thins out" as it flows out into the solar system. Imagine the light to be like a gas that can get thinner. As it flows away from the Sun, it has to flow through ever increasing spherical surfaces—the same amount of gas (or rather light) must be spreading over this growing surface. Important for the Earth, at the distance of our planet, all the light of the Sun goes through the spherical surface having the Sun-Earth distance as its radius.

The surface of the Sun is smaller than this surface at the distance of the Earth by a factor that is the square of $150 \cdot 10^6 / 0.7 \cdot 10^6$ which is equal to 46,000. This also means that the density of the flow of light, and therefore also of the energy carried by the light, is 46,000 times higher at the surface of our central star than at the distance of the Earth. This means that the energy current density at the surface of the Sun equals $63 \cdot 10^6$ W/m^2. Incidentally, that makes the total energy current carried by sunlight away from the Sun equal to $3.8 \cdot 10^{14}$ TW—that's a pretty strong lamp!

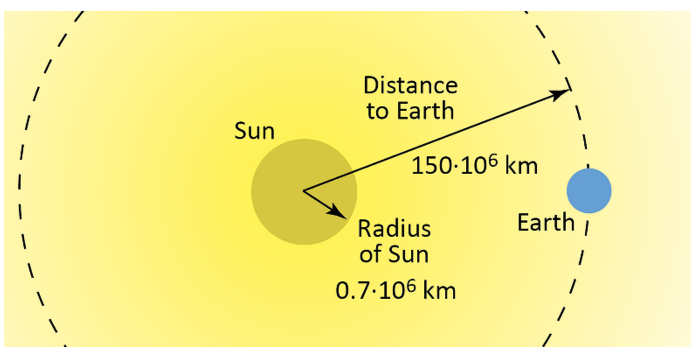


Figure 4.34: *Diagram suggesting the relative sizes of the Sun's surface and the surface of a sphere having the radius of the Sun-Earth distance (not to scale).*

What physicists have found out about light emitted by hot surfaces can be used to calculate how hot such a surface must be, given the flow of energy and heat radiated into space by that surface. To emit an energy current of $63 \cdot 10^6$ W/m^2, the Sun's surface must be at a temperature of about 5800 K; this is the number we reported earlier. If our planet had no atmosphere and was similar to the Moon, its surface temperature would be an average of about 270 K because it needs to emit the heat it receives with sunlight, and the heat produced with the help of the energy it absorbed with sunlight (see below); as this happens, the Earth emits the amount of energy absorbed with sunlight back into space. The temperature resulting from this simple model is lower than the actual average temperature of the Earth which is close to 290 K—luckily for us, the temperature is higher because the atmosphere is like a blanket over the planet and keeps us warm enough for liquid water to exist. This effect is called the *greenhouse effect*. When we are saying that we are in the midst of making the planet even warmer because of the greenhouse effect, what we actually mean is that we are making this effect stronger by changing the chemical makeup of the air.

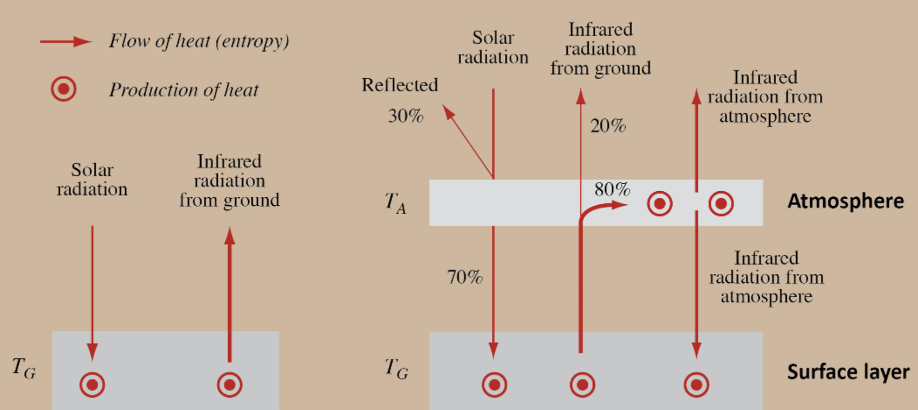
Greenhouse effect

Greenhouse effect

Sunlight, atmosphere, and the greenhouse effect

The Earth's atmosphere works like a blanket in warming the surface of the planet. Without an atmosphere (see the figure below on the left), and if the Earth were a perfect absorber and emitter of sunlight and „earthlight," respectively (solar radiation and infrared radiation from the ground, respectively), the surface temperature would be around 270 K (a little below freezing of water). The temperature is the result of heat from solar radiation being absorbed, and absorbed plus produced heat re-emitted to outer space.

Note that every act of absorption and emission of radiation is irreversible: heat is produced.



If we had an atmosphere above the surface of the planet (here it is modeled as a single layer), and if this atmosphere could absorb some of the infrared radiation coming from the ground, we would get a greenhouse effect. What is happening is this. First, the atmosphere with its clouds will reflect some of the Sun's light (this is about 30% in the case of the Earth; on the other hand, the air absorbs only little of sunlight—we assume this to be negligible). If this were the only effect of the atmosphere, it would make the surface colder (255 K).

However, the radiation from the ground will be partly absorbed by the atmosphere (the fraction absorbed is about 80%). This will make the atmosphere somewhat warm, which means that it will radiate its heat in both directions, up and down. Since the Earth's surface is assumed to be a perfect absorber (and radiator), it will absorb this heat (and again produce some more), and get warmer. For the model developed here, and with the fraction of infrared radiation absorbed at 80%, the temperatures of ground and atmosphere turn out to be about 290 K and 244 K, respectively.[54]

Rate of production of heat on Earth. We shall now use some of the knowledge concerning thermal processes we have collected in this chapter and calculate how much heat is produce on our planet by absorbing sunlight, every second. Let us assume for the moment that sunlight carries no heat but lots of energy and that all of the energy of absorbed light is made available for producing heat (the energy of sunlight does not do much else except for that small fraction, maybe 2%, that drives photosynthesis in plants and bacteria in the oceans). According to Eq.(4.9), we need to know the power of the process (which is the rate at which energy is made available by absorbed sunlight) and the temperature at which this happens (which is the average temperature of the Earth's surface, 300 K). Therefore, the rate of production of heat on our planet, due to the absorption of sunlight, equals $1.23 \cdot 10^{17}$ W / 300 K $\approx 400 \cdot 10^{12}$ W/K.

We can use the same reasoning as before and determine how much heat the Sun emits with the light that is absorbed by the Earth. If we take the surface temperature of the Sun to be about 6000 K, the current of heat lost together with the light that makes it to the Earth is $1.23 \cdot 10^{17}$ W / 6000 K $\approx 20 \cdot 10^{12}$ W/K, which is only 1/20th (300K / 6000 K!) of the heat produced on Earth and making the planet warm. This means that sunlight carries only 1/20th of the heat that is produced when it is absorbed at the surface of our planet.

Twenty times more heat is created here than brought from Sun

We might wonder why we don't burn up in the Sun's light, if it is almost 6000 degrees hot? This is because, as we have seen, the light of the Sun is very much diluted from what it is at the Sun by the time it has spread out through space and reached the Earth (it is diluted by a factor of 46,000). All in all, there is very little heat delivered by sunlight per square meter per second. With what little comes from the light, and with the roughly 20 times bigger part that is produced, the objects on Earth become as warm as we know them to be: between about − 60°C at the poles and + 50°C in the deserts (averaged over surface and the seasons, the temperature of the Earth is about 15°C). If we concentrate the Sun's light again here on Earth using concentrating mirrors, we can make objects in its light almost as hot as the surface of the Sun.[55]

Sunlight is strongly diluted

Heat from the interior of the Earth

As we dig deep down into the Earth's crust (which is actually not deep at all compared to the size of the planet!), we find higher and higher temperatures. This means that heat must flow from deeper down up toward the surface. The flow of heat and energy can be estimated from measurements of how the temperature changes with every meter of depth and how easily different parts of the materials of the Earth's crust let heat pass.

It is assumed, that the oceanic crust lets energy pass with heat at a rate of about 0.1 W for every square meter. In the continental crust, the value is estimated to be about 0.06 W/m^2. Given that oceans cover about 70% of the Earth's surface, we get an energy flow roughly equal to 45 TW from the Earth's interior. Compared to the rate at which energy is absorbed from Sunlight, this is less by a factor of almost 3000. This means, among many other things, that the temperature of the surface of our planet is determined by the Sun and not by what is inside the Earth. It also means that the amount of energy flowing from the interior is only about twice as much as what we humans use in our technical civilization (see Fig.3.29).

Energy flow from the depth of the Earth: 45 TW

We might wonder where the heat that flows from the depths of our planet is coming from. There is definitely some trapped inside the planet from the huge amounts that were produced when the Earth formed. The dominant model of the formation of planets in our solar system has it that planets formed by small rocks and dust collecting, which let the ball that became the Earth grow to today's size. All the stuff falling in toward the growing planet released a lot of energy that led to the production of heat.

The planet is certainly still cooling, but a good portion of the heat comes from continuous production in the mantle as a result of radioactive decay of mostly uranium, thorium, and potassium. The rate of energy made available is very small per kilogram of mantle material, but given the huge size of the mantle, one can estimate that the rate of dissipation[56] due to radioactivity is at least 25 TW. Ancient plus new heat keeps the interior of the Earth pretty hot: about 3000 K at the base of the mantle, and 7000 K at the center of the planet.

Gently heating fluid layers from below: Observing convection

We are now in a position to discuss the origins of winds, volcanoes, and continental drift. Briefly put, winds are the result of a „heat engine" in the atmosphere driven by the heat created when sunlight is absorbed at the surface of the planet; air, heated at the ground, moves up, cools and moves north or south, and then descends just to flow back on the ground from where it came (Fig.4.30).

Continental drift—where oceanic and continental plates „drift" on the surface of the very slowly moving mantle of our planet—is caused by „ancient" heat flowing out of the center of the cooling planet, plus the heat created even today from the decay of radioactive elements within Earth. Both atmosphere and mantle are heated from below and cooled from above. This leads to convection cells—vertical „rolls" of air or mantle material ascending and descending (Fig.4.30). As a „by-product" of the activity of heat in the Earth's interior, we get volcanism.

The important difference between the two layers, apart from their different chemical makeup, is their vastly different thickness (Fig.4.30: the atmosphere is very thin compared to the size of the planet, maybe 20 km thick, whereas the mantle has planetary proportions and is easily more than a 100 times thicker than the atmosphere. This affects the type of convective cells that can be observed (Figs.4.35 and 4.36).

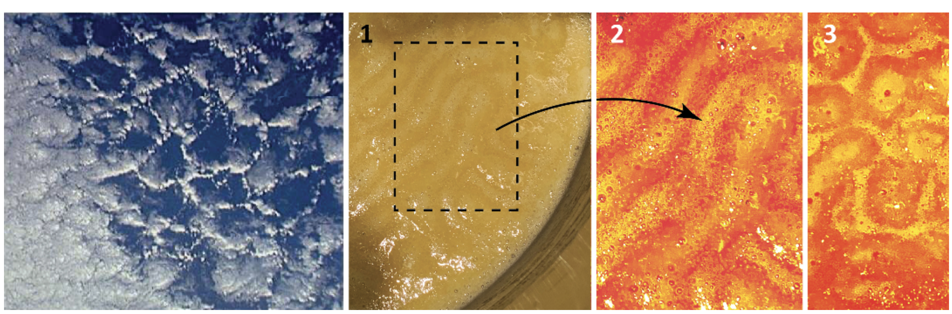


Figure 4.35: *Left: Satellite image of Rayleigh-Benard convection cells in the atmosphere (Image: ©EUMETSAT [2001]). (1) Original photo of first step in making béchamel sauce (butter and flour) in a pot on the stove gently heated. When well mixed and stirred, and then resting over low flame for a brief moment, a pattern of up- and downwelling crests and valleys is formed. (2) Enhanced part of the photo on the left (yellow ridges: upwelling; red valleys: downwelling). (3) Sometimes, polygons can be observed.*

The kitchen is a great place to observe convection, i.e., convective heat transfer, at work. For this, we need the right fluid, the right thickness, and the right strength of heating from below—cooling at the surface will happen naturally if we do not put a lid or some insulating stuff on top of the fluid. In Figs.4.35 and 4.36, we have two examples of what can be observed in the two steps involved in making béchamel sauce.

Thin layer heated from below

First, butter and flour are mixed and gently heated—heating needs to be gentle not just for the right culinary product but also for observing convection. With strong heating, fluids will easily begin to boil and that is not what we want to see happening. In the right size pot, a little bit of butter and flour will form a thin layer which, after the first couple of minutes and when left unstirred for a moment, develops an interesting pattern of crests and valleys of up- and downwelling viscous fluid (Fig.4.35, (1) and (2); (3) sometimes, we see polygons, as in the atmosphere).

Rayleigh-Benard cells

What we get here are relatively small-scale structures. This is something that readily happens in the Earth's atmosphere (Fig.4.35, left) as well—remember that the atmosphere is a very thin fluid layer when compared to the size of the planet. The surface of the planet is heated, and the heat produced will let air rise in some areas and descend in others, creating what are called Rayleigh-Benard cells. In the satellite image, the cells are so-called open cells where warm air rises at the edges and the downwelling happens at the center (giving us clouds at the edges and clear sky at the center).

Thick layer heated from below

The next step in making béchamel sauce has us adding a lot of milk; we need to continue heating while stirring vigorously. After a few minutes, the material of the now fairly thick layer starts thickening, i.e., it turns highly viscous. If we stop stirring for a moment, but continue heating gently, we see the topmost thin layer taking on a relatively dry look and moving very slowly across the surface (Fig.4.36, left). In the particular example observed here, a „trench" has formed in the middle of the surface. The drying top layer moves toward this „trench" where it disappears into the depth of the thick layer of sauce (see the sequence of enhanced photos 1-3 in Fig.Fig.4.36).

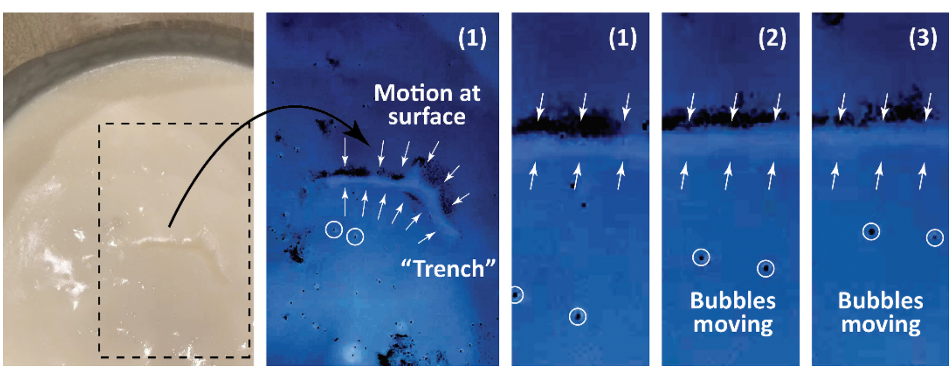


Figure 4.36: *Left: Original photo of final step in making béchamel sauce (butter, flour, and milk) in a pot on the stove at low heating power. A „trench" formed in the relatively cool surface layer with „plates" of surface material moving toward it from both sides and disappearing into the depth of the hot sauce. When observed carefully, one can see the motion directly at the „trench" and through bubbles moving toward it.*

In this example, convection has formed a couple of large-scale, slow-moving vertical rolls: the béchamel sauce comes up at the walls of the pot and submerges at the center. Hotter sauce rises, cools at the surface and then sinks down to be heated once again. This gives us a useful image for convective heat transfer in the thick layer of the Earth's mantle (see Fig.4.30).

How *heat* created by the Sun's light drives the „wind engine"

Convection cells in atmosphere

In our atmosphere, there is a pattern of a few large-scale vertical cells of flowing air that dominate the smaller-scale weather events. If we make a cut through the planet and the atmosphere (Fig.4.37, left), we can see six of these dominant cells which are called northern and southern Hadley cells, northern and southern Ferrel cells, northern and southern Polar cells, respectively.

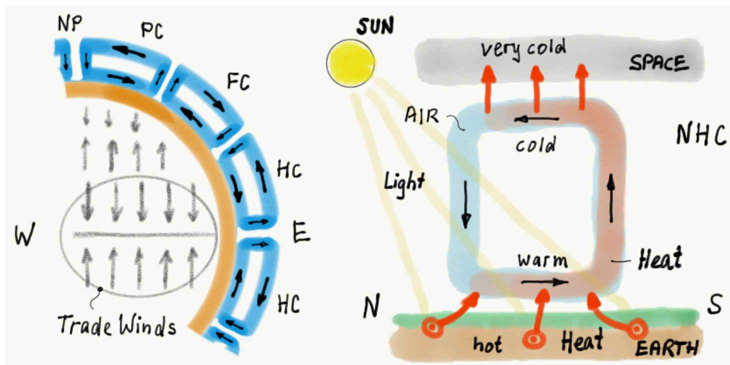


Figure 4.37: *Left: Looking down at the equator of Earth. There are several global-scale cells of air rising and falling in the atmosphere. In the quadrant of the planet, surface winds are shown (Winds will be deflected from their North-South or South-North direction because of the rotation of the planet). E: East, W: West, NP: North Pole, PC: Polar Cell, FC: Ferrel Cell, HC: Hadley Cell. Right: Cross section of a Northern Hadley Cell (NHC) of circulating air. N: North, S: South. Heat and Light are Forces; SUN, SPACE, EARTH, AIR are objects serving as the ground for the Forces to act upon.*

In one such cell, the air rises at a certain latitude, flows poleward or equator-ward at great height, flows down again and then flows back along the surface to where the cell started. The flow along the surface is what we experience as wind. Take the Northern Hadley cell. Heated by the Sun, air rises at the Equator, leaving a low-pressure area (the location changes northward or southward with the seasons); then it flows northward at great height and comes down again at about 30° north. From there, air flows along the ground back toward the equator. This flow is known as the (northern) *trade winds* that blow almost constantly. Because of the rotation of the Earth, these winds do not blow exactly north-south but rather north-east to south-west in the northern hemisphere (see Volume 2).

Trade winds

Wind resulting from the atmosphere acting as a heat engine. What we have just described in very rough and superficial terms is the result of a heat engine powered by the heat created with the help of sunlight. This engine works as follows. When sunlight flows through the air to the ground, it is absorbed in the ground and heat is produced (Fig.4.37, right). As a result, the ground is heated and gets warmer than the air itself. So, there is a temperature difference between ground and air that makes heat flow into the air.

Atmosphere as heat engine

In response to taking up heat, the air expands and then rises (as a consequence of buoyancy: see p.160ff.). As it rises, it keeps its heat but gets colder—we will explain this behavior of air a little further below. As the air reaches the uppermost layers of the atmosphere, its heat is radiated into outer space, so the air gets even colder, shrinks and then sinks down toward the ground, creating a high-pressure area. Arriving at the ground, it is warmer again (but not as warm as when it first started rising). Because of the pressure difference, it will flow back to where it came from. This flow across the ground is what we call wind.

The power of the winds on Earth, averaged over the entire surface and over time, is about 7 $\mathrm{W/m^2}$. For the surface of the planet that makes 3600 TW, about 35 times smaller than the power of absorbed sunlight. This means, that the overall efficiency of the thermal wind engine is about 3%.

The power of winds on Earth: 3600 TW

The response of air to heat. Liquids and solids have a simple response to heating and cooling (if we neglect possible changes of state): upon heating, they get warmer, upon cooling, they get colder. Air responds in a much more interesting way simply because it can change its volume greatly as it interacts with heat (Fig.4.38). Depending upon what happens to the volume of the fluid, the change of temperature can be very different when we heat or cool the air.

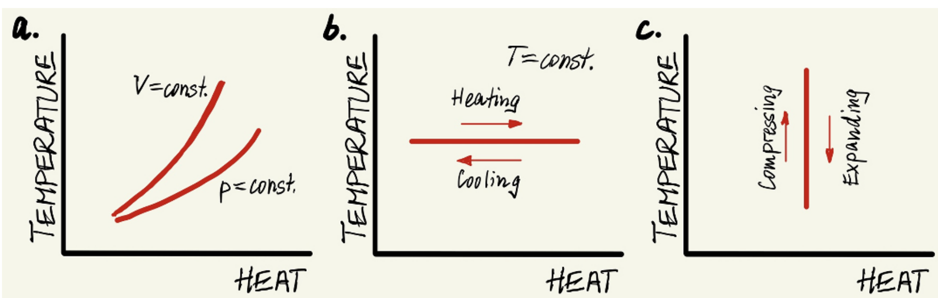


Figure 4.38: *Temperature-heat diagrams for air undergoing various changes of heating/cooling and/or compressing/expanding (thermodynamicists call these diagrams TS (temperature-entropy) diagrams).*

Maybe the effect understood most easily is heating at constant volume (upper curve in Fig.4.38a). We put a certain amount of air inside a container, add known amounts of heat and record how the temperature goes up. Fundamentally, this is the same as what happens with liquids and solids when heated.

We have seen in Section 4.3 in the box on p.209 that air expands as it picks up more heat, as long as we do not restrict the expansion completely. In a balloon, temperature, volume, and pressure of the air all go up as heat is added. What exactly happens with these values depends upon how the rubber membrane controls pressure as a function of volume and temperature. If we have no walls restricting the expansion of air being heated, we can obtain a situation of heating, expansion, and temperature rise that takes place at constant pressure—this happens when we heat a part of the air in the atmosphere (see the lower curve in Fig.4.38a).

Heat makes things warm and lets them expand. When we heat a gas at constant pressure, its temperature rises less fast than when we do this at constant volume—this is something we can easily experience when cooking, particularly if we make use of a pressure cooker. We can understand the difference (see Fig.4.38a) quite easily: when heating air at constant volume, all heat needs to do is raise the temperature; when heating at constant pressure, part of the heat is needed to expand the volume, and there is less for raising the temperature. Observing the need for heat to let the volume expand led to the important concept of *latent heat* *of gases*—as an extension of Black's conceptualization (p.209ff.)—at the start of the 19th century. John Ivory wrote this in 1827 (Ivory, 1827):

> "[. . .] the absolute heat which causes a given rise of temperature, or a given dilatation, is resolvable into two distinct parts; of which one is capable of producing the given rise of temperature, when the volume of the air remains constant; and the other enters into the air, and somehow unites with it while it is expanding [. . .]. The first may be called the *heat of temperature*; and the second might very properly be named the *heat of expansion*; but I shall use the well known term, *latent heat*, understanding by it the heat that accumulates in a mass of air when the volume increases, and is again extricated from it when the volume decreases." [Emphases in the original.]

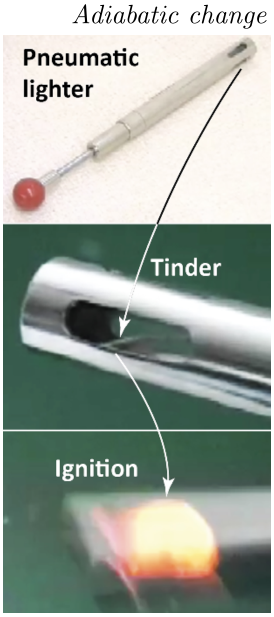
Joseph Black introduced the term *latent heat* for melting and vaporizing of substances only. The term is used to denote amounts of heat that do not do what we believe heat must normally do: raise the temperature of a substance. Therefore, using *latent heat* for heat that is responsible for the change of volume of air is an apt description.

Isothermal heating & cooling

Carnot cycle

This explains the rather special circumstance of heating and expanding air at constant temperature (see Fig.4.38b). We can build machines where air in a cylinder is both heated and let expand at the same time. If we find the right balance between rate of heating and expansion, the temperature of the gas stays constant: all the heat that goes in is used for increasing the volume, not raising the temperature. This process, called *isothermal*, was important in Carnot's development of an imagined cycle a gas could undergo in a heat engine: he composed his model of a cycle of, first, heating at constant temperature; then expansion without heating or cooling, letting the temperature drop; third, cooling at lower constant temperature; and, fourth, compression without heating or cooling, bringing the temperature back up to the starting point. The net effect of this cycle is transporting heat from high to low temperature and, as Carnot put it, „develop motive power."

Adiabatic change



Changing volume and temperature without heating or cooling. In the description of Carnot's cycle, there is a step appearing twice which we have not yet described and explained: compression or expansion without at the same time cooling or heating the gas. Scientists call this *adiabatic change*: a change where volume is changed while the amount of heat in the gas is kept constant.[57] Upon compression, the gas gets hot, upon expansion, it gets cold (see Fig.4.38c).

We all know this operation of air from bicycle pumps. When we compress the air in the pump, the pump casing eventually becomes warm or hot, indicating that the air has become hot. How hot it becomes can be seen quite dramatically if we use a *pneumatic lighter,* which is basically an air pump such as a bicycle pump with a piece of tinder placed inside. When we swiftly compress the air in this lighter, it becomes so hot that the tinder spontaneously ignites.

Why does the air become hot even though we do not heat it, and why does it become cold upon expansion even though we do not cool it? What is actually happening with the air in the bicycle pump or the pneumatic lighter? When first confronted with this phenomenon, observers often say that it must be friction in the air. After all, higher temperature surely means there is more heat, and we know from everyday life that rubbing things produces heat. And, finally, we have all been told that air consists of little particles—so, clearly, they must be rubbing against each other. Never mind that this explanation runs into difficulty when we try to explain why the air becomes cold when expanded without heating or cooling taking place.

When told that the air in the pump is quite elastic—we can impress the piston and let it bounce back to feel this „spring-like" behavior of the air, which tells us that there is only very little friction if at all—some observers change their mind and spontaneously say that, when we compress the air, the heat inside has much less space than before and that is why the air must have become hot. This is precisely what happens: the density of heat in the air increases, so the temperature of the material goes up.[58] Conversely, if we expand the air without changing the amount of heat inside, its temperature drops.

We can get a clear understanding of this adiabatic effect by performing the Embodied Simulation described in Fig.4.7. There, we discussed the feeling of thermal tension when people representing heat crowd into a certain area on the floor representing the body containing heat. We did that for water and what happens when we change its amount, but we can equally well use the size of the area on the floor „containing" people as a measure of the volume of air. If we suddenly make the area accessible to people playing „heat" much smaller, tension goes up very high, representing a much raised temperature. When we allow for much greater space, the same number of people will be much less stressed: the material must have become colder.

The wind engine, in greater detail

Here is how the wind engine functions. Let us start with heating at the surface of the Earth in the cycle undergone by air in the atmosphere, as suggested on the right in Fig.4.37. The wind blowing across land lets the air pick up heat from the warmer ground—this is like heating steam or some other agent in a heat engine. This step of heating, i.e., of increasing the amount of heat in the air, happens at roughly constant pressure, so the temperature of the air might not go up much and we have a process similar to Carnot's isothermal heating in a heat engine (his step 1). Importantly, the air expands, becomes less dense and therefore „lighter" in the sense important for understanding the phenomenon of buoyancy (Chapter 3, Fig.3.13 and, in particular, Figs.3.26 and 3.27).

Air undergoing a Carnot cycle

The warmer expanded air with more heat in it will now rise. Heating from the ground is interrupted, sunlight steaming through it will not add much heating (air is almost perfectly transparent to sunlight), and it cannot yet cool, i.e., lose heat because all the air surrounding a blob of rising air is a very bad conductor for heat. In short, the air will rise adiabatically—the amount of heat in a given body of air will stay constant. However, since the pressure of the air goes down as the body of air goes up, it expands and the temperature drops. This is step 2 in Carnot's cycle: adiabatic expansion.

Third, when the air has reached the upper layers of the atmosphere, nothing prevents heat from being lost by radiation to the very cold universe. The air is cooled, i.e., it loses heat, possibly at nearly constant temperature, shrinks, gets „heavier" and begins to sink. Sinking is step 4 in the cycle: it will happen adiabatically, as when the air was rising. The body of air is compressed, its temperature rises while the amount of heat contained in it stays constant. Eventually, the air has reached the ground, having the original values of heat, volume, temperature, and pressure, and the cycle can start anew.

Forces at play in the wind engine

Let us briefly count the *Forces* that are at play in this drama. It all starts with *Light* at the surface of the Sun, or even with nuclear reactions at the center of the Sun, if we wish to go back that far. Next is *Heat* produced at the surface of the Earth (or already in the depths of the Sun). Then there is *Gravity*, and *Light* (infrared light emitted to outer space) again. In the wind engine, air mediates between these *Forces*, it is the playground upon which the drama unfolds; and for all of us to experience, there is *Wind*.

Sea breeze

Sea breeze and land breeze

Wind from the sea (or any large body of water) toward the land, and from the land to the sea, are smaller scale examples of wind systems that operate on the same principles described for global wind systems.

Consider an area of land adjacent to a large body of water during the day when the sun shines strongly. A hillside or mountainside exposed to the light will heat up strongly. Air will get heated and rise, letting the air pressure on land drop and so making air flow from the cooler water surface toward land. This is called a *sea breeze*.

At night, we have the opposite situation. The landmass will cool down fast and below the temperature of the water (which will stay pretty much constant during a day). Air will rise from the water surface, letting air flow from land to sea. This is a *land breeze*.

How *Heat* from the Earth drives plate tectonics and volcanism

Our solid earth is alive—we can see this most clearly in volcanic activity. But even the structures we believe must be forever, like continents and mountains, are changing. The change happens exceedingly slowly so that only indirect evidence can tell us the story of how the solid surface of the planet has changed through the eons. To get an impression of what kind of change occurred over hundreds of millions of years, consider the history of the continents. About 200 million years ago, the continents we know today must have formed a contiguous landmass called *Pangea*. This structure eventually broke apart with the pieces slowly drifting away from each other—floating on the convecting mantle of the planet.

If we consult a map of the Earth showing structures of the ocean floors, we see ridges and trenches. At the ridges, material from deep below pushes through the oceanic crust and drives the parts of the crust—called *plates*—apart. For example, there is a ridge going all along the middle of the Atlantic, separating Europe and Africa on the East from the Americas on the West, making them continually drift apart. Since there is nowhere else to go, these plates will be swallowed again by the Earth—this happens at the trenches such as the Aleutian Trench in the North Pacific (see Fig.4.39)—just to be reworked and reborn at the ocean ridges.

Continental drift

Traces of history

Continental drift, suggested by Alfred Wegener in 1912, can now be measured directly with the help of precise satellite observations. However, this does not really let us „see" the motion—we need some visual history told by the traces continental drift has left behind. There is one particularly beautiful example of

Hawaiian-Emperor chain of islands

this, the *Hawaiian-Emperor chain of volcanic islands and seamounts* (guyots or undersea mountains) shown in Fig.4.39. The chain stretches from the bottom right edge of the picture—with the island of Hawaii—to the top left near the peninsula of Kamchatka and the Kuril trench with the last of the known underwater mountains called Meiji, all of this for a length of about 6000 km. Meiji is the last of the seamounts if we start counting from Hawaii but, as we shall see, it is historically the first in the story to be told; and the story is again one where the central protagonist is *Heat*.

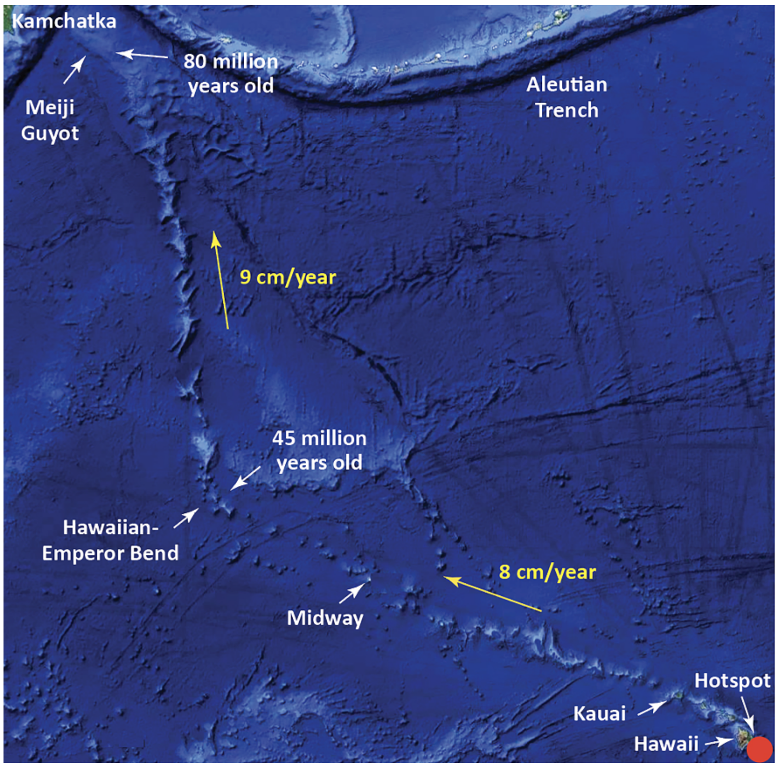
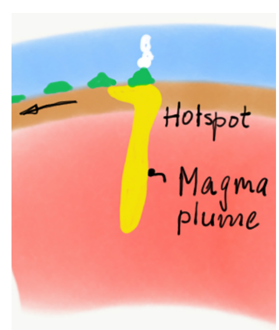


Figure 4.39: *Hawaiian-Emperor Seamount Chain (source: Google Maps).*



Some 80 million years ago, a hotspot formed deep in the mantle of the Earth below what today is Hawaii (red dot in the bottom right corner in Fig.4.39). It is a plume of hotter than usual material (about 1800 K) in the mantle, reaching way down (about 2000 km), sending magma up and through the Pacific Ocean crust. This hotspot is far from any of the ridges and trenches where we find most of the volcanic activity, in the middle of the vast Pacific, at 20° northern latitude. When the hotspot became active, it formed the first known volcanic island, Meiji, that is now near the Aleutian and Kuril trenches, ready to be given back to the depths of the Earth.

The original model of what then happened was proposed by John Wilson in 1963. The Pacific plate which is penetrated by the magma of the hotspot was then moving almost northward, at a speed maybe a little lower than 10 cm per year. The first volcanic island formed would therefore move away from the location of the hotspot—if we assume it to be stationary in the Earth's mantle—and lose its connection to the upwelling magma. The island that had grown over hundreds of thousands of years would then have stopped growing, slowly being eroded and finally sinking under the surface of the ocean as it moved away.

New volcanic islands would form, always somewhat south of a former one, always meeting the fate first reserved for Meiji, caused by the drift of the Pacific plate and eventual erosion. Then, about 45 million years ago, Daikakuji formed, but this island and all the others that were to form later now moved north-westward—it seems that at that point the Pacific plate changed its direction of drifting on the convecting mantle below it. [A newer model has it that, for the first 35 million years, the hotspot drifted in the mantle as the Pacific plate moved over it, but since then, the hotspot has most likely been stationary, as suggested by the straight line formed by Hawaiian islands and seamounts stretching from Hawaii to Daikakuji at the Hawaiian-Emperor Bend; see Fig.4.39.]

Lava flow on Hawaii (Vecteezy / created by petrzurek)

About 5 million years ago, the island of Kauai formed, moved north-west, and successively made room for Oahu, Molokai, Lanai, Kahoolawe, Maui, and Hawaii. Most of Hawaii (the Big Island) is about half a million years young. Actually, the Big Island consists of 5 volcanoes: Kohala, Mauna Kea, Hualalai, Mauna Loa, and Kilauea. Kilauea is still very active, still forming new land, but like the rest it is moving away from the hotspot. There is actually a new volcano forming south-east of the island of Hawaii which has been given the name Lo'ihi. Lo'ihi's summit is currently about 1000 m below the ocean surface.

◦ ◦ ◦ ◦ ◦

Physics picks out the simple cases. In concluding this chapter, here is a question that throws light on the nature of physics: Why would Carnot want to study heat engines—apart from his keen interest in matters of engineering—rather than the „great movements" caused by *Heat* he spoke of? This shows something very basic about physical science: most phenomena in nature are simply too complex and complicated to be studied by formal science, at least in as much detail as our beautiful and messy nature confronts us with.

