Neo-Aristotelian Metaphysics and the Theology of Nature

Edited by William M. R. Simpson,
Robert C. Koons, and James Orr

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William M. R. Simpson

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1. Introduction

What is the world made of, and how do we fit into it? If it is made out of something, then are there *many* things or is there really just *one* thing, of which everything else is derivative? Philosophical questions about the nature of matter did not begin with the Scientific Revolution, nor with the advent of modern philosophy. In fact, in seeking to make sense of modern theories like quantum mechanics, both pioneering physicists, like Werner Heisenberg, and leading philosophers of science, like Nancy Cartwright, have found themselves reaching as far back as the metaphysics of Aristotle for inspiration, whose philosophy was shaped in turn by Plato and the pre-Socratics.

In this chapter, I shall argue that the existence of quantum entanglement and the phenomenon of emergence in finite temperature quantum systems have called into question the microphysicalist conception of nature that dominated the landscape of modern philosophy, in which the world of ordinary experience was reducible to a spatiotemporal arrangement of microscopic constituents. I shall further argue that they have opened a path toward a non-reductive conception of nature familiar to medieval theologians like Thomas Aquinas, in which many of the objects of ordinary experience possess 'forms' that determine their natures.

Although the philosophy of the Middle Ages was far from monolithic, medieval metaphysics from the thirteenth century can be broadly characterised within the Latin tradition by its explicit commitment to Aristotle's hylomorphic analysis of substances in terms of 'matter' (*hyle*) and 'form' (*morphe*).[1] Whilst strict demarcations between medieval and early modern philosophy are increasingly discouraged by historians of philosophy, the widespread rejection of form as the determining principle of matter,[2] led by the early modern philosophers René Descartes and John Locke, is nonetheless a striking discontinuity between medieval and modern notions of the natural order. The abandonment of Aristotle's hylomorphic doctrine of substances laid the foundation for a microphysicalist conception of nature in which the whole of reality is reducible to some set of

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microscopic constituents whose physical properties are arranged according to universal laws. Indeed, the rise of microphysicalism has sometimes been presented as one of the lasting and inevitable triumphs of modern science, in which an opaque medieval philosophy was forced into retreat by a more perspicuous account of nature committed solely to the existence of properties which can be measured.

I aim to put such hackneyed claims into question by raising doubts about the compatibility of microphysicalism with contemporary physics and by drawing upon the doctrine of hylomorphism to make sense of physical phenomena at certain points where a dogmatic commitment to microphysicalism may be inhibiting understanding.[3] Just as Aristotle's conception of causal powers has recently been reclaimed in contemporary philosophy, I shall argue, hylomorphism is ripe for rehabilitation. The discussion is divided into the following sections.

In Section 2, I consider Aristotle's doctrine of hylomorphism, as it was interpreted by Aquinas, and suggest that the widespread rejection of substantial form was partly the consequence of a 'physicalisation' of hylomorphism in which matter came to be seen as having physical properties independently of substantial form, combined with a faith in the explanatory power of microphysical reductionism which contemporary science no longer supports. In Section 3, I argue that the phenomenon of quantum entanglement gives us good reason to question whether microphysical systems have *intrinsic* physical properties, and I sketch my recent neo-Aristotelian account of the de Broglie-Bohm version of quantum mechanics in which substantial form plays a fundamental role in *grounding* the physical properties of particles. In this metaphysical model, the only fundamental physical entity is the cosmos. In Section 4, I argue that the phenomenon of emergence in finite temperature quantum systems gives us good reason to doubt whether the world is a single, closed quantum system whose behaviour can be understood in terms of universal laws. I offer a hylomorphic account of the 'contextual wave function collapse' theory of quantum mechanics put forward by the physicists Barbara Drossel and George Ellis, for whom the evolution of quantum systems is open to their 'classical' environments and subject to local, macroscopic boundary conditions. In this alternative metaphysical model, there are a plurality of substantial forms which determine the natures of different 'thermal substances'.

2. Matter Physicalised

2.1. Modern Microphysicalism

The writer and lay-theologian, C. S. Lewis, who held the chair of Mediaeval and Renaissance Literature at Magdalene College, Cambridge, described the highest achievements of the Middle Ages as the 'medieval synthesis itself, the whole organisation of their theology, science, and history into a single, complex, harmonious mental model' (Lewis, 1964, p. 11). The medieval mind had a genius for developing systems in which 'highly original and soaring philosophical speculation squeezes itself into a rigid dialectical pattern copied from Aristotle' (p. 10).

Modern philosophy, in contrast, has typically adopted a more piecemeal approach to reality. Among analytic philosophers, the question of how human beings fit into the world, for example, is sometimes framed (ironically) in the following way: when God made the physical world, did he have to *add* anything in order for there to be human agents, who (apparently) have causal powers to act in pursuit of their various purposes and goals? Under these rules, the aim of the game for philosophers of mind, or theologians, or anybody whose subject matter is deemed less respectable than physics, is to relate those things that they want to talk about to the fundamental physical facts, without helping themselves, ontologically speaking, to anything more than is strictly necessary.

According to David Lewis – a leading analytic philosopher of the last century and a staunch microphysicalist – the answer to this ontological question is a decided negative:

> all there is to the world is a vast mosaic of local matters of particular fact, just one little thing and then another . . . We have geometry: a system of external relations of spatio-temporal distances between points . . . And at those points we have local qualities: perfectly natural intrinsic properties which need nothing bigger than a point at which to be instantiated. For short, we have an arrangement of qualities. And that is all.
>
> (Lewis, 1986, p. ix)

For the modern disciple of David Hume, who denied any necessary connections between the properties of things and the causal powers we happen to associate with them, the law-like way in which the world appears to be organised reflects nothing more than a human habitus for systematisation. According to David Lewis, the sparse natural properties picked out by our best physics are related within a 'best system', in which a law of nature is simply a 'contingent generalization that appears as a theorem (or axiom) in each of the true deductive systems that achieve a best combination of simplicity and strength' (Lewis, 1973, p. 73). Since dispositions are to be worked out in terms of counterfactuals that depend upon the truth of physical laws, and laws are contingent regularities in the spatiotemporal distribution of sparse natural properties, a neo-Humean microphysicalist, such as Lewis, is committed to the following claim:

Proposition 2.1. *The whole truth about nature supervenes upon the intrinsic physical properties of (and spatiotemporal relations between) some set of fundamental microphysical constituents.*

Yet Humeanism is now on the defensive in academic philosophy: the Aristotelian notion that things have 'powers' to bring about necessary change was reintroduced within mainstream analytic philosophy by Rom Harré and E. H. Madden (Harré and Madden, 1973). The concept of causal powers was further developed by George Molnar in the 1990s (Molnar, 2006), and has recently become the foundation of a non-Humean theory of causation put forward by Stephen Mumford and Rani Lill Anjum (Mumford and Anjum, 2011).[4] It has been championed in the philosophy of mind by John Heil and C. B. Martin (Heil, 2003; Heil, 2012; Martin, 2007) and advanced in the philosophy of science by Brian Ellis and Alexander Bird (Ellis, 2001; Bird, 2007), among others.[5]

A world with powers is a world in which entities have fundamental *agency*, since causal powers are features of reality that bring about change by natural necessity, and they are irreducible to 'categorical' properties which make no reference to change. The case for reconceiving natural properties as having (or being) causal powers, however, has done little to extend the fundamentally real domain beyond the microphysical to include macroscopic agents such as human beings.

Analytic theologians have typically found microphysicalist accounts of nature too sparse for articulating a theological anthropology, whether or not they admit causal powers. Something more is often supposed to be needed in order to get the facts right about human persons as purposive and responsible agents, created in *imago dei*. Yet whatever these extra-physical entities are taken to be – whether they're Cartesian souls which somehow act upon physical bodies or mental properties which are somehow distinct from physical properties – our 'best physics' is still widely supposed to provide a unified account of the material world in terms of microphysical properties that can be measured and manipulated. The quandary which confronts those who are tempted to add something non-physical to this picture of nature, however, is whether the microphysical description of reality that they are seeking to augment should be regarded as 'causally closed'. This is the kind of tribute that modern philosophers are generally expected to pay for the triumph of scientific empiricism and reductive simplicity over the kind of rationalism and ontological extravagance exhibited by ancient philosophers like Plato, for whom the truth about nature was a matter of armchair speculation.

2.2. The Doctrine of Hylomorphism

It would be caricature, however, to portray every ancient and medieval philosopher as being insensitive to the role of empirical investigation in finding out about nature. Although Aristotle was famously the protégé of Plato, and both philosophers aspired to universal truths about reality, including the truth about human souls, it is widely acknowledged by scholars of ancient philosophy that these great thinkers of antiquity diverged in their methodology and their metaphysics.[6]

For Plato, reality lay beyond our experience of the world of concrete physical things in a transcendent realm of universals that he called the 'forms', which somehow cause the plurality of particulars with which we are acquainted – or which serve as the mental templates by which 'the Demiurge' moulds the world's matter – and in which these particulars are said to 'participate'. A form is the universal essence which bestows qualitative similarity upon particular things – such as the form of the triangle, or the form of man – and can only be known through a kind of philosophical recollection (see e.g. [Plato, *Meno*, 71–81, 85–86]).[7] In his treatise *On Generation and Corruption*, however, Aristotle criticised Plato's treatment of the forms on the grounds that, since they are transcendent entities, they cannot function as efficient causes in the physical world, and it is implausible that embodied beings such as ourselves could ever come to know them (Aristotle, *Gen. & Corr.*, 335b, 18–24). If the forms are to explain the characteristic activities of concrete particulars, they must be *immanent* within the physical world, and embodied beings must come to know them by causally interacting with the substances that they are said to 'in-form' (Aristotle, *Metaphysics III*, 34). It is substances, not forms, that act as efficient causes in nature. For Aristotle, ontological commitment is guided by the Eleatic principle:[8]

> **Proposition 2.2.** *A thing exists just in case that thing has the causal power to affect and/or to be affected, to bring about change and/or to suffer change.*

Whilst the ontological status of the forms in Aristotle's metaphysics is still vigorously debated, Aristotle maintained a robust commitment to the concrete reality of in-formed substances, which are fundamental wholes whose causal powers are irreducible to the powers of their material parts. His broadly empirical stance is manifest in his systematic study of natural phenomena and his indefatigable classification of substances into natural kinds. For Aristotle, philosophical inquiry began with the study of nature as it presents itself in ordinary experience, proceeding to more abstract reflections upon the nature of time and change (in the *Physics*), and thence to fundamental questions about the nature of being (in the *Metaphysics*). For these reasons, I suggest, it is not unreasonable to consider Aristotle as a kind of proto-scientist who inaugurated the empirical tradition of scientific inquiry – a tradition characterised by a remarkable confidence in the powers of reason *and* observation to uncover the truths about nature.

To understand Aristotle's philosophical account of nature, we must begin with the reality of change in the natural world. Aristotle distinguished two ways of being in his account of change: there is *being-in-potency* (or potentiality) and there is *being-in-act* (or actuality) (see

[Aristotle, *Physics*, I.7]).[9] According to Aristotle,[10] the natural order is fundamentally composed of *substances*, which are concrete particulars which have the *potential* to change in various ways. For example, animals are organic substances which actualise their potential for gathering flesh by exercising their powers of growth and nutrition.[11] Yet organic substances cannot persist through all kinds of change but are transitory entities, which are subject to processes of death and decay. Aristotle introduced the co-relative concepts of *matter* (hyle) and *form* (morphe) in his account of how substances change (see e.g. [Aristotle, *Physics*, II.3]). Matter is that which changes and gets determined (or actualised), and form is that which determines (or actualises) matter. Both metaphysical principles are required to explain the changes that we observe in ordinary experience, along with the concept of privation, which is the lack of the form that is required by whatever the goal of the change happens to be.

