Routledge Research in STEM Education

INVENTION PEDAGOGY – THE FINNISH APPROACH TO MAKER EDUCATION

Edited by
Tiina Korhonen, Kaiju Kangas and Laura Salo

Invention Pedagogy – The Finnish Approach to Maker Education

This collection, edited and written by the leading scholars and experts of innovation and maker education in Finland, introduces invention pedagogy, a research-based Finnish approach for teaching and learning through multidisciplinary, creative design and making processes in formal school settings.

The book outlines the background of, and need for, invention pedagogy, providing various perspectives for designing and orchestrating the invention process while discussing what can be learned and how learning happens through inventing. In addition, the book introduces the transformative, school-level innovator agency needed for developing whole schools as innovative communities. Featuring informative case study examples, the volume explores the theoretical, pedagogical, and methodological implications for the research and practice of invention pedagogy in order to further the field and bring new perspectives, providing a new vision for schools for decades to come.

Intermixing the results of cutting-edge research and best practice within STEAM-education and invention pedagogy, this book will be essential reading for researchers, students, and scholars of design and technology education, STEM education, teacher education, and learning sciences more broadly.

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Foreword

Invention Pedagogy: Bringing Equal Access to Progressive Pedagogies for All Children

Paulo Blikstein

Picture two groups of students. One is sitting stiffly in rows, memorizing equations. The second group is standing with its teacher on the roof of a tall building. Below, they see the pattern made by the business and industrial zones, surrounded by the greener residential districts. They go down to the street. Explore their city at close range. Then they go back to their classrooms, compare notes, and discuss what's right and wrong with the city and what to do about it. The first group, meantime, is still memorizing equations. This is the difference between old and progressive education. It is based on the theory that schools should be adapted to the needs of children and of the increasingly complex society in which they are being trained to live. And this theory is not brand-new: it has been practiced for more than 20 years, but mostly in exclusive private schools.

These opening lines were shamelessly lifted, almost verbatim, from a *Life* magazine article published in the United States. They sound remarkably familiar, almost as if they could have come from the latest issue—after all, at the time of publication, "progressive schooling" had been practiced for two decades already. And yet, stunningly, the article is dated 5 June 1939 (for the full piece see "Young Americans Study America", 1939).

That must give researchers and policymakers some pause and cause for humility. We have been trying to reform schools for 100 years, but is it working? Common sense appears to suggest that schools never change. This "standard critique of education" asserts that schools are the same as they were a century ago, with their focus on memorization, control, and standardization. I used to be a firm believer in this critique, but a few years ago, I started to realize that the full story is more nuanced and layered.

My doubts about the "standard critique of education" began when I started detecting, in multiple press pieces about new "edtech" companies and their CEOs, a common thread: the idea that we need to upend the "one-size-fits-all", "passive" model. For example, in 2012, the CEO of Khan Academy said, "The old classroom model simply doesn't fit our changing needs. [...] It's a fundamentally passive way of learning, while the world requires more and more active processing of information" (compare that to "schools should be adapted to the needs of children and of the increasingly complex society" from 1939!). He was not alone. For most of the 2010s, the CEOs of the largest edtech companies such as Knewton and alt.school have claimed that "schools never change", condemned their standardized "soul-killing" lectures, and prescribed data-driven, personalized learning (for extensive documentation, see Blikstein & Blikstein, 2021; Reich, 2020; Watters, 2021).

As the son of a semioticist, I grew up overhearing weirdly sounding names such as Greimas, Foucault, and Bakhtin, so the claims of the CEOs sounded suspicious. Semiotics is a science of "detectives": it puts discourse under a microscope, looking for patterns or unintentional fragments to reveal larger overarching themes and intentions. When venture-capital-fueled companies and entrepreneurs offer critiques that resemble those of luminaries of (true) progressive education such as John Dewey, Cynthia Solomon, and Paulo Freire, something might be amiss. And indeed, even though at first glance the words read similarly, one key element was missing: *politics*.

Freire's or Papert's critiques were not merely a commentary on "soul-killing" classroom pedagogy but on the politics of education and its societal goals. Far beyond being simply concerned with making classrooms more engaging or resuscitating the soul destroyed in the lecture hall, they had developed a pedagogical project that was enmeshed in a political one. Instead of compliance, tracking, and labor market preparation, they advocated for emancipation, youth empowerment, and knowledge-driven agency—not for a privileged few, but *for all*. And this crucial element was right there in the 1939 *Life* magazine article: "[Progressive education] has been practiced for more than 20 years. But mostly in exclusive private schools." *In other words, it is not that we have not known what emancipatory education looks like*. We have for at least a hundred years: in one of *Life* magazine's photos from 1939,[1] students are learning math by building their own train tracks, in a room without desks and chairs, sitting on the floors, and working in groups. In another set of photos, they are actively investigating their own city, interviewing residents, and collecting data in the stockyards, the sewage plant, the local courtroom, and the low-income areas. With all this information, they go back to the classroom to design solutions to fix different urban problems. Thus, this type of work has been going on in schools for a century: the point is not that we do not know what to do. *It is about who we allow to participate in these kinds of learning experiences*.

Thus, when corporations and entrepreneurs advocate for "personalization" and "free-spirited" education, we should take a moment to consider their motivations. *Personalization for what, and for whom?* How far will those free-spirited students be allowed to go in corporate-driven "personalized" education? And what compromises, hidden curricula, underlying assumptions, power dynamics, and ethical principles lie behind these new visions?

There is no better example or explanation than the trajectory of one of the most well-known video-based learning platforms, Khan Academy. First, it got famous by proposing that its vast library of online videos would break the one-size-fits-all model of schools, bringing free, high-quality education to the masses and leading to a revolution in how the world learns. Anyone with basic training in education could recognize this as a 21st-century instantiation of Skinner's "miraculous" teaching machines: not only a long-disproven but also a hardly novel solution for education (for an extensive historical account of the 100-year-old history of "teaching machines", see Watters, 2021; for empirical studies of these types of environments, see Reich, 2020). Khan Academy was not all bad: it did become a valuable resource for many students, especially as supplementary material, but it never achieved the overnight disruptive revolution it (very strongly and intentionally) promised. Realizing that the video library would not do the trick, and eager to keep its centrality in the education reform conversation, Khan Academy announced in 2014 the "Khan Lab School"—a school for a few dozen students, in which pupils would be able to follow their intellectual passions with a flexible curriculum and lots of contact time with human teachers—just like in the 1910s.

This astonishing move, rather than an exception, became the rule. When faced with the harsh realities of "revolutionizing education" with a glorified video library, and realizing that their solutions were utterly unscalable, Knewton, alt.school, and others either closed down or pivoted to serving corporations or affluent customers. Unencumbered by weighty theoretical or political commitments, they were free to leave behind their educational saviorism and quickly embrace the business-as-usual corporate modus operandi. By the 2020s, the Silicon Valley–inspired promise of free, high-quality education for the masses, driven by miraculous AI-powered systems, was all but history. But it left behind a narrative that might still ring true for many: schools never change, teachers are unprepared, the system is beyond repair, and education reformers are touchy-feely hippies who do not know how to get things done. And, crucially, to change education, we need to bring in entrepreneurs who know how to "move fast" and deliver reform "at scale."

Yet there is a competing, more subtle narrative that counters the "schools never change" story: the ecosystem of education has in fact been changing, albeit slowly, for well over 100 years. The theoretical musings of Dewey did not stay only within academic debates: they were applied in his Lab School at the University of Chicago (founded in 1896), which inspired numerous other experiences, including the consequential "Escola Nova" movement in Brazil. Democratic, Freire-inspired schools and projects have existed in the hundreds, and Papert's and Ackermann's constructionism has impacted public policy in tens of countries. All these initially academic ideas filtered through into K–12 schools through teacher professional development programs, partner lab schools, and many other mechanisms. But since education is a politically contested territory, it is always subject to the push and pull of larger ideological and policy conversations: reforms are implemented when the environment is favorable, rolled back when the opposition gets into power, and then implemented again (case in point: recent conservative back slash in the United States on teaching about racism, the Holocaust, or evolution). And yet there is change—not a sprint, but a marathon. As a result of decades of research, activism, design, and experimentation led by intrepid innovators in schools around the world, change has happened. These long-game innovators are not, for the most part, technology entrepreneurs, and you do not often see them delivering TED Talks. They are educators, principals, cognitive scientists, educational researchers, computer scientists, and young students, who relentlessly experimented with new ideas for education, despite stern resistance.

In this new narrative, it is not that "schools never change" but that even though multiple stakeholders have been working tirelessly, public education reform is hard and time-consuming. It requires complex consensus-building, risk-minimization, and other structural changes that take decades to become firmly established. Additionally, most progressive education scholars have always made it clear that their reforms were indissociable from a political agenda, so it is no surprise that there was enormous resistance.[2] Conservative groups thus are not simply willing to let things "change".[3]

This unfair competition—between simple and complex change—is no more visible than in the current discussion on the implementation of computer programming in school curricula. In 1967, while technologists were envisioning a future in which robot teachers would be taking over, the Solomon-Papert team counterproposed the revolutionary idea that children should program computers, not be programmed by them. They were not concerned with feeding the job market with more coders but giving *all* children powerful ways of self-expression. They refused the idea of canned computer curricula and instead advocated for children to engage in building projects of their interest, proposing radically new ways to organize schooling. In the 2010s, however, a new incarnation of computer programming in schools came to be, this time sprouting from tech companies or nonprofits led by industry tycoons. Even though they seemed to advocate for the same ideas, there was a fundamental difference: programming was a tool to get the "jobs of the future", canned curricula were the rule, and the entire enterprise was sanitized to appear as just a "neutral" educational reform. Evidently, these latecomers got the reputation of being the people who "really did it", leaving behind the disheveled constructionist hippies advocating for their complicated reforms. The constructionists wanted a lifetime of different learning experiences for kids—we got an hour of code.

The same happened with the idea of a dialogical education that brings students' lives and cultures to the classroom. The Freirean version talked about changing the enterprise of designing curricula by making it more personally relevant, thus changing power relations in classrooms. Too complicated. Does not scale. Too political. Instead, in the 2010s, the idea of "personalizing" education was appropriated by a plethora of institutions that offered a sanitized, easy-to-scale version in which students are bestowed the amazing power to choose which prerecorded videos to watch, and—drumroll—even to watch them twice!

The absence of politics is significant because it turns the affair into very unfair competition. The "neutral", sanitized version of the reforms is much easier to implement and publicize, while the nuanced, complex ones take much more time and effort. But the original, powerful, and deep versions of those ideas have often found a safe home. Over the last 100 years, each time a progressive idea failed to take root in public education, it would end up spirited away into private schools, where—given a fighting chance—it sometimes blossomed. As a result, today we have a number of private schools around the world offering 21st-century learning in a wide array of ways, while most public systems struggle to leave the now-distant 20th century. This was as true in 1939 as it is today. We imagined that the big factor of 21st-century educational inequity would be the "digital divide" (unequal access to the internet), but it ended up being about the "pedagogy divide": unequal access to progressive pedagogies.

But there is hope. What if instead of embracing the discourse of "schools never change and we need outsiders to show us the way", we start to adopt a new narrative? It would start with the recognition that there are three levels for systemic school change: (1) generating new ideas, (2) piloting projects or experimenting with new ideas, and (3) transforming entire public systems. We have plenty for the first two levels: educators, researchers, communities, and students have been pushing schools to do different things for decades. We should acknowledge, embrace, and elevate those efforts. The fact that transformations of public systems are so rare should not be attributed to a lack of ideas or willingness to change. They are just extremely hard to pull off and require sophisticated theorization, strong empirical evidence, and buy-in from multiple stakeholders. And that is where this book comes in.

Throughout the last decades, whenever we needed an example of a country that had successfully implemented student-centered, progressive, advanced educational innovation, we would look to Finland. It became a new paradigm in education by achieving the best results in international rankings while having a progressive system. This was revolutionary because, before Finland's success, it was believed that to do well on international tests, you had to "teach to the test." Finland showed the world that it was, in fact, possible to top every international ranking and yet also be profoundly innovative. It showed that it was possible to change a system without completely breaking it. Disrupting and breaking systems might work for private schools, which can afford the risk—but a public system cannot.

This requires scalable, research-based, empirically tested models that could make those new ideas a reality for all children. Finland is, again, showing that not only is it possible to have advanced models, but it is possible to keep iterating and improving them to make those models scalable.

It's not hard to say that schools need to change—the difficult part today is to do it systemically, at scale, and with a sound theoretical basis. And this is exactly where *invention pedagogy* comes in. The three perspectives of invention pedagogy—learning to invent projects, facilitation of fitting the invention process, and co-development of an invention school culture—address the pillars of a sustainable and comprehensive way of bringing this kind of work into schools at scale. Invention pedagogy explicitly asserts that this requires a new type of classroom orchestration, on teachers designing, implementing, and evaluating projects, and on breaking peer-learning barriers by enabling students to learn from each other, even across age groups.

By tackling systemic issues, this book also addresses some of the thorny questions that have plagued progressive education, such as the incentive systems and promotion mechanisms in our schools. Students love doing projects in makerspaces, but that does not get them, in most countries, to the next grade or into the best universities. Publishers have no way of producing hundreds of versions of a textbook; national tests or teacher preparation programs cannot change every year. Accommodating new ideas into existing systems is a monumental task, but it is work that needs to be done. Doing it "halfway" will increase inequality: if we create systems in which we have solutions, curricula, and technologies that work only at a small scale, they will stay in private schools. We need to go "all in." That means having the courage to deeply change national standards, transform how pupils are assessed in schools, redesign university admission processes, rethink how children might show their expertise and talents far beyond school grades, and update teacher preparation programs. And on top of all that, we should reward schools that implement those changes and create campaigns to communicate to families what it is all about.

Finland is uniquely positioned to put forward these ideas because it has shown, over decades, that it can create innovative but sustainable public policies. And these reforms came from teachers, researchers, scientists, and educators who built them over decades, not outside "miracle workers" with their gadgets and sanitized reforms. Finland engaged with the difficult politics of education, tackling challenging consensus-building, long-term, invisible reforms; creating new metrics; valuing the teaching profession; and respecting students' brilliance.

Our educational systems should forever be a work in progress. There will never be a perfect system that we can replicate and be done with. School systems are always a moving target because they should reflect how we want to live as a society. Instead of being a force for keeping things as they are, pushing societies back to the past, they should always be a force pushing us into the future. This book, with its razor-sharp vision of where we should be, deeply rigorous theoretical work, and careful data analysis, is likely the most advanced attempt at systematizing a new vision for schools for decades to come. Instead of just repeating the same old critique of school, the same old clichés and platitudes about the need to change education, it courageously faces the unimaginable complexity of the task head-on, examining the architecture of the problem and designing realistic, yet innovative solutions.

Ultimately, the point is not that we do not know how to truly improve our educational systems. *The point is how to build robust systems to enable everyone to participate in new forms of learning*. Finland, and invention pedagogy, might just be the key that unlocks the gates that have been closed for a century.

Notes

1 We could not reproduce these for copyright issues, but they are available online at https://books.google.com/books?id=fkkEAAAAMBAJ&pg=PA40).

2 Ackermann was a student activist in Switzerland in the 1960s; Papert fought apartheid in his youth in South Africa; Freire was jailed by the Brazilian military dictatorship.

3 For example, in the 1950s, in the United States, there was a concerted effort by right-wing political groups to sideline progressive education, undoing much of the progress that had happened in the three previous decades.

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1 Introduction

Roots and Key Elements of Invention Pedagogy

Tiina Korhonen, Kaiju Kangas, and Laura Salo

Introduction

The focal questions for scholars, professionals, and policymakers in the field of education have been the same for a long time: How do we cultivate learners' capacity to meet future challenges? What skills do children and adolescents need to become active, responsible, and happy citizens? What competencies will they require to make an impact in the future societies of the planet? How can we ensure that subsequent generations are more capable of solving the increasingly complex problems of our society than we have been, which include enormous cultural, societal, and environmental challenges, economic inequalities, and pandemic outbreaks? In invention pedagogy, we approach these questions through fostering the innovative and creative capabilities of school communities that will be needed in the rapidly digitalizing innovation society.

The United Nations' (UN) Sustainability Goal 4 states that by 2030, all learners need to have acquired the knowledge and competencies needed to promote sustainable development (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2016). Further, the UN's sustainability goals require that schools make the necessary changes to address marginalization so that all students are able to learn. Polarization is a concern, especially in relation to invention opportunities, digital technologies, access to technology, and the ability to develop the skills needed to use technology in creative ways (e.g., Blikstein, 2013). To address these challenges, school reforms have been pursued to enhance creativity, innovation, and educational practices that facilitate 21st-century competencies, creative learning outcomes, and deeper learning that are critical in today's digital society (Binkley et al., 2012; Dede, 2009).

In recent years, maker education has been brought to the forefront both in learning sciences research and in public discussions, as it has been recognized as a strategic component of future-oriented education (e.g., Bransford et al., 2006). Maker education and maker-centered learning practices provide ample opportunities for bridging digital divides, overcoming creative participation gaps, and connecting informal and formal learning activities (e.g., Clapp et al., 2016). Maker education encourages students to develop a growth mindset (Dweck, 2017) through hands-on project-based learning and to engage in the creative practices of inventing and making artifacts (Halverson & Sheridan, 2014; Hsu et al., 2017). Such practices are

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often strongly associated with science, technology, engineering, arts, and mathematics (STEAM) learning (Bevan et al., 2014). It has been argued that, through maker education, we can prepare new generations of students for our rapidly changing society as well as capitalize on the novel pedagogical opportunities for digitalization.

In this book, we will introduce invention pedagogy, which is a distinctive Finnish research-based approach to maker education. This approach focuses on teaching and learning 21st-century competencies through nonlinear, multidisciplinary, creative technology-enhanced design and making processes in formal educational settings and expands the principles of invention pedagogy to the systemic development of schools. The origins of invention pedagogy date back to the beginning of the current century when the researchers and practitioners behind this book started to collaborate with each other. Back then, Finnish education was internationally renowned, but we began to notice that there were students who were not motivated by externally driven and repetitive ways of teaching and learning. Further, many students were proficient technology users, but instead of using technology creatively for educational purposes, they used it mainly for entertainment and social activity. The 'creative participation gap' (Jenkins et al., 2009) or innovation inequality was increasing; some students received support from their homes and social networks to develop their creative and technological competencies, while others did not. This gap expanded even further during the COVID-19 pandemic (Korhonen et al., forthcoming). Invention pedagogy has grown due to the joint efforts of researchers and teachers to develop accessible educational practices that help mitigate such inequalities in formal education and support students in cultivating the competencies that they need today and will need in the future.

In the following sections, we first explore the underlying needs of future-oriented education, that is, the competencies and skills that students should acquire through formal education. Next, we present the key elements of invention pedagogy and related approaches, such as maker education. Finally, we discuss school-level development by highlighting the joint efforts by researchers and practitioners that are needed to invent and innovate in education.

21st-Century Transformative Competencies

Various researchers and organizations have outlined frameworks for defining and describing 21st-century skills (e.g., Binkley et al., 2012; van Laar et al., 2017), that is, the competencies needed for a successful life and a well-functioning society. These frameworks share many elements but differ to a certain extent in terms of their terminology and connotations. For example, the universal learning framework by UNESCO (2013) defines the type of learning that is necessary for all children and youths to have a good life in the 21st century. In turn, the eight key competencies for lifelong learning proposed by the European Parliament and the Council of the European Union (2006) (also see European Commission, 2019) underline the knowledge, skills, and attitudes needed for personal fulfillment, a healthy and sustainable lifestyle, employability, active citizenship, and social inclusion. The most recent framework is the Learning Compass 2030 published by the

Organisation for Economic Co-operation and Development (OECD), which emphasizes transformative competencies and "the need for students to learn to navigate through unfamiliar contexts and find their direction in a meaningful and responsible way, instead of simply receiving fixed instructions or directions from their teachers" (OECD, 2019, p. 20).

In the Finnish National Core Curriculum for Basic Education (Finnish National Agency of Education [FNAE], 2016), 21st-century competencies are referred to as transversal competencies, which are defined as an entity that consists of knowledge, skills, values, attitudes, and will. In the core curriculum, transversal competencies are classified into seven competence areas: thinking and learning-to-learn; cultural competence, interaction, and expression; taking care of oneself and managing daily life; multiliteracy; digital competence; working life competence and entrepreneurship; participation, involvement, and building a sustainable future. The transversal competencies have a cross-curricular nature, and each school subject has objectives related to them along with subject-specific aims. Furthermore, multidisciplinary learning is emphasized in the curriculum. Each school is expected to ensure that all students' studies include at least one multidisciplinary module (i.e., a project or unit) every school year. The objectives, contents, and implementation of the modules are defined and specified in local curricula and schools' annual plans. The modules provide opportunities to teach and learn both interdisciplinary and disciplinary knowledge and skills, as well as transversal competencies.

The Learning Compass 2030 by the OECD (2019) also identifies the types of knowledge and skills that students require to contribute to and flourish in the world. Disciplinary, interdisciplinary, epistemic, and procedural knowledge include both theoretical concepts and ideas, as well as practical understanding based on experience. Skills refer to one's capacity to perform processes and the ability to use knowledge to achieve goals and include cognitive and meta-cognitive skills, socio-emotional skills, as well as practical and physical skills. An important challenge is to learn creative thinking and develop innovative abilities (Rotherham, 2009). To become productive contributors in the 21st-century society, students need to be able to master a broad portfolio of essentials in learning, innovation, technology, and careers skills that are needed for their career and life while simultaneously learning the core content of a specific field of knowledge (Trilling & Fadel, 2009; also see Binkley et al., 2012).

The OECD has further specified skills related to innovation (Vincent-Lancrin et al., 2019), which are especially interesting for pedagogical approaches, such as invention pedagogy, that aim to nurture students' innovative and creative capabilities. Similar to the Learning Compass, the "skills for innovation" framework includes three overlapping categories that need to be developed in parallel: (1) domain-specific skills, (2) creativity and critical thinking skills, and (3) socio-emotional skills. Domain-specific skills refer to the know-what and know-how of a certain subject or field of study, while socio-emotional skills include self-regulative, behavioral, and social skills, such as self-confidence, perseverance, passion, communication, and collaboration. Creative and critical thinking skills are necessary for inquiring, imagining, doing, and reflecting on activities where ideas and solutions are created and evaluated.

Key Elements of Invention Pedagogy

The various frameworks described in the previous section characterize the competencies, skills, and knowledge needed in the 21st century. Invention pedagogy addresses the question of how these could be cultivated in formal education through rigorous research and development work carried out in Finnish schools. The research foundations of invention pedagogy projects are based on knowledge creation (Hakkarainen et al., 2004; Paavola et al., 2004), learning by collaborative design (Seitamaa-Hakkarainen et al., 2010), creative problem-solving in science and technology education (Lavonen et al., 2004), and inclusive education (Sormunen et al., 2020). A distinctive feature of invention pedagogy is that it has been developed through the sustained, joint partnership efforts of researchers and practitioners. Cross-fertilizing academic research and extensive experience from the field have enabled us to create novel, yet accessible educational practices together with new scientific knowledge.

Invention pedagogy is anchored in formal education contexts and the aims and objectives defined in the core curriculum. It shares many similarities with other educational approaches, such as maker education, STEAM, and Design and Technology education, which emphasize creativity, innovation, interdisciplinarity, learning by doing, collaboration, and the use of technology. In addition to the STEAM subjects, invention pedagogy is combined with other subjects such as language (e.g., storytelling) or physical education (e.g., dancing with robot inventions) in a multidisciplinary way. Moreover, the school subject 'crafts' plays an essential role in invention pedagogy. In Finland, crafts has been a part of formal education since 1866 and remain a mandatory subject for all students in grades 1–7 (see Porko-Hudd et al., 2018). Crafts is a multi-material subject that includes the materials and methods of both textile and technical work, such as sewing, knitting, wood-, and metalwork, and digital fabrication (Pöllänen, 2020). This subject provides the means for creative ideation and experimentation with activities based on craft expression, design, and technology (FNAE, 2016). In addition, the concept of holistic craft is emphasized, i.e., a student or group is responsible for the entire craft process, from ideation and design to making and evaluation (Pöllänen, 2009). Embedded with the versatile use of creative technologies, multidisciplinary invention pedagogy projects provide students with the possibilities to acquire transformative 21st-century competencies in an inspiring and future-oriented way.

Through the invention process, students learn how to deal with challenging scientific, technological, and design problems and collaboratively develop creative solutions (inventions) using various digital and traditional technologies. Every student is an inventor – a maker – who is encouraged to share their knowledge when constructing a shared artifact (Riikonen et al., 2020). Organizing an invention pedagogy project requires close cooperation between different subjects and teachers. Two or more teachers with different perspectives and varying expertise come together to plan and implement the project. During a project, the presence of several teachers enables the implementation of flexible and creative teaching arrangements and solutions. The curriculum also requires teachers to include students in planning multidisciplinary entities and the choice of the theme, taking into account the students' interests and experiences that motivate and engage them to study. However, it is the teachers who are responsible for maintaining students' motivation and engagement, meeting the objectives of the curriculum, and fitting the whole project into restricted time, space, and material resources. Invention projects may vary significantly in their contents and implementation, but they all share certain key elements. These include (1) students' and teachers' inclusive innovator mindset, (2) multifaceted real-world phenomenon as a starting point for a project, (3) co-creation of knowledge and artifacts, and (4) technology-enriched tools and materials.

Inclusive Innovator Mindset

Invention projects require and develop a certain type of mindset for the students and teachers. The inclusive innovator mindset is closely related to the maker mindset (Dougherty, 2013), that is, it involves a can-do attitude that includes elements such as resilience, creativity, willingness to tinker, and collaboration orientation (also see Cohen et al., 2018), which enables students to see themselves as the makers and shapers of the future. Further, a sense of curiosity (Regalla, 2016), playfulness (Honey & Kanter, 2013), and grit (Clapp et al., 2016) are also included in this kind of mindset. In addition, the inclusive innovator mindset is closely related to the growth mindset, which refers to an outlook that involves tolerating risk and failure and believing that all capabilities can be developed, improved, and expanded (Dweck, 2017). Invention pedagogy is also an inclusive pedagogy, as it relies on the assumption that the potential and abilities of every student are acknowledged and accepted (Spratt & Florian, 2015). This type of inclusive innovator mindset is committed to co-developing creative new ways of working with others and modeling and testing new ways to develop learning and teaching in practice (Sormunen et al., 2020). In invention pedagogy, students, teachers, and other actors in the school community continuously improve their thinking and understanding of themselves as the makers of their own and others' future.

Multifaceted Real-World Phenomena

The starting point of any invention project is a real-world phenomenon, which is studied from various points of view, crossing the boundaries between school subjects. Students are encouraged to pose their own questions and challenges, which they approach by co-creating inventions that address these challenges (Silander et al., 2022). Such learning increases students' motivation, their readiness to solve complex problems, their ability to combine school and everyday knowledge, and the competencies associated with applying, evaluating, and creating new knowledge (Markauskaite & Goodyear, 2017). In invention projects, the work is carried out cyclically by experimenting, receiving feedback, reflecting on the progress of the process, and changing the operation based on the same. The teachers link the phenomenon under study flexibly to the aims and objectives of the curriculum, loosely, as the learning goals, practices, information required, and outputs only become apparent during the process.

Thinking of the interests and abilities of all students is imperative when designing the invention process and framing the underlying phenomenon. Previous studies indicate that active construction, maker activities, collaborative learning tasks, and an opportunity to influence the selection of the learning task engage students to learn, for example, science in more depth (Martinez & Stager, 2019; Sormunen et al., 2020). Invention pedagogy enables the teacher to add more variety to the activities related to students' abilities, strengths, and interests, which helps engage students to learn (see Krajick & Merritt, 2012; Sormunen et al., 2020). Such co-creation also enhances a student's sense of being a full-fledged member of the learning community (see Laurell et al., 2021).

Co-creation of Knowledge and Artifacts

Invention pedagogy leans on sociocultural theories of learning, that is, learners are regarded as active creators of knowledge, and knowledge is seen to be formed in settings mediated by social interactions and materials and tool use. Students work together to create a shared understanding of the challenge to be solved, to determine the constraints outlining the possible solutions, and to co-construct ideas and solutions for an invention. As each team has its own approach to the objectives of an invention project, the students also need to share knowledge and experience between teams to create a comprehensive perception of the underlying phenomenon. Co-creation skills are developed when students discuss and evaluate their own responsibilities and tasks. They learn to evaluate and justify their own and each other's ideas and reflect on the possible bias in their own perspective compared to other perspectives (see Vincent-Lancrin et al., 2019). Invention pedagogy also involves the concept of cross-age peer tutoring, which means that older students with technological expertise systematically support their younger peers in invention projects (Tenhovirta et al., 2021).

An essential aspect in invention pedagogy is working with shared intangible and tangible artifacts through visual representations, conceptual models, tools, and materials. Collaboration in invention projects is intrinsically material; the students interact not only with each other verbally but also have conversations with and through materials as they contribute to shared goals with direct material manipulations (Mehto et al., 2020a). The sociomaterial theories enable the consideration of materials and tangible objects as active agents that constrain and enable the invention process. The meaning of materials emerges in action through relationships (Orlikowski, 2007); it is the entanglements of social and material that determine the nature of collaboration and knowledge creation in invention projects (Mehto et al., 2020a; Mehto et al., 2020b).

Technology-Enriched Tools and Materials

Invention projects require high-tech tools such as programmable microcontrollers and 3D printers, and low-tech tools and materials, such as arts and crafts tools and traditional craft machinery. Technologies are regarded as both the objects and the tools of learning. Students' ideas determine which technologies are to be used in an invention project, although teachers can also constrain the objectives of the project by providing certain technologies to the students. One of the primary aims in invention pedagogy is to provide students with support and models of how technologies can be used for creative and academic purposes. Although many children and adolescents use technologies fluently for social and recreational purposes, there are serious concerns related to a widening "digital divide" or "creative participation gap" (Jenkins et al., 2009), that is, unequal access to learning opportunities owing to, for example, different socioeconomic backgrounds. Further, although technologies are fundamentally transforming everyday life and interactions, their applications in schools are largely limited to consolidating existing educational practices instead of creating new ones (Hakkarainen et al., 2015). Invention projects provide students, and teachers, with the ability to use technologies in a sophisticated and creative manner, thus facilitating their understanding of and participation in the ever-changing technological world.

Joint Development of Teachers and Researchers

Invention pedagogy has grown from a joint and intertwined effort by teachers and researchers that brings forth the persistent and long-term work of the authors, which aims to develop 21st-century competences and innovation. The teachers in our partner schools have developed invention pedagogy and innovation education teaching practices in their own schools and networks. At the very heart of these practices is the 20-year-old Innokas Network (www.innokas.fi/en). The nationwide network works in close collaboration with teachers, researchers, and international partners. The researchers in our author team have studied design, technology, craft, and science education within basic education through various research projects since the turn of the century. They are especially interested in multidisciplinary and collaborative innovation and knowledge building through hands-on activities. Through research-practice partnerships (RPPs) (Coburn & Penuel, 2016), we have created accessible educational practices and enabled the ongoing co-development of invention pedagogy.

At the heart of RPP is the assumption that the "socially sustainable knowledge" required for school development (Nowotny, 2003) can only be created through interactions with researchers and practitioners such as principals, teachers, and students. Finnish primary and secondary teachers are educated at the university level through a five-year master's program and are responsible for participating in the local curriculum design, designing learning environments and courses, and assessing both their own teaching and their students' learning outcomes (Lavonen, 2020). This research-oriented professional background represents a good foundation for RPP. The starting point for an RPP is the practical problems experienced in the field (Coburn & Penuel, 2016) instead of the researchers' own academic and scientific interests. The purpose of RRPs is to combine relevant research information with the relevant practical knowledge of the professionals working in the field. This requires mutual learning between researchers and practitioners; both must work in the zone of proximal development to learn new ways of working and build a shared understanding (Juuti et al., 2016) to develop schools. Ideally, an RPP involves the joint development of solutions for the practice-based problems of pedagogical innovations. Ultimately, this is tied up in the holistic development of the whole school. A successful RPP generates both new educational practices and new academic knowledge.

The RPP and co-creation between teachers and researchers that has been going on for over 15 years, and our joint drive to develop schools and to teach holistically, have made possible the creation of this book, which encompasses both the grass-roots level of teaching and research-based knowledge. RPPs and persistent network-based development work have been the prerequisites for any new practice for change. This change extends beyond individual pilot projects to established and continuously developed practices and ways of working at schools. RPPs, network-based development, and dissemination work have enabled the pedagogical innovations presented in this book to make their way into hundreds of Finnish schools, forming functional everyday practices.

This book introduces the ongoing journey in the development work of invention pedagogy as well as the results obtained thus far. Part I lays the foundation for invention pedagogy by describing the emergent and nonlinear nature of knowledge-creating learning in invention projects. The chapters in this part present various perspectives regarding learning through invention pedagogy related to epistemic objects and knowledge creation, collaboration and co-regulation, creativity, materiality, sustainability, and technological competences. Part II examines the facilitation of invention projects, depicting the designing, structuring and orchestration of innovation projects. In addition, it highlights the importance of team teaching and students' peer tutoring in the designing and implementation of invention projects. The part ends with a discussion of the evaluation of innovation projects. Part III discusses the co-development of the inventive school culture by analyzing the learning environments of invention pedagogy as well as teachers' transformative digital agency. The last chapter considers a school as an innovative community and expands invention pedagogy to the systemic development of schools.