Physics, in particular, has made an art of isolating and creating the simplest possible circumstances that could then be studied easily, formally, and in great detail. So it is with *Heat*—simple applications of heating and cooling of materials, and the operation of *Heat* in heat engines, prove to be the right playground for us wanting to learn about *Heat* as a *Force of Nature*. Still, there is much more to nature than this. Maybe, by telling stories we can get a feeling for how rich this world is and for how *Forces of Nature* do their work creating it.

Notes

[1]Sadi Carnot (1824, p.1): „C'est à la chaleur que doivent être attribués les grands mouvements qui frappent nos regards sur la terre; c'est à elle que sont dues les agitations de l'atmosphère, l'ascension des nuages, la chute des pluies et des autres météores, les courants d'eau qui sillonnent la surface du globe et dont l'homme est parvenu à employer pour son usage une faible partie; enfin les tremblements de terre, les éruptions volcaniques reconnaissent aussi pour cause la chaleur." English Translation by R. H. Thurston, 1897.

[2]Sadi Carnot (1824, p.1-2).

[3]This is certainly so for the languages we personally know: English, Italian, German, and French, and as far as we can tell, it is so for many more. In each of these languages, we have to deal with the challenge of distinguishing between a name for the phenomenon as a whole and its extensive aspect.

[4]Clausius R. (1850).

[5]Fuchs H.U. (1986).

[6]Clausius R. (1865).

[7]Clausius R. 1865, p.46. Very fittingly, in the title of this paper, Clausius wrote about „forms of the fundamental equations of the mechanical theory of heat" that would be „convenient for application." Indeed, entropy is „convenient" because we need it for completing the mutilated form of thermodynamics he had developed in 1850. Only, Clausius, and apparently hardly anyone else, realized for decades to come that entropy had a lot of resemblance with the old caloric. See Calendar (1911), Job (1972), Mares et al. (2008), Fuchs, Corni, D'Anna (2022).

[8]Fuchs (1987); Fuchs (2010[1996]); Fuchs, Corni, D'Anna (2022).

[9]It has been reported that John von Neumann told Claude Shannon, who invented the statistical measure of information, „You should call it entropy, [. . .] no one knows what entropy really is, so in a debate you will always have the advantage." This is what Shannon told Tribus (Tribus & McIrvone, 1971, p.180) in 1961. Tribus & McIrvone(1971) continue: „The point behind von Neumann's jest is serious. Clausius' definition of entropy has very little direct physical appeal. It can be derived with satisfactory mathematical rigor and can be shown to have interesting and useful properties, particularly in engineering, but in a direct aesthetic sense it has not been satisfactory for generations of students. Simple physical arguments lead one to believe in the correctness of most quantities in physics. Surrounding Clausius' entropy there has always been an extra mystery."

[10]Fuchs, Corni, D'Anna (2022), sections 3.3.4, 3.5.1, and 4.4.3.

[11]Embodied Simulations in which we play the roles of agents representing the extensive and intensive aspects of *Forces of Nature* are described in some detail in Fuchs, Corni, & Pahl (2021), and Corni & Fuchs (2021). We can use our body and we can design board games in analogy to the embodied simulations that allow students to learn much about the properties of the conceptualizations of *Forces of Nature* we are developing here (see Section 5.6). Embodied Simulation do not include the role of energy played in physical processes—energy will be incorporated into what we call Forces-of-Nature Theater performances (see Chapter 5, Section 5.6).

[12]In fact, it has eluded physics ever since. If we do not have an extensive quantity of heat, we cannot speak of its production. Amount of heat as (a form of) energy cannot be produced.

[13]In contrast to the cases of up $\leftrightarrow$ down and open $\leftrightarrow$ close(d) where DL's usage was unequivocal, we cannot be quite sure about the case of cold (and warm). In the former, he would say *up* both when he wanted to be lifted up or put down or go up the stairs or down; and he used the word *open* both when he opened or closed a door or a lid on a pot, In the latter case, he used *cold* for *warm* only on a very few occasions, leaving room for doubt. Did he have a sense of *Cold* as independent of *Heat* and simply did not yet verbalize the experience of *Heat*, maybe because the words *warm* and *hot* simply developed later?

[14]When presenting the *Winter Story* as an example of stories of *Forces of Nature* at conferences, we have been told that using it in school should not be permitted—it would confuse learners. We do not agree. If it is possible to read that „The cold is produced very near to the customer" in an EU directive, or that „Cold is produced from heat" in slides used at the Technische Universität Berlin, and if, finally, Sadi Carnot can write „D'après ce principe, il ne suffit pas, pour donner naissance à la puissance motrice, de produire de la chaleur: il faut encore se procurer du froid; . . . " (1824, p.11), we certainly do not have to be shy about speaking about *Cold* and, at least initially, treating it as a *Force of Nature* alongside *Heat*. After all, what is important about our encounters with nature and machines—that there are Forces characterized by intensity and tension, extension, and power—can very well be learned when speaking sensibly about a Force everyone recognizes. Having to learn that *cold* can be understood as the absence of *heat* is the least of the problems for students of thermodynamics.

[15]We can easily make such a cold mixture today with crushed ice and a lot of salt. This mixture reaches and stays at a temperature of about -20°C for a pretty long time.

[16]Today's traditional theory of thermodynamics insists that it is impossible to calculate processes; only equilibrium states are accessible to theory.

[17]Magalotti (1667), p.cxxviii.

[18]Magalotti (1667), pp.cxxviii-cxxix.

[19]Black J. (1803), p.27. Black's lectures of the 1850s were not published until the beginning of the 19th century.

[20]Black J. (1803), p.28.

[21]From a purely formal scientific viewpoint, it would be possible to create the theory of thermal processes upon Cold as a Force of Nature. We would introduce degrees of coldness in place of temperature, and amount of cold instead of amount of heat (caloric). Since, as we shall see, hotness has a lowest point (the point of absolute zero temperature), degrees of coldness would have a maximum value—we would count degrees of coldness down from this highest value. And since caloric can be produced but not destroyed (see further down in this chapter), amount of cold would have to be destroyed but not produced—which is a strange notion: the universe would have to be filled with an infinite amount of cold that slowly „evaporates" as history progresses.

[22]E. Mach (1896). With the exception of the choice of a term the translation is from C. Truesdell (1980).

[23]E. Mach (1896). The translations are ours.

[24]Die Temperatur ist nach dem bisher Ausgeführten, wie man unschwer erkennen wird, nichts als die Charakterisirung, Kennzeichnung des Wärmezustandes durch eine Zahl. Diese Temperaturzahl hat lediglich die Eigenschaft einer Inventarnummer, vermöge welcher man denselben Wärmezustand wieder erkennen, und wenn es nöthig ist, aufsuchen und wiederherstellen kann. Diese Zahl lässt zugleich erkennen, in welcher Ordnung die bezeichneten Wärmezustände sich folgen, und zwischen welchen andern Zuständen ein gegebener Zustand liegt.

[25]Der Temperaturbegriff ist ein Niveaubegriff wie die Höhe eines schweren, die Geschwindigkeit eines bewegten Körpers, das elektrische, das magnetische Potential, die chemische Differenz.

[26]See Fuchs, D'Anna, Corni (2022); in particular, see section 2.

[27]The example is described in Corni & Fuchs, 2021, p.232. It is used as the starting point of a larger empirical investigation of children's learning about heat (Pahl, Fuchs, & Corni, 2022)

[28]Beccari G. (2016). The original version of the story is in Italian.

[29]Lakoff & Kövecses (1987). The main metaphors embedded in the story are ANGER/HEAT IS A FLUIDLIKE SUBSTANCE, THE BODY IS A CONTAINER FOR ANGER/HEAT, and ANGER/HEAT IS A POWERFUL AGENT. The assumption in Beccari's (2016) thesis was that since *Heat* and *Anger* are presented together to children, metaphors for *Anger* should apply analogously to *Heat* (see Fig. 9 right). Example expressions for the three metaphors are "*Then, Anger and Heat suddenly entered his body*;" "*Anger and Heat, meanwhile, had left Spike's body*;" "*And he felt sick because he couldn't control all that rage and all that heat inside his body*."

[30]Magalotti, 1667, p.cxxvii.

[31]See values of albedo: https://en.wikipedia.org/wiki/Albedo. When we consult an educational source, however, we are told that „Land surfaces absorb much more solar radiation than water" (https://www.education.com/science-fair/article/land-or-water-warm-faster/; visited on Dec. 19, 2021)—this is obviously wrong.

[32]The question of daily warming of land and water is different from that of the differing responses of land and water to global warming—here, too, land warms faster than water, but the reason is different; it has to do with different rates of evaporation (see https://www.carbonbrief.org/guest-post-why-does-land-warm-up-faster-than-the-oceans; visited on Dec. 19, 2021).

[33]Cristina Mariani called questions of this type „embodied questions." See Mariani, C., Laurenti, E., Corni, F. (2012); and Mariani, C., Corni, F., Fuchs, H.U. (2011). These „embodied questions" call upon a form of imagining that has been described as *imagining-how*: „This kind of imaginative activity is not realized by projecting an unfolding scene of which the imaginer is the mere witness, but rather by entertaining an imagined state of affairs in which he [...] is envisaged as *himself an active and embodied participant*." (Casey, 2000[1976], p.45).

[34]Note that this situation is very different from the microscopic interpretation of temperature as somehow resulting from the "trembling" or "shaking" of "molecules." In an ES as described here, persons are not molecules, and they neither shake nor tremble, nor race around randomly. All persons together performing the ES are an extensive fluidlike quantity (amount of heat, i.e., entropy), and the tension of this thermal fluid represents temperature. If anything, a person would represent a „quantum of heat" (i.e., a quantum of entropy).

[35]This is exactly what happens in adiabatic expansion (of a gas). Alternatively, if we reduce the size of the space on the floor, people in there will be more crowded—the temperature goes up; this is adiabatic compression (of a gas). In adiabatic compression (compression without heating), the temperature goes up not because „little wiggling particles" rub against each other and produce heat, but because heat inside the material gets more crowded!

[36]It is important to realize that the statement that tension goes up as the amount of fluidlike quantity goes up may be wrong in some cases. Figuratively speaking, the situation depends critically upon the „container" for fluidlike quantity: if its „size" changes, the tension might not go up, it might even go down. Concrete cases are air in a balloon: shortly after starting to blow up a balloon, it usually becomes easier for a bit to do so because of the particular properties of the rubber membrane; phase change: the temperature does not change as we add more heat (see Section 4.3); changes of volume of a gas while heating or cooling; and generally changing the amount of material the „container" is made out of.

[37]This point needs to be clarified further. Note that, at a given point in time, the rates of change of temperature of two bodies in thermal contact need not be the same—see the diagram on the right in Fig.4.8. Since the heat capacities of two bodies are usually different, their temperatures react differently to the flow of heat. If, as is the case in the example of Fig.4.8, the capacity of water is greater than that of the body made of copper, the magnitude of the rate of change of temperature of water will be lower than that of the block of copper. Still the magnitude of the flow of heat is the same for both bodies at that moment—at every moment, the body of water loses as much heat as the body of copper gains. (Actually, the flow into the cooler body will be a little stronger than the flow out of the warmer one. The reason for this is production of heat when heat is diffusing through a material—a little bit more heat arrives at the new place than left the old one. However, this does not change the rest of the argument.)

[38]For a detailed description, see Fuchs (2014c).

[39]Richard Rorty (1979) argues that, starting with Descartes, philosophers have developed a (mistaken) view of the human mind as a „mirror of nature" that directly reflects reality.

[40]If exactly all the *amounts of heat* (entropy) arriving here and being produced here were to be emitted again to outer space, the Earth should not warm up. The point is that the amount of heat (entropy) needed to warm up the atmosphere is very little compared to the amount of heat (entropy) produced here. The current ratio of rate of growth of heat in the atmosphere to rate of production of heat at the Earth's surface is roughly 1:30,000 (this is based on assuming that the atmosphere's temperature is going up 2°C in 50 years). In other words, flows and production rates of heat (entropy) are huge compared to rates of change of stored heat (entropy). So, we are (almost) right when we say that all the heat that gets here and is produced here leaves the Earth again—even in the face of global warming.

[41]See Fuchs H. U., 2010[1996], Section 5.5

[42]Black J., 1803, vol. I, p.127

[43]We could use Carnot's idea of how to express the power of thermal processes in order to take an important step in the direction of the concept of energy, but we shall not do this here. However, remember the discussion of the concept of energy in Section 3.7; moreover, we shall take up the issue of the role of energy in physical systems and processes in more detail in the next chapter. We have alluded to the notion of energy a couple of times by suggesting that we understand energy as something that is passed from agent to patient(s) as they interact. As a scientific concept, the idea of energy had surfaced in mechanics but was limited to phenomena having to do with motion. Finally, in the science of *Heat*, it was released from its confines and made into the general concept that helped, and still helps, to relate different phenomena to each other, ushering in a science of *Forces of Nature*.

[44]See the animated gif showing the operation of a Newcomen engine on the Wikipedia page „History of the steam engine;" https://en.wikipedia.org/wiki/History_of_the_steam_engine

[45]Carnot (1824). This is Thurston's translation, p.46.

[46]Carnot (1824). This is Thurston's translation, p.45. Remember that Carnot used the words heat and caloric interchangeably. *Caloric* is our *extensive quantity of heat*, what we have simply called *heat*.

[47]Sadi Carnot (1824), p.28 (French original).

[48]Sadi Carnot got this result in 1824. Unfortunately, the state of experimental investigations was poor, and the notion of energy and the problem with the production of caloric made themselves felt. It seems that he became unsure of his own result; at least this is what one might assume from notes of his that were published after his early death in 1832. It took another 25 years for the idea to take hold that *quantity of heat* could not be this fluidlike quantity Carnot and most of his contemporaries had called caloric; rather, *quantity of heat* had to be „quantity of energy" in some form. Ever since, this way of looking at thermal processes has been taken as literal, objective truth burying, as a consequence, a simple imagistic approach to thermodynamics. Sadly, the consequence is that we learn to mistrust our most fundamental images created by experience.

[49]Consider the entries in Table 1.2 (Chapter 1). Volume of fluid, amount of heat (entropy), and amount of substance are not conserved, and their potentials are absolute. On the other hand, electric charge, momentum, spin (angular momentum), and (gravitational) mass are conserved, and their potentials are arbitrary.

[50]Carnot (1824, p.23). Translation by Thurston.

[51]If we combine our previous results (Figs.4.19 and 4.23), we can write *(T_high – T_low) * Flow of heat = T_low * Rate at which heat is produced*.

[52]Remember that (amount of) heat is not energy! Therefore, heat must have its own unit, different from that of energy (which is Joule, J). We give the unit of heat its own name: Carnot (Ct)—a usage that was suggested by F. Herrmann (2000). Therefore, the unit of heat (Ct) equals J/K = W·s/K.

[53]For readers accustomed to quantifying amounts of heat in terms of energy dissipated or transferred, the values in Table 4.5 can simply be multiplied by the (average) temperature at which the process takes place. For the Sun, use a factor of 6000 K, for many of the processes on Earth use a factor of 300 K in order to find rough equivalents in energy units.

[54]See Fuchs H. U., 2010[1996], Section 9.6.1 and 9.6.2. See also https://www.acs.org/content/acs/en/climatescience/atmosphericwarming/singlelayermodel.html (visited on August 6, 2022).

[55]Concentrating the Sun's light is important in thermal solar energy engineering and in (materials) research. In a parabolic trough concentrator (Fig.4.1, right), sunlight is concentrated by factors of up to 100, and the temperature achieved in the absorbing materials is up to 400°C. In solar tower thermal power plants (Fig.2.8, left), the concentration ratio can be up to 1000, and the temperature of the absorber can reach 1000°C or higher. In so-called solar furnaces (such as one built in the French alps, see https://en.wikipedia.org/wiki/Odeillo_solar_furnace, visited on October 1), concentrations ratios of up to 16000 (that is 1/3 of the concentration of sunlight at the Sun's surface) have been reached; temperatures can be close to 4000°C.

[56]Dissipation refers to the energy used during the production of heat (caloric, entropy)—the energy used is said to have been dissipated. The rate of dissipation equals the power of the process of producing heat, i.e., the rate at which energy is used for producing heat.

[57]We need to reason, and to speak, more precisely here. *Adiabatic* only means „no heating or cooling." By itself, this does not mean that the amount of heat in the air needs to stay constant: heat can be created inside a body of air. So, if we want *adiabatic* to also mean *constant amount of heat*, we need to add the condition that processes happen to run reversibly. A *reversible adiabatic change* indeed keeps the amount of heat in a body constant. Such processes are called *isentropic* (running at constant entropy = constant amount of heat).

[58]Doubling the density of heat in a body of air does not lead to double the temperature—the relation is more complicated.

Chapter 5

Imagining Forces – Towards Visual Storytelling

The Perpetuum Mobile machine.
© Marion Deichmann, 2014.

In 2014, Marion Deichmann (2014a,b) set out to explain the inner workings of natural and technical systems in an imaginative manner. She produced an animated story—called *Perpetuum Mobile*—that makes *Forces* and their properties and activities visible for us. We shall now use Deichmann's animation as a starting point for investigating different forms of visualizing *Forces of Nature*. In particular, we shall see how to picture the role of *energy* in physical processes.

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The act of imagining has played a central role in our discussion of *Forces of Nature* in the previous chapters, and, occasionally, we have asked the reader to visualize certain aspects of our understanding of such *Forces*. Despite what we might think is required of us in the act of imagining, this mental activity need not lead to the production of visual images. Rather, the images that come up as we imagine are very often of an abstract schematic type—they are abstract figures or shapes that arise in emotion and feeling.[1] They are subsequently made use of in different forms of communication of which visualization is only one.

Visual storytelling

Still, visual imagining plays an important role in understanding experience. In this chapter, we want to ask how we can visualize *Forces* at work in physical systems—after all, we should be able to tell stories of *Forces of Nature* in a medium other than natural language. How can we use visual media such as drawings, paintings, and animations to tell such stories? How can we visually render the schemas and metaphors we have created for speaking about Forces? In particular, how can we visualize the power of *Forces of Nature*, and how can this be extended to include an understanding of the role of *energy*?

Visual metaphor

The following story, called *Perpetuum Mobile*, shows how this can be done and what it means for the direction our acts of imagining can take. We shall sketch the story, study its particular form of rendering extensive and intensive aspects, and use its visualization of energy to suggest its general properties. We will then extend the investigation to additional forms of *visually metaphorizing Forces*: in the form of *Process Diagrams*, and by suggesting how to create theatrical, i.e., mimetic, plays—so-called *Forces-of-Nature Theater* performances—of agents and patients acting in natural and technical scenes.

5.1 The *Perpetuum Mobile* Story

The animation[2] tells the story of an inventor who dreams of the perfect perpetual motion engine (Fig.5.1, left). When he finally builds it, it seems to work at first. He starts the generator by hand, turning its axle (Fig.5.1-1).

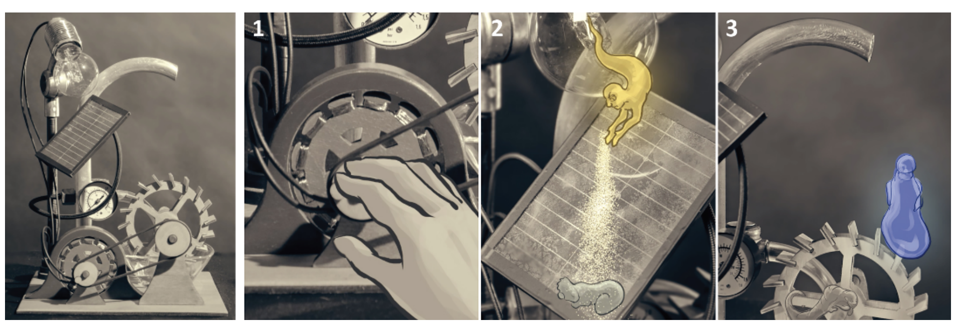


Figure 5.1: *Scenes from Perpetuum Mobile. Left: The Perpetuum Mobile machine. (1)-(3): The inventor starts the generator of the Perpetuum Mobile machine by hand (1) to make a lamp burn. Light drives the solar cell (2), a pump pumps water high up whereupon it falls down (3). There are "ghosts" or "spirits" at work in the machine. Pictures are taken from Deichmann's animation (2014b).*

This makes electricity flow which, in turn, lights the lamp. The light of the lamp drives the solar cell (Fig.5.1-2) which drives a water pump. The water is pumped high, falls down upon the water wheel (Fig.5.1-3) which now turns and so drives the generator, and so on, ad infinitum or in perpetuity...

However, since every operation produces some heat, the amount of energy made available by the inventor in the initial „push" and then „handed" from part to part inside the machine, becomes less and less. In the end, inevitably, the engine will stop. When it becomes clear that it will never work, the machine is put under a glass cover near a window in the attic of a museum (Fig.5.2).

There, by chance, the sun shines through the window, its light falls upon the solar cell (photovoltaic cell) that is a part of the engine. The engine starts working, the heat generated in every step of the operations lets the glass cover break and so sets the engine free—from now on, it will work „forever," at least as long as it does not break and as long the sun keeps shining.

Figure 5.2: *Put under a glass cover, the machine is tucked away in the attic of a museum. Luckily, its solar cell faces the window. When the sun shines through the windows into the room, the machine starts running. Heat is produced in the engine which breaks the glass cover and finally sets the machine free (pictures: MD).*

Apart from how the engine works internally, apart from the Forces that operate in its interior, there are two noteworthy external circumstances that let the engine work. First, there is the Sun that sends its light to Earth. Second, the heat inevitably produced in any real operation in nature and in engines, can escape to the environment and from there to outer space (Fig.5.3). The engine has been „freed;" it has become a mechanism that works in an open flow system such as the surface of our planet.[3]

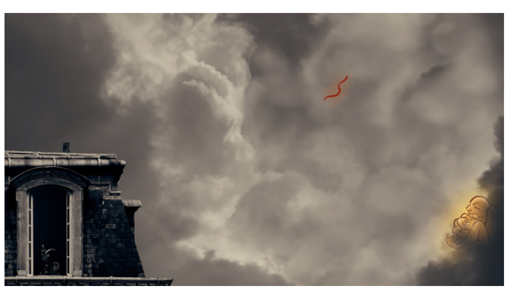


Figure 5.3: *The sun sets, and the heat produced in the operation of the engine escapes to space. The engine can rest; but the Forces making it run in the first place will resume their work the next morning (pictures: MD).*

The story not only explains why a perpetual motion machine cannot work. Embedding the animation in its earthly and cosmic settings, the story is actually a beautiful allegory of our planet as an open system where new tensions are continuously created that make *Forces* powerful and let processes, including life, continue.

The Story...

The Perpetuum Mobile Story narrated (M. Deichmann, 2014)

It was supposed to be the best invention ever: The perpetuum mobile, a machine that powers itself. An unending cycle made up of light, electricity, water and motion.

However, the machine initially stands still, at rest in a state of equilibrium. It can only start running if given a push.

With the push, energy enters the generator. This energy is taken up by the electricity, causing its voltage to rise. The electricity uses the energy to make the lamp glow. At the same time, the electricity flows back to its original level.

In turn, this light becomes the energy carrier. Wherever the light shines on the solar cell, the energy is used to raise the voltage once again. Unfortunately, the electricity can only take a part of the energy with it...

The electricity now powers the pump that forces the water through the pipe to a higher level. In the process, it gives its energy to the water and the electric voltage is lowered again.

Gravity causes the water to flow downward by itself, releasing its energy, which is taken up by the momentum of the wheel.

The motion carries the energy from the water wheel over the drive belt and wheels to the generator—and the cycle of the perpetual motion machine begins all over again.

However, whenever energy is transferred, a part of it gets lost. Eventually there is not enough of it left over to start the next process. This alleged miracle machine will never work.

Written off as a useless curiosity, it might find its way into a glass case in a corner of a museum where it is eventually forgotten.

Picture by MD

If the room in the museum is not totally windowless and the machine is positioned just right at a window, a new element can come into play!

The sunlight shining on the machine is so strong that the amount of energy it carries is more than enough to drive the electricity in the solar cell—causing the cycle to begin again.

The energy that is unused does not get lost. It generates heat.

As long as the sun shines, the processes continue to run. However, they must accomplish more because much more energy is coming into the machine:

The wheels turn faster. The light burns brighter. And it gets hotter inside the glass case.

Wherever energy leaves the cycle, there is friction causing the heat to increase, expanding the air inside the glass case until...

Now the cycle has been broken: The sun brings energy.

It is transferred from process to process without increasing or decreasing ... and is finally carried by the heat back into the atmosphere.

5.2 Forces of Nature in the *Perpetuum Mobile* Animation

What is the concrete imaginative approach to Forces of Nature used in the *Perpetuum Mobile* animated movie? In order to present a detailed description, we shall refer to specific parts of the movie by reporting the starting and ending times of selected sequences. The version of the movie we use for this purpose is the one found on vimeo.com.[4]

Matter (or physical objects) and energy

The animation starts with a view of the engine at rest (Fig.5.1, left). Shortly after the start, there is a crucial scene that explains how humans may think about processes in nature and machines (time stamps: 00:38 to 00:42; see Fig.5.4).

In order to start the machine moving, the inventor turns the wheel of the generator. By doing this, he gives the generator some energy that is needed to drive the engine. In the animation, dust is used as a *visual metaphor*[5] for *energy*.

Visual metaphor

What we see here is a standard form of conceptualization of the material world and how it works: the physical world is made of two things—*objects* and *energy*. Energy is needed to make the objects move, and their motion explains what is going on in the world and why. Only, as we shall learn from the *Perpetuum Mobile* animation, this form of natural philosophy does *not* work.

The world as made of matter and energy...

...or maybe not?

Figure 5.4: *The inventor starts the engine by giving it a "push" by hand—he passes energy to the generator. Dust is used as the visual metaphor for energy in Perpetuum Mobile (pictures: MD).*

Spirits run the world. If we continue with the events recounted in the animation, something rather unexpected is happening (time stamps: 00:43 to 00:53; see Fig.5.5). A spirit appears; it swallows the dust and *tenses up*. We see this in its posture and (facial) expression. It *moves up* the wires that connect the generator at the foot of the perpetuum mobile with the lightbulb at the top. As we shall see shortly, this spirit is a visual metaphor for Electricity—let us call it an *electricity spirit*.[6] We shall learn about its properties and behavior in the following scenes.

Figure-Ground Reversal

Where does this spirit come from? We might think that it appeared out of nothing, or that it was produced from dust. Actually, this is not the case as we learn in the course of the animation. The electricity spirit has been there all along, it was just invisible (Fig.5.6, right and center).

What the movie hints at is that the spirit must appear to the "mind's eye" as the result of a well-known experiential (perceptual) process called *Figure-Ground-Reversal* (Fig.5.6, right). We first experience the machine with its parts as *Figures* before a *Ground* or background—our mind picks out the material objects and makes them visible (Fig.5.6, left). We are able, however, to "move" the material parts to the *background* (making them the *Ground*) and let new figures appear in our imagination.

Transforming matter into a background

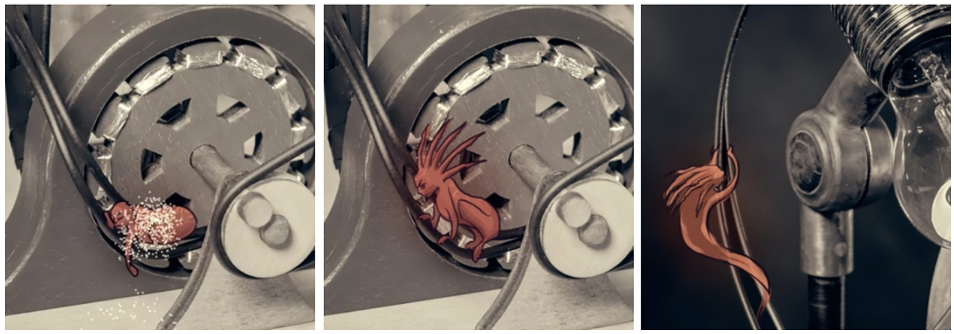


Figure 5.5: *Behind the vail of dust, a spirit appears that swallows the dust, tenses up and moves up along the wires that connect generator and lightbulb (pictures: MD).*

This is the same process we know from certain visual scenes where we can make ourselves see one image or another (Fig.5.6, right; we might see a vase before a dark background at first and two faces facing each other after Figure-Ground-Reversal). What we are dealing with in the case of experiencing Forces of Nature is not visual in this sense; still, in analogy to visual Figure-Ground-Reversal, our mind lets the material objects of the physical world become the ground (Fig.5.6, center), and upon this ground we „see" spirits or ghosts as new figures or *agents* that represent Forces of Nature. The animation simply visualizes what is otherwise a non-visual process.

Spirits as agents

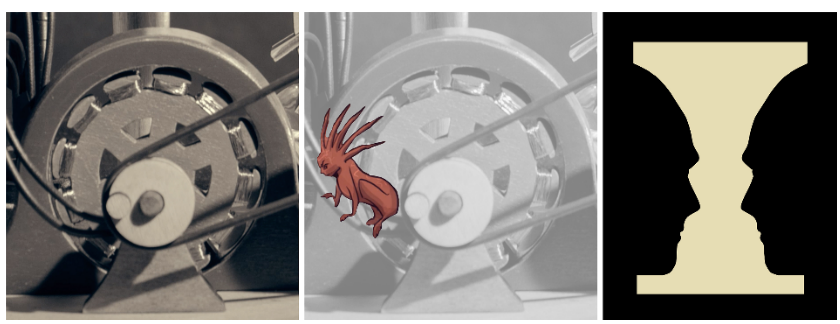


Figure 5.6: *Left: Generator as a figure on a ground (picture: MD). Center: The generator and other material bodies have become the ground with an electricity spirit as an active character (the figure) (picture: MD). Right: A drawing that lets us see either a light vase or two black profiles facing each other.*

Properties and activities of spirits

Let us continue to explore the physics of the *Perpetuum Mobile* story (time stamps: 00:51 to 01:05, and again at 02:02 to 02:18). The electricity spirit has woken up out of a kind of sleep or totally relaxed state. It has tensed up and then moved up to the lightbulb. Both tensing and moving up are (visual) metaphors for what we imagine is happening to Electricity when it receives energy (dust): it „moves" or changes to an „elevated" state,[7] which physicists call a state of *higher electric potential* (intensity). There is a tension (visualized by the bodily state of the spirit) between the higher and the lower states of *intensity of electricity.*

Tensing & moving up

Electric intensity or potential

An interaction. Starting at 00:56, the electricity spirit is at the lightbulb where we see a second sleeping spirit or ghost—*Light* (Fig.5.7(a) on the left). Until 01:04, the two *interact*; we shall describe some aspects of this interaction again in the next section where we discuss the notions of *energy* and *power* (Section 5.3). For now, let us just note that, at the end of this phase, the electricity spirit relaxes and moves back down (to a state of lower potential, as we say in physics). As a consequence of the interaction, the light spirit is awoken and becomes tense (this starts at 01:07).

Interacting agents

We do not see this at first, but later in the story (between 02:02 and 02:18), the electricity spirit is where we encountered it first near the generator, relaxed and ready to be woken up and tensed up again for new action. What we learn from this is that Electricity (represented by the spirit) was not created or produced at the start of the story. It had been there all along, just waiting for its turn to do its job in the lightbulb. All the electricity spirit does is „run around in circles" and interact with other spirits (we can see two wires going from the generator to the bulb and back again, and the spirit moves up along one of them and down along the other). In the generator, the spirit interacts with a rotation spirit (02:10 to 02:12), tenses, then interacts with the light spirit and relaxes.

Getting ready for new action

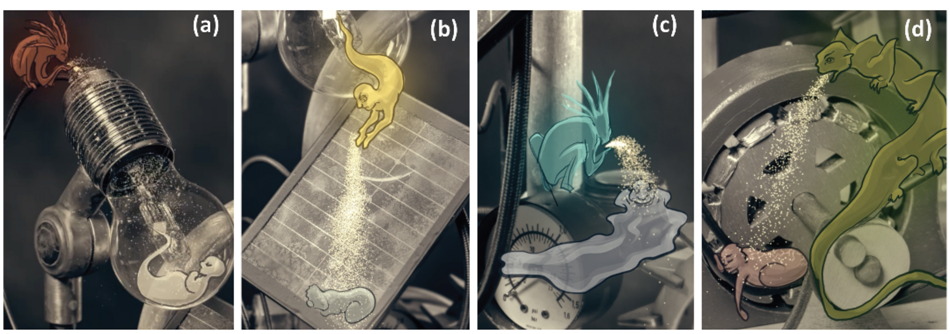


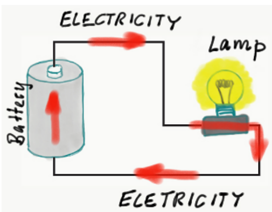
Figure 5.7: *Four different types of interactions ((a) Electricity and Light, (b) Light and Electricity, (c) Electricity and Water, (d) Motion and Electricity) are represented identically: dust is made available by an agent and accepted or used by a second (the second agent is sometimes called a patient) (pictures: MD).*

Light as a spirit. Let us now turn to Light, to the light spirit (time stamps 01:07 to 01:21). The spirit has been awoken by Electricity (Fig.5.7(a)), it has become tense and ready to act. Its activity consists of flowing toward the photovoltaic cell, which is part of the perpetuum mobile, where it interacts with a new spirit, which, as we find out, is Electricity (Fig.5.7(b)). As before, when the inventor brought Electricity „to life" and Electricity got the light spirit going, the interaction of Light and Electricity is accompanied by an exchange of dust—Light gives Electricity some dust. Then it relaxes and goes back to sleep in the lamp.

„Embodiment" of Light and Electricity. In the animation, Light and Electricity are each given a body. Let us briefly reflect upon what the body might symbolize.

We have seen that the spirits can change their bodily expression or demeanor—they can tense up and relax, which expresses intensities and tension, an experience we are all familiar with. But what does the body of a spirit stand for?

Electric circuits



Electricity (or rather, electric charge) cannot be consumed

Electric circuits

We can connect a lightbulb to a battery (which is a kind of generator) to make the bulb light up. To do so, we need two (metal) wires that connect the two ends (terminals) of the battery to the two terminals of the lamp. The battery makes electric charge flow through the wires, from what is called the high (positive) terminal of the battery to the low (negative) terminal. The electricity flows through the lamp and the battery as well (see Volume 2 for details).

In terms of (visual) metaphors, the battery makes the *electric charge* tense up and flow toward and through the lamp where it relaxes again, just to flow back to the battery to be tensed again. Electric charge is always there, it is not "produced" in the battery, and it is not "consumed" in the lightbulb. In many ways, it simply flows around in a closed circuit. It behaves like a fluid would; that is why we call it a *fluidlike quantity.*

Body as extension

We have to recognize that the „embodiment" of a FoN is not introduced just to make Forces visible in the visual medium of the animated story. The spirits' bodies have a deep physical meaning: they represent the *extensive* aspect of Forces of Nature. As we said before when we discussed Forces having a fluidlike aspect (Chapter 2, Sections 2.4-2.6, and, in particular, Volume 2), they are characterized not just by an intensity but also by an amount of some „stuff" that fills parts of space, i.e., has an extension.

Since the „stuff" of the Basic Forces of Nature of physical science are fundamentally invisible, they easily elude our attention. This is one of the great challenges for learning to understand a science such as physics—we need to learn to „see" what cannot be seen. Amounts of electricity, motion, heat—and even light and water—are invisibles. Deichmann's animation helps us to approach the abstract nature of our experience of Forces by expressing visually what we otherwise might overlook—Forces are given a „body" so we know they have an extensive aspect.

In the cases of Light and Electricity, the way „embodiment" is approached in the animation is quite instructive. As we have all heard on many occasions, Light is commonly *equated with* energy. We can give many reasons why this is simply wrong (see Chapter 2, p.95, and Volume 2), but none may be as emotionally convincing and imaginatively clear as giving Light a „body."

Light-as-substance

Light is a *chemical substance*; it is often an important ingredient in reactions such as photosynthesis in leaves or the production of smog in air polluted with exhaust gases from combustion engines. Light just isn't material in the usual sense of the word, but it suits chemicals quite well: Like all chemicals, it will be produced and destroyed in reactions and in the processes of absorption and emission.[8]

Giving Light a body can help us understand its nature still more clearly. Light as a „substance" *carries* energy and makes it available for new actions—it is an *energy carrier*, not energy!