For instance, when an animal consumes a plant, by exercising its powers of growth and nutrition, it transforms the matter of the plant into its own flesh. In so doing, the substance of the animal is a subject of change: by gathering flesh where there was previously a privation, the *matter* of this substance is determined by a different *accidental form*. In being consumed by the animal, the matter of the plant is also a subject of change: by being transformed into the flesh of the animal, the matter of the plant is stripped of powers that are essential to the nature of the plant and acquires powers that are essential to the nature of the animal. In this case, it is the matter underlying the substances of the plant and the animal which is said to be determined (or actualised) by the *substantial form* of the animal, since the animal now exists where its form was previously in privation.

Aristotelian substances have a *per se unity* which other kinds of entities lack. In order to distinguish an Aristotelian substance, like an animal, from an aggregate, like a pile of sand, we must distinguish between *actual* and *potential* parts. An aggregate is composed of actual parts that have their own determinate physical natures. These parts can exist independently of the wholes of which they are parts, and they retain their natures and identities even whilst they are composing them. They are separate actualities which can be analysed in terms of matter and form. An aggregate derives its nature and being from the sum of its actual parts.

An Aristotelian substance, by contrast, does not consist of actual physical parts into which it can be decomposed. Rather, all the physical parts of a substance are dependent for their physical natures upon the substantial whole of which they are part, whose physical existence depends on the action of a substantial form. Whilst a living substance, such as an animal, can decompose into a collection of non-living chemicals, which do not depend upon the original substance for their existence or their physical natures, these physical entities are not *numerically identical* to any of the parts of the substance that existed prior to its decomposition.

The separate physical entities into which a substance may decompose are said to exist only in *potential*, just so long as the substance itself exists.[12] The metaphysical unity of the substance pertains to its having a single nature, upon which the natures of all of the parts of the substance jointly depend. It is the metaphysical unity of the substance that distinguishes it from an aggregate.[13]

According to a traditional line of interpretation that is often attributed to Aquinas, substantial form is *both* the principle of unity of a substance *and* that by which substances are fundamentally and objectively *what* they are (Aquinas, *De Principiis Naturae*, 5, 30). For Aquinas, whilst a substantial form is not a *physical part* of a substance, a substantial form may be said to unite itself to the matter of a substance in virtue of being the *formal cause* of its *nature* (Aquinas, *De Ente et Essentia*, 6). Matter and form, on this account, may be thought of as *metaphysical parts* of a substance.[14] The matter which is in-formed by the substantial form of the substance is the *prime matter* underlying all substances, which is the very potentiality for substantial being. These ‘metaphysical parts’ cannot be physically isolated by manipulating the entity in a scientific experiment but can only be separated by metaphysical abstraction, which is a purely intellectual process. Without *form* as well as *matter*, a physical substance would be *incomplete*.

Aquinas considered the world to be carved into a plurality of substances with different natures: among the world of inorganic substances, he distinguishes various minerals and metals; among the world of organic substances, he admits a hierarchy of plants, animals, and people, according to their various powers. Animals have powers of perception and locomotion (as well as various passions) that plants do not, and humans have rational or intellectual powers that other animals do not. Since all of these substances are subject to generation and corruption, however, and neither arise out of nor disappear into nothingness, we require an explanation of *substantial change*. According to Aquinas’s interpretation of Aristotle, the fact that there are substances in the world with different powers, which are not simply aggregates of more fundamental physical parts, is explained by the existence of different substantial forms, which determine the prime matter underlying all substances in different ways (Aquinas, *De Principiis Naturae*, 5). This interpretation of hylomorphism is thus committed to the following proposition:

> **Proposition 2.3.** *The physical parts of a (macroscopic) substance do not have microphysical properties independently of the substances of which they are part.*

This proposition contradicts the claim that the whole truth about nature – including the truth about plants, animals, and people – supervenes upon an arrangement of microscopic properties (2.1). According to Aristotle and Aquinas, many of the objects of ordinary experience are substances which are irreducible to their parts, including biological agents like human beings. So why was this metaphysical account abandoned in favour of microphysical reductionism?

2.3. Matter and Form in Late Scholasticism

Whilst the concepts of matter and form were widely deployed in scholastic metaphysics in accounting for the nature and unity of substances, these doctrines were developed by some scholastic philosophers in ways that were incompatible with the Aristotelian-Thomistic conception of hylomorphism. No single systematic view characterises the scholastic period. Nonetheless, it is possible to pick out some suggestive tendencies within medieval metaphysics that served as a prelude to microphysicalism.[15] I shall use the term *physicalise* to refer to the tendency to treat the matter of a substance as having the same ontological standing as the substance by attributing to matter intrinsic properties or causal powers.[16]

The necessity of some material substrate underlying all forms of change was widely accepted within the Latin tradition. As Franco Burgersdijk observed, ‘all seem to have granted to Aristotle that the generation and corruption of natural things requires a common subject’.[17] In this way, medieval scholastics sought to affirm the continuity of natural processes and to avert the supposition that change must involve creation from nothing. However, Aquinas’s characterisation of this substrate as a *determinable potentiality* was widely criticised by other scholastics for failing to bottom out in anything concrete or determinate and was never widely accepted, even in the thirteenth century. William of Ockham, writing in the early fourteenth century, echoed Averroes in requiring that matter should have extension.[18] Duns Scotus insisted against Aquinas that this material substrate should have actual parts.[19] The metaphysical misgivings concerning a merely determinable substrate were starkly expressed by the seventeenth-century Ockhamist, André Dabillon, who insisted that either ‘the things that compose an actual being actually exist, or a substantial whole would be composed of nothing’. Since this position is untenable, he claimed that it must be the case that both ‘matter and form are real substantial beings that exist actually in nature’.[20]

In addition to physicalising the material substrate of change, increasing its independence from substantial form, some scholastics seem to attribute a quasiphysical status to form, suggesting that it interacts with other entities like an efficient cause. A significant example of this tendency lies in the widespread rejection of the so-called unitarian doctrine of substantial form.[21] In Aristotelian-Thomistic hylomorphism, a substance has a single substantial form, which is the principle of unity of the substance and determines its nature. For some scholastics, however, such as Scotus, a plurality of substantial forms were said to exist within the same substance.

For example, the form of *corporeity* (by which an animal is embodied), and the form of the *soul* (by which an animal is living), were held to be present simultaneously within a human substance.

Yet if multiple substantial forms can exist within a substance that simultaneously determine its causal powers, wherein lies the unity of the substance, and how do they determine its properties? For certain scholastics, it seems the temptation was to preserve their commitment to the unifying character of forms by portraying them as elements within the composite with powers to *organise* their various parts into a *functional whole*. Francisco Suárez, a philosopher of the late sixteenth and early seventeenth centuries, seems to be considering such a position when he writes,

> The aggregation of multiple faculties or accidental forms in a simple substantial subject is not enough for the constitution of a natural thing . . . A form is required that, as it were, rules over all those faculties and accidents, and is the source of all actions and natural motions of such a being.[22]

Yet once matter and form have been physicalised, formal and efficient causation become difficult to distinguish from one another. For the Aristotelian-Thomistic hylomorphist, substances share a substrate of determinable potentiality, which is in-formed one way and then another. For certain scholastics, however, substantial forms seem to act directly as efficient causes, since that is the only way in which they can make a difference to things that have their own intrinsic and determinate natures.[23] Whilst the metaphysical roles of matter and form remained the same in intention, the ways in which their tasks were implemented rapidly shifted from their Aristotelian-Thomistic moorings. Matter and form were physicalised and formal causation confounded with efficient causation, a circumstance that would place substantial forms in direct competition with physical mechanisms.

2.4. *The Rise of Microphysicalism*

The mechanical philosophy of the seventeenth century, far from arising in a philosophical vacuum, represents a development in these tendencies within medieval philosophy, which culminated in the complete physicalisation of the material substrate of change, combined with an explicit rejection of the notion of substantial forms. Abandoning the hylomorphism of late scholasticism, the corpuscularianists proposed an alternative ontology consisting of corpuscles arranged within physical space which have intrinsic and determinate properties, echoing the atomism of Leucippus and Democritus that Aristotle had so vehemently opposed. In this new vision of the world, nature wears all of her properties on her sleeves where they are exposed to being measured and manipulated, unlike the metaphysical principles underlying the world in medieval philosophy, which are only uncovered through a process of metaphysical abstraction.

Not all of the early mechanists were committed to an ontology of discrete corpuscles. In the mechanical philosophy of Descartes, reality was divided between thinking things (*res cogitantes*) and extended things (*res extensa*), where the extended things are wholly characterised by the geometric properties of 'shape, size [and] position' and their motions are governed by universal laws. A thoroughgoing reductionist in his approach to the material world – which included flora and fauna and the animal kingdom but excluded human persons who are immaterial souls – Descartes believed 'there is nothing in all of nature whose character (ratio) cannot be deduced through these same principles' and dismissed substantial form as 'a philosophical being unknown to me'.[24, 25]

It would be difficult to overstate the enduring influence of Descartes's metaphysics, although Cartesian physics was a short-lived affair by contrast: Isaac Newton rejected Descartes's identification of matter with extension and proceeded to develop an alternative account of motion that would rapidly secure Newtonian mechanics as the archetype of modern physics.[26] Nonetheless, the common commitment to a physicalised form of matter continued to set the agenda for natural philosophers from the seventeenth century. Buoyed by swift advances in the experimental sciences, corpuscularianism swiftly supplanted scholasticism in many parts of Europe, as scientists like Robert Boyle contrived plausible mechanical explanations for natural phenomena, specifically targeting cases in physics where scholastics had attributed phenomena to the activities of forms.[27] Henry Oldenburg, who served as the first secretary for the Royal Society, memorably complimented Boyle for having 'driven out that drivel of substantial forms' which 'has stopped the progress of true philosophy, and made the best of scholars not more knowing as to the nature of particular bodies than the meanest ploughmen'.[28]

Whilst corpuscularianists maintained a commitment to the notion of a material substrate underlying all change – in Boyle's view, a 'substance extended, divisible, and impenetrable'[29] – the doctrine of substantial forms was swiftly abandoned during the course of the seventeenth century (albeit with some notable dissenters, such as Leibniz (1976)). This extirpation of form was accompanied by a different account of the generation and corruption of the things we encounter in experience. As Silva observes, without forms to determine the intrinsic powers of substances, natural philosophers increasingly relied upon 'laws of nature that extrinsically guided the movements of corpuscles and atoms in a void' to explain how things (apparently) come into and out of being (p. 64), and thus 'intrinsic natural formal causes were replaced by extrinsically imposed laws of nature' (Silva, 2019, p. 65).[30] According to Boyle, the material world that is laid bare by the physical sciences should be regarded as a 'contrivance of brute matter managed by certain laws of local motion' (Boyle, 2000, vol. 10, p. 447). The matter of which everything is made persists through time and only changes with respect to accidents like position.

By the eighteenth century, David Hume had sought to 'introduce the experimental method into moral subjects', in *A Treatise on Human Nature* (1739–40), laying the foundations for a microphysicalist account of the mind, and the French mechanist Pierre Simon de Laplace had given voice to a *mechanical stance* toward the whole of nature that would dominate the imagination of philosophers until the turn of the twentieth century. According to the new philosophy of nature, the state of the whole cosmos at any future time, including human beings, is entirely fixed by the present locations and momenta of small particles and the laws of Newtonian mechanics.[31] The only changes in such a world are the accidental changes in the arrangements of the particles. This is the world of 'classical physics' with which most philosophers are familiar, in which the mechanical laws of physics determine all the physical possibilities of nature. It is a causally closed world in which substantial forms have no role to play in bringing about change.