The invention projects discussed in this book have been inspiring experiences for students, teachers, and researchers alike. They have challenged us to think and act in new ways and have encouraged us to take a leap into the unknown without knowing the product of the project or how we will reach the finish line. Invention projects have allowed the achievement of competencies that have rarely been attained through traditional teaching. Through this book, we want to share these experiences and research results with those academics and educators who are interested in developing future-oriented education. At the same time, we want to encourage every educator to consider their own role and practices. Can you become an innovation educator? Can you guide invention projects? Can you create innovations that support schoolwork with students and colleagues? As is generally the case with creating new things, the path to completing this book has been multifaceted and winding. It has also been an extremely rewarding process of learning together, which is still ongoing. We hope to have many new innovators and inventors join us on this journey!

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Part I

Learning by Inventing

Invention pedagogy guides students in learning transversal, cross-disciplinary, and disciplinary competencies through nonlinear, open-ended, and creative design processes that deviate from traditional ways of teaching and learning. Rather than assimilating predetermined knowledge and skills, students engage in finding, defining, and solving authentic and challenging scientific, technological, and aesthetic problems by using both traditional and digital tools and processes.

The first part of the book explores invention pedagogy, developed collaboratively by Finnish teachers and researchers, from the perspective of learning. The part begins by laying the theoretical foundation of learning by inventing and by exploring the nature of epistemic objects and knowledge creation involved in invention projects. In addition, the chapters examine learning by inventing through the viewpoints of collaboration and co-regulation, materiality, and sustainability, as well as through competences related to creativity and technologies.

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2 Learning by Inventing

Theoretical Foundations

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Introduction

Invention pedagogy engages teams of learners across all ages in computer-supported collaborative learning (Stahl & Hakkarainen, 2021), which involves using traditional and digital fabrication technologies for ideating, designing, and making complex artifacts sparking intellectual, engineering, and aesthetic challenges. Education for invention is required because humans are facing increasingly severe cumulative problems and risks related to climate change, sustainability of the earth, geopolitical crises, and radical inequality. Investigators are concerned that there is an increasingly severe ingenuity gap (Homer-Dixon, 2001) between such challenges and the limited problem-solving capabilities inculcated by the prevailing educational practices. Productively participating in the rapidly changing innovation-driven knowledge society requires young people in Finland and elsewhere to start practicing personal and social-creative competencies, including complex problem-solving, invention capacity; entrepreneurial skills and risk-taking adaptability; and skills related to effective teamwork and sharing of knowledge from the beginning of education. Instead of merely promoting intellectual elites, all citizens need to be more capable of seeing things in fresh perspectives, enhanced creative self-efficacy, and associated identities as potential creators of knowledge (Bereiter, 2002; Hakkarainen et al., 2004). Coping with a constantly changing society requires *epistemic fluency* (Markauskaite & Goodyear, 2017), i.e., the capability to integrate formal and informal knowledge, and go beyond information given in contexts that require the application and creation of new knowledge. Learning to find solutions to varying open-ended complex problems is the only known way of preparing young people to overcome the unforeseen problems of the future (Bransford et al., 2006; Marton & Trigwell, 2000).

Productive participation in invention processes can be facilitated in educational institutions by engaging students in the skilled use of sociodigital technologies, i.e., the recently emerged integrated system of mobile devices, social media, digital fabrication, and the internet, for creative work with knowledge and media (Hakkarainen et al., 2015). Sociodigital technologies mediate all creative work in modern society shaping personal epistemic practices, collaborative activity, and interaction with extended, collective knowledge networks across domains (Jenkins, 2007; Ritella & Hakkarainen, 2012; Stahl & Hakkarainen, 2021). Although the

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sociodigital revolution is disrupting human activity across all spheres of life (Christiansen et al., 2011), educational institutions tend to reduce digital innovations to those merely sustaining prevailing reproductive educational practices. Moreover, young people are not given enough structured support to learn advanced academic and creative practices of using digital technologies, creating an increasingly severe creative participation gap (Jenkins, 2007), and innovation inequity (Barron, 2004). As we apply the term, knowledge creation is the opposite of repetition and reproduction; such shallow epistemic practices are found even among the best students because of the low expectations they encounter in routine learning tasks. According to the Cambridge English Dictionary, *invention is "something newly designed or created, or the activity of designing or creating new things"*. We use the term *invention pedagogy* to refer to the process of engaging the learning community supported by traditional and digital fabrication technology to design, invent and make complex artifacts and build new knowledge, at least locally. By talking about inventors and invention processes, we would like to make both students and their teachers see themselves as prospective creators of knowledge and artifacts.

Invention Pedagogy as a Form of Knowledge-Creating Learning

Invention pedagogy is anchored on knowledge-creating learning framework developed for examining novel affordances of technology-mediated collaborative learning (Paavola et al., 2004; Paavola & Hakkarainen, 2014, 2021). *The knowledge-creation metaphor* of learning was proposed as a response to Sfard's (1998) well-known distinction between *the knowledge acquisition* and *the participation metaphors* of learning. The traditional acquisition metaphor examines learning as an individual cognitive process; the human mind is seen as a kind of container and the learning process that fills the container with knowledge (Bereiter, 2002). An individual has an important role in learning because no one can learn difficult things on an agent's behalf. Simultaneously, addressing mere individual capabilities would mask various materially and socially distributed resources that enable humans as species as well as individuals to surpass themselves (Clark, 2003; Donald, 1991; Hutchins, 1995; Skagestad, 1993). Proponents of the sociocultural participation metaphor have argued since the 1980s that ultimately learning is a process of growing up in a community and moving from peripheral to more central participation as a function of learning to master cultural norms and practices and forming one's identity (Holland et al., 1998). If we would like the young generation to acquire advanced inventive skills, we need to provide them with expanded opportunities for authentic cultural participation: However, understanding of the creative edge of such practices necessitates going beyond the participation metaphor.

Paavola et al. (2004) argued that a third knowledge-creation metaphor is needed to account for learning relevant to the future innovation-driven knowledge society. To meet the future challenges, it is neither sufficient to assimilate already existing textbook information (as assumed by the "monological" acquisition metaphor) nor to grow up with prevailing community practices (as often assumed by the "dialogical" participation metaphor). Knowledge creation entails a deliberate process of inquiry that involves creating a joint epistemic object (the concept will be explained in detail in next section), whether invention, artifact-in-making, or practice being improved. The knowledge-creation metaphor is considered to be "trialogical" in nature because it examines learning in terms of heterogeneous interaction between individuals and communities, concepts, tools, and practices, as well as shared invention objects being developed. The knowledge-creation metaphor was inspired by the theories of Peirce (1992–1998), Popper (1972), and Vygotsky (1978), and by educational and organizational theories by Bereiter (2002), Engeström (1987), and Nonaka and Takeuchi (1995). We have observed that knowledge-creating learning has become accessible even for elementary school students when they are supported by sophisticated sociodigital technologies and guided to appropriate innovative practices of working with knowledge and media.

Theories, practices, and technologies mediating learning appear to be sociomaterially entangled (Orlikowski & Scott, 2008; Stahl & Hakkarainen, 2021). Available technologies virtually structure human activity, and prevailing social practices shape the ways of using technologies and their affordances. In accordance with both reproductive educational practices and available information repositories, search engines, and discussion forums, investigators long emphasized either information genre or communication genre when addressing educational use of technologies (Paavola et al., 2004). Pioneering research of Scardamalia and Bereiter (2021) and Bereiter (2002) changed the scene and contributed to the emergence of collaborative technologies supporting knowledge creation. Their experiments engaged young students in constructing textual and graphic notes for building a local body of "world 3" – cultural knowledge (Popper, 1972) in the Knowledge Forum environment. Knowledge building aimed ambitiously at the Copernican revolution of placing students' ideas, understood as conceptual artifacts (Bereiter, 2002), in the center rather than on the periphery of education. When the present authors engaged in research and development of the Future Learning Environments in Finland (see https://github.com/LeGroup/Fle4), their aim was to expand technology-mediated learning to provide support for the collaborative design of materially embodied artifacts (Seitamaa-Hakkarainen et al., 2001, 2010). To deepen the understanding of sociomaterial aspects of knowledge-creating learning, we looked more deeply at emerging science and technology studies (Knorr Cetina, 1999; Latour & Woolgar, 1986; Pickering, 1995), theories of cognitive evolution (Donald, 1991; Malafouris, 2013; Skagestad, 1993), distributed cognition (Clark, 2003; Hutchins, 1995), and actor-network theory (Latour, 2005). It was soon realized that knowledge creation is not a mere mental or conceptual process but is a messy struggle of creating, developing, and extending epistemic "things" or artifacts across long-term iterative efforts of individuals, teams, and learning communities supported by epistemic technologies. The design experiments we carried out in schools involved increasing hybrid physical, digital, and virtual practices and making materially embodied artifacts (Kangas et al., 2007, 2013).

Many investigators from Vygotsky to Piaget and Papert (1980) have emphasized the importance of learning through constructing artifacts. Although Hakkarainen and colleagues approached knowledge-creating learning from a direction that differed from Papert's (1980) constructionism, they were familiar with Papert's thinking and inspired by it. Papert emphasizes the importance of engaging students in the active construction of tangible artifacts and developed associated instruments and tools, such as the accessible Logo programming language. He criticized acquisition-oriented "instructionism" and considered long-term work with meaningful products to be educationally most valuable. Further, Papert argued that novel pathways of learning are opened when students take part in improvisational exploration involved in making of artifacts. Moreover, he saw that artifacts mediate creative activity, may become both external and internal tools of thinking, and thereby inflame learning. The pioneering efforts of Papert (1980) and his followers Blikstein (2013), Kafai and Peppler (2011), and Resnick (2017) played a crucial role in establishing the educational maker culture that the invention pedagogy currently relies on. Students' knowledge-creating activities are augmented with instruments and materials of laboratories in art, craft, technology, and science education. Further, they are introduced to digital fabrication technologies, such as designing and constructing robotic systems, additive (3D printing) and subtractive manufacturing (e.g., laser cutting), designing and constructing circuits, programming microcontrollers and sensors, and many other relevant tools. Inventions are instantiated in a series of successively more refined transitional artifacts and productions, which enable novel ideas and perspectives to be found. Finnish exceptional craft and technology education infrastructure allows learning by inventing integrated with regular educational activity (Korhonen & Lavonen, 2017; Riikonen et al., 2020).

The following principal features of knowledge-creating learning appear relevant for the creative, intellectual, motivational, and artistic potentials of invention pedagogy in the context of Science, Technology, Engineering, Arts, and Math (STEAM) education practices:

- A defining characteristic of knowledge creation is its object-centered nature; the process is driven by invention objects that represent what the participants are seeking to create but have not yet mastered at the beginning of the invention process.
- Invention is an embodied collaborative process mediated by various tools and materials in maker spaces in which teams of inventors iteratively pursue advancement of their ideas.
- There is interaction between the levels of knowing from conceptual ideas to fuzzy hunches and tacit situational understanding, giving rise to gradually more elaborated ideas as the process goes on.
- Creative externalization occurs: Gesturing, sketching, and prototyping play a central role in articulation of ideas and giving them a material form through successive efforts.
- Invention is a nonlinear, improvisational, and emergent process that involves continuing hindrances, sudden breakdowns, and emergent lines of inquiry that could not have been anticipated at the beginning.
- Although an individual participant may have a central role in constructing new ideas, invention takes place in the fertile soil provided by social collaboration within teams and across the network of teachers, researchers, parents, and experts.

Epistemic Objects of Invention

As explained in the previous section, the defining feature of knowledge-creating learning is its object-driven nature (Paavola & Hakkarainen, 2021). Accordingly, invention processes are supported by collaborative interaction organized around the artifacts being invented. Papert and Harel (1991, p. 1) observed that young people's learning "happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it's a sandcastle on the beach or a theory of the universe". Invention projects involve envisioning a product idea, developing it through iterative efforts, carrying out multifaceted explorations, overcoming initial failures, and implementing successive improvements until a final prototype is obtained. The process involves asking students to invent solutions to the challenges they encounter rather than following linear instructions for making a specific product in a way that was once common in craft education (Riikonen et al., 2020).

In the present chapter, we refer to envisioned solutions or inventions-in-making as "*epistemic objects*"; this theoretical concept is anchored on studies by Knorr Cetina (1999). The concept of "object" has its philosophic roots in studies by Hegel and Marx as well as Peirce and Popper, and psychological roots in activity theory as developed by Vygotsky (1978) and elaborated by Engeström (1987). The object arises, within Vygotsky's (1978) perspective on human activity, as being a sign and tool mediated in nature. Following Popper's (1972) lead, Bereiter (2002) interpreted epistemic objects mainly as conceptual entities; the material embodiment of the ideas is, however, critically important from the semiotic perspective (Paavola & Hakkarainen, 2021; Ritella & Hakkarainen, 2012; Skagestad, 1993). We examine epistemic objects as symbolic-material entities that are embodied in successive textual, visual-graphical, or physical (e.g., prototype) versions. Post-humanist approaches highlight the active role of artifacts, as well as physical, virtual, and hybrid environments (e.g., makerspaces) on which enacted collaborative activity is embedded (Mehto et al., 2020; Stahl & Hakkarainen, 2021).

Accordingly, students' invention processes are directed toward the epistemic objects (Knorr Cetina, 2001), i.e., their ideas and thoughts, envisioned options, and future-oriented projections regarding the nature of the invention. Epistemic objects are incomplete, being constantly redefined, and located at the edge of knowing and help to crystallize what the participants seek to accomplish, what they aim at, and what they do not yet know or understand. Yet, Knorr Cetina (1999) also pointed out that the artifact-in-making involves implicit hints about missing pieces or lacking features that assist in directing further invention activities. Students' invention ideas are drafted by sketching and prototyping, which provide "material anchors" (Hutchins, 2005) for subsequent ideation, reflection, and making processes. In invention processes, it is always necessary to make compromises according to available material, production procedures, and fabrication opportunities. Despite being imperfect and partial in nature, the epistemic objects guide and direct inventive activity and the associated process of building a successive series of half-baked and limited solutions. Further, transforming ideas into materially embodied forms is a troublesome process that requires iterative efforts.

Moreover, the members of a team may not always have a similar view of the emergent but fuzzy object that they are working with. Given the learners' limited skills, resources, and sometimes overambitious designs, it follows that the artifact created may not represent all the envisioned features. Although epistemic objects have tangible, thing-like characteristics, they also represent deeper purposes or motives that they are directed at, sparking students' passions (Engeström, 1987; Paavola & Hakkarainen, 2021).

Creative Epistemic Practices

Creativity researchers have distinguished four P-variables related to creativity, i.e., Persons, Process, Product, and Place (Kozbelt et al., 2010). What appears to have been missing from psychological accounts of creativity is the fifth P – Practice, i.e., inventive practices that tools and studio environments of creative-disciplinary communities enable. The rationale of having researchers support invention projects is to provide participants with access to creative practices of using traditional and digital fabrication technologies that expert communities have generated. To cultivate creative capabilities that the invention process requires, both learners and teacher practitioners have to develop, enhance, and expand their *epistemic practices* (Hakkarainen, 2009). When using the term "epistemic", we refer to knowledge in the broadest sense, to include beyond discursive entities (e.g., texts), knowledge-laden in skills ("procedural knowledge"), and to what is implicit, informing pre-reflectively one's habits, and further yet to "thing knowledge" (Baird, 2004) embedded in design and use of tools and studio environment. By epistemic practices we refer to dynamic game-like social practices of using tools and technologies for pursuing knowledge-creating inquiries. In this regard, they come close to *epistemic games* (Markauskaite & Goodyear, 2017; Shaffer & Gee, 2007), i.e., identifiable but partially hidden patterns and operational procedures that disciplinary epistemic cultures have cultivated for enculturating new cohorts of creative knowledge workers. Epistemic practices represent generative systems of creative habits, patterns, routines, practices that mediate inventive activity, corresponding to flexible cultural scripting of open-ended creative activities. Although epistemic practices sometimes support routine learning (transmission), at their creative edge, they diverge from other routine social practices because they occur in deliberately cultivated dynamic and fluid settings that foster innovation (Knorr Cetina, 2001).

The point of invention pedagogy is to engage students in appropriating disciplinary epistemic practices. Science and technology studies indicate that creativity does not lie merely within the human mind but is embedded in shared epistemic practices cultivated by innovative knowledge communities and their networks (Paavola et al., 2004). Although many students have problems in appropriating formal-logical scientific competencies, they can productively appropriate epistemic practices such as inventive epistemic games, operational competencies, and habits of mind that characterize scientific and professional activity. Maker instruments and practices of knowledge creation given to young students function as "cognitive prostheses" (Clark, 2003), which expand and augment their personal and collaborative creative resources in a way that makes deliberate pursuit of invention feasible if they have sufficient social support and creative motivation of their own. Using sophisticated instruments to create artifacts enhances thinking through doing (i.e., manipulative abduction; Magnani, 2009) and elicits gradual emergence of so-called thing knowledge critical in use of instruments (Baird, 2004). Such instruments and practices may be interpreted to provide material agency (Pickering, 1995) for pursuing more complex and challenging inquiries than the participants would otherwise be able to accomplish. Simultaneously, interrelations between human and material agencies are complex and vary situationally across the invention process (Mehto et al., 2020). Overall, the aim of invention pedagogy is to foster a renaissance of practical thinking and actionable knowing (Markauskaite & Goodyear, 2017) at school by providing diverse learners with opportunities to appropriate practical and operational aspects of STEAM practices.

The epistemic-practices framework is compatible with the next-generation standards of science education that highlight the importance of bringing disciplinary practices to school for guiding, structuring, and fostering knowledge-creating learning in the context of invention projects (Krajcik et al., 2014; Osborne, 2014). Invention projects can be anchored on integrated scientific, engineering, design, and entrepreneurial practices that structure and support knowledge-creating learning in open and flexible ways. Scientific practices involve cultivating inquiry-based methods of learning science, such as progressive inquiry (Hakkarainen, 2003) or project-based learning (Krajcik et al., 2014) that engage students in posing questions, generating working hypotheses, carrying out experiments, analyzing results, visualizing and modeling results, presenting evidence-based arguments, and building and reporting knowledge. Engineering practices engage students in investigating complex phenomena, envisioning potential solutions, determining their criteria, and iteratively modeling, constructing, and testing solutions, comparing their strengths and weaknesses, and building and communicating results (Krajcik et al., 2014). In advanced art and craft classrooms and creative STEAM projects, scientific and engineering practices are intertwined with design practices (Peppler et al., 2016; Seitamaa-Hakkarainen et al., 2010). Collaborative designing involves iterative team efforts to ideate, create, modify and test artifacts to find solutions to design challenges. The roles of scientific, engineering, design, and entrepreneurial practices and possible cross-cutting curricular challenges vary, according to teachers' and researchers' preferences, from one invention project to another (see Chapter 10 of this book for examples of enacted disciplinary practices and Chapter 9 about epistemic structuring of invention projects).

Orchestrating Nonlinear and Emergent Processes of Invention

Scardamalia and Bereiter (2014) emphasized the self-organized and emergent nature of knowledge creation and argued that the pursuit of novelty and invention cannot be scripted. Although structuring, scaffolding, and guiding student activity are crucial, overly stiff scripting may hamper or even eliminate the emergence needed to pursue knowledge-creating learning and innovation (Sawyer, 2011; see Chapter 10 of this book for a detailed examination). Scripting is closely related to social practices understood as patterns and sequences of goal-directed actions based on certain technological and epistemic systems that both guide and constrain activity. In the school context, scripts are sequences of typical instructional or learning activities that follow one another in a predictable way. Further, scripts vary from explicit and rigid micro-level regulation of learning tasks (e.g., patterns of teachers questioning) to macro-level structuring of educational activity, for instance, in terms of disciplinary epistemic practices (e.g., learning through collaborative design, Seitamaa-Hakkarainen et al., 2010). Such pedagogic activities are openly and flexibly structured; the various aspects of the overall process do not mechanically follow one another but advance in an adaptive and dynamic way according to the progress of the invention process. Expanding knowledge-creating learning beyond the conceptual realms to the world of material culture and fabrication of materially embodied artifacts appears only to foreground the emergent and self-organized nature of invention.

From the sociocultural perspective, scripts may be understood as cultural models that learners appropriate through their sociomaterially mediated epistemic activity. Accordingly, scripting is related to cultural mediation involved in using artifacts as tools of activity. Long ago, Vygotsky (1978) addressed the crucial importance of engaging learners themselves in creating artifacts for transforming problem situations; this is a central aspect of his method of double stimulation. When planning their invention activity, students may construct scripts mediating their creative activity in terms of selecting tools and materials, organizing training of necessary skills, creating timetables, distributing work among the team, and so on. However, authentic open-ended invention projects cannot rely on predetermined steps, ready-made alternatives, and well-defined solutions. Invention projects engage students in iterative testing, improving, and advancing ideas that guide the direction of subsequent inquiries. Yet, invention is not only about the process of ideation but also mediated by traditional and digital instruments and materials. The appropriation of associated operational practices and ideating, drafting, and materializing artifacts-in-making requires sustainable iterative efforts. Intertwining traditional and digital technologies may cause its own challenges because different aspects of an invented artifact have to be seamlessly integrated. The material ecology of maker activity is not understood well, although it has been part of human activity for much longer than the literacy-based school culture (Donald, 1991; Malafouris, 2013). Moreover, many aspects of the present types of invention and making projects mediated by digital fabrication technologies have not previously been implemented or investigated in school contexts. Finding promising directions of advancement takes place at various stages of complex and multifaceted investigations in ways that are difficult, if not impossible, to anticipate.

Further, it appears crucial that the development of teachers' epistemic flexibility should be fostered so that they learn to orchestrate nonlinear, open-ended, and inventive study processes rather than highly scripted, closed, and reproductive learning tasks (Sawyer, 2011). Although student agency and initiative are important in knowledge-creating learning, the teachers' strategic guidance also plays a crucial role due to their higher-level visions of knowledge-creating learning projects (Viilo et al., 2018). Nevertheless, pursuit of manifold investigations may go to unforeseen directions unfamiliar to both students and teachers; the nonlinear nature of the invention process may make scaffolding challenging (Härkki et al., 2021). However, linear and nonlinear processes are not mutually exclusive (Sawyer, 2005). Sometimes it is necessary to interrupt invention processes and focus on systematic step-by-step efforts of learning to master tools or to seek relevant new knowledge. Moreover, teachers are sometimes foregrounding joint inventive actions rather than being willing to put in the extra effort needed to implement an additional reflective layer of engaging students in appropriating disciplinary epistemic practices and building and synthesizing knowledge in their projects. Epistemic practices necessitate engaging students in documenting the invention process with intensive reflection on the phenomena investigated, rather than merely coming up with the invention artifact requested. Simultaneously, it is essential to provide student teams with enough freedom to work with emergent objectives, stages, social structures, and methods.

Concluding Comments: Appropriating Figured World of Invention

The present investigators have pursued invention pedagogy for several years. Initially, we were uncertain about the extent to which young students can engage in invention-driven knowledge creation. After various encouraging experiences that involved creating sophisticated and non-trivial innovations (e.g., Riikonen et al., 2020), we became bold enough to talk about "invention" pedagogy (rather than mere innovation education). Although the students' creative processes are not at a professional level (Pro-C), their inventions may represent minimal creativity (mini-C) referring to locally novel creative production and meaningful "creative experiences, actions, and events" (Beghetto & Kaufman, 2010, p. 195). In the present context, it involves producing tangible creative productions, i.e., the inventions being developed. Such processes involve creative insights and artifact designs that sometimes have also broader potential significance. Blikstein's (2013) observations indicated that a significant percentage of young people's inventions anticipate ones that professional experts and organizations later produce. We have also had an invention being commercialized by business organizations, suggesting that, in some cases, mini-C becomes stretched toward Pro-C.

To have students appropriating the *figured world* (Holland et al., 1998) of engineering, designing and inventing, and experience themselves as inventors, we have invited professional designers, product developers, and inventors to join teachers in guiding, coaching, and supporting students' invention processes (e.g., Kangas et al., 2013). Occasionally, students' invention projects have gone in such a surprising direction that it has been necessary to find external experts (e.g., a mobile application developer) with the relevant knowledge to support students' invention projects. Figured worlds are cultural models of disciplinary epistemic practices that learners may appropriate to expand their own creative capabilities. The symbolic and sociomaterial activities of invention lead potentially to remixing students' educational activities with the disciplinary cultures of experts they are interacting and collaborating with. Leaning in a figured world opens possible worlds for authoring oneself (Holland et al., 1998) and engaging in improvisation building of creativity and identity (Hanson, 2015).

Invention processes are distributed among a multifaceted and dynamic network of more distant (external experts and stakeholders) and proximal (inner team and community) actors (Clapp, 2017). In the background of maker activity are experts who crystallized ("black boxed") their creative achievement in the systems of digital fabrication technologies. Participation in using sophisticated maker instruments and expert epistemic practices augment students' creative capabilities in Douglas C. Engelbart's sense (Skagestad, 1993, see also Clark, 2003): They become part of a complex distributed sociotechnical system in which ordinary minds and capabilities suffice to make more or less remarkable inventions. In such cultural activities as complex as invention, diversity appears to overcome ability (Page, 2007) in terms of heterogeneously distributed knowledge and skills playing a crucial role. Invention is a purposeful and deliberate activity (Gruber, 1981; Hanson, 2015) that is critically dependent on both personal and collaborative contributions. Further, there are always multiple pathways for participating in invention activity, enabling diverse people to make a valuable contribution to joint creativity.

Clapp (2017), Glaveanu (2014), and Hanson (2015) are developing a participatory synthesis of creativity that fits very well in the theoretical framework of invention pedagogy. The fundamental ethos of our invention pedagogy is democratization of invention; in accordance with Glaveanu's (2014) We-paradigm, anybody can be an inventor when sufficiently supported and guided (Blikstein, 2013). Many of our invention projects have included students with special educational needs, who have demonstrated capabilities of productively participating in invention processes (Sormunen et al., 2020). When embedded in meaningful contexts sparking academic curiosity and creative expression, learning by inventing is likely to be equally motivating to female and male, low- and high-achieving students. Knowledge-creating learning becomes accessible when students, their thoughts and interests, are taken seriously and provided with adequate facilitation and support (Bereiter, 2002). Invention projects spark interest and motivation, provide personal and social challenges, enhance collaborative skills, and lead to shared creation of novelty and innovation. Participation in invention projects develops students' own thinking and their ability to tinker with workable solutions and build knowledge-creating agency. Our experiences indicate that participation in collaborative invention provides students with a strong sense of contribution (Honneth, 1995); they receive social recognition of their achievements when presenting their team inventions at invention fairs or national tournaments at universities. Creative capabilities are likely to grow through pursuing a whole network of creative projects facilitating learning and development (Gruber, 1981).

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3 Epistemic Objects and Knowledge Creation in Invention Projects

Sini Davies

Introduction

In this chapter, we approach collaborative invention projects in an educational setting through their nature as artifact-mediated, knowledge-creating learning processes. We examine how these projects extend beyond knowledge acquisition and social participation to involve systematic collaborative efforts in creating and advancing shared epistemic objects by externalizing ideas and constructing various types of intangible and tangible artifacts (see e.g., Burke & Crocker, 2020; Paavola et al., 2004; Scardamalia & Bereiter, 2014a). An epistemic object in the context of invention projects can be defined as a conception of the invention, with all the visions, aspirations, projections, processes, and knowledge involved. Epistemic objects are characteristically open and complex, constantly evolving and question-generating (Knorr-Cetina, 2001). They can exist simultaneously in many forms, both abstract and material, such as figurative and scientific representations, and material prototypes that enable and promote them to further evolve into something else, by raising new questions and revealing what is missing (Ewenstein & Whyte, 2009; Knorr-Cetina, 2001). By investigating epistemic objects and how student teams develop them during invention projects it is possible to gain understanding on the learning that takes place through inventing.

Participation in knowledge creation through invention projects and collaborative design provides learning experiences that promote young people's creative thinking, teamwork, progressive inquiry, and problem-solving skills (e.g., Binkley et al., 2014; Ritella & Hakkarainen, 2012; Seitamaa-Hakkarainen et al., 2010). The Organisation for Economic Co-operation and Development (OECD) Learning Compass 2030 (OECD, 2019) considers innovation, collaboration, and co-creation as key competencies that young people need to cultivate to meet the challenges of an emerging innovation society. These knowledge-creating skills must be promoted from a young age (Aflatoony et al., 2018; Carroll et al., 2010). In the Finnish context, the emphasis on the development of students' wide transversal competencies in the national curriculum, and lack of standardized testing, provide a fertile ground for knowledge creation through multifaceted innovation projects (Finnish National Agency of Education [FNAE], 2016).

In the following, I first present theoretical aspects related to knowledge-creating learning and epistemic objects. We then introduce a case example of our investigation

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into knowledge creation and a model of conceptual knowledge dimensions in the epistemic object of a student team that took part in an invention project in a secondary school in Helsinki, Finland.

Knowledge-Creating Learning and Epistemic Objects in Invention Projects

We consider that invention processes represent artifact-mediated knowledge creation. Through these processes, students must solve complex and ill-defined design challenges through iterative processes, in which design ideas are elaborated and refined through analysis, evaluation, sketching, prototyping, and making (Blikstein, 2013; Papavlasopoulou et al., 2017; Seitamaa-Hakkarainen et al., 2010). In invention projects, students engage in joint efforts to create tangible and digitally enhanced objects using various technological resources, including digital fabrication and programming. Numerous researchers have emphasized the benefits of such participation in embodied design activities and of working with materials and artifacts in learning (e.g., Blikstein, 2013; Kafai, 1996; Kangas et al., 2013; Kolodner, 2002). Artifact-mediated knowledge creation is an emergent and nonlinear process in which the actual goals, objects, stages, digital instruments and results cannot be predetermined and the flow of creative activity cannot be rigidly scripted (Scardamalia & Bereiter, 2014b). Inventions can be designed only through repeated iterative efforts to solve complex problems, overcome obstacles and repeated failures, obtain peer and expert feedback, try new approaches, and end up with outcomes that may not have been anticipated at the beginning.

Collaborative invention projects that include usage of digital devices can be regarded as a form of computer-supported collaborative learning (CSCL). According to Stahl and Hakkarainen (2021), CSCL is a form of educational technology that engaged students in collaborating over networked devices. Students' collaboration may take place "through" technology-mediated learning environment or occur "around" digital devices in learning spaces (Lehtinen et al., 1999). Further, CSCL is distinguished from "cooperative" learning, in which tasks are divided among members of student teams, whereas collaborative learning involves the joint pursuit of shared objects (Dillenbourg, 1999; Knorr-Cetina, 2001). Moreover, post-humanist approaches highlight the active role of materially embodied digital and other artifacts in collaborative learning processes. Such an "inter-objective" (Latour, 1996) framework guides one to examine how students as teams, communities, or networks create knowledge and construct shared artifacts within technology-enhanced physical, virtual, and hybrid learning environments. The theories of technology-mediated knowledge communities provide a basis for a third approach to learning through CSCL—the knowledge creation metaphor of learning (Hakkarainen et al., 2004; Paavola et al., 2004), as separate from the knowledge acquisition and participation metaphors (Sfard, 1998). The knowledge creation view represents a "trialogical" approach because the emphasis is not only on individuals or community but on the way people collaboratively develop mediating artifacts (Paavola & Hakkarainen, 2014).

Knowledge creation may be guided and directed by envisioned epistemic objects that are incomplete, being constantly defined and instantiated in a series of successively more refined visualizations, prototypes, and other design artifacts (Ewenstein & Whyte, 2009; Knorr-Cetina, 2001). Previous studies of knowledge creation processes suggest that advanced collaboration requires group members to focus on a shared object that they jointly construct (Barron, 2003; Hennessy & Murphy, 1999; Kangas et al., 2013; Paavola & Hakkarainen, 2014). Epistemic objects are critical in knowledge creation because they can be endlessly re-interpreted, and their evolving network used as a starting point to articulate and iteratively improve novel epistemic artifacts (Bereiter, 2002; Paavola & Hakkarainen, 2005). Knorr-Cetina (2001) emphasized how creative knowledge work focuses on incomplete epistemic objects, objects that are open-ended, constantly generate novel questions, and become increasingly complex when pursued:

> Objects of knowledge appear to have the capacity to unfold infinitely. They are more like open drawers filled with folders extending infinitely into the depth of a dark closet. Since epistemic objects are always in the process of being materially defined, they continually acquire new properties and change the ones they have. But this also means that objects of knowledge can never be fully attained, that they are, if you wish, never quite themselves.
>
> (p. 181)

Knorr-Cetina (1999) also observed that epistemic objects and their material instantiations, such as prototypes, involve "pointers" (hints, guidelines, directions) regarding how to focus further activities. The objects in making imply both limitations and weaknesses, as well as provide novel ideas and suggestions, and, thereby, guide further inquiries. Consequently, the epistemic objects created provide intuitive support, suggesting which way to proceed. Further, epistemic objects in invention projects guide and direct the process as students are constantly generating, defining, and ideating conceptual and visual design ideas and instantiating in a series of successively more refined visualizations and prototypes (Seitamaa-Hakkarainen et al., 2010). Moreover, based on our findings on invention projects (Mehto et al., 2020), students' epistemic processes are materially entangled as the material objects being worked on deeply affect the interwoven generation of more redefined design ideas.

Case: Conceptual Knowledge Dimensions of a Student Team's Epistemic Object in a Secondary School Invention Project

Invention Project and Data Gathering

This case example of knowledge creation by a student inventor team took place in spring 2018 in a lower secondary school in Helsinki, Finland, where we organized an invention project. A seventh-grade technology-focused class comprising 18 students aged 13 to 14 participated in the project. For assistance, teachers relied on collegial resources to negotiate emerging challenges (Riikonen et al., 2020). Two craft-subject teachers and a visual arts teacher took the main responsibility for the project. Science and information and communication technology (ICT) teachers participated in the project when their expertise was needed. In addition, we engaged eighth-grade students as "digital technology" tutors to provide additional support to the participating inventor teams (Riikonen et al., 2020, see Chapter 12 of this book.). The teachers were familiarized with the digital fabrication technologies before the project and given pedagogical support.