The „body" of Electricity. Everything we have said here—with the exception of production and destruction—also holds for Electricity. The „embodiment" of Electricity in the form of a spirit reminds us that Electricity is not energy—the spirit's body symbolizes the extensive aspect of Electricity as a Force of Nature, i.e., the quantity physicists call *electric charge*. We have to learn to „see" electric charge if we ever want to understand electricity. Charge is not energy, it is an *energy carrier*. Importantly, all the spirits we see in the animation are *carriers of energy*. (Section 5.3).

Electric charge

Energy carriers

Light causes Electricity to tense up and flow. From what happens between time stamps 01:21 and 01:35, we can tell that the new spirit that is awoken by Light in the solar cell must be Electricity. It is of the same type as the first electricity spirit, but it is independent in that it has its own circuit for flowing and acting in. After 01:35, this agent interacts with a water spirit in the pump of the perpetual motion machine, relaxes and returns to the solar cell (ending at 01:45).

◦ ◦ ◦ ◦ ◦

The imagery encountered during these first few moments is repeated as processes act and interact, creating a chain bending into an apparent cycle (p.254). Each phenomenon has its own spirit. A spirit changes its demeanor from relaxed to tensed (and back), and its body symbolizes the extension of the Force represented. Furthermore, a spirit can transport energy (dust) from place to place and „hand" it to another spirit during an interaction. This is true as well of Forces we have not yet discussed in any depth: Electricity, Substances, and Motion. We shall study these new Forces in Volume 2, but for the moment we simply accept what analogical reasoning—applied so vividly in the *Perpetuum Mobile* animation—can teach us: these processes are experienced and explained in ways that are fundamentally similar to the phenomena we have already dealt with.

Motion is explained in analogy to the other Forces of Nature

Producing heat—the role of irreversibility

There is one phenomenon, however, that deserves particular attention: We hear in the story that the perpetual motion machine will never work, and we learn that this is related to the creation of heat that accompanies interactions. We have studied processes that produce heat and the notion of irreversibility before in Chapter 4 (Section 4.2), but the animated story lets us experience what this means much more vividly than could ever be the case if we only read an explanation or viewed and manipulated some equations.

Visual imagery applied to the production of heat. In almost all processes in nature and in machines, *heat is produced* (see Table 4.3). In the animation, during the scene lasting from 03:21 to about 03:31, we see that what is happening here can be represented imaginatively—using visual schematic structures and metaphors—by letting a new agent (spirit) come to life, namely *Heat* (Fig.5.8). In an interaction such as that of the spirit of *Electricity* with the spirit of *Water* (in the electric water pump), dust is handed from the agent to the patient, but some dust will invariably fall to the ground. The dust that is „lost" has the power of letting *Heat* come into existence and properly tense up (and so represent the temperature of the objects in which it was created).

Producing heat

In summary, irreversible processes let a *heat spirit* emerge, tense up, and do its work. For example, they heat up the machine and air under the glass cover, braking it (at 04:10). Importantly, we have to learn that this new spirit is *created*;

it did not exist before! And, unlike what we have said about light, it does not get destroyed at the end of its duty; rather, if allowed to, it will escape into the atmosphere and from there into outer space (from 04:44).

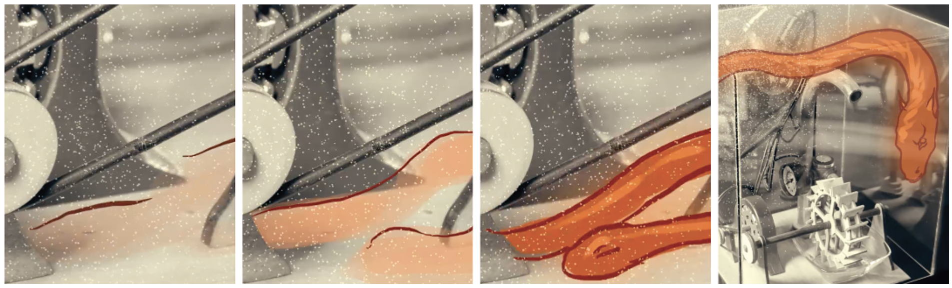


Figure 5.8: *A heat spirit is produced in (almost) all physical processes. As time goes on, we get more and more of it, i.e., of heat-as-a-substance, and, if this spirit is collected, bodies become warmer (pictures: MD).*

A spirit interacts with more than one other spirit at the same time. A spirit can interact with more than one other spirit at the same time. Note that the production of heat usually accompanies other interactions between spirits. When Electricity produces Light in a lamp, when Light interacts with Electricity in a solar cell, when Electricity interacts with Water in a pump, each time when these interactions between two spirits happen, another interaction takes place at the same time. Put differently, production of heat takes place *in parallel* to the other activities we observe in nature and machines. A spirit normally interacts with two spirits at once, one of which is the heat spirit. [Importantly, we also have phenomena where a driving agent interacts only with heat; this is the case in mechanical friction; when electric charge flows through a wire making it hot; or in combustion; see Table 4.3.]

Parallel processes

5.3 Energy in the *Perpetuum Mobile* Animation

So far, we have not spoken much about an aspect of metaphoric visualization that is quite prominent in the movie and important if we wish to understand the interaction of physical and chemical *Forces* more profoundly. We are referring here to the dust carried by the spirits and exchanged between them (Fig.5.9).

Dust as visual metaphor for energy

Energy as dust

As mentioned before in passing (Section 5.2), the dust is used to metaphorically refer to what physicists call *energy*. Let us see if we can learn about the aspects of this concept—called the *energy principle* in continuum physics—by watching the behavior of the dust in the movie.

Dust is brought into the scene for the first time at 00:39; it is „presented" to the perpetual motion machine by the inventor. Watching this, we might be inclined to assume that the inventor has *produced* the energy he transferred. This is a form of language used informally by laypeople and experts alike. However, as we shall see, this does not quite square with what is happening with and to the dust in the course of the movie. For the moment, let us set this question aside.

Dust is exchanged in interactions. As we continue, from about 00:42 to 00:46, we see the dust converging onto the first spirit (Fig.5.9, left; remember that this spirit should be thought of as having been there already; it did not get produced, and it definitely was not made „out of" dust!). The images suggest two things: first, the electricity spirit absorbs some of the dust and the rest falls to the floor (since the spirit is not transparent, we cannot see the dust that has been collected in its body, but it is there); second, upon receiving dust, the electricity ghost tenses up.

Tensing upon receiving dust

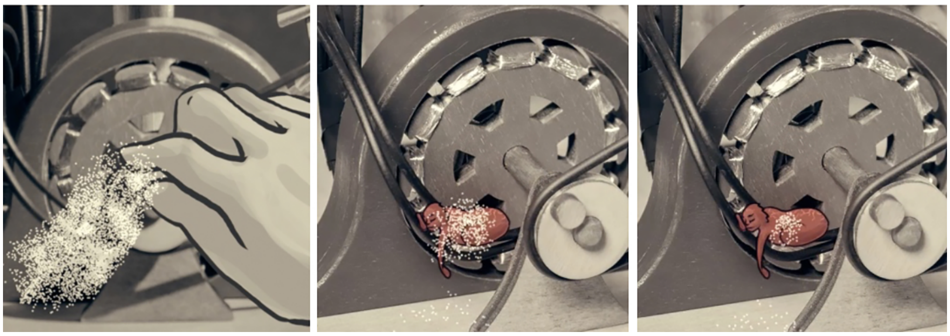


Figure 5.9: *The dust transferred from the inventor's hand to the engine is partly absorbed by the electricity spirit; the rest falls to the floor (pictures: MD).*

What is happening between the hand of the inventor and the first spirit (an electricity spirit) repeats itself over and over again in the course of the story: dust is *exchanged* between spirits when they meet inside physical devices such as a lamp, a photovoltaic cell, a pump, and a water wheel. For example, from 00:56 to 01:11, during the interaction of the electricity and light spirits inside the lamp (Fig.5.7, left), the first passes dust to the second and the second spirit absorbs the dust. We might say that the first spirit *makes* dust *available* to the second one. As it absorbs dust, the second spirit gets *tense*. In response, the first spirit *relaxes*.

Exchange of dust

Dust made available

Tensing and relaxing

Inefficient interactions—missing some dust. In the next scene where dust is exchanged between a light spirit and an electricity spirit, from 01:15 to 01:20, we are told that the receiving agent (Electricity) misses some of the dust made available by the light spirit. Clearly, dust can fall by the wayside—we have already noticed this during the first example of an interaction, that between the hand of the inventor and the first electricity spirit.

Dust can fall by the wayside

Dust is transported by agents. After the electricity spirit has received dust from the hand of the inventor, it tenses and moves up along one of the wires to the lightbulb. Presumably, it *carries* the dust it absorbed to the new location where it interacts with the light spirit. The new light spirit now moves toward a new location where the processes undergone by the dust repeat just like before (time stamps: 01:13 to 01:23).

Transport: spirits carry dust

Always after a spirit has received dust (and has become tense as a consequence), it moves toward a new location to meet a different spirit in order to interact with it. Even though it is not shown explicitly in the animation, the spirit carries the dust it just received to the new location.

Dust does not come in different „forms." What we have just observed is repeated again and again as the dust is carried through the chain of events and handed from spirit to spirit if it does not fall to the floor (Fig.5.7). Importantly, note that it is *the same dust everywhere* that „moves" through the chain; it does not change its appearance—it is not transformed!

Only one tape of dust

Efficiency and ideal interactions

Efficiency of interactions and ideal interactions

In science and engineering, it is customary to quantify the *efficiency* of an interaction (see Section 4.5). Usually, in an interaction, we have a primary *caused* process in mind, but there is a second one as well. If Electricity is used to pump Water, the interaction between Electricity and Water is called the *primary interaction.* However, since there is also a secondary interaction between Electricity and Heat, we want to know the fraction of the energy that is made available by Electricity that goes to pumping Water. This fraction is called the *efficiency* of the pump.

If the efficiency were equal to 1 (or 100%), we would call the device where the interaction takes place, or the interaction itself, an *ideal* one.

Dust stays dust

Dust is not converted into spirits, nor are spirits converted into dust. Maybe even more importantly, we note that dust is not converted out of spirits or spirits out of dust. Except for spirits that can be „born" or „die:" a spirit is always there, always responsible for its own phenomenon. There is no „conversion" of one kind of spirit out of another, or into another!

No „loss" of dust

Dust is never really lost. As we learn later in the animation, the dust falling to the ground is *not lost.* It makes the appearance of a special spirit possible: heat is produced (time stamps: 03:23 to 03:31). This new spirit picks up the dust that was needed in its creation and carries it out to the atmosphere and then to outer space (this is how the Earth is cooled).

Storing dust

Dust can be stored in physical objects, together with spirits. The treatment of thermal processes occurring in the perpetual motion machine hint at something new that may be overlooked. The heat spirit lingers for quite some time in the engine under the glass cover. Since it has absorbed the dust used in its creation, the dust is obviously present, or stored, in the material elements of the engine; dust can be stored.

Properties of energy—suggested by properties of dust

If we accept that the dust in Deichmann's animation is meant to represent the quantity called *energy* in physical, chemical, and biological systems and processes, we can summarize its basic aspects and describe in what sense it is an integral part of the notion of *Force of Nature*:[9]

1. In *interactions* of *Forces of Nature*—when two *Forces* „meet"—*energy* is *made available* by the (causing, driving) agent and *accepted* or *used* by the patient. An agent can make energy available only if it is tense. In sum, energy is *exchanged* between agent and patient, the agent relaxes, and the patient tenses up and becomes powerful.

2. Energy *is the same in all processes*, there aren't any different types of energy. Energy *is never converted* into different forms or types.[10]

3. A patient usually "misses" some of the energy made available by the agent. Energy that is „missed" by a patient in an interaction is not „lost." It is

used by a new patient we call *Heat*. (Amount of heat is produced when energy that was „missed" by a patient during an interaction is used; physicists and engineers say that the energy used during the production of heat is *dissipated*.)

4. Energy can be *transported*. Agents *carry* the energy they have accepted from one place of interaction to the next (these places where interactions occur may be called *„meeting places"*). We call the agents *energy carriers*.[11]
5. Energy can be *stored* in physical objects (together with agents that carry the energy) and help make the stored agents tense.
6. When energy is stored in physical objects such as material fluids (water and air) and light (electromagnetic radiation), it will be transported along with them if they are flowing. Such transports are called *convection* and *radiation*. Material fluids and light are *not* energy carriers in the sense introduced in point 4.
7. Energy is neither produced nor destroyed (or lost). *There is always the same amount of energy in nature.* (Physicists say that energy is *conserved*.)
8. Even though energy exists everywhere and all the time, *energy can be used only if it has been made available by an agent*, and an agent can make energy available only if it is *tense*—tensions are primary.

At least some of the properties of energy listed here clash with how laypeople and experts speak about energy. In textbooks, we hear that energy is produced and lost, and that it is converted from one form to another. Interestingly, the talk of "energy conversion" is a tool for avoiding the agents that represent the *Forces of Nature*. If we say that "a solar cell converts light into electricity," we (1) assume that light and electricity are energy (rather than metaphorizing them as agents and energy carriers), and (2) by doing so, we cover up what actually matters in physical systems and processes, namely, the existence, properties, and activities of the agents our mind introduces as representants of *Forces of Nature*.

Energy „conversion:" How we avoid talking about Forces of Nature

Energy carriers making energy available

Agents as energy carriers, interacting and making energy available

Our mind lets us imagine agents as representants of *Forces of Nature*. These agents can be understood metaphorically as *energy carriers*. It is important to realize that an agent is not energy itself! It is a figure having a certain size and expressing a certain tension; together, these properties are related to how much energy an agent can carry.

When an agent has carried energy to a scene where it can interact with a second agent (patient), it will make energy *available*. As a consequence, its tension goes down whereas the tension of the patient rises. The patient accepts („uses") energy and carries it away.

Why doesn't a perpetual motion machine work?

As has been demonstrated quite vividly in the movie, a perpetual motion machine cannot work (time stamps: 02:13 to 02:33). There are two related ways of expressing why this is so. The narrator of the story tells us that, in an interaction between two agents, the second agent does not manage to "catch" all the energy made available by the first.

Energy that "falls by the wayside" is still available, though—it is available for producing heat. Since the *Heat agent* does not drive any of the processes the perpetual motion machine was designed for, the energy used by the Heat agent is effectively „lost" to the engine.[12] As we know, if allowed, the heat agent will escape to the environment and take the energy used in its production with it (Fig.5.3). After a short time, the operations of the engine will stop since Electricity, Light, Water, and Motion cannot make energy available any longer.

A second but related way of expressing this starts with the assumption that production of heat is inevitable in nature and in machines; in interactions there are always at least two parallel processes of exchange occurring, usually a „productive" one and a „parasitic" one (i.e., the production of heat). Since production of heat does not happen "for free," some energy cost is incurred. The rest of the argument is then the same as the one just given.

Power—measuring the magnitude of ongoing causation

Forces of Nature are powerful, or they are made to be powerful. This is how we have described our experience of causation: we see a phenomenon preceding another and, for whatever reason, we feel that the former has caused the latter. Speaking of *power* is our means of quantifying *how powerful* a phenomenon is when causing other phenomena. By way of example we have already made an important step in the direction of formalizing the notion of the power of processes when we described the power of *Gravity* (Section 3.6) and of *Heat* (Section 4.4). We shall now continue this description by following the imagery created in Deichmann's animation (Fig.5.10). Most importantly, this serves to clarify the *relationship between power and energy*.

Power and energy

Power as rate at which energy is exchanged

Formally speaking, power is the *rate at which energy is exchanged*, i.e., passed from an agent to a patient. Less formally said, power describes how active an agent is, i.e., the rate at which an agent „works."

In science, the concept of power applies to both agents and patients, as the rates of *making energy available and using it*. Since interactions are non-ideal, we need to be clear whose power are we referring to. In the example of a solar cell, Light makes more energy available than is used by Electricity; the magnitude of the power of Light is greater than that of Electricity.

We experience the notion of power of *Forces of Nature* most directly when they interact, when, say, Electricity is used for pumping Water. In other words, we need the idea of power when we experience causation, when we perceive an agent acting and a patient suffering, receiving, or accepting. Starting with this experience, we shall take *power* to mean the *magnitude* or strength *of ongoing causation*. Power relates to ongoing processes, to action, not to states of being. For our purpose here, it is a measure of how strongly two Forces interact and how fast things happen in nature as a consequence of the strength of the interaction.

Ask yourself what it means for agents to interact more or less powerfully. There are a number of scenes in the animation that make this quite clear. Watch what happens during the scene lasting from 1:35 to 1:39 (see Fig.5.10, a1-a3). As you can see, *the rate at which dust is exchanged* between Electricity and Water changes in the course of time: it goes from weak to strong and back again.

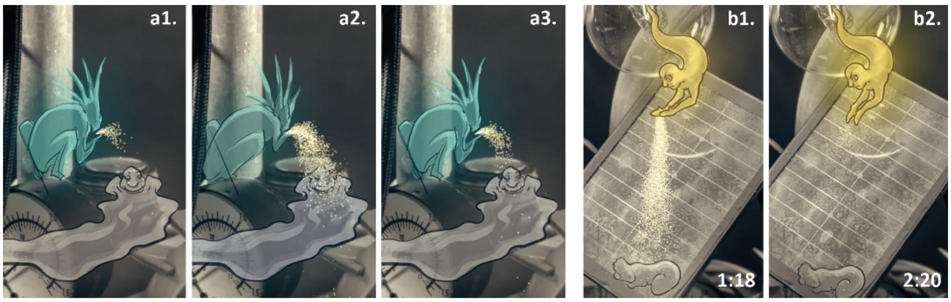


Figure 5.10: *Left (a1-a3): The power of electricity interacting with water metaphorized as the rate of exchange (the strength of flow) of dust from an electricity agent to a water patient, shown at three different moments (note that part of the dust „falls by the wayside"). Right (b1 & b2): Power when Light interacts with Electricity at two points in time when the power of Light is very different (pictures: MD).*

Energy is fluidlike, to some degree...

Energy is partly fluidlike

If we accept the characteristics of energy listed starting on p.262, especially those listed as points 2 and 7, it appears that we can think of energy as being similar to a fluid. If we add point 5, it is even like a conserved fluid (one that can neither be produced nor destroyed). Indeed, this is how one thinks in science and engineering about energy when *amounts of energy* are *accounted* for. A mathematical rule for accounting for energy has the same form as an accounting rule for amounts of water. If we need to do energy accounting, this image is quite helpful.

Accounting rule

However, the first entry in the list of properties starting on p.262 shows that energy has an important property that the fluidlike quantities representing Forces of Nature do not have. Energy is made available in interactions; it is "offloaded" from a carrier. *Amounts* of *heat*, *electricity*, *motion*, and all the other fluidlike quantities, are energy carriers (but they are not energy). They obviously cannot be "offloaded" off themselves; they cannot be made available in the sense of how energy is made available!

So, energy is different—we call it *quasi-fluidlike*. It is not in the same category as *amounts* of fluidlike quantities of *heat*, *electricity*, *substances*, *motion*, or *gravity*. We need to understand that energy is altogether different. Energy belongs to every phenomenon, i.e., to every Force of Nature and their interactions, and it plays the same role in every case. But it is not a Force of Nature itself!

Energy isn't really a fluidlike quantity

Now, compare the two scenes lasting from 01:13 to 01:22 and from 02:19 to 02:24, the strength of the exchange of dust (energy) is quite different in the two scenes involving Light and Electricity which refer to two different circumstances.

Power as rate of exchange of energy

What we see as the strength of the flow of dust going from one agent to the next is a visual metaphor for what is called *power* in the physical sciences. Put formally, *power is the rate at which energy is exchanged between Forces of Nature.*

There is another brief sequence in the animation that lets us experience and imagine the magnitude of power: from 3:37 to 3:51, we are told that all the processes run faster and so are more powerful. Here, a particular interaction between two agents would presumably be identical to what we have seen in the animation during an earlier period; however, interactions occur more frequently now.

We can even think of a third manner in which power can be visualized. We could leave interactions as they are rendered in the first part of the movie and also leave the speed at which the spirits „run" but have several of the same agents waiting „in line" to do their work. This would raise the rate of interactions as well. Actually, having more—possibly very many—identical agents moving toward a location where they can interact with different spirits, one after another, can be seen as a move toward „smearing" the spirits over some space. Instead of having a single spirit changing its bodily size, we can have more of them „flowing" with varying speeds along their paths. This appears as a visualization of agents as fluidlike rather than „concentrated" in a spatially delineated body. We shall make the move from bodies to fluids below in Section 5.4.

Agents at work

Physics, as a science, has always borrowed heavily from basic human experience for its concepts. Here is a notion that has led to the construction of a concept of great historical weight in physical science—the concept of *work*.

We have chosen to describe phenomena as agents and patients acting, interacting, causing, driving, receiving, suffering, and so on. We could just as well have said that an agent is working or doing its work. Humans and animals work in order to achieve a goal. This experience has been transferred from engineering to early physical science in the study of mechanics. Mechanical devices have always been built to „perform work," to help us in our work. Scientists slowly developed a formal concept of „work done" in a mechanical process which later was seen as an instance of a quantity of energy transferred.[13] As a result of historical development, we still hear that energy „is" work (rather than a measure of how much a Force has worked), or work is a form of energy.

The concept of work in mechanics

Strictly speaking, in physics, the concept of *work* is used for a quantity of energy transferred in a mechanical process. However, we can generalize the notion of work to all types of interactions, and sometimes this is done in the sciences where we see terms used such as electrical, gravitational, chemical, or thermal work. Indeed, now and then we will say that a *Force of Nature* „has done its work," which, in this book, we interpret as meaning that a certain amount of energy has been made available in an encounter with another *Force*.

5.4 Visual Metaphors for Fluid and Potential

The acts of visual imagining presented in the animation of the *Perpetuum Mobile* story will now be carried one step further—we want to use paper and pencil as tools and create drawings as a new medium through which we tell the same stories as through an animation (or as through a theater performance, see Section 5.6).

In physical science, the *Forces of Nature—Fluids*, *Heat*, *Electricity & Magnetism*, *Chemicals*, *Gravity*, and *Motion*—are those that have a fluidlike aspect. We literally „see" fluids flowing in hilly landscapes. For this reason, we shall now take a step in the direction of visually bringing to prominence this property. What we need to do is choose the type and form of schemas and metaphors that are appropriate (1) for representing our imaginative understanding of *Forces* having a fluidlike character, and (2) lend themselves to simple sketching by hand.

Fluids flowing in hilly landscapes

We shall see that imagining the extensive property of *Forces* as fluid amount is easily sketched with the help of visual schematic elements; this includes flows and general transport phenomena, falling, pumping, storage, and even production and destruction. Tensions will be portrayed as differences of levels which are metaphors for what we experience as potentials. We shall deal with visual elements for energy in the next section (Section 5.5).

Schemas of fluids and levels

The schema of fluid substance

Let us shift our acts of imagining from agency represented by individual spirits having a more or less well delineated body to *fluidlike substances* representing the extensive aspects of Forces of Nature. Fluids come much closer to the mathematical description of amounts of heat, electricity, substances, or motion, than agents that are "concentrated" in individual bodies. If you wonder if fluids can be seen to be "agents" as much as spirits or ghosts can, just think of how fog affects us visually and emotionally (Fig.5.11). Fog is often used as a representant of something mysterious or even menacing in literature and movies.

From individual bodies to fluids

Figure 5.11: *Fog as a fluidlike agent. Fog perfectly represents a fluidlike quantity: it fills spaces, is variably dense („thick"), flows, and is produced and disappears again.*

Instead of having embodied spirits moving and tensing and relaxing, we can imagine physical processes as the *flow* of fluidlike quantities, either *falling* from higher to lower metaphoric levels or being *pumped* from lower to higher levels (Fig.5.12). The interaction of two processes consists of the latter—*pumping*—following the former—*falling*. If a fluidlike quantity falls from a higher to a lower level it can „empower" a previously „powerless" phenomenon by setting up a potential difference and forcing a fluidlike quantity to „flow uphill."

The schema of fluid substance. Let us now make this move from individual spirits to fluids representing the *extension* of *Forces*; this will allow us to create metaphoric visualizations of the activity of *Forces* as simple sketches, examples of which we are going to discuss in quite some detail in Section 5.5. Here are the most basic (schematically abstract) aspects of fluids—which we learn about by bodily or embodied experience with real fluids. When we summarize our everyday experience with fluids, we see that a fluid can...

1. ...flow spontaneously from points of high to low stress; we can imagine this to be metaphoric motion from points that are high to points that are low (Fig.5.12, left) in a metaphoric landscape (remember water flowing along gradients, Fig.2.13, and the coldness landscape, Chapter 2, Section 2.6).
2. ...be forced to go against the spontaneous direction of flow; for this, pumps are needed (Fig.5.12, right). In this case, a fluid is a patient, not an agent.

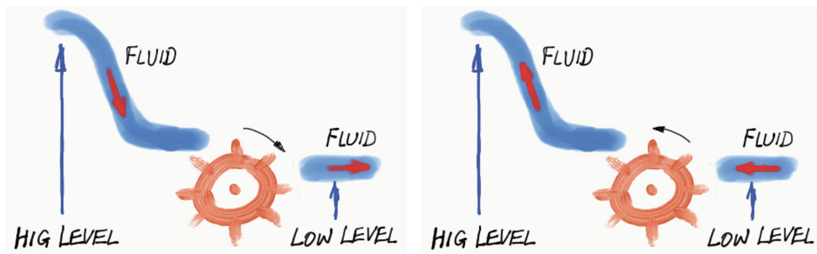


Figure 5.12: *Spontaneous flow (left) and pumping (right) of a fluid.*

3. ...fill space and adjust their form easily to whatever shape a space provides; they are stored in bodies and in gravitational and electromagnetic fields filling space. They flow through space and materials, and some types can be produced or destroyed (Fig.5.13).

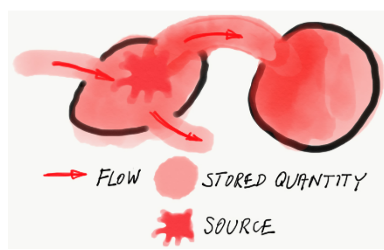


Figure 5.13: *Fluids fill space, flow, and can be produced (and destroyed).*

4. ...be more or less dense; their density can vary from point to point.
5. ...be stressed or relaxed. If we consider fog or air, we can imagine stress being a consequence of the degree of compression (in physics, we use pressure for measuring the state of stress of a real fluid).
6. ...be imagined to be powerful agents; they are agents that drive other processes. They carry energy, make energy available or collect it (use it).
7. ...be produced or destroyed, at least in some cases (heat can be produced, and substances can be produced and destroyed).
8. ...make energy available when they flow from points (or states) of high stress to points of lower stress, or disappear (Fig.5.12, left); the higher the drop of level, the more energy is made available.

9. . . . use (accept, pick up) energy when they are pumped from points of low to points of high potential, or appear (Fig.5.12, right); the higher the difference of level through which a fluid is pumped, the more energy it picks up.

10. . . . transport energy; the higher their state of stress (level, potential), the more energy they transport.

If we want to make these schematic properties concrete, we can simply think of water and waterfalls. Water is the quintessential material fluid, and a waterfall is the archetype of a physical process where energy is made available and used (Fig.5.12, left). The only thing we usually don't see happening with water is production or destruction. We normally assume that amounts of water stay the same overall. However, if we allow for chemical reactions involving water, even this well-known "stuff" undergoes processes of production and destruction (for example, water can be destroyed in electrolysis where hydrogen and oxygen are produced, and it is produced in the reaction of hydrogen and oxygen).

Bodies and fields

Bodies and fields as physical objects

The modern view in physics with regard to *physical objects* populating the universe is this: there are two types, *material bodies* and *fields*. We all know material bodies in their solid, liquid, and gaseous forms (there are a few other states of matter, but they do not need to concern us here).

Fields are harder to "grasp." Indeed, we cannot grasp them with our hands, they are not material in the everyday sense. Still, they are physical objects with properties partly similar to those of objects made of standard matter.

In classical macroscopic physics, two different fields are introduced: *gravitational* and *electromagnetic*. They fill space like material bodies, they transport heat (entropy), light, momentum, angular momentum, and energy, and they can contain these "fluidlike" quantities as well. Very importantly for our everyday life, electromagnetic fields are the „substrate" for light which can transport heat and momentum. Indeed, *light* is called *electromagnetic radiation* (i.e., a wavelike transport through the electromagnetic field).

In microscopic physics, two more fields have been introduced to interpret interactions between matter at very small spatial scales (the interactions are called *strong force* and *weak force*). Interestingly, in microscopic physics, researchers are more and more interpreting all matter as types of fields. Talk of "particles" is giving way to talk of "fields." [Among the books that introduce non-experts to modern quantum physics, those by Carlo Rovelli stand out; see Rovelli (2017).]

Unfortunately, it is often said that *fields are energy*, as opposed to standard matter, which *is mass*. The common interpretation of Einstein's $E = m\,c^2$ may add to this form of speaking. This is in no way correct and helpful, not from the viewpoint of *Forces of Nature*, and not from the viewpoint of the most recent quantum physics available to us.

Above all, fluids—both real and metaphoric—are characterized by an *amount*. We see fluids as some kind of stuff; „stuff" cannot be counted (like a number of

Accounting for amount of fluid: laws of balance

stones) but its amounts are easily quantified—this is something we do informally in everyday life and formally in diverse fields ranging from finance and economics to physical science. When dealt with formally, we speak of *accounting* (Fig.5.13): we apply rules of accounting or *laws of balance* (as they are called in physics).

Experiencing and visualizing potential

Potential of a situation

By now, we have used the term *potential* quite a few times, first at the end of Chapter 2, then again in the context of gravitational potential (Chapter 3), and now for *electric potential* (p.256). There is an aspect of experiencing Forces of Nature we have neglected to discuss so far—the emotion and the feeling of *potential* associated with a *situation*—to use a very general and fuzzy term for everything that could *be potential* or *have a potential*. Investigating our experience of *potential* will help us understand how it is used in physical science.

In everyday life, we use the term *potential* mostly for humans and human made institutions, and for cultural and technical artifacts. The meaning of *potential* is this: a person, a thing, a situation could possibly do something, create something, influence something, lead to something, or, generally speaking, *cause something* to happen. Persons, things, and situations could do this, they *have the potential for* doing this, but they do not do it—or have not done so yet.

Potential in nature. Clearly, *potential* applies to situations in nature as well. Water in a lake high up in the mountains promises the possibility of its use in a hydroelectric power plant; dark, towering thunderheads in the sky ominously suggest that lightning bolts might light the sky any moment now; acid in a container threatens to burn a hole into the container wall; hot coffee in a thermos bottle holds the promise of warming us up on a cold morning.

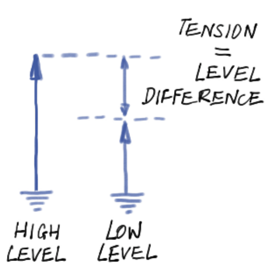
Potential is not power!

Potential (level), tension, and power

Our feeling of potential *is related to* power and we might be tempted to use the term *potential* as meaning „unfulfilled power." But potential needs to be distinguished from power!

In oder to disentangle the ideas, we have to remind ourselves of the three fundamental aspects of a *Force of Nature*: intensity (and tension), size or amount, and power. We should never confuse the three, and we should not confuse potential with power. In physical science, *potential* is a generalized term for what we have called *intensity* and imaginatively rendered as a *level*.

Potential as level



Actually, the potential of a situation—the possibility that a Force can be active and cause something to happen—is more closely related to tension. There need to be tensions for something to happen. Still, physicists have chosen to use the term potential for intensity itself. Therefore, *tension is the difference of two values of potential* at two different locations in a physical system.

Metaphorically speaking, potential is a *level*, and *tension*, i.e., potential difference, is a *level difference*. Potentials are high or low, not big or small!

We have called *Water*, *Electricity*, *Substances*, and *Heat*, etc., *Forces of Nature*. Clearly, then, *potential* is related to what we have called *power of a Force*: a *Force* has the potential for effecting something, for causing something else to happen. The *Force* does not have to do this, not yet at least, but it could. So, what is the condition for a *Force of Nature* to have the potential to be powerful?

We can get closer to an answer to this question if we first consider what the condition is for a *Force not to have* the potential for making something else happen. Obviously, this is the case when the *Force* is relaxed, i.e., not tense. In other words, this is the case if there is no level difference, no electric tension, no intensity associated with a substance, and if the coffee is no warmer than we already are, i.e., if there is no temperature difference. In equilibrium, the potential of a *Force of Nature* for doing something is non-existent.

No potential in equilibrium

Alternatively, then, a potential for causing something exist if there is a *tension*. As we have said on multiple occasions, a tension is a difference of intensities or qualities and, if measured against the intensity in equilibrium as the base level, it is the value of intensity itself. This is the reason why, in physical science, the term *potential* is now used generally for the intensities of all different types of *Forces of Nature* (Table 5.1; see also Table 1.2).

Table 5.1: Forces and their potentials

Force of Nature	**Potential**
Water (fluids)	Pressure
Gravity	Gravitational potential
Heat	Temperature
Chemical substances	Chemical potential
Electricity	Electric potential
Translational motion	Speed
Rotation	Angular speed

Tensions, in other words, are *potential differences*. Therefore, we might say that our feeling of potential is caused by a felt *difference* of qualities or intensities relative to a state or level of equilibrium—if there is such a difference, there is a potential for something to happen.

Tension are potential difference

Potential as vertical level. Figuratively speaking, *potential is a level*, and this is how we are going to visualize it. Put still differently, it describes the compulsion, urge, or drive of water, heat, substances, charge, etc., to go somewhere else or „be" something else. If water is at a high level, at high potential, it „wants" to go lower. When it finally arrives at ground level, there isn't really anywhere else to go. Heat at high temperature, i.e., at high thermal potential, „wants" to go to where it is cooler. In its hot state, heat is tense, „cramped" in its place, so it is natural for it to flow away if we let it. A chemical substance has a drive to go somewhere else where it is „less crowded;" and in what we call reactions, it has a drive to simply „disappear" into nothing—die, so to speak.

Potential as level

Potential as drive to „move" or „disappear"

Potentials and power. It is important to differentiate between potential and power. *Potential*, at least in modern terminology, including in science, can be taken to mean as yet „unfulfilled" causal power—just the possibility of „exerting" power. We can have a feeling of an agent being powerful even if it is not causing anything. Still, we want to reserve the notion of power for the *actuality* of powerful interaction—when a powerful agent causes a patient to undergo a process, i.e., when the agent is actively powerful.

Interestingly, in ancient Greek, the word from which we derive the term *energy* was associated with the realization of possibilities. The potential for something was related to the word *Force* or *power* (*dynamis* in ancient Greek). We now use the word *dynamics* rather differently—for something happening, for change occurring in the course of time.

Dynamis & Energeia

Dynamis and Energeia

The Greek word $\delta\upsilon\nu\alpha\mu\iota\varsigma$ (dynamis) roughly means force, power, ability, strength, possibility, potential. It does not mean that something *will* change but we can understand by *dynamis* the *possibility* of change. An ancient form of thought tells us that, in order for something to change, there have to be forces or powers. We shall take *dynamical system* to mean a system where „forces" or „powers" are at work and thus lead to change over the course of time.

Aristotle called the realization of a possibility $\epsilon\nu\epsilon\varrho\gamma\epsilon\iota\alpha$ (energeia). This is the root of the word, but not necessarily of the meaning of, *energy*.

5.5 Visualizing *Forces of Nature* in Process Diagrams

The list of properties of fluids and potentials presented above quite clearly fits and fills our previous descriptions of *Forces of Nature*, especially those in the category including *Water*, *Heat*, *Light*, and *Electricity*. We shall now use and combine the visual schemas for potentials and fluid quantities created above in Section 5.4 with a generalized schematic representation of the role of energy in physical processes (see Section 3.7) and so construct visual metaphors and stories of Forces acting and interacting in physical scenes. Basically, we shall extend the diagrams of processes introduced in Chapter 3 (Figs.3.4 and 3.25) and Chapter 4 (Figs.4.19 and 4.21-4.28). We call these schematic, metaphoric, and narrative visualizations *process diagrams*.[14] Originally, such diagrams were used to inspire the imagistic depiction of physical processes in Deichmann's perpetual motion machine.