3. Form in Standard Quantum Mechanics

The confidence of the corpuscularianists in their capacity to explain everything in terms of the properties of material corpuscles, and the animus displayed by early philosophers of science like Oldenburg against the medieval scholastics, effectively banished the doctrine of hylomorphism from mainstream philosophical discourse. Yet the microphysicalism that came to dominate the Anglophone philosophical tradition, which eventually dropped any commitment to corpuscles, has run into difficulties with contemporary physics. It is widely accepted, for example, that the theory of quantum mechanics, which superseded classical physics, is incompatible with the doctrine of Humean supervenience, as it was formulated by Lewis (2.1). As Maudlin has pointed out: the standard doctrine of Humean supervenience is inconsistent with the existence of quantum-entangled states, which are indeterminate states of a physical system that cannot be characterised in terms of the intrinsic properties of spatially separated microscopic constituents (Bell, 1964; Maudlin, 2007). In what follows, I shall discuss this problem and consider how it can be addressed by adopting a hylomorphic framework in which matter ontologically depends upon form for its physical properties.[32]

3.1. Quantum Entanglement

The fundamental mathematical object within quantum theory is the quantum state, which encodes the probability of an arbitrarily complicated physical system having a particular configuration. In the famous EPR experiment involving two microscopic particles originally proposed by Einstein and his collaborators (Einstein et al., 1935), as it was subsequently presented by David Bohm, one particle is constrained to be 'spin-up' $|\uparrow\rangle$ when another is measured to be 'spin-down' $|\downarrow\rangle$, and vice versa, however far apart the two particles are spatially separated.[33] The physical system in this case is said to be in a 'quantum superposition' that is described by the singlet state:

$$|\psi\rangle_{1,2} = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2\right). \tag{1}$$

According to this formalism, when a system comprised of two particles (1 and 2) is in the singlet state $|\psi\rangle_{1,2}$: there is a probability of 1/2 that we will observe particle 1 to be 'spin up' $|\uparrow\rangle_1$ and particle 2 to be 'spin down' $|\downarrow\rangle_2$; and there is a probability of 1/2 that we will observe particle 1 to be 'spin down' $|\downarrow\rangle_1$ and particle 2 to be 'spin up' $|\uparrow\rangle_2$. There are no other physically possible outcomes.

3.1.1. Non-Local Correlations

The challenge that such systems pose to the doctrine of Humean supervenience is the fact that we cannot explain their measurement statistics in terms of the local properties of their constituent parts. Suppose two quantum-entangled particles that are emitted from a common source fly off in opposite directions, and two experimenters (traditionally, 'Alice' and 'Bob') measure the spins of each particle once they are sufficiently separated using different measuring devices. Let φ_A specify the configuration of Alice's apparatus, and A the outcome of her experiment; likewise, φ_B for Bob's apparatus, and B for his outcome. Let λ denote whatever in the past may have influenced the behaviour of the system that is being measured. In this example, λ includes the physical state of the two-particle system, prior to measurement. The measuring apparatus in each case is a Stern-Gerlach device, in which a pointer has the possibility of being deflected up or down, and the configuration parameters are the two angles of polarisation of each device, φ_A and φ_B. These parameters can be set at an appropriate angle for measuring vertical spin (that is, 'spin-up' or 'spin-down'), but can also be adjusted separately to produce a range of measurement outcomes. According to the physicist John Bell (Bell, 1964), the principle of locality requires:

$$P_{\phi_a,\phi_b}(A \mid B, \lambda) = P_{\phi_a}(A \mid \lambda) \tag{2}$$

$$P_{\phi_a,\phi_b}(B \mid A, \lambda) = P_{\phi_b}(B \mid \lambda). \tag{3}$$

The formalisation of the first equation can be read as follows: if the principle of locality is true, then the probability P for Alice obtaining outcome

A can be fixed by conditionalising on the configuration of her apparatus φ_A and whatever in the past influenced its behaviour λ, such as the local properties of the particle she measures. Significantly, in a world in which locality holds and the two measurements are conducted simultaneously, conditionalising on the configuration of Bob's apparatus φ_B and outcome B does not change the probabilities for Alice's outcome. Hence, the two probabilities in the first equation are stated to be equal. This is also the case for Bob's outcome with respect to Alice's apparatus, hence the equality of the two probabilities in the second of the two equations.

However, Bell's theorem demonstrates that the principle of locality is violated by the phenomenon of quantum entanglement. According to quantum mechanics, the probabilities for obtaining a measurement outcome in one part of the experiment depend on the outcome obtained in the other part of the experiment, in spite of the fact that the two measurement events are represented as 'space-like separated' in the theory of special relativity, because they are conducted simultaneously within the frame of reference of the experiment.

To visualise the limits on signalling which are imposed by the theory of relativity (in this case, between the two wings of the EPR experiment), the mathematician Minkowski suggested imagining a flash of light, confined to a two-dimensional plane, which spreads out in a circle from an event E at some time t (Minkowski, 1908). If we graph the growing circle using time as the vertical axis, we obtain a 'light-cone' for event E that extends to include any past event $t' < t$ in which a signal could have been sent which would have time to reach E and causally influence this event. Any event which falls outside of the light-cone of E is 'space-like separated' from E and cannot be causally related to E by a classical mechanism.[34] Since the measurement events in the two wings of the EPR experiment corresponding to A and B do not belong within each other's past light-cones, they are space-like separated. In other words, the assumption that the behaviour of the particles can be explained by a (subluminal) physical mechanism that governs their local properties implies one set of measurement statistics, whereas quantum mechanics predicts another. Significantly, in the case of the EPR experiment, quantum mechanics predicts that the measurement statistics will depend on the relative angle between the two devices, $\varphi_A - \varphi_B$; a fact that neither particle, considered separately, is in a position to 'know'.

Whilst the EPR experiment was originally proposed as a thought experiment by Albert Einstein and his associates, and was intended as a *reductio ad absurdum* of quantum mechanics, subsequent experiments – in particular, those of Alain Aspect in the 1980s (Aspect et al., 1982) – are now widely regarded as having confirmed the statistics predicted by quantum mechanics and established non-locality as an empirical fact.[35] Contra Laplace, we cannot explain the physical behaviour of everything in nature in terms of the mechanical forces between physical bodies and the intrinsic properties of their microscopic constituents. The phenomenon of quantum entanglement suggests that the mechanical stance toward nature which was adopted by the corpuscularianists offers an *effective* description of physical phenomena which holds only at certain scales.

3.1.2. The Measurement Problem

The existence of quantum superpositions, such as the quantum states of entangled particles, confronts us with the additional problem of reconciling the formalism of quantum mechanics with the reality of determinate measurement outcomes. Prior to any measurement of a quantum system – or any collapse-inducing event, the quantum state evolves according to the time-dependent Schrödinger equation,

$$\hat{H}|\psi\rangle = i\hbar\frac{\partial|\psi\rangle}{\partial t}, \tag{4}$$

where $\hat{H}$ is the Hamiltonian of the system which represents its energy, and *ħ* is the reduced Plank's constant. The formal solution of Equation (4) is the quantum state (or, wave function) $|\psi(t)\rangle$. The quantum state can be expressed in terms of an operator $\hat{U}$, such that the state of a system at some arbitrary time *t* can be obtained from its state at some earlier time *t* = 0 through the action of this operator: $|\psi(t)\rangle = \hat{U}(t)|\psi(0)\rangle$.[36] This formula tells us how to start from a given state of a system and evolve the probability amplitudes for all the possible configurations of the system in time. Yet suppose we perform a 'non-demolition' measurement on the system, which does not destroy the quantum system being measured (Dong et al., 2008). After this measurement, we know more about the state of the system than the information contained in the quantum state.

For example, the measurement outcome of the EPR experiment will have ruled out one of the combined states of the two particles to which $|\psi\rangle$ assigns a non-zero probability; perhaps the state in which particle 1 is spin-down and particle 2 is spin-up $|\psi\rangle_{1,2} = |\downarrow\rangle_1|\uparrow\rangle_2$. To obtain the correct results for future experiments, we have to *update* the wave function of the system we are measuring with the empirical knowledge we have gained from our experiment. Yet this updating is not performed by the time evolution operator $\hat{U}$. For instance, suppose at time *t* we find that particle 1 is spin-up and particle 2 is spin-down: $|\psi\rangle_{1,2} = |\uparrow\rangle_1|\downarrow\rangle_2$. The wave function has to undergo the following *discontinuous* modification:

$$|\psi(t-\delta t)\rangle_{1,2} = \hat{U}(t-\delta t)|\psi(0)\rangle_{1,2}$$

$$|\psi(t+\delta t)\rangle_{1,2} = |\uparrow\rangle_1|\downarrow\rangle_2, \tag{5}$$

where δt denotes an infinitesimal period of time. This discontinuous change in a system's quantum state is known as the 'collapse of the wave function', and it is necessary to properly account for any non-demolition experiment. There is no agreed understanding of this physical process (Omnés, 1994). Even if the phenomenon of decoherence is taken into account, in which the quantum nature of the system is said to 'leak' into its environment, the time evolution operator must be supplemented with a discontinuous change in the system's state. This disconnect between the quantum formalism describing the physical state of a system, which can only be specified empirically in terms of an indeterminate superposition of mutually exclusive measurement outcomes, and the 'classical' world of observation occupied by scientists, in which measurement always give rise to a determinate physical outcome, naturally gives rise to the question of why this apparent indefiniteness in the microrealm is not transmitted up to the macroworld (as in the notorious 'Schrödinger's cat' thought experiment). Is quantum mechanics about an objective world that exists independently of scientists and their measurements, or does it merely keep track of the state of our knowledge during the course of an experiment?

3.1.3. Matter Without Intrinsic Physical Properties

According to Bell, any realist approach to quantum mechanics that seeks to explain the existence of determinate measurement outcomes must come to terms with a dilemma: either the dynamics of standard quantum mechanics is wrong, and the wave function evolves according to a non-linear Schrödinger dynamics that permits the wave function to collapse independently of the 'observations' of any scientist, or there are 'hidden variables' in addition to the wave function, which evolve according to some non-linear dynamics of their own (Bell, 1987). In either case, standard quantum mechanics must be regarded as *physically incomplete*. Maudlin has argued that the choice comes down to two possibilities (Maudlin, 1995): either we should adopt something like the modified Schrödinger dynamics proposed in Ghirardi et al. (1986) (GRW theory), in which the wave function undergoes spontaneous collapse, or something like the pilot wave theory of de Broglie and Bohm (Bohm, 1951, 1952; de Broglie, 1928), which includes an equation of motion for a particle configuration.[37]

The GRW theory seizes the first horn of the dilemma by incorporating a stochastic mechanism which produces random 'hits' on the wave function that occur universally for microscopic particles and result in an objective collapse of the wave function (Ghirardi et al., 1986). The effects of this non-linear modification to the Schrödinger equation become significant when a large number of quantum-entangled particles are involved, such as the particles composing a measuring device. The theory of Bohmian mechanics seizes the second horn of the dilemma by positing a global configuration of particles whose trajectories are choreographed by the wave function (Bohm, 1951, 1952; de Broglie, 1928). The guiding equation for the particles depends in a non-linear way upon the wave function, which evolves according to the standard Schrödinger equation.

According to Allori et al. (2008), however, the difference between these apparently opposite approaches to fixing standard quantum mechanics is not as stark as it seems. GRW theory and Bohmian mechanics may be interpreted as sharing a common structure: 'they are ultimately not about wave functions but about "matter" moving in space, represented by either particle trajectories, fields on space-time, or a discrete set of space-time points.' This configuration of matter makes up the world of macroscopic objects, including our measuring devices, and 'the role of the wave function . . . is to govern the motion of the matter' (p. 353).