Before the actual invention project started, the students visited The Design Museum in Helsinki and participated in two warm-up sessions. During the first session, the students experimented with electric circuits by making postcards with copper tape, simple LEDs, and a coin cell battery, following the idea of twenty-first-century note booking. The eighth-grade tutor students arranged the second warm-up session, which consisted of a microcontroller workshop, to familiarize the students with the opportunities and infrastructure of microcontrollers, such as GoGoBoard and Micro:bit, and to promote the emergence of ideas on how microcontrollers can be used in inventions (Ching & Kafai, 2008). The actual invention project was initiated in February 2018. The collaborative invention challenge, co-configured between teachers and researchers, was open-ended: "Invent a smart product or a smart garment by relying on traditional and digital fabrication technologies, such as microcontrollers or 3D CAD". The project involved eight or nine weekly design sessions (two to three hours per session) in spring 2018.

This case example focuses on one of the teams that were followed and video-recorded during the project. The team consisted of two girls and two boys aged 13 or 14 years old: Jessica, Carla, Leo, and Ray. The teams were randomly formed at the beginning of the project through a draw. The team examined in this article invented a banana-shaped light that could be attached to a laptop lid to light up the keyboard. Their invention included a lamp with a bendable inner structure and a microcontroller that provided sensor-based, on-off functionality and automatic light brightness control. A prototype of the light is presented in Figure 3.1. Throughout the process, the team worked in intensive, self-driven collaboration, with all members being highly engaged. They demonstrated strong motivation to participate in the project and appeared to enjoy the design process and its epistemic challenges.

Our analysis relied on ethnographic video data and observations of the student team's invention process (see Derry et al., 2010). The video recordings were made using a GoPro action camcorder, placed on a floor-standing tripod, and a separate wireless lavalier microphone. In total, 12 hours and 40 minutes of video data were gathered and analyzed. The first author was present during every design session and made observations and field notes to support in-depth analysis of the data. We also collected sketches and documents created by the team and photographed the team's invention and prototypes.

Methodology and Analysis

By relying on the ethnographic video data and observations of the student teams' collaborative invention processes, our aim was to examine the knowledge creation that took place during the projects and to investigate the knowledge dimensions and themes of the epistemic objects that the student teams developed. To gain

Figure 3.1 Prototype of the Banana Light.

Photograph by the author.

insight into the epistemic object of the team studied in this article, we first analyzed the evolution of the design ideas by systematically picking out all ideas that the team generated from the video data. We used an expression of a design idea as an analysis unit. For every idea, we determined the following factors: (a) the theme of the idea; (b) possible preliminary parent ideas; (c) whether the idea was included in the final design—that is, was a final design idea; and (d) if the idea was materially mediated, meaning was the student holding, looking at, pointing to, or modifying a design artifact or materials while generating the idea. The team generated 77 ideas, of which 40 were materially mediated and 30 were included in the final design.

During the idea evolvement analysis, it became evident that the ideas and their development unfolded concepts of knowledge that were more profound and wider than just the evolution of the design ideas. Ideas represent answers to design problems, but the complexity of the problems and the knowledge work required to solve them remained hidden. For a more detailed examination of the epistemic work involved in the team's invention process, a second round of video data analysis was conducted. In this round, we isolated expressions of design problems and the conversations related to solving them and analyzed them using qualitative content analysis. We used one question or problem and the discussions related to it as our unit of analysis. The analysis was conducted separately for each team in two phases: first, we determined themes and phenomena covered in solving each problem, and second, we further clustered the themes into four knowledge dimensions: (1) computing, (2) design and making, (3) usability, and (4) physics. From our analysis, we constructed a model of the knowledge dimensions and themes of the

Banana Light team's epistemic object that describes the invention process and invention from the perspective of conceptual knowledge. Through the epistemic object model, we captured the complexity and magnitude of the knowledge creation required in the team's collaborative invention processes.

Conceptual Knowledge Dimensions of the Banana Light Team's Epistemic Object

The design ideas describe the invention through the development of the properties and characteristics of the object being invented, whereas the knowledge dimensions of the team's epistemic object describe the invention and invention process through the knowledge work required for its creation. This model is presented in Figure 3.2. From the close, object-driven collaboration of the team, it follows that

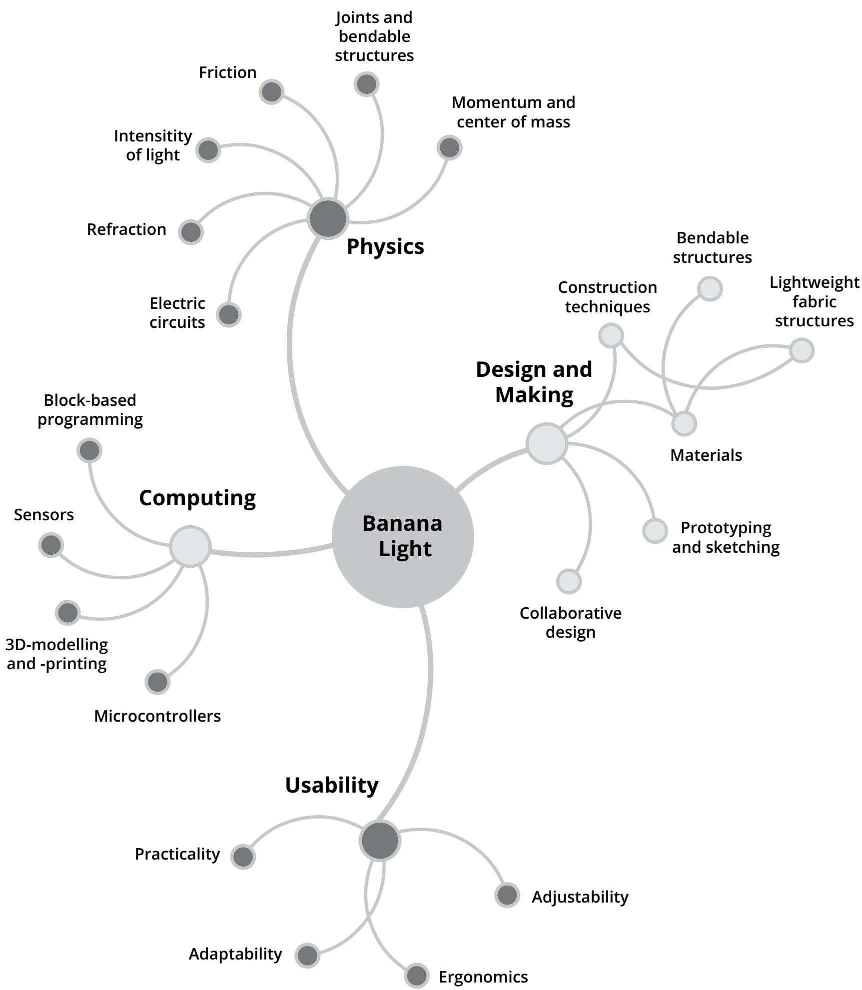

Figure 3.2 Model of the knowledge dimensions and themes of the Banana Light team's epistemic object.

the team members shared the same epistemic object throughout the process of active development. Toward that end, the democratic nature of their teamwork and decision-making was also important. The atmosphere in the team for the entirety of the project was very open, and the students encouraged each other to come up with and voice ideas.

The knowledge that the team created over the four dimensions was intertwined in nature. Usually, the team worked with knowledge from several dimensions and developed and maintained many ideas and idea strings simultaneously in their discussions. This required the team to fully commit themselves to the process, use each other's existing knowledge, seek new knowledge, and combine this knowledge with new ideas through ideation, experimentation, and prototyping. They used sketching intensively to visualize structures and ideas and communicate them to the other team members.

The Banana Light team concentrated primarily on physical functionality and the structure of their invention, creating knowledge, particularly around mechanics, such as momentum and the center of mass and friction, through material experimentation. Their invention had several mechanically challenging elements, such as how to direct the light onto the keyboard and how to attach the lamp to the laptop. They explored making bendable structures with metal and chicken wire, a bendable ruler, revolute and spherical joints, and hybrids of bendable and solid structures. The following quote illustrates their development of a clip holder that grabs the laptop screen. The discussion demonstrates both how mechanics was fundamentally intertwined with their invention process and how the open atmosphere of the team allowed ideas to be challenged and discussed. In this discussion, the students were ideating a mechanical button that could push open a clip that would hold the lamp on the laptop lid. After the discussion, they tested possible solutions with a binder clip and a clothes peg.

JESSICA: Yes, but then it [the clip] has to be pushed from both sides.

CARLA: No, it doesn't have to, because when the button is pressed, we put something there that pushes the clip claws open. Like in the clothes peg. When you press from the sides, the peg opens … the same mechanism.

JESSICA: But you will have to press from the other side as well. You will have to press from both sides for it to open.

CARLA: Oh, yes.

JESSICA: So, could we make two things that press it from both sides?

CARLA: Yes, okay, we can do that.

The students also had to create knowledge about different physical aspects of light, such as intensity and refractions and how to control them. They put the knowledge they had gained from the copper tape card workshop into action when connecting the LED lights to the microcontroller. Through actual making and experimenting, the team learned, for example, how different sensors detect movement, how to make electric circuits for one and several LEDs, what different kinds of LEDs are available, what a short circuit is, and how voltage changes affect the intensity of light.

On the theme of design and making, the students built knowledge around various ways of making bendable structures. One of their early prototypes is presented in Figure 3.3. With this prototype, they experimented with a bendable structure made of chicken wire and modeled the possible aesthetic design of the light. When reflecting on their design with this prototype, they discovered the importance of making the lamp as light as possible, which became another key area of construction that they built knowledge around.

Regarding computing, 3D modeling was one of the themes that the team explored. One of their ideas was to create ball-and-socket joints that could be 3D-printed to achieve the bendable structure needed to adjust the direction of the light. They sought knowledge on using 3D-modeling software and experimented with different ways to create 3D models and modify ready-made models to suit their needs. They also received help from a tutor student. Although they did not complete their 3D model of the lamp during the design sessions, their knowledge work on the subject was intensive. Furthermore, none of them had previous knowledge of this topic.

In addition to 3D modeling, the team attached a microcontroller (Adafruit Circuit Playground Express) to their invention to control the lights. They used block-based programming, building knowledge around the two following areas in particular: using sensor data to trigger the on-off functionality of the LED light and controlling the light's brightness and color. Experimenting with different sensors provided the students with ample opportunities to create knowledge about programming. They had to use conditional if-statements and familiarize themselves with the functionality and concept of events and variables in programming. To solve the programming challenges, they collaborated intensively and asked for help from teachers and tutor students when they felt they needed it. The programming seemed to be very rewarding for them, and they even celebrated together when they succeeded in making the light work as they wanted it to.

The team considered usability at all stages of the design process. First, they approached it from the point of view of the product's practicality and usefulness. Later in their process, they moved toward more specific usability issues, such as

Figure 3.3 Early prototype of the Banana Light.

Photograph by the author.

adaptability and adjustability. These themes are not only important in terms of knowledge about usability, but they are also a vital aspect of creating sustainable products.

Making, prototyping, and working with materials and tools were central elements of the team's knowledge creation process. By making, the team was able to create knowledge about science themes that they were not familiar with at a theoretical level. They also experimented with a wide range of design techniques, such as sketching and ideation methods, building knowledge about them. They learned to engage in collaborative design—a valuable skill in itself that is not often obtainable in a school setting. The students had to organize their process, divide tasks, consider each other's ideas, and build on them. Traditional craft techniques played a fundamental role in their project. The importance of using traditional craft and prototyping techniques cannot be overlooked from the point of view of knowledge creation as the teams were able to handle and materialize complex conceptual knowledge through actual making activities.

Discussion and Conclusions

Open-ended invention challenges offer numerous opportunities for knowledge-creating learning and inventive thinking. If the project is planned and scaffolded well, and sufficient support and material resources are provided to the inventor teams, students can take on substantial epistemic challenges that may otherwise seem advanced for their age. These challenges can be solved through collaborative iterative efforts at working out complex problems, overcoming obstacles and repeated failures, obtaining peer and expert feedback, trying again, and ending up with outcomes that may not have been initially anticipated. During invention projects, student teams jointly create and build knowledge through processes of collaborative design and inquiry into challenging phenomena with scientific and practical experiments. Successful invention processes, and the knowledge creation that accompanies them, require teams to identify together the design problems related to the task, set up an epistemic object of invention, determine constraints around the possible solutions, and actively engage in and take responsibility for the process (Paavola & Hakkarainen, 2014; Sawyer, 2006; Scardamalia & Bereiter, 2014a).

In our case example, it was remarkable how versatile and sophisticated the epistemic concepts that the team had to handle were, ranging from actual making to theoretical scientific concepts. Furthermore, the case example highlights the importance of making and working with physical materials, as well as prototyping with traditional craft techniques. When building their prototypes, the team members worked iteratively with their epistemic object, generating, testing, evaluating, and refining their ideas to improve their design. Making and material artifacts play an important role in stimulating and enabling ideation and knowledge creation. This aspect has also been highlighted in previous research (Blikstein, 2013; Ewenstein & Whyte, 2009; Knorr-Cetina, 2001; Mehto et al., 2020; Vossoughi & Bevan, 2014). In the Banana Light team's projects, science and making were fundamentally entangled. By making, the team was able to investigate and simultaneously consider aspects from several themes of conceptual knowledge.

To conclude, the open-ended design and making challenge set the stage for knowledge creation. Design problems trigger the knowledge creation process, leading to new ideas through the application of maker practices. During the invention process, new ideas bring forward new design problems and refine old ones. Further knowledge must then be built to solve these emerging design challenges. Working with physical materials enables student teams to test their ideas, create new ones, and build an understanding of the science concepts related to their invention. Hence, supported by the findings from our previous studies (Mehto et al., 2020; Riikonen et al., 2020), we conclude that open-ended, materially mediated, invention projects offer ample opportunities for knowledge creation and multifaceted learning in schools.

Further research is needed to investigate how epistemic objects develop during invention projects, as well as how invention projects could be further designed to offer the best possible setting for knowledge creation. Moreover, future research is required on opportunities for invention projects to be carried out several times during a student's school path. Creating a continuum of innovation education could offer young people a way to learn the skills of innovation, collaboration, and co-creation.

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4 Collaboration and Co-regulation in Invention Projects

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Introduction

Long-term collaborative work requires students' commitment to coordinated problem-solving, the development of a shared object, and the division of labor to support their collaborative work (Barron, 2003; Järvenoja & Järvelä, 2009; Riikonen et al., 2020).

When developing invention pedagogy, it is essential to understand how students collaborate in teams when pursuing open-ended and emergent invention challenges. It also means understanding how to support the learning of all students according to the principles of inclusive education (United Nations Educational, Scientific, and Cultural Organization [UNESCO], 2016). One of the general aims of Finnish education is to foster socially sustainable inclusive education and thus eliminate the exclusion that might reduce students' social relationships (e.g., Honkasilta et al., 2019). It means an increased risk of reducing options for students with special educational needs (SEN) to follow their educational aspirations and citizenship skills in education.

The invention challenges, which are completely beyond students' capabilities, may be experienced by SEN students as challenging. However, little is known about how students with diverse capabilities have been able to participate in long-term collaborative invention projects. Previous research indicates that learning methods in which knowledge is built collaboratively in iterative cycles and through working with real-life challenges are of benefit to all students' learning (McGinnis & Kahn, 2014). However, such diversity of academic knowledge and learning skills might have a negative influence, especially on SEN students' active participation in collaborative groups (e.g., Anderson et al., 2008; Cohen, 1994). Through the case examples, we will examine the level of socially shared regulation in invention teams in which students with or without SEN collaborate. From the perspective of successful invention projects, the extent to which students are taking other team members into account and how they are mutually carrying out the responsibilities for achieving common goals is critical (Barron, 2003; Damşa et al., 2010; Pijl & Frostad, 2010). We examine collaboration and social regulation as an activity in which students jointly regulate their design and making activities as a team in relation to attaining a shared object.

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Teachers see students' participation in the social regulation of invention activities and their pursuit of the joint object with a flexible division of labor as active involvement, which also engages SEN students in learning (Sormunen et al., 2020). Students are engaged in co-designing their knowledge-creating inquiries and deliberately organize team processes to maintain a shared understanding of the unfolding process and evaluate their progress toward the shared invention (Dillenbourg, 1999; Miyake & Kirschner, 2014). We focus especially on the development of small group learning and the shared regulation of collaborative activities. In this chapter, we will introduce two invention projects that we organized. Both cases focus on the inclusive class settings typical of today, and we spotlight invention teams in which students with or without SEN collaborate. We seek to deepen the current knowledge on the emergence and flow of collaboration in longitudinal invention projects; the principles and findings addressed are adaptable for all learning by making environments.

Invention Projects Require Object-Centered Social Interaction

Our investigations engaged teams of students in pursuing invention projects and ideating, designing, and making artifacts. Collaboration within student teams has been investigated rigorously, especially in relation to collaborative talk and action (e.g., Barron, 2003; Buchholz et al., 2014). In many cases, collaboration is studied intensively in the field of design and technology education (Hennessy & Murphy, 1999; Kangas et al., 2013; Rowell, 2002). The invention projects represent nonlinear knowledge-creating learning processes, through which teams of students are engaged in long-standing collaborative efforts of solving an open-ended challenge and pursuing emergent epistemic objects such as ideas, visions, and artifacts in making. The co-regulation processes involved in virtual settings of technology-mediated learning have attracted the interest of many investigators (Järvelä & Hadwin, 2013). However, invention projects diverge from traditional computer-supported collaborative learning (CSCL) in terms of being embedded in a shared physical maker space (e.g., a craft classroom). Our data involve the video recording of collaborative interaction by student teams *around* digital fabrication tools and instruments instead of interaction *through* virtual learning environments (Riikonen et al., 2020); this makes the social regulation of maker activity less problematic.

Yet, invention projects may involve overwhelming challenges for all team members due to working with unfamiliar digital fabrication technologies, encountering unanticipated construction problems, and carrying out inquiries leading to unforeseen directions (Gutwill et al., 2015). Such projects create unique learning situations as students struggle with joint efforts of finding solutions, achieving goals, sharing experiences and knowledge, and having a sense of making a creative contribution. Participating in a collaborative group alone can be challenging for struggling students, especially SEN students. Participants must negotiate between various invention ideas, available tools and technologies, and constraints inherent in designing and making (Petrich et al., 2013). If a student feels that they are not a productive member of the team, it will affect their cognition and behavior, leading them to withdraw from the work (Anderson et al., 2008; Cohen, 1994). Instead, if a student feels accepted by peers, they may dare to express opinions and participate in negotiations and joint decision-making (Jordan & McDaniel Jr., 2014; Pijl & Frostad, 2010). To address an invention challenge successfully, a team must simultaneously deal with epistemic and technological challenges as well as organize, in real time, their ongoing design and making processes (Mehto et al., 2020; Riikonen et al., 2020).

The students' collaboration requires the team members to focus on a shared epistemic object, that is, an artifact-in-making that they need to build together during the invention process (Mehto et al., 2020). The success of collaborative teamwork is critically dependent on students who actively engage in and take responsibility for the learning process. To ensure student collaboration in inclusive classes, the teacher should pay attention to the grouping so that socially competent students support less competent peers (Webb et al., 1998). During the process, the teacher facilitates learning by encouraging independent work as much as possible but also offers support when required. It should also be noted that students must be given time to build their collaboration independently (Barron, 2003).

Further, variations in interactional processes between students can lead to productive collaboration (Barron, 2003). The collaboration requires an adequate division of labor (Barron, 2003) that is seen as more than just accomplishing a task because it involves agreed-upon but flexible roles and active interactions between team members. Although it is beneficial to participate equally, participants may also have various roles and relationships during the project (Mercier et al., 2014). The idea exchange may both facilitate and hinder ideation and tinkering, which is dependent on the quality of a teams' collaborative discourse interaction. Some students can take a leadership role or have more initiative; however, the level of initiation and intentionality (Gutwill et al., 2015) can change across the course of students' interaction (Mercier et al., 2014). Most commonly, the initiation and leadership are related to handing over certain tasks, checking on the following of the given instructions, coordinating the team members' attention, and directing the tools and materials used.

Appropriate social settings (i.e., a supportive atmosphere and close relationships, positive social norms, participant engagement, and social recognition of team achievements) facilitate participation for sharing ideas, organizing the process, and supporting the emergence of a commitment toward a shared epistemic object. Furthermore, teachers' interaction with students as part of organizing and facilitating teamwork is an important aspect of collaborative learning in school settings as well as in maker spaces (Gutwill et al., 2015). These include sparking initial interest, providing stimulus, giving demonstrations and modeling, making new tools and material available, and scaffolding participants through frustrating moments, as well as providing hints and help to teams to overcome challenges related to the division of labor and the distribution of the workload evenly (Gutwill et al., 2015). During the maker project, the teacher should actively pay attention to how the ideas are developed together and how the agreed-upon division of labor among the team members is realized.

From Self-Regulation to Co-regulation and the Socially Shared Regulation of Inventive Activity

The self-regulation, co-regulation, and socially shared regulation of learning are distinguished from one another (Hadwin et al., 2017; Panadero & Järvelä, 2015); a successful invention process is critically dependent on all these forms of regulation. Research on self-regulated learning assists in understanding and examining the role of intellectual, social, and emotional engagement in learning processes (Järvenoja & Järvelä, 2009). Järvelä and colleagues see self-regulated learning as a social process embedded in and mediated by a learning environment; it not only shapes personal activity but also that of other team members. Self-regulated learning refers to a student's capacity to manage their own activity, thinking, and motivation so as to achieve learning goals and objects. It also involves adapting one's own activity according to the team's shared objects, available tools, and epistemic and material resources, as well as the conditions of the learning environment (Järvelä & Hadwin, 2013; Järvenoja et al., 2015). Learning activities that rely on students' self-organized teamwork, collaborative interaction, and pursuit of novelty and innovation challenge students to interrelate their own activities with those of other team members and at the same time cultivate their self-regulative and collaborative competencies.

Co-regulation, in contrast, requires that the members of the team participate in the ongoing monitoring of mutual activity, cognition, emotions, and motivation (Järvelä & Hadwin, 2013). Panadero and Järvelä (2015) anchor co-regulation on Vygotsky's (1978) sociohistorical theory: Higher cognitive processes are assumed to develop through socially contextualized and tool-mediated interaction at the zone of proximal development. In the context of invention projects novel to all participants, co-regulation cannot merely be a matter of an asymmetric relation of more knowledgeable students supporting their peers but involves all team members and the task, tools, and learning environment providing reciprocal support to one another. Through teamwork, students are developing both their collaborative and metacognitive skills. Co-regulation is a metacognitive process of planning, monitoring, and directing team-based creative activity. The development of metacognitive skills requires that the students reflect on their own as well as the whole team's activities by asking about joint achievements, challenges, and required improvements of activity. In the context of team-based invention processes, metacognitive capabilities not only represent the personal awareness of one's own learning activity but expand to the awareness of socially distributed learning processes and the relevant knowledge and skills of fellow team members. Hadwin et al. (2017) argued that co-regulation plays a crucial role in fostering the development of both the self-regulation of learning and the socially shared regulation of learning (SSRL).

Learning in invention teams is mediated by the mutual pursuit of the shared ideas and visions of invention. Indeed, such an undertaking corresponds closely to SSRL (Panadero & Järvelä, 2015), which strongly underscores the object-driven aspects of the social regulation process. Shared regulation refers to a team's deliberate planning of its activity, the team members' co-configuration of the invention idea, the mutual shaping of the making processes, associated joint deliberation and reflection, and the reciprocal adaptation of activity. It is based on students' knowledge, beliefs, and experiences, which have to be mutually adjusted for the coordinated pursuit of the teams' shared epistemic object (Isohätälä et al., 2017,). SSRL requires that the team members jointly assume metacognitive control of the invention project in terms of negotiating and iteratively developing the invention idea and aligning teamwork activity cognitively, motivationally, and emotionally in pursuing the shared object (Hadwin et al., 2017). It means that the whole team should pursue the shared epistemic object as a collective after interactively working out the invention object and employ co-regulative efforts for successively forming as a team. SSRL is revealed in terms of active participation and mutual recognition and responsibility for achieving a common goal, that is, as a form of shared epistemic agency (Barron, 2003; Damşa et al., 2010). In such socially shared co-regulation of activities, the team members also observe and direct each other's activities (Panadero & Järvelä, 2015). Therefore, the team manages and directs the task in question through jointly agreed-upon methods and practices, but the members can also take on various roles during the process (Mercier et al., 2014).

In collaborative teamwork, reaching a shared understanding and elaborating a shared epistemic object are the most important aspects. Students' teamwork aims at making the invention. To that end, it is critical to support and strengthen the students' sense of belonging to a team and thereby increase each student's commitment to the joint invention project. A key part of the sense of belonging is a commitment to the shared invention process and agreed-upon ways of working. The cohesion of the team is enhanced by treating each participant equally, providing encouragement, and creating an adequate but flexible division of labor between the team members. Social interaction and open discussion in the team assist students in understanding each other's perspectives, making compromises, compensating for each other's weaknesses, and gradually building mutual practices. Understanding the skills and strengths of other team members is valuable when a certain kind of knowledge or skill is needed for solving a novel problem. The teacher can foster the development of teams' metacognitive skills by asking students repeatedly to reflect on their ongoing activity and advancement toward the artifact-in-making during the invention project.

The shared regulation of the invention process is a transactive process in which the initial epistemic object is invented, iteratively refined, modeled, prototyped, and manufactured. Accordingly, the invention project is not only a socially mediated process in nature but also a materially mediated one (Kangas et al., 2013; Mehto et al., 2020). To construct an adequately functioning artifact, the students have to employ diverse traditional and digital fabrication tools and multifaceted materials. Sociomaterial interaction with the various models and prototypes help the teams to explain, verbalize, communicate, and materialize initially vague ideas (Mehto et al., 2020). Further, the use of certain tools and materials is likely to impact the division of labor; the possession of a particular tool could, for instance, give authority in the use of the materials shaped by that tool (Buchholz et al., 2014; Rowell, 2002). Alternatively, the material mediation involved in making tangible artifacts enables all team members to observe the development and fabrication of the artifacts in making in real time; the material embodiment makes the diverging intuitions and expectations visible to all participants.

The focused social-creative pursuit of invention requires students to work toward a joint object; to listen to, understand, and help each other; and to engage in shared efforts of testing and constructing the artifacts being developed (see, e.g., Barron, 2003). The term process organizing (Riikonen et al., 2020) is used here to refer to the social-epistemic regulation of collaborative design and making processes. Such discourse interactions have been empirically identifiable across many investigations; they share characteristics of both the co-regulation and SSRL. The team members' belief in their capacity to solve the invention challenges requires unity, which should be supported in a range of ways. The teacher can see the togetherness of the team members in the way the students negotiate and build on the insights from each other's ideas, how they plan the task at hand, how they talk about the team's strengths and weaknesses, and how the members express their feelings about the task. Successful teamwork is clearly organized around joint problem-solving attempts, in which students have a shared idea of the designed object, and the team wishes to take the joint ideation forward. For the teacher, this commitment is clearly visible when the participants are talking about "us" as a team and referring to each other's ideas by expanding and developing them together. In the following, through two case examples, we will examine the level of socially shared regulation in invention teams.

Invention Project Settings and Method of Data Analysis

The two invention projects were organized at a primary and a lower-secondary school, respectively. In the project implemented in primary school, we explored collaboration and co-regulation in two inclusive teams including SEN students. In the lower-secondary school project, in turn, we traced the social regulation in the invention projects of five student teams. In both projects, student teams received an open-ended invention challenge jointly designed by the teachers and researchers. At the primary school, the student teams were challenged to "design an intellectually challenging, aesthetically appealing, and personally meaningful complex artifact making daily activities easier. It could be a new or improved invention, and it should integrate material and digital elements". At the lower-secondary school, the student teams were requested to "invent a smart product or a smart garment by relying on traditional and digital fabrication technologies".

The projects involved 8 to 12 weekly design and making sessions (two to three hours per session) over three months. The research data consists of video recordings of the seven teams. The fifth-grade teams worked on the Gel Comb and Key rack projects, and in the seventh-grade teams dealt with the Bike, Mobile Gaming Grip (MGG), Moon, UrPo, and Plant projects. We analyzed the video recordings using the Making-Process Rug method. Altogether, approximately 83 hours of video data were analyzed and coded in three-minute segments. The method of data analysis was based on two stages of (1) systematic coding of the video data and (2) converting these data into a visual form that enabled us to perceive the collaborative invention process and its flow. With that end in mind, the analysis produced color-coded, layered diagrams referred to as Making-Process Rugs because they resemble woven rugs (see Figure 4.1, which we have made available via the link in the footnote[1]).

From the visually coded video data together with ethnographic notes, we illustrated the commitment of the team members. The coded data provide a variety of indicators for assessing student teams' shared responsibility and motivation. These included (a) the extent to which the team members were involved in the activities and (b) how they focused on the specific activities or stages, (c) how much they were interested in the task, (d) how the members of the team interacted with each other, and (e) how the division of the work between members took place, that is, how the team members organized their collaborative process. Process organizing (see green color in Figure 4.1[1]) represents verbal interaction through which team members negotiated mutual responsibilities, talked about what should be done next, and analyzed the specific tools and programs needed in the next stage.

Findings

When analyzing teams' collaborative designing and making processes, some possible drivers of successful invention were identified. Extensive video data revealed each member's participation, engagement, and the quality of interaction between the members of the team. As the invention projects lasted 8 to 12 weeks, it is evident that the teams' engagement and intensity varied at different stages of the project. However, we were surprised that the student teams at both school levels were able to maintain their enthusiasm and motivation throughout their longitudinal invention processes.

Shared Responsibility at the Primary Level

At the primary level, we followed two inclusive student teams that we chose because of the participant structure, size of the team, and the team composition in terms of having both mainstream students and SEN students. Table 4.1 shows the team members and their inventions at the primary level.

In the larger Gel Comb team, students were divided into smaller sub-teams to work on their areas of responsibility. Some members were more active in advancing the invention, and they also directed the team's activities more than others. The Making-Process Rugs of the Gel Comb team revealed that the team had to repeatedly return to the process organizing, and the team also had more off-task work (see black color in Figure 4.1[1]), which can be interpreted as an inconsistency in the

Table 4.1 Primary school student teams and their inventions

Name	*Team*	*Basic idea*
Gel Comb	Five boys (three SEN students)	The Gel Comb is an invention where hair gel is applied directly to the user's hair so that the user's hands will not get dirty.
Key Rack	Three girls (one SEN student)	The Key Rack was intended to keep keys in a designated place with color-coded hooks for each family member's key(s).

team's activities and a challenge in terms of focusing on the targeted invention. The Gel Comb team reorganized its activities throughout the process and on several occasions during one session. The smaller-sized Key Rack team, in contrast, functioned in a very organized way right from the beginning, and the participation was more equally distributed, and the team was committed to promoting their invention process. The following three themes related to the regulation and organization of the teams' activities emerged from the material of the primary class: (1) shared responsibility, joint decision-making, and co-regulation; (2) reconciling tensions and dilemmas; and (3) social support, encouragement, and participation.

Shared Responsibility, Joint Decision-Making, and Co-regulation

In the Gel Comb team, one student had greater responsibility for the team's processes and the completion of the invention. The student took responsibility for the team's activities, and his leadership was manifested in terms of sharing instructions with others and the completion of tasks. Other members of the team relied on his opinions and his organization of work assignments. The student was also responsible for involving other team members and personally completing tasks that might otherwise have been left undone. Although in the Gel Comb team the members gave the main responsibility to one student, they mainly shared their decision-making in the team.

In the Key Rack team, there was no single leader or responsible person; rather, the process was more evenly co-regulated among the students. There was constant consultation between the two mainstream students about who was allowed to make decisions, such as who was responsible for writing the learning diary or what the invention should eventually become. They both had a strong desire to take responsibility and make decisions. However, the authoritarian attempts of an individual student to regulate team activities were thwarted, and the students sought to make team decisions jointly. In particular, the third student played an essential role as a mediator. Joint decision-making appeared to be important in both teams.

The activities of the invention teams were jointly co-regulated within the teams in many ways. The co-regulation aimed to ensure that the activities of the teams were continuous and desirable. In the Gel Comb team, the participation in the invention process was organized by regulating the behavior of the team members, particularly limiting off-task activity. The manifested leader often asked the other team members to focus on the essentials, calm down, and listen to each other. He emphasized the importance of focusing on the work for completing the invention, and he patiently structured the activity of the other members by guiding and encouraging them. Despite strong leadership, the activities of the Gel Comb team were more fragmented than those of the Key Rack team. The larger the team size and the larger the number of SEN students in the team may have contributed to the challenges of focusing on the main activities.

Participation in team activities and interactions can be considered to be one of the critical dimensions of collaboration. The team members regulated each other's behavior by obligating them to participate in joint activities. The obligation was manifested explicitly and verbally to focus on the task at hand or participate more actively. Invitations to concentrate on the task were especially addressed to the

SEN students in both teams. In both teams, the SEN students sometimes lost focus until they were encouraged to return to the invention. In both teams, efforts were made to find suitable tasks for each team member even though the situation might not have required that activity.

Leadership, responsibility, and social support may appear to be more prominent forms of team activity, but participation in social interaction is also essential. Learners who for one reason or another are unwilling or unable to take on a visible role in their team's activities may still bring their own way of taking part in creating the social order. This was the case especially with SEN students. For example, in the Gel Comb team, one SEN student's role as being socially funny may seem disruptive; nevertheless, the student participated in social interaction, brought out his ideas, and created a friendly, lighter atmosphere for the team by having fun with others. Although the responsibility for team activities was not evenly distributed among the team members, and commitment to team activities varied during the project, neither team completely excluded any members from team activities.