Process diagrams

Visualizing the energy exchanged in interactions

There is an additional imagistic element derived from our experience of interactions. Interactions between humans, in particular, are imagined as consisting of agents „giving something" to the patients: he gives her a headache; she passes her good mood to her friends, and so on. This type of reasoning is often applied to purely physical situations where we hear people say that „power" is transferred (it is passed from the agentive to the passive element in an interaction).

Interaction as exchange. Purely as an image, this is alright: something is happening and something is being handed or passed from agent to patient—note the arrow labeled „empowering" at the center of the diagram in Fig.3.4. We can describe the activity as *exchange*: in an interaction, something is exchanged.

Interaction as exchange

When it comes to words, though, we should be more careful about how to use them for creating meaning. It is true that we use the term *power* as a noun and say, for instance, we *have* power. So why not say we *hand power* to another person or thing? However, the feeling for the meaning of *power* is not really that of a thing; rather, as we have said above, *power* is our measure of the strength of ongoing causation—*it describes an act, not a thing.*

Power as an act, not a thing

Indeed, there is no need for using the word *power* in the sense of a thing. As we have learned from Deichmann's animation, the concept of *energy*—as it is used in macroscopic physics—carries a meaning that comes close to that of some kind of „stuff" that can be exchanged. So, the word we use for *what* we imagine being *passed* or being *handed* from agent to patient is *energy*, not power (Fig.5.14).

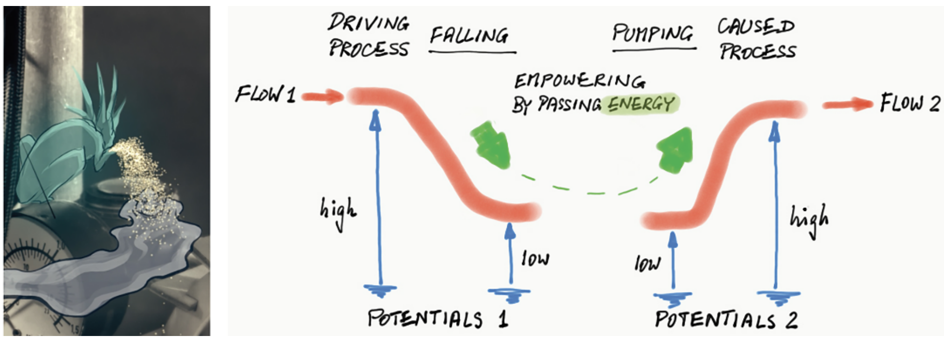


Figure 5.14: *Visual metaphoric rendering of the interaction of two Forces. Left: Dust is exchanged between two spirits (picture: MD). Right: Energy as „stuff" that is handed from agent to patient—the handover is symbolized by green arrows (cf. Fig.4.21). The size of the arrow is a visual metaphor for the rate at which energy is handed over.*

Being careful about how we use words. Here is our suggestion for using notions related to *power* and *energy*. Informally, we should use *power* as an adjective—being *powerful*—and as a verb—as *empowering* and *being empowered*. In science, however, it denotes the *rate at which energy is handed or passed from agent to patient* in an interaction (Fig.5.14). To use an analogy, power is to energy as payment is to money. Empowering and payment give us the feeling of an act, of an *exchange* or a *transaction* (see p.117); what happens in the act is the exchange of an *amount* of something—*energy* or *money*.

Energy as an amount exchanged

In other words, *power* is used in relation to the *strength of an interaction*, and this makes profound sense. *Power* does not denote how much has happened but rather *how fast something is being made to happen* (and has happened). Strength of interaction is associated with the experience and feeling of an ongoing process, of dynamics. It denotes a rate, i.e., the „speed of a process." On the other hand, energy or, more precisely, *amount of energy exchanged*, will be used as a measure of *how much has been done and achieved.*

Speed of a process

Transmitting and storing energy

Energy is exchanged—made available, handed over, and then accepted—when two Forces of Nature interact. This gives us a first inkling that energy denotes something „fluid-like" (see the Box on p.265). If this idea is solid, we can try and spin it further. Maybe, the energy exchanged in the „meeting" of agent and patient(s) does not simply see the light of day and then disappear again into the night when and after they interact. Rather, we may imagine that the energy made available and used is brought to the place where the interaction is taking place, and then carried away from that place—it is *transferred*.

Energy transferred by energy carriers

The fluidlike quantities interacting may be considered the *carriers of energy* when it is transferred (Fig.5.15).

That leaves us with still more questions: Where does the energy come from, and where does it go after the interaction? If energy has this „fluid-like" quality, we will be forgiven if we think it already existed „somewhere" and will continue to exist „somewhere else." „Somewhere" and „somewhere else" are simply places—physical objects, i.e. materials and fields—where *energy is stored*. Storage elements are the places where we can put energy for later use; that is, if there is a tension between the storage unit and the world so that a process can be initiated.

Energy storage

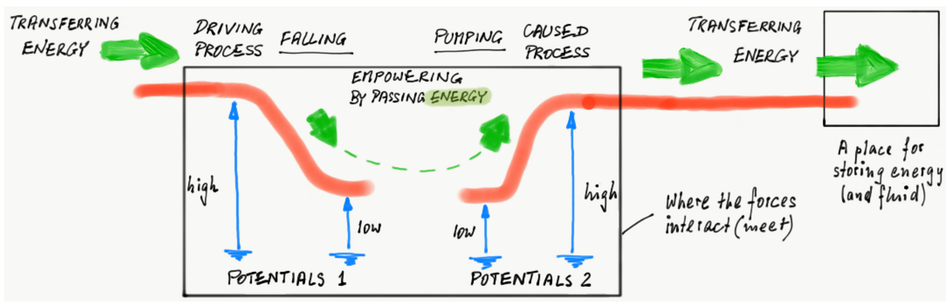


Figure 5.15: *Two additional ideas extend the notion of energy. (1) Energy exchanged in an interaction is brought to the place of interaction and then carried away from there. (2) Energy can be stored in physical objects.*

We are ready now to create a form of visual metaphoric presentation of the activities of Forces of Nature in physical and technical systems. The presentation will be in the form of sketches that can easily be made by hand; these sketches are based upon the schematic and metaphoric structures we just discussed.

A list of visual schemas in process diagrams

To start a list of visual metaphoric elements needed to represent our imaginings of the activities of *Forces of Nature*, let us remember that the physical objects within which agents are active, need to recede to the background, i.e., become the *ground* upon which the stories play out. A gray rectangle can serve as a schematic rendering of a metaphoric object (*Ground*: Fig.5.16, top left) where agents meet to interact and exchange energy, i.e., make it available and use it.

Meeting places for agents

Second, agents have a "fluid" character—they can flow (down, up, or horizontally, i.e., at a constant level), can be stored, and, in some cases, can be produced and/or destroyed. This means that we need symbols for simple *flow*, downhill and uphill flows, *storage*, and *sources* and *sinks*. These properties of fluidlike quantities will be represented by red symbols: arrows, sources and sinks (Fig.5.16, upper right), and reservoirs (bottom line).

Flow & storage, sources & sinks

Third, potentials need to be represented metaphorically as levels. We use vertical blue arrows including a symbol for „ground-level" for denoting potentials. Typically, a fluidlike quantity such as heat flows into or out of a physical object at a certain temperature level. Inside the object, it will flow down or up (see Fig.5.15), or be produced or destroyed (at given levels).

Potentials as levels

Fourth, energy can be transported, made available (released), used (picked up), and stored. The symbols created for these are horizontal, downward, and upward arrows (Fig.5.16, center right), and a reservoir (bottom right), respectively. To distinguish energy from the fluidlike energy carriers, we commonly use the color green for arrows and storage elements.

Symbols for energy

Here is a point that needs to be explained. Instead of using a horizontal green arrow to denote exchange of energy between agent and patient in an interaction (as in Figs.3.4 and 3.27), we explicitly distinguish between making energy available and accepting/using it. That is why we have chosen to introduce the green up and down arrows for making energy available and using it, respectively.

Distinguishing between making energy available and using it

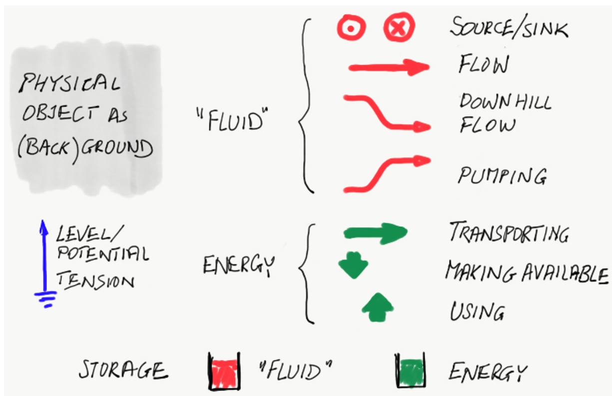


Figure 5.16: *Schematic representations of visual metaphors applicable to properties and activities of Forces of Nature. Gray rectangles are physical objects that form the ground for actions. Blue vertical arrows represent levels/potentials. Red is used for various aspects of fluidlike quantities, green is for energy related concepts. Note the storage elements at the bottom of the diagram.*

Examples of process diagrams

The simplest examples of process diagrams are those that show the interaction of Forces of Nature in a single physical element. We shall call such elements *couplers* because this is where different Forces of Nature couple (meet and interact). Some prominent cases are seen in the *Perpetuum Mobile* animation in scenes lasting from 00:56 to 01:12 (coupler: lamp), 01:14 to 01:23 (photovoltaic cell), 01:33 to 01:41 (electric water pump), 01:51 to 01:56 (water wheel), 02:06 to 02:15 (generator), and 03:20 to 03:30; in this last scene, which basically takes place everywhere in the engine, heat is produced with the help of energy that "fell to the ground" during *non-ideal interactions* between agents.

Couplers

A real (non-ideal) electric water pump. Let us start with the example where Electricity and Water interact in the electric water pump (during the scene lasting from 01:33 to 01:41; see also Fig.5.17, left). As indicated before, the physical object where the interaction takes place will be represented as a gray rectangle; in our imagination, it denotes the ground upon which the actions take place (Fig.5.17, diagram on the right).

To capture processes that run over a certain period of time in a single snapshot picture, we can imagine agents as fluidlike quantities doing their jobs during a steady-state process (this isn't necessary, but it helps; we shall see a little later

Steady-state process

on p.282 how to create process diagrams for dynamical phenomena; see Fig.5.24). A steady-state process is one where things go on unchanging over time. High and low potentials are stable, flows are fixed, production rates are constant, and energy currents and power do not change either. So, let's leave the imagery of single-body spirits aside and think in terms of fluids.

Here is a narrative of what we imagine is going on, and why. We see the spirit representing Electricity entering the space where it will interact with Water; this act will be rendered as a flow of electric charge into the coupler (the water pump). Note that charge is in an electrically "high" state at this point (we can see this expressed by the tension of the spirit used to visualize Electricity; Fig.5.17, left). In a process diagram of an electric water pump, this part of the processes is visualized as a (horizontal) red arrow entering the coupler (see the left side of the process diagram in Fig.5.17). To indicate its high state of electric tension, a vertical "potential" arrow (blue) will be drawn from an assumed ground level to the high level at which electric charge enters the coupler.

Electric charge flows like water

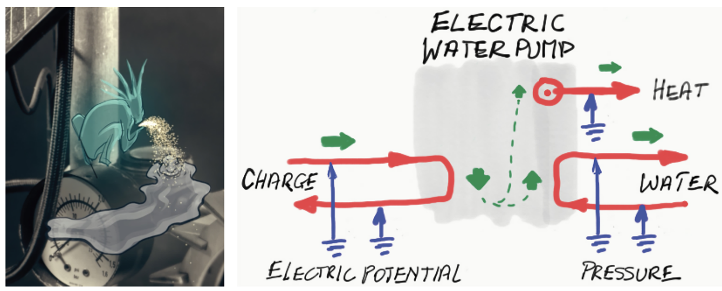


Figure 5.17: *In the drawing on the left (MD: Perpetuum Mobile at time 01:36), Electricity and Water interact. A process diagram representing our imagery and conceptualization of what is going on during the interaction is shown on the right. The physical object where the interaction takes place is represented as a gray rectangle in the background.*

Charge carries energy

Energy current

As this happens, the current of charge at high level will carry energy at a certain rate into the coupler; this rate is what we call an *energy current* (see Section 3.7 for how to quantify currents of energy of this type). The current of energy is represented by the fat green arrow above the red line depicting the flow of charge.

Charge makes energy available

The electric charge will now flow "downhill" to a lower electric potential and exit the pump (again, see the left side of the process diagram in Fig.5.17). When a fluidlike quantity such as charge flows from a higher to a lower level, it "relaxes" and makes the energy it is carrying available to the fluidlike quantity it couples with; here, this is Water (as a fluid *Force*). Energy is made available at the rate it is carried into the pump; we shall call this rate the *power* of the electric process. The visual metaphoric symbol used for power is a fat green vertical arrow (Fig.5.17, bottom left of the gray rectangle). Here, the arrow is pointing down, denoting the idea that energy is released from or made available by the carrier.

Water uses energy and tenses up when it is pumped

The story continues with Water picking up a part of the energy that has been made available by Electricity. Picking up energy, i.e., using it, is visualized by the fat green vertical arrow pointing up (lower right of the pump rectangle). As a consequence, Water "tenses up." Naturally, the water must have entered the coupler earlier at a low state of tension, i.e., at low pressure.[15] The pump's function, after all, is to raise the pressure of the water to a higher level at which point it flows out of the coupler. The energy picked up by the second agent, by

Water, is then carried away with the water; this is visualized with the help of the second fat green (horizontal) arrow above the red arrow at high pressure.

Water carries energy

Deichmann's animation beautifully visualizes that the water picks up only part of the energy (the dust in the metaphoric rendering; scene lasting from 01:37 to 01:40) that has been made available. As we learn later in the movie, the energy that „falls by the wayside" is not lost; it is picked up by a new agent—*Heat*—that is created in the act. In a process diagram, we depict production by the symbol of a source (red circle with a dot inside). Heat produced in the pump will eventually leave the coupler and flow into the environment. The heat leaves the coupler at its temperature, i.e., at the thermal level or potential which is sketched as another of the vertical blue arrows (see the upper part on the right of the process diagram in Fig.5.17).

Some energy falls by the wayside

A mechanical water pump. Before we could not make use of electricity, water pumps were driven mechanically, by hand or with the help of animals. A pump has a shaft that needs to be turned. As one does this, water is pumped through the device and its pressure is raised. This means that the caused processes (pumping of water and production of heat) are exactly the same as in the case of the electric water pump discussed above. The difference lies in the process that drives the pumping action, which usually is a process of rotational motion (Fig.5.18).

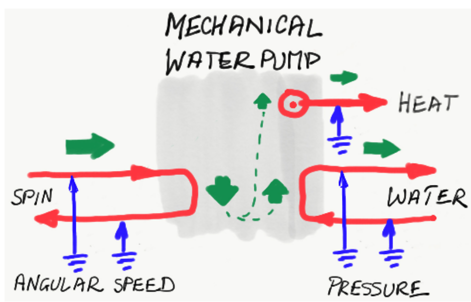


Figure 5.18: *Process diagram of a mechanical water pump driven by rotation. In rotation, spin is the name of the fluidlike quantity that enters the pump at high rotational speed and drops to zero speed (the speed of the ground). As spin flows downhill, it makes energy available that is used by the pumping of water and the production of heat.*

A process diagram of a mechanical pump therefore looks very much like that of the electric water pump (see Fig.17, below). We simply replace electric charge by what is called *spin* (or angular momentum), and electric potentials by angular speeds, and voilà, we have the process diagram for the mechanical pump. [What we are doing here is making use, once again, of analogical reasoning that has served us so well in our imaginative journey through the world of *Forces of Nature*. By saying that we can treat *Rotation*, or at least the flow of spin, in analogy to the flow of electric charge, we take a tremendous short-cut that leaves out everything specific about *Rotational Motion* as a *Force*—we shall have to come back to study this Force on its own; see Volume 2).]

Spin is the fluidlike quantity of rotation

A solar cell (photovoltaic cell or PV cell). Next, let us study the processes that make a solar cell work. As we can see most directly, light falls on a cell and electricity flows (watch the scene in Deichmann's animation from 01:14 to 01:23). This direct observation often leads to the short but shallow and misleading statement that "a solar cell converts light into electricity." Speaking and thinking like this does not really tell us anything about the physical processes at work in this device. If we accept the *Perpetuum Mobile* movie as a lead for our imagination, we can learn a lot more (see the process diagram in Fig.5.19).

Charge is pumped

Let us start the explanatory narrative of how a solar cell works by first observing the processes that are caused—they are represented on the right of the process diagram in Fig.5.19. Clearly, electric charge is driven from low to high electric potential. We can use the image of pumping of a fluid quantity (charge) that enters the device at low tension and leaves it again at high tension. Figuratively speaking, *charge is pumped*; the solar cell works as an *electric generator*—its use is analogous to that of batteries, fuel cells, or the large-scale generators in wind turbines and hydro-electric and thermal power plants (see Volume 2).

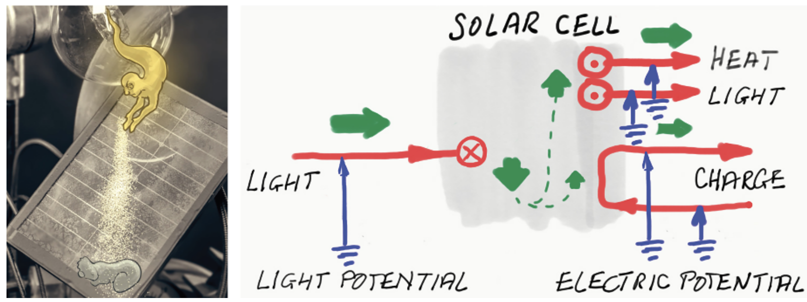


Figure 5.19: *In a solar cell, Light and Electricity interact (left, picture: MD). The process diagram (right) shows the visual metaphors used to conceptualize how a solar cell works. Importantly, from the perspective of users of solar cells, these cells are electric generators: they pump electricity; however, they do so fairly inefficiently.*

Heat and infrared light are produced

Of the energy brought to the cell by sunlight and made available there, only a relatively small fraction (some 10-20%, usually) is used for pumping charge. So what is all the rest good for? There is a phenomenon we can observe directly—the cell gets warm—and another one we could only „see" if we had a thermal camera (an infrared camera). What is happening is this: The part of the available energy not used by charge is used for producing heat. The cell gets warm, and because it is now warmer than the environment, heat will flow out of the cell together with some energy. In addition, again because it is warm, the cell produces invisible infrared „light" that is emitted with heat (and with the some of the energy).

Absorbed light makes its energy available

What is the causing process of the phenomena arising in a solar cell (see the left side of the process diagram in Fig.5.19)? Solar Light is the driving force of all of this. Sunlight flows into the cell, is absorbed there and disappears. However, the energy carried along by the Light, all the way from the Sun to the Earth, cannot disappear—it is released and made available for the follow-up processes which have just been described. As usual, the Force of Nature we build solar cells for, i.e., *Electricity*, picks up only a fraction of the energy. Indeed, this fraction is relatively small in practice, typically only 10-20%.[16]

Mechanical electric generators and electric motors. It is not so difficult to create new process diagrams such as those for mechanically powered electric generators and electric motors. We have learned how to model the Forces of *Electricity* and *Rotation*. All we have to do is combine our knowledge to arrive at useful metaphoric representations of these devices (see Fig.5.20).

Coupling Rotation with Electricity

In Deichmann's movie, we see the interaction between (rotational) motion and Electricity in the generator during the scene lasting from 02:06 to 02:15. Rotation drives Electricity, i.e., electricity is pumped as in any electric generator (such as solar cells and batteries). Mechanical generators make use of the power of *Rotation* as a *Force*. Such generators range from small dynamos on bicycles (Fig.4.13, right) to huge devices in large electric power stations.

As before, rotational motion as a driving agent is modeled by spin flowing from a point of high rotational speed (the drive shaft of the generator) to ground (zero rotational speed). Metaphorically speaking, it flows downhill and relaxes. As it does so, it makes the energy it carries into the device available. Part of the energy will be picked up by electric charge which is pumped from low to high electric potential. The rest of the energy is available for generating heat. In total, the energy delivered by spin is carried off by charge and heat (Fig.5.20, left).

Generator: Spin drives Electricity

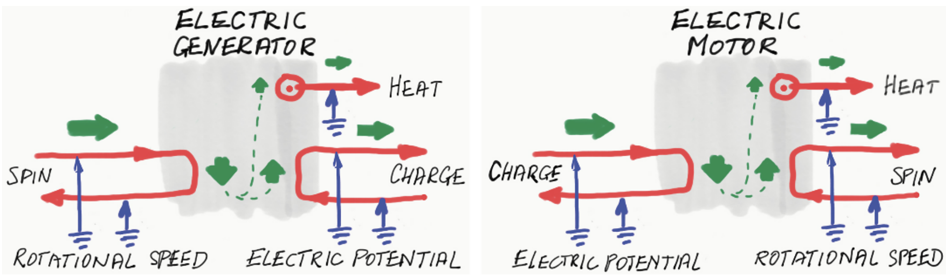


Figure 5.20: *Process diagrams of a mechanical electric generator (left) and an electric motor (right). Notice the reversal of processes except the one producing heat.*

If we reverse the mechanical and electric processes, we obtain the process diagram of an electric motor (Fig.5.20, right). Electricity drives rotation where charge flows downhill and spin is pumped. Part of the energy will be picked up by spin which is pumped from low to high rotational speed. The rest of the energy is available for generating heat. In total, the energy delivered by electricity is carried off by spin and heat (Fig.5.20, left).

Motor: Charge drives rotation

Again, *heat is produced* just as in the mechanical electric generator. This means that of the three processes depicted in the process diagram of the generator, only two can be reversed! The third, the production of heat cannot! This and many other related observations tell us that heat can be produced but cannot be destroyed. Heat has this rather special property of being “one-sided.” Physicists sometimes say that heat obeys half a conservation law—it is “conserved on one side”, but not on the other. The general technical term for this is *irreversibility* (remember the discussion on pages 201-205).

Heat can be produced but not destroyed!

Chains of couplers and processes. We know from everyday experience that there can be chains of processes where one Force of Nature interacts with a second one, and the second with a third, and so on. We see this in the *Perpetuum Mobile* animation as well. Let us study a case with just two couplers, an electric motor driving a mechanical water pump (Fig.5.21).

This particular example is part of the *Perpetuum Mobile* story even if it cannot be seen in this form. The electric water pump in Fig.5.17 consists of exactly this: a combination of an electric motor and a mechanical water pump. It is simply not possible for Electricity to directly pump Water—a mechanical process must normally mediate between the two. If we wanted Electricity to directly interact with Water, the stuff water is made out of would need to be „made electric or magnetic.”[17] This indeed happens with fluids on the surface of the Sun, and we do this here in attempts to produce fusion reactors that mimic the nuclear processes going on at the center of the Sun. There, the fluids are so hot, they are turned into plasmas—gases where electrons are separated from atoms and form their own charged component of the gas.

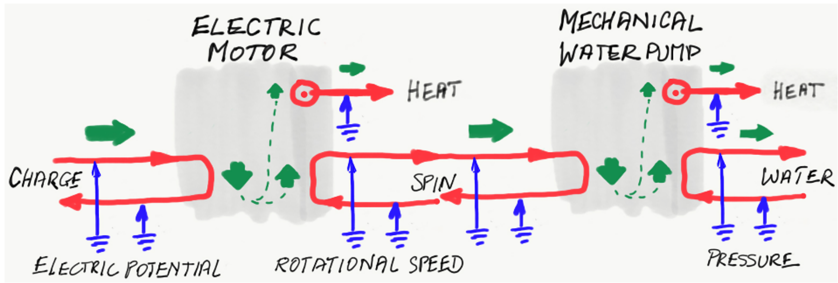


Figure 5.21: *An electric motor drives a mechanical water pump. Left: Process diagram of the motor where electricity (as FoN) drives rotation (as FoN). Right: Process diagram of the water pump where rotation drives a hydraulic process. Note that this establishes a circuit for the flow of spin from the motor to the pump and back.*

A second example of a short chain directly taken from the *Perpetuum Mobile* story is presented in Fig.5.22. In the animation, the scene lasts from 01:14 to 01:49. It shows how we can explain the operations of a photovoltaically driven electric water pump. At the beginning, we see Light (the light spirit in the lamp) passing energy to the „relaxed" Electricity in the solar cell (the photovoltaic cell or PV cell). Electricity „wakes up" by accepting (part of) the energy and moves toward the sleeping water spirit in the pump. There, energy is made available by Electricity and used by the Water. At the end of this sequence, water moves up the pipe, getting ready to drop onto the water wheel.

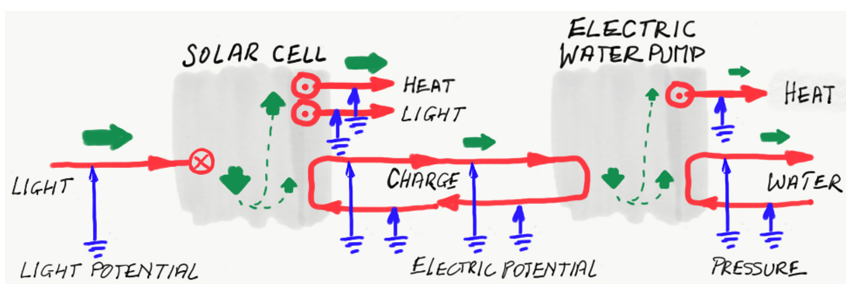


Figure 5.22: *Process diagram for a PV-water-pump chain. Note that this diagram is a simple combination of those presented in Figs.5.19 and 5.17.*

Analyzing couplers. This raises an interesting question: Is the analysis of the electric water pump presented above in Fig.5.17 bogus? No, not at all, it is perfectly legitimate! A concrete case and form of analysis depends upon the choice of the person studying a particular system—this is the freedom of the analyst.

If we choose to take an electric water pump as a single unified element in a larger system, then the process diagram in Fig.5.17 is the proper representation of the processes that can be seen and identified. The processes are electric and hydraulic; Electricity interacts with Water, i.e., Electricity drives the pumping of Water. The mechanical (rotational) process mediating between and electric motor and a mechanical pump is hidden from the view of the analyst.

If, however, we decide to imagine the electric water pump to consist of two elements, then a new and different analysis will emerge (Fig.5.21). If we take the system called "electric water pump" to consist of the two elements "electric motor" and "mechanical water pump," we have to imagine three Forces of Nature at work and interacting (apart from the interactions that produce heat). There are two interactions: (1) charge interacting with spin in the motor, and (2) spin interacting with water in the pump.

Analyzing an object as two elements

If we want to create a process diagram of the short chain of processes just discussed, we can simply combine the diagrams created in Figs.5.20 (right) and 5.18. The result is the sketch shown in Fig.5.21. Note, in particular, that the flow of energy transported by spin is weaker than that transported by electricity, and the flow of energy transported by water is weaker than the one that accompanies the flow of water.

Process diagrams for dynamical systems

Systems that are intrinsically dynamic are those that can store one or more of the fluidlike quantities that represent Forces of Nature (Fig.5.23). In such systems, energy will be stored alongside the agents that carry it and make it available or pick it up. As the amounts of fluidlike quantities change, so do their potentials. More air in a balloon will make the pressure higher, and there will be more energy stored alongside the air at higher pressure.

Much of the *Perpetuum Mobile* story is one of steady-state processes. The only case of obvious storage is that of heat generated and caught under the glass cover (in the scene lasting from (03:07) to (04:10)). Before the glass cover is shattered (04:11), heat produced cannot escape and will accumulate in the (material) parts of the engine (see the red symbol of a storage element at top right of the process diagram in Fig.5.23). This will let the temperature of the parts climb higher and higher so that, finally, the cover is broken, and heat can escape (this is symbolized by the horizontal red arrow leaving the engine at the level represented by the temperature of the engine). When heat is stored, so is some energy (green storage element), and when heat escapes, so will some energy.

Accumulating fluidlike quantities

Energy storage

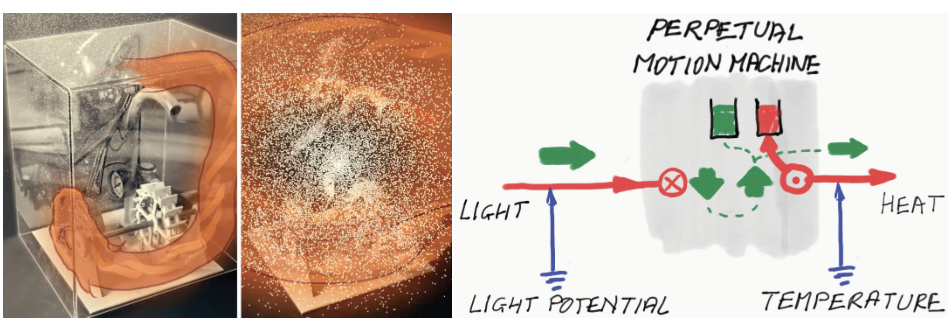


Figure 5.23: *Left: Heat is generated and collected under the glass cover (04:09; picture: MD). Center: Once enough heat has been collected and temperature (and pressure) are high enough, the glass cover is destroyed, and the engine is freed (0:410; picture: MD). Right: A process diagram that treats the entire engine as the unit to be analyzed.*

Processes of the engine as a whole will be truly dynamic if and when the amounts of heat (and other energy carriers) and energy stored, change. The amounts of heat can increase (when the engine becomes warmer) or decrease (when it gets

Dynamics as change of stored quantities cooler). And as the temperature changes, so will the production rate of heat and the flows of escaping heat and energy.

Process diagrams are snapshots—like photographs. There is change all around us, and Forces of Nature are at the center of all of this change. This makes it necessary for us to talk about an important limitation of many forms of representation of how we see nature working: they are often static or, if we are lucky, snapshots of scenes that are otherwise dynamic. They catch moments but do not let change appear directly before us.

Catching moments

Process diagrams exhibit this limitation. They are snapshots like photographs; they show a scene at a given moment in time. Whether or not the situation modeled is one of complete rest, or steady-state (as assumed in the examples laid out in Figs.5.17-5.22), or dynamical (as in Fig.5.23), does not matter. The appearance of symbols for storage (of heat and energy, as in the diagram on the right in Fig.5.23) suggests an explicitly dynamical situation, but the diagram is only capable of showing the state of a system at a particular moment.

Consider the example of heating of a body of water which has a rather simple process diagram (Fig.5.24, left). A pot of water is held over a fire and the water is assumed to be well stirred at any time. This means that we need only a single value of temperature in order to characterize the state of the water at any desired moment—this point will become important in a moment.

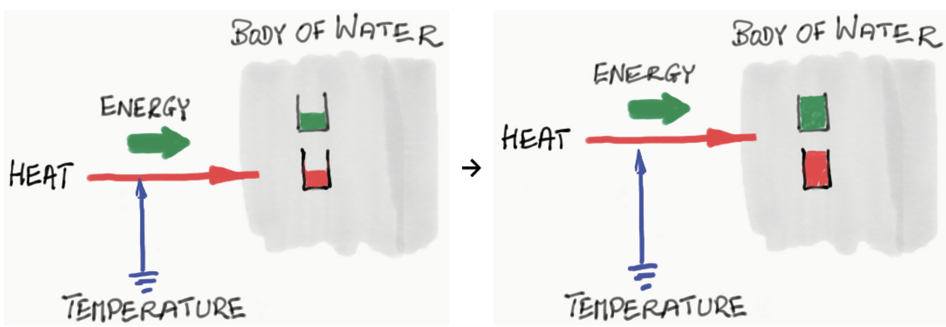


Figure 5.24: *Left: Process diagram of heating of a body of water (which is assumed to be perfectly insulated so heat is not lost to the environment). Note the symbols for storage of heat (red container) and energy (green container). Right: Same diagram for a later (hotter) state.*

From the viewpoint of the activity of Forces of Nature, all we need to say is that heat—the extensive aspect of the Force we call *Heat*—flows from the flame into the water. Since we are not interested in the flame, we indicate the thermal level in the process diagram at which heat enters the water (this is, at the same time, the temperature of the water). The heat flowing in will be stored in the water. For this we employ the *symbol of a storage element.* In addition to heat, energy carried by heat also enters the water and will be stored there as well. (Note that we did not include a possible second process, that of heat loss, i.e., the flow of heat from the hot water to the environment. Let us assume that the water is perfectly insulated.)

Symbol of storage

Since we know the situation to be dynamic, we also know that the values of quantities characterizing the system and processes are changing over the course of time. Typically, the amount of heat stored in the body of water will increase and the temperature will go up. Importantly, we cannot show these changes in

Change cannot be shown in a diagram

the same diagram. The only sensible procedure is to repeat the sketch for one (or many) later states that would show changing sizes of symbols for thermal level and heat and energy stored. In Fig.5.24 (diagram on the right), we can see such a „raised" state represented.

This is not exactly an elegant solution—in order to give the viewer an impression of „continuous" change, we would need many such diagrams in series, each a little different from the one before. Naturally, in a movie we could show this happening. The amount of heat in the storage symbol would get bigger, and the thermal level, i.e., the level at which heat flows into the body of water would go up, and the changes would be (more or less) continuous. In a sketch of a process diagram, however, this type of representation is not possible—we simply have to imagine these changes and accept that a process diagram is a „view" of a system and processes at a particular moment.

Stories give us a feeling for time

Fortunately, there are tools that allow us to represent dynamic behavior: movies, animations, embodied simulations, board games, and, yes, stories. Narratives (stories, tales, myths. . .) probably constitute the most generic cognitive tool that presents us with a feeling for, and basic understanding of, time and change. We have presented and used stories before, and we have been presented with the animated story of the Perpetuum Mobile in this chapter.

◦ ◦ ◦ ◦ ◦

This concludes our introduction to visual metaphors and analogies, and to visual means of presenting stories of *Forces of Nature* in general. We shall create one more qualitative tool for „talking" about processes in nature below in Section 5.6, where we create theatrical embodied simulations of what we have discussed so far.

5.6 Forces-of-Nature Theater as Embodied Simulation

If a story of Forces of Nature acting and interacting can be brought to life in an animated film, we surely should be able to bring it to the stage as well. Indeed, Deichmann's *Perpetuum Mobile* story has inspired us to transfer the visual metaphors created in the animation to a theater performance where we use our bodies as representants of Forces of Nature.[18]

In the present section, we shall suggest how we can use a stage (a large enough empty area on a floor), some material props, and our body to create theatrical performances of Forces of Nature interacting.[19] In the animation, Forces of Nature have been visualized as agents at work against the backdrop of physical objects—remember our discussion of *Figure-Ground-Reversal* in Section 5.2 (p.255). Two simple moves let us create what we call *Forces-of-Nature Theater* performances: (1) we designate areas on a floor as physical devices where the agents meet, and draw connecting lines as paths for the movement of agents (Fig.5.25), and (2) we let people take the roles of agents and give them confetti to carry as a symbol of energy (see Fig.5.26).

Let us start the description of such a performance with the simplest case possible: a system consisting of a single device (such as a water wheel or turbine; see the period in the animation lasting from 01:48 to 02:02) connected to the rest of the world by paths, creating the ground for two agents (such as water and spin).

Couplers and paths

Physical objects are part of the stage

To set the stage, we need to create an abstract representation of parts making up a physical object in which Forces act and interact; such parts are devices and their connections. The devices are turned into *meeting places* called *couplers*—these are the locations where Forces couple or interact. Their connections are the paths that make it possible for agents to move from coupler to coupler. Whatever we do, the layout of the stage must map the main features of the topology of the physical system we wish to model (Fig.5.25).