In the Bohmian primitive ontology, this configuration of primitive matter consists of *N* discrete particles. The trajectory of every particle is governed by an equation of motion that is first-order in time, which depends upon both the universal wave function ψ and the positions $\{\mathbf{Q}_1, \ldots, \mathbf{Q}_N\}$ of all the other particles comprising the global configuration:

$$\frac{dQ_i}{dt} = v_i^{\psi}\left(Q_1,\ldots,Q_N\right) \propto m_i \,\mathrm{Im}\frac{\psi \nabla_i \psi}{|\psi|^2} \tag{6}$$

where v_i^{ψ} is the velocity of particle *i* at time *t*, and m_i is its gravitational mass.[38] In the GRWm primitive ontology for GRW theory, which was first suggested in Ghirardi et al. (1995), the matter is not discrete but consists of infinitely divisible gunk. It is a matter-field whose distribution of matter-density $m(\mathbf{x}, t)$ expands with the unitary evolution of the wave function ψ and contracts in spontaneous localisation events, which is governed by an equation of the form:

$$m(x,t) = \sum_{i=1}^{N} m_i \int_{R^{3N}} dq_1 \cdots dq_N \,\delta\left(q_i - x\right)\left|\psi\left(q_1,\cdots,q_N,t\right)\right|^2, \tag{7}$$

where the sum ranges over the *N* quantum 'particles' in the physical system (from $i = 1$ to $i = N$), and the integral ranges over the whole of the 3*N*-dimensional configuration space in which the wave function ψ is defined. (In computing $m(\mathbf{x}, t)$ for a given position $\mathbf{x}$ and time *t*, the integration of the wave function ψ combined with the Dirac delta function $\delta(q_i - x)$ gives us the marginal distribution of the *i*th degree of freedom $\mathbf{q}_i \in R^3$, by integrating out all other variables $\mathbf{q}_j$, then one takes the mass-weighted sum of these contributions for all of the particles.)

In both cases, the *microscopic* description of standard quantum mechanics is completed, and the existence of determinate measurement outcomes is ontologically explained, by the introduction of a spatiotemporal distribution of primitive matter, which is choreographed by a wave function that is defined as a *holistic* feature of the physical system. In both cases, this distribution of matter lacks any intrinsic physical properties. The particles (or parcels of gunk) are holistically individuated by the distance relations in which they stand, deriving their physical natures from the wholes of which they are parts. The wave function of quantum mechanics, which is defined in a high-dimensional configuration space, is not included as part of the fundamental ontology, to avoid creating an interaction problem involving two separate domains, but is assigned a nomological role in explaining the motion of the matter in physical space.

It must be emphasised that the matter in these primitive ontologies cannot be read off the formalism of standard quantum mechanics or deduced from any other physical concept or from the vocabulary of any physical theory. It is posited for the sake of *empirical adequacy*, since there are facts about which way the pointers on our measuring devices are pointing. A primitive ontology approach aims to explain the measurement outcomes of quantum experiments, like the EPR experiment, and more generally to explain the behaviour of the macroscopic objects upon which scientists depend to make their measurements, by offering an account of the empirical content of a physical theory that is exhausted by its statements about this primitive distribution of matter (Maudlin, 2019).

3.2. Cosmic Hylomorphism

There is good reason to think, however, that a fundamental ontology consisting solely of matter without intrinsic physical properties is too sparse to account for the truth of the laws that determine the spatiotemporal development of the matter. Something more is needed, in addition to a distribution of particles or gunk, in order to explain the phenomena that scientists observe in quantum experiments.

3.2.1. Bohmian Mechanics

I wish to focus in the remainder of this section on the Bohmian solution to the measurement problem, which attributes to the cosmos a universal wave function that does not collapse. In Section 4, I will consider a different approach to quantum mechanics, in which the wave function is permitted to collapse.

Bohmian mechanics takes the non-locality of quantum mechanics seriously, providing an account of quantum experiments in terms of *both* the universal wave function ψ *and* a set of N particles. Although we cannot measure the universal wave function, nor can we trace the trajectories of the Bohmian particles, it is possible under certain conditions to provide an empirically adequate account of a subsystem of physical particles in terms of the *effective* wave function of the subsystem, which encodes the statistical information about the positions of the particles that can be recovered in an experiment. According to Bohmian mechanics, it is only effective wave functions which are subject to collapse.

For Bohmians, the quantum spin of a particle is explained by the effective wave function of the particle and its initial position. Suppose we direct a spin 1/2 particle at the magnets of a Stern-Gerlach device, such that its wave function splits into 'up' and 'down' wavepackets. The way in which the particle travels within the apparatus – its 'choice', let's say, to travel *up* rather than down – is determined by its initial position in relation to the magnets and their fields. If this particle is entangled with another particle in the singleton state (1), however, that choice changes the wave function of the other particle, guaranteeing that it will go *down* when it is measured. In effect, the wave function of the second particle has been forced to evolve non-locally in three-dimensional space, with the local behaviour of particle 1 nomically determining the wave function of particle 2. Consequently, after the measurement of particle 1, the 'spin' of particle 2 – and hence its trajectory – is no longer a function of its position in relation to the magnets used to measure it.

If the orientation of the magnetic field used to measure particle 1 were reversed, however, and one measured the spin of particle 1, particle 1 would travel *down* rather than up, assuming the initial position of particle 1 to be the same with respect to the apparatus. In that case, one would obtain a wave function for particle 2 in which it travelled *up* instead, irrespective of its initial position. The Bohmian is thus committed to the existence of action at a distance – an action that cannot be explained by mechanical contact or the intermediation of physical fields – since the scientist's choice of the orientation of the magnetic field which measures the spin of particle 1 affects not only the motion of particle 1 but also of particle 2, however far apart the two particles are from one another.

The Bohmian is also committed to the existence of a world in which there are definite physical objects and determinate measurement outcomes: there is always a fact of the matter about where every particle stands in relation to one another, and the macroscopic devices which are used to make measurements are composed of particles. According to the kinematic interpretation of Bohmian mechanics, the particles do not have any intrinsic physical properties, but every particle in the cosmos is assigned an instantaneous velocity which depends on the definite positions of all the other particles and the universal wave function. The Schrödinger equation and the guiding equation comprise the non-classical dynamics of a particle configuration that exists independently of our observations.

The Bohmian theory, for all practical purposes, is empirically equivalent to standard (non-relativistic) quantum mechanics.[39] Agreement with the Born rule, which gives the probability that a measurement of a quantum system will yield a given result, is secured via the quantum equilibrium hypothesis: specifically, if the initial configuration of the particles at t may be supposed to be randomly distributed with a probability distribution $\rho(t=0)=|\psi_{t=0}|^2$, then it follows as a consequence of the Schrödinger equation and the Bohmian equation of motion that this relationship will hold at some later time $t > 0$ for the distribution $\rho(t)=|\psi_t|^2$.[40] Although the particles have determinate positions, we cannot *know* where all of the particles are, and so we must resort to the probabilities of quantum mechanics in order to make any predictions. Nature does not wear all of her properties on her sleeves. Nonetheless, the physical state of the world is completely specified by the wave function and the positions of the particles.

3.2.2. Rival Views of Laws

Yet why would particles without physical properties follow the trajectories laid out for them in Bohmian mechanics, supposing a theory like Bohmian mechanics were true? The Armstrong-Dretske-Tooley conception of lawhood as a second-order relation between universals, for example, is unsuitable, since the particles do not have any properties that could instantiate necessitation relations and the wave function is not part of the primitive ontology. According to the 'primitive ontology approach' to quantum mechanics espoused by Allori et al. (2008), the wave function of quantum mechanics plays a nomological role in the temporal development of the particles. However, there are two ways of spelling out this role: namely, by appealing to a Humean account of laws, in which laws are merely summaries of regularities for all space and time, or to some form of dispositionalism, in which laws are grounded in powers (Esfeld et al., 2017).

Michael Esfeld has proposed an ontology for Bohmian mechanics in which the world is composed of 'matter points', which are nothing over and above the distance relations in which they stand (Esfeld and Deckert, 2017). To accommodate the truth of the Bohmian law of motion, which is specified in terms of both the particles and the wave function, Esfeld adopts the Mill-Ramsey-Lewis account of laws, in which a regularity only qualifies as a law of nature just in case it is an axiom in the 'best system' that balances strength and simplicity in deriving the facts about the positions of the matter points.[41] According to this Humean account of the quantum state, the Bohmian law and the quantum state supervene upon nothing less than the global configuration of particles for all time.

However, many philosophers have found Humean accounts of laws to be deeply unsatisfactory. For instance, Humeanism fails to capture the intuition that laws have metaphysical work to do in explaining what happens. According to Humeans, the Bohmian law depends for its lawfulness upon the global configuration of particles and is thus constituted by that which it seeks to explain. Yet 'a fact cannot be used to explain itself' (Armstrong, 1983, p. 40), as Armstrong complained. In making this claim, Armstrong was echoing Plato's insight that things are explained by being referred to a 'higher principle'. The Mill-Ramsey-Lewis account, however, not only fails to maintain the necessary metaphysical distance between *explanans* and *explanandum*, but also reverses the proper order of explanation: laws are supposed to explain instances that fall under them, yet the lawfulness of laws in this model is grounded in the instances they are supposed to explain. Doubts have also been raised about the logical coherence of the Super-Humean's attempt to make the doctrine of Humean supervenience compatible with quantum entanglement.[42] For example, in rejecting an ontology of sparse natural properties in favour of a supervenience base consisting solely of positions, the Super-Humean removes an objective constraint upon what could count as a 'best system' of laws, leading to the well-known problem of 'immanent comparisons' and to subjectivism about the laws of nature (Matarese, 2018).

In order to build a metaphysical model that incorporates a *power* to choreograph the trajectories of the particles according to the Bohmian law of motion, however, a dispositionalist must answer a number of metaphysical questions. For instance: what sort of thing might be supposed to *possess* a causal power which could ground the Bohmian law of motion? Some dispositionalists have been tempted to attribute Bohmian particles with their own intrinsic dispositions. For example, Suárez has suggested that each Bohmian particle has powers to change its velocity which depend upon the spatial configuration of *all* the other particles for their stimulation (Suárez, 2015). It is doubtful, however, that this conspiracy model offers any advantage over Super-Humeanism. For one thing, Bohmian dispositionalism fails to capture intuitively correct counterfactuals about what would happen in Small Worlds which have only a few particles, since the lawfulness of the Bohmian law of motion is not due to any intrinsic features of the particles which could be duplicated in other possible worlds, and so we should expect a Small World to have different laws. For another, it seems that Bohmian dispositionalism is subject to a serious dilemma: either time must be regarded as discrete rather than continuous, or the powers of the particles fail to determine the particles' trajectories (Simpson and Pemberton, 2021).

A dispositionalist might propose that the plurality of particles has a single, collective property – namely, the property of instantiating a power to choreograph their trajectories according to the Bohmian law. This property would be intrinsic to the plurality of particles, rather than to any of the individual particles. Yet such an account faces two metaphysical challenges (Simpson, 2021). In the first place, the Bohmian law of motion is specified not merely in terms of the positions of all the particles but in terms of a universal wave function, which does not supervene upon the particle configuration but evolves according to the Schrödinger equation. To explain the law-like behaviour of the particle configuration, this global power would have to persist through time and ground the lawfulness of the Schrödinger equation. In the second place, in order to capture intuitively correct counterfactuals about what would happen in Small Worlds which have only a few particles (Carroll, 1994; Demarest, 2017), the identity of this global power should not depend upon the number of particles in the global configuration. There would have to be possible worlds in which the same global power is instantiated by a different number of particles. What we require, then, is a metaphysics that can explain both the *diachronic* and *transworld* sameness of this collective causal power. Cosmic Hylomorphism provides such a model, in which the only fundamental physical entity is the cosmos.

3.2.3. Cosmic Form

According to the Cosmic Hylomorphist, the cosmos is a substance which is metaphysically composed of both matter and a Cosmic Form (Simpson, 2021; cf. Schaffer, 2010). The matter of this substance may be identified with the Bohmian particles, which are endowed with causal powers to change their velocities. However, these particles are not substances which possess their own essential and intrinsic powers. Rather, their causal powers are *metaphysically grounded* in the Cosmic Form, which manifests a cosmic process.[43] The material particles, thus empowered, are transformed into the integral physical parts of a cosmic whole.