Reconciling Tensions and Dilemmas

There are many challenges in the invention process and the team seeks to address these together through a range of ways to strengthen collaboration. Conflicts that arise in collaborative situations can allow students to take on a new kind of responsibility for team activities, participate actively, and thus express their role by calming the situation and contributing to the smooth continuation of team activities. In the Key Rack team, there were several conflict situations. Disagreements arose between two mainstream students; their close friendship outside the project may have influenced the situation. Interestingly, the SEN student took the initiative to keep the group dynamics harmonious by addressing disagreements between the other team members. For example, she resolved a potential conflict even before it broke out by intervening in a discussion that had turned into a debate between two members; she encouraged each student to have their say and thus allowed all members to express their own opinions in order to resolve the situation. Her effort of giving turns and asking questions was proactive in nature, which may be interpreted as an expression of the student's agency in relation to SSRL.

The difficulties of the Gel Comb team were different. They appeared as a continuous reorganization of the process and a lack of focus concerning targeted action. However, there were no actual emotional episodes that could be classified as conflicts in the Gel Comb team. The tensions of the Key Rack team, in turn, arose when the team members did not meet their implicit quality requirement or when joint decision-making turned out to be difficult. Disagreements within the team swelled to interfere with targeted team activities when a lot of time had to be spent resolving them and when they became emotional and offensive. However, the team resolved the conflicts together, and activities continued. Despite the Key Rack team's disputes, the videos show that keeping the team together was vital to all members. Disagreements appeared to strengthen the Key Rack team and focus the team's activities on the invention after conflicts. With persistent cooperation, both teams completed their inventions.

Social Support, Encouragement, and Participation

Overcoming tensions and dilemmas together can strengthen the team and support its activities later. In both teams, students also provided each other with social support, encouragement, and guidance during the invention process. By supporting and encouraging others, it is possible to increase the sense of contribution, thereby strengthening the role of the actors in the team (Sormunen et al., 2020). The Gel Comb team's video material revealed that the students recognized each other for a job well done. For example, the students praised the contribution of the slightly passive SEN student. Positively encouraging an individual about their own work can strengthen their sense of contribution, which in turn can enhance agency and a sense of inclusion (see, e.g., Damşa et al., 2010). Also, at many points in the Key Rack project, the members encouraged each other and considered the effects of encouragement and positive support on the team's good atmosphere.

Experiences of the Social Regulation of the Invention Project at the Secondary School

In the secondary school project, the size of the teams varied from three to seven members, which clearly affected the teamwork (see Table 4.2). All students were mainstream students. The results indicated that four of the five teams were able to take on multifaceted challenges and come up with novel inventions.

The analysis of the video data revealed that the collaborative processes within the larger teams (six to seven members) were more fragmented than those in the smaller teams (Riikonen et al., 2020). Moreover, off-task work was more common in the larger teams than in the more compact ones. The following three aspects related to co-regulation and process organization emerged from the data: (1) joint commitment and engagement, (2) importance of model making and experimentation, and (3) topics of process organizing.

Table 4.2 Secondary school student teams and their inventions

Name	*Team*	*Basic idea*
Bike	3 boys	A three-wheel bike containing smart technologies, such as an environment-responsive, rechargeable LED lighting system
MGG	4 boys	MGG, a pair of handles that improves the ergonomics of a mobile phone while playing games
Moon	6 girls	A smart outfit for sports, including an environment-responsive lighting system to improve safety
UrPo	6 boys	A smart insole for sport shoes, including an automatic warming system for winter sports
Plant	7 girls	An automatic plant care system incorporating decorative elements

Joint Commitment and Engagement

In most of the teams, the design challenge clearly appeared to be transformed into a joint effort for the team as the project progressed, that is, a joint commitment and shared engagement to develop their own inventions. Only one team (the Plant team) really found it difficult to find commonly shared ideas and to organize their process together. Moreover, other large teams appeared to have some problems engaging all team members in working consistently to advance their invention. However, when the design process proceeded, all members were able to participate equally. The interaction between the members of the team was generally positive, and the resulting conflicts related to the divisions of work were solved by consensus, thus fostering collaboration within the team. This is important as negative socio-emotional experiences may challenge the teamwork and undermine the team's chances for success (Barron, 2003).

The smaller teams were more committed and enacted the socially shared co-regulation more readily. During their design and making processes, the teams produced multidimensional and relevant ideas for inventions to drive their design forward into more specific ideas and new products. Although the members of the team could have different ideas or views related to the ideas of invention at various stages of the process, they nevertheless endeavored to produce the best possible joint solution and to consider each other's views. Beyond team size, group dynamics and the nature of the inventions may have also affected the observed differences.

Importance of Model Making and Experimentation

The data analysis revealed the importance of model making in the successful completion of the making process (Riikonen et al., 2020). In the processes of the Bike, MGG, Moon, and UrPo teams, model making was the most noticeable activity that was intertwined with ideation, with discussion about manufacturing and evaluation occurring either in parallel or following model making. These teams dealt with the complexity of invention challenges by spending a great deal of their time in model making and digital experimentation. The importance of tangible, hands-on work for the successful teams is also emphasized in the results of previous studies (Kangas et al., 2013). Therefore, it can be argued that without the creation of prototypes, there would have been a lack of fruitful opportunities for shared regulation. The model making gave the proposed solution a tangible form, enabling the evaluation and acceptance or rejection of the prospective solution, and helped the members to focus on joint decision-making. The prototypes integrated the ideas and solutions and materialized all aspects of the team's invention. Sociomaterial engagement (Mehto et al., 2020), both in materially mediated making and in focused social interaction, was critical in inventing tangible artifacts. The Plant team did not engage in any model making over the course of the project, and the team spent most of its working time on off-task actions. For example, they experimented with materials and digital tools, but these experiments did not lead to model making, and the potential to advance their invention never materialized: they were not able to develop a shared understanding of the object.

Topics of Process Organizing

Common to most of the successful teams was concentration on shared working and a commitment to it. The process organizing involved the social-epistemic regulation of collaboration to engage in shared efforts of testing and constructing the artifacts being developed. The topic of process organizing focused on:

1) Organizing making activities covering the discursive aspects of doing or performing something, including discussions concerning next steps, such as 3D modeling, sewing fabric, or searching for more information about coding LED lights
2) Constraints and resources, including discussions on how to find certain materials, scheduling future activities, or acquiring social resources such as help from a teacher, and finally
3) Teamwork, covering how various tasks would be divided among team members

The Bike and MGG teams focused on organizing making activities and tight teamwork among all team members. In the MGG team, one student had a leading role in the organizing process, but he provided the other team members opportunities to participate. Further, the lack of teacher involvement was striking in both teams, and the teachers were only needed to provide assistance in deciding how to proceed or material resources and guidance regarding 3D printing (for example). In the Moon team, the design and making processes were also organized in a very collaborative manner through negotiations within the whole team, and they composed sub-teams to conduct certain tasks. The UrPo team's process organizing was led by the two team leaders and supervised by the teacher. It was rare in the Plant team's process for the entire team or even most of the members to take part in organizing the process.

In general, the teams' engagement evolved as the teams' solutions advanced: they enjoyed problems-solving and making, and the teams' activities were self-regulated. Their own meaningful invention challenge combined with the freedom of making choices can be seen as major elements contributing to the creation of the shared objectives of the internally motivated teams. For example, the teams did not discuss the teacher's expectations about their invention projects; instead, the discussion and activities focused on the realization of a shared object and the setting of the teams' own goals on the basis of their own starting points. The teams' collaborative process of organizing can be characterized by joint project management, continuous shared responsibility, and mutual control of the various aspects of the multifaceted project.

The successful teams managed to sort out most of the teamwork challenges themselves, and they addressed related issues in most sessions. Thus, the commitment and co-regulation of shared working appeared in terms of enjoyment, capability, orientation toward destination, and commitment to problem-solving. Developing their inventions together and the shared motivation among the team members seemed to constitute a self-inducing positive cycle in which the team members became increasingly motivated to achieve the objectives they had set, which in turn encouraged the team members to set new goals and to work hard to achieve them. However, as stated earlier, such corresponding shared motivation was not observed in only one team: the team did not develop common problem-solving goals that would have created commitment within the team members to develop their own invention. On the contrary, over time, these students made it clear that they did not have inner motivation and were not able to organize their process.

Discussion

The aim of the invention projects was to provide a variety of students with the experience of participation, that is, to persuade them to make something relevant together, thereby stimulating their internal motivation, referring to the desire to promote commonly agreed-upon objectives and to commit to the completion of the project. In teams, the close commitment and positive attitude and flow reinforced the view of how important it is to develop teams' inner motivation and commitment to their work. It can be said that in both school cases, most of the teams had positive learning experiences in terms of having ambition, dedication, and flow. The achievement of positive learning experiences as part of the curriculum content can be regarded as significant, and these experiences may have far-reaching implications as students move to adulthood and to the world of work.

Equal participation and the sharing of tasks evenly promoted the co-coordination of the team's activities, which is a prerequisite for successful collaboration. The unclear role of the students in the group interferes with the teamwork. Working in small teams in which all members interact actively to achieve a shared goal and object is usually inspiring and creates a positive cycle. Creativity in designing requires the bravery of the members to present their own ideas and experience. The quick drawing of ideas and testing of details are situations in which joint work becomes visible. When working is at the center, students convey and make visible their design ideas through discussion, drawings, and various material 3D models and prototypes. This provides an opportunity for further processing ideas and discussing them and producing more advanced ideas. However, getting students into this state of mind may be challenging as they may have varying skills and knowledge, and the teams may thus be highly heterogeneous.

In the primary class project, the activities of the teams were co-regulated in many ways. Shared responsibility for the team's activities was taken both at the individual level and collectively. Making decisions jointly was sought, or team members gave one team member the responsibility for leading the team's activities and the division of labor. The teams regulated activities to influence the behavior of other team members, involved all team members in joint tasks, and resolved any difficulties and disagreements that arose during the project. The team members gave each other additional social support and encouragement to ensure harmonious and smooth group activities. Students sought to compromise, work together, and keep the team together during the project. Working together was perceived as meaningful.

Directing the teams' motivation and interest toward a common goal may become a challenge for joint activities. This is influenced by the instructions, open-ended but jointly negotiated and comprehensive assignment, and previous experiences of school practices. Further, the team must put joint effort into working out the shared epistemic object of their activity; that is already an achievement rather than something pre-given. Collaborative learning also takes shape differently depending on whether the members of the team are allowed to choose their own team and working space or whether they participate in collaborative activities on their own initiative, on the initiative of a teacher, or under compulsion. In addition, during the long-term invention project, the motivation, commitment, and dynamics of the team members may vary.

The teacher can assist in the accomplishment of effective collaboration by monitoring the interaction between team members and by scheduling the various stages of the invention project—and also by practicing it with students, getting them to use nonlinear working, and managing anxiety. In inclusive classes with SEN students, collaboration and co-regulation can be supported by creating different routines for working, including starting sessions with the team's joint review of ongoing phases (where we are now), what should be achieved during this session, and at the same time, agreeing on which team members are responsible for which phase or sub-task. At the end of the working session, it is also important to reflect briefly on how the objectives of the working session were achieved, whether everyone has had enough opportunity to contribute, and how collaboration between the members of the team has proceeded. Agreement on the division of labor can be reviewed separately in each session.

Note

1 https://growingmind.fi/inventionpedagogy_makingprocessrugs/

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5 Learning to Create

Creating to Learn

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Learning to Create

Invention projects engage students in nonlinear, multifaceted hands-on processes, through which they collaboratively generate creative solutions to open-ended, real-life design challenges. The aim is to support students in learning to be curious problem finders and solvers and to enhance their confidence to act in creative ways (Goldman & Kabayadondo, 2016). Furthermore, several future competencies linked with creativity and considered essential for well-functioning future societies, such as empathy and collaboration, can be developed in invention projects (Noweski et al., 2012). Within invention pedagogy, creativity emerges as a form of sociomaterial action as the material world is explored by students through collaborative generation of shared artifacts (Clapp, 2017; Mehto et al., 2020).

Throughout its history, creativity has been given multiple definitions. A widely accepted definition focuses on creative outcomes that need to have both novelty value and be appropriate or useful for their purpose (e.g., Stenberg, 2022). However, these elements are always determined in particular social, cultural, and historical contexts (Beghetto & Kaufman, 2014). In schools, teachers and students are the experts who recognize the creativity in students' solutions, and novelty value means that a solution is new to students or exceeds what can be expected from them (Clapp, 2017). In education, it is essential to understand that anyone can be creative at a certain level and can develop from one level to the next (Beghetto & Kaufman, 2014; Clapp, 2017). Creativity can be seen "as a capacity to imagine, conceive, express, or make something that was not there before" (Durham Commission on Creativity and Education, 2019, p. 3).

Sawyer (2021) suggested that the goal of teaching for creativity could be for students to understand creativity as an iterative, improvisational, and nonlinear process. Helping students to navigate in such uncertain and undetermined contexts cannot be guided by fixed instructions (Sawyer, 2018); instead, a creative approach to teaching is required both in terms of pedagogical methods and simultaneously enhancing competencies for creativity in students (Patston et al., 2021). Despite the significant role of creativity in the future society, there is the lack of research on pedagogies in nurturing learners' competencies for creativity in K–12 education (Cremin & Chappell, 2021).

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In this chapter, we explore how students' and teachers' *competencies for creativity*, that is, a dynamic set of knowledge, skills, and attitudes (Noweski et al., 2012), can be applied and developed through participation in invention projects. We present a case, an invention project called We Design & Make, in which the design thinking approach was used for teaching and learning competencies for creativity. In the project, eighth-grade students (ten girls aged 14–15 years) co-created e-textile products for local preschoolers according to their wishes and needs. The class met 12 times in weekly lessons facilitated by a craft teacher (later referred to as the teacher) and a researcher (the first author of the present chapter). The project engaged the students in a collaborative, open-ended design and making project which emphasized textile craft practices, new e-textile technology (programmable microcontroller), and development of a certain type of we-can-do attitude. In what follows, we first describe how the design thinking approach was used to structure and facilitate the creative process and practices in the project. Second, we explore the teacher's and researcher's roles and pedagogical practices in building a classroom culture for creativity and in supporting students' creative confidence. Finally, we provide an overview of the competencies for creativity applied and developed in the project and highlight how several types of competencies are involved in creative learning projects.

Learning Competencies for Creativity through Design Thinking

Design thinking is an approach to creative problem-solving in which several cognitive and affective processes, skills, and mindsets are applied (Goldman & Kabayadondo, 2016; Noweski et al., 2012). The process is dynamic in nature; processes of defining the challenges and generating solutions are simultaneous, and they require sustained, iterative efforts and various domain-specific and domain-general skills and competencies from students, as well as teachers (Sawyer, 2018). Both creative and critical thinking skills can be enhanced with methods and activities that encourage divergent (widening the solution space) and convergent thinking (narrowing the solution space) (Noweski et al., 2012; Razzouk & Shute, 2012).

Design thinking is characterized as a human-centered and collaborative process that generally involves five steps: empathize, define, ideate, prototype, and test. These steps support novices in the process, as they provide them orientation and stability (Noweski et al., 2012). However, learning through design thinking aims at not simply following the process steps but also developing a change of mindset through participation in an action-oriented collaborative problem-solving process (Goldman & Kabayadondo, 2016). Further, hands-on exploration with materials and tools has a fundamental role in many fields of designing, and embodied practices are a significant part of learning creative ways of working (Groth, 2016). In invention projects, students practice and develop several competencies for creativity in close collaboration with peers using a variety of materials, while they explore the context, generate solutions, prototype, receive feedback, evaluate, and refine their designs. Perseverance and coping with uncertainty and failure become necessary aspects of the iterative process (Goldman & Kabayadondo, 2016).

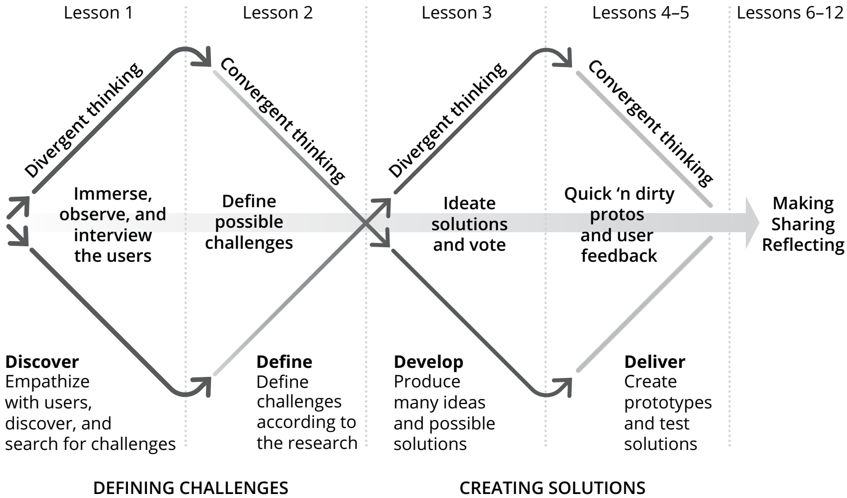

Figure 5.1 The creative process in the We Design & Make invention project.

Adapted from British Design Council, 2004.

Our case example, the We Design & Make project, followed the Double Diamond design model (British Design Council, 2004). The model is used in professional design, particularly human-centered design, and was slightly adapted to better suit the needs of a school project (Figure 5.1). The model consists of two "diamonds" (i.e., process phases): (1) defining the challenges, and (2) creating the solutions. Both phases involve divergent and convergent thinking, but in practice, the phases and modes of thinking are partly parallel. In our case example, the first phase or "diamond" focused on discovering the context of designing (divergent thinking) and defining the challenges to be solved during the invention process (convergent thinking). In the second phase, the aim was to develop many ideas and solutions (divergent thinking), and to deliver prototypes and to test the solutions (convergent thinking).

During the process, the Double Diamond model was shown to the students at the beginning of each lesson to visualize how the creative process was evolving, what steps needed to be taken, and why and how these steps were taken. This exercise helped the students to understand the iterative and lengthy nature of the process. In the following, we describe the use of the model as part of the pupils' co-design process and explain its theoretical pinnings using practical examples from the project.

Defining Challenges

The foundation of an educational invention project can be laid out in a design brief created before the project, which outlines the project's overall goals and constraints but does not predetermine the challenge for the students. Setting up the brief for students' demands constantly seeking to balance the openness and constraints of the task. Too much openness or a lack of constraints may lead to unrealistic ideas or recycling already familiar patterns, whereas tasks with balanced constraints help the students toward more advanced conceptions (Sawyer, 2018). In the We Design & Make invention project, the design brief was formulated as follows: "*Co-design and make an e-textile product for preschoolers according to their wishes and needs*." This brief emphasized collaboration between team members, consideration of the ideas, feelings, and needs of others, and creative and critical thinking about how technology could be used in the products. Yet, the brief was open-ended enough to leave space for students' explorations around the theme before defining the final challenge. Although educational invention projects do not encounter all the constraints of professional design projects, it is essential that students learn to understand the complexity of working with open-ended challenges, communicate initially vague ideas and challenges, and deal with the ambiguity of the process.

The invention process generally begins by exploring the design context to discover the challenge and discussing to build shared understanding of the design context and its dependencies. It is critical that the student team shares the same understanding of their challenge or problem (Noweski et al., 2012). The We Design & Make project began with the eighth-grade students discovering the context, which entailed empathizing, observing, and interacting with the preschoolers. At the beginning of the process, students recalled their own preschool experiences, wrote memories on Post-it notes, and made empathy maps. In this way, the students were more able to empathize with the preschoolers and to become attached to the We Design & Make project theme. The students also visited the local preschool to conduct observations and user research, using the interview forms and other supportive material prepared by the researcher. They were encouraged to observe the space with all the senses; they took photos and asked questions of the preschoolers and preschool teachers to understand the end users' needs and perspectives better.

Discovering the context helps students recognize and define the challenge they want to solve during the invention project. Defining the challenge and the related constraints takes place at the beginning of a project but continues in the later phases through iterative efforts. Students simultaneously elaborate the challenge at hand and create ideas for its solution, constantly alternating between divergent and convergent thinking. In our case example, the definition phase was strongly interrelated with the development phase. Based on the insights from the user research, observations at the preschool, and the preschool teacher's suggestions, the researcher put together various "how might we …" questions, such as "*How might we make dressing up more fun*?" By brainstorming solutions for the needs identified in the preschool, the students were also able to further define the challenges to work with. Many innovative ideas for challenges and solutions were on the table, and the students voted for their favorite ideas and started to work with the chosen idea.

Creating Solutions

The second main phase of the Double Diamond model focuses on creating solutions to the defined challenge, including developing ideas and solutions, and delivering prototypes to test those ideas (see Figure 5.1). The first stage emphasizes divergent thinking and seeing beyond the obvious, and when students generate and play with several ideas, they develop an understanding that there is more than one solution to a problem (Goldman & Kabayadondo, 2016). During the delivery stage, students evaluate ideas from several perspectives and develop appropriate solutions through prototyping, feedback, and other testing strategies. Invention projects involve reflective practices in all stages, and sociomateriality has an essential role in helping students to think and communicate their ideas verbally and non-verbally through sketches, prototypes, and other design artifacts (Mehto et al., 2020; see also Chapter 6 of this book).

In the We Design & Make project, different methods were offered to support the students' creative ideation and critical evaluation of ideas. In the ideation phase, inspirational visual materials, idea maps, and supportive questions about the use and the users of the preschool space were placed on the walls and tables of the craft classroom. Various solutions were discussed and enriched by the students, and the goal was to develop adequate plans for starting the prototyping and testing phase. In addition, the student teams were given large pieces of cardboard on which they could write ideas, draw models and shapes, and visualize proportions, measures, and materials so that they were visible to everyone. This practice supported communication and evaluative and reflective discussions among all the group members, the teacher, and the researcher.

In our case example, the process then continued with the delivery phase and prototyping. The ideas were further developed and materialized with rapidly constructed prototypes made from recycled cardboard and fabrics, felt, and other cheap and easy-to-manipulate materials, which were available in the craft classroom. In addition, to support idea development, prototyping helped the students visualize their ideas to others, as the preschoolers visited the school for presentations and a feedback session. According to the comments and feedback from the preschoolers and their teachers, the students elaborated their designs and continued toward the making phase.

Making the Inventions

The making phase in invention projects is strongly interrelated with the earlier stages, and many competencies for creativity are applied and developed during this phase. Students need to modify their ideas according to the constraints posed by materials, tools, and their skills to use them, as well as the restrictions of time and space at school. By making finished products, students also learn many craft skills, such as implementing an entire craft process; using materials, tools, and machinery; understanding craft concepts, signs, and symbols; and perceiving and anticipating risk factors related to work safety (Finnish National Agency of Education [FNAE], 2016). In addition, students can assess the novelty and usefulness of their own inventions and those of their peers and evaluate and acknowledge their limits. Moreover, students usually find the finished inventions to be meaningful and anticipate presenting them to wider audiences in the final stage of the invention project. This was also the case in our example project, to which fully functional needs-based products were brought to the enthusiastic preschoolers (see Bosch et al., 2022).

Creative Confidence and Classroom Culture for Creativity

Kelley and Kelley (2014) suggested that the focus of teaching for creativity should be helping people rediscover their creative confidence, that is, the ability to produce novel, unexplored ideas, and the courage to try them out without fear of failure or shame. People with creative confidence challenge the ways of doing, cope well with uncertainty, trust their intuition, and are curious and interested in others. Young children display many aspects of creative confidence but tend to lose it when they grow up participating in cultures and activities that are more focused on right answers than creative ideas (Kelley & Kelley, 2014).

Creative confidence is reciprocal to a student's creative agency, and their development is strongly interrelated. Student agency is regarded as an essential element in future-oriented learning, and it is conceptualized as a will, ability, and opportunity to act upon and positively influence and transform activities and circumstances in their own lives and the world around them (Rajala et al., 2016). Following Bandura (2001), Karwowski and Beghetto (2019) stressed the importance of people's creative self-beliefs reflecting the degree of confidence that they feel in their ability to act or think creatively. However, they have further suggested that to act creatively, mere creative confidence is not enough; rather, people also need to see personal value in acting creatively.

As students learn and exercise their competencies for creativity in social contexts at school, both personal agency and co-agency are crucial (Clapp, 2017). Co-agency develops in an interactive, mutually supportive, enriching learning community, which supports social and emotional skills, such as empathy (Clapp et al., 2016). Research has shown that creative making with and for a community can be an important way for students to build these identities and abilities, and thus add value to the process (Clapp et al., 2016).

Teachers' Role in Nurturing the Creative Confidence

Many researchers have emphasized the teacher's role in the creative classroom, where students need many social and emotional skills, such as flexibility and perseverance, to cope with unfamiliar and uncertain design processes (e.g., Beghetto & Kaufman, 2014; Davies et al., 2012). Recent research has suggested that social and emotional support may be more important for teaching for creativity than other forms of encouragement (Gajda et al., 2017). According to recent review studies of creative pedagogies and of nurturing creativity in classrooms (Cremin & Chappell, 2021; Davies et al., 2012; Richardson & Mishra, 2018; Sawyer, 2017), the teacher should fulfill the following role:

- Act as a facilitator, guide, and co-learner
- Guide and support students to actively navigate the open-ended, uncertain creative process, and balance between structure and freedom
- Scaffold students' work with open-ended questions by offering several perspectives, modeling, and simplifying

- Demonstrate sensitivity to learners' individual needs and diverse perspectives and stand back when needed to support students' ownership of learning
- Create an open, joyful, caring atmosphere that encourages free ideation, supports risk-taking, and accepts and values new, original ideas
- Base relationships with students on trust, equality, and collaboration
- Organize collaboration with external partners to increase the meaningfulness of learning and to support students' social identity and sense of belonging
- Organize physical spaces, materials, and other resources to support students' free choice, play, and flexibility

Although the teacher's role in supporting students' competencies for creativity, including creative confidence, has been recognized as essential, and the core curricula emphasize creativity in an increasing number of countries, teachers are given little support to turn policy into practice and include practices that nurture competencies for creativity in their classrooms (Patston et al., 2021). Therefore, next we provide a narrative description of how the teacher and the researcher in the We Design & Make project controlled the learning environment dimensions that directly affected the development of classroom culture for creativity and thus the students' competencies for creativity (see Richardson & Mishra, 2018).

Classroom Culture for Creativity in the We Design & Make Project

In the We Design & Make project, various practices were used throughout the process to develop classroom culture for creativity. The teacher and the researcher worked side by side, and both were responsible for addressing the curriculum goals. Together, they built the constraints into the process, organized the time and material resources, and formulated the design brief to collaborate with the preschool. They worked as facilitators in the design and making process, offered a range of ideation methods for ideation and provided support for regulating the process. The teacher and the researcher also acted as peers for the eighth-grade students in figuring out the programming and sewing e-textile components with conductive thread.

The teacher and the researcher sought to create a safe, caring classroom culture suitable for creative work in which the eighth-grade students could practice and develop their competencies for creativity. To do so, they used multimodal methods, such as pedagogical talk and practices (e.g., explaining), dialogic teaching/moves (e.g., questioning, suggesting), embodied support (e.g., modeling), and emotional support (e.g., encouraging). The teacher and the researcher emphasized explanation, collaboration, experiential and experimental attitudes, process orientation, and multiplicity. They also built connections outside the classroom and paid attention to the students' experiences and own explorations.

During the process, the teacher and the researcher explained the overall project plan, learning goals, assessment practices, and reasons behind each design task for the eighth-grade students, so everyone had an idea of what would happen in the coming three months and why. Creative confidence and we-can-do attitude were supported when the researcher emphasized that there was no one way to do things. The students were supported to envision new ways of doing things, take risks, and make mistakes.

RESEARCHER: Let's be brave in exploring. You are allowed to make mistakes because you can learn from them. Without mistakes, you cannot really learn much. And then let's try to think outside the box—not how things are supposed to be or that there is only one way to do things because that is not true.

The teacher's statement in the first lesson that "We don't know how these technologies function, but let's try to solve it together" made the teacher, the researcher, and students equal learners in the situation. The teacher and the researcher had a low authority position, and this offered the students autonomy within the open-ended challenges, as well as freedom to use the material resources and tools as they wanted. As one student explained, "We were allowed to work as we wanted to. The teachers were supportive and tried to help if something went wrong."

The teacher and the researcher continuously walked around the classroom, made themselves available, and offered the students empathic support and encouragement. They observed which students and groups needed help, stayed close to students by sitting next to them, and offered help by suggesting, re-voicing, and simplifying. The teacher and the researcher offered embodied support with materials, tools, and programming.

RESEARCHER: You know, you learn these things [refers to the microcontroller] much faster than I or Mia [the teacher].

TEACHER: It's so great.

RESEARCHER: Which is great. Marvelous.

TEACHER: You can teach us.

The process strongly emphasized collaboration and peer support. As a student on one team learned to program certain functions, the researcher shared this knowledge with all the class and invited other students to come over to learn. The students also had to collaborate with students with whom they were not familiar. The teacher aimed to mix established groups of friends and encouraged the students to work on diverse teams. A student reflected, "I learned to collaborate with people other than just my friends. It is useful anywhere, for example, here at school, at work." Moreover, the students were given predefined team roles (e.g., leader, documenter, programmer), but the roles were not necessary as the students offered peer support within and between the teams. As one student wrote down in a post-questionnaire:

SOFIA: My role was to be a leader, but I think the roles were unnecessary as we did everything together anyway. I always helped others on my team and contributed ideas, and the team also helped me. Our team shared work well, and we all designed and made the product together, and no one did just one thing.

The design brief and the methods used had a role in motivating and engaging the students in the creative process. The process included designing for a specific group of people, so empathy, perspective-taking, and meaningfulness were built into the design brief and the process. Preschool is obligatory in Finland, so every student had experienced it, making it easier to step into preschoolers' lives and build relationships with preschoolers. Working with real-world challenges motivated the students, and students' engagement became visible when they discussed their own preschool experiences. As one student explained in the post-questionnaire, "I learned to observe various challenges and to think how these could be solved."

The process involved challenges and failures that required perseverance. The teacher and the researcher praised the students' work, encouraged students to ask peers to help, and suggested that students try new ways of solving challenges. The parents' help was sought; for example, one student invited her father to help with programming on the school's open day. Humor and laughter were important in building an easy-going, encouraging classroom environment and sometimes served as a useful tool to overcome a difficult moment.

From the teacher's point of view, the most significant challenge was changing the mindset of a teacher to a facilitator, sharing authority, and letting students try and fail on their own. From the students' point of view, the most inspiring and important aspects of the project were the collaboration with the preschool children and the sense of purpose in making functional things for those children. Students also said that planning their own work and collaborating with their own teams were important aspects of the project. The students referred to the importance of helping each other and trying out new ideas with an open mind. Students used technology creatively, rather than following step-by-step instructions.

VIOLA: I felt that I could have a say in the way the process progressed, and all ideas from our team members were happily received. Our team had an encouraging atmosphere, and the teachers knew how to support and help when needed. The freedom to explore was obvious in our work. For example, we did diverse designs for the appearance of the product.

This experimental project was challenging but rewarding in many ways. As in all open-ended, undefined design processes, the beginning is generally messy and uncertain, and it might feel difficult to get down to work. Both the students, the teacher, and the researcher had to overcome elements of uncertainty, roll up their sleeves, and start working. They worked together in a community of practice in which every member was invited to join, interact, and co-construct.

SENJA: Being a designer was difficult at times as we had to design everything ourselves, for example, how the product would be durable and how to even make the product. It was also a lot of fun to let your creativity run free, but, as I said, it was difficult at times.

Nevertheless, we want to point out that the project was organized in Finland with its low-hierarchical school culture, where relaxed teacher–student relationships might have supported the co-construction of ideas and artifacts. Although the teacher and the researcher tried to sustain an easy-going, flexible design process, the time limits and school structure posed challenges to the process. Several classes had to be rescheduled due to various school happenings or other events, such as a climate strike. Although the Finnish curriculum emphasizes the importance of such open-ended multi-disciplinary projects that develop transformative competencies in all school subjects, it is challenging to adapt them with the rigorous schedules of formal education.

Creating to Learn

In this chapter, we have described the nature of creative processes and practices and illustrated how several competencies were entangled in a creativity-supportive invention project. Our aim was to explore how the students', the teacher's, and the researcher's competencies for creativity can be applied and developed in invention projects. In this concluding section, we provide an overview of these competencies with three broad but overlapping themes (Figure 5.2), following loosely the three innovation skill categories by Vincent-Lancrin et al. (2019). The overview emphasizes that design thinking processes involve many cognitive, affective, and embodied capabilities and practices (Goldman & Kabayadondo, 2016), that are all important building blocks when learning competencies for creativity.

The students applied and developed *creative and critical thinking* as they discovered the design context and its constraints and defined the design challenges through inquiry. They brainstormed various ideas, generated and evaluated several solutions, and continuously reflected on their ideas, solutions, and the process. The Double Diamond model provided structure for the iterative, nonlinear, and sometimes messy design thinking process, supporting students in shifting between divergent and convergent modes of thinking. One of the outcomes of going through such creative processes can include the new mindset that enables students to approach problems in more experiential ways, learn from failures, and be more confident in their ability to create (Goldman & Kabayadondo, 2016).

During the project, the students practiced several *social and emotional skills*, such as empathy and perspective-taking. Working in groups demanded ongoing collaboration and communication, and the students peer-supported and encouraged each other in many moments. Both individuals and the group had to regulate their work to be able to complete the products within the given constraints, although some students with predefined leadership roles paid the most attention to co-regulating the process (see Chapter 4 of this book). The openness of the design brief offered many uncertain paths to follow during the process, which demanded flexibility, but the students exercised a responsible and perseverant attitude to finish the products. Total frustration was close many times, but confidence could grow as challenges were resolved with the help of teachers, peers, and parents, and the students expressed pride in the results.