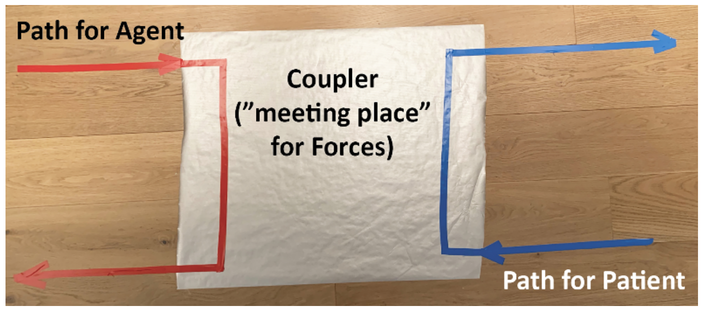


Figure 5.25: *Sketch of the floor-plan for a single coupler of a Forces-of-Nature Theater performance. In the simplest case, we have an area marked as meeting place, plus indications of paths to be followed by agents representing the quasi-material („embodied") aspect of Forces of Nature.*

In general, a *coupler* will be marked as a simple schematic form on the floor, maybe a rectangle chalked on the ground or a large blanket laid out. We simply need a *bounded space* big enough for at least two persons meeting and exchanging energy; ideally, the space should be bigger, allowing for a „chain" of persons marching through as individuals interact (see Fig.5.26). In our example, the space would represent the water wheel.

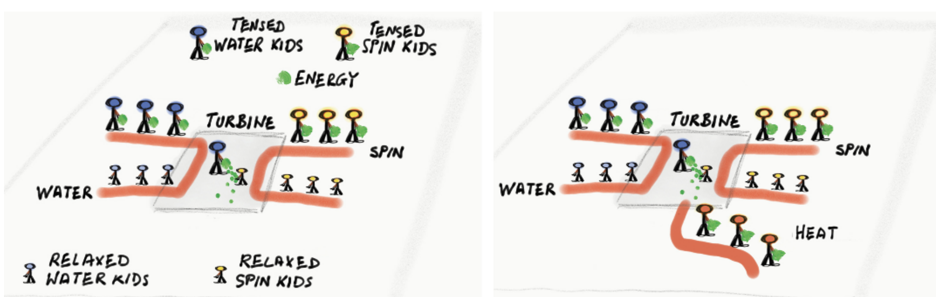


Figure 5.26: *Sketch of the floor-plan and actors of a Forces-of-Nature Theater performance representing the operation of an ideal turbine (left), and a real turbine (including production and emission of heat; right). For graphical simplicity, varying states of tension of agents and patients are represented by their sizes.*

The paths taken by the agents need to be marked clearly as well (colored lines on the left and the right in Fig.5.25). In real life, these paths might be electric cables, water pipes, or any other physical object through which quantities such as electricity, water, amount of heat, or amount of motion (in our case, spin) can flow. If we have two agents such as Water and Rotation that can be neither produced nor destroyed, and if we assume steady-state operation of the device, all we need are two continuous lines along which actors for Water and Rotation can move.

The case of water is clear: it enters the coupler from above (metaphorically speaking, at high level or tension), flows through the device and leaves at a lower point. Spin behaves quite analogously to water: it enters the wheel or turbine through the mount on the ground (at low tension, actually at a point whose rotational speed equals zero), is pumped to a higher metaphorical level (high rotational speed) in the turbine and leaves the device. The colored paths taped on the floor in Fig.5.25 help the „movements" of water and spin to take the correct form.

Agents and patients, interactions, and energy

Our material body as extensive quantity

Now we are prepared for step 2. Remember that we identify Forces of Nature by three fundamental characteristics: *extension* (often as amount of fluidlike quantity), *intensity* and its *differences*, and *power*. The first of these is suggestive of a metaphoric quasi-material which we now render physical by employing our own bodies; more precisely, we use the material aspect of our body for representing the *extensive aspect* of fluidlike quantities—size or amount.

Extensive quantities. In a *Forces-of-Nature Theater* performance with children, we should use as many kids as can fit onto our floor designs, and divide them into two groups: *Water-kids* and *Rotation-kids*. The two groups form moving queues for water and spin, respectively (Fig.5.26). Ideally, this will allow the actors to get a feeling for the strength of the current of a fluidlike quantity by adjusting the speed at which they move along their assigned paths.[20]

Note that this design element introduces a difference compared to Deichmann's animation: we do not represent a Force by a single spirit but employ as many „bodies" as possible. This will move us closer to how we imagine properties and behavior of fluidlike quantities such as water, heat, electricity, and spin, and constitutes an important step towards a more formal scientific representation of processes.

The two moving columns of actors representing Water and Rotation, respectively, will meet—possibly in a counter-flow arrangement as suggested by the floor plan in Fig.5.25 and in the diagram on the left in Fig.5.26—in the designated space for the coupler (i.e., the water wheel or turbine) and exchange energy. We shall discuss the role of energy in a *Forces-of-Nature Theater* performance below.

Water and spin are „*conserved*," a property that is easily modeled if „bodies" do not get lost, and no new ones get added, along their paths and during interactions. Moreover, if we make it quite clear to participants that they do not „mix," that Water-kids do not become Rotation-kids and vice-versa, we create the foundations for an all-important insight: the extensive aspects of Forces of Nature, i.e., amount of water and spin, can no longer be confused with energy.[21]

Performing „birth" and „death"

Representing *non-conserved quantities* such as heat or light in an embodied performance poses a certain challenge—actors cannot literally be created or destroyed. The choreographer of the enactment of interactions of Forces of Nature will have to use his/her imagination and instruct actors in how to interpret production („being born") and destruction („dying"), and use props that may help in simulating the processes so they become „believable." In the sketch on the right in Fig.5.26, we have included the irreversibility of the interaction of Water and Rotation in a real turbine—it is clear that we need to somehow create a „source" of actors (representing Heat) that can move out of the couplers as they are „created" or „born." In other words, we need a third group of agents, namely *Heat-kids*.

Tensions expressed through demeanor

Tensions. Tensions are exactly what we feel and imagine them to be—differences of intensities such as brightness, hotness, or speed, which we measure as degrees along a scale. Our body conveys this feeling, and we can use our body in various ways for expressing it. If I am a representant of water at high pressure, I can exhibit this by my posture or through facial expressions—I walk upright, erect, and my face shows high tension or happiness. In Deichmann's animation of the Perpetuum Mobile story, we see this in the expressions displayed by the little spirits.

When I am water, spin, or heat at low pressure, rotational speed, or temperature, respectively, I can exhibit this by slouching and letting my shoulders droop, and by showing a sad, droopy face.

When an agent meets a patient and they interact, what happens is this: the agent goes from a state of high to a state of low intensity or tension, whereas the patient undergoes the reverse process (in Fig.5.26, these changing states are expressed in terms of size of individual figures). The agent becomes ready to be a patient, the patient turns into an agent, and activities can continue down a line of couplers and processes (Fig.5.27). Actors playing Forces in *Forces-of-Nature Theater* performances will be asked to perform exactly these *embodiments of states of high or low tension* in order to show what is happening in the physical situation they enact.

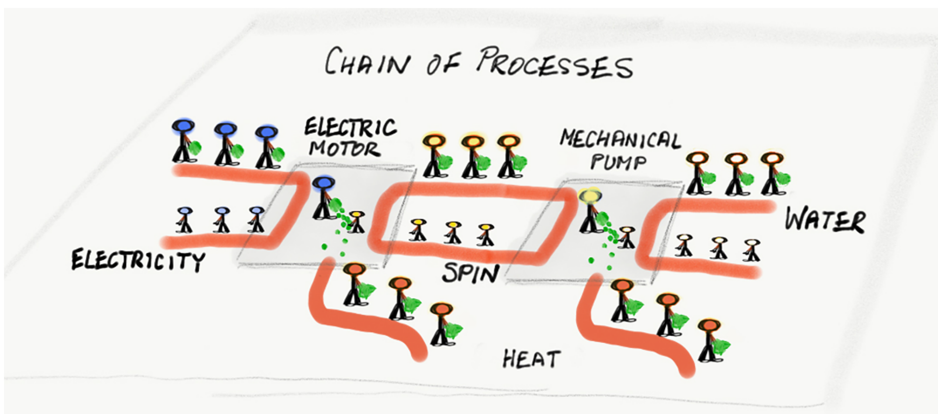


Figure 5.27: *Sketch of a Forces-of-Nature Theater performance involving more than a single coupler. electricity flows toward and through an electric motor, driving rotation (pumping spin) and a thermal process (producing heat). Rotation subsequently drives the flow of water through a pump (where more heat is produced).*

Actors are energy carriers

Energy. Add energy to all this, and you have created a performance analogous to Deichmann's animated story. In place of the dust in the animation (see Figs.5.9 and 5.10), we can use anything that comes in lots of small pieces that are easily carried in our hands and handed from agent to patient—confetti or gravel or sand will do just fine.

Exchange of confetti

Agents at high tension are „loaded" with energy, they have their hands full with this stuff. In the situation depicted in Fig.5.26, *Water-actors* bring energy with them when they enter the coupler; they hand what they carry to the waiting Rotation-actors, relax, and leave the meeting place. The relaxed *Rotation-actors* catch some of the confetti or gravel, tense up, and move out of the coupler on their way to the next meeting place where the play continues (see Fig.5.27).

Naturally, some confetti or gravel or whatever will fall to the floor (Fig.5.26, right). This is the opportunity for Heat-actors to „come into being" as they pick the confetti up that fell to the floor. They tense up and leave the coupler, never to be seen again...

Losing confetti is „losing" energy

Summary. In order to make a Forces-of-Nature Theater performance possible, a number of things are needed. We need a stage, and time—after all, a story is to be told. We need some materials for creating spaces representing couplers and paths connecting them on the floor. We need actors that represent Forces of Nature and two of their three fundamental aspects: extension (bodies) and tension (demeanor). And we need some dust-like stuff that symbolizes energy as it is carried around and exchanged in interactions (see Table 5.2).

Table 5.2: Animation and embodied performance compared

Scientific elements	Deichmann's animation	Forces-of-Nature Theater
Physical elements (devices and connectors)	Drawings of physical objects	Spaces and paths on floor
Extensive aspect of Force of Nature (amount of fluidlike quantity) ... ... and its flow	Drawings of „spirits" Speed at which spirits move through scenes	Bodies of actors Speed at which columns of actors move along paths (or rate at which they are „born" or „killed")
Intensive aspect of Force of Nature ... ... and its change	Demeanor of spirits (expression of tension) Tensing and relaxing	Demeanor of actors (expression of tension) Tensing and relaxing
Energy and power	Dust and rate of exchange of dust	Confetti and rate of exchange of confetti
Interaction	Meeting of spirits and exchange of dust	Meeting of actors and exchange of confetti

In all of this, the persons acting as Forces of Nature will *experience an embodied (physical) logic* of what Forces of Nature can and cannot do, and what happens to energy (confetti, gravel, sand...) and what not. Just to mention a couple of points: agents need to be tensed (i.e., „strong") in order to carry energy; agents do not "convert" into one another; agents are not energy; energy is always the same as it makes its way through a chain of devices and processes—energy does not change form or the like; energy is „handed" from agent to patient; and there is always the same amount of energy around in the system and its surroundings—it's just not available all the time.

Embodied logic

◦ ◦ ◦ ◦ ◦

Physical science is an imaginative affair—not in every aspect and not exclusively, but foundationally. There are many elements of science, such as its experimental and formal aspects, that are needed for establishing what we rightly call „real" science. However, what we have seen in this chapter is in no way „un-scientific;"

rather, the way Deichmann's animation speaks of physical phenomena provides us with the figures of thought and language (and other forms of expression) that are needed for grounding science and providing meaning and understanding.

Scientific thinking and working—especially the creation and use of models, at any level of formality—are figurative at their core, they make use of figurative tools of the human mind such a schematic abstraction, metaphor and metonymy, analogy, and narrative that serve us well, and not just in science (Volume 2). Humans experience a gestalt—an experiential unit—which is best called *Force*. There are natural, social, cultural, and psychological Forces, just to name the most important and largest classes. *Forces of Nature* present us with a fairly simple and recurring form of this gestalt and its aspects, and we can learn about them without having to be specialists.

Notes

[1]Consider an experience where you carelessly step out onto a street and are almost run over by a truck. Very likely, you will experience a powerful rush—a feeling of fear and terror, possibly accompanied by a feeling of heat—coming over you, rising from nothing at extreme speed, reaching a climax, after which it dies down more slowly than it arose. There is an obvious shape apparent in the dynamics of this experience. The particular figure or shape is „learned," i.e., it is laid down as an experiential trace in our organism, a trace that can and will be re-used for understanding and communicating about similar or totally different phenomena as well. Clearly, the shape of such experience is not a visual image, even though it can be rendered as one.

[2]M. Deichmann (2014b).

[3]An open flow system is an object in nature or an element of space that is open to flows, i.e., to transports of all sorts of physical quantities across its surface (or boundary). Such quantities may include fluids, chemicals, electric charge, quantity of heat, momentum, and energy. The surface of the Earth is such an open flow system that exchanges mostly light and energy with outer space, and heat with the Earth's interior.

[4]Deichmann M. (2014b).

[5]Visual metaphors have been studied extensively in the last few decades, mostly alongside the study of metaphor in cognitive linguistics (for an overview, see Forceville & Urios-Aparisi, 2009). It is important to recognize that visual experience is intelligent; it is a cognitive power that parallels linguistic action and perception (Arnheim, 1954, 1969). More generally put, metaphor does not just appear when we speak (or write). While the structure of visual and verbal (linguistic) metaphors may be the same (Yus, 2009), St. Clair (2000) argues that we need to distinguish between the two since metaphors (and therefore thinking and understanding) would be visual in oral cultures and verbal in print cultures—visual metaphoric thinking leads to different forms of meaning-making when compared to the understanding afforded by literacy. In Chapter 1, we have made the point that the development of children from mythic (oral) to romantic (literate) forms of understanding is a central factor that needs to be taken into consideration in our designs of science pedagogy. For this reason, St.Clair's argument is an important one for our imaginative and narrative approach to encounters with Forces of Nature (see Chapter 6 where we present arguments why myth should serve as a guide to the first few years of educational engagement with nature).

[6]As before, we shall capitalize terms such as *Electricity*, *Light*, *Heat*, *Water*... if it is important to emphasize that we are speaking about a phenomenon as an experiential unit (a gestalt), rather than an aspect of the phenomenon. Often, what may be the *Name* of a phenomenon is used for denoting the extensive aspect as well. Heat, electricity, and light are important examples: we regularly use words such as *heat*, *electricity*, and *light* for what would properly be amount of heat (caloric, entropy), quantity of electricity (electric charge), and amount of light, respectively. In other words, names for phenomena are often used for the fluidlike quantities stored in and flowing through physical objects. If the fluidlike quantities are meant, or if the distinction between gestalt and (fluidlike) aspect does not matter, we shall use lower cases for the words.

[7]Expressing changes of state as motion (as changing location) is inherent in the ubiquitous conceptual metaphor CHANGE OF STATE IS MOTION (to a new location). Examples can be found in everyday life as well as in science: „The situation went from bad to worse;" „An electron will jump to a higher energy level...." See Lakoff & Johnson (1999); Gibbs (2019).

[8]This is an aspect of the *Perpetuum Mobile* animation that is not rendered physically correct. Light is a spirit that actually does not persist. It is produced and destroyed. It is produced in lamps or at the surface of the Sun, it flows through space and transparent materials, and it gets absorbed by other materials. After light has been absorbed, it has disappeared; it does not exist

any longer, it has been destroyed. Moreover, light can be produced and destroyed in chemical reactions (see the chapter on substances in Volume 2).

[9]We obviously disregard the properties of energy made visible in the theory of relativity: energy is „heavy" and „inert."

[10]The point that we should reason in terms of energy carriers rather than energy forms (and that „forms of energy" should definitely never be applied to storage of energy) has been made by Falk et al. (1983). Energy carriers are the extensive quantities such as momentum, charge, and entropy for which they introduced the term „substance-like" (this is what we have called fluidlike, following the usage in Fuchs, 2010[1996]). Largely based upon this imagery, Falk, Herrmann, Job, and co-workers created the foundations of what they call the Karlsruhe Physics Course for middle school and high school (Herrmann, 2000; Herrmann, 1990-2020; for physical chemistry, see Job & Rüffler, 2016). In our approach this becomes clear when we think of energy as something that is „handed" from agent to agent through chains of processes (see point 1 on p.262)—what changes are the agents (and patients), not energy. Before and after being „handed over," energy is imagined to be carried by the agents and patients (unless it is stored; see point 4 on p.263).

[11]Energy carriers proper are those that flow conductively, that means their flow is driven by a gradient of their associated potential (temperature for heat, electric potential for electric charge, speed for momentum, etc.). Since energy can be transferred convectively and radiatively as well, we need to have theories of the properties of material fluids and radiation if we want to deal with these cases as well. Importantly, the relations between potentials, currents of fluids and radiation, and energy currents are different from the primary case of conductive transports (see Fuchs, 2010[1996]).

[12]With the exception to when the heated air makes the glass cover burst (time stamp: 4:10), Heat is effectively a patient, not an agent in what is happening in Deichmann's story (recounted on p.254).

[13]In order to understand the formal concept of *work* in mechanics, we need to sharply distinguish between energy *exchanged* in the interaction of two Forces of Nature and energy *transferred* into or out of a physical system. We shall develop *Process Diagrams* (see Section 5.5) that visualize the distinction very clearly. In mechanics, *work* refers to the latter of the two cases: energy *transferred*. In our imaginative rendering of physical processes, however, *work* is much more closely related to the former: energy *exchanged* (made available and used) when agents interact.

[14]Process diagrams of the form used here were introduced by Fuchs H. U. (2010[1996]): *The Dynamics of Heat*. They represent systems and processes in a manner that derives from Sadi Carnot's analogy of the operation of heat engines with waterfalls (Carnot, 1824).

[15]Technically speaking, at this point we should add a green fat horizontal arrow denoting energy entering the engine together with water. This is so because the pressure of the water at the entrance is not equal to zero—pressure is an absolute potential as opposed to electric potential. This also means that the energy leaving the pump together with water will be equal to the sum of the energy current going in and the rate at which energy is picked up by the water from what the Electricity has made available. Actually, we should have talked about this issue a little earlier already: what about the energy carried away by electric charge leaving the pump at low potential? Remember that the electric potential is not absolute. For this reason, one usually assigns a value of 0 (Volts) to the lower potential, which means that the charge does not carry energy with it; our drawing faithfully represents this particular choice.

[16]There is no „shame" in this—by itself, nature is even more „wasteful." The efficiency of photosynthesis is maybe 2%, that of the wind-engine (Section 4.6) is barely higher. Naturally, if solar cells used on the roofs of our buildings were more efficient, our job of replacing fossil fuels would be made easier—we would need less space and fewer materials. Still, 15% average efficiency is not bad at all.

[17]It is possible to pump pure water (and other polar fluids) directly through an electric field—this is called electro-osmosis (see https://www.youtube.com/watch?v=zzVa_tX1OiI; visited on August 8, 2022). For a short overview, see Wiley D. & Fimbres Weihs G. (2016).

[18]See Fuchs, Corni, & Pahl (2021); Corni & Fuchs (2021).

[19]This will be particularly valuable in our work with young children. Even though it will be of great importance in concrete educational settings, we shall not discuss the utility of various embodied simulations and plays or games for different age groups. This issue needs to be left to more detailed pedagogical and didactic studies.

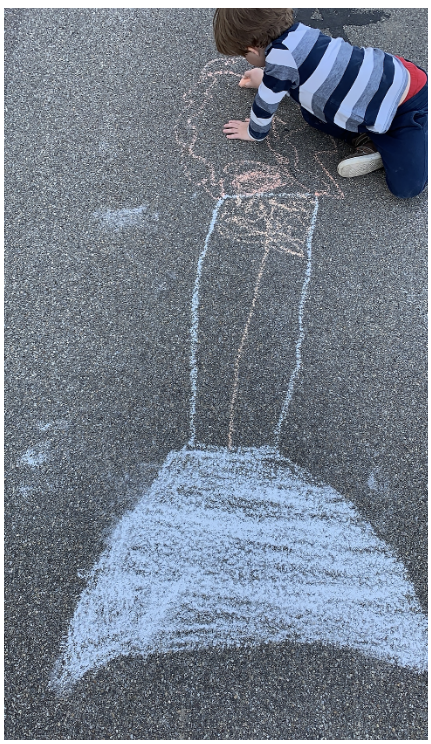
[20]Naturally, this needs to be practiced with the actors, especially if they are relatively young learners.

[21]This confusion constitutes one of the enduring misconceptions learners of physical science carry around. Typically, the issue is not expressed explicitly in the teaching of physics. This may

very well be for a lack of knowledge of imaginative structures of understanding our encounters with Forces of Nature. Formalisms do not help learners to overcome this misconception, and neither does our penchant for mechanical explanations of everything happening in nature. If the world is made of two things—matter and energy—everything „invisible" or „immaterial" must surely be energy, and this includes heat, electricity, and motion.

Chapter 6

Science for Children?



„Volcano" by DL (4 years 6 months)

A primary, mythic approach to nature pedagogy for the youngest learners is guided by direct experience of Primary Forces entwined with narrative, mimetic (theater based), and generally artistic expression and communication. This allows us to engage with Forces acting and interacting in real natural systems, for example those involved in the production of Wind and Rain. We do this long before a more formal, scientific approach to nature becomes a reasonable and useful aspect of primary education.

H. U. Fuchs, F. Corni, *Primary Physical Science Education*,
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We have added the question mark to *Science for Children?* for a reason. In this last chapter of Volume 1 of *Primary Physical Science Education*, we would like to sketch an answer to what it means to be or *not* to be scientific in our primary encounters with physical Forces of Nature. Here are a few of the questions we would like to address: What is the role of science in experiencing and learning about nature for the youngest students in our schools, for those in the age range of, say, four to eight? What about those who are nine to about twelve years old? And how would we design a curriculum for the younger group that makes nature an important element of pedagogy?

No science for the youngest learners...

If asked about the role of science in primary physical science education, our answer is quite clear and direct: there is none, science cannot matter—at least not for the group of younger children. Naturally, it all depends upon what we mean by science. If it is science when a teacher lets kindergarten or early primary school students experience some of the primary Forces (Chapter 2) and uses stories and nature myths as part of jointly communicating about this kind of experience, then, yes, science is a part of early primary pedagogy. If, however, science is characterized by a different attitude towards and method(s) for dealing with experience; if science requires forms of understanding developed in a culture of literacy not yet available to the youngest students; then early nature pedagogy cannot be scientific. If, as we have argued in Chapter 1, our primary understanding of experience is mythic, and if myth is not science (p.10), then primary nature education cannot be a form of science for the youngest of our students.

... but for their teachers

To be certain, physical science will matter for the teachers of these children. They need to understand what science is and is not—specifically, they need to understand how primary (mythic) experience of Forces of Nature can be stimulated and how such experience can become the foundation of forms of scientific activity and understanding later in life. This is a demanding dual task: teachers must approach nature pedagogy from a mythic and generally imaginative (schematic, metaphoric, and narrative) perspective for the youngest learners; they also need to have a qualitative understanding of macroscopic physical science that can inform them about specific elements of a mythic curriculum.[1]

These issues define what needs to be done as we conclude Volume 1 of *Primary Physical Science Education*: after a brief summary of what we have discussed so far, we want to sketch, by way of example, how a primary, mythic interaction with Forces of Nature is put into practice, and what this has to do with mimetic (theater-based) and narrative forms of expression and understanding. At the same time, these issues point to an important task for Volume 2 where we need to show how an imaginative approach to encounters with Forces can evolve and take a simple scientific form.

6.1 Engaging with Forces of Nature—A Summary

We have argued that primary experience of nature is mythic and therefore not scientific. However, if understood in the context of the development of forms of understanding through human cultural history, it is apparent that mythic consciousness must underlie our scientific forms of acting and understanding. Specifically, if we accept that mythic engagement with physical phenomena creates the experience of Forces of Nature, we see that primary meaning-making and understanding serve as the foundation of later (formal) scientific engagement with nature (Chapter 1). Viewed from this perspective, we do not need to be worried that an approach which begins with a child's encounters with nature will lead us astray—Forces of Nature are the core subject of modern macroscopic physical science. We can keep science in the back of our minds and focus upon what happens when a child engages with Forces and, supported by caregivers, learns to communicate about the experience. In short, we can confidently develop a mythic approach to primary nature pedagogy for the youngest students.

Recapitulation of cultural forms of understanding

Chapter 1 introduces us to the idea of how mythic culture can be understood as an element of child development and education: we follow Kieran Egan's scholarship which lays out an educational scheme that makes use of the idea of cultural recapitulation in ontogeny.[2] When oral language skills develop in a child, this child is effectively a member of an oral mythic „society." Later, as a consequence of the development of tools of literacy, children enter a romantic phase, which is followed by a philosophic or theoretic phase when adolescents are around 15 years of age. Egan has listed and described the different cognitive tools that shape our forms of understanding as we pass through these stages or phases (see, in particular, Sections 1.3 and 1.4 in Chapter 1).

Cultural phases interact

It is important to realize that these phases do not simply follow one another, in the sense that a former phase will be replaced by a later one; nor will a later phase (say, romantic) subsume a former stage (mythic)—myth stays myth, and romance will still be romance. What this means is that the forms of understanding of an older or earlier phase, the cognitive tools that go with each phase, survive the development of later phases. We remain mythic beings even when we are scientists involved in highly sophisticated and formal activities; and we remain members of romantic culture even when we work as philosopher.[3] However, we run the distinct risk of losing awareness of the importance and meaning of earlier phases as we grow up and acquire more of the newer cultural tools. Witness how we commonly treat the issues of metaphor and narrative in physical science: it is assumed that they do not have a place in „real" science which must deal in literal rather than figurative forms of reasoning—or so the argument goes.[4]

Primary Forces

From the perspective of mythic understanding of nature, Chapter 2 is the most important one in this volume: there, we describe how *Primary Forces* are encountered and list the basic characteristics of these Forces as they arise in experience. A list of these Forces of Nature includes Wind, Rain, Fire and Ice, (Sun-)Light, Thunderstorms and Lightning, Water, Air, Heat and Cold. Some of these are activities; others (such as Water, Air, Heat and Cold) point our imagination toward fluidlike entities. Either group is imagined as agentive, letting images of characters arise in the mind.

All Forces share some basic properties

What makes the different Forces members of the same *family of Forces of Nature* are the shared properties of *intensity* and *tension* (generally speaking: the *quality* of a phenomenon), *extension* (spatial size or quantity of some imagined „stuff"), and *power*. These are the same characteristics we associate with agents—be they „willful" like animals and humans or agentive in the more general sense like rivers, glaciers, thunderstorms and hurricanes, or volcanoes, just to mention some of the large-scale natural entities we often associate with Forces of Nature.

Stories of Forces

The stories of Forces of Nature and the form of natural language used in discussing Forces demonstrate that a primary approach to these phenomena is mythic and generally imaginative—the material of Chapter 2 suggests that a mythic approach to nature pedagogy is possible and sensible. Still, we have taken pains to lay out the scientific foundations for an engagement with physical processes. This paired form of describing and arguing has been expanded and refined in Chapters

3 and 4 where we have introduced the Forces of Fluids, Gravity, and Heat. These chapters serve a double purpose: (1) they narrate the most basic aspects of Fluids, Gravity, and Heat in a manner suggesting how primary understanding can be formed, and (2) introduce the reader to an imaginative form of the science that can grow upon its mythic foundation. Moreover, the examples given will hopefully convince the reader that physical phenomena are not alien to nature pedagogy; in fact, studying the physical Forces of Nature allows us to discuss large-scale natural systems such as the winds, rivers and waterfalls, volcanism, and continental drift.[5] When we introduce Electricity and Magnetism, Substances, and Motion in Volume 2, we shall see that, in addition to important technical applications (particularly in the field of energy and environmental engineering), natural systems such as thunderstorms, trees, the water cycle, the carbon cycle and global warming, and aspects of the solar system and the universe are at our fingertips.

Real natural systems

As we have mentioned before, this book is not a manual for day-to-day teaching, but the approach outlined here lends itself to suggesting forms of interacting with Forces that can be put into didactic practice. Apart from what seems to be most natural—direct physical interactions with Forces—our model of experience (Fig.1.2) tells us that narrative and other tools of communication should be integrated with direct physical experience if we wish to create a coherent imaginative approach.[6] This is why we have included a few stories in Chapters 1-4, and why we have extended forms of expression to include (a) *Forces-of-Nature Theater* (FoN-T) performances and (b) *process diagrams* in Chapter 5. These latter tools of communication allow us to explain the difference between a mythic and a more formal scientific approach to encounters with Forces of Nature. Theater performances can be designed as part of primary pedagogy (even though they can be structured to include more formal scientific elements); process diagrams, on the other hand, will rarely be used in a science class even in later primary school. Rather, process diagrams are explanatory tools for more formal scientific aspects. As we have used them in Chapter 5, they are a great tool for teachers who wish to create FoN-T performances—they are a kind of formalized visualization or „story-board" for the stories told in such performances.[7]

FoN-T performances & Process Diagrams

6.2 Learning About FoN—An Example of Primary Pedagogy

In this section and the one following, we shall sketch an example of physical processes in nature and in nature-human interactions by focusing upon the phenomena we have discussed in this volume, i.e., upon Primary Forces such as Wind, Sunlight, Heat, and Water. The example is used for suggesting and outlining steps teachers can take in transforming their understanding of processes into a concrete case of learning about nature for young students. The example can be scaled, both in scope and in its use for different age groups.

Theme, context, and motivation

We outline an example of nature pedagogy that can stretch over months or years, with parts made suitable for kindergarten and up to the middle of primary school. Actually, the theme can be picked up again, in whole or in part, in later years when students have some mastery of romantic understanding. We are thinking of a central theme where we learn about Wind and how it is made use of for empowering Water by pumping it to higher locations. Going outward from this core, we can ask where Wind and Water come from in the first place, and how we make use of Wind and Water for driving additional processes.

People interacting with nature

It probably makes sense—especially for younger learners—to begin with something where humans interact with nature, giving people a particular reason for being attentive to nature. What comes to mind—given the Forces we have learned about—is how the Dutch have claimed land from the sea starting as far back as the 11th century. We can imagine groups of mostly illiterate people desperately clinging to bits of land sticking out of the sea, building the first windmills with which they were able to drain land (Fig.3.2). What started there and in other areas on Earth will most likely become a challenge for many more people in the not so distant future: with rising sea levels, many island nations and large population centers near the ocean will have to fight the sea or simply give up.

An extended unit of primary nature pedagogy

Let us briefly sketch elements that go into a unit of nature pedagogy where we integrate direct experience, use of stories, and possibly FoN-T performances; a more in depth description of design principles for these forms of expression is presented further below in Sections 6.4-6.6. We assume at this point that teachers have prepared themselves by studying the natural science (and technical) background of the theme in the manner of an imaginative approach to physical systems and processes we have outlined in this volume—how this is done for the present theme is described in some detail in Section 6.3.

What remains is creating an opportunity for young children to explore the issues from a primary perspective—what is created will depend heavily upon the age of children, examples of nature pedagogy involving Forces of Nature that went before, and space, materials, and time available. For this reason, we can only suggest a few elements and aspects we believe are important.

Physical interaction

Children should be given an opportunity for direct physical interaction with the relevant Forces: Sunlight, Heat, Wind, and Water. For the following outlines, let us assume that some of this exposure, including relevant stories, went before. We want to create a fairly large-scale unit which a teacher can let play out over weeks, if not months. We may actually start with a story that allows children to become motivated for the issue: draining land to make it habitable. In this story, we make sure that people (children) interact with nature and its Forces. Most likely, this introductory story will not be the only one told during the unit described here.

Integrating a story of Wind

Having prepared and motivated the students for the larger issue,[8] we may, in a second step, build an experience of how Wind can be used to bring Water from a lower to a higher level. If it has not been done yet, children should definitely be given the opportunity to explore properties and the power of Wind—using all the means we have been suggesting already: direct exposure to Wind; playful activity with toy windmills or blowing water drops up on a tilted piece of glass (against the spontaneous tendency of the drops rolling downward); a story of Wind (maybe the story *Why We Need Wind*, Section 1.1, p.5) that allows children to communicate about the properties of Wind (intensity, extension, power); and finally a very simple version of a Forces-of-Nature Theater performance derived from a process diagram such as the one in Fig.6.1 (see Sections 6.4-6.6).

We are not done yet: now comes the challenge of dealing with the origin of Wind. Again, we want to take the perspective of the younger students in primary education. Let us leave aside the question of whether or not we want to include a FoN-T performance (along the lines of Fig.6.2). Dealing with the origin of Wind from a mythic perspective that includes Sunlight (and possibly Heat) as the causes of Wind goes beyond what we learn from *Why We Need Wind*: there, Wind already exists in the form of the character Wocawson (the Wind Eagle).

Candle carousel

Since it seems to be difficult if not impossible to directly observe Sunlight producing Wind, a more indirect path is advised. One possibility is to use phenomena that allow us to create an analogy to the full-fledged system. Maybe we can use a candle carousel that demonstrates that heated air rises and powers the motion of the blades of a toy windmill. We might even be able to heat the blackened base plate of the carousel with some strong light (for this to work, the upper part of the carousel needs to be kept cool, demonstrating that a temperature difference is need for heat to work in a heat engine).[9] Moreover, we can again make use of a story of Forces of Nature (one we probably need to write ourselves) that transports children imaginatively into a world where Sunlight makes Wind.

6.3 Studying the „Technical" Background

If teachers set their mind on the topic sketched in the previous section, they will certainly inform themselves about the context—Wind, Water, and Sunlight, their origins, and their meaning through history of the planet and human history—so they are prepared for creating context for their students to get excited and motivated for studying Wind, Water, and Light. We shall not dwell on this important aspect but jump right into the middle of the „scientific" matter underlying our understanding of the physical aspects of our theme. In this section, we suggest how teachers can enlist the technique of Process Diagrams (see mainly Section 5.5) for gaining an understanding of the relevant physical systems and processes. In the following sections, we shall outline details of how to produce materials for the different imaginative forms of expression available to their students: using their bodies and artifacts in direct physical exploration of phenomena, stories of Forces of Nature, and Forces-of-Nature Theater performances.

Wind interacting with Water

The study of Wind interacting with Water was introduced in Section 3.1—see Figures 3.2 and 3.3. The second of these figures suggests the more formal explanation of how these Forces interact: as Wind goes from a state of high to a state of low intensity, the case for Water is exactly the opposite—it is forced from a lower to a higher level, going against the „natural" or spontaneous flow, which is always downward.

Visual metaphors

It pays for an educator to first sketch a more or less formal scientific understanding of the situation: the process diagrams that were introduced in Chapter 5 (Section 5.5) are the perfect visually metaphoric tool that does not require quantitative (mathematical) expressions. In Fig.6.1, we see how Wind, Water, and Heat interact in a windmill whose purpose is pumping water rather than grinding grain. Wind—or if you prefer, air—flows into the abstract space representing the wind-driven water pump. Wind comes at high intensity and, figuratively speaking, flows down to a state of lower intensity. In doing so, Wind makes a part of the energy it carries available for the processes it couples with: raising water from a lower to a higher level and producing heat (see Fig.4.23 for what this entails). Each of the caused processes takes a part of the energy made available by Wind.

The processes coupling in the windmill pumping water can, at first, be represented more simply by neglecting irreversibility—the production of heat can always be added later. It is important, though, that we understand how the process diagram in Fig.6.1 simplifies the given situation. Depending upon how the pump is realized, engineers will need to understand that pumping water from a lower to a higher vertical level involves an interaction of Fluid and Gravity. As a Force, Water involves the concepts of pressure and volume, and Gravity involves those of gravitational potential and mass, of water; see Sections 3.4-3.6. Furthermore, we might want to represent the mechanical interactions inside the windmill, which would require an additional coupler similar to what we see in Fig.5.21. However, it helps knowing that this is not necessary, certainly not for a first mythic experience of how Wind and Water can interact.

Different forms of formal representation

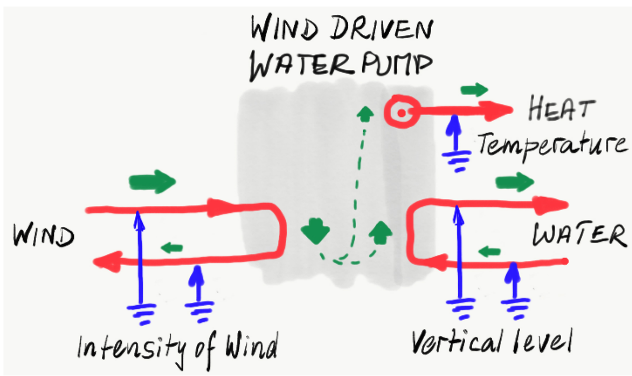

Figure 6.1: *Process diagram of Wind pumping water (and producing heat). In this compact model, the most important element is the interaction of Wind with Water: Wind „flows" from a higher to a lower level (wind intensity), whereas water is pumped from a lower to a higher level. As in all real interactions, heat is produced in parallel to the central process we focus on.*

Where does Wind come from?