In this model, Cosmic Form is a simple and fundamental particular with the power to manifest a cosmic process (cf. Koons, 2018). The Cosmic Form is not located in physical space, along with the particles it transforms, since it does not stand in any distance relations, nor is it the *efficient cause* of their motion, since they have their own causal powers to bring about change. Rather, the Cosmic Form brings about change *indirectly*, in the course of manifesting the cosmic process, by *grounding* the powers of the particles at each moment of time. In so doing, the Cosmic Form *unites* itself to all of the particles to compose a single substance with an intrinsic power to choreograph their trajectories according to the Bohmian law.[44] It is the Cosmic Form that explains the diachronic and transworld sameness of this collective power.

Although this neo-Aristotelian account of Bohmian mechanics departs in significant ways from Aristotle's hylomorphic account of nature, as it was understood by Aquinas, it nevertheless deploys Aristotle's fourfold conception of causation to provide a non-mechanical explanation of quantum phenomena. The similarities with the ancient doctrine of hylomorphism are evident in at least three respects.

In the first place, the material particles that it posits are at least analogous to Aristotle's concept of matter: by supplying a persisting substrate which has the potential to bear causal powers, they serve as the *material cause* of the cosmic whole. The Cosmic Substance has no physical existence apart from its matter. Unlike Aquinas's concept of prime matter, the particles are metaphysically discrete and stand in distance relations. Prime matter is more than a substratum of bare potentiality, on this account, since it is spatially extended. The particles constitute a *materia prima*, however, in the restricted sense that they lack any *intrinsic* physical features. The phenomenon of quantum entanglement gives us good reason to doubt that particles have intrinsic physical properties independently of the wholes of which they are parts (Section 3.1).

In the second place, the Cosmic Form is analogous to Aristotle's concept of substantial form: by grounding the causal powers of the particles, the Cosmic Form acts as the *formal cause* of the Cosmic Substance, causing it to be the kind of unified substance that it is. Unlike Aristotle's account of the forms, there is only one substance in nature, and none of the objects of ordinary experience – including biological entities – are said to have substantial forms. A 'formal cause' that operates instantaneously upon matter can provide a non-mechanical explanation of the non-local correlations associated with quantum phenomena, however, since it is only efficient causes which are mediated in space and time. The Cosmic Form can explain the motion of the Bohmian particle configuration without violating the 'superluminal ban' in physics.

In the third place, this account reintroduces an element of teleology within physics: the ultimate explanation for the motion of the Bohmian particles is that the activity of the Cosmic Substance is a teleological process. The ordering of this process cannot be explained mechanically in terms of laws that connect one set of properties instantiated at time t with another set of properties instantiated at time $t' > t$, since the wave function is not an element of the fundamental ontology and the particles do not have intrinsic physical properties which stand in law-like relations. Rather, the ordering of this process is only explained by taking a *teleological stance*, in which the temporal development of the Cosmic Substance has an intrinsic *direction* (that is, the substance admits a final cause). Unlike Aristotle's concept of final causes, the final cause of the Cosmic Substance can be described mathematically in terms of the boundary condition on a universal wave function defined in an abstract configuration space, which contains information about possible trajectories of particles in different possible worlds. However, the universal wave function of the cosmos is not a property that we can measure.

Cosmic Hylomorphism is of course a far cry from that medieval vision of nature in which many of the objects of ordinary experience, including human beings, were substances with their own natures. Nonetheless, it represents a decisive break with the microphysical reductionism that dominated the philosophy of the last century and the corpuscularian assumption that nature wears all her properties on her sleeves for scientists to inspect. According to the Cosmic Hylomorphist, the cosmos is unintelligible apart from its substantial form, which grounds the properties of its matter, but the only way in which its matter and form can be separated is by metaphysical abstraction rather than scientific manipulation.

Cosmic Hylomorphism offers a way of understanding what the world might be like, if the laws of Bohmian mechanics were true, in which the universal wave function is not an element of the fundamental ontology, but represents an intrinsic power of a Cosmic Substance that is grounded in its substantial form. Yet there are reasons to doubt the claim that the cosmos can be represented as a single quantum system with a universal wave function – even in principle – which I shall discuss in the following section.

4. Form in Quantum Statistical Mechanics

The phenomenon of quantum entanglement is not the only reason to reconsider the supposed redundancy of hylomorphism. The microphysicalism that dominated analytic philosophy in the last century has also run into difficulties in accommodating novel and robust phenomena that emerge at higher scales. According to the standard *monistic approach* to realism adopted by many philosophers, a physical theory is supposed to provide a universally true and exhaustive description of the world in all physical respects and at all physical scales. However, the turn toward scientific practices in the philosophy of science has given rise to a pluralistic understanding of scientific theories, which has called into question the philosopher's aspiration of advancing a fundamental physical ontology. In what follows, I shall discuss the dilemma that an alternative *pluralistic approach* to realism faces between pragmatism and reductionism, in the context of quantum statistical mechanics, and will propose a way of splitting the horns of this dilemma by adopting a *hylomorphic approach* to realism that admits a plurality of fundamental substances (instead of a single Cosmic Substance).[45]

4.1. A Question of Context

4.1.1. Unitarily Inequivalent Representations

According to the standard approach to scientific realism, a scientific theory's explanatory virtues gives us good reason to attribute (some aspect of) that theory with representational content. There is a striking disparity, however, between the standard approach to realism and the way that quantum theories are used to explain phenomena *in practice*. For the purposes of this chapter, I shall focus on phenomena described by the theory of quantum statistical mechanics, although the same difficulties arise in quantum field theory.[46]

At the core of any quantum theory are the canonical commutation relations between conjugate quantities such as position and momentum – or the anticommutation relations that hold between the Pauli spin matrices – which encode Heisenberg's uncertainty principle. Any quantum theory which specifies a quantum state $|\psi\rangle$ of a physical system defined in a Hilbert space H, and a set of bounded self-adjoint operators corresponding to observables (H, $\hat{O}_i$) which act upon the quantum state $\hat{O}_i|\psi\rangle$, must realise the Weyl algebra associated with these relations. When the operators on a Hilbert space conform to these commutation relations, they are said to be a 'representation' of these relations.

Unitary equivalence is widely considered the standard of empirical equivalence: if two representations are unitarily equivalent, there is some unitary operator $\hat{U}$ that transforms one representation into the other U: H → H′, such that they both determine the same expectation values for the various observables which they define: $U^{-1}\hat{O}_i' U = \hat{O}_i$. However, the theory of quantum statistical mechanics generates a continuum of unitarily inequivalent representations in the so-called *thermodynamic limit* (Ruetsche, 2002, 2003, 2006, 2013), where it is necessary to adopt models which have infinite degrees of freedom in order to describe many kinds of physical phenomena. Whilst the *Stone-von Neumann theorem* establishes that any pairs of distinct representations for a finite system will be unitarily equivalent to the irreducible Schrödinger representation, since there is a unitary operator that transforms one into the other, infinite systems admit infinitely many Hilbert-space representations which fall outside of the scope of the Stone-von Neumann theorem (Ruetsche, 2011, chs. 2–3).

Let us consider the example of a ferromagnet. When a physical system experiences a phase transition, certain properties of the system undergo discontinuous change due to some macroscopic change in their immediate external conditions. An iron bar that is at thermal equilibrium, for instance, exhibits a paramagnetic phase above a critical temperature $T \geq T_c$, in which it experiences no net magnetisation. Below this critical temperature, however, it exhibits a ferromagnetic phase, in which it experiences spontaneous magnetisation. In the presence of an external magnetic field, the ferromagnet admits two possible metastable states which are characterised by opposite magnetic polarisations. These two states, as it turns out, must be defined using unitarily *inequivalent* representations.

> *Proof*: To demonstrate this inequivalence for the more mathematically minded (others may prefer to skip this argument), suppose we set up a Hilbert space for a system whose ground state is characterised by a sequence $s_k = +1$ for $k \in \mathbb{Z}$, then add all the sequences that can be obtained by making finitely many local modifications to this sequence which replace some of the entries with −1.[47] Let us label this Hilbert space H$^+$. A set of operators $\hat{\sigma}_z^j$ may then be introduced such that sequences s_k whose jth entry is ±1 correspond to the eigenvector in the Hilbert space associated with the eigenvalue ±1. A magnetic polarisation observable
>
> $\hat{\mathbf{m}}$ can be defined for the composite system with the components:
>
> $$\hat{m}_i^N = \frac{1}{2N+1}\sum_{k=-N}^{k=N}\hat{\sigma}_i^k,\ i \in \{x,y,z\}, \tag{8}$$

> which has a limit $N \to \infty$ in the weak topology of H^+. Let $[s_k]_j \in \{-1, +1\}$ denote the *j*th entry in the sequence s_k. For every state, the expectation value of $\hat{\mathbf{m}}$ will be oriented along the *z* axis and will take the value of +1 in the thermodynamic limit, breaking the rotational symmetry of the system's dynamics, since only a finite number of spins take the value –1. But what about states that break this symmetry in the opposite direction? For these cases, we begin with a ground state characterised by a sequence $s_k = -1$ for $k \in Z$, adding all the sequences that can be obtained by making finitely many local modifications which replace some of the entries with +1. Let us label this alternative Hilbert space H^-.
>
> It is obvious that our two representations of the ground state are inequivalent. The proof may proceed by contradiction. Suppose there is some unitary transformation, U: $H^+ \to H^-$, such that $U\hat{\sigma}_n^{+}U^{-1} = \hat{\sigma}_n^{-}$ for all *n*, which implies that $\hat{m}^{N-} = U\hat{m}^{N+}U^{-1}$, and suppose that $\left|\psi^+\right\rangle$ and $\left|\psi^-\right\rangle$ are unit vectors in the Hilbert spaces H^+ and H^- respectively. Assuming that these two vectors are related by the transformation $|\psi^+> = U^{-1} |\psi^->$, it follows that
>
> $$\left\langle \psi^+ \middle| m_z^{N+} \middle| \psi^+ \right\rangle = \left\langle \psi^- \middle| m_z^{N-} \middle| \psi^- \right\rangle. \tag{9}$$
>
> However, this identity does not hold in the thermodynamic limit $N \to \infty$, since the right-hand side evaluates as +1 and the left-hand side as –1. These two representations do not admit a unitary transformation, and the Hamiltonians defined on these two infinite models describe physically different situations.

Nonetheless, the use of infinite models defined in the thermodynamic limit, which deploy unitarily inequivalent representations, turns out to be necessary for empirical adequacy in describing quantum systems.[48] The statistical physics of finite systems identifies equilibrium states with unique Gibbs states (Ruetsche, 2011, p. 3), implying that the phase available to a system at temperature *T* is unique for all *T*. Yet this is contrary to what we observe in experiments. According to Ruetsche, it is 'only in the thermodynamic limit [that] one can introduce a notion of equilibrium that allows what the Gibbs notion of equilibrium for finite systems disallows: the multiplicity of equilibrium states at a finite temperature implicated in phase structure' (p. 3). It is a detail which the more pragmatically minded physicist will doubtless be tempted to gloss over, but one which a scientific realist in search of an ontology will have to take into consideration.

4.1.2. Scientific Pluralism

According to the standard approach to realism, a realist should be preoccupied with the counterfactual question: what would the world be like if this scientific theory provided a universally true and exhaustive description of the physical world? According to Ruetsche, however, it is incumbent upon any would-be interpreter to answer the question: ‘does this interpretation allow the theory to discharge all of its scientific duties?’ The problem with the standard approach to realism, from this practical standpoint, is that ‘there often isn’t a single interpretation under which a theory enjoys the full range of virtues realists are wont to cite as reasons for believing that theory’ (Ruetsche, 2011, p. 5). In practice, physicists deploy a plurality of inequivalent representations to capture the phenomena in which they are interested, for which the correct choice is *context-dependent*.