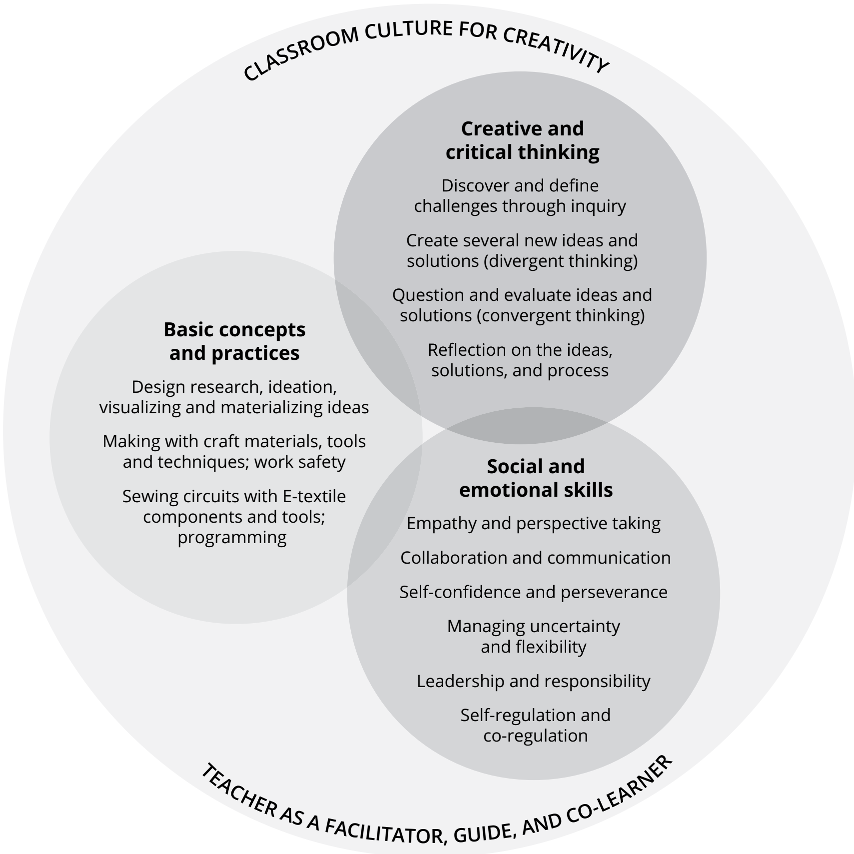

Figure 5.2 Competencies for creativity applied and developed in the We Design & Make invention project.

Adapted from Vincent-Lancrin et al., 2019.

Besides domain-general creative and critical thinking and socio-emotional skills, some more domain-specific *basic concepts and practices* were also introduced to students. These were related to design, craft, engineering, and programming. Design concepts and practices were used as the students iteratively developed their shared ideas for the e-textile products by using various ideation methods, and by visualizing and materializing their ideas through sketching, drawing, model making, and prototyping. Familiar craft concepts and practices were reinforced, and new ones learned through the use of textile craft materials, tools, and techniques, for example, in patternmaking and sewing with conductive thread. E-textile technology itself introduced many new engineering and programming concepts and practices into the process, while the students became familiar with circuitry, e-textile components, and tools, as well as programming and troubleshooting.

The project engaged the students in a collaborative, open-ended design and making project, which emphasized human-centered design, new e-textile technology, and development of a certain type of we-can-do attitude. Moreover, we want to highlight that many of the skills and competencies for creativity concerned both the students, the teacher, and the researcher. As co-learners, the teacher and the researcher developed their own skill sets and creative confidence while guiding this uncertain, multidimensional project. New digital technology introduced in the invention project caused significant demands and challenges in the process, but in the post-questionnaires, many students said that their most important learning outcomes were related to new digital technology and its wide range of uses.

Invention projects can focus on developing many competencies for creativity if they are carefully implemented in the process. Competency development is both a learning process and a learning goal, and it requires teachers to have extensive knowledge of creative learning processes and creative learning environments. For example, it is important for teachers to understand how both individual and social factors play roles in creative processes (Beghetto & Kaufman, 2014) and that students need various means of support to unleash their creative capabilities. Moreover, as suggested by Sawyer (2021), we should emphasize creativity as an iterative process, a journey, more than an outcome of the process. Instead of educating kids "how to be creative," we should emphasize "how to participate in creativity" (Clapp, 2017).

We believe that in our project, designing for a community (preschoolers) offered the students an opportunity to take part in meaningful creative work and build their creative confidence to act as designers and makers, creating minor changes in the world around them (see Clapp, 2017; Clapp et al., 2016). The students, as well as the teachers, learned to create, and simultaneously, they created to learn.

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6 Materiality in Invention Pedagogy

Varpu Mehto and Kaiju Kangas

Introduction

Making practices are central to invention pedagogy, in which abstract ideas are transformed into tangible forms and functional prototypes. Materiality transforms the process and requires the students and teachers to be ready to alter their plans and adapt to surprises as they are learning to work with the materials, technologies, and schedules at hand. In this chapter, we discuss invention pedagogy from the point of view of materiality. We consider how active and dynamic matter alters practices and how this perspective enriches our understanding of the aims of inventive learning. Theoretically, this chapter builds on the traditions of Nordic research on craft education and the concept of relational materialism. Further, our thinking is positioned with the insights from the Finnish educational system and the school subject *crafts*.

We perceive the process of making as an entanglement of maker and matter, where the human participants think with the matter and learn from it (Ingold, 2013). Materials are not considered merely as resources; instead, material transformations and related bodily movements emerge from dialogical negotiations between maker and matter (Aktaş & Mäkelä, 2019). With cultivating their craft practice, the maker develops their knowledge of materials and techniques, as well as people and culture reciprocally (Lahti & Fernström, 2021). Materiality embeds processes of learning and knowing into the tangible world (Mehto et al., 2020). Making provides an opportunity to reflect on one's position in the world and to sensitize to the dependencies and responsibilities with the environment (Groth, 2020).

Within invention pedagogy, we have illustrated how prototyping practice acts as an aid for thinking, as a social mediator, and provides inspiring constraints through materiality (Yrjönsuuri et al., 2019). Further, we have analyzed how materiality constrains and enables collaboration, for example by hindering opportunities for participation or providing tangible access to common ideas (Mehto et al., 2020). Focus on the epistemic roles of materiality emphasized the importance of thinking with materials in making (Mehto et al., 2020). During these studies, our perspective has gradually shifted from how students use materials to perceiving relationalities of materiality. Such a perspective aims to enrich the prevailing human-centered perspective by shedding light on the edges of the intentional learning process and the obscure, wide-reaching connections of matter.

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To help us understand how matter affects situations, we turn to theories that flatten the ontological hierarchies between humans and non-humans (e.g., Bennett, 2010). Perceiving humans as parts of the world unravels dichotomies, such as mind/body or nature/culture, highlighting the interdependency of humans and environments (Latour, 2005). Therefore, we emphasize the indeterminacy prompted by materiality in making. Further, the perspective of sociomaterial entanglements is steered toward seeking more-than-human collaborations that are crucial for living on a damaged planet (Haraway, 2016; Tsing, 2015). Thus, we highlight making as sensitizing to materiality to seek collaborations with the material world. The call for re-evaluating the position and responsibilities of humans also includes knowledge practices and pedagogies (Braidotti, 2019), setting demands for futures of education (Common Worlds Research Collective, 2020). In this chapter, we discuss the potential that making could have for cultivating learning with the world. Our approach is practical, as we consider how ontological ideas of relational materialism could relate to everyday life in school.

In addition to these onto-epistemological stances, our thinking is based on the practices of Finnish education, in which material making is present especially in the school subject crafts. Materials play an essential role in the tasks, objectives, content, and learning environments of crafts (Pöllänen, 2020; Porko-Hudd et al., 2018), and they can be used for their expressive qualities, as resources that are tested and analyzed for creating design solutions, or as constraints that enable or hinder technological activities (Finnish National Agency of Education [FNAE], 2016). Materiality requires appropriate learning environments for crafting, where versatile equipment, machines, and tools enable adopting a responsible attitude toward working (FNAE, 2016; Jaatinen & Lindfors, 2019). Further, Nordic research on craft and sloyd (a school subject equivalent to crafts) education emphasizes materiality. Working with materials develops students' material knowledge that contributes to advancement in their designing (Härkki et al., 2016); therefore, students should be encouraged to work with materials to experience both their potential and limitations (Illum & Johansson, 2012). Communication and meaning-making in crafts take place through several connected levels of interaction: between humans; between humans, tools, materials, and the surrounding space; and between mind and body (Kangas et al., 2013a). Teaching and instruction in crafts rely on the multimodality of interaction (Ekström, 2012; Koskinen et al., 2015), providing students with multifaceted opportunities to generate and communicate their ideas and knowledge (Kangas et al., 2013b). Materiality of crafts can also promote awareness of sustainability as well as critical and ecological stances toward consumption (Väänänen et al., 2018).

To bridge the practical and theoretical takes on materiality, we discuss the theoretical approaches with an invention project in which students aged 14–15 designed and built smart products in small teams. The aim of the design task was to orient students toward the problems in their everyday lives and the artifacts involved. Initial ideas were first materialized as mock-ups and then as functioning prototypes. Two researchers were present in the classroom throughout the process, making field notes, videorecording the teams' design activities, and conducting short interviews with the teachers and the students. This chapter focuses on two example vignettes that are written based on video recordings and complemented by our field notes and student interviews. The vignettes consider the making of two inventions: a smart piggy bank, which counts the money inserted and announces when a target sum is reached, and a smart shirt with LED lights that turn on in the dark.

In this chapter, we first discuss material agency, that is, how matter contributes to creating the unpredictable nature of the invention project, and second, how materiality allows acting amidst this complexity by embedding the creative process into local materialities. The approach is inspired by the methodology of thinking with theory (Jackson & Mazzei, 2012). Next, we illustrate the concept of assemblage with a vignette about a striped fabric. Then, we discuss potentials for acting with uncertainty with a vignette about an abrasive belt grinder. We conclude with implications for research and practice.

Material Agency

Matter matters: it affects situations. However, claiming that matter is agentic can be problematic, especially in the education field, where agency has traditionally been a human ability with connotations of intentionality and power. Therefore, discussing the agency of matter requires a different perspective. In this chapter, we reframe the concept of agency, not as an attribute of someone or something, but as emerging in encounters (Latour, 2005). Instead of focusing on what someone or something does, the interest turns to relations—how entities transform each other. Thus, flattening the ontological hierarchy between humans and non-humans shifts the focus from individual actors toward loose, messy gatherings. We follow the example of thinkers such as Mol (2002) and Tsing (2015) and choose the term *assemblage* to illustrate this open, fluid, dynamic, entangled nature of reality. Next, we describe how the theoretical concept of assemblage changes our thinking about the example vignette about a striped fabric that participated in the materialization of the idea about a smart shirt (Jackson & Mazzei, 2012).

> Team Smart Shirt collaboratively designed a shirt for each team member. They chose fabrics for each team member from a large plastic box filled with leftover fabrics from other projects. Alice (pseudonym) spotted a black-and-white striped fabric. It was thin, almost see-through. Alice was delighted. She stated that she did not currently have a striped shirt in her wardrobe.
>
> Pinning the plastic sewing pattern onto the striped fabric turned out to be difficult. The fabric curled, crumpled, and slid away. Other team members were already sewing. Alice was distressed and said, "This will take the whole session, but okay. It's because my fabric is like this; it, like, moves and…well, sucks. More rigid [fabric] would be easier". The teacher came to help. She set the fabric on the table and, with slow and careful movements, smoothed out the wrinkles with her palm, emphasizing that the most important thing to have with this fabric was patience. When Alice finally began sewing, she noticed that the stripes of two pieces did not meet unless she paid special attention when aligning the pieces. Careful alignment made the hem straight,

also. She told her team members that starting the project made her anxious, but now she liked crafts and sewing. When the shirt was sewn, Alice wore it and danced around a bit.

Sewing the shirts took most of the design sessions; therefore, the team decided to pare down smart functionalities and focus on making the LED lights light up with the push of a button instead of using sensors that reacted to the environment. However, in Alice's case, the e-textile equipment, LED lights, microcontroller, thick conductive thread, and battery pack were too heavy and clunky for her lightweight fabric. The teacher confirmed that her shirt would not be able to carry such heavy components; even the needle required for the conductive thread would make holes big enough to result in the fabric's unraveling. The team decided to attach the smart functionalities to a separate, sturdier piece of fabric, which could be attached and detached from the shirt.

In the vignette, matter was intentionally given space to affect (Braidotti, 2019). The making process was not predefined but instead adapted to the properties of the materials. The striped fabric was not intended to be included in this particular project, but it was part of the rich material resources of the classroom that allowed multiple opportunities for learning to emerge (Keune & Peppler, 2019). So, the properties of the striped fabric transformed the course and rhythm of the invention process. For example, the problems sparked by the thinness of the fabric required slow, careful work, i.e., time. This affected what else the team could do during their limited time, and thus restricted other features of the initial planned invention. The thinness of the fabric caused trouble only when combined with the limited resource of time, relatively thick pins, plastic patterns, and the student's lack of experience with sewing such fabric. This transformation emerged through encounters. The invention process could not be reduced merely to the rational reasoning of the students, but instead, the process emerged from the more-than-human assemblage.

In addition to transforming the invention process, the striped fabric itself was constantly changing and transformed during encounters (Latour, 2005). Its stripes were a fashionable element that would complement Alice's wardrobe at one moment, and at the next, a structural element complicating the sewing process by making the pattern alignment visible. The thin softness of the fabric, which made the finished garment light and flowing, was at first alluring, making it stand out amidst other fabrics in the box. However, during sewing, those attractive qualities became problematic. These examples illustrate how turning one's gaze from singular stable properties to fluid assemblages allows for acknowledging the agency of matter.

The striped fabric was not only part of an assemblage but an assemblage itself. It consisted of matters and their properties, such as color, texture, and physical structure. These assemblages within assemblages relate to each other in the classroom and beyond. When reflecting on the relations among assemblages, a useful comparison is with the metaphor of rhizomes (Deleuze & Guattari, 1987). Unlike roots, rhizomes are not hierarchical and have no center, beginning, or ending. The striped fabric also has these wide-reaching "rhizomes". Research centralizing materiality could follow the entanglements of the fabric manufacturing or, further, the chemicals used for dying the fabric and how they affect the environment. This kind of research would link local and global scales and provide an understanding of the politics of specific material practices (Gallagher, 2019). Thus, turning one's gaze to agentic matter explicitly emphasizes how the invention process is rooted beyond the classroom.

Amidst these endless connections, students, teachers, and researchers make decisions on which "rhizomes" to focus on. These decisions are also affected by non-human participants (Bennett, 2010), such as curriculum, sociomaterial practices, or material resources. For example, the stripes of the fabric prompted a conversation about consumer culture and fashion when students were selecting fabrics. These aspects were not deliberately addressed later; however, they remained present in the matter and artifacts (Latour, 2005). Not all choices to address certain connections were verbal; connections were also met with actions. For example, the teacher had organized the classroom in a way that allowed storage and re-use of leftover materials, such as the striped fabric. This practice considered the topic of waste and the problematic relationship with maker education and the use of matter. Similarly, the focus on proficient sewing brought up issues relating to quality, usability, and the life cycle of artifacts. These issues were not solved or rationalized but handled in a tangible manner.

Perhaps the most practical consequence of acknowledging more-than-human agency is the expansion of responsibility. When considering matter as more than a mere resource for inventing, we must acknowledge how pedagogical choices or making activities affect humans and more-than-humans not directly present (Bodén et al., 2019). However, constantly changing and endlessly expanding assemblages make it impossible to determine outcomes. Therefore, responsibility requires staying with the trouble and responding with action or by giving space and listening (Haraway, 2016). Next, we discuss how making practices might enable learning that cannot rely on definite conclusions.

Acting with Uncertainty

Attuning to rhizomatic relationships, open-ended questions, and thus the relational and unpredictable nature of the invention project might feel overwhelming. Educators, students, makers, and researchers must act amidst uncertainty when hierarchical categorization falls short. Braidotti (2019) has emphasized that embracing uncertainty does not mean falling into relativism, but instead requires acknowledging the embodied and embedded nature of knowing. To learn with the world, instead of mastering it from the above, Tsing (2015) advocates for cultivating "arts of noticing", becoming attentive to the vibrant more-than-human details (Bennett, 2010), that are sometimes deemed as a passive backdrop. The attentiveness should aim not only to understand and explain the world but also to generate something new, being conscious of the material consequences of knowledge practices (Haraway, 2016). Next, we reflect on the encounter of an abrasive belt grinder and two students, from the perspective of acting with uncertainty.

Team Magic Bunny ideated a smart piggy bank, shaped like a magician's top hat. When they started to search with the teacher for materials, they came across a drawer filled with metal clippings from another project. The teacher showed them a metal sheet and asked if that could work; metal would be lighter and easier to handle than wood that they had initially planned on using. The students agreed and decided to adjust other parts of the piggy bank to the size of the metal sheet so that they would not have to cut it.

The teacher instructed the students to make a cylinder by spot welding the edges of the metal sheet together. After welding, the edges of the cylinder were still sharp and had to be smoothed. The teacher recommended using an abrasive belt grinder, which was located in a separate small room with transparent walls. Two students, Haley and Lily (pseudonyms) were tasked with using the machine. As the teacher demonstrated how to use it, a loud noise filled the room and sparks flew. Haley and Lily jumped back and screamed, nervously said they would not do that. The teacher gave Haley and Lily protective gloves and safety goggles and reassured them, "Those are just sparks. They won't hurt you".

In the hallway, Haley put on the gloves and goggles. Lily laughed and took out her smartphone; Haley posed for some pictures. They giggled and danced around, but when Haley stepped into the room with the belt grinder, her movements slowed. The teacher took a step back and let Haley do the work by herself. Her gaze was focused on the edge of the metal while she carefully rotated the cylinder. Lily recorded the whole process with her smartphone. Afterward, Lily and Haley ran to excitedly tell their classmates what they did.

The materiality of making requires attention to detail. While working with the powerful and cacophonous belt grinder, it was necessary to slow down to notice the movement of sparks and metal. Hayley's embodied activities adapted to the rhythm of the matter and tools (Aktaş & Mäkelä, 2019; Groth, 2020). Further, the making process required deliberation of functionality of the artifact in everyday life. Considering the cultural aspects of the piggy bank was not enough, but the students also had to focus on materiality, such as the sharpness of the edges of the metal sheet. However ambitious or imaginative the initial idea was, the students had to grapple with the mundane details during making (Haraway, 2016) (Figure 6.1).

Making rooted the abstract and somewhat universal idea into local materialities. It was no longer a common piggy bank: it was a piggy bank made with materials available in the classroom using the combined skills of the students and teacher within the time constraints of the school day. The metal sheet, excess material from an earlier project, transformed not only the structure of the artifact but also which craft practices were learned during the project. Inventing was explicitly situational in that aim was not to discover general facts; focus was on finding solutions that would work in the specific time and place. Materiality made visible the embeddedness of inventing (Braidotti, 2019), providing an opportunity to experience learning as a balancing act. When adapting design aspirations to local constraints, students were balancing creativity with practicality.

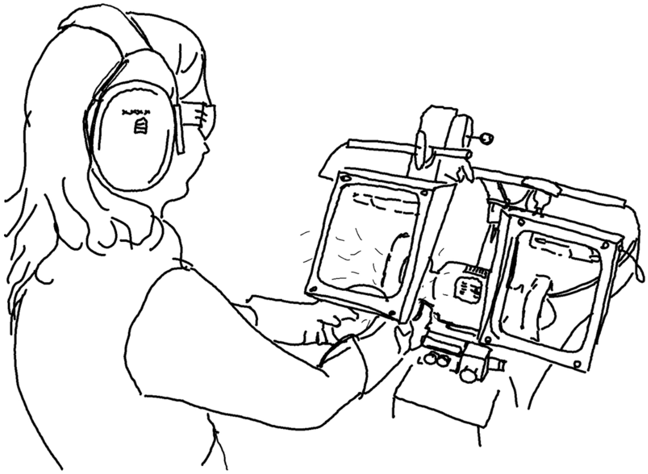

Figure 6.1 Haley using the abrasive belt grinder.

While constraining action, the unscripted material making also allowed students to focus on more than just predefined learning tasks—there was plenty of space for non-task-related play and material experimentation. In the vignette, the invention process was simultaneously a learning task and play. These two seemingly contradictory making practices were able to co-exist (Mol, 2002). On one hand, making scaffolded complexity with situated activities, and on the other hand, allowed co-existence of multiple practices. Even though the students were obliged to act within the institutional setting of the school and from the position of students, they were also able to transform the process according to their own interests.

Conclusions

We have illustrated with examples how matter can be agentic and how it can aid action amidst uncertainty. Open-ended tasks and unscripted making sessions provide space for matter to affect. Matter transforms a process through relations; therefore, its effects are not prefixed. Also, matter itself changes throughout processes depending on what and whom it encounters. These connections of matter reach beyond the boundaries of the classroom; societal, ethical, and ecological questions are present, whether addressed deliberately or not. While matter creates unpredictability and forms endless rhizomatic connections, it can also aid in acting amidst the uncertainty. Materiality insists on careful deliberation and attentiveness to details. Adapting the process to material constraints makes the embedded nature of inventing tangible, highlighting learning as a balancing act.

Considering the perspective of agentic matter can deepen the understanding of complex practices. First, sensitizing oneself to matter may help shed light on practices or technologies whose roles are taken for granted, thus revealing actors hiding in mundanity (Bodén et al., 2019). Attentiveness to material details can therefore reveal situations and places that call for a response (Haraway, 2016). This responsibility reaches beyond humans to all those we share the planet with (Tsing, 2015).

Methodologically, the more-than-human perspective requires the readiness to follow even the most surprising trains of thought, the ability to shift one's focus to relations instead of singular actors, and the use of firmly situated perspectives instead of universal claims (Bodén et al., 2019). Finding ways to attune to the more-than-human requires embracing all fields of knowledge (Tsing, 2015). Educational research could offer a functional platform for bringing together humanism and sciences since we already have plenty of experience in coping with a broad and somewhat incoherent discipline that is nevertheless based on practice.

Second, acknowledging agentic matter can widen our understanding of what kind of learning matters. Philosophers such as Braidotti (2019) and educational researchers, such as Common Worlds Research Collective (2020) have argued that education and pedagogies should learn to place students and teachers in, and have them be parts of the world, not outside observers. However, what this more-than-human learning could be in practices of formal education is still an under-researched area. In this chapter, we illustrated how material-making practices enable and require learning beyond traditional academic skills, such as situated and embodied knowledge, attentiveness to mundane details, and generative action. As these skills are crucial for cultivating "the arts of noticing" (Tsing, 2015), the potential of craft practices should be further explored in various educational settings.

In practice, taking the more-than-human perspective turns one's attention to the fluidity of matter. In other words, when planning an invention project, it is not fruitful to attempt to fully predetermine the effects of materials. Providing rich material resources and an adaptable learning environment can enhance opportunities for learning on students' own terms (Keune & Peppler, 2019). These opportunities depend not only on the properties of the material, but also on the uncertain relations; for example, on the skills (or lack thereof) of the user, time resources, and/or available tools. Therefore, cultivating students' craft skills can also aid the process of ideating and making. However, learning with matter requires time and opportunities to adjust to the tempo of work, emphasizing the importance of allocating enough time for making.

Matter carries with it connections to political, environmental, and societal issues. Even non-verbal practices can address wide-reaching connections. Therefore, to grapple with such complicated issues ethically, careful attention needs to be paid to the design task, material resources, and classroom practices. Involving matter into pedagogical practices introduces global connections into the classroom thus providing natural opportunities for addressing wide-reaching issues. Considering questions of responsibility through making shifts the focus from rationalizing an external abstract phenomenon to mundane details at hand. Therefore, making promotes sensitizing to matter and affirmatively generating something new. Instead of aiming at mastering the world, this kind of situated knowledge emphasizes living with it.

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7 Toward Sustainable Lifestyle by Means of Invention

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Sustainability Education and Circular Economy

Sustainability refers to a system's capacity to maintain its own vitality, and sustainable actions are those that in principle can be continued indefinitely. The planet cannot sustainably support humankind's current lifestyle and rates of consumption. A range of human-induced threats, such as increased CO_2 emissions, may influence climate change and negatively impact the preconditions of life, by reducing the diversity of ecosystems and species, by escalating extreme weather phenomena, and by increasing uninhabitable areas and mass migrations. In addition, human activities affect the unequal distribution of resources as well as poverty and hunger, access to clean water and sanitation, and a wide range of additional conflicts. These challenges can be linked to the dimensions of sustainability: ecological, social, cultural, and economic (Pop et al., 2019). Ecological sustainability is related to the reasonable use of natural resources, the conservation of ecosystems and biodiversity, and the reduction of waste and pollution (Gast et al., 2017). The social dimension of sustainability can be understood as promoting equity and ensuring protection in situations of vulnerability; it also includes built environments that are healthy and promote a sense of community (Eizenberg & Jabareen, 2017). The cultural dimension of sustainability encompasses the principles of cultural heritage conservation and ensuring access to cultural resources. In addition, it incorporates the idea that development can be implemented in a way that respects cultural capital and social values (Pop et al., 2019). Economic sustainability refers to the reasonable use of non-renewable natural resources and the impact of products on the planet, including the price paid by the consumer and the profits for the producer (Chouinard et al., 2011). The use efficiency of non-renewable raw materials can be increased by circulating these materials for as long as possible.

It is important to understand the systemic structures of the different sustainability dimensions to employ strategic competence to promote change. In sustainability education, the dimensions should be regarded as being interrelated rather than separate constructs, as they clearly influence one another. For example, projects addressing ecological sustainability also have an economic impact; likewise, social sustainability projects have an ecological impact. Sustainability dimensions appear in the UNESCO Agenda 2030 (UNESCO, 2021), which acts as a guide for national education policy documents, albeit with varying emphases. The inclusion

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of a sustainability focus in a curriculum requires an interdisciplinary approach to teaching and should include the systemic nature of the sustainability concept as a starting point (Lozano et al., 2021). Furthermore, to strengthen the role of sustainability in the curriculum, the summary by Lozano et al. (2021) called for pedagogical innovations that provide interactive, experiential, transformative, and real-world learning. Thus, the multidisciplinary module introduced in this chapter emphasizes interaction, innovation, and real-world connection. These fundamental aspects of the module are most closely aligned with the economic dimension of sustainability; however, depending on the design, other dimensions can also be present.

A circular economy uses a sustainable approach to consumption that re-thinks the use of resources and the ownership of objects. Unsustainable consumption of raw materials is a threat to the planet and its ecosystems; therefore, the core concept of a circular economy is to minimize waste by extending the circulation of raw materials. The primary objective is to ensure that 'the product value chain and life cycle retain[s] the highest possible value and quality [for] as long as possible and is also as energy efficient as it can be' (Korhonen et al., 2018: 38). However, using recycled materials in production and manufacturing is beyond the scope of decision-making in everyday life. Instead, an ordinary person can contribute to a circular economy by re-thinking their ownership and use of objects and equipment. To support this shift in focus, novel services of lending, sharing, and renting need to be developed.

To operationalize this process in schools, Juuti and Gericke (2022) have defined four circular economy transitions that manifest this change: (1) from disposable to fixable (lengthening the lifespan of a product by improving its quality and by paying particular attention to reparability), (2) from waste to raw material (during the product's lifetime, technical and biomaterial cycles are separated), (3) from product to service (when a commodity is available as a service, there is no need for universal individualized ownership), and (4) from owning to sharing (people share material resources via online platforms). The aim of this project was to identify which circular economy transitions the students utilized in their inventions and designs.

In this chapter, we introduce a multidisciplinary module for primary schools that is situated within the context of sustainability education and employs an invention pedagogy approach. During the project, sixth-grade students (aged 11–12 years) were familiarized with the concept of using a circular economy as a way to support a sustainable future. By using digital tools, the students collaboratively designed prototypes of circular economy mobile applications. The primary aims were to identify the types of inventions the students designed and developed and reveal what understandings of sustainability were expressed in their inventions. In addition, we examined the influencing mechanisms the students utilized during the project.

The specific research questions were as follows:

1 What sustainability dimensions and circular economy transitions do the inventions embody?
2 Which means of influence are employed in the inventions?

Sustainability Competencies

Targeted skills and knowledge are required to address the various sustainability dimensions. More specifically, these abilities can provide people with the tools to manage anxiety and frustration that is caused by environmental issues. A person's well-being may be enhanced by knowing that their actions can have a positive impact. This is especially important when examining sustainability issues with children and adolescents, as they may experience acute feelings of future uncertainty.

Lozano et al. (2021) created a summary of the sustainability competencies as a way to describe the desired sustainability-related educational outcomes. Competence-based education, instead of surface-level repetitive learning, is needed to address complex problems. After reviewing the existing literature, Lozano et al. (2021) suggested a structure of 12 sustainability competencies, while Wiek et al. (2011a) suggested a construct of five competencies. Both studies identified the following sustainability competencies as essential: systems thinking, futures thinking, strategic thinking, interpersonal skills, and the ability to employ a perspective that incorporates ethics and norms. Critical thinking and communication skills are also regarded as crucial aspects. However, while Wiek et al. (2011a) regarded critical thinking and communication as foundational skills, Lozano et al. (2021) included them as key sustainability competencies. In addition, Lozano et al. (2021) emphasized the interdisciplinary nature of sustainability skills and acknowledged the importance of empathy, participation, evaluation skills, and a tolerance for uncertainty.

Strategic competency is critical regarding the promotion of change, as it is central to the ability to design and implement sustainability-related strategic plans (Wiek et al., 2011b). Strategic competency encompasses the understanding of strategic concepts as well as the skills related to designing, implementing, evaluating, and adapting policies and programs (Wiek et al., 2015). The ability to employ strategic knowledge also requires other sustainability competencies, particularly systems-thinking competency, anticipatory competency, and interpersonal competency. Systems-thinking competency refers to the ability to understand the complexity and systematic nature of sustainability problems and address them from a more holistic perspective. Systems thinking requires a variety of methodological skills to manage distinct types of data. In addition, systematic knowledge is necessary to understand motives and cause-effect relations, which are at the core of this multidisciplinary module. Moreover, analytical skills, such as articulating a system's structure and its key components, are fundamental aspects of systems-thinking competence (Wiek et al., 2011a).

Anticipatory competency, which involves analysis skills that focus on future scenarios, is another precursor for strategic competency. In particular, anticipatory competence requires future-oriented knowledge and skills that can facilitate simulation and scenario analyses (Wiek et al., 2015). Being able to 'see the future' was a starting point for the students as they worked on their inventions in this project. Sustainability concepts address questions relating to how systems should function and what changes are needed; therefore, sustainability is a value-laden concept. The values that motivate actions and decisions (such as justice and equity) are actualized in the ethical aspects of inventions as well as in the empathy that students may express in their problem setting and solution development.

Effective sustainability actions require the involvement of many people, and therefore interaction is required for goal setting and goal attainment. Successful interactions may also require the ability to influence the behavior and decisions of other people. In practice, influential actions can be straightforward or more discreet. The term nudging is used to describe discrete influencing that aims to draw benefits from automated system one decision-making (Sunstein, 2015). In nudging, the default choice is automatically the most sustainable, and it is selected by the people who seek the easiest option. It is essential to consider the ethical implications associated with nudging, as people may feel manipulated and exploited if the activities are not transparent. The ability to influence people also requires interpersonal competence, and the process can be made more effective by encouraging a sense of empathy. Interpersonal competency is necessary to co-construct knowledge and practical solutions for transformative actions (Wiek et al., 2011a). In this chapter, we examine how the students' interpersonal competence was manifested in their solutions and how they aimed to influence the end users of their inventions.

Sustainability in the Finnish National Core Curriculum

The Finnish national core curriculum places the value aspects of sustainability in the value section (FNAE 2016). Sustainability knowledge and the objective of learning sustainable ways of living are also integrated into every school subject. While the national core curriculum does not directly introduce sustainability competencies, they are referenced in the transversal competencies section. More specifically, it is a requirement that students are guided to use information both autonomously and collaboratively to solve problems, argue, reason, draw conclusions, and generate novel inventions. Students should also be taught how to search for reliable information, critically analyze topics from several perspectives, and effectively evaluate their thought processes. Students are guided to understand how their choices, lifestyle, and actions have an impact on themselves and on their community, society, and the environment. The aim is to foster a readiness to evaluate and change the procedures and structures of their community and develop their constructive actions to build a sustainable future (FNAE 2016). Furthermore, the national core curriculum provides an outline of science content that promotes competencies of strategic action and tolerance for uncertainty: 'A collaborative influencing project is carried out where the pupils practice participation and involvement at the local or the global level'. To implement the directives of the national guidelines, we can use the framework developed by Lozano et al. (2021), which describes pedagogical approaches that support the development of sustainability competencies.

Transversal competencies are pursued through a multidisciplinary approach, and the Finnish curriculum has introduced multidisciplinary modules to highlight the holistic nature of various phenomena and support students' systemic understanding. The module introduced in this chapter has an inbuilt multidisciplinary approach and follows a key requirement outlined in the environmental studies section of the Finnish national core curriculum: the school program must include a collaborative project in which the pupils practice participation and involvement. The module structure is introduced in more detail later in this chapter.

Solely focusing on a discussion of environmental threats may needlessly promote feelings of guilt and anxiety about everyday choices; therefore, we have employed an activity based on classroom teaching. By following procedures that encourage invention, students can actively develop their sustainability competencies as well as consider and practice how they can resolve problems through creative thinking and design.

Our Study

Context and Participants

This study presents a collaborative multidisciplinary module for primary schools that supports participation and encourages involvement; the module was trialed in a Finnish comprehensive school.