Starting with pumping water with the help of the power of Wind, we may ask what comes before this: where does Wind come from? We have discussed the scientific background of the production of Wind in Section 4.6. The Sun's light heats the surface of the Earth; as a consequence, air is heated and rises in the gravitational field, taking its heat with it. After the air arrives at great height, it radiates its heat to outer space, cools and sinks back down to the ground.

This, in a nutshell, is the great heat engine that drives the flow of air at the surface of our planet. The details of processes operating in this „engine" are fairly intricate, but we can, just as in the case of a windmill pumping water, take a perspective that lets us strongly simplify the situation. Saying that Sunlight causes Wind, as might make a lot of sense to a child, we could create a process diagram with a single coupler (which, from a more scientific perspective includes ground, air, and gravitational field) where Light and Wind interact: Light is absorbed and destroyed, makes its energy available, which is used by Wind to raise its intensity; naturally, the coupling is irreversible: heat is produced.

Global heat engine driving the winds

We shall discuss a slightly more complicated model (Fig.6.2): there are two couplers, which we identify with the ground and the atmosphere. The ground is the place where Sunlight powers the production of heat. In the atmosphere, Heat drives Wind, just as Motion or Electricity are driven in heat engines such as combustion engines in cars or thermoelectric generators (Section 4.4).

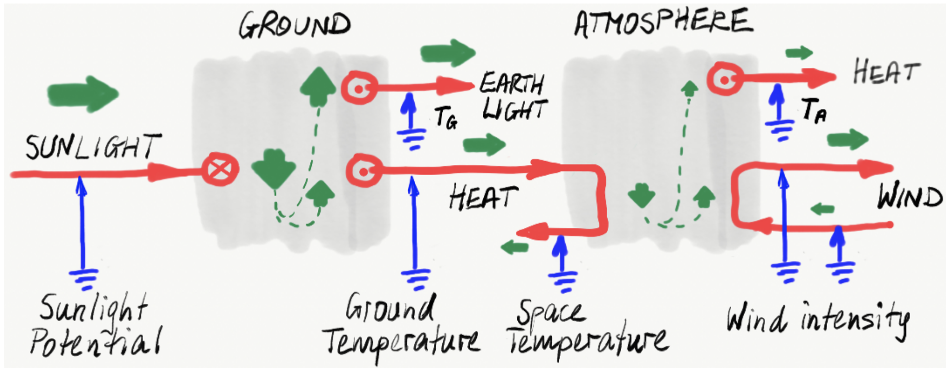

Figure 6.2: *Process diagram of Sunlight producing Wind, in two steps: Sunlight produces Heat, which drives Wind.*

Again, some of the aspects of what is going on here are intricate in detail and will never be presented to children. But for the educator, qualitatively understanding the processes that are involved, pays off. Take what is happening in the coupler called *Ground*: The energy made available by Sunlight is used to produce heat which raises the temperature of the ground. Part of the heat will heat the air over it, the larger part will be carried away by what we call „Earth-Light" in the diagram of Fig.6.2; this is the invisible infrared light emitted by the warm Earth out toward outer space. Note that the heat that first goes into the air ends up in outer space as well—that is why the temperature at which heat leaves the heat engine made up by the atmosphere is labeled „Space Temperature."[10]

Heat couples to Wind in the atmosphere (see the right part of Fig.6.2); at the same time, more heat is produced which lowers the efficiency of the Heat-Wind interaction. The temperature at which production of heat happens in the atmosphere is the temperature of the air.

The origin of Rain

If we wish to create a unit of „pure" nature pedagogy, without involving socially mediated technical systems and processes, we can turn to Rain as a Force that brings Water high up into the mountains (pp.72-75). We can extend the topic to the water cycle driven by Sunlight, not unlike the circulations in the atmosphere that bring us Wind. Water will rise from the oceans, rain onto the mounts from where it will flow back by itself into the oceans.

Here is a very brief account of the origin of Rain. If Sunlight is able to power Wind (which we explain by conflating the two couplers in Fig.6.2 into a single one), and since air can be humid, Wind can carry water high up into the atmosphere where it will rain onto a mountain lake from where it can run down into the valleys. A process diagram explaining this has two parallel Forces being powered by Light: Wind and Rain.

We can also imagine a water planet having a water-vapor atmosphere. The circulation of this atmosphere is driven by Sunlight, just like the circulation of air that give us the winds. The difference is this: the fluid involved in this cycle undergoes phase changes, first from water to water-vapor and back again from vapor to liquid water. At the surface of this water planet, Sunlight will be absorbed and produce vapor which will rise up, taking heat with it. At the top of this vapor atmosphere, the vapor will release its heat, condense and fall back to the surface. If we neglect phase change in the fluid and treat the details of the cycle simply as the result of a heat engine (as in Chapter 4, and as we have done for air undergoing its cycle), a process diagram for the water cycle here on Earth can look pretty much like the one in Fig.6.2 where we replace Wind by Water.

6.4 Designing Direct Physical Experience

In physics, at least, physical experience usually takes the form of experimenting, which, by its very nature, is immediately quite scientific and therefore not the role model we are looking for when we create a primary approach to our physical environment. Astronomy, as a physical science, is the exception here: all we can do is observe, but apart from what moves us emotionally when viewing and studying the planets, stars, and galaxies, we do not get any direct physical impact. All this changes, however, if we turn to experiencing physical Forces of Nature where we have a chance to be impacted directly and forcefully.

In our scheme, we need a pedagogy of direct engagement with physical Forces, which will most likely be different from how children can explore biological and geological environments. Part of this is the tight integration with stories and plays of Forces interacting and communicating with us—we will say more about this below. Here are some thoughts concerning how to create a path toward primary engagements with Forces. First, listen to what Kieran Egan[11] had to say about early steps one can take:

> When we look at oral cultural inquiry into the natural world, we see something rather different from science, something more intimately participatory in the objects of the natural world that seems alien and uncomfortable to the scientific mind. [...] The beginning inquiry, reflecting that of oral cultures, is less an attempt to know about nature as to know it in some participatory way, to know it as something we are an intimate part of, not set off from. One component of our early science curriculum might involve each student "adopting" something in the natural world—say, a tree, a patch of grass, a spider's web, rain, a dog or cat, or clouds. Students would be expected and helped simply to observe their adopted piece of the natural world, not in the sense that is currently common in which students have checklists, learn the names of the object and those of its parts, have drawing equipment or make notes, and deliver reports of a kind appropriate to their ages. In the Mythic curriculum they would observe silently for sustained periods of time with no other aim than to feel their way into the nature of what they are observing. They will feel how the tree stretches its leaves out to the sun, how the rain trickles down it, and how the branches move in the various winds. [...] The aim is a kind of dreamlike absorption into the object being observed or rather being participated in. The dreamlike mind will tie the object into emotions and half formed stories.

Egan does not particularly emphasize the physical Forces we are interested in, but we can easily see how his description applies to Wind, Rain, Light, Water, etc.[12] We can also see how we are able to interact with these Forces using our body and simple artifacts. Take again the example of Wind. We can explore the power of Wind by changing the area of exposure—maybe directly with our body by changing how we „stand in the Wind." While it may take hours to experience changing strengths of Wind, we can simulate the production of Wind at variable intensities by blowing air, and we can have several kids blowing with a given intensity at the same toy windmill or leaves on the ground, and so experience the difference this make upon the power of Wind.

Moreover, it should have become fairly obvious by now how, through communicating about such experience, the basic properties of these Forces can take form in the child's mind. Depending upon the age of the students and our objectives, communicating by using the embodied imagery created by experience, we can guide the young learners to some forms of imaginative reasoning that may tell us how the power of Wind depends upon its intensity and its extension (its „size"). Observing, using body and artifacts, and communicating must create a unity at the beginning of which we may have the „mythic communion" described by Egan, and at the end of which children will be able to speak fluently about their encounters with the Primary Forces of Nature.

6.5 Designing Stories of Forces of Nature

Communicating about Forces can take many different forms that may occur separately or in parallel and interacting. Simply speaking about physical experience as it happens is the easiest, and in some sense most important, of these forms. However, its impact will be greatly enhanced by additional communicative methods such as those we have listed in Fig.1.7—the basic methods of miming, drawing, singing, and speaking and the integrated tools that make use of them such as creating art and music, designing and building objects and environments, playing and acting, and storytelling. Here we shall recall and list a few important aspects of story design.

Designing and using stories. For the following description, we shall refer to (1) *When Heaven and Earth Were Created* (p.64), (2) *A Winter Story* (p.100), (3) *Spike, the Little Angry Dragon* (p.188), and (4) *Hurricane Sandy* (p.39). The features we can observe here tell us something about purpose and design of stories of Forces of Nature.

The first, as opposed to the other three, deals mainly with a single aspect of Forces: how they arise through polarities; stories (2)-(4) introduce us quite explicitly to one or more Forces. While stories (2) and (3) describe mainly a single Force (Cold and Heat, respectively), story (4) tells us about Forces interacting and creating a chain of events. Story (3) builds around an analogy between a psychological Force (Anger) and a natural Force (Heat); the other tales do not do anything like this explicitly.

Children and Forces interacting in stories

When we create stories of Forces of Nature, we face the challenge of making them emotionally engaging and interesting for children (and, for that matter, for us adults as well). Importantly, all four stories do not just speak of nature by itself, but they involve people—children—interacting more or less directly and intensely with nature and the Forces active in it. This can be important if we wish to create a narrative approach to nature and science. In narratology, researchers stress that stories are, above all, about people, their hopes, fears, and all the other emotions, and conscious acting and perceiving[13]—which makes it easy for us to get emotionally involved with a story.[14] While a well-crafted story of Forces of Nature will let us experience characters and agency just as in a typical story about people; and while it is therefore possible to speak about nature in prototypical narrative form;[15] we should remember that we are not just indifferent spectators of a drama unfolding before our eyes. We are involved with our natural environment, even if we think we have removed and shielded ourselves from it in our modern cultures. Therefore, it is by no means farfetched to include children and other sentient beings in the stories we write and use.

Designing stories of Forces of Nature...

Designing and writing stories of Forces of Nature

Here is a short list of dos and don'ts applying to the design of stories. Stories of Forces of Nature ...

- can, and maybe should, involve people (children) and/or animals experiencing (i.e., interacting, and possibly communicating, with) Forces;
- will be generated by one or more tensions (polarities) that drive the actions of both Forces and people;
- will use natural language (which is naturally schematic, metaphoric, analogical, without needing to be embellished);
- should not, or do not need to, personify Forces—the language used should let Forces emerge easily and naturally as characters or agents;
- can be of a single Force or several Forces interacting;
- can be specifically about an aspect of a Force or Forces;
- should be written so that they let the characteristics of Forces emerge in mind;
- can draw on analogies between natural, psychological, and social Forces;
- should *not* contain overt explanations (i.e., explicitly telling how phenomena arise and proceed from a formal scientific point of view).

Personification is not needed in stories

Moreover, none of them use a direct personification of Forces. We might get confused by the story of Spike, but the dragon is not a Force; he is the *Ground* upon which Forces act as *Figures* (remember the issue of Figure-Ground Reversal playing an important role in the experience of Forces (see Chapter 5, p.255 and Section 5.6). As we have stressed several times throughout this volume, there is no need for personification—in a strongly anthropomorphizing sense—of Forces of Nature. We may do so under certain circumstances, we may have animals representing Forces as we can see done in nature myths of indigenous peoples, or we can simply give a Force a voice without turning it into a person.

However we deal with this issue, we should keep in mind what Elisabeth W. Barber and Paul T. Barber said about this: „[...] the original [myth] had to have been told by people who reasoned that, if something happened, it had to be willed. But then it was transmitted down through history to people who no longer believed that—people for whom things could happen without a conscious Will being involved. But those people, looking at the original story, could only conclude that the 'actor' in the story must have been something animate by their new standard: a person, or perhaps a god or a giant."[16] The desire to personify Forces—when we deliberately take a narrative and imaginative stance—is a modern impulse, caused by our distance to and separateness from nature. If we were still a part of nature, we would not wonder about animals representing Forces, or interacting with them, and speaking to each other and to us.

Using stories. As to the use of such stories, there is not just one way of making them part of a concrete didactic process. We may wish to first let children experience nature directly, physically, and then use a story as part of our acts of communicating about the experience. On the other hand, we may very well be in a situation where it makes sense to first tell a story, then go out into nature, and then talk about the experience and possibly tell the story once again or use a different one. There are strong indications that, no matter how we integrate a story, stories of Forces of Nature have a strong impact upon imagination and the use of imaginative (schematic and metaphoric, i.e., generally figurative) language and understanding.[17]

Variations on a theme

Options for differentiation and variation

There is not just one way of creating a mythic curriculum of „nature studies." Indeed, encountering Forces of Nature and learning to communicate with and about them opens an exceptionally wide range of concrete paths teachers can choose from. This applies to...

- the forms of engagement and representation (direct physical, narrative, artistic, mimetic...);
- the list of possible examples of natural and technical systems and processes;
- the degree of complexity of systems represented;
- and to the degree of involvement of students, the acts of communication (direct physical, narrative, artistic), and in designing, enacting, and observing mimetic plays.

The language of stories is natural

Metaphorical language and stories. Stories guide us in the understanding of metaphorical language. The meaning of „*cold found its way*," if detached from all context, may not always be crystal clear; if, however, the expression is embedded in a story where Cold emerges as a (fluidlike) character or agent, we know exactly what we are speaking of—like a fluid, cold flows, moves through space, finds its way from one place to another, and so on.[18] Note that, in general, the language used in the four stories mentioned here is imaginative and metaphorical—it is simple everyday language. We do not need to resort to unduly flowery and otherwise embellished language that may strike us as contrived and unnatural. Natural spoken language provides a child, and us, with all the tools needed to sensibly communicate about encounters with nature and its Forces.

Do we speak of energy in stories? In our discussion of a primary approach to physical phenomena for the youngest group of children, in listing ideas important to the design of direct physical experience and stories of Forces of Nature (pp.301-305), we have not mentioned *energy*.

This may seem odd, given the importance of energy in physical processes and the fact that the term *energy* has become an often used word in modern life, so much so that young children are frequently exposed to it and use it as well (remember DL's „Dangerous Ener-Gee" in Fig.1.6; and all of us who observe children will have other examples to report). Nevertheless, we do not think that the concept of energy is part of mythic culture, at least not in its generalized form available to us in macroscopic physics (Sections 1.5 and 3.7), and not even in its visual and mimetic metaphoric rendering (see Chapter 5 in general, and Sections 5.3 and 5.6 in particular). Just because we are able to create visual and mimetic metaphors allowing us to communicate about its role in physical processes, does not make energy a part of our primary experience.

Therefore, when we design elements of primary nature pedagogy, it pays to take a step back and refrain from using the term *energy* in stories of Forces of Nature designed for the strictly mythic phase of young learners. Again, the examples referred to here, including *Why We Need Wind* (Chapter 1), demonstrate that we do not need to refer to energy to tell a complete story. What we need to do, however, is let the aspect of *power* arise in our mind—power as denoting the level or potential for interaction of an agent, and the actual strength of interaction of two agents or Forces.

Power vs. energy in stories of Forces

We need to keep in mind that the mythic concept of power is not the same as the full-fledged energy principle, which arises only in a more structured, formal approach to physical processes. For this reason, we would advise teachers not to include the concept of energy in a mythic approach to Forces.[19] Both stories and Forces-of-Nature Theater performances present us with ample opportunity to work on the concept of power as a mythic foundation of what later can become our understanding of the role of energy in natural processes.

6.6 Designing and Using FoN Theater Performances

Creating performances that show how Forces act and interact in natural and technical systems—along the lines sketched in Section 5.6—presents us with several challenges, particularly if we wish to use them as a part of primary nature pedagogy. As we have just stated, the generalized energy principle made available to us in visual metaphoric form is not really an element of mythic understanding. So our first question will be how we deal with this aspect.

Second, there is the concrete issue of how extended or complex the design of a performance can be. Do we tell a story involving one or more couplers, two or more Forces? Do we include processes where the Force is born or dies, as in the case of Light and Heat?

A third question arising here is more general, and partly independent of, the age of primary school students: How do we make sure that students understand their roles in a FoN-T performance? It is one thing to be instructed by a teacher how to move and act, moment by moment; it is another still to actually know and understand what all the different actions mean; for example, how does moving into, through, and out of a coupler (Fig.5.25) represent certain characteristics of a particular Force?

For the following discussions, we shall, explicitly or tacitly, refer to the examples sketched in Figs.6.1 and 6.2; remember the Forces involved: they are Sunlight, Wind, Water, and Heat (Heat may be an agent driving an important process, or simply the product of non-ideal processes).

Representing power, not energy. Let us begin with the first of these questions. If we agree that the full energy principle—as exemplified by the use of confetti or sand or the like (dust in Deichmann's animation; see Figs.5.4 and 5.7, and Section 5.3) is considered too much of a good thing for young learners, we simply leave out this prop and concentrate on what it means for an agent to be powerful and interact powerfully with a patient. As children's cognitive tools evolve and mature, a teacher will find the right moment for introducing a list of aspects that can be represented in FoN-T performances.

Embodying power through tension...

Representing the feeling of being powerful or powerless, and interacting powerfully or being made powerful, is quite easy without using the metaphor of possessing and passing some „stuff" (that symbolizes energy). Children acting in the role of a Force can learn that being tense or relaxed, lively or tired, awake or asleep, makes all the difference for how powerful they are. So, at the beginning of an interaction of an agent (such as Wind in Fig.6.1) with a patient (such as Water in the same diagram), the agent is tense, the (waiting, expecting...) patient is relaxed; now, the agent can simply touch, or possible shake, a patient and so (a) make the patient tense up (become lively or awake) while (b) becoming relaxed (tired, asleep) herself. Children can experience the change of intensity or tension they go through (Fig.6.3).

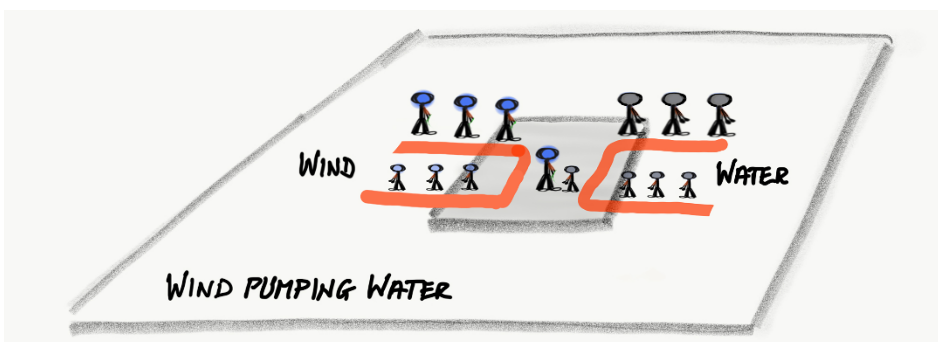

Figure 6.3: *Sketch of a Forces-of-Nature Theater performance: A simplified (aggregate) example of a direct interaction between Wind and Water, where we neglect irreversibility. Compare this to the more detailed representation in Fig.6.1. See Chapter 5 (Section 5.6 for descriptions of sketches of FoN-T performances).*

... and speed of the interaction

A performance is dynamical, i.e., as it proceeds through time, the second factor affecting power—this time, power of interaction—becomes apparent: the group of children acting as agents or patients can move along their paths faster or more slowly, interact faster or more slowly. Obviously, we have the extensive aspect here of a quantity, a number, interacting in a given period of time; more specifically, we physically represent the experience of flows.

Sooner or later, maybe motivated by questions the students could come up with, teachers will find an opportunity to discuss the issue of imagining interactions as cases of „something" being passed from agent to patient. Here is an example of an interaction of a different type of pedagogical weight: that of language used and subject studied. Linguistic exercises, be they small-scale in the form of listing expressions or large-scale involving complete stories, can show children how we use the figure of „something" being given to Peter when Mary interacts with him—this „something" can be an object or immaterial, a book or a headache or some motivation. What this tells us is this: learning deeply about interactions, about the roles of agents and patients, and, more generally, about causality, will take time; it will mean traveling a path along which our images evolve and become more vivid, strong, and numerous.

Learning about causality

Complexity of play. Fortunately, involving oneself in a case of encounters with Forces allows for a great diversity of concrete actions and approaches. We have already seen and described some of these when we described the examples of Wind and Water interacting (Fig.6.1), and Wind (Fig.6.2) and Rain arising. We are basically free, for example, to represent the interaction of Wind and Water directly, as in Fig.6.1, or mediated by other Forces (those of linear and rotational motion; see Volume 2), which makes a great difference in how complex a FoN-T performance will turn out to be. In other words, we have enough leeway to adapt the design of mimetic plays to suit concrete circumstances reflecting the age and level of maturity and sophistication of a group of students (not to speak of the circumstances dictated by available material, space, and time).

How to deal with production processes?

The question of how to deal with the aspects of production of Light (in emission) and Heat (in irreversible processes), and the destruction of Light (as a consequence of absorption) may be less easily answered. For obvious reasons, teachers may hesitate to include these phenomena in their nature pedagogy—the physics we are exposed to in school and through the media has never given us, parents and teachers, an opportunity to understand processes of production and destruction as being fundamental in modern physical science. Consider the production of heat when sunlight is absorbed in a material, as shown in the part on the left in the diagram of Fig.6.2: it puts into sharp relief the question of understanding or not understanding Forces of Nature. The standard way of speaking about the situation is „light is converted into heat." Here, light and heat are conflated with energy, with all the negative side effect resulting from an „explanation" that hides more than it reveals, that destroys more than it creates (Chapter 4); we can tell that this is a poor substitute for a full explanation in terms of Forces (Fig6.4).[20]

This raises two questions: Should we include the production of heat in an example such as the one presented by the interaction of Wind and Water (Fig.6.1)? And, are the processes of production and destruction of light and heat beyond mythic understanding of young learners? The first of these questions is answered quickly: we may very well leave out irreversibility when first choosing the example of pumping water with the help of wind (see Fig.6.3). This choice simply means that we want to focus upon a single interaction between just two Forces, between an agent and a patient. This is a legitimate and important move, certainly in primary education: when learning about the meaning of interactions, let us not get distracted by what else may happen; simply let an agent face a patient, and see what emerges. This, however, does not mean that we cannot deal with production of heat or production and destruction of light (see Fig.6.4).

Production and destruction are known from the phenomenon of life: they are the analogs of birth and death. While a teacher may hesitate to make birth and death a part of a curriculum oriented toward physical processes, we cannot argue that children do not know about birth and death; neither should we argue, we believe, that young children are too young to make these phenomena part of communication. If anything, birth and death are among the most profound forms of mythic experience.[21] Therefore, discussing early on what happens to Light when it is absorbed in a material seems not only possible but advisable. Maybe, we should remember the old joke „Where does the light go at night? ... Did you look in the refrigerator?" to realize that Light is really gone when its gone.

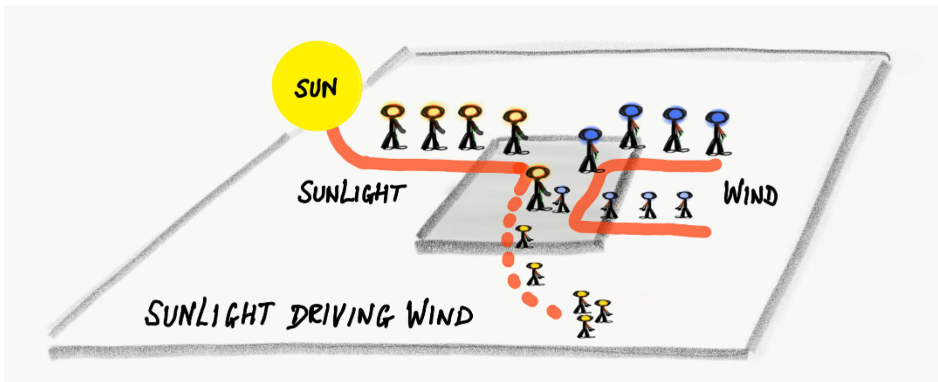

Figure 6.4: *Sketch of a Forces-of-Nature Theater performance: A strongly simplified (aggregate) example of a direct interaction between Sunlight and Wind. Compare this to the more detailed representation in Fig.6.2.*

Children should be able to understand the notion of powerful Light—they can represent it through the expressive form of bodily tension. In a FoN-T performance, children playing Sunlight can help create Heat as a new agent and make it powerful in turn (as stated above, we do not need the extended notion of energy in order to do this). And, again, if this seems to be too much at the start of a primary curriculum, we still do not need to shy away from asking where Wind comes from. A strongly simplified version of a FoN-T performance has Light kids come into the space of a coupler called „Earth" (or „Atmosphere" or „Air"), shake awake, i.e., empower kids representing Wind, and then relax and move out the coupler and take a break (Fig.6.4). It should become obvious though, that there is a difference between Light-kids and Wind-kids. The Light-kids originate at the Sun but never return to it, whereas the Wind kids, after driving some process, can return to the first meeting place, to be empowered once again.[22]

Choreography vs. co-construction

Planning and playing FoN-T: Involving children. Our third question concerns the issue of how to involve children meaningfully in mimetic plays of the sort offered by Forces-of-Nature Theater performances. Will performances be choreographed by the teacher and the children just mechanically follow instructions? Or, could children design and perform their own plays of interacting Forces, with hardly any input of the teacher?

There will not be a simple and single answer. What is possible depends upon the particular situation. However, there are points to be kept in mind of rules we should follow. First and foremost, FoN-T performances need to be embedded in larger units of nature studies, similar to the one sketched at the beginning of this chapter (pp.296-300). Such units are driven by direct and narrative experience, possibly involving working with artifacts. There should be ample opportunity for oral and possibly artistic expression. Most importantly, one or more stories telling about the adventures of Forces will have gone before. Having a FoN-T performance as the very first activity in engaging with Forces will not work.[23]

Second, young students will not necessarily understand their roles in mimetic plays if they are fully choreographed by the teacher. They can follow instructions all right, but that does not make the play meaningful. At minimum, we may want to build up a first performance in short, deliberate steps—always accompanied by oral interchange—involving one or just a few children in a first step and allow the other students to watch before roles of actors and observers are switched, and the whole procedure is repeated. A performance is built up from such steps.

Pumping of water by wind as mimetic play

Consider (direct) pumping of Water by Wind which may result in a mimetic play as sketched in Fig.6.3. Assume a story has gone before, and agents called Wind and Water and their basic characteristics of intensity, extension, and power have been talked about. We now ask one student or a small group to mimetically portray intensive Wind (embody the strong Wind). There are various ways for doing this, and we can let the group of observers comment upon this simple activity—let children judge its quality or aptness and maybe suggest alternatives. We may have suggestions such as fierce facial expression, erect posture, tensed posture, or even just running fast. As the co-construction of the play continues, we might get additional insight into the usefulness of these various ways of displaying high intensity of Wind.

Designing & using FoN-T performances

Designing and implementing FoN-T performances

Here is a short list of dos and don'ts in designing, choreographing, and using stories. FoN-T performances...

- need to be embedded in units involving other forms of engagement with Forces (such as direct physical and narrative experience);
- should be built bottom up, with the simplest examples first, and then expanding to include larger systems and greater numbers of interacting Forces (FoN-T plays are modular);
- should allow for students being involved in the design of a play;
- need to be organized so that students can both participate (learn to play roles) and observe (in order to better understand the meaning of roles);
- need to be immediately, frequently, and extensively communicated about (among students, and students with teachers);
- should not be carried out only once but should be performed repeatedly for different systems and processes.

The next step most likely involves interaction with Water which must be pumped from a low to a higher point. We need (a small number of) children ready to embody Water, first in its „low" and „powerless" state. The question to be discussed, and answered, is this: how does powerful Wind get powerless Water from a low reservoir into a higher one?[24] If this is the first time that an interaction between agents and patients is played, we again can let actors try out, and observers suggest, ideas. Assuming that we do not (yet) use a prop for representing energy to be passed from agents to patients, there will be some physical form of interaction. If someone suggested that Wind children literally carry Water children from a lower to a higher reservoir, this would be a great opportunity for changing the pace of activities and to go back to studying Wind physically (maybe with the help of ventilators and toy windmills) or talk about previous experience, to realize that the Wind goes its own way—it does not accompany Water from one place to another. Wind comes out of interacting with the blades of a windmill in a relaxed (slower, less intensive) state and continues on its own.

Embodied logic in FoN-T performances

FoN-T performances let us „feel" the logic of physical processes

FoN-T performances give us access to embodied logic: we feel what Forces experience, and what is logically possible and impossible. Here are some rules of this logic (see also Table 5.2):

- Kids are „spirits" embodying *Forces*, which means that they are *not* physical objects. Physical objects are the stage upon which Forces act—they are couplers. Do not let kids represent the Sun, a windmill, etc.!
- Kids representing a particular Force do not „convert" into a different Force—if they represent Heat, they can be born, if they are Light or Substances, they can be born or die, but they never change what they are.
- In general, kids move (flow) into and out of couplers; they can come out of or collect in storage elements (which may be couplers).
- In general, even allowing for birth and death, kids of a given group (Force) can embody the logic of accounting for amounts of „stuff."
- With their demeanor, kids embody intensity or tension of a Force; with their numbers, they embody the extensive aspect of a Forces.
- Through the „vigor" and speed of interaction with a different group of kids, actors representing a Forces embody its power; through interacting, they empower a different Force (make it tense); however, as a consequence, they relax and lose (some of) their power.

Experiencing an interaction

Now comes the crucial point children need to experience as they go through the concrete physical form of interacting: they need to get to the point of realizing that (a) if they are Wind, they will relax (become less powerful), and (b) if they are Water, they will tense up or move up (and become more powerful). Moreover, in the cases of Wind and Water, there will be movement of agents and patients into and out of the coupler, i.e., the area on the ground designated at the wind driven water pump. Again, there are various ways in which the imagined interaction can play out, but the main lines must become clear. How strongly a teacher will need to direct her students through this phase will depend upon the concrete situation.

Having arrived at this point, the pieces can be assembled into a complete story where activities proceed through space and time. Having gone through the steps of building the play, the class can now be divided into two groups representing Wind and Water. The activities rehearsed in steps will be combined into a fluid event where Wind kids „flow" toward and into the space designated as the water pumping windmill, interact with relaxed Water kids, become relaxed themselves and wander out of the coupler (in fact, they could return to become tensed, empowered, by some mechanism as that provided by Sunlight). The Water kids will be tensing up (be empowered) as a consequence of the interaction and move from a place called „low reservoir" into a space called „high reservoir."

Telling a story and exploring fictional worlds. Summing up, what is happening here is again the narration of a story, just in the form of mimetic, embodied activity. Stories, whether delivered orally or acted out as described here, are a great means for exploring fictional worlds.[25] As always, a story allows us to get to know the characters populating the story-world. Here, the characters are Forces of Nature.

6.7 Where We Go from Here

There are a few things that we still need to work on to complete our plan for *Primary Physical Science Education.* A couple of these we have mentioned already: we need to conclude describing the *Basic Forces* that form the foundation of macroscopic physical science, i.e., Electricity & Magnetism, Substances, and linear and rotational Motion; and we have to make clear, by concrete example, how a scientific attitude can be raised and cultivated in the course of primary school. The former task will increasingly open up new phenomena occurring in natural and technical systems; the latter brings up the issue of scientific methods and how to let young learners participate in the culture of science.

Above all, we want to extend what we started here with the examples of the production of winds, continental drift, and volcanism: we want to demonstrate how an imaginative approach to physical science based upon Forces of Nature can support us in the study of natural systems. The mythic, imaginative path toward nature studies we have started here is exceptionally well suited for allowing us to come closer to real-life systems and processes—presenting us with an opportunity we should not miss.

We conclude this chapter with a few words concerning what it means to open up children's minds to scientific approaches to nature and its Forces. We need to accept that there is no sharp line separating mythic from scientific engagement with the world around us; we cannot really say when myth ends and science starts. We have mentioned prerequisites for scientifically oriented tasks and activities: we need to nurture literacy and at least some of the cognitive tools that come with it. Eventually, but clearly not during the period of primary school, a sense of the theoretic will need to arise. It seems to be likely, however, that some theoretical understanding might evolve when students are in their romantic phase, and some sense-making associated with literacy will grow already during the years when children are clearly part of a mythic culture. This simply means that we have to be open to a number of different ways for dealing with out encounters with nature and machines—we should think of being placed in a fabric with its many threads criss-crossing, allowing us to move here and there, consecutively or in parallel, coming back and moving on, rather than having been put at the beginning of a straight path leading us directly and efficiently from A to B, from myth to formal science.

The example of pedagogy afforded by Forces-of-Nature Theater performances might help us clarify this point. While we may think of the experience of Forces that lets the figure of agents arise in our minds as strictly mythical; and while we might accept our ability to recognize these agents as more or less intense, big or small, and variously powerful, as an element of myth; embarking upon a discussion and an exploration of how power will depend upon intensity and „size," can become part of more formal reasoning. It can do so quite early on when a child's mythic encounters with Forces has in no way been concluded, i.e., before a lot of mythic experiencing is still to happen, long before the phase where we work mostly on the cognitive tools of myth has run its course in our educational scheme.

◦ ◦ ◦ ◦ ◦

Living in this world, we enter a phase of mythic awareness when we have become proficient speakers of a first natural language, maybe around the age of three or four. This manner of experiencing the natural, cultural, and personal (psychological) realms makes the gestalt of *Force* arise in us. The expression of Force in us and in communicating with people around us is mythic: it is abstract schematic, metaphoric, and narrative, i.e., generally imaginative. Once again, let a child tell us what form experience and expression, this time directly of Forces of Nature, can take:[26]

> On a winter day, when he was five years old, Alex came home from kindergarten. He talked to his grandmother about how the teacher had told them they should close the door or cold would come in. His grandmother wanted to know from Alex what cold was. He said that cold was a snowman. A snowman was very cold and if he hugged Alex, the boy would get cold too and could get sick.
>
> Alex and his grandmother were outside and decided to build a snowman. When his grandmother wanted to build a big one, Alex said that a big snowman would be so cold it could even kill young Alex. Alex thought it would be better to build a small snowman.
>
> Now his grandmother wanted to know what he thought heat was. Alex said, heat was a man of fire, or maybe a dragon. Alex could play with little dragons, they were not so hot and dangerous, but a really big dragon would be so hot and strong, its fire could kill the boy.

We have used our knowledge of how we experience Force as a tool for sketching how nature can be explored. In short, we have embarked on a path where we are putting human nature back into the scientific exploration of the world around us.

Notes

[1]This may sound like a contradiction: why should we have a scientific understanding for a mythic curriculum that is not scientific? Here is why: modern popular physical science, including what is taught at high school and at university (and not just for non-science majors), commonly takes a naive philosophic perspective that leaves us in the dark regarding what is mythic about the experience of physical Forces of Nature. We have mentioned before that if all we know about is a theory of physical phenomena ruled by mechanics and the belief that everything in nature follows form the motion of little particles , we will be led astray—we will never understand what actually happens when we (and young children in particular) encounter, i.e., experience, Forces of Nature. One of the clearest signs of this challenge can be found in the widespread refusal to see modern science as an expression of schematic, metaphoric, analogical, and narrative understanding.

[2]Egan, 1988, 1990, 1997, 2005. Egan emphasizes the importance of nurturing and using the cognitive tools associated with the phases of cultural development. For primary education, he develops the theory of mythic understanding that is associated with oral language use.

[3]It seems that different phases will partly develop and „run" in parallel, and tools of understanding associated with a particular phase—once developed—will need to be used concurrently, in „mixed mode." This will become painfully clear when we design examples of nature pedagogy or science subjects to be included in primary education (ranging from kindergarten to the end of primary school): are our students (still) in a mythic phase or are they (already) well versed in the tools of romance? Or are they in both at the same time? There will not be a clear and easy answer—it will all depend upon the age of a child and, in the case of a group of children, on the diverse momentary „states" each child is in.