In our example of the ferromagnet, it is evident that the quantum theory that describes the behaviour of the physical system admits of (at least) two representations, and that these representations are not empirically equivalent. There is no obvious reason for preferring one to the other, and there is good reason to doubt that they share a common structure which completely determines the physical content of both representations. How should we proceed?

On the one hand, to privilege the physical content of one particular representation (‘Hilbert space conservatism’) would be to reduce the number of physically significant states to a subset of those that are generally accepted within successful scientific practices (Ruetsche, 2003). On the other hand, to confine the physical content of a quantum theory to the algebraic structure that is shared by different Hilbert space representations (‘algebraic imperialism’) would be to reduce the number of physically significant observables that are measured within successful scientific practices. Either of these moves fails to support the explanatory agenda of our best quantum theories and is inconsistent with the practice of adopting a realist stance toward physical theories in virtue of their explanatory successes. It seems there is no single universal representation in which all the observables of a complex system can be defined and in which they evolve in a continuous way.

Porter Williams argues that philosophers should content themselves with adopting an *effective realism* (Williams, 2017). According to effective realists, physical theories are not absolutely true in all physical respects and at all physical scales, but that should not matter to philosophers of science, as they are only ever applied within limited regimes in successful scientific practices. The task of the effective realist is to identify elements described by an effective theory that are ‘stable and robust’, inasmuch as they are detectable and measurable and ‘can be expected to survive future episodes of theory change’ (p. 218). It is these elements to which we should be ontologically committed.[49] Williams articulates his brand of effective realism within the context of quantum field theory, which is widely acknowledged to be an effective field theory that breaks down at small scales and that depends upon the practice of renormalisation to secure limited regimes within which empirically adequate models can be constructed.

There is much to recommend this pluralistic approach to realism to metaphysicians seeking to be guided by scientific practices. As Williams observes, the attempt to extract a single fundamental ontology from a physical theory, which characterises the standard approach to realism, 'leaves one with an interpretation unequipped to support the theory in the performance of its explanatory duties' (p. 228), whereas a pluralistic approach to realism which acknowledges the context-dependence of our interpretations opens the prospect of uncovering 'a rich, layered ontology' that is otherwise hidden from the standard realist (p. 220). There is also something salutatory about his exhortation to technically minded philosophers of physics that the business of constructing ontologies 'contains considerable amounts of art as well as science' (p. 233). It is questionable, however, whether effective realism can steer a middle course between the Scylla of pragmatic empiricism and the Charybdis of microphysical reductionism.

On the one hand, it is unclear why philosophers should prefer an effective realism that embraces a complex ontology to a pragmatic empiricism that shuns ontological commitment, on the basis of the reasons put forward by Williams. As Ruetsche points out, both approaches oppose physical fundamentalism by seeking to disentangle the question of explanatory power from the question of universal truth (Ruetsche, 2020). The philosopher who is seeking to extract a fundamental ontology from some physical theory *T* 'has to endow a physical theory with explanatory self-sufficiency. Otherwise, something exogenous to *T* is required to explain why *T* works in some regimes but not others, and why things aren't quite the way *T* says they should be' (p. 308). The effective realist, however, believes we can construct explanations of *T*'s success which make no appeal to *T*'s truth, since we have good reasons to think that *T* is only an effective theory, and hence to reject the fundamentalist's assumption of *T*'s explanatory self-sufficiency. According to Ruetsche, 'Fundamentalism's sin isn't to interpret *T*. It's to decide that, having interpreted *T*, no further explanatory work remains – and thereby suppress the possibility that *T* is merely effective' (p. 309). Ruetsche argues that effective realism can be exchanged for a humble empiricism which eschews ontological commitment without sacrificing explanation. 'The humble empiricists answer is that our theory succeeds as well as it does where it does, not because it's true, but because, whatever the true theory is, our theory approximates it in its domain of application' (p. 310).

On the other hand, it is unclear why philosophers who are strongly committed to realism over pragmatic empiricism should prefer an effective realism that produces a fragmented picture of reality to some form of weak emergence that maintains a commitment to the unity of nature. It may be argued that the interpretation of quantum theories only *appears* to be context-dependent because we are cognitively incapable of modelling complex systems without introducing approximations, and that the existence of unitarily inequivalent representations of quantum theories is merely an artefact of reifying the infinite degrees of freedom which are introduced in the thermodynamic limit (or in quantum field theories). After all, it is doubtful that many physicists take any infinities literally, regarding them rather as idealisations or abstractions (Ellis et al., 2018). According to Wallace (2011), the problem of unitarily inequivalent representations is circumvented in conventional quantum field theory by the introduction of cutoffs which limit its application to systems with only finite degrees of freedom. Yet, as Fraser (2009) has argued, the necessity of cutoffs suggests conventional quantum field theory is only an effective field theory and unsuitable for standard interpretation. In that case, it may be urged, realists will have to wait for some better theory.

4.2. Hylomorphic Pluralism

For the contemporary philosopher of science, it may seem as though the options lie between some kind of fragmented pluralism, which rules out a single unified account of how everything hangs together, or some sort of eschatological monism, which allows the possibility of a theory of everything but admits that such a theory may lie forever beyond our grasp. Yet there may be a third way, which affirms the plurality of physical being and the existence of entities at different scales, without abandoning the commitment to a fundamental ontology.

4.2.1. Contextual Wave Function Collapse

I wish to consider the possible existence of *macroscopic* entities between the microscopic and the cosmic scale, which are neither integral parts of a single Cosmic Substance nor reducible to a single set of microscopic constituents, but which may nonetheless be said to have microscopic parts. For an Aristotelian who is committed to the Eleatic principle, a substance which has fundamental physical being is marked by its possession of irreducible causal powers (Section 2). A macroscopic substance would have to have causal powers over and above the powers of any of its constituents to be included in the fundamental ontology. Yet is there room in contemporary physics, which is widely supposed to concern the properties of point-sized particles and fields that make up everything else, for the existence of substances which have irreducibly macroscopic powers?

In fact, there are many cases where microscopic physical theories contain physical quantities which are not determined by the theory but depend upon large-scale properties of the physical system. For example, most physical theories are written in terms of differential equations, yet physical models can only produce testable predictions once boundary conditions for these equations have been specified. These physical boundary conditions often have a *macroscopic* origin.

The standard approach to realism downplays the role of macroscopic properties in specifying the boundary conditions of physical systems, because it assumes that the total state of the physical world can be *uniquely represented* by our best physical theory as a single closed system which evolves according to the universal laws of our 'best physics'. For example, in the de Broglie-Bohm version of quantum mechanics, the temporal development of the matter is determined for the whole configuration by a law of nature which is specified solely in terms of microscopic quantities (positions) and a global quantity (the wave function) defined at the cosmic scale. The evolution of the total configuration of matter does not depend upon any *macroscopic* (intermediate-scale) quantities. Yet there are good reasons, as we have seen, to doubt whether there is an interpretation of quantum mechanics that is true in all physical respects and at all physical scales.

An alternative 'contextual' model of the quantum dynamics is available, however, proposed by Barbara Drossel and George Ellis, in which the interaction of a quantum system with the intrinsic heat bath of a macroscopic system, such as the measuring device that a scientist might deploy in a laboratory, plays a key role in solving the measurement problem (Drossel and Ellis, 2018). In this interpretation, quantum systems are individual systems, which are 'open' to the influence of a 'classical' environment that cannot be modelled as a single quantum system, and the macroscopic, thermal properties of certain features of the environment have the power to collapse their wave function.

The *CWC model* (contextual wave function collapse) drops the assumption of physical monism that underpins the choice between GRW theory and Bohmian mechanics (Section 3.1.2) by denying that the theory of quantum mechanics is endowed with explanatory self-sufficiency and allowing something exogenous to quantum mechanics to complete its physical description in different contexts. According to Drossel, a thermalised system cannot be described by a many-particle wave function (Drossel, 2017). There is more to the intrinsic heat bath of a macroscopic system than the sum of its microscopic parts. Whilst this approach to quantum mechanics has certain features in common with the GRW and Bohmian theories, it also differs from them in significant ways.

As in the GRW modification of quantum mechanics, the CWC model seizes the first horn of Bell's dilemma, allowing the wave function to become localised with respect to position. It likewise distinguishes scientific measurements from localisation events in general, removing the necessity of a scientific 'observer' in order for there to be any facts about the physical properties of quantum systems. Unlike GRW theory, however, the corrections that achieve these localisations of the wave function depend upon the *macroscopic context* of a physical system, which includes systems which instantiate macroscopic thermal properties, rather than the introduction of an additional collapse mechanism. In short, the

CWC model proposes incorporating a feedback loop – from a particle, via the intrinsic heat bath of a macroscopic system, back to the particle – which introduces non-linear terms into the Schrödinger equation:

$$i\hbar\frac{\partial\psi}{\partial t}=H\psi+f(\psi)\psi \tag{10}$$

where H is the Hamiltonian of an idealised closed system and f is a non-linear contribution due to the external environment. This extra term is physically motivated: it can be accounted for in terms of thermodynamics and solid-state physics (Drossel and Ellis, 2018, pp. 13–19).[50]

As in Bohmian mechanics, the CWC model relies upon the effects of the environment upon the measuring process to explain why the outcomes of quantum experiments, such as the EPR experiment (Section 3.1), conform to standard quantum statistics and obey Born's rule for connecting quantum 'observables' with the wave function of a physical system. Unlike Bohmian mechanics, the CWC model does not conceive the environment that is relevant to the measuring process in terms of a many-particle system with a wave function that is subject to the unitary and reversible time evolution described by Schrödinger's linear dynamics. In fact, the heat bath of any finite temperature system that is capable of collapsing the wave function is characterised as having only a limited 'memory', since it radiates irreversibly into the heat sink of its surroundings. Consequently, the CWC model does not leave any physical system entangled with any part of its environment beyond the usual time scale of decoherence, placing a limit on the extent of quantum entanglement in nature. According to the CWC model, the heat bath of a macroscopic instrument of measurement serves as a bridge between quantum systems and their classical environment, since the heat bath of a macroscopic system can induce the collapse of the wave function.

The CWC theorist agrees with the GRW and Bohmian theorists that standard quantum mechanics is *physically incomplete*. Unlike GRW theory and Bohmian mechanics, however, CWC theory does not offer a universal way of completing quantum mechanics that purports to describe every physical aspect of the world at every physical scale, but restricts itself to describing the quantal properties of open quantum systems whose dynamics depend upon macroscopic features of their classical environments. From this standpoint, a purely quantal system (in which $f \to 0$ in (10)) is an idealised isolated system that does not exist in the real world. Drossel and Ellis believe that we should reject 'the untestable and implausible claim that the environmental heat bath can be described by an infinite-precision wave function that is subject to unitary time evolution' (p. 4).

In this contextual approach to quantum mechanics, classical properties are supposed to be higher-level, strongly emergent properties of physical systems, which have top-down causal powers to change the microscopic properties of systems. They derive these causal powers from the fundamental role that they play in defining the Hilbert spaces and the time scales within which the unitary time evolution of an open quantum system takes place.

4.2.2. Rival Views of Macroscopic Entities

Yet how are macroscopic properties like temperature and chemical entropy, which characterise complex physical systems like measuring devices, supposed to 'emerge' from simpler microphysical systems, and what is the nature of the microphysical substrate from which a macroscopic entity is supposed to emerge? Drossel and Ellis's commitment to strong emergence may seem to confront an ontological dilemma between microphysical reductionism or substance dualism.