Sixth-grade students (aged 11–12 years) were assigned a task that employed an invention procedure and introduced and developed the concepts of influencing and sustainability. The students were asked to design mobile applications with the aim of changing the culture and actions of a community and generating support for a more sustainable future. The prototypes of the mobile applications were created using the Marvel application (https://marvelapp.com). An essential element of the project was to identify a positive way to support the development of understanding and a willingness to change; the project aimed to avoid the promotion of guilt and dystopian concepts.

The sequence of aims in the module was grounded in curriculum content and related to transversal competencies and subject-specific objectives. Furthermore, the invention pedagogy protocol formed the structure of the sequence. The course of the module was established as a general sequence plan with additional specific lesson plans. The structure covered the iterative process of drafting and refining the conceptual ideas that arose during the needs assessment and during the development of the final prototype applications. Throughout the process, the collaborative student teams were asked to explain and justify their ideas within the group and between groups.

In the module described in this chapter, the students were asked to design an interactive mobile application prototype using the Marvel app prototyping tool. The purpose of their prototype was to invent a product that supported sustainability. Two problem spaces have been identified in design activities: composition, represented by visual design, and construction space, represented by technical design (Goel & Pirolli, 1992; Kangas et al., 2013; Seitamaa-Hakkarainen & Hakkarainen, 2001). In the context of this invention project, the emphasis was on the composition space, but the students also addressed the construction space by adding hotspots, interactions, and layers in their prototype applications; thus, they modeled the technical functions of the design solution. The construction of functioning applications was beyond the scope of this project, as it would have required additional time and scaffolding skills to teach the students code writing. Instead, the digital prototype application offered students a shortcut to the construction space and enabled them to overcome the technical obstacles caused by the restricted period and their limited coding skills.

Phases of a Participatory Circular Economy Inventions Module Employing an Invention Pedagogy Approach

The phases of the multidisciplinary module followed the phases of the invention process, as described in Chapter 9 of this book. In the context of this project, the phases were as follows: (1) Orientation to the topic and the work; (2) defining the invention challenge; (3) brainstorming, information gathering, and testing of ideas; (4) presenting the ideas and evaluating and approving the plan; (5) fabrication of the prototype; (6) implementation and modification of the prototype and feedback; and (7) presentation and launching of the prototype.

The multidisciplinary project was started during Finnish language lessons by studying the concept of influence and examining its meaning and methods. Drama activities were also used to familiarize the students with well-known influential people and inventors. In science lessons, the students were introduced to the concepts of sustainability and circular economy and their various related dimensions and transitions. During mathematics lessons, the students employed statistical methods to examine the most popular mobile applications used in the class. This orientation phase was designed to familiarize the students with the project's context and the required takeover concepts.

In the second phase of the project, the students were asked to list the sustainability-related problems that they had observed in their own environment: at home, at school, or in the classroom. The students were then given the opportunity to implement and practice meeting protocols during their Finnish language lessons, and in small groups, they selected one interesting problem to explore further. The students were also asked to self-evaluate their meeting skills. The aim of these activities was to enable the observation and examination of sustainability phenomena in a context that was familiar to the students. Furthermore, the students were encouraged to identify and apply the concepts and skills that they had learned.

In the third phase, the aim was to employ creative ideation methods to identify the sustainability problems and support the generation of multiple ideas and solutions. In the idea generation phase, the students applied ideation methods (e.g., the 8x8 method) and searched for information online. During visual arts classes, the students examined prominent mobile applications and interviewed each other to find out why certain applications were popular. Finally, they familiarized themselves with the user interfaces of the applications and discussed how visual design elements, such as logos and colors, are used to communicate ideas and influence the decisions of the end users.

In the fourth phase of the invention process, the students practiced giving and receiving constructive feedback. In small groups, each student introduced their design solution ideas and obtained feedback from their classmates. Based on the feedback, they chose a final design solution that could be developed into a prototype. The students evaluated their group's work at the end of the idea generation phase. The aim of this phase was to develop reasoned decision-making and employ group support to aid the selection of a suitable solution idea.

The multidisciplinary project then proceeded to the fifth phase. During mathematics lessons, the students used the Marvel app mobile application to draw the display images that would be required for the construction of their prototypes. The aim of the prototype generation phase was to identify the technical mechanisms of the prototype application that could be used to influence the end users' behaviors and choices.

Once the prototypes were finalized, the working groups entered the sixth phase of the project and received feedback from the teacher regarding their prototype's user interface. Based on the feedback, the students further revised their application designs. An essential aim of this phase was to learn to use feedback to improve a design solution. In addition, it was important that the teachers noted any significant emotions that were expressed during the process so that they could support the students in identifying and exploring these feelings.

The collaborative project was finalized by introducing and launching the prototypes. The characteristics of influential communication were covered in Finnish language lessons, and the students were given a task to construct a draft speech at home. In their small groups, the students prepared speeches that introduced their choice of sustainability problem and its intended circular economy solution. They presented the details of their solution, focusing on its usefulness. The students were also asked to explain why their sustainability problem was personally significant and describe what experiences they had related to its context. Finally, the students evaluated their process of working and the mobile application prototype they had constructed. The aim of this final phase was to collect data on the students' experiences of influencing and inventing while activating their awareness of these aspects.

Data and Analysis

The data for this study consists of (1) the students' notes that were generated in small groups during the various phases of the project, (2) the completed mobile application prototypes, and (3) the students' speeches that explained the sustainability problems that were selected, introduced the design solutions, and considered the usability and potential impact of the prototypes. Furthermore, the data analysis was targeted at the sequence plan of the multidisciplinary invention project. Two researchers conducted the analysis, deductively when using existing theory and inductively when the interpretations were based on the data that were collected.

The researchers started the analysis using a deductive approach. The students' working notes and final design solutions were examined to identify the sustainability problems that served as the starting points of the invention process; the researchers also established the characteristic operational principles of the suggested design solutions. The sustainability dimensions (economic, ecological, cultural, or social, as described in the introduction section) represented in each prototype were defined by applying the different dimensions of the sustainability concept (Pop et al., 2019) and the circular economy transitions (Juuti & Gericke, 2022).

The analysis phase then proceeded using an inductive method. Special consideration was given to the mechanisms of influence employed in the prototypes, from both the external and internal perspectives. The external perspective was based on the researchers' observations of the prototypes. The working groups had generated the internal design view, and the data relating to the methods used to influence sustainability behavior was sourced from the working groups' introductory speeches. These aspects were then reduced to interpretations that were classified using the principles of data-based analysis.

Students' Inventions

Throughout the project, the students worked in small groups. During the phases of the invention pedagogy process, they identified a problem and then worked toward designing a mobile application as the outcome. The collaborative invention process resulted in 12 mobile application prototypes, and the design outcomes were related to one or more dimensions of sustainability. Furthermore, the students were directed to include a circular economy transition as a starting point for their design. The project revealed that students employed their interdisciplinary competence when they worked together, co-invented, and negotiated their decisions. In addition, students employed and practiced their media use and evaluation competencies when designing and revising application prototypes. The design outcomes are introduced in Table 7.1.

The students first addressed the various problems that motivated their invention process; they identified a range of the sustainability-related issues mentioned in the

Table 7.1 Outcomes of the invention process

Mobile application prototype	*Sustainability perspective*
Garbage Swipe *Problem:* Limited recycling; the impact of recycling on climate change *Solution:* A game that teaches people to sort waste	*Sustainability dimension:* Ecological Economic *Circular economy transition:* From waste to raw material
Banana Bottles *Problem:* Poverty *Solution:* A game that simulates helping disadvantaged people by recycling waste bottles and donating the money	*Sustainability dimension:* Social Ecological *Circular economy transition:* From waste to raw material
Disposable Fashion Calendar (DFC) *Problem:* Pollution, water consumption, and poor working conditions caused by throwaway fashion *Solution:* An application that helps to monitor garment purchase, use, and repair	*Sustainability dimension:* Ecological Economic Social *Circular economy transition:* From disposable to fixable
E-Paper *Problem:* Deforestation *Solution:* An application for taking notes	*Sustainability dimension:* Ecologic Economic *Circular economy transition:* From disposable (to fixable) From product to service

(Continued)

Table 7.1 (Continued)

Mobile application prototype	*Sustainability perspective*
Vege *Problem:* Deforestation of rainforests *Solution:* An application for increasing the consumption of vegetarian food; includes a collection of recipes	*Sustainability dimension:* Ecological Economic *Circular economy transition:* From product to service
World travel *Problem:* Racism *Solution:* A game that familiarizes people with different countries and cultures	*Sustainability dimension:* Social Cultural *Circular economy transition:* --
Nonelectric *Problem:* Consumption of electricity *Solution:* An application to monitor and control electric devices at home	*Sustainability dimension:* Ecological Economic *Circular economy transition:* --
Recycling spigot *Problem:* Availability of tools and equipment; consumption *Solution:* An application that facilitates the lending, borrowing, and renting of equipment	*Sustainability dimension:* Economic Ecological *Circular economy transition:* From owning to sharing
Puuhuut *Problem:* Lack of knowledge about sustainability issues *Solution:* A quiz application that presents participants with information on a range of sustainability topics	*Sustainability dimension:* Social Ecological *Circular economy transition:* --
Bensappi-fuel-app *Problem:* Excess driving *Solution:* An application that monitors the kilometers driven	*Sustainability dimension:* Ecological Economic *Circular economy transition:* --
Wuokraut-car-renting-app *Problem:* Renting cars *Solution:* An application that enables people to rent out their cars	*Sustainability dimension:* Ecological Economic *Circular economy transition:* From owning to sharing
Eco-info *Problem:* Lack of sustainability-related knowledge *Solution:* An application that enables people to share their best tips for a sustainable lifestyle	*Sustainability dimension:* Ecological Economic *Circular economy transition:* --

Agenda 2030 (UNESCO, 2021). For example, the students highlighted limited recycling and its influence on climate change, poverty, pollution, throwaway fashion and its association with extreme water consumption and poor working conditions, fuel consumption, deforestation of (rain)forests, racism, excessive consumption of electricity, excessive consumption of materials related to owning tools and vehicles, and a lack of knowledge about sustainability issues. The inventions included games and applications that facilitated the monitoring of sustainability-related behavior, the provision of sustainability knowledge, support for recycling, the presentation of sustainable choices, and platforms for sharing knowledge and commodities. Most of the inventions were related to the ecological and economic dimensions of sustainability. Four innovations were linked to social sustainability and one to cultural sustainability.

The inventions were classified deductively based on their circular economy content. Several circular economy transitions were evident in the inventions, and some inventions were associated with two transitions. Two inventions dealt with the transition '*from waste to raw material*' and another two addressed the transition '*from disposable to fixable*'. The perspective '*from owning to sharing*' was associated with two solutions as was the perspective '*from product to service*'; however, the connection to '*from product to service*' in one solution was not so obvious. Five inventions that were monitoring, entertainment, or educative applications did not clearly connect with a circular economy transition. Overall, the solutions emphasized waste reduction or recycling. Material or item-related transitions are more tangible and therefore are easier to use as a starting point for an invention process; in contrast, services that are intangible may be more difficult for a student to visualize.

Based on the external view, the inventions contained several mechanisms of influence, such as gamification, education, effortless usability and clarity, support for social relations, an appeal to empathy, and sanctions and rewards. Based on the external evaluation, five solutions appeared to rely on education as a means of influence. Three solutions were based on gamification. Empathy, collaboration, personal benefits, and tangible solutions for sustainability problems each appeared as the mechanism of influence in two solutions. Most solutions included more than one mechanism of influence.

The designers' views that related to the mechanisms of influence were more multifaceted than the assessments carried out by the external reviewers. The designers' explanations for nine of the prototypes referred to a solution to a sustainability problem as a means of influence; in addition, nine solutions identified usability that can be attained through effortless use, gamification with rewards, enjoyment and entertainment, and personification. In seven speeches, the designers referred to education and empathy as their mechanisms of influence; in six solutions, the designers relied on facts. Collaboration, personal benefit, gamification, and entertainment were each identified in four solutions. Two solutions introduced narrativity as a means of influence. Most of the inventions introduced more than one mechanism of influence.

In summary, the mechanisms of influencing in the applications have been considered from many perspectives. On the other hand, whether the application seeks to appeal to emotions or facts has also been considered. On the other hand, several routes of influence have been used: Influencing can focus on an individual's actions, or it can exploit the social context and the power of cooperation. In addition, influencing can be either indirect through education or direct influence, giving tangible solutions to problems. Finally, the usability and personalization of the application as well as the aspects of personal comfort and benefit are also considered.

Examples of the outcomes of the students' group work are presented in Figures 7.1 and 7.2. The idea of the Garbage Swipe app is to throw used items in the right recycling bin and thus learn how to recycle (Figure 7.1). The players

Figure 7.1 Example of the application prototype, Garbage Swipe.

are motivated by following their own progress from 'Trophy Road' and competing with others. The players can also customize the look of the app.

The intention of the DFC application is to increase people's awareness of the problems of fast fashion and encourage them to repair and recycle clothing (Figure 7.2). The app guides people to set goals for their responsible consumption and illustrates the consumption choices and actions made with color codes and diagrams.

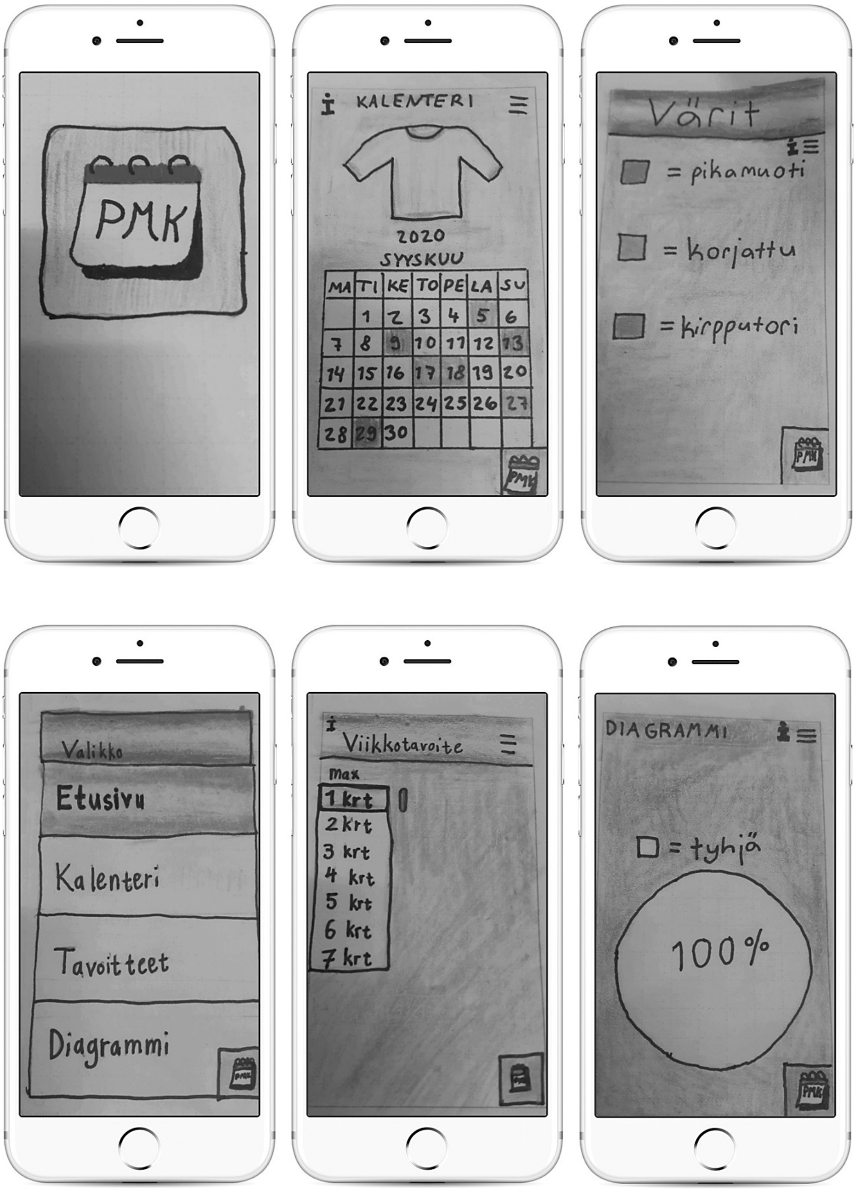

Figure 7.2 Examples of the application prototype, DFC.

Conclusions

In the first phase of the project, the students identified a wide variety of problems that were large-scale and addressed a range of sustainability dimensions, such as racism, climate change, and poverty. Most inventions focused on the ecological and economic aspects of sustainability. Only four innovations were connected to social sustainability and only one to cultural sustainability. The results indicate that schools focus on the ecological aspect of sustainability, such as by addressing how students can take care of their own environment. In contrast, economic sustainability may be discussed more often at home during family conversations that address the consumption of resources and money-saving habits. Social and cultural sustainability concepts are often more complex and less tangible; therefore, they may not be at the forefront of the students' minds when they first approach sustainability topics. In this study, it should also be noted that several of the problems that were established as starting points for the students' invention process were more strongly linked to the adult world. For example, it is unlikely that a primary school student would be responsible for a vehicle's fuel use.

The circular economy concept is often linked to a more effective use of materials (Webster, 2017). This includes the reconceptualization of waste as a side product of an industrial process. Thus, it is possible to use 'waste' from one process as raw material for another product. However, viewing waste as a new raw material may not encourage people to reduce consumption; instead, it could be used to justify current processes and thus hinder a reduction side product (waste). Therefore, the effective use of side products can limit necessary change relating to the primary use of materials. In our case, the students' inventions *Garbage Swipe* and *Banana Bottles* reflected a viewpoint that well-resourced families do not have to change their consumer behavior. It is challenging to rethink and facilitate practices that will lead to a reduction in the use of primary materials. However, the students' invention *DFC* did reflect this process: the application encouraged users to reduce their clothing consumption and facilitated the selection of more durable garments.

Through the process of inventing, the students became familiar with the dimensions of sustainability and circular economy transitions. They practiced a range of transversal skills, such as collaboration, argumentation, and giving and receiving feedback. The module avoided focusing on negative emotions that related to the behavior of humankind and the state of the world; instead, the students employed a solution-based approach and experienced taking positive action when facing problematic issues. The use of digital tools converted the project's design concepts into tangible solutions; in other words, the compositions were enriched with construction space aspects that would have otherwise been unattainable (Kangas et al., 2013). The evaluation of the design outcomes revealed the sustainability dimensions that the students embedded in their designs. Based on these evaluations, the students' learning outcomes in relation to the sustainability topic can be observed. The aims set out in the sequence plan could be used to define the explicit evaluation criteria; however, this was not a focus for this chapter. The designers' explanations clarified the influential potential of their prototypes. In their introductory speeches, the students presented inventions that used a range of methods to influence consumer behavior. These descriptions were useful, as it was not always easy to determine the influencing context when examining a prototype. However, this uncertainty may also apply to real-world inventions, which often have an indistinct means of influence; many commercial applications rely on subtle nudging techniques to influence the behavior of the end user (Sunstein, 2015).

The challenge for sustainability inventions is to ensure that they do not create additional sustainability problems. A focus on increasing the efficiency of a product's production may reduce production costs and generate cheaper prices that may boost sales. Thus, sustainable inventions that reduce the use of materials can potentially increase the consumption of raw materials and energy. As Korhonen et al. (2018: 44) emphasized, '[I]f the current consumption culture will not change, [the] CE [circular economy] will remain as a technical tool that does not change the course of the current unsustainable economic paradigm'. Therefore, it is important that schools reflect on current consumption practices and encourage students to consider decoupling material use and economic activities. This could be facilitated by highlighting the circular economy transitions '*from product to service*' or '*from owning to sharing*' (c.f. Juuti & Gericke, 2022). This approach creates challenges for the idea generation and idea evaluation phases of the invention process. Therefore, students should be guided to evaluate the whole invention life cycle, as well as the behaviors and values of people. These processes have been addressed by Wiek et al. (2011a) in their model of sustainability competencies. Product life cycles and consumption behaviors are complex systems that require knowledge of the physical and social sciences and an understanding of value systems. The invention pedagogy approach offers an instructional method that contains inbuilt motivating features, such as collaboration and autonomy, and thus encourages students to spend time on this interesting albeit challenging topic.

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8 Framework for Technological Competence in Invention Projects

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Introduction

At the core of the fourth industrial revolution (4IR) are pervasive digital technologies, which make it possible to radically change the nature of product and service innovations and continuously form new technological innovations (Anderson, 2012; Oke & Fernandes, 2020; Yoo et al., 2012). Therefore, there is a need to engage young people to participate in the technology-mediated practices and for them to learn to integrate ubiquitous and complex technology competence with innovating. The meaning of technology is determined by its use, and technological competence is learned through sustained use. A particular technological competency is learned by appropriating it as a tool of learning, such as in maker activities. Sustained use of the tool makes it a part of one's system of activity. Such a developmental process is referred to as an instrumental genesis (Rabardel & Bourmaud, 2003; Ritella & Hakkarainen, 2012). Maker-centered learning involves using a wide variety of tools and a participant does not have to master them very deeply to be able to use and take advantage of them; in many cases, there is "performance before competence" (Cadzen, 1997) as well as overcoming obstacles by social sharing of competence.

There are varying interpretations of how the nature of technological competence is understood and how people should be educated in this era of industrial revolution. Many recent studies and policies place a strong emphasis on digital competence, such as knowledge acquisition, structuring, construction, and sharing (e.g., Li et al., 2020; Redecker, 2017). A wider technological landscape that includes all human-designed technological products, systems, processes, and services in which technology is integrated into products, has been addressed especially in the field of technology education. Recent research and policies in this field underline technological literacy (i.e., the capability to understand, use, create, and assess technologies) as the key component in teaching and learning with and about technologies (International Technology and Engineering Educators Association [ITEAA], 2020; Jones et al., 2013). Yet, the concept of technological literacy has been criticized because of the dichotomist premise about a person as either technologically literate or not (Dakers, 2018). Further, it has been argued that more attention should be paid to the interdependence of social and technological innovations (de Vries, 2018); technological developments provide new possibilities for social

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activities which, in turn, affect the future direction of technology development (Orlikowski & Scott, 2008).

In the Finnish curricula, teaching and learning technological competence are approached in a cross-curricular and multidisciplinary manner. A future-oriented approach to technology requires a broad perspective and strong connections to 21st-century competencies (Binkley et al., 2012; Finnish National Agency for Education [FNAE], 2014). Technological competencies are underlined in several areas of the curricula, from the transversal competencies (see Chapter 1 of this book) to general competence objectives, as well as in many individual school subjects. In addition, the teaching of programming has been introduced into the curriculum as a completely new theme.

The push for integrating the teaching and learning of technological competence into schools has not been without challenges in Finland. The content and methods in the core curriculum and the strategies adopted to further the use of digital technology in schools have raised numerous arguments for and against both among teachers and in the public discourse (e.g., Kokko et al., 2020; Saari & Säntti, 2018). The primary challenges are related to schools' equipment infrastructure, teachers' lacking competence (e.g., Tanhua-Piiroinen et al., 2019, 2020), sometimes fearful attitudes about content or tools that are new to them or their school, and how ubiquitous technologies should be addressed in teaching (e.g., Kokko et al., 2020). Further, our latest research indicates that teachers and students consider their academic digital competencies to be good but face various challenges related to the creative use of technologies (Korhonen et al., 2020; Korhonen et al., forthcoming).

In the following sections, we respond to the challenges by proposing a framework that conceptualizes and operationalizes the technological competence that students and teachers can apply and learn through invention projects. We first describe the theoretical foundations and pedagogical principles behind the framework and then depict its five dimensions: crafting, designing, engineering, programming and reflecting, documenting and sharing. Each dimension is elaborated upon through its central concepts, aims, examples of the technological tools, and pedagogical practices associated with their use. In addition, we note how the dimensions are considered when planning invention projects and discuss the relevance of the framework for the future work of teachers and researchers.

Technological Competence Framework

In invention pedagogy, technology encompasses a wide technological landscape, including all human-made technological products, systems, and processes that may be used in designing and making targeted inventions. By providing students with traditional or digital fabrication tools, their personal and social capabilities become significantly extended, enabling the creation of complex artifacts. The focal assumption in invention pedagogy is that the cognition not only takes place in the human head but that it is materially (between mind and tool) and socially (between minds of invention team) distributed (Clark, 2003; Pea, 1993). The recently emerged perspective of 4E cognition (i.e., embodied, embedded, enactive, and extended cognition) (Newen et al., 2018) provides a useful way of thinking about the distributed creative processes in the context of teaching and learning technological competence. Learning technological competence is embodied through active engagement in invention projects. Cognition, affect, and behavior emerge from the body being embedded, enacted, and extended across external tools (e.g., art and craft tools and materials, rapid prototyping and programming technologies), and processes and structures (invention projects and processes), and environments (e.g., learning environments for invention pedagogy). It follows that learning and teaching technological competence through invention projects does not represent reproduction but instead radically remediate a learner's cognitive processes toward new inventions.

In each phase of an invention project, students make use of technology in various ways to achieve their envisioned invention. The creators can share the purpose of their invention, the identified issue that it resolves, and the technologies that it employs. Because students' inventions may extend in several directions, the relevant technological tools and instruments cannot often be predetermined, and prevailing skills and capabilities have to be significantly extended. This challenge not only concerns the students, as teachers cannot be assumed to be proficient with all the requisite technology. Nevertheless, in many cases, the learning community involves students who are already familiar with the required technologies and associated competence and may share their knowledge both with peers and their teachers (see Chapter 12 of this book).

Designing and creating an invention motivates a student to experiment and test novel technological instruments as well as to put effort into acquiring and deepening their technological competence. At the same time, the invention being created teaches both the students and the teacher something new about the surrounding technological world. This assists participants to gradually cultivate a more general understanding about broader domains of technology, cultivate a sense of available instruments, and cultivate functional principles of their operation. Thus, students and teachers apply and acquire technological competence both for defining their inventions and as a tool for developing the same during invention projects.

To help conceptualize the technological competence that students and teachers can apply and learn through invention projects, we have categorized them into five broad dimensions: (1) crafting, (2) designing, (3) engineering, (4) programming, and (5) reflecting, documenting, and sharing. These competence domains are close to the disciplinary practices that the invention pedagogy aims at bringing to the classroom. Each area is very complex and multifaceted and involves numerous skills and competence that learners may appropriate through participating in invention processes. Participation in the invention process, as explained in Chapter 2 of this book, involves implementing learning through participating in collaborative design and crafting (Kolodner et al., 2003; Seitamaa-Hakkarainen et al., 2010) and engineering (Ceylan et al., 2020; Cunningham & Carlsen, 2014). Scientific practices (Krajcik et al., 2014; Paavola & Hakkarainen, 2014) are involved both in programming (Blikstein, 2015; Kafai & Burke, 2015) and reflecting, documenting and sharing, i.e., in epistemic mediation (Ritella & Hakkarainen, 2012). The dimensions of technological competencies and their interrelations are illustrated in Figure 8.1.

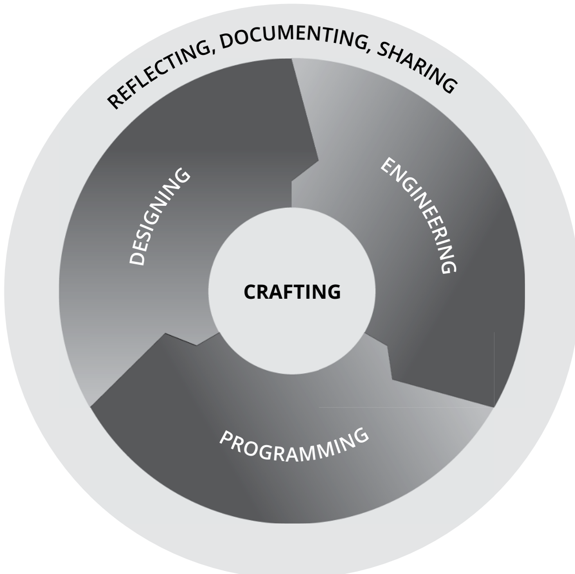

Figure 8.1 The framework for technological competence in invention projects.

Together the five dimensions form the framework of technological competence in invention projects. The framework serves as a tool for integrating technological competence in the designing and implementation of invention projects. Technological competence is perceived in terms of technological artifacts and systems, which are actively employed and developed through social processes of the invention community. The categorization of the relevant technology-competence dimensions is rooted in our sustained research-practice partnerships focused on understanding and identifying the dimensions of technology being implemented in early childhood and basic education classrooms.

The dimensions of the framework are partly overlapping, and it should be noted that not all areas are covered in all invention projects. For example, some projects do not include programming at all, some emphasize designing, while others focus more on engineering. In the following sections, each dimension of the framework is elaborated through its central concepts and learning goals as well as examples of the technological tools and pedagogical practices associated with their use.

Crafting

Working with tangible tools, materials, and artifacts using traditional and digital fabrication techniques plays a crucial role in knowledge-creating learning through invention processes (Blikstein, 2013; Kafai et al., 2014; Kangas et al., 2013; Riikonen et al., 2020a). In invention pedagogy, the material approach through crafting and making is present throughout the whole process, enabling and often triggering the implementation of all the other technological competencies of the project. It provides the means for creative ideation and experimentation with technologies to develop students' understanding of the technological world. It is noteworthy that crafts is a separate subject in Finnish school and thus offers a special context for the teaching and learning technological competence in invention projects (Finnish National Agency for Education [FNAE], 2016).

It must be noted that both students and teachers need adequate expertise in the relevant aspects of these tools, materials, and techniques to creatively and productively utilize them in their invention processes (Riikonen et al, 2020b). On the other hand, such expertise also guides the invention process. For example, learning how to use a hammer, a sewing machine, or a laser cutter expands students' understanding of the options provided by these tools and therefore promotes the creation of functional and pedagogically appropriate inventions.

Due to the unpredictable nature of invention processes and their outcomes, it is not always possible to predetermine the adequate tools, materials, and techniques that will be needed during the process. However, by selecting specific tools, materials, and fabrication techniques, teachers can constrain the open-ended design task to create focused and well-framed invention challenges that are appropriate for the students' age and skill levels. It is also important to remember that the focus of an invention project is not on manufacturing perfectly finished end products but, instead, on the knowledge-creating learning and invention process. On the other hand, students are often highly motivated to learn new craft techniques while working with their invention, which is a valuable learning outcome in itself.

In the following, we have divided crafting into four levels, based on the tools, materials, and techniques used, suitable for different ages and skill levels. Special attention should be paid to teaching the students how to use the materials, tools, and facilities safely.

Simple Crafting

When working with small children, simple craft materials and techniques are often the most suitable for invention projects. Basic materials that the children are already familiar with, such as paper, cardboard, steel wire, felt, yarn, wooden sticks, rings, and pearls, allow for multifaceted experimenting and prototyping. Soft metal sheets, easily workable plastics, and modeling clay are suitable for small children. With these materials, it is also possible to build simple mechanical inventions with small children, such as moving toys and pop-up cards. For fabricating moving parts, commercial assembly kits can also be used. Craft techniques suitable for small children include cutting, gluing, knotting, and sewing simple stitches.

Hand Crafting

In tandem with the development of the hand-eye coordination and motor skills of the students, new craft materials and hand manufacturing techniques and tools can be introduced to them. For example, wood, metal, plastic, fabric, yarn, and wool can be used with the relevant fabrication techniques. Simple machinery, such as a sewing machine and a fretsaw, can also be introduced to the students. If possible, the co-invention project should be carried out in dedicated craft classrooms or makerspaces.

Machine Crafting

On this level, the students move on from using hand tools and simple machines to more sophisticated traditional fabrication machinery, such as a wood lathe and band saw, and to digital production, such as that using 3D printers and laser and vinyl cutters. There are plenty of premade examples and projects for digital fabrication tools available online that can be used to familiarize students with the same. More sophisticated materials, such as leather or harder metals can also be introduced at this level.

Hybrid Crafting

Finally, when students become familiar with the main techniques and machinery involved in the previous three levels, they can be allowed to use them, and the corresponding facilities, extensively, as well as on their own, to create sophisticated inventions combining multiple fabrication techniques, tools, and materials. Students can also be encouraged to use the makerspaces and digital fabrication tools available outside the school premises, such as those found in a library. They can also be guided to use the internet more to find instructions, tips, and example projects to support their co-invention process. At this level, the co-invention process and the inventor team become increasingly independent; they can even become experts in using novel digital technologies

Designing

One of the aims in invention pedagogy is to help students understand that technology is man-made and that before technological solutions take their physical or digital form, they need to have been designed by someone. This understanding develops gradually in invention projects, through which students learn to apply design principles to address invention challenges and use technological means to express their design ideas. Thus, in invention projects, technology is both the object and the tool of design.

Designing can be roughly divided into three overlapping phases: ideation, visual designing, and technical designing. The emphasis in design ideation is on gaining new insights and looking beyond the obvious; it is the start of a process in which the aim is to create something new (Laamanen & Seitamaa-Hakkarainen, 2014). Visual and technical design can be characterized as a search within two problem spaces: the composition space and the construction space (Seitamaa-Hakkarainen, 2001) (also see Goel & Pirolli, 1992). The composition space consists of the organization and manipulation of visual elements and principles such as the shape, pattern, and color of the invention. The construction space includes the design of technical elements, such as structure, materials, and production methods. Within the composition space, the students consider how the outcome of the design process (the invention) will appear, whereas in the construction space, they analyze how the invention functions and how it will be fabricated. The students move within and between these spaces both horizontally (i.e., generating several parallel ideas) and vertically (i.e., developing the ideas further and adding more details) (Kangas et al., 2013; Seitamaa-Hakkarainen & Hakkarainen, 2004). In invention pedagogy, the understanding of these two problem spaces, and of the deliberate horizontal and vertical movement within and between them, enhances the quality and versatility of students' design ideas.