[4]Fortunately, more and more philosophers of science, cognitive scientists, and educators are becoming aware of the role of figurative structures of mind and what tools they afford us in our encounters with nature and science. See, for instance, Levy & Godfrey-Smith (2020), Kind (2016), Lakoff & Nuñez (2000), Amin (2009), Amin et al. (2015), Corni (2013), Fuchs (2014b), Fuchs (2015), Corni et al. (2019a,b), Corni & Fuchs (2020), Corni & Fuchs (2021), Fuchs, Corni, & Pahl (2021), Pahl et al. (2022).

[5]Except for maybe continental drift, these systems are important material for the myths that have been created, told, and re-told through time. Barber & Barber (2004) show how many myths created in ancient Europe, the Near East, and the Americas deal with natural systems and phenomena. Volcanoes are a particularly pertinent example: the Barbers discuss volcano myths of indigenous peoples of North America and show that Prometheus (and his equivalent from the Caucasus region) is a volcano. What transpires here is the same point we have already discussed in Chapter 2 (p.92ff.): what we refer to today as gods (or giants, etc.), were actually natural, psychological, and social Forces. Personification or deification are relatively modern (post-myth) phenomena. As we can see in the case of our *Winter Story* (Section 2.6), personifying Forces such as Cold is not necessary. As an element of narrative experience, the tools of natural language (schematism, metaphor, analogy) let Cold and other Forces emerge directly as characters—we do not need to make them into and give them specific names of monsters, gnomes, giants, or gods. See also further below in this chapter, p.303.

[6]This tells us that a mythic approach to (Primary) Forces of Nature is not the same as Folk Physics or forms of understanding and bodies of knowledge often called common sense or intuitive science or „theories." While aspects of such a mythic form of early engagement with nature will appear in Folk Physics or common sense „theories," the former is distinguished from the latter in that it is a deliberate pedagogical interaction between children and caregivers. The interaction found in a mythic cultural stage is best described as one of apprenticeship—caregiver and child interact as they jointly encounter nature (and technical systems); importantly, the interaction makes use of the tools of orality such as metaphor and narrative, games, songs, art,

and mime and theater performances. What arises in such activity should not be confused with theories: myth does not create theoretical knowledge and understanding; theories have to await a later stage of understanding. Joseph Campbell (1990, p.1) wrote „The material of myth is the material of our life, the material of our body, and the material of our environment, and a living, vital mythology deals with these in terms that are appropriate to the nature of knowledge of the time." If we take „the time" as meaning the time when we are very young, we have here a description of how myth is appropriate for primary education.

[7]See Landini et al. (2019), and Pahl et al. (2022).

[8]Stories are a perfect tool for creating context and motivation. We have suggested that the history of the last 1000 years of Holland may be used for such context and background. However, this concrete example lets some educators hesitate: surely, their students, especially if they are still in kindergarten or the first couple of years of primary school, have never been to Holland and have most likely never seen one of the historical windmills that will play a central role in our story—therefore, the reasoning goes, we cannot possibly use the example of the struggle of the Dutch with the sea as a background story for children in the rest of the world.

This misjudges the power of imagination of children and what kind of educaitonal material this makes available to them. Following Egan (1988, 1997) and what we know from the development of schematic abstractions and the use of metaphor, analogy, and narrative by children (see our Chapter 1, and Mandler, 2004), it is clear that the right kind of story transports children, and not just them, into worlds they have never seen before and yet can be imagined and enjoyed. It would be too bad if teachers were to take the fact that in their neighborhood they cannot find windmills or modern wind turbines were to rule out using such a story and its theme. If using Holland as a concrete example were to strike someone the wrong way, we surely could change the setting to a magical island somewhere far away, and so catch our students' imagination with no problem at all.

[9]Building your own candle carousel: https://www.sciencebuddies.org/science-fair-projects/project-ideas/Aero_p051/aerodynamics-hydrodynamics/make-a-candle-carousel. We can find quite a few sources for how to build a windmill driven water pump: https://www.youtube.com/watch?v=5TfWn_JKHzY and https://www.youtube.com/watch?v=drsWxr8R_QM. Again, the answer to the question how far we want to or can go very much depends upon the students we deal with and the resources and time we have available. Most or all of the activities discussed here can be realized at different levels, ranging from mythic awareness to technically and scientifically sophisticated practice.

[10]Despite all the simplifications made, the process diagram in Fig.6.2 is fundamentally correct. We may call it a first pass through analyzing the mechanism that leads to the production of Wind. In a second pass, we may, for instance, note that the atmosphere (the air) receives heat at a somewhat lower temperature than Ground Temperature, and emit it to outer space at a temperature above Space Temperature—there need to be temperature differences for heat to be transferred, as discussed in the section including Fig.4.26. Such changes are important if we wish to create a more detailed (and quantitatively accurate) model, but they do not change the basic message of Fig.6.2.

[11]K. Egan (1997), pp.213-214.

[12]Note that these Forces are medium-scale gestalts somewhere between a pond or a tree or the atmosphere and the Basic Forces we have identified as making up the subject of modern macroscopic physical science (Section 1.5). They are not as complex as typical natural systems, but they allow for more structure than the „bare-bones" Basic Forces such as Fluids, Gravity, Electricity, and Motion. Simply think of Fire—which, despite its dangers for small children, should not be excluded from a mythic curriculum—which is a perceptual unit created by the interaction of Substance (such as Wood), Heat, Air (Wind?), and Light.

[13]See David Herman, 2002, 2009, 2013. In particular, see Herman (2009), pp.89-100, where he describes story as the central member of the radial category of narrative; and (2013), where he describes the roles of agency and (conscious) experiencing by agents as important elements of stories. See also our Volume 2.

[14]Egan stresses this aspect of stories in his educational scheme. For the theoretical background, relating stories in primary education to mythic understanding, see Egan, 1988, Chapter 3. For teaching with stories, see Egan (1986).

[15]Fuchs (2015).

[16]Barber & Barber (2004), p.229.

[17]Pahl et al. (2022); Pahl et al., forthcoming.

[18]Fuchs et al. (2019).

[19]There will always be exceptions to this rule, particularly since modern children are exposed to the term *energy* early on. However, it is not necessary to go into lengthy explanations every time a child mentions energy. There is a certain fuzzy and qualitative feeling associated with the word, which is alright, and we can leave it at that.

[20]Fuchs et al. (2022).

[21]Nixon (2010) discusses the meaning of the experience of death in the killing of animals for the evolution of human consciousness and myth.

[22]That is, if we do not take Wind purely as an activity that arises and dies down (Section 2.4), but rather let the notion of something „indestructible," namely air, arise in our imagination. Air is cycled through the atmosphere in the wind engine driven by heat (Section 4.6).

[23]On the other hand, if such plays have been performed before, as part of a larger unit, it is possible to create a short unit on, say, a battery driving a little ventilator. All we might do in such a case is present the artifact, let students play with it, discuss the Forces making an appearance in the system, and set up and act out a FoN-T performance. Such a short unit may very well work for older students in primary school.

[24]Pumping water from a low-lying place into a higher one is only one possibility; others are raising the pressure of water or making it flow (faster). Which of these characteristics is we want to work with depends upon several factors (such as the concrete physical situation to be represented, specific imaginative aspects to be displayed, age and sophistication of students, and spatial and material constraints for playing).

[25]Gelmi (2022) is exploring the relation between FoN-T performances proposed here and the pedagogy of Conceptual PlayWorlds (Fleer, 2019; see also https://www.monash.edu/conceptual-playworld, visited on August 31, 2022). PlayWorlds originated in Lindqvist's work (Lindqvist, 1995). What we present here is an example of the world that opens up for mimetic play in fields such as nature pedagogy.

[26]Alex' grandmother, Elena Sassi (Sassi, 2006), told us this story after we presented the idea of force-dynamic experiential gestalts of physical processes at a conference in Napoli.

Glossary

Short descriptions and explanations of terms from physics (and the sciences more generally), cognitive science, and philosophy. Please use the Index for finding the terms listed here in the text.

Abbreviation used: FoN for Force of Nature.

Absolute potential. Certain → Potentials have an absolute zero value (this is the case for → Temperature, → Pressure, and → Chemical potential). See also *Relative potential value*.

Abstraction. The term is generally used in a number of different ways. Here, we take it in a sense that is close to abstract art: it is a result of the → Schematizing action of the human mind. Example: Our physical experience lets the sense of (physical, bodily) → Balance grow in us (see → Image schemas). We form an abstract → Gestalt (or → Experiential/perceptual unit) which is used for understanding and reasoning.

Accounting. Applying a law of → Balance for a → Fluidlike quantity.

Action. Part of → Experience (i.e., part of the feedback cycle in the interaction of an organism with its various environments). It is the part that goes from the organism to an environment.

Agent. General: any → FoN. Specifically, in an → Interaction: the driving or causing → FoN. See also *causation* and *drive/driving force*.

Agency. The feeling generated in experience that causal → Agents exist.

Air (as fluid FoN). The → Fluid our atmosphere is made out of. It should be distinguished from Wind (Wind is not simply moving air but its own primary phenomenon: a → FoN), and from the chemical substance called air.

Air (as chemical FoN). Air is a mixture of different chemicals (mainly oxygen and nitrogen). Each of these chemicals is a → Force of Nature exhibiting the three basic → Aspects of → Intensity (chemical potential), → Amount (→ Amount of substance), and → Power. As a chemical FoN, a component of air can migrate into and through matter, and it can participate in chemical reactions.

Amount (of. . .). Amounts of electricity, heat, water, air, etc. measure the → Extensive aspect of a → Force of Nature. Amounts of this type are imagined as → Fluidlike quantities for which laws of → Balance hold. See also *Extension*.

Amount of electricity. The → Extensive quantity of → Electricity as a → FoN (also called (electrical) → Charge). It is imagined as a → Fluidlike quantity for which a law of → Balance holds. It can flow and be stored. Specifically, amount

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of electricity (charge) can be neither produced nor destroyed (it is a → Conserved quantity). Units: Coulomb = Ampère·second. See also *Extension*.

Amount of fluid. The → Extensive quantity of → Fluid as a → FoN: this is its volume. It is imagined as a → Fluidlike quantity for which a law of → Balance holds. It can flow and be stored. Specifically, volume can both be produced and destroyed (in expansion and compression). Unit: Cubic meter. See also *Extension*.

Amount of gravity. The → Extensive quantity of → Gravity as a → FoN (also called (gravitational) → Mass). Unit: kilogram. It is imagined as a → Fluidlike quantity for which a law of → Balance holds. It can flow and be stored. Specifically, amount of gravity (mass) can be neither produced nor destroyed (it is → Conserved quantity). See also *Extension*.

Amount of heat. The → Extensive quantity of → Heat as a → FoN (also called → Caloric, thermal → Charge, or → Entropy). Units: Joule/Kelvin = Carnot. It is imagined as a → Fluidlike quantity for which a law of → Balance holds. It can flow and be stored. Specifically, amount of heat (caloric, entropy) can be produced but nor destroyed. See also *Extension*.

Amount of motion. The → Extensive quantity of (→ Translational) Motion (also called → Momentum). Units: kilogram·meter/second = Newton·second. It is imagined as a → Fluidlike quantity for which a law of → Balance holds. It can flow and be stored. Specifically, momentum can be neither produced nor destroyed (it is → Conserved quantity). See also *Extension*.

Amount of rotational motion. The → Extensive quantity of → Rotation (rotational motion) (also called angular momentum or → Spin). Units: Newton·meter·second. It is imagined as a → Fluidlike quantity for which a law of → Balance holds. It can flow and be stored. Specifically, amount of rotational motion can be neither produced nor destroyed (it is → Conserved quantity). See also *Extension*.

Amount of substance. The → Extensive quantity of → Substance as a → FoN. Unit: mol. It is imagined as a → Fluidlike quantity for which a law of → Balance holds. It can flow and be stored. Specifically, amount of substance can be both produced and destroyed in chemical reactions. See also *Extension*.

Ampère. → Unit of → Electric current. Alternatively, Ampère = Coulomb/second (C/s, where C stands for the unit of → Charge).

Analogy. Analogy arises in different circumstances. We are interested in the analogy between different → Forces of Nature that results from each FoN being metaphorized in terms of the same basic → Metaphoric web. If, for example, we have a web for → Heat, we can form the same metaphoric web by replacing the word HEAT by ELECTRICITY in the metaphors that constitute the web. This type of analogy allows us to (partially) transfer our knowledge of one field of science to another field (and back: analogy is bi-directional). See also *Metaphor*.

Angular momentum. The → Extensive aspect of → Rotational motion, i.e., the → Amount of rotational motion (also called → Spin). It can flow and be stored. Unit: Newton·meter·second.

Aspects (basic) of FoN. A → Force of Nature is first of all an experiential unit (→ Gestalt). However, when analyzed, it exhibits three basic → Aspects or characteristics that make it a Force. The three aspects are → Intensity, → Extension, and → Power.

Balance (as equilibrium). An → Image schema resulting from our bodily/physical sense of balance. The schema is used widely for metaphors (example: mental balance/equilibrium; chemical equilibrium; etc.).

Balance (law of...). Quantities that can accumulate (such as → Amount of water, heat, electricity, etc.) are subject to a „law of balance." Such a relation expresses how fast the → amount of the quantity → stored changes in response to (in- and out-) → Flows (relative to a container or storage device) and → Production and → Destruction rates. Example: The rate at which the number of inhabitants of a city changes is given by the net migration (flow) and the (difference of) rates of births and deaths.

Basic Forces of Nature. In macroscopic physics (as in → Continuum physics), the short list of basic phenomena for which theories have been developed. The list is made up of → Fluids, → Electricity & Magnetism, → Thermodynamics, → Chemical substances, → Gravitation, → Translational (Linear) Motion, and → Rotational Motion. See also *Force of Nature*.

Basic metaphor. A category of (conceptual) → Metaphor where the source domain is constituted by an → Image schema.

Binary opposites. Similar to polarity, but usually assumed to be the opposition between terms of a duality (dead ↔ alive may be taken as having only two values and nothing in between).

Brightness. Nominalized form of the → Polarity denoted by light ↔ dark.

Buoyancy. The effect of a → fluid environment (air of the atmosphere, water in a lake) upon the motion (or rest) of a body submerged in the fluid. Alternatively, it is the effect of the fluid upon the „apparent" → weight of the body. See also *heaviness*.

Caloric. Term denoting the extensive quantity of heat, i.e., → amount of heat (→ Entropy) in the caloric theory of heat (used by researchers until about 1850, and again since a few decades; we use this term when referring to the → Extensive thermal quantity in colloquial terms appropriate for lay persons). It can flow, be stored, and produced. Units: Joule/Kelvin = Carnot.

Capacitance. The factor that tells us how much of a → Fluidlike quantity needs to be added to a s → Storage device if we want the → Intensity to rise by a certain value. It is used to rate storage devices such as our aorta (for blood), materials for storing → Amount of heat, or electrical capacitors (for storing → Charge). Units: (Unit of → Fluidlike quantity) divided by (Unit of associated → Potential).

Carnot. → Unit of → Amount of heat (→ Caloric, → Entropy). Alternatively: Carnot = Joule/Kelvin (J/K).

Causation. In the examples treated in this book, causation denotes how a powerful → Agent causes (one or more) → Patients to become powerful in turn (i.e., when agent and patient interact). See also *Interaction*.

Charge (electrical). The → Extensive quantity of → Electricity. It can flow and be stored. See also *Amount of electricity*.

Charge (general). As in → „Amount of something" that can accumulate, i.e., → Amount of an → Extensive (→ Fluidlike) quantity. Examples in physics: electric → Charge, gravitational charge (→ Mass), thermal charge (→ Amount of heat or → Caloric, → Entropy).

Chemical potential. The → Intensity (intensive quantity) of (chemical) → Substances. Imagined as a → Level. Units: Joule/mol = Gibbs.

Chemical reaction. In a chemical reaction, one or more chemicals (→ Substances) are destroyed and one or more chemical are created. Example: Hydrogen and oxygen gases can react with each other and disappear. In their place, water is produced.

Circuit. In the simplest case, a single closed path for the → Flow of a → Fluidlike quantity (in particular, for electrical → Charge).

Cognitive tools. We use this term in the sense developed by K. Egan (*The Educated Mind*, 1997). Examples of cognitive tools are → Metaphor, → Story, mimesis, song, humor, sense of reality, sense of theory, etc. Cognitive tools develop through cultural stages (from mythic to romantic to philosophic/theoretical). See also *Myth* and *Romantic culture and understanding*.

Cold (as FoN). Counterpart to → Heat as a → FoN.

Concentration. → Amount of a → Fluidlike quantity divided by the volume the quantity is found in. Used in particular for chemical → Substance.

Conductance. The quality of a material that tells us how easily it lets a → Fluidlike quantity pass in conductive flow (see also *Conduction*).

Conduction. The phenomenon of → Flow of a → Fluidlike quantity driven by its own → Tension (such as when → Heat flows because of a → Temperature difference). In other words, the flow is in the direction of the downhill → Gradient of the potential associated with the fluidlike quantity. Also called → Diffusion.

Conserved quantity. A quantity that can neither be produced nor destroyed (its amount in the „universe" is fixed and constant), no matter what happens). This applies to electric → Charge, → Mass, → Momentum, → Spin, and → Energy.

Continuum physics. The collection of macroscopic theories of → Basic Forces of Nature, presented in their most general mathematical form applicable to temporally and spatially continuous models.

Convective transport (convection). The transport of → amounts of heat, substance, electricity, motion, and → spin carried by a flowing → fluid. We can imagine these quantities (such as heat or sugar) to be „dissolved" in the fluid, so a flowing fluid carries them along.

Coulomb. → Unit of electrical → Charge (abbreviation: C).

Current. Formal measure of the strength of → flow of a → fluidlike quantity (such as → amount of water, heat, or electricity). Examples: current of → Heat, current of → Water, current of → Charge.

Degree. The value of a particular → intensity (the mark of a position along the → scale stretching between or the path going from the first to the second pole of a → polarity). Example: → Temperature as the degree of → hotness; → pressure as the degree of → fluid → Tension.

Density. → Amount of a → Fluidlike quantity divided by the volume the quantity is found in. Used in particular for → Mass. Basically equivalent to → Concentration.

Destruction (rate). Certain → Fluidlike quantities (→ Amount of substance and biological organisms) can be destroyed (die). The destruction rate denotes the rate at which the fluidlike quantity disappear.

Diffusion. In chemical processes, the → flow of → Amount of substance driven by chemical → Tension (i.e., the difference of chemical potential at two locations), i.e., the flow is in the direction of the downhill → Gradient of chemical potential. More generally: any conductive transport. See *Conduction*.

Dissipation. Dissipation refers to the → Energy used during the production of heat (→ Caloric, → Entropy)—the energy used is said to have been dissipated. The rate of dissipation equals the power of the process of producing heat, i.e., the rate at which energy is used for producing heat.

Drive/Driving force. A → Tension, i.e., the difference of values of → Intensity of a → FoN at two different locations. Example: The temperature difference between hot coffee and cool environment is the drive for the flow of heat out of the coffee into the environment.

Dynamo. See *Generator (electrical).*

Efficiency. Relating to → Interactions of → FoN. The efficiency of an interaction is the ratio of the useful → Power of the desired process caused by the interaction and the power of the driving → Agent. Alternatively, the efficiency averaged over a period of time is the ratio of the energy used by the desired driven process and the energy made available by the driving agent.

Electric current. Magnitude of → Flow of electric → Charge. Unit: Ampère = Coulomb/second.

Electric field. The → Field created by electric → Charge. It is the physical object filling space (in the presence of electric charge) that mediates electric effects. It is an aspect of the → Electromagnetic field.

Electric fluid. Old name (used by Benjamin Franklin and others) of → Amount of electricity (→ Charge).

Electric potential. The → Intensive quantity of → Electricity. Metaphorized as electrical → Level. Unit: Volt = Joule/Coulomb (V = J/C).

Electric tension. The difference of → Intensity of → Electricity at two different locations (in some cases, it can be felt by the strength of an electric shock). It is the → Driving force for electrical phenomena (the flow of → Charge). In English, the technical term for it is → Voltage. Unit: Volt = Joule/Coulomb.

Electricity (as FoN). One of the → Primary FoN. Like every FoN, it is experienced as a → Gestalt having the three main aspects of → Intensity, → Extension, and → Power. Its intensity is what we feel as electrical → Tension.

Electromagnetic field. The → Field associated with electrical and magnetic phenomena. Electricity and magnetism are considered the two sides of the same coin—in physics, we say that there exists a unified theory of → Electricity and → Magnetism. In this theory, there is a single (combined) field that is called electromagnetic field. Transports of → Energy, → Momentum, → Spin, → Amount of heat (→ Caloric,→ Entropy) through the electromagnetic field are called → Electromagnetic radiation (of which visible → Light is an example).

Electromagnetic radiation. The → Transport of → Amount of substance, → Momentum, → Spin, → Amount of heat (→ Caloric,→ Entropy), and → Energy through the → Electromagnetic field. See also *Light*.

Electromagnetism. Theory of the → Electromagnetic Field.

Embodied cognition. Most generally, the position that mind is the result of organism-environment → Interactions. One of the important consequences is the assumption that concepts are embodied: they arise through the activity of the → Imagination, which makes use of → Image schemas, their metaphoric projections (→ Metaphor), → Analogy, and → Narrative. Therefore, concepts are figurative (imaginative, metaphoric...) rather than literal. Their understanding arises through the embodiment of our mind—a particular concept is embedded in a figurative (imaginative, metaphoric...) web. See also *Experience*.

Embodied simulation. Using one's body (or a of a group of people) to simulate tensions and amounts. A form of play for experiencing through one's body the meaning of tension (such as thermal, fluid, and electrical) and its relation to quantities (such as heat, fluid, charge) stored and flowing. A special case is the use of a (large) group of persons in oder to represent dynamical → Accounting for → Amounts of → Fluidlike quantities.

Enactivism. A form of → Embodied cognitive science with an emphasis on how the environments of an organism „arise" in mind through being enacted (as a result of the sensorimotor processes of the organism).

Energy. Quantity needed to express our experience of the „amount of interaction" between two → FoN. An → Agent driving a → Patient makes a certain amount of energy available, and the patient picks up (uses) a part of this energy (in an ideal → interaction, the part would be 100%). In this case, energy lets us quantify two aspects: „how much" an agent can potentially „do to" one or more patients, and „how much" has been done to the patient (for example: how much water has been pumped how high). Furthermore, energy can be transported (by → FoN or by → Fluids), and it can be put in → Storage (materials and → Fields serve as storage elements). Unit: Joule (non-standard unit: → Kilo-Watt-hour or kWh). See also *Energy, making available.*

Energy (balance of. . .). Since energy can be stored and transferred, it satisfies a law of → Balance. Specifically, energy can neither be produced nor destroyed (energy is a → Conserved quantity).

Energy carrier. A → Force of Nature is an energy carrier. → Energy can be carried by (→ amount of) heat, electricity, substances, motion, etc. In → conductive → flows, the amount of energy that is carried by (→ amount of) heat, electricity, substances, motion, etc., depends upon the → current of these quantities and the → potential at which they flow.

Energy, making available. → Energy is exchanged in → Interactions of → FoN. The energy released by the driving FoN is said to be made available. Only energy that has been made available can be used. For energy to be made available, there needs to be a → Tension so that a → Fluidlike quantity can flow from a point of high to a point of low → Potential.

Entropy. → Extensive thermal quantity (→ amount of heat, → caloric, thermal → charge). It can flow, be stored, and produced. Units: Joule/Kelvin = Carnot.

Equilibrium. State when the → intensity in two different locations in a system is the same, i.e., when there is no → tension between the two locations. See *Balance.*

Experience. The result of organism-environment interactions; in general, an „experiential" interaction is a feedback process of action and perception between body and environment(s). This includes the forming of understanding, i.e., the creation of what is traditionally called mental conceptualization. We may look upon experience as the unified action of perception and conception. In theories of → Embodied cognition, mind is thought to be the result of of experience understood in this generalized way.

Experiential/perceptual unit. See *Gestalt.*

Extension. One of the three main aspects of a → Force of Nature. It describes, variously, spatial size (and possibly temporal duration), or → Amount.

Extensive quantity. For every → FoN, there is an extensive aspect, which measures spatial extension („size"), temporal duration („length" of time), or → amount. Examples: → amount of heat, → amount of electricity, or spatial and temporal „size" of → Wind, etc.

Field (as mathematical concept). In general, a field is any real or theoretical „object" that extends in space. Examples of theoretical or abstract fields are „fields" of physical quantities such as → Temperature, → Pressure, level, → Electrical potential, etc., i.e., of quantities that can vary from point to point in space.

Field (as physical object). Fields are (immaterial) physical objects. Like any object, fields can store certain → Fluidlike quantities or transport them. In macroscopic physics, the fields of interest are the → Gravitational field, → Electric field, and → Magnetic field.

Figure-Ground-Reversal. In → Experience, we discern Figures before a Ground; Figures appear in different perceptual modalities: visual, acoustic, tactile, olfactory, chronological, etc. Our mind is capable of changing the „order" between Figure and Ground: a previous Figure becomes the Ground, and vice-versa. Famous visual examples of FGR include Rubin's vase (where we either see the two faces in profile or a vase), the duck-rabbit picture (where we see either a the head of a duck or of a rabbit), and illustrations by M. C. Escher. FGR is important in our approach to → FoN where FoN are seen to arise as Figures upon physical objects/devices appearing as the Ground upon which the Forces act and interact. See also *Interaction*.

Flow. The phenomenon of (literal or metaphoric) „motion" of a („real" or → Fluidlike) entity. Fluids, → Amount of heat (→ Caloric,→ Entropy), → Charge, → Momentum, → Mass, → Spin, etc., all can „flow" into, out, and through physical objects (materials and → Fields). The phenomenon of flow is used metaphorically as well in social and psychological settings (money and gossip „flow").

Fluid. Fluids are liquids and gases (as opposed to solids). Typical everyday fluids are → Water, blood, oil, and → Air.

Fluidlike quantity. Some of the → Forces of Nature have → Extensive quantities (→ Amounts) that behave almost as → Fluids. Examples: Electric → Charge can flow and „fill up" materials; → Amount of heat (→ Caloric, → Entropy) can flow, „fill up" materials, and be produced. The extensive quantities of → Basic Forces of Nature are all fluidlike.

Force in mechanics. In (formal) physics, the word *force* is used only for mechanical interactions (to be precise: only for interactions in → translational motion). Formally, *force* denotes the rate of transfer of → momentum when bodies touch (surface forces; examples: contact forces, pressure force, mechanical tension, friction, etc.) and in the interaction of bodies and → fields (volume forces; example: force of gravity). Note that it would be wrong to use the word force for → convective transports of momentum (when a flowing fluid carries momentum).

Force of gravity. Bodies (having → Mass) attract each other as a consequence of the effect of → Gravity. The rate of transfer of → Momentum through the → Gravitational field between two bodies is called the force of gravity. This is what is called → Weight in everyday life (such as the weight of an apple at the surface of the Earth).

Force of Nature (FoN). Any phenomenon experienced as agentive (i.e., a phenomenon where our mind provides us with imagery of an agent/character we „meet" and can interact with). Examples are → Wind, → Water, → Heat & → Cold, Food, → Electricity, → Gravity. A FoN is characterized in terms of three basic aspects: → intensity and → tension, → extension (quantity, size, → amount), and → power. See also *Primary Forces of Nature*; *Basic Forces of Nature*; *Fundamental Forces*; *Force in mechanics*; *Interaction*; *Figure-Ground-Reversal*.

Forces-of-Nature Theater (FoN-T) performance. An embodied rendering of the interaction of two (or more) → Forces of Nature, where different groups of actors (children) represent different FoN that carry and exchange a prop (such as confetti or sand) representing → Energy.

Fundamental forces. Currently, physics identifies four fundamental forces (in the sense of mechanics, i.e., affecting motion) or, more generally, fundamental → Interactions: → Gravitation, → Electromagnetism, weak force, and strong force (weak and strong force act at the subatomic level). Physicists are currently trying to unify all four forces in a single theory. Even if they should be successful one day, such a theory will be essentially useless for doing applied science (astronomy, earth science, physics of living systems, ecology, etc.) and engineering—models in these fields use explanatory approaches at many different levels and of many different forms. See also *Force in mechanics*.

Generator (electrical). An electrical generator is a device that allows for quantity of electricity (electrical → Charge) to be forced to go from a place of low to a place of high → Electrical potential (against the direction of spontaneous flow). Batteries, fuel cells, solar cells, thunder clouds, and generators driven by rotatory machinery (such as dynamos) are all electrical generators.

Gestalt. In experiencing, experiential/perceptual units (called gestalts) are formed. Gestalts are → Abstractions from the unstructured flow of experience. Usually, when analyzed, gestalts reveal a number of aspects or characteristics. Examples of gestalts are → Image schemas, → Metaphors, and → Forces of Nature.

Gibbs. → Unit of → Chemical potential (also: G = J/mol).

Gradient. Measure of how „steep" a → Potential field is at a given location. Literally: the slope („steepness") of a hill. Examples: → Temperature gradient measures how fast, spatially speaking, the Temperature changes at a given location (always at a fixed point in time); therefore, the unit of temperature gradient is K/m (Kelvin per meter). Any potential field (such as level above ground, electric potential, gravitational potential, speed) can have a gradient. See also *Potential* and *Field (as mathematical concept)*.

Gravitation. See *Gravity (as FoN)*.

Gravitational field. The → Field created by (gravitational) → Mass. It is the physical object filling space (in the presence of mass) that mediates gravitational effects. See also *Gravity (as FoN)*.

Gravitational field (strength of). The strength of the → Gravitational field at the Earth's surface tells us how heavy a body of given → Mass will be, or how fast all bodies will accelerate in free fall. It is the measure of how fast the → Gravitational potential changes with height above ground. More generally, it is equal to the → Gradient of the gravitational potential. The value of the strength of the gravitational field at the Earth's surface equals roughly 10 standard SI units (J/(kg·m)).

Gravitational potential. The intensive quantity of → Gravity. Metaphorized as gravitational → Level. Unit: Joule/kilogram (J/kg).

Gravity (as FoN). As a → Force of Nature, Gravity shares the basic → Aspects of → Intensity (or → Tension), → Extension (or → Amount), and → Power with all the other FoN. Gravitational tension is the difference of values of the → Gravitational potential (which depends upon heights in a → Gravitational field). The quantity of gravity is (gravitational) → Mass. Gravitational power reveals itself when materials having mass go through a gravitational potential difference.

Heat. Often used as an abbreviation for → Amount of heat (→ Caloric).

Heat (as FoN). As a → Force of Nature, Heat shares the basic → Aspects of → Intensity (or → Tension), → Extension (or → Amount), and → Power with all the other FoN. Thermal tension is the difference of two values of → Temperature. The quantity of heat (→ Amount of heat) is what used to be called → Caloric (modern technical term: → Entropy). Thermal → Power reveals itself when quantity of heat goes through a temperature difference.

Heat pump. A heat pump is a device that allows for quantity of heat (→ Amount of heat) to be forced to go from a place of low to a place of high → Temperature (against the direction of spontaneous flow).

Heaviness. Nominalized form of the → Polarity denoted by heavy ↔ light. The → Degree of heaviness (apparent → Weight) of a body depends upon the surrounding → Fluid (such as air or water).

Hotness. Nominalized form of the → Polarity denoted by warm ↔ cold. See also *Temperature*.

Image schema. An → Abstraction (a → Gestalt) formed by recurring embodied → Experiencing. Examples: up-down (verticality), path, container, → Fluid substance, → Resistance, process, and many more. Image schemas are pre-conceptual; they are used, often → Metaphorically, in the construction of concepts.

Imagination. Very generally, the power of simulating → Experience in mind (rather than undergoing „external" physical experience). More specifically, the (mental) power of forming and manipulating (mental) „images." Images can be but do not need to be of a visual form.

Imagination (tools of). Important tools of → Imagination are → Image schemas, their metaphoric projection (→ Metaphor), forming → Analogies, and creating and understanding → Narrative forms.

Intensity. One of the three main aspects of a → Force of Nature. It describes the (feeling of) intensity of a phenomenon—usually as a → Tension, i.e., the difference of values of intensity of a phenomenon. Intensity is understood metaphorically as level (high ↔ low).

Intensive quantity. Formal measure of notion of → Intensity. For every → FoN, there exists an intensive quantity (such as → Pressure for → Fluids and → Temperature for → Heat).

Interaction (of FoN). We speak of interactions of → Forces of Nature where an → agent „meets" one or more → patients and „hands" → energy to the latter. „Meetings" take place in what are normally called devices (material objects: an electric motor, a windmill, a leaf on a tree...). Through → Figure-Ground-Reversal, FoN appear as figures (characters) acting and interacting on the „ground" formed by the material „meeting places."

Interaction (Fundamental Forces). In the theories of physics developed mostly in the 20th century, i.e., quantum mechanics and the physics of the four → Fundamental Forces, an interaction is a process of the exchange of → momentum, → spin, and → energy between two material particles (these exchanges are quantized, i.e., the smallest „packages" or „grains" of momentum, spin, and energy are going from particle to particle). The four → Fundamental Forces are associated with fields, and the interaction (i.e., the exchange) takes place through the fields in form of bosons (bosons are called the „force particles" as opposed to fermions, which are the „particles of matter").

Joule. → Unit of → Energy. Alternatively: Joule = Watt·second (J = W·s).

Kelvin. → Unit of → Temperature.

Kilo-Watt-Hour. Non-standard unit of → Energy. 1 kWh = $3.6{\cdot}10^6$ J (Joule).

Level. Literally: Height above ground. Figuratively: → Intensive quantities (→ Temperature, → Pressure, → Speed, → Brightness, ...) are metaphorized as levels (in terms of the → Image schema called VERTICAL SCALE; they are high or low).

Light (as electromagnetic radiation). In general, light is → Electromagnetic radiation; more specifically, it is that part of the spectrum of electromagnetic radiation that is visible to humans. Technically speaking, electromagnetic radiation is the transport of certain physical quantities (→ Amount of substance, → Spin, → Momentum, → Entropy, and → Energy) through the electromagnetic field.

Light (as FoN). As a → Force of Nature, Light shares the basic → Aspects of → Intensity, → Extension, and → Power with all the other FoN (particularly those we call activities). The power of Light reveals itself when Light causes other processes, such as the production of → Heat or the pumping of electric → Charge in a solar cell.

Loop rule (Kirchhoff's second rule). If we move along a closed path in a potential → Field (such as of → Level, → Temperature, → Electrical potential), we go „up" and „down." The sum of all → Potential differences will be equal to zero.

Magnetic field. The → Field created by magnetic charge, i.e., by magnetized materials, or flowing electrical → Charge (i.e., by → Electric currents). It is the physical object filling space (in the presence of magnetized materials) that mediates magnetic effects. It is an aspect of the → Electromagnetic field.

Magnetism (as a FoN). Just like many other phenomena, magnetism appears to us as a → FoN, i.e., it is characterized by → Intensity, → Amount, and → Power. Magnetism gives rise to → Electricity, and Electricity gives rise to Magnetism. Magnetism and → Electricity are seen as two sides of the same unified phenomenon, called → Electromagnetism.

Mass. The → Extensive quantity of → Gravity. It can flow and be stored. Unit: kilogram. See also *Amount of* gravity.

Matter. One of the types of „stuff" physical objects are made out of (the other type of „stuff" of physical objects are → Fields).

Mimesis (mimetic culture). The use of our body for acts of expression.

Metaphor (conceptual). A (unidirectional) mapping from a source domain onto a target domain (example: ANGER IS A HEATED FLUID, where elements of understanding of heated fluid are projected onto our experience of anger). A (conceptual) metaphor constitutes an essentially unconscious element of our understanding of the world in and around us. A metaphor is recognized through concrete → metaphoric expressions that consistently express a certain imaginative rendering of an element of the world. A → Basic metaphor is a mapping of an → Image schema upon an aspect of a phenomenon. Metaphor (as a → Cognitive tools) needs to be distinguished from → Metaphoric expression.