On the one hand, suppose the causal powers of an emergent macroscopic whole can be explained entirely in terms of the properties and causal powers of its microscopic parts. These microphysical parts do not depend upon the whole for their physical properties but have their own intrinsic natures. In that case, the emergent macroscopic whole must be ontologically reducible to or supervenient upon the aggregation of its microscopic parts and should not be counted among the fundamental entities of nature. Yet CWC theory does not appear to be compatible with microphysical reductionism, since it provides the macroscopic properties of one system (such as a measuring device) with an irreducible role to play in collapsing the wave function of another system, thus endowing macroscopic properties with top-down causal powers.

It may be argued that the macroscopic properties of an emergent whole do not locally supervene upon its microscopic constituents, but globally supervene upon nothing less than the entire cosmos: the cosmos as a whole is an emergent entity with its own intrinsic nature. In that case, the macroscopic emergent whole should be regarded as an integral part of the physical cosmos and should not be counted among the fundamental entities of nature. Such entities are merely artefacts of the boundary conditions that we impose upon physical systems. Yet CWC theory does not seem to be compatible with cosmic holism, since it rejects the claim that the cosmos as a whole has a universal wave function as an 'untestable and implausible' assumption (Drossel and Ellis, 2018, p. 4) and insists on adopting a contextual approach to the wave function's dynamics.

On the other hand, suppose that the activities of an emergent macroscopic whole cannot be explained in terms of the causal powers of its microscopic constituents, but that the macroscopic whole has a novel and irreducible causal power which directly acts upon the microscopic constituents and causes them to change their collective behaviour. In that case, there would be good reason to count this macroscopic entity as a separate entity that *interacts* with these microscopic entities rather than being *composed* of them (Gillett, 2016, p. 247). If the relation between this macroscopic entity and these microscopic entities is merely a *causal relation* between different entities which have their own intrinsic causal powers, then the macroscopic entity and the microscopic entities are ontologically independent substances, since they do not depend upon one another for their physical natures. Yet CWC theory does not appear to be compatible with a dualism of microscopic and macroscopic entities, since it does not supply a complete quantum mechanical characterisation of any microscopic entity but only characterises quantum systems within different macroscopic contexts.

It may be argued that the emergent causal power which is exercised by the macroscopic whole is not a fundamental power of the whole, which has its own nature and primitive identity, but is a 'structural power' that is instantiated by its microscopic constituents, which arises from a kind of conspiracy that occurs between them whenever they are spatiotemporally configured in a certain way. In that case, we would have good reason to count this macroscopic entity as a *functional whole*, since its behaviour would be a non-linear function of the intrinsic properties of its microscopic constituents. Such macroscopic entities are not fundamental substances, as they do not constitute any addition to being over and above their constituents. Yet CWC theory leaves us unenlightened concerning the microscopic domain of these non-linear functions, since it has nothing to say about the properties of microscopic constituents independently of their different macroscopic contexts. What we require, then, is a metaphysics that can elucidate a *non-causal* relation of composition between the emergent macroscopic whole and its microscopic parts. Hylomorphic Pluralism provides such a model.

4.2.3. Substantial Forms

Hylomorphic Pluralism affirms the existence of a variety of substances in nature which are metaphysically prior to their physical parts. These substance are not built of entities which possess intrinsic physical natures apart from the substances of which they are parts. Rather, their material, spatially defined parts are ontologically dependent for their causal powers, and hence their physical natures, upon the wholes of which they are parts. Hylomorphic Pluralism, I suggest, can make sense of the existence of wholes with 'emergent' macroscopic causal powers.

In the first place, Hylomorphic Pluralism offers an alternative account of composition to microphysical reductionism. In this model, a macroscopic entity which has irreducible causal powers is not an arrangement of microphysical constituents which have their own intrinsic physical natures. Rather, this entity is metaphysically composed of both matter (which has no intrinsic causal powers) and substantial form (which determines the powers of the substance): the essential powers of the substance are metaphysically grounded in its substantial form.

Unlike the Cosmic Hylomorphist, the Hylomorphic Pluralist does not posit the existence of a single Cosmic Substance, of which everything else in the world is only a part, but admits a plurality of different substances, which exist at different physical scales. Among the substances which make up the physical world, it may be supposed, are some of the objects of ordinary experience that were familiar to the investigations of Aristotle, such as plants, animals, and human beings, although I shall leave discussion of the biological world to the next chapter.

In the second place, Hylomorphic Pluralism is able to avoid dualism by providing an account of the composition of a metaphysically unified whole in which the parts are not themselves substances. In this metaphysical model, the world is not divided into microscopic entities that have quantal properties, on the one hand, and macroscopic entities that have classical properties, on the other hand, which somehow interact with one another despite being governed by incommensurate laws. Rather, we can think of the (inorganic) world as being made of thermal substances which have *both* quantal *and* classical properties, as Koons and I have suggested elsewhere (Koons, 2019; Simpson, 2019), which are metaphysically composed of matter and substantial form. A thermal substance, on this view, is not a unified and fundamental physical whole because it micromanages its microphysical parts by pushing them around, and the relation between its substantial form and its material parts is not an (efficient) *causal* relation. Rather, the substantial form is the formal cause of the unity of the substance by determining the powers of its parts, and the relation between the substantial form of the substance and its material parts is one of *metaphysical grounding*.

Unlike the Cosmic Hylomorphist, the Hylomorphic Pluralist does not conceive of physical substances as existing in a state of causal isolation, but allows substances to interact with one another through the exercise of their causal powers. A substance therefore has an *accidental form*, in addition to its substantial form, which is subject to change as it interacts with other substances.[51] The causal powers through which one substance interacts with another substance depend jointly upon both its substantial form and its accidental forms.

I shall outline briefly how this hylomorphic metaphysics might be applied to a contextual approach to quantum mechanics, whilst restricting the scope of this toy model to thermal phenomena. According to this metaphysical model, the physical world is 'tiled' with thermal substances which have intrinsic causal powers,[52] such that any change in the physical world necessarily involves a change in one or more of these physical substances, which is brought about through the exercise of their causal powers. The matter of a substance S_i is a parcel of gunk $m_i(x,t)$.[53] The matter-fields of two substances S_i and S_j are distinct from one another in virtue of the prior distinctness of their two parcels of gunk $m_i(x,t)$ and $m_j(x,t)$; they do not share any metaphysical parts. The metaphysical substrate from which physical substances are carved lacks any intrinsic causal powers: it only has the *potential* to bear causal powers. A parcel of matter-density must be combined with a substantial form to compose a physical substance. A parcel of matter-density which – *per impossibile* – were not combined with a substantial form would be a 'compositional zombie' that lacked any causal powers. When substances interact with one another by exercising their causal powers, they exchange matter-density with each other's matter-fields.

We may think of a substance as having an internal matter flow which is choreographed by a wave function via the matter-field equation (7). The wave function evolves according to a non-linear Schrödinger equation (10), where the non-linear terms depend on the macroscopic context in which the substance is situated. There is no universal wave function in this model: it is only possible to define a wave function in those circumstances in which the system has been isolated from the noise of its environment and its boundary conditions are relatively stable. The laws in this model are thus 'dappled' laws (to use Cartwright's nomenclature), since they are not universal regularities but are restricted to the 'nomological machine' constructed by the experimentalist (Cartwright, 1999). However, the Hylomorphic Pluralist is committed to a realist approach to quantum mechanics: the wave function governed by the non-linear Schrödinger equation represents a real power of the substance to regulate its own parcel of matter, which is grounded in its substantial form.[54] We might think of this power as a *multi-track* power, where each track corresponds to a different macroscopic context.

In addition to having a power to regulate their own parcels of matter, the thermal substances comprising the environment of any quantum system have causal powers to bring about changes in the matter of other substances. These macro-level powers of the substance are sustained in existence by the micro-level parts of the substance. The matter of a thermal substance, however, does not relate to space and time merely as a set of discrete physical units, and the macroscopic properties of a thermal substance at a particular time are not reducible to the spatial arrangement of its matter at a particular time: the material parts of the substance also 'cooperate' with one another over time as an undivided continuum, generating dynamical situations which can only be modelled using Hamiltonian functions defined on an infinite (continuum) model, cf. Koons (2019) and Simpson (2019). The proper way of taking this limit for a given substance (that is, the correct choice of physical representation) is determined by the substantial form of the substance, which confers a monadic nature upon the substance as a whole and grounds the powers of its micro-level parts.

The Hylomorphic Pluralist is committed to a realist approach to the macroscopic properties of physical substances, but one that resists microphysical reduction: each thermal substance has a Hilbert-space representation that defines macroscopic observables for its emergent properties, but different substances admit different representations. The macroscopic properties of a thermal substance cannot be explained mechanically in terms of laws that connect one set of microscopic properties instantiated at time t with another set of microscopic properties at time $t' > t$, where these microscopic properties are defined in terms of a unique representation which characterises the total state of the physical world. Nonetheless, there is no need to suppose that the macroscopic powers of thermal substances demand new fundamental forces (or non-physical 'configuration forces') in order to make a causal difference to where their matter ends up, since the quantum dynamics is context-dependent and the macroscopic properties of thermal substances play a role in defining the Hilbert spaces and time scales within which the unitary time evolution of quantum systems takes place.

The Hylomorphic Pluralist, unlike the effective realist, can thus steer a course between pragmatic empiricism and microphysical reductionism. On the one hand, the Hylomorphic Pluralist can agree with the pragmatic empiricist about the disconnect between the explanatory power of a theory and the universal truth of its description, whilst maintaining an attitude of ontological commitment. Quantum theories are not successful because they uncover a single set of microscopic constituents of which everything is made, but because they isolate certain causal powers of substances which manifest under certain conditions. These causal powers are *real* properties of different thermal substances, but they are metaphysically *grounded* in their substantial forms.

On the other hand, the Hylomorphic Pluralist can agree with the microphysicalist that the thermodynamic limit is an idealisation, without abandoning an ontological commitment to the reality of macroscopic entities. Quantum theories about finite temperature systems are not successful because they truthfully represent the degrees of freedom in a physical system but because their different representations capture something of the different ways in which their material parts cooperate in determining the thermal properties of a system. These properties are real properties of thermal substances, which are grounded in their substantial forms. The necessity of adopting a change in the physical representation of a system – when it undergoes a phase transition, for example – is due to the occurrence of a *substantial change* taking place in the system,[55] which is a *discontinuous* change in which the microscopic powers of a parcel of matter are redetermined by a different substantial form.

The Hylomorphic Pluralist, like the effective realist, affirms the existence of entities which exist at different physical scales, but remains committed to a fundamental ontology of substances which are metaphysically composed of matter and form. Matter and form are affirmed for the sake of both empirical *and* explanatory adequacy, rather than being read off the formalism of quantum physics or isolated in a scientific experiment. We can only reach them by metaphysical abstraction in the context of an empirical inquiry that affirms the reality of change (Section 2.2). Like the people in Plato's cave, we find ourselves unable to look directly at the forms, which cast shadows on the wall of our cave. Unlike the situation in Plato's cave, however, these forms are immanent within substances which we can manipulate within different scientific practices, and they cast different shadows depending on how they are manipulated. The role of the metaphysician is like that of someone who infers the shape of an object from the variety of shadows that it projects as it is held to the light in different ways.

5. Concluding Remarks

At the beginning of this chapter, I observed that the Aristotelian concept of causal powers, which was widely rejected during the Scientific Revolution, is now at the forefront of contemporary philosophical discussions. In the course of this chapter, I have argued that it also time to reclaim the Aristotelian doctrine of hylomorphism. By restoring the concept of substantial form, it is possible to provide a realist account of quantum physics in terms of an ontology of powers.