As with any other form of intelligence, design competence is not a given "talent" or "gift." In invention projects, students are systematically facilitated to learn and develop design competencies. During the early stages of learning design, the function and significance of various design tools and representations, such as sketches, mock-ups, drawings, and prototypes, may not be apparent to the students (e.g., Hope, 2005; MacDonald et al., 2007; Welch et al., 2000). Therefore, students are explicitly taught how to use various tools and techniques to facilitate the generation (not just the execution) of ideas (MacDonald et al., 2007). In invention projects, various technological tools, both digital and non-digital, offer age-appropriate means for students to create, visualize, and further elaborate their ideas.

Sketches and Mock-Ups

Hand-drawn or digital sketching is typically the first step of design, which is used to externalize and visualize the very first, often fuzzy and vague, ideas. Sketching plays a crucial role in generating, developing, and communicating ideas; it is both a powerful form of thinking and the fundamental language of designing (MacDonald et al., 2007; Welch et al., 2000). In invention projects, students usually create simple idea sketches to quickly externalize their thoughts, study sketches to investigate the idea in more detail, or use memory sketches such as visual mind maps to substantiate their thoughts (cf. Pei et al., 2011). Designing inventions is also a material-centric and embodied activity; engagement with and the manipulation of physical materials is an intrinsic part of the invention process, which inspires and constrains students' ideation and designs (Mehto et al., 2020a; Mehto et al. 2020b). Students create sketch models to explore their ideas in 3D form usually using cheap materials that are easy to manipulate, such as cardboard, playdough, or construction kits. However, rapid prototyping tools, such as 3D printers, have also been used to create early phase models of students' inventions. Sketch models often capture the key characteristics of the form, but they can also be used to test and experiment the functional properties of an invention (Pei et al., 2011).

Scale Drawings and Projections

Non-digital and digital drawings are used for both visual and technical design; students make drawings on different scales and visualize their inventions with various projections. Realistic renderings can be made to investigate and communicate the shape, colors, patterns, and other visual elements of the invention, while perspective drawings and projections, as well as technical illustrations, can be used to execute the technical design (Pei et al., 2011). Making drawings requires the spatial ability to perceive the dimensions of the invention; therefore, novice designers benefit from embodied activities in which they build 3D models and practice using measuring tools such as rulers and tape measures (see Kangas et al., 2013). For young designers, it is also helpful to start drawing their invention designs by hand at the 1:1 scale and then move on to digital drawing and more complicated scales as their skills develop. Drawing various projections of the invention enhances students' perspective skills and their competence in envisioning and externalizing something that does not yet exist. For learning computer-aided design (CAD), students can first use software platforms such as Tinkercad or Minecraft, through which designs can be created from blocks of various shapes and sizes. Software intended for 3D drawing, such as SketchUp, requires students to possess more skills but includes more possibilities for designing complicated forms and mechanical or electronic parts for their inventions.

Functional Prototypes

In professional designing, a prototype refers to a full-size three-dimensional material design representation that includes working and functional components and that is used to test and communicate various elements of a design (Pei et al., 2011). Prototypes are usually employed in the later phases of the process and provide a more finished representation of the design than models. Here, however, we refer to the prototypes that are used to experiment with the functionalities of inventions and that are constructed using simple materials and mechanical, electronic, or programmable parts. These functional prototypes can be either full-size or smaller-scale models of the invention design or some of its parts. Various tools and technologies can be used to produce the required functionalities – from simple moving parts made from cardboard or using construction kits to more advanced functionalities realized using programmable tools, such as educational robots or microcontrollers. As the students' design and making skills are still developing, prototypes function both as tools for idea refinement and as practical training in making (Yrjönsuuri et al., 2019).

Engineering

In addition to design intent and vision, the physical or digital form of technological solutions is determined by engineering decisions. In invention pedagogy, engineering knowledge is needed to create functionality in an artifact (Fortus et al., 2004). Engineering builds a bridge between intuition and science, allowing the students to measure, predict, and explain the built environment (Martinez & Stager, 2019). To solve real-world problems, the students need to employ mathematical and scientific principles and apply engineering ideas and practices (Krajcik & Delen, 2017; Nadelson et al., 2015). Solutions are often found by students through various experiments. Fortus et al. (2004) note that teachers need to be explicit in exposing the relationship between engineering concepts and their underlying mathematical and scientific principles; otherwise, they would not be apparent to students. We foreground three elements of engineering competence that are frequently addressed in maker and invention projects (e.g., Davies et al., 2022; Kangas et al., 2022): structures (Fortus et al., 2004), simple machines (Dotger, 2008), and electronics (Litts et al., 2017). However, an invention project may just as well address other engineering topics such as pneumatics or earthworks.

An organic way for students to start developing engineering competence is to observe their environment. Armed with experience in observing the existing functionality, students can begin building the functionality required for their own inventions. For example, at school, teachers can encourage students to observe and discuss relevant engineering topics, for instance, by asking them which structures they can identify in a chair or desk (structures), what benefits a bicycle gearbox provides to a rider (simple machines), or which electronic circuits they have used during the day (electronics). Students can then continue exploring the relevant parts of engineering, such as structures, by implementing their own simple versions of the observed engineering concept. This activity prepares students for invention projects, providing them with a template for building the functionality that they need in their invention in a way that is relevant to their vision and that fulfills their expectations for their self-placed constraints, such as function and durability. By combining such templates from multiple areas of engineering competence, students can engineer technologically multidimensional invention artifacts.

Structures

Mechanical structures form the basis of most of the built environment, which manifests as, for example, poles, beams, trusses, plates, or shells. Technological competence regarding structures allows students to understand why things break in the real world and to build the structural scaffolding needed for their invention project artifacts. Structures and structural systems are present in children's lives from early on. Children are natural engineers and build structures with all kinds of materials – from blankets and cushions to blocks and sand (cf. Stylianidou et al., 2018). At the playground, children experience exciting structures by testing different climbing frames, swings, and slides.

Teachers can expand this initial model of structures to an understanding of structural engineering principles and connect it to science core ideas (e.g., matter and its interactions, and forces and interactions) (Fortus et al., 2004). By understanding this connection, students can not only apply structures in invention projects but deepen their understanding of underlying connection between disciplines. The teacher can set up various motivational tasks and playful competitions in which students can apply the structural templates that they have observed. For example, students can experiment with structural principles by building a tower as high as possible or by building a durable bridge in 20 minutes. Basic craft materials found in the classroom can be used for the same. After the students complete such a learning task, it is essential that the teacher leads a review of the rigidity of the various built structures and helps students draw analogies between the structural engineering principles, such as triangular and beam forms, in the structures they have observed and those that they have built. Regardless of the form of the learning task, it should allow students to experiment with structural principles using different materials, reflect on structural systems, and consist of several repetitions or cycles. Several exercise cycles help students to develop more challenging solutions and promote a deeper understanding of concepts (Schunn, 2009).

Simple Machines

In addition to static structures, structures that move and form mechanical systems are central building blocks in mechanical engineering. Indefinite variations of simple mechanisms are present in our built environment, making it easy for students to discover their application and observe their related kinematic (motion) phenomena (e.g., Dotger, 2008). For example, by playing on a swing, a student can experience the working of a pendulum. The movement of the bicycle accelerates on its own downhill, and with the help of the crank mechanism, you can pedal to accelerate on even ground (see Taylor, 2001).

Mechanical principles connected to science core ideas of motion and stability can also be easily explored with students in class using familiar craft materials. Students can experiment with and observe the mechanics of levers, wedges, wheels and axles, screws, pulleys, cranks, and inclined planes in this manner. Based on their experience, they can develop simple machines that use leverage mechanisms and cultivate an understanding of the relationship between shape and movement. Subsequently, students can apply the template ideas of simple machines to more complex mechanical systems such as gears and transmissions. They can also add mechanical properties to their inventions using rubber bands, springs, and wires or pneumatics. The invention can be, for example, a mechanical hand whose fingers can be operated by pulling on cables that are attached to the same.

While basic mechanisms can be easily built and explored using craft materials, using these materials to build more complex mechanical solutions from scratch is challenging for younger students and tedious for older ones. Mechanical building kits, such as Lego Technics, allow for a fast and easy exploration of basic mechanical principles as well as scale to very complex mechanical systems.

Electronics

Most of the products and systems that we consider "technology" in contemporary everyday language are produced using electronic circuits. In fact, a simple circuit is a good focus point for initial invention projects. A learning task for exploring electrical principles can guide students to consider which devices in the classroom and their homes are powered by electricity. It is very important that students grasp the basic concept of an electrical circuit, as this knowledge forms the basics of electrical safety. According to Osbourne (1983), even very young schoolchildren can learn to build a circuit independently. The teacher can provide students with a battery, wires, and a lamp. The learning task is to make the lamp light up through experimentation. Such a simple electrical circuit can be used to study conductive and nonconductive materials. Students can add a ready-made switch to the circuit or build a membrane switch. Subsequently, the lamp can be replaced by an LED, motor, or buzzer, making visible the range of electrically operated devices.

The construction of the circuits does not need to be limited to wires and traditionally packaged electronic components. Using new and unorthodox materials, such as electrically conductive tape or playdough for wires and glued-on LEDs, can make the construction process easier, allow inventions that require a different form factor, and deepen students' understanding of electrical phenomena in materials (Litts et al., 2017). Osbourne (1983) emphasizes that by using the correct terminology with students even on projects that feature extremely basic electrical circuits and gradually building an engineering competence regarding concepts such as electric current, voltage, and resistance, students can advance to understanding the principles underlying devices such as sensors and transistors. With an engineering competency in these basic concepts, students can calculate the value of the resistor that will provide the desired amount of current in an LED circuit. They can also practice more complex electronics connections in simulation environments (e.g., Circuits.io).

Programming

Mirroring real-world technological products, the inventions created in invention projects may be controlled through a software that runs on a computer embedded in the invention. The software adds "intelligent behavior" to an invention, making it come to life in the eyes of students. An invention project can also produce a completely digital invention, which can be manifested only as a computer program, with no material components (e.g., games) (see Laakso et al., 2021 for more examples). Programming competence includes the programming languages, programming tools, and practical methods that students need to create the software for their invention. We suggest separating this practical competence from competence in software engineering principles.

In the context of invention projects, the key programming competence is related to robotics kits, microcontrollers, and programming languages.

Robotics Kits

Robotics kits such as Lego Mindstorms EV3, have proven to be very useful for easily implementing even extremely complex artifacts in invention projects. Although electronics hobby and teaching kits have been available for a long time, similar kits incorporating a programmable element are a relatively recent addition to the toolset. The area of robotics combines computer control with a physical structure, moving mechanisms, and electronic circuits. As such, it provides a flexible platform for inventions that may not count as typical robots but that bring together the various technological competence involved in invention pedagogy.

Robotics kits offer several convenient ways for crafting an invention. The kits are often designed to be directly compatible with those meant for building structures and mechanisms; for example, EV3 robotics can be easily interfaced with Lego Technics building blocks. With prepackaged sensors and actuator components featuring standard electrical connections, the kits significantly simplify the electronics craft. In addition, the kits are supported by approachable, often visual, programming tools. The overarching simplicity motivates learners, as they can get the first iteration of their invention moving quickly.

Surprisingly, despite the emphasis on simplicity, the kits also feature the capacity and flexibility for more complex projects. They can be used for a range of invention themes – from "future transportation" that innovates on moving robots to "smart homes" where students can trigger actions using light and sound sensors. However, the key challenge associated with robotics kits also arises from the prepackaged simplicity; students often wish they could have different physical forms for the "one-size-fits-all" sensors and actuators included in the kits. The controller unit provided is often physically large, complicating its use in most portable or wearable projects.

Microcontrollers

The controller unit of a robotics kit contains a microcontroller, which is a small, specialized computer that runs the software programmed for the unit. Microcontrollers are also available separately – both as individual electronics components and as more convenient pre-built microcontroller boards. Microcontrollers allow students working on invention projects to overcome the physical size limitations of robotics kits. Microcontroller boards are available in a variety of shapes and sizes, with a range of onboard functionality. Examples of popular beginner microcontroller boards include the BBC micro:bit and the Adafruit Circuit Playground Express (e.g., Litts et al., 2017). Despite having different form factors, both these boards include a set of sensors, such as a motion sensor, and several LEDs for display, which require minimal additional components to be used for an invention.

Students can embed a compact microcontroller board in their invention to make it "intelligent." Some boards are specifically designed to allow easy attachment to fabric materials by sewing to create so-called e-textiles (see e.g., Kafai et al., 2014). Their programs can use the onboard or separately attached sensors to monitor the surroundings, control movement through servo motors, and communicate with the user using LEDs, buzzers, and speakers. The microcontroller board can also be considered to be an electronics component in an electronic circuit that connects the various sensors and actuators. Thus, students will have many opportunities to apply their engineering competence in electronic circuits. For example, they can be introduced to using electronics prototyping boards, or breadboards, to easily test the many sensor and actuator connections in a microcontroller board. They can also simulate such circuits before building them using free online circuit simulation tools such as Circuits.io.

Students who are already experienced with programming can implement inventions with more advanced microcontroller boards or use full single-board computers such as the Raspberry Pi. One of the key benefits of invention projects is that students with different levels of competency can find challenges and learn new things. In addition, by serving as tutors (see more in Chapter 12 of this book), students who are more competent can guide other students by sharing their own learning experiences.

Programming Languages

The primary goal of invention projects is not to make students proficient in a particular programming language but to provide the students with age- and competence-appropriate tools for experiencing the practice of creating software components that can help them achieve their vision of their invention. The first programming projects are typically completed using visual languages such as the LabVIEW visual programming language, which is often used to program Lego Mindstorms EV3 robots, or the Scratch language, which is often used with many robotics kits but can also be used to build games and other non-robotics software.

When students are introduced to microcontroller boards, they can gradually move to using text-based programming environments and languages. Hybrid programming tools, such as the Microsoft MakeCode language (which is often used with the BBC micro:bit), are useful for making this transition, as they allow the student to switch back and forth between visual and text-based representations of their program. In addition, the versions of general-purpose programming languages specifically designed for programming microcontrollers (e.g., CircuitPython) can help introduce students to full text-based programming, such as the C programming language used in the Arduino framework.

Reflecting, Documenting, and Sharing

The technological competence that students can use and learn in invention projects extends beyond the capabilities that they use directly to design, engineer, program, and craft their invention. In addition to the physical or digital creation activity, students also create a vast body of knowledge through social interaction during invention projects. Diverse everyday socio-digital practices provide versatile learning opportunities and enable young people to participate in developing their technological competence (Hakkarainen et al., 2015). Previous research indicates that the academic and creative competence of using socio-digital technologies may be fostered through knowledge building (Scardamalia & Bereiter, 2014), knowledge-creating learning (Paavola & Hakkarainen, 2014), the educational maker movement (Blikstein, 2013; Halverson & Sheridan, 2014; Kafai & Peppler, 2011), and connected learning (Ito et al., 2013), which emphasize learning through collaborative inquiry and the making of artifacts and knowledge.

In invention projects, documentation is included as a natural part of the invention process. Documentation refers not only to the reviewing and archiving of the project afterward but also the real-time journaling and presentation of ideas during the project. Student-created documentation targets both intra-team use and external audiences. Note-taking using various tools allows both individual and team reflection on the project's goals, targets, progress, and hits and misses. Documentation creates a path of knowledge creation that the students undertook while designing and making their invention (Saarinen et al., 2021), including the decisions made by them at various phases of the invention process. For teachers, the documentation and reflection content created by the students provide a tool for assessing their learning during and after the project (see Chapter 13 of this book for more detail on assessment).

Pictures and Videos

The technological competence of using digital tools for documenting, reflecting, and sharing is developed gradually. Starting from preschool, students can capture photos that can be inspected and reflected on together. Both younger and older students enjoy creating journal- or log-type videos in which they narrate their project progress. Tools originally developed for making digital books or films, such as Apple BookCreator and iMovie, offer approachable tools for documentation, which allow students to create impressive presentations that they can be proud of easily. Through positive feedback on their presentations, students become more motivated and enthusiastic regarding their projects.

Portfolios, Cloud Services, Web Pages, and Social Media

While they progress through multiple invention projects, students can start to build a portfolio of their inventions (see Chapter 13 of this book for more details on portfolios). A simple digital book creator software is a useful tool for starting with this activity. Documenting each invention project can progress gradually from the journaling of the different phases of a project and the iterative shapes of the invention toward a more reflective approach. The students can first start documenting their successes and failures and progress in determining their causes as well as their own learning. As students become more competent, they can start employing more complex digital tools. For example, students can use a cloud service to build a shared invention space in the class in which each team documents their project phases. Students can also engage in blog writing, recording and editing vlogs, or building their own web pages.

An invention project provides a good opportunity for students to gain technological competence in communicating to a wider audience outside their own class or school. Students can share pictures and videos of their projects on the class or school web pages or on appropriate social media platforms. The sharing of their digital media creations provides a natural opportunity to discuss safe and appropriate internet practices as well as the concept of digital copyrights. Ideally, the sharing of inventions on various forums could generate positive social feedback that motivates students to engage with new inventions and to seek further feedback. With adequate attention to proper user practices, social media can provide an invaluable tool for developing invention ideas, seeking peer support, and sharing best practices.

To conclude our discussion on the technological competence framework, it should be noted that in classroom settings, the dimensions overlap and entangle in many ways. For example, exploring structures or functionalities of their inventions develops both students' technical design competence and engineering competence. "Software engineering" is situated in the terrain between engineering and programming; while applying computational tools, models, and ideas in their inventions, students develop an understanding of the operating principles of software. Crafting, as well as reflecting, documenting, and sharing dimensions are cross-cutting in nature, and they overlap with all the other dimensions while students develop their ideas into material forms and create knowledge through socio-digital participation. However, considering the dimensions both together and separately helps teachers and students to perceive the variety of cultivating technological competence that can be included in invention projects. Further, it supports teachers in planning the projects, as will be elaborated in the following.

Technological Competence in Invention Project Planning

A key part of planning an invention project is to determine which technological skills the students should learn through the project. To inform this planning, the teacher should survey the preexisting technological knowledge and skills of the participating students, which may vary widely depending on the students' interests, hobbies, and the scope of teaching in the various classes in the school. For example, when assessing the programming competency of the students, the teacher can consider students who have already used programming tools in their spare time, as well as those who have been introduced to programming as a part of their classes. It is worth noting that one does not have to practice all the competencies at the same time. Teachers can choose to focus on supporting the development of some of the competencies based on the goals of the project, students' age, or their existing competence. It is similarly important to note that the project planning should not be overly constrained by considerations regarding the availability of the latest digital tools and software – the students can learn a variety of technological skills even with a basic supply of traditional art and craft materials and tools.

It is also important to not limit the learning of technological competence in innovation projects to a purely linear activity by covering a large body of theoretical engineering competence before allowing students to design their own project concepts (for example). Presenting endless "basic skills" lessons before the project activity will bore the students and lead to them losing interest in the project activity (Schunn, 2009). In an invention project, students learn the competence through iterative activity, which entails proceeding from a very basic idea of each competence to a deeper understanding as they apply their current capabilities and realize the need for additional knowledge and skills to achieve their own project goals. However, it is worth noting that certain basic skills should be practiced before proceeding to more demanding applications. For instance, realizing projects that combine crafting with multiple physical materials or techniques would require mastery over the corresponding constituents. Similarly, a basic understanding of software engineering principles is needed before starting programming activities using visual or text-based tools. A teacher can address the need for prerequisite knowledge in invention projects by planning appropriately timed, preparatory "mini-lessons" as needed.

Conclusions

In invention pedagogy, technological competence refers to both the students' and teachers' capability to observe and understand the built technological and digital environment, readiness to use technology to support personal and group activities, and possession of skills for using technology as a tool for creativity and innovativeness. In this chapter, we proposed and described five dimensions of technological competence and their embodied learning through invention projects: (1) crafting, (2) designing, (3) engineering, (4) programming, and (5) reflecting, documenting, and sharing. Crafting competence is cross-cutting in nature and refers to the knowledge and skills related to the way an invention is fabricated into its physical form. Designing refers to the knowledge and skills related to the original context and intention of the form and function of an invention, i.e., its "design." Engineering refers to the knowledge and skills related to the optimization of an invention regarding the various constraints or imposed by external factors. Programming competence refers to the knowledge and skills related to the implementation of computer programs using programming tools. The reflecting, documenting, and sharing competence is developed throughout the invention process and covers the capabilities to reflect, create, use, and share the knowledge related to the process and its outcomes.

Underlying the development of this framework is our notion that for both teachers and researchers, reaching a holistic understanding of technological competence in invention projects is challenging. Many teachers have limited personal experience of learning or teaching technological competence within anything that even resembles an invention project. Thus, they may find it difficult to think about what technological knowledge and skills are involved in invention projects and how these relate to the teaching and learning of the other competence described in this book (e.g., creativity, collaboration, or sustainability competence). Similarly, researchers are in the process of establishing an understanding of how these embodied, embedded, enactive, and extended (Newen et al., 2018) competence are developed in everyday school practices. A joint understanding is developed through an research-practice partnership (RPP) with teachers who are experts in the pedagogical implementation of technology-enhanced invention projects. The teachers' ability to support age-appropriate and curriculum-based development of technological competence, and to fit the project into the restricted time, space, and material resources of schools, is essential when planning the skills that are to be practiced in invention projects. With the help of this framework, our goal is to continue to support and research the development of teachers' pedagogical skills and practices related to the technological competence involved in invention projects. Above all, our future goal is to explore how our framework supports the development of teachers' pedagogical competence and epistemic technological knowledge (see Chapter 15 of this book) and how this affects students' learning.

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Part II

Facilitating the Invention Process

The facilitation of multifaceted, phenomenon-based invention projects constantly seeks balance between openness and structure. The task for teachers who design, structure, and orchestrate invention projects is to guide student groups in setting goals, team activities, and interactions with consideration of students' individual needs and the nonlinear nature of the invention process. The facilitation of projects is supported by teachers' teamwork and tutor-student collaboration.

The second part of this book explores invention pedagogy from the viewpoint of facilitation and answers the questions of how invention projects are planned, implemented, and evaluated. The part begins by delving into the designing, structuring, and orchestrating of the invention process. Further, the chapters in this part highlight the importance of team teaching and cross-age peer tutoring in invention projects and address the questions concerning student evaluation in nonlinear learning.

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9 Designing and Structuring the Invention Process

Kati Sormunen, Kaiju Kangas, Tiina Korhonen, and Pirita Seitamaa-Hakkarainen

Introduction

Implementing an invention project at school and intertwining it with transdisciplinary curriculum contents can be challenging and require much effort from the teachers. Further, many Nordic countries have revised their K–12 curricula for education to provide knowledge that reflects current and future society. It has raised a question of how to develop the professionalism of the teachers and the student teachers to address new needs of curriculum change and digital competencies (Kjällander et al., 2018). Especially when implementation of new fabrication technologies in formal school settings is in its initial stages, maker projects have not yet built up to the clearly defined best practices.

The teacher has a crucial role in developing students' creative and innovative qualities and habits by engaging them in participating in the sociocultural world through authentic making activities (Härkki et al., 2021). Invention projects are not based on a distinct subject but on skills that can be integrated into many disciplines. The meaning of the invention projects is built on transdisciplinary and engaging learning activities, but the implementation of these projects needs careful planning, designing, scaffolding, and support. The challenges are related to the transdisciplinary nature of nonlinear invention projects, new curriculum changes, projects' structures, and teachers' collaboration. The challenges include teachers' competencies in teaching new digital tools and how fabrication technologies are introduced into existing school environments. Also, teachers might not have personal experience with these novel ways of learning.

Previous studies have revealed that teachers need pedagogical support for practical examples, models, and structures to design and conduct meaningful maker projects (Andersen & Pitkänen, 2019; Smith et al., 2016). In our research projects, we have worked closely with teachers in the field and organized workshops aimed at developing teaching practices by modeling invention project phases, supporting teachers' digital competencies to implement invention projects in their schools, and getting familiar with pedagogical practices of team teaching (Härkki et al., 2021; see also Chapter 11 of this book). Similarly, the teacher education program addresses the same needs. The invention projects challenge student teachers' existing competencies, and there is a need for a framework that considers how invention projects need to be designed and what significant components and phases they

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should consist of to be appealing to various kinds of learners. In several workshops and courses in the teacher education program, we have introduced design principles and models for nonlinear learning projects complying with the National Core Curriculum for Basic Education (Finnish National Agency of Education [FNAE], 2016) policies and providing practical training for relevant digital technologies such as e-textile, programming, and robotics. A fundamental principle has been to engage and empower teachers and student teachers to innovate invention projects rather than to implement them directly (Andersen & Pitkänen, 2019; Kjällander et al., 2018). In this chapter, the invention pedagogy process model is based on research-based models of project-based engineering and learning by collaborative design (LCD). As a practical example of professional development of teaching new pedagogies, since 2016 we have been using the invention pedagogy course organized annually for master's-level teacher education students.

Pedagogical Processes for Invention

In an invention project, the work is guided by an open problem, which becomes more precise as the solution develops. Students work actively together toward a common object. The intermediate stages of the process (ideas) and the final output (the solution) are modeled with different artifacts. Perceiving the holistic view of the invention process helps both teachers plan activities and students in their work. It also enables teachers to facilitate, mentor, and supervise students' collaborative learning process (Jenkins et al., 2003; Stamovlasis et al., 2006). The invention projects are often longitudinal and can last from a few months to an academic year to provide enough opportunities to develop and experiment with common ideas through several iterative invention cycles. The first invention projects are often shorter experiments in which the skills needed to invent are practiced, and they can be implemented by organizing a one-week invention week. Such short experiments allow the teacher to experiment with structures that support students' active participation and for students to perceive how the project is progressing and learn what is expected of them. Learning can be supported by various participatory models and methods that highlight the steps of a nonlinear process typical of an invention process. Models are helpful, especially in project design, even if the invention process does not proceed linearly from start to finish in stages.

Several models and methods are suitable for the pedagogy of invention in which the student is an active actor (e.g., Krajcik & Shin, 2019; Schwarz et al., 2016; Seitamaa-Hakkarainen et al., 2010). At its simplest, an inventing process can be encapsulated into three steps: think, make, and improve (Martinez & Stager, 2019). Martinez and Stager (2019) based the process on the "learning by making" concept, in which making stands for working with tools and materials; tinkering for a playful mindset with problem-solving, experimentation, and discovery; and engineering for the "application of scientific principles to design, build, and invent" (Martinez & Stager, 2019). However, relying on learning sciences research, we argue that students also need to learn how to construct their understandings actively, make connections between disciplines, and apply them by working with and using ideas in real-world contexts (Sawyer, 2019). To this end, the teacher and the student need more detailed process phases, especially in early experiments, to identify related disciplinary practices and orient their work in the direction of an open-ended problem. Since the invention projects often emphasize science and craft and technology education, we have framed the pedagogical process of inventing on the project-based learning (PBL) that connects scientific and engineering practices as well as the LCD model in which knowledge creation is enrichened with design practices (Figure 9.1). Although created in different disciplinary contexts, the selected process models are close.

The Project-Based Engineering Process

The PBL is widely used globally and is also applied in Finnish science education (Sormunen et al., 2020) and various STEM or STEAM projects. PBL has its roots in Dewey's (1959) idea of real-world problems capturing students' interest and provoking serious thinking as the students acquire and apply new knowledge in a problem-solving context. Learning scholars (e.g., Krajcik & Shin, 2019) have refined Dewey's original idea that active inquiry produces deep learning. PBL is based on an active construction of knowledge by participating in real-world activities, experiencing phenomena in various scientific practices, constructing shared understanding in collaboration with teachers, students, and community members, and using cognitive tools to support students' problem-solving skills.

Figure 9.1 depicts the project-based engineering process, which emphasizes the engineering practices that are essential in solving real-world problems and creating artifacts. It is cultivated from the PBL process moving through overlapping phases (Krajcik & Shin, 2019). The process is initiated by asking and refining questions, but when the emphasis is on designing and engineering, the process begins with identifying a problem, which can direct learning in numerous directions (Krajcik & Delen, 2017; Krajcik & Shin, 2019). However, emerging real-world questions and teacher-set learning goals guided the project throughout the process: Students search for solutions in collaboration with their peers by designing and conducting investigations and gathering, analyzing, and interpreting information and data. Students are scaffolded with learning technologies to solve emerging problems during the inquiry process and to help them move beyond the information gathered toward a tangible artifact. Students' learning is visible by creating shared artifacts and reporting on the process. During the project-based engineering process, they learn about and apply scientific concepts, principles, and practices, much like in the complex social situations of expert problem-solving (Krajcik & Shin, 2019). Many methods and models focus on engaging students in design to learn science, but we claim that design as its own discipline has its own design practices that need to be emphasized, such as the role of external constraints and various mediums for external representations.

The Learning by Collaborative Design Model

Previously, we have developed the LCD model to facilitate design processes and students' design thinking (Seitamaa-Hakkarainen et al., 2010). Theoretically, the

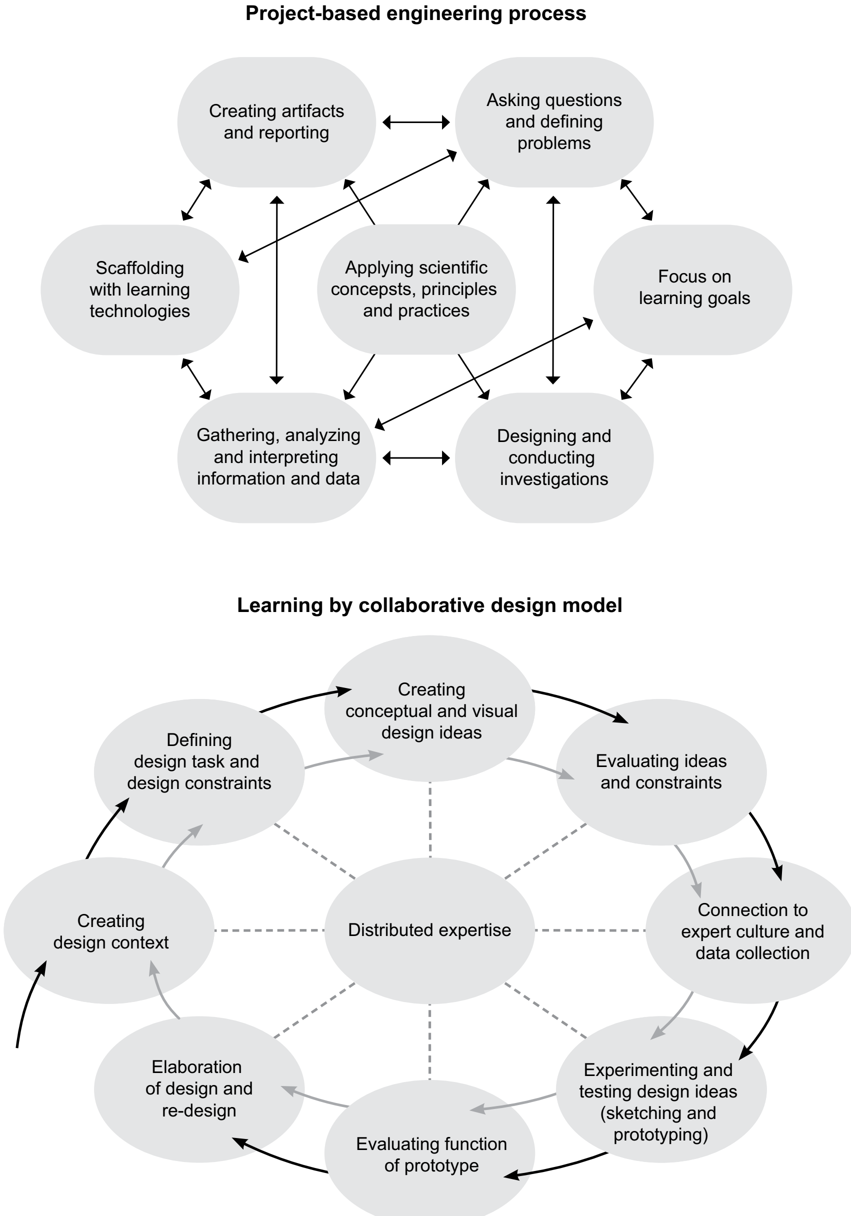


Figure 9.1 The project-based engineering process modified from Krajcik and Delen (2017) and Krajcik and Shin (2019), and the LCD model modified from Seitamaa-Hakkarainen et al. (2010).

LCD model is based on academic concepts of progressive inquiry and design thinking (Cross, 2011). According to Cross (2011), design thinking can be seen as a designer-like way of knowing: designers need to have the capability to define, redefine, and change a given problem situation through design activities. In the design process, problems and solutions co-evolve, and designers problem-solve in solution-focused tackling of ill-defined design challenges (Cross, 2011). Within the LCD model, the design integrates thoughts and actions, and designers navigate complex and messy design situations through iterative reflection-in-action and the creation of various external representations and material prototypes. The aim of the LCD model is to engage the students in collaboration toward an explorative and iterative design process to generate knowledge through making (Seitamaa-Hakkarainen et al., 2010). Thus, the LCD model emphasizes the socio-material aspects of designing: how conceptual design ideas are cyclically developed through various visual sketches, mock-ups, and prototypes toward final artifacts. The model describes the design process as a spiral in nature by approaching the optimal design iteratively through successive design cycles. In the LCD model, a starting point is an idea in which all participants are working to develop the shared design object by sharing their expertise socially. The model emphasizes that collaboration should occur at all stages of the design process by creating shared design contexts, analyzing design constraints, collecting, and sharing new knowledge, prototyping, and providing feedback for the artifacts being designed. The question is not simply to divide labor between various parts of the overall design project, but the whole design team has a central role in this activity.