Metaphoric expression. Any concrete linguistic (or visual, gestural, artistic...) expression based upon a → Metaphor. For a given metaphor, there may be dozens or hundreds of expressions. Examples: For ANGER IS A HEATED FLUID, we may have *he did this in cold blood*, or *she blew her top;* for HEAT IS A POWERFUL AGENT, we may have *internal heat drives Jupiter's giant storm* or *heat counteracts the cold.*

Metaphoric web. A group of (conceptual) → Metaphors that together characterize a more or less complex → Experiential unit. Example of a metaphoric web for → Heat: HEAT IS A POWERFUL AGENT; HEAT IS A FLUID UNDER TENSION; HOTNESS

FORMS A LANDSCAPE; TEMPERATURE IS A VERTICAL SCALE; THERMAL TENSION IS A DRIVE; etc.

Mol. → Unit of → Amount of substance.

Molar mass. The → Mass of one mol of amount of substance. Unit: kilogram/mol.

Momentum. → Extensive quantity of → Motion (as a FoN). It can flow and be stored, but not created or destroyed; it is subject to a law of → Balance.

Motion (linear motion) as a FoN. As a → Force of Nature, Motion shares the basic → Aspects of → Intensity (or → Tension), → Extension (or → Amount), and → Power with all the other FoN. The intensity of Motion is the → Speed of a body. The quantity of motion → Momentum. The power reveals itself when momentum flows through a speed difference.

Myth/Mythic culture/Mythic consciousness. A form of human consciousness, understanding, or culture strongly related to primary → Experiencing, oral language, and storytelling. It is a form of human expression where outer and inner realms of existence are united to form a new unity. It is historically early (starting with Homo Sapiens), and early in the development of an individual as well. See also *Orality* and *Oral culture*.

Myth. A type of → Story created in → Oral society. Myths convey important knowledge of a society that needs to be handed down orally from generation to generation. Many myths speak of the relationship between humans and nature.

Mythic experience. The form of → Experience giving rise to mythic images.

Narrative. A category of spoken or written forms related to large-scale → Experiencing. → Story is the prototypical member of this category (there are many different forms of stories such as myth, fairy tale, short story, novel, news stories, etc.), but there are non-central members such as narrative explanation and explanatory narratives. A story is characterized by the following elements: (1) events; (2) (conscious) → Experiencing of events by → Agents; (3) → Tension for creating events; and (4) reason or occasion for telling by a narrator. Narratives can be contrasted with scientific papers (having a formal purpose), business documents, speeches, recipes, dictionary entries, and many more. See also *Stories of Forces of Nature*.

Newton. Unit of mechanical → Force.

Oral culture. A culture that rests upon the use of oral language (without having developed literacy). Children are in an oral culture before literacy has reached a certain degree of maturity.

Orality. The use of spoken language, or the ability to use it as a cognitive tool. See also *Oral culture*; *Literacy*; *Cognitive tools*.

Pascal. Unit of → Pressure.

Path. → Image schema. A schematic structure (→ Gestalt) having a number of aspects used in structuring → Experience. Example: → Polarities include a path between the poles with locations along the path (where a location stands for a degree of the intensive quantity characterized by the polarity). The path schema is used in many everyday → Metaphors (examples: Roman society moved towards self-destruction; by itself, heat flows from hot to cold).

Patient. In an → Interaction: the driven or caused → FoN. Example: heat that is produced with the help of electricity is the patient (here, electricity is the → agent). See also *Causation* and *Drive/driving force*.

Perception. Part of → Experience (i.e., part of the feedback cycle in the interaction of an organism with its various environments). It is the part that goes from an environment to the organism. See also *Gestalt*.

Polarity. A quality typically experienced quite directly such as → Hotness (→ Temperature), → Brightness, (the) good, or health. A polarity spans the distance between its poles, i.e., the extreme values (degrees) of a quality. Hotness spans degrees from extremely hot to absolutely cold (we use the symbol hot ↔ cold to denote the polarity of hotness); brightness is denoted by light ↔ dark, god by good ↔ bad, health by healthy ↔ ill. We usually have a number of different adjectives to express different degrees of a polarity (such as freezing cold, very cold, cold, tepid (lukewarm), warm, very warm, hot, very hot...). A polarity is structured by → Image schemas we call → Scale and path. Polarities are experienced as generating the Forces of Nature by giving us immediate access to the intensive aspect of a FoN and so suggesting the gestalt of a FoN. See also *Binary opposite*; *Image schema*; *Force of Nature*.

Potential. Technical term for → Intensive quantity associated with a → FoN. Used in particular for → Electric potential, → Gravitational potential, and → Chemical potential.

Potential difference. Difference of values of a potential (→ Intensity) at two positions; felt as → Tension, serves as → Driving force of processes.

Power (aspect of FoN). Qualitatively speaking, power measures the strength, vigor, or „force" of the interaction of two → Forces of Nature, i.e., of an → Agent and a → Patient. We might also say it measures how fast and how strongly the agent empowers the patient.

Power (as physical quantity). Quantitatively, power is the rate at which an → Agent make → Energy available, or the rate at which a → Patient uses energy (to become powerful in turn). The power of a process equals the product of the → Tension (→ Potential difference) undergone by a Force, and the → Current of the → Extensive quantity flowing through the potential difference. In case of → Production or → Destruction of the extensive quantity (in thermal or chemical processes), power equals the product of associated tension and → Destruction rate or → Production rate. Depending upon the process involved, we can speak of gravitational, thermal, hydraulic... power.

Pressure. → Intensive quantity of → Fluids. If taken as absolute pressure, it is the same as fluid tension. Unit: Pascal. See also → *Tension* and → Absolute potential.

Primary Forces of Nature. Examples are → Wind, → Rain, → Light, Fire, → Water, → Air, → Heat & Cold, Food, → Electricity, → Motion, → Gravity; even complex active systems such as volcanoes, rivers, ocean currents, forests, etc., appear as Forces. See also *Force of Nature*.

Production (rate). The rate at which a → Fluidlike quantity is produced (in physical processes, this applies to → Amount of heat (→ Caloric,→ Entropy) and → Amount of substance; in biology, this would be a rate at which organisms are born).

Process diagram. A diagram using visual → Metaphors for representing the → Interaction of → FoN. A PD makes use of → Figure-Ground-Reversal: physical objects are represented as backgrounds, FoN are shown in visual metaphoric representations. It uses graphical symbols for representing metaphoric renderings of → Potentials (→ Levels), → Flows, → Production and → Destruction rates,

→ Power, and → Energy currents. In case of non-steady-state phenomena, the diagrams include symbols for → Storage.

Radiation. Generally speaking, it is a transport process. In the case of → Electromagnetic radiation, it is the transport of certain physical quantities (→ Amount of substance, → Spin, → Momentum, → Entropy, and → Energy) through the electromagnetic field. Radiation can also refer to the (high energy) flow of → Matter (such as so-called alpha- and beta-radiation) through empty space or through materials.

Rain (as FoN). As a → Force of Nature, Rain shares the basic → Aspects of → Intensity, → Extension, and → Power with all the other FoN (particularly those we call activities, like → Wind and → Light). The power of Rain is seen in the filling of lakes and rivers and in making the soil moist. Rain, as a → Perceptual unit, should be distinguished from „falling" water.

Reaction. See *Chemical reaction.*

Resistance. In general, the abstract schema of something resisting a process. In physics, resistance measures the quality of a material that tells us how hard it is for a → Fluidlike quantity to pass through the material in conductive → Flow. It is equal to the inverse of → Conductance. See also *Conduction.*

Romantic culture and understanding. As postulated by K. Egan (*The Educated Mind*, 1997), the phase of cultural understanding following the mythic phase. It is marked by understanding enabled by early literacy. See also *Myth* and *Cognitive tools.*

Rotation (rotational motion) as a FoN. As a → Force of Nature, Rotational motion (short: Rotation) shares the basic → Aspects of → Intensity (or → Tension), → Extension (or → Amount), and → Power with all the other FoN. The intensity of Rotation is the → Rotational speed of a body. The quantity or → Amount of Rotation is → Spin (angular momentum). The power reveals itself when momentum flows through a speed difference.

Rotational speed. The → Intensive quantity of → Rotation (rotational motion). Alternatively: the rate at which the angle of a rotating body changes. Unit: 1/second (angle does not have a unit!).

Scale (image schema). → Image schema. A schematic structure (→ Gestalt) having a number of aspects used in structuring → Experience. Example: A scale is superimposed upon the → Path between the poles of a → Polarity and so constructs the sense of degree of the intensive quantity characterized by the polarity.

Schematizing action (of mind). In → Experiencing, the interaction of body and mind lead to the construction of schematic structures. See *Image schema.*

Speed. The → Intensive quantity of → Translational motion. Alternatively: the rate at which position of a body changes. Unit: meter/second.

Spin. The → extensive aspect of rotational motion, i.e., the → Amount of rotational motion (also called → Angular momentum). It can flow and be stored. Unit: Newton·meter·second.

Storage. Term denoting the imagined storing of → Fluidlike quantities in storage devices (materials and → Fields).

Story. The prototypical member of the category of → Narrative.

Story of Forces of Nature. In stories of → FoN, Forces are the → Agents, and → Tensions (→ Potential differences) are the tensions associated with FoN. See also *Story* and *Narrative.*

Substance (as FoN). The myriad chemical substances can all be considered to act as → Forces of Nature. As a FoN, a Substance shares the basic → Aspects of → Intensity (or → Tension), → Extension (or → Amount), and → Power with all the other FoN. Chemical tension is the difference of two values of → Chemical potential. The → Amount of substance is what the name indicates: it tells us how much of a chemical is involved in a process. Chemical → Power reveals itself when an amount of substance goes through a chemical potential difference (this happens in → Diffusion and in → Chemical reactions).

Temperature. Mark on the → hotness → scale: temperature measures how hot/warm/cold a material is. Alternatively, the → Intensive quantity of → Heat. Metaphorized as thermal → Level. Unit: Kelvin.

Tension. The difference of values (→ degrees) of → intensity of a FoN at two different locations. Tensions are felt directly/physically/bodily. Examples: → temperature difference, difference of → brightness, difference of sweetness, etc.

Thermoelectricity. A phenomenon where → Charge and → Amount of heat (→ Caloric,→ Entropy) flow together (directly coupled to each other). The phenomenon is used to build devices that can work either as electrical → Generators or as → Heat pumps.

Translational motion (linear motion). See *Motion (linear).*

Transport. → Fluidlike quantities are transported (flow by themselves of are carried → Convectively or with → Radiation) from one location to another (through bodies and → Fields).

Unit (of a physical quantity). When quantifying a physical quantity, i.e., when giving it a numerical value, a unit needs to be associated with the value to give the number any concrete meaning. There are different systems of units. The standard one in physics is the SI-system of units.

Volt. Unit of → Electric potential.

Voltage. In English (but not in German, Italian, or French), voltage denotes the → Electric tension. Unit: → Volt.

Water (as FoN). Water appears as the „background" of different → FoN. Examples: it can be a → Fluid FoN (like → Air), or a chemical FoN like *Air (as chemical FoN)*. When we speak of Water as FoN, we often use it in the sense of Fluid FoN (as a hydraulic → Agent).

Watt. Unit of → Power (as physical quantity).

Weight. Qualitatively, this is the → Degree on the → Scale of → Heaviness, or simply how heavy an object appears. Formally, it is the → Force of gravity upon an object at the surface of a planet such as the Earth.

Wind (as FoN). As a → Force of Nature, Wind shares the basic → Aspects of → Intensity, → Extension, and → Power with all the other FoN (particularly those we call activities). The intensity of Wind is related to the speed of flow, and the extension is measured by the area perpendicular to the flow through which Wind goes. The power of Wind reveals itself directly in driving → Motion or → Rotation. As a → Perceptual unit, Wind should be distinguished from „moving" → Air.

References

Amin, T. G. (2009). Conceptual metaphor meets conceptual change. *Human Development*, 52(3), 165–197.

Amin, T. G., Jeppsson, F., & Haglund, J. (2015). Conceptual metaphor and embodied cognition in science learning: Introduction to special issue. *International Journal of Science Education*, 37(5–6), 745–758.

Arnheim R. (1954): *Art and Visual Perception*. University of California Press. Berkeley, CA.

Arnheim R. (1969): *Visual Thinking*. University of California Press. Berkeley, CA.

Atkins, L. J. (2004). *Analogies as categorization phenomena: Studies from scientific discourse*. PhD Thesis, University of Maryland. https://drum.lib.umd.edu/handle/1903/2040 (visited on 26 of May, 2022).

Barber E. J. W., & Barber P. T. (2004): *When They Severed Earth From Sky. How the Human Mind Shapes Myth*. Princeton University Press, Princeton, NJ.

Beccari G. (2016). C'era una volta Rabbia, c'era una volta Calore. Basi emotive del pensiero razionale. Master Thesis, Dipartimento di Educazione e Scienze Umane. University of Modena and Reggio Emilia, Italy.

Bergen, B. K. (2012). *Louder Than Words. The New Science of How the Mind Makes Meaning*. New York: Basic Books.

Black J. (1803). *Lectures on the Elements of Chemistry*. Volume I. Edinburgh: W. Creech.

Boohan R. & Ogborn J. (1992-1995): *Energy and Change*. Available at https://www.stem.org.uk/resources/collection/3624/energy-and-change.

Borer T., Frommenwiler P., Fuchs H. U., et al. (2010): *Physik, ein systemdynamischer Zugang*. 3rd edition. h.e.p. verlag, Bern.

Calendar, H. L. (1911): The Caloric Theory of Heat and Carnot's Principle. *Proc. Phys. Soc.* **23**, 153–189.

Campbell J. (1990): *Transformations of Myth Through Time*. Harper Perennial, New York, NY.

Caracciolo, M. (2014). *The Experientiality of Narrative: An Enactivist Approach*. Berlin: de Gruyter.

Carnot, S. (1824). *Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance.* Paris: Bachelier. R. H. Thurston (1897). *Reflections on the Motive Power of Heat*. Second revised edition. Trans. and edited. New York: John Wiley & Sons.

Casey, E. S. (2000). *Imagining. A Phenomenological Study*. Bloomington and Indianapolis, IN: Indiana University Press.

H. U. Fuchs, F. Corni, *Primary Physical Science Education*,
https://doi.org/10.1007/978-3-031-43953-7

Cassirer, E. (2020/1925). *The Philosophy of Symbolic Forms, Volume 2: Mythical Thinking*. London, UK: Routledge (German original: 1925).

Chemero, A. (2009). *Radical Embodied Cognitive Science*. Cambridge, MA: The MIT Press.

Clausius R. (1850). Über die bewegende Kraft der Wärme und die Gesetze, welche sich daraus für die Wärmelehre selbst ableiten lassen. *Annalen der Physik*, 155(3), 368-397.

Clausius R. (1865). Über verschiedene für die Anwendung bequeme Formen der Hauptgleichungen der mechanischen Wärmetheorie. *Vierteljahresschrift der Naturforschenden Gesellschaft* (Zürich), 10,1-59.

Cook, J. (2013). *Ice Age Art—The Arrival of the Modern Mind*. London, UK: The British Museum Press.

Corni, F. (ed.). (2013). *Le scienze nella prima educazione. Un approccio narrativo a un curricolo interdisciplinare*. Trento: Erickson.

Corni, F., Fuchs, H. U., Landini, A., & Giliberti, E. (2019a): Visual and gestural metaphors for introducing energy to student teachers of primary school and kindergarten levels. *Journal of Physics: Conference Series*, 1287, 012043. https://doi.org/10.1088/1742-6596/1287/1/012043.

Corni, F., Fuchs, H. U., & Dumont, E. (2019b): Conceptual metaphor in physics education: roots of analogy, visual metaphors, and a primary physics course for student teachers. *Journal of Physics: Conference Series*, 1286, 012059. https://doi.org/10.1088/1742-6596/1286/1/012059.

Corni, F., & Fuchs, H. U. (2020). Primary physical science for student teachers at kindergarten and primary school levels: Part I—foundations of an imaginative approach to physical science. *Interchange*, **51**, 315–343.

Corni, F., & Fuchs, H. U. (2021). Primary Physical Science for Student Teachers at Kindergarten and Primary School Levels: Part II—Implementation and Evaluation of a Course. Interchange, **52**, 203–236.

Deacon, T. (1997). *The Symbolic Species: The Co-Evolution of Language and the Brain*. New York: Norton.

Deichmann M. (2014a): Im übertragenen Sinne. Metaphern und Bildvergleiche in der Wissenschaft; Bachelor thesis, Zürcher Hochschule der Künste, Zürich.

Deichmann M. (2014b): *Perpetuum Mobile*, found at http://vimeo.com/98311515.

De Jaegher, H., & Di Paolo, E. (2007). Participatory sense-making: An enactive approach to social cognition. *Phenomenology and the Cognitive Sciences* **6**(4), 485-507.

Dewey, J. (1925). *Experience and Nature*. In J. A. Boydston (Ed.), The later works (1925–1953, Vol. 1). Carbondale, IL: Southern Illinois University Press.

Di Paolo, E. A., Cuffari E. C., & De Jaegher H. (2018). *Linguistic Bodies. The Continuity between Life and Language*. Cambridge, MA: The MIT Press.

Donald, M. (1991). *Origins of the Modern Mind: Three Stages in the Evolution of Culture and Cognition*. Cambridge MA: Harvard UP.

Duff, M. C., Covington N. V., Hilverman C., & Cohen N. J. (2020). Semantic Memory and the Hippocampus: Revisiting, Reaffirming, and Extending the Reach of Their Critical Relationship. *Frontiers in Human Neuroscience*, 24 January 2020.

Egan, K. (1986). *Teaching as Story Telling*. Chicago: The University of Chicago Press.

Egan, K. (1988). *Primary Understanding. Education in Early Childhood*. New York: Routledge.

Egan, K. (1990). *Romantic Understanding. The Development of Rationality and Imagination*. New York: Routledge.

Egan, K. (1997). *The Educated Mind. How Cognitive Tools Shape our Understanding*. Chicago IL: The University of Chicago Press.

Egan, K. (2005). *An Imaginative Approach to Teaching*. San Francisco CA: John Wiley & Sons.

Falk G., Herrmann F., & Schmid G. B. (1983): Energy forms or energy carriers? *Am.J.Phys.* **51**(12), 1074-1077.

Fleer, M. (2019). Scientific Playworlds: A model of teaching science in play-based settings. *Research in Science Education*, **49**(5), 1257-1278.

Forceville C., & Urios-Aparisi (eds.) (2009): *Multimodal Metaphor.* Mouton de Gruyter, Berlin.

Fuchs H. U. (1986): A surrealistic tale of electricity. *Am. J. Phys.* 54, 907–909.

Fuchs H. U. (1987): Entropy in the teaching of introductory thermodynamics. *Am. J. Phys.* 55, 215-219.

Fuchs, H. U. (2006). System Dynamics Modeling in Fluids, Electricity, Heat, and Motion. GIREP Invited Talk, Amsterdam. In E. van den Berg, T. Ellermeijer, O. Slooten: Modeling in Physics and Physics Education. *Proceedings of the GIREP Conference* 2006, August 20-25, Amsterdam. (ISBN 978-90-5776-177-5)

Fuchs H. U. (2010[1996]): *The Dynamics of Heat. A Unified Approach to Thermodynamics and Heat Transfer*. Second Edition (First Edition: 1996), Springer, New York.

Fuchs H. U. (2011): Force dynamic gestalt, metafora e pensiero scientifico. In F. Corni, C. Mariani, & E. Laurenti (Eds.), *Innovazione nella didattica delle scienze nella scuola primaria: Al crocevia fra discipline scientifiche e umanistiche* (pp. 8–18). Modena: Artestampa. English version: Force Dynamic Gestalt, Metaphor, and Scientific Thought. http://www.hansfuchs.org/LITERATURE/Literature.html.

Fuchs H. U. (2014a): Dal pensiero mitico alla conoscenza della natura. In Corni F. & Altiero T.: Innovazione nella didattica nella scuola primaria e dell'infanzia. Universities Studiorum, Mantova. English version: H. U. Fuchs (2012): From Mythic Thought to an Understanding of Nature; found at http://www.hansfuchs.org/LITERATURE/Literature.html.

Fuchs, H. U. (2014b). The narrative structure of continuum thermodynamics. In C. P. Constantinou, N. Papadouris & A. Hadjigeorgiou (Eds.), *E-book proceedings of the ESERA 2013 conference: Science education research for evidence-based teaching and coherence in learning.* Part 1 (pp. 50–51). Nicosia: European Science Education Research Association.

Fuchs H. U. (2014c): A Direct Entropic Approach to Uniform and Spatially Continuous Dynamical Models of Thermoelectric Devices. *Energy Harvesting and Systems* 1(3-4): 253–265.

Fuchs, H. U. (2015). From stories to scientific models and back: Narrative framing in modern macroscopic physics. *International Journal of Science Education*, **37**(5–6), 934–957.

Fuchs H. U. & Fuchs R. (2012): A collection of short stories of forces of nature.

Fuchs, H. U. & Cervi, M. (2015). Wind or Air? A dialogue about forces of nature, emotion, and good stories. In F. Corni & T. Altiero (Eds.), *Innovazione Nella Didattica Delle Scienze Nella Scuola Primaria e Dell'Infanzia: Al Crocevia Fra Discipline Scientifiche e Umanistiche*. Mantova IT: Universitas Studiorum. ISBN 9788899459284, p. 87-108.

Fuchs, H. U., Contini, A., Dumont, E., Landini, A., & Corni, F. (2019). How metaphor and narrative interact in stories of forces of nature. In M. Hanne & A. A. Kaal (Eds.), *Narrative and Metaphor in Education: Look Both Ways* (pp. 91–104). Routledge, London, UK.

Fuchs, H. U., Corni, F., & Dumont, E. (2021). Narrativity in Complex Systems. In A. Zeyer & R. Kyburz-Graber (Eds.), *Science / Environment / Health. Towards a Science Pedagogy of Complex Living Systems*. Springer, Cham, Switzerland.

Fuchs, H. U., Corni, F., & Pahl, A. (2021). Embodied Simulations of Forces of Nature and the Role of Energy in Physical Systems. *Educ. Sci.* **11**, 759.

Fuchs, H. U., d'Anna, M., & Corni, F. (2022). Entropy and the experience of heat. *Entropy* **24**, 646. https://doi.org/10.3390/educsci11120759.

Fuchs, H. U.; Dumont, E.; Corni, F. (2023). Narrative minds in the construction and use of theories of Forces of Nature— A model of experience at different scales. In *Narrative and Cognition in Literature and Science*; Sinding, M., Heydenreich, A., Mecke, K. Eds.; ELINAS Series; De Gruyter: Berlin, Germany.

Fuchs R. & Fuchs H. U. (2010-2023): *Collected Stories of Forces of Nature*. Unpublished.

Gebser, J. (1986). *The Ever Present Origin*, vols. 1&2. Athens OH: Ohio University Press. Original German: *Ursprung und Gegenwart* (2 vols.), 1949-1953. 2nd ed., Schaffhausen, Switzerland: Novalis Verlag, 1999.

Gelmi A. (2022). Creative imagination in primary science education: Scientific Playwords and Forces of Nature. Report, Free University of Bolzano, Italy.

Gibbs R. W. (2019): Metaphor as Dynamical–Ecological Performance, *Metaphor and Symbol*, **34**(1), 33-44, DOI: 10.1080/10926488.2019.1591713.

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. Boston: Houghton-Mifflin.

Giere, R. N. (2006). *Scientific Perspectivism*. The University of Chicago Press, Chicago Ill.

Gingerich, O., & Voelkel J. R. (2005). Tycho and Kepler: Solid Myth versus Subtle Truth. *Social Research*, **72**(1), 77-106.

Grady J. (2005): Primary metaphors as inputs to conceptual integration. *Journal of Pragmatics* 37, 1595–1614.

Gyori, G., & lren Hegedus, I. (1993). Is everything black and white in conceptual oppositions? *Issues in Cognitive Linguistics*. In Leon de Stadler & Christoph Eyrich: *Proceedings of the International Cognitive Linguistics Conference*.

Hampe, B. (2005). *From Perception to Meaning. Image Schemas in Cognitive Linguistics*. Berlin: Mouton de Gruyter.

Herman, D. (2002). *Story Logic*. Lincoln, NE: University of Nebraska Press.

Herman, D. (2009). *Basic Elements of Narrative*. Chichester: Wiley-Blackwell.

Herman, D. (2013). *Storytelling and the Sciences of Mind*. Cambridge, MA: The MIT Press.

Herrmann F. (1990-2021): *The Karlsruhe Physics Course*. The KPK is available for download in many different languages. Here is the English language version: https://www.physikdidaktik.uni-karlsruhe.de/publications/englisch.html.

Herrmann F. (2000). The Karlsruhe Physics Course. *Eur. J. Phys.* **21**(1), 49-58.

Hobson A. (2013): There are no particles, there are only fields. *Am.J.Phys.*, **81**, 211.

Hutto, D. D. (2007). The Narrative Practice Hypothesis: Origins and Applications of Folk Psychology. *Royal Institute of Philosophy Supplement* **60**, 43-68.

Hutto, D. D., & Myin E. (2013). *Radicalizing Enactivism. Basic Minds Without Content*. Cambridge, MA: The MIT Press.

Ivory J. (1827): Investigation of the heat extricated from air when it undergoes a given condensation, *Phil. Mag*. (n.s.) 1, 89–94.

James, W. (1890/1950). *The Principles of Psychology*. 2 vols. New York: Dover.

James, W. (1911). Percept and Concept and Their Practical Uses. In *Some Problems of Philosophy*, 21-60. Cambridge, MA: Harvard University Press.

Job, G. (1972): *Neudarstellung der Wärmelehre—Die Entropie als Wärme*; Akademische Verlagsgesellschaft: Frankfurt, Germany.

Job G. & Rüffler R. (2016). *Physical Chemistry from a Different Angle: Introducing Chemical Equilibrium, Kinetics and Electrochemistry by Numerous Experiments*. Cham, Switzerland: Springer.

Johnson, M. (1987). *The Body in the Mind*. Chicago, IL: University of Chicago Press.

Johnson, M. (2007). *The Meaning of the Body. Aesthetics of Human Understanding*. Chicago, IL: University of Chicago Press.

Keil, F. C. (2010). The Feasibility of Folk Science. *Cognitive Science* **34**, 826–862.

Kind, A., ed. (2016). *The Routledge Handbook of Philosophy of Imagination*. London and New York: Routledge.

Koestler A. (2017[1959]). *The Sleepwalkers—A History of Man's Changing Vision of the Universe*. London UK: Penguin.

Lakoff G. (1987): *Women, Fire, and Dangerous Things. What Categories Reveal about the Mind.* The University of Chicago Press, Chicago Ill.

Lakoff, G., & Johnson, M. (1980). *Metaphors We Live By*. Chicago: University of Chicago Press.

Lakoff, G., & Johnson, M. (1999). *Philosophy in the Flesh*. New York: Basic Books.

Lakoff, G., & Kövecses, Z. (1987). The cognitive model of anger inherent in American English. In D. Holland & N. Quinn (Eds.), *Cultural models in language and thought* (pp. 195–221). Cambridge University Press.

Lakoff G., & Nuñez R. E. (2000). *Where Mathematics Comes From. How The Embodied Mind Brings Mathematics Into Being*. Basic Books, New York, NY.

Landini, A., Giliberti, E., & Corni, F. (2019). The Role of Playing in the Representation of the Concept of Energy: A Lab Experience for Future Primary School Teachers. In E. McLoughlin & P. van Kampen (Eds.), Concepts, Strategies and Models to Enhance Physics Teaching and Learning (pp. 125–137). Springer. https://doi.org/10.1007/978-3-030-18137-6.

Lavoisier A. L., (1789). *Traite elementaire de chimie*. Paris: Cuchet.

Leavitt, R. M. (2011). Reading a Dictionary. How Passaquamoddy Language Translates Concepts of Physical and Social Space. In B. Swann: *Born in the Blood. On Native American Translation*. Lincoln NE: University of Nebraska Press.

Lévi-Bruhl, L. (1985). *How Natives Think* (Lilian A. Clare, trans.; C. Scott Littleton, Intro.), Princeton, NJ: Princeton University Press (French original: 1910).

Lévi-Strauss, C. (1966). *The Savage Mind*, Chicago: University of Chicago Press.

Lévi-Strauss, C. (1969). *The Raw and the Cooked*, New York: Harper & Row.

Lévi-Strauss, C. (1978). *Myth and Meaning*, London and New York: Routledge.

Levy, A. & Godfrey-Smith, P., eds. (2020). *The Scientific Imagination. Philosophical & Psychological Perspectives*. Oxford, UK: Oxford University Press.

Lindqvist, G. (1995). The aesthetics of play: a didactic study of play and culture in preschools. (Doctoral dissertation). Uppsala Studies in Education, 62, 1–234. Uppsala, Sweden: Acta Universitatis Upsaliensis.

Losev, A. F. (1930). *The Dialectics of Myth*. Translated form the Russian by Vladimir Marchenkov. London and New York: Routledge (2003).

Mach E. (1896). *Die Principien der Wärmelehre. Historisch-kritisch entwickelt*. Leipzig: Barth. https://archive.org/details/dieprincipiender00mach

Magalotti L. (1667). *Saggi di naturali esperienze fatte nell'Accademia del Cimento sotto la protezione del serenissimo principe Leopoldo di Toscana e descritte dal segretario di essa Accademia*. Library of Congress, https://www.loc.gov/resource/rbctos.2017gen22504/?sp=7. English translation: *Essayes of natural experiments made in the Academie del Cimento* [...] Englished By Richard Waller (1684).

Mandler, J. (2004): *The Foundations of Mind: Origins of Conceptual Thought*. Oxford, UK: Oxford University Press.

Mares, J. J.; Hubik, P.; Sestak, J.; Spicka, V.; Kristofik, J.; Stavek, J. (2008): Phenomenological approach to the caloric theory of heat. *Thermochim. Acta* **474**, 16–24.

Mariani C., Corni F., Fuchs H. U. (2011). A didactic approach to and curricular perspectives of the construction of the energy concept in primary school. In: A. Lindell, A.- L. Kähkönen, & J. Viiri. Physics Alive. *Proceedings of the GIREP-EPEC 2011 Conference*. Jyväskylä, 1-5 Agosto 2011, p. 248-253.

Mariani, C., Laurenti, E., & Corni, F. (2012). Hands-on , minds-on activities to construct the concept of energy in primary school : Experiments , games and group discussions. *Latin American Journal of Physics Education*, 6(August), 105–111.

Maurer, D., Riboni, C., & Gujer B. (2009). Early pictures in ontogeny. *Image*, **9** (1), 2-21, (d/e). https://www.early-pictures.ch/de/publications/Image_9_1.pdf (visited on May 18,2022).

Maurer, D., & Riboni, C. (eds.) (2010). *Bild und Bildgenese*, Berlin: Peter Lang Verlag.

Maurer, D., et al. (2013-2019). *Wie Bilder „entstehen."* 5 vols. Berlin: Peter Lang Verlag. https://www.peterlang.com/search?searchstring=Maurer+Riboni (visited on 18 May,2022).

Mithen, S. (1996). *The Prehistory of the Mind. A Search for the Origins of Art, Religion and Science*. London: Thames and Hudson, Ltd.

Morgan M. (2012): *The World in the Model. How Economists Work and Think.* Cambridge University Press, Cambridge UK.

Müller, I. (1985). *Thermodynamics*. Boston, MA: Pitman.

Neumann E. (1949/1954): *The Origins and History of Consciousness*. Princeton, NJ: Princeton University Press.

Newton I. (1687). *Philosophiae Naturalis Principia Mathematica*. Londini, Societatis Regiae ac typis Josephi Streater.

Nixon, G. (2010). Myth and Mind. *Journal of Consciousness Exploration & Research*, **1**(3), 77-125 (ISSN:2153-8212).

Noble, P. S. (2005). *Plant Physiology*, 3rd edition. Amsterdam, The Netherlands: Elsevier, Academic Press.

Noë, A. (2004). *Action in Perception*. Cambridge, MA: The MIT Press.

Ong, W. J. (1982). *Orality and Literacy*. London and New York: Methuen.

Pahl, A.; Fuchs, H.U.; & Corni, F. (2022); Young Children's Ideas about Heat Transfer Phenomena. *Educ. Sci.* **12**, 263. https://doi.org/10.3390/ educsci12040263.

Pahl, A.; Fuchs, H.U.; Corni, F. (forthcoming).

Parry, A. ed. (1987). *The Making of Homeric Verse. The Collected Papers of Milman Parry*. Oxford, UK: Oxford University Press.

Petrarch, F. (1336/1948): *The Ascent of Mount Ventoux, The Renaissance Philosophy of Man*, eds. E. Cassirer et al. Chicago: University of Chicago Press.

Rorty R. (1979). *Philosophy and the Mirror of Nature*. Princeton NJ: Princeton University Press.

Rosch E. (1973): Natural Categories. *Cognitive Psychology*, **4**, 328-350.

Rosch E., Mervis C., Gray W., Johnson D., & Boyes-Broem P. (1976): Basic Objects in Natural Categories. *Cognitive Psychology*, 8, 382-439.

Rosch E., & Lloyds B. B., eds. (1978): *Cognition and Categorization*. Lawrence Erlbaum Associates, Hillsdale, N.J..

Rovelli C. (2017): *Reality is Not What it Seems*. New York, NY: Penguin Random House LLC.

Rowett C. (2016), "Love, Sex and the Gods: Why Things Have Divine Names in Empedocles' Poem, and Why They Come in Pairs", *Rhizomata*, 4(1): 80–100.

Sassi E. (2006): Personal communication.

Simons D. J., & Keil F. C. (1995): An abstract to concrete shift in the development of biological thought: the insides story. *Cognition*, **56**, 129-163.

Sproul B. C. (1979): *Primal Myths. Creation Myths Around the World*. Harper Collins, New York.

St. Clair R. N. (2000). Visual Metaphor, Cultural Knowledge, and the New Rhetoric. Chapter 8 (pp. 85-101) of *Learn in Beauty: Indigenous Education for a New Century*, edited by Jon Reyhner, Joseph Martin, Louise Lockard, and W. Sakiestewa Gilbert.

Talmy, L. (2000). *Toward a Cognitive sSmantics*. Volume I: *Concept structuring systems*. Volume II: *Typology and process in concept structuring*. Cambridge: The MIT Press.

Tomasello, M. (2008). *Origins of Human Communication*. Cambridge, MA: The MIT Press.

Tomasello, M. (2014). *A Natural History of Human Thinking*. Cambridge, MA: Harvard University Press.

Tribus M., & McIrvine E. C. (1971). Energy and Information. *Scientific American*. Vol. 225, No. 3 (September 1971), pp. 179-190.

Truesdell C. (1980). *The Tragicomical History of Thermodynamics*. New York, NY: Springer-Verlag.

Truesdell, C. a. (1984). *Rational Thermodynamics*, 2nd ed.; New York, NY: Springer-Verlag.

Tulving, E. (1985). How many memory systems are there? *American Psychologist*, **40** (4), 385-398.

Tulving, E. (1986). What kind of hypothesis is the distinction between episodic and semantic memory? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **12** (2), 307-311.

Varela, F. J., Thompson, E., and Rosch, E. (1991). *The Embodied Mind: Cognitive Science and Human Experience*. Cambridge: MIT Press.

Weber K. (2006): Evolution des Bewusstseins. Lecture notes, Department of Applied Linguistics, Zurich University of Applied Sciences at Winterthur.

Wiley D. & Fimbres Weihs G. (2016): Electro-osmosis, Overview of.... In Drioli E. Giorno L. (eds.), *Encyclopedia of Membranes*. Springer-Verlag, Berlin.

Wilson C. (1972). How Did Kepler Discover His First Two Laws? *Scientific American*. Vol. 226, No. 3 (September 1971), pp. 92-107.

Wittgenstein L. (1953): *Philosophical Investigations*. Macmillan, New York.

Wood, R. (1767). *An Essay on the Original Genius and Writings of Homer*. Miami FL: Hard Press (2017).

Yus R. (2009): Visual metaphor versus verbal metaphor: A unified account. Chapter 7 of Forceville C., & Urios-Aparisi (eds.) (2009): *Multimodal Metaphor.* Mouton de Gruyter, Berlin.

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