The two hylomorphic models which I have discussed correspond to two incompatible versions of quantum mechanics: Cosmic Hylomorphism offers an ontological account of Bohmian mechanics, which attributes the cosmos a universal wave function and a global configuration of particles (Section 3); Hylomorphic Pluralism offers an ontological account of CWC theory, which divides the world into separate parcels of gunk and requires the wave function of quantum mechanics to collapse (Section 4). Granted the unitarian doctrine of substantial form, which Aquinas affirmed and Scotus rejected, the ontologies of these models would seem to be mutually exclusive: if there is a Cosmic Substance, of which every particle is a part, there can be no thermal substances, on pain of violating the unity of the Cosmic Substance – unless the thermal substances could be *embedded* in a Cosmic Substance without being *mereological parts* of it (cf. Dumsday, 2016). We might think of the cosmos as beginning as a single substance, from which macroscopic thermal substances are subsequently derived.[56] There is scope here for developing a neo-Aristotelian cosmology.

Both of my metaphysical models, I suggest, also hold interest for contemporary discussions of theology and science, although each of them has its limitations. Cosmic Hylomorphism opens the prospect of reviving something like the neo-Platonic conception of a 'world soul', which could play a role in a scientifically informed account of special divine action that is able to resist common objections (Dumsday, 2019a). The global perspective of Cosmic Hylomorphism, however, encounters difficulties in explaining the emergence of specific physical entities, which a localist perspective like Hylomorphic Pluralism can readily accommodate. Although the sketch of Hylomorphic Pluralism that I have offered in this chapter only includes thermal substances, the following chapter shows how to extend this account to include biological as well as inorganic entities, gaining the explanatory advantage of being able to include human beings within nature as embodied and responsible agents, created in *imago dei*.

In putting forward these two hylomorphic models, however, I do not wish to suggest that the quantum theories for which they offer ontologies are without their difficulties or theoretical costs: Bohmian mechanics only secures agreement with the Born rule of standard quantum mechanics via the quantum equilibrium hypothesis, which has been criticised for being ‘artificial’ (Valentini, 2019); CWC theory rejects the theory of decoherence, a theory many physicists find appealing. Both Bohmian mechanics and CWC theory come at the cost of denying Lorentz invariance, sacrificing an observational symmetry of special relativity.

Whether these are perceived as theoretical costs, and if so, just how they will be weighed against one another, will vary among both philosophers and physicists. Some physicists – particularly mathematical theorists – are strongly attracted to simplicity and symmetry, although such an attraction is not without its perils, since it can lead to physical models that are oversimplified or are endowed with symmetries that do not appear to correspond to anything in reality. Other physicists – perhaps the more practically minded experimentalists – may be sympathetic to some degree of dappledness in nature’s laws.

In any case, I do not wish to suggest that Bohmian mechanics and CWC theory are the *only* quantum mechanical theories which admit hylomorphic models. Adrian Kent has proposed a way of solving the measurement problem that does not entail a rejection of decoherence theory and which may admit a hylomorphic interpretation (Kent, 2015).[57] Alexander R. Pruss has offered a hylomorphic account of quantum mechanics that adapts the so-called travelling minds interpretation (Pruss, 2017). There are doubtless other areas for exploration.

Before closing, I should emphasise that the two metaphysical models that I have outlined in this chapter are not simple restorations of Aristotle’s original doctrine of hylomorphism: the matter they posit is not merely a substrate of potentiality but consists of particles or parcels of gunk which play a role in individuating physical objects, and the notion of formal causation is explicated in terms of a grounding relation. These are features which may attract the censure of classical

Aristotelians or Thomists. I am offering these 'neo-Aristotelian' models, however, as philosophical sketches which are intended to inspire further discussion.[58]

Notes

1. The term 'hylomorphism' is a portmanteau of these Greek words.
2. Widespread, but not universal: Leibniz was a notable exception to this trend (Leibniz, 1976).
3. Physicists have often denied the intelligibility of quantum mechanics (Dürr et al., 2012, ch. 4).
4. Anna Marmodoro has expounded its Aristotelian roots by linking the concept to Aristotle's discussion of potentiality and actuality (Marmodoro, 2014, ch. 1).
5. For a recent discussion of the return of powers to mainstream philosophy, see Lagerlund et al. (2021).
6. Famously, in Raphael's School of Athens, Plato is portrayed pointing a finger upward toward the sky, whilst one of Aristotle's hand is stretched toward the earth with his fingers splayed.
7. For a discussion of universals in Plato and Aristotle, see Scaltsas (1994).
8. See Plato's *Sophist* in (Cooper, 1997, 247d-e, 269).
9. In my references to Aristotle, I am relying upon Barnes (1984).
10. That is, according to how Aristotle has generally been understood. For an alternative reading, in which Aristotle is fundamentally committed to *powers* (or power tropes), see Marmodoro (2014).
11. That is, in virtue of their having animal forms, or souls.
12. See e.g. [Arist., *Gen. & Corr.*, I.10] in Barnes (1984); in particular, 327b23–b33. Also, [Arist., *Metaphys.*, b5–15 & 1040b5–15].
13. For further discussion of integral wholes and potential parts, see Simons (2000, ch. 9).
14. According to Aquinas, in *De Principiis Naturae* (following the translation in Skrzypek, 2019): 'Matter and form are said to be intrinsic to a thing, in that they are parts constituting that thing' (ch. 3); 'matter and form are said to be related to one another . . . they are also said to be related to the composite as parts to a whole and as that which is simple to that which is composite' (ch. 4). For a contemporary account of forms as metaphysical parts of substances, see Koslicki (2008, 2018).
15. For a more detailed narrative about the physicalisation of matter and form, see Pasnau (2011). Sections 2.3 and 2.4 also draw upon parts of a previously published paper of mine concerning the fall and rise of hylomorphism, and some sentences are verbatim (Simpson, 2018).
16. Following Pasnau's discussion in Pasnau (2011).
17. [Burgersdijk, F. 1650, *Collegium Physicum*, II.34, pp. 1314], as translated in Pasnau (2011).
18. For a discussion of Ockham's view, see Pasnau (2011), 'Matter and extension'.
19. See [Scotus, *Rep.* II.12.2 n. 7 (XI:322b)] in Wolter and Bychkov (2004).
20. See [Dabillon 1643, *Physique*, I. 3.2, p. 103] as cited in Pasnau (2011).
21. William de la Mare targeted Aquinas affirmation of unicity in Correctorium Fratris Thomae in 1279.
22. [Suárez, *Disputationes metaphysicae*, 15.1.7] as quoted in Pasnau (2011). The text is somewhat ambiguous.
23. A Scotist might seek to develop a response to my physicalisation argument in which some instances of causation could count as being efficient *and* formal, rather than having to count as one *or* the other.

24. From C. Adam and P. Tannery eds., *Oeuvres de Descartes*, rev. ed., 12 vols. (Paris: Vrin/CNRS, 1964–76), as quotes and translated in Pasnau (2011).
25. See René Descartes to Morin, 12 September 1638, in *The Philosophical Writings of Descartes*, vol. 3, ed. J. Cottingham et al. (Cambridge: Cambridge University Press).
26. Significantly, Newton rejected the claim that a physical explanation had to trace everything down to the motion of the smallest corpuscles. His theory of universal gravitation afforded a physical explanation even though it did not describe what push or pull between corpuscles caused gravitational phenomena.
27. See R. Boyle, The Origin of Forms and Qualities, in *The Works of Robert Boyle*, ed. M. Hunter and E. Davis (London: Pickering & Chatto, 1999–2000).
28. H. Oldenburg, *Correspondence*, ed. and trans. A.R. Hall and M.B. Hall (Madison: University of Wisconsin Press, 1965), III:67.
29. See Works of Boyle, V:305.
30. I have not space here to address Newton's changing views on powers, or Thomas Reid's defence of dispositionalism against Hume, etc. For a more adequate historical account, see Lagerlund et al. (2021).
31. See P.-S. Marquie de Laplace, *A Philosophical Essay on Probabilities*, trans. F. W. Truscott and F. L. Emory (New York: John Wiley & Sons, 1902).
32. Section 3 draws upon the hylomorphic interpretation of Bohmian mechanics suggested in my doctoral thesis (Simpson, 2019), which was further developed in Simpson (2021).
33. In Einstein's original version of the EPR experiment, the measurements are of position and momentum.
34. For a more detailed but accessible discussion, see Maudlin (2011).
35. For three recent experimental tests of Bell's inequalities, which close two 'loopholes' in Bell's theorem and underscore the failure of locality, see Giustina et al. (2015); Hensen et al. (2015); Shalm et al. (2015).
36. The operator $\hat{U}$ is a unitary operator. The meaning of 'unitarity' is that the probabilities computed from $|\psi\rangle$ always sum to unity. The operator $\hat{U}$ redistributes the probabilities between different possibilities as time goes on. It also induces superpositions.
37. Maudlin admits that besides GRW theory and Bohmian mechanics, 'there are others that can survive the test' (Maudlin, 1995, p. 14). I discuss a third possibility called CWC theory in Section 4, which is like GRW theory except that the wave function collapse dynamics is context-dependent.
38. The particles are each attributed gravitational mass, m_i, but the COW experiment suggests mass delocalises over the wave function and need not be regarded as an intrinsic property (Brown, 1996). (COW refers to the scientists: Colella, Overhauser and Werner.)
39. Concerning relativistic versions of Bohmian mechanics, see Dürr et al. (2014).
40. Since the theory allows non-equilibrium solutions $\rho \neq |\psi|^2$, this restriction to quantum equilibrium has generally been taken as a necessary postulate to introduce the element of randomness that is essential to quantum mechanics (Dürr et al., 1992). Some see this move as 'artificial', e.g. Valentini (2019).
41. For details of this account of laws, see Ramsey (1978), Lewis (1973, pp. 73–75), Lewis (1987, postscript), and Mill (1875, Book III Chapter IV).
42. For further discussion, see Lazarovici (2018), Matarese (2018), Simpson (2020), and Wilson (2018).
43. This model deploys the notion of grounding championed in Schaffer (2009, 2010).

44. Concerning the nature of this substantial unity, see Simpson (2021, Section 3) and Peterson (2018).
45. Section 4 draws upon my hylomorphic interpretation of contextual wave function collapse theory in my doctoral work (Simpson, 2019).
46. This section discusses a problem I describe at greater length in (Simpson et al. in progress).
47. This technique maintains the tradition of using separable Hilbert spaces in quantum mechanics.
48. In statistical physics, classical models of coupled spins (like Glauber models) are also used which show phase transitions for *finite* systems. These models have flip rates that depend on the orientation of their neighbours. With increasing system size, however, the time required for flipping the preferred orientation becomes larger than the lifetime of the universe. So for all practical purposes, ergodicity is broken and different phases coexist. I would like to thank Barbara Drossel for pointing this out.
49. Cf. Brian Ellis's causal process realism (Ellis, 2001, pp. 157–160).
50. Of course, this is only a simplified example of what this feedback might look like. The final equation in an elaborated theory of feedback will look more complicated and will involve stochasticity.
51. For a discussion of accidental forms as metaphysical parts of material substances, see Skrzypek (2019).
52. Regarding the 'tiling constraint', see Schaffer (2010). See also its application in Koons (2019).
53. In another version of this model, the gunk might be replaced with infinitely divisible 'extended simples'. For the sake of simplicity and continuity, however, I have inherited the gunk from the GRWm ontology.For further discussion of material composition and substance ontologies, see Dumsday (2019b, chs. 4–5).
54. On this view, the linear Schrödinger equation familiar to standard quantum mechanics is an idealisation that only exists in the limit of perfect isolation $f \rightarrow 0$, which cannot be attained in practice.
55. As opposed to an *accidental* change; the only kind of change admitted in the mechanical stance.
56. The Cosmic Substance, in that case, would also be a thermal substance.
57. Correspondence with Robert Verrill.
58. The author would like to thank (in alphabetical order) Thomas Davenport, Barbara Drossel, Travis Dumsday, George Ellis, Simon Horsley, Robert C. Koons, Anna Marmodoro, John Pemberton, Javier Sanchez-Canizares, and Robert Verrill, among other friends and colleagues too numerous to name, for critical feedback and discussions.

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