The LCD process starts with all participants performing a joint analysis of the design task and design context. They must analyze the design constraints (i.e., external requirements). Various, sometimes conflicting, factors that affect the design process and define its requirements must be considered when framing the design context. The design constraints form the design context by defining the intended users and their unique needs for the artifact, the function of the artifact, and the resources available. The efforts of the participants are organized toward developing shared design ideas (conceptual artifacts), embodying and explaining those ideas in visual sketches (graphic artifacts or inscriptions), and giving the ideas a material form as prototypes or results (e.g., produced products). The design process appears mediated by the shared artifacts being designed from the beginning to the end. Thus, constant cycles of idea generation and testing of design ideas by visual modeling or prototyping characterize the design process.

The Invention Pedagogy Process Model

Both previously presented models have been the backbone when we developed our invention pedagogy process model. Both project-based engineering and LCD models are well known in Finland, and we have introduced them in our workshops for teachers in the field and teacher education courses. Both models view the complete science or design process as involving several phases. The invention pedagogy process model has been developed in research-practice collaboration since 2015. Through over 50 invention projects organized in early childhood and school settings, we have found that the classes benefit from a well-structured and designed project plan and a visual process model that structure students' open-ended, nonlinear creative processes. Nonlinear learning does not mean aimless and unrestricted activities, but the process requires clear planning and structuring. Based on participants' experiences and research findings, we have designed, tested, refined, and developed the invention pedagogy process model (Figure 9.2), which follows a seven-phase path: (1) orientation to the topic and work; (2) defining the invention challenge; (3) brainstorming, information gathering, and evaluation of ideas; (4) testing and developing the chosen idea; (5) evaluation and approval of the plan; (6) modification, implementation, and fabrication of the artifact; and (7) presentation and evaluation of the work. Understanding the holistic invention process helps teachers and students to work.

Careful planning is essential in the implementation of invention projects. A project's planning considers the various phases of the process. It ensures that some of the tools, materials, and content used during the process and the skills required are already familiar to the students. These cannot be entirely determined in advance, but the teacher can ensure that students are not overburdened with new content and skills to be learned in the assignment. When planning invention projects, it is worth considering the boundary conditions of the project, which are based on the skills of the participating students and the available resources. The larger the project is, the more it requires teachers' well-designed orchestration. It is worth outlining the project schedule and phases when planning a project. The plan is unlikely to materialize as expected, but it will help teachers and students to understand the use of time and the extent of the output to be implemented. In addition, it is necessary to consider how to involve students in the planning of the project. Preplanning also

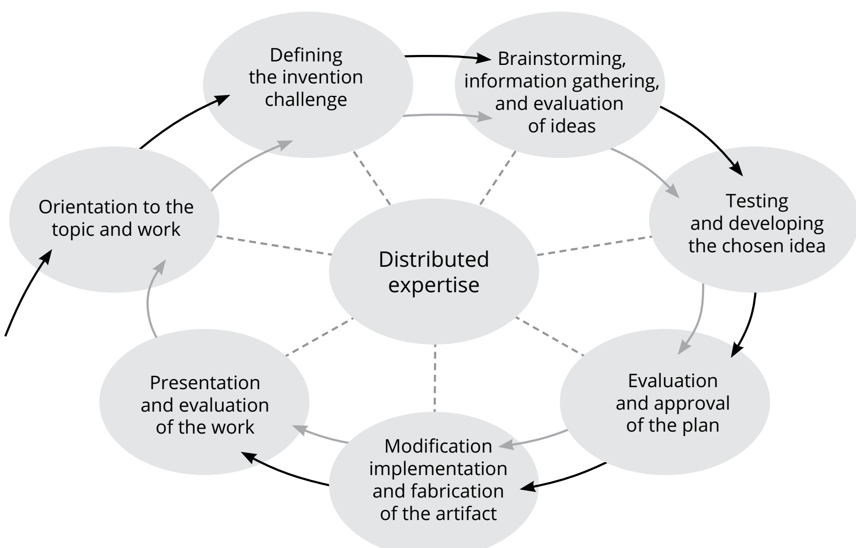


Figure 9.2 The invention pedagogy process model

helps to assess whether students have the skills to use the tools needed to work. These issues are discussed further in the next chapter (see Chapter 10 of this book).

Case: Invention Pedagogy in Teacher Education Course

This case example illustrates how the implementation of the invention pedagogy process model was taught to teacher education students. Teacher education has a crucial role in supporting teachers' learning of new knowledge and competencies that they may not have learned in their initial days (Lavonen, 2021). Therefore, it is essential to connect novel development and research findings like designing and structuring the invention process to the teacher education program. In Finland, the high quality of education is based on university-level teacher education, equipping teachers with deep and broad research-based professional knowledge and skills (Lavonen, 2021). When entering the field, they have the competencies to phase practical challenges, apply research-based knowledge about teaching and learning, and develop their expertise further (Lavonen, 2021).

Invention Pedagogy Course Design

The invention pedagogy course (five credit points, optional studies) was organized at the University of Helsinki for master's level teacher education students following the principles of research-based teacher education. The objectives of the course were to become acquainted with the pedagogical aspects and components of invention pedagogy, become familiar with research and practices in the field, and plan and implement transdisciplinary and phenomenon-based teaching that utilizes pedagogical approaches to maker and design education. The main goal was that after completing the course, the student teachers could design, apply, and develop learning entities that support creative invention.

The course design began with an orientation lecture (1.5 hours) on the theoretical basis of invention and maker pedagogy and two three-hour sessions during which student teachers learned technology orientations of inventing. After these orientation sessions, the students participated in the invention pedagogy workshop, including four three-hour sessions that followed the invention pedagogy process model. Student teachers kept a learning diary during the course and an invention process portfolio during the invention process sessions. In both, they mirrored their experiences with national and international articles.

The rationale was that teachers or student teachers have rarely been involved in nonlinear and open-ended design projects addressing real-life contexts and lack the experience to manage such processes (Andersen & Pitkänen, 2019; Smith et al., 2016). Further, within short technology sessions, we guaranteed that they have some understanding of digital tools and materials to work while inventing. Further, by the invention pedagogy process model structure, we can demonstrate and provide student teachers with their own experiences from a learner's perspective. We have used a similar approach with similar content in all our workshops for teachers in the field. In the following, we present the invention pedagogy process model through these course sessions, enriching them with examples from course implementation and teacher-student portfolio entries.

The Phases of the Invention Pedagogy Process

The actual invention process was introduced to the student teachers in the fourth session, in which they participated in the teacher-led process. To design the structure of the invention process, the teacher educator used research-based good practices gained from several co-invention research projects conducted at schools.

Orientation to the Topic and Work

The invention process begins with an orientation phase in which group work is set up. The creative process requires a creative atmosphere (Fisher, 2014) in which group members encourage and support each other, so it is worth doing exercises that help grouping for the first few times.

> *Orientation to Work and Building Team Spirit.* The invention pedagogy workshop began with a group exercise aimed at building team spirit and tracing and making visible the knowledge and skills of the group. The teacher had prepared a list of words that described the strengths and skills needed during the project. First, the student teachers chose three to five words that represented them. Then we grouped them into teams of four, and each student presented their strengths and skills to the other group members. The team's final task was to visualize their group's strengths using the word cloud or graphic design tools.
>
> *Orientation to the Topic.* Before the workshop, the student teachers had to do an orientation task to envision the future (Perttula & Sääskilahti, 2004). The assignment was as follows: "You travel in time, first, five years, then 50 and 100 years onwards. You are standing in a place where the kitchen of a Finnish home was in 2021. Fill in the worksheet: What do you see around you when you look at (1) the kitchen as a space, (2) the person in the kitchen, and (3) the technology?" The student teachers discussed their envisioning in their teams and gathered a common vision using Google Jamboard.

Defining the Invention Challenge

After orientation, an invention challenge is determined, and the teams set out to find a solution. The form of the challenge and design constraints (Cross, 2011) has a vital role for students: It should be challenging enough to engage in problem-solving but not too hard for them to follow the challenge independently. When implementing an invention project for the first time, starting with a limited topic is recommended. It is also necessary to plan the goal of content and skills pursued in learning.

> *The invention challenge* was introduced to student teachers using a recent newspaper article about how stress negatively influences people's eating habits. Student teachers defined the concept of eating habits so that everyone had an understanding of the subject and listed lousy eating habits on sticky notes.

The goal was to bring together as many perspectives as possible for the next phase. Finally, the teacher educator introduced the actual invention challenge: "How will unhealthy eating habits affect humankind if we ignore our habits?" The teacher educator used a picture of morbidly obese humans from the Wall-E movie to evoke thoughts.

Brainstorming, Information Gathering, and Evaluation of Ideas

At the beginning of the brainstorming phase, students throw in ideas, i.e., they try to produce as many crazy and playful ideas as possible. In this phase, it is worth utilizing various ideation methods and encouraging students to familiarize themselves with previous applications of the research subject (see Chapter 5 of this book). Information gathering provides new perspectives on ideation. At this stage, students try to delineate the problem by evaluating the ideas produced and considering the boundaries set by the teacher for the invention challenge. These can include the tools or materials available or the conditions set by the teacher in relation to the teaching objectives.

The brainstorming session began with the automation and robotics ideation connected to the visions of the future kitchen from the previous phase. The teacher educator reviewed the most common sensors (e.g., temperature sensor, motion sensor, light sensor, and touch sensor), and the student teachers became familiar with the operating principles of the sensors. Then a distant model ideation method was used, and the teams tried to find inspiration for the design problem using distance domains. In this case, the teams looked at the analogies using the Wall-E robot and its features and properties.

1. *A distance model*: In the first stage, the teams produced at least five qualities from the image of a distant model (e.g., expressive, compassionate, able to stretch the "hand").
2. *An "insanely fun" idea*: In the second stage, the team produced five insanely fun apps based on their features (e.g., a human-like product that looks nice, makes good choices, and jokes quite often. It can pick up stuff with telescopic hands and tell jokes when it brings food).
3. *A plausible solution*: In the third phase, the teams develop one workable solution (e.g., a Miracle Machine, which makes the day's meals and encourages good eating habits). The plausible solution had to fulfill one condition: The object of the invention had to be a product from which teams could build a prototype by using the skills acquired.

Testing and Developing the Chosen Idea

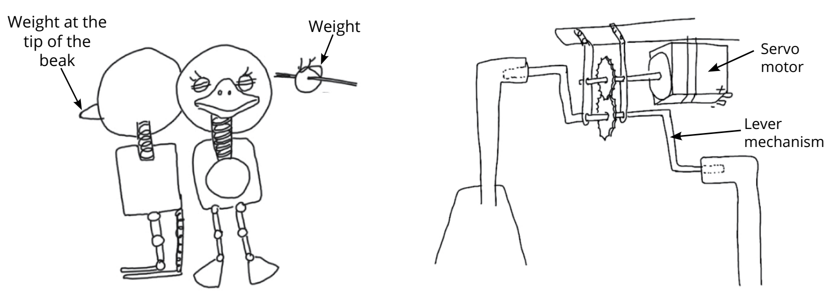
When the team has defined the problem, they evaluate ideas further by experimenting, testing, and redefining ideas. They may have one or more ideas before the group decides on the final subject of the invention.

> The student teachers had to make a design plan for the invention and a prototype to test and develop the idea. The design plan must include a sketch or blueprint and a description of the invention's functions. The teams also had to plan how they would utilize the technology in the product and what materials they would use to make it. Student teachers were encouraged to share tasks (e.g., programmer, designer, and prototype builder). Also, the teacher educator introduced the student teachers to the materials that were available for making the prototype. At this point, the educator also connected the content of technology education from the curriculum as conditions. Student teachers were required to use at least one of the technology dimensions learned in their work (e.g., 3D modeling, electronic and maker kits, simple machines, electricity, or app development software). Figure 9.3 illustrates one student teacher team's invention idea, the Empathetic Reminder, with excerpts from one team member's portfolio entries.

It is worth including digital tools the students are familiar with in the invention project. Otherwise, a large portion of the time is spent learning the basic use of the device. When students are already familiar with the tools, materials, contents, and skills required, they can deepen their knowledge or create something new. Teachers can also include some new elements, but it is necessary to consider what is being practiced or learned and what aspects are to be deepened when drawing up learning objectives. Especially when working with new technology, students benefit from a one-hour introduction to the tool. For example, if the learning objectives involve the creative use of a programmable device, the teacher should carefully teach the students the basic use of the device. As work methods and tools become familiar, it is natural for teachers to expand on the topics and guide the work.

The Empathetic Reminder

The Empathetic reminder blinks the lights and makes funny moves. It reminds me to eat every three hours. The device also talks to other kitchen equipment. For example, it makes food in the future kitchen, that is, fries worms.



Idea sketch: We could make the mock-up with Tinkercad and 3D print it. At school, each student could customize the product's look and think about how to make it move.

Technical drawing: We could mimic walking with a servo motor. It could also dance or shake. We could play Stayin' Alive in the background. This silly and funny reminder gets you in a good mood.

Figure 9.3 A student teacher team's idea sketch and technical drawing of their invention idea.

Evaluation and Approval of the Plan

Students present their idea to other students in a class or experts during the evaluation phase and receive feedback. Based on the feedback, the teams refine the plan of the object of the invention. They also collectively accept the final artifact to be implemented.

> Student teachers presented the plan and prototype of their invention idea to others whom the teacher educator asked to give one piece of positive feedback and one development proposal. Positive feedback was intended to help teams identify workable solutions, while development suggestions helped teams develop their inventions.

The peer feedback given and received during the invention project helps students understand their studying (process) and learning (outcome) and identify their skills and areas in which skills were not yet sufficient. Students also learn to correct their mistakes and develop their work to achieve the goals set for competence and learning. Giving and evaluating feedback can be done verbally or in writing.

Modification, Implementation, and Fabrication of the Artifact

The team makes prototypes, models, or products based on their ideas and plans. These artifacts can be business models, various presentations, or hand-touch products. The value of the models and intermediate outputs is that they make it possible to look at the solution from a new and different perspective. It makes it easier for students to detect the solution's functionality or the need for further development. Often, the invention process does not proceed linearly from start to finish in stages. Especially at this stage of implementation, it can be noticed if the chosen solution does not work, in which case it can be revisited to come up with new solutions and/or modify the plan.

> When working with groups of students, teams would typically set out at this stage to further develop their inventions based on peer feedback. However, because the aim of the invention pedagogy course is to apply the invention pedagogy at schools, the student teachers set out to work on an invention process plan for students, basing it on their own invention process experience. The task was to produce a project plan in groups and a related prototype (i.e., a model of the final output). The student teachers received support materials for planning, e.g., project guidance, project topic selection, student-level brainstorming, planning, design, and technology use. The materials included both literature and inspiration videos or pictures. The student teachers made their project plans on a template, which guided them (e.g., setting goals).
>
> The course ended with an invention fair in which students presented their plans and prototypes to others. One student teacher group elaborated their innovation idea, the Empathetic Reminder further (Figure 9.3), by developing an invention project titled Everyday Eco-machine for fifth and sixth graders.

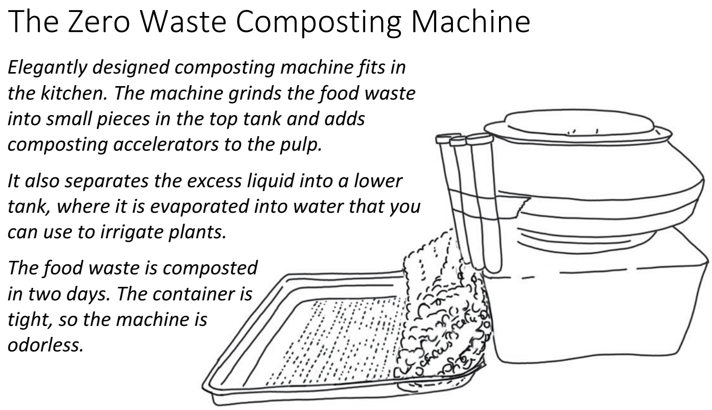


Figure 9.4 The prototype of sixth graders' invention solution: The zero waste composting machine.

> "The idea is that student teams design the future machine that can solve food and environmental challenges. The machine prototype is built from recycled materials. In addition, one or more functions or features are modeled on the prototype on the Adafruit Circuit Playground. A portfolio is compiled of the stages of the work. Finally, teams will present the inventions at the Invention Fair."
>
> (Student teacher's portfolio entry)

The teacher-student team's invention solution for the project is presented in Figure 9.4. Pictured is a drawing of artifacts made from students' recycled materials and an excerpt from one team member's portfolio entry.

An invention fair is an event at which students present the invention and its phases to the audience and receive feedback on their work. The audience can consist of other students in the class or school, parents, experts, or teams from other schools in bigger invention fairs. Before the fair, student teams plan the presentation, prepare an inspiring presentation, and practice presenting it. The invention process portfolio helps teams in this process. The invention fair can be held either during or at the end of an invention project. When the fair is held during the project, the presentation will focus on presenting the prototype of the invention. At the end of the project, student teams will present both the process and the finished inventions at the fair. The fair also provides a natural endpoint for the project.

Conclusion

The education of future creators and inventors emphasizes open-ended learning tasks in which students apply learned knowledge and skills to learn more in collaboration with their peers. The teacher's most important responsibility in these learning projects is to realize transdisciplinary learning. The goal is that no subject alone guides the learning process, but they are seamlessly combined into a holistic unit that is strongly connected to the real world. Often, transdisciplinary learning projects are driven by a pedagogical model developed in the context of a single subject or discipline. However, our goal has been to create a pedagogical model that supports the learning of today and the future in which activities that disrupt subject boundaries are possible. This chapter introduced the invention pedagogy process model based on the project-based engineering process and LCD models highlighting knowledge creation, science, engineering, and design practices. The end goal is to support the teacher and student teachers in designing pedagogically meaningful learning activities and engaging and getting the first experience of an explorative and open-ended process.

According to Smith et al. (2016), teachers have insufficient understanding of complex design processes and awareness of digital technologies and tools, and consequently, they experience a loss of authority and control of the teaching (Andersen & Pitkänen 2019; Härkki et al., 2021). We have developed a model of transdisciplinary cooperation in which the disciplines provide an inspiring context. The invention process model makes it easy for the teacher to lead the learning process in the classroom and provides the possibility to change traditional teaching methods in the school. When organizing workshops and courses related to invention pedagogy, we have aimed to empower teachers and student teachers to increase their understanding of invention pedagogy and related technologies in a way that strengthens their capability to try and take control of unfamiliar and unexpected aspects of the design process and to feel more confident applying it in their teaching. Also, the research-practice partnership (Coburn & Penuel, 2016) has allowed us to involve more teacher practitioners that were initially unfamiliar with the maker technologies and principles of nonlinear invention pedagogy. This opportunity has made it possible to support teachers during the invention projects we have initiated together.

It is self-evident that there are plenty of other design or maker-centered learning process models, such as design thinking (IDEO), that emphasize participatory and emphatic designing with users (see Chapter 5 of this book). We strongly encourage teachers and student teachers to familiarize themselves with these models and learn to find suitable tools to apply in their invention projects. Similarly, we support the teachers and student teachers in using various design materials and technologies in the design process.

Guiding open-ended learning assignments is often challenging for teachers, especially if they are leading the project for the first time. Although the invention challenge should be connected to the curriculum, at the same time, students should be given opportunities to work in the direction of their vision. A range of pedagogical models facilitate the teacher's designing and orchestration of work and help to anticipate challenges that students might encounter. Especially for teachers guiding a nonlinear learning process for the first time, the model helps outline the learning entity. For this reason, student teachers must gain firsthand experience with open-curricular learning tasks and nonlinear learning processes in teacher education.

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10 Orchestrating Invention Activities through Teacher's Multilayered Work

Kati Sormunen and Marjut Viilo

Introduction

The classroom conditions based on the invention pedagogy assume that the design processes are based on collaboration and anchored on students' ideas, questions, and current skills. It follows that the invention processes are often nonlinear, emergent, and open-ended in nature (see Chapter 2 of this book). In the pedagogical settings, aiming to develop the process and the object of the design process with the students, the outcomes, the content, or the process phases cannot be entirely known beforehand. The classroom discussion carried on by all participants, and based on collaboration and shared expertise, is described as improvisational (Sawyer, 2004, 2019). The individual members bring their contributions to the process by discussing and trying to build on the process turn by turn. Thus, the participants complement each other's skills and orientations. Working in such diverse groups offers several options for differently oriented students. On the one hand, the talented students can be inspired to take on more challenging tasks in the group, and on the other hand, working in cognitively diverse groups provides an encouraging example to those students who struggle with their learning for different reasons (Sormunen et al., 2020).

Despite the teachers' growing understanding of the student-driven design learning or inquiry processes, the ideal ways to support student participation or create compatible classroom activities may be challenging (Bielaczyc, 2013). In addition, a major challenge is the organization of collaborative and nonlinear activities with different kinds of learners. Even though collaboration relies on positive interdependence, peer support is often insufficient for struggling students. On the one hand, students need support and advice to function as active participants in the invention process. In contrast, too much structuring and direction may diminish their initiatives or ideation. The teachers need to accept openness, but at the same time provide sufficient structuring and scaffolding for the process (Jenkins et al., 2003; Viilo et al., 2018). These open-ended settings require creativeness in orchestration and teaching (Hämäläinen & Vähäsantanen, 2011; Sawyer, 2019). The concept of orchestration is used for describing the teacher's efforts in organizing and supporting the students' processes in individual, social, tool-mediated, and changing learning situations (Littleton et al., 2012).

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This chapter offers a perspective on orchestrating that can aid in understanding the organization or the procedural and timely guidance needed in the design, making, and invention activities. In these settings, the processes are open-ended, and the working methods are based on collaboration. First, we offer an overview of the elements within orchestration and distinguish between orchestration design and dynamic orchestration. Second, we illustrate the orchestration solutions in four different invention pedagogy settings with a lot of student diversity. Examining cognitively diverse classes provides an overall understanding of the intensity of orchestration in relation to the need for student support. Finally, we discuss the experiences learned from the settings.

Elements of Orchestrating Invention Process

When implementing the ideas of invention pedagogy and designing, the teacher's challenge is to engage all students in learning. In collaborative efforts, the teachers' primary aim is to sustain the practices that involve the students using their own ideas and organizing their collaborative process (Hakkarainen, 2009). In cognitively diverse classes, the need for differentiation is necessary because "one-size-fits-all" education must be changed to methods that support and inspire all students learning. Orchestration-minded invention pedagogy is convenient in cognitively diverse inclusive classes because invention activities are adaptable to various kinds of learners (e.g., Sinervo et al., 2021). To succeed, cognitively diverse student teams need support to participate in and develop the shared community. Overall, it requires orchestrating and promoting the collective pedagogical settings in which idea improvement is the central focus rather than a separate learning task or activity (Zhang et al., 2018).

Effective participation in design-oriented approaches to learning requires teachers' timely guidance in several layers of ongoing team, personal, and tool-mediated processes in changing situations. When describing this multilayered work, the concept of orchestration has frequently been used as a metaphor. It involves managing the collaborative processes within several ongoing trajectories in complex learning settings where the tools, materials, and supportive learning technologies are all connected and mediate the collective process (Littleton et al., 2012). Significantly, the concept captures the unplanned aspects of the enacted situations and therefore is well placed in the context of nonlinear settings (Hämäläinen & Vähäsantanen, 2011; Seitamaa-Hakkarainen & Hakkarainen, 2017).

On the other hand, the orchestrated settings can be positioned along a line between research perspectives highlighting the importance of structuring and scripting the processes of learning beforehand and perspectives emphasizing the emerging need for activities (Hämäläinen & Vähäsantanen, 2011; Prieto et al., 2011; Viilo et al., 2018). At one extreme, within a classroom based on pre-given and scripted procedures, the teacher often controls learning despite the student-centered aims (e.g., Kirschner et al., 2006). At the other extreme, there is a need to highlight the principle-based emergent knowledge practices that emphasize student and teacher invention and ownership (Sawyer, 2004; Zhang et al., 2018). Therefore, the success of invention pedagogy requires the right amount of structure and flexibility, with the teacher balancing between them. Only the teacher, who is familiar with the students and their needs, can define the suitable higher-level objectives and apply the strategic guidance of the process based on contextual knowledge.

When defining the elements of orchestration, it is helpful to distinguish the two meanings of orchestration, *orchestration design* and *dynamic orchestration*, as suggested by Sharples and Anastopoulou (2012). Designing of orchestration covers the previous arrangement of the learning setting. Dynamic management defines regulating and adapting the plans in unfolding activities and enacted practice to achieve productive results (Prieto et al., 2011; Sharples & Anastopoulou, 2012). Whether the aim is to create a structured or open-ended setting, both orchestration phases are present. However, the desired setting and the local context strongly affect how the orchestration design or the dynamic orchestration is created.

Creating Orchestration Design

When creating the design for inventory activities, it is essential to plan for improvisation and open spaces where teachers can support the students' ideas and lines of inquiry. However, sometimes designing orchestration has been associated with instructional planning (Prieto et al., 2011). The design can model learning activities, sequencing their time, event, and participant perspectives (Dillenbourg, 2015). It may include flexible macro scripting that supports the educational practices and actions of the proposed invention process and a collection of micro scripts to help the participants perform them. For instance, the invention pedagogy process models may be considered macro scripts (see Chapter 9 of this book). Nonetheless, the more explicit and rigid the educational structure or script, the less opportunity exists for flexible adaptation and improvising and spontaneous solutions present in genuine invention processes (Sharples & Anastopoulou, 2012). On the other hand, the teacher must work out beforehand how to help students with different learning orientations to be active participants in emerging processes. Especially in cognitively diverse classes, the students who struggle with their learning may benefit from well-designed learning tasks and adaptable approaches to fit different learners (Norwich & Lewis, 2001; Sormunen et al., 2020).

The overall orchestration design for implementing inventory and emerging activities can also be approached with the help of the pedagogical infrastructure framework (Lakkala et al., 2008). The framework suggests four supportive infrastructures: technical, social, epistemic, and cognitive, designed when creating student-centered pedagogical settings. The perspectives are partly overlapping in practice, but a teacher may use the framework as a thinking tool when creating the learning setting. In the context of invention pedagogy, the pedagogical infrastructures framework has also been applied in makerspace studies (e.g., Riikonen et al., 2020; Chapter 14 of this book).

In the infrastructure framework, the technological arrangements include the affordances of the tools for promoting design activity and the arrangements for providing access to and guidance for using the technology and tools (technical infrastructure). For example, the purposeful usage of technology embedded in students' practices mediates the participants' ideas and processes to team members or the whole learning collective. It makes the process stages or planning visible (Littleton et al., 2012; Viilo et al., 2011). Digital technology can also be viewed as a mechanism for inclusive, differentiated pedagogy that enables the use of multimodal learning materials, provides access to information and resources, and enhances function without stigmatizing any student (e.g., Cumming & Draper Rodríguez, 2017). It can be beneficial to struggling students, helping them to meet their curricular goals and to assist them in gaining social and functional skills (Sormunen et al., 2019).

In invention pedagogy, the social arrangements should entice the participants to collaborate and create a common ground (social infrastructure). The solutions to be made include how to foster interaction and collaborative action. Productive collaboration may require, for example, explicit rules, agreements, and organizational structures (Lakkala et al., 2008). Typically, a task that leads to productive interaction requires cognitive diversity and heterogeneous group structures (Hämäläinen & Vähäsantanen, 2011). Teachers can also support the collaborative process through flexible grouping in various forms, such as learning with a partner or in small groups (e.g., van de Pol et al., 2014). However, cognitively diverse groups often require teachers' support when preparing and implementing a project. Also, the learning task can be designed according to individual students' differentiation needs, such as integrating the differentiated academic content (e.g., more demanding aims for the more talented) into a student's group role (Sormunen et al., 2020).

In the spirit of design learning and invention activities, learners must treat ideas, plans, and prototypes as epistemic objects (see Chapter 3 of this book) that can be shared and jointly developed (epistemological infrastructure). In addition, educators should facilitate the participants' understanding and reflection on practices and processes to organize their developmental process (cognitive infrastructure). Students' self-regulative competencies and meta-skills for planning, monitoring, and reflecting on their work should be supported; this could take place through providing conceptual tools such as guidelines, models, or templates. When creating orchestration design, the infrastructure framework helps prepare the task structures, beneficial ways to interact, and other resources to support the process in well-working combinations. However, defining the best solution of task structuring between open-ended or structured tasks without contextual knowledge is not possible. Both ends may develop a sound basis for collaboration and invention (Hämäläinen & Vähäsantanen, 2011).

Dynamic Orchestration during the Invention Process

Hämäläinen and Vähäsantanen (2011) have pointed out that the main idea of orchestration is to combine design and improvisation; this means considering the unplanned aspects of the ongoing nonlinear invention processes. Dynamic orchestration focuses on the need for teachers to maintain the simultaneous ongoing activities on different planes: personal, group, and class (Sharples & Anastopoulou, 2012). When the orchestration design has been adapted to the local context, and the emerging occurrences in practice, the teachers' assessment provides insight into the progress and adequate adjustment (Prieto et al., 2011). Therefore, the teacher and students must iteratively reflect on learning and advancement of invention activity. However, in a well-orchestrated process, the teacher regulates the various aspects of the learning situation across multiple time scales: First, longitudinally from stage to stage adjusting the support as the process develops, and second, in real-time, during the enacted moments (Prieto et al., 2011; Viilo et al., 2018).

During the dynamic orchestration of the longitudinal invention process, the teachers cannot concentrate only on what any student or team requires at the moment, but also on what they believe the collective invention project and attaining its objectives require (Puntambekar & Kolodner, 2005; Viilo et al., 2018). It means supporting the long-standing efforts to create conditions for advancing the invention process such as guiding participants to document the advancement of inquiry, organizing, and planning the design process further (Hakkarainen, 2009; Seitamaa-Hakkarainen & Hakkarainen, 2017). It also means that the teachers must follow and reflect on the process in the background, and design the support needed based on the participants' achievements (Viilo et al., 2018).

The dynamic orchestration in real-time involves the features of improvisational teaching (Sawyer, 2004). The invention pedagogy that aims to support students' self-regulation, invention, and design activities, entails emergent and improvisational aspects during the process due to its nonlinear nature. In creative improvisational teaching, the teacher works with a unique group of students responding to their emergent needs (Sawyer, 2004). The processes need to be constructed as a shared social activity in which the students and the teacher manage and participate in the collective process together (Sawyer, 2004). However, improvisation in teaching should not be associated with unconstrained creativity and personal expression. The researchers who call for creativeness or improvisation in teaching also call for purposeful structures (Parker & Borko, 2011; Sawyer, 2019). To succeed, teaching needs to be anchored on disciplined or guided improvisation that gives students the freedom to build and create their knowledge while shifting between carefully chosen elements of structure (Sawyer, 2004, 2019).

The invention process based on students' plans and designing creates genuine opportunities and a need for collaboration and sustains collective object-oriented classroom discourses. However, the emerging classroom collaboration may require the management of the participatory aspects of social interaction that help participants contribute so that everyone in the team is participating and listening. The teacher also must observe and comment on students' reciprocal interlinkages and their relations to the materials and objects of inquiry. The genuine need for collaboration provides support for practicing collaboration skills through differently supported learning tasks (Hämäläinen & Vähäsantanen, 2011). Participants also need to have enough common ground and an emotionally safe atmosphere in which diverging beliefs and disagreements are critically examined, but not in a disputational way (Hämäläinen & Vähäsantanen, 2011).

The following sections illustrate four cases of orchestrating invention pedagogy in which the decisions involving the differently balanced structures and freedom varied. We concentrate on cognitively diverse classes, especially the student teams including struggling students. The purpose is to recognize the ways of working that may help all kinds of students' participation in invention pedagogy processes.

Context and Analysis

Orchestration of invention activities varies in cognitively diverse classes. We followed four invention projects in four classes using a multiple case study method (Stake, 2005) (Table 10.1). The classes had a similar variation of gender and ethnicity, and some of the participating students had been identified as struggling learners. In *Classes 1 and 3*, the struggling students worked among cognitively diverse teams during the projects. In *Class 2*, struggling students worked alone or with a pair and in *Class 4* in cognitively similar teams. We only followed a few teams in each class, although there were many more.

The aim of all projects was to design and invent an intellectually challenging, aesthetically appealing, and personally meaningful complex artifact that integrated physical and digital elements. The project name and learning objectives varied within projects. In *Class 1*, the student team's challenge was narrower than others focusing on a similar output, a scale model house. Other projects sought to find diverse, inventive solutions to everyday problems. The duration of the projects ranged from 11 to 14 weekly lessons (90 minutes per lesson).

The data were collected from teachers' project plans, researcher's observation notes, and students' portfolios. All teachers made detailed project plans in which they set the learning objectives. One of the authors participated actively in planning all the projects. During the project, she created detailed observation notes from each lesson. The researcher's role is significant, especially in cognitively diverse classes, in which the researcher must have participants' complete trust (Stake, 2005). The observation notes were compared to project plans and students' portfolios. The data was systematically investigated through theory-guided content analysis (Stake, 2005) grounding it on previous studies presented at the theoretical background. The pedagogical infrastructure framework (Lakkala et al., 2008) and the improvisational teaching (Sawyer, 2004) served us as the thinking tools when defining how orchestration design and dynamic orchestration were formed within the cases (Tables 10.2 and 10.3, first column). The primary aim was to illustrate how the enacted process took its form into practice by elaborating on the teacher's

Table 10.1 Background information and data collection of participating classes

Project	*Grade*	*Number of students (struggling students)*	*Teachers (assisting staff)*	*Number of co-inventions (personal inventions)*
Class 1: Scale model house	6 (ages 12–13)	44 (10)	3 (1)	4 (–)
Class 2: My invention	7 (ages 13–14)	6 (6)	3 (2-3)	1 (3)
Class 3: Everyday challenges	6 (ages 12–13)	47 (9)	3 (1)	13 (–)
Class 4: Smart product	7 (ages 13–14)	7 (7)	1 (1)	4 (–)

background organization and guidance during the unfolding activities. Our previous analyses have defined similar elements (Sinervo et al., 2021; Sormunen et al., 2020;Viilo et al., 2011, 2018).

Findings

The nature of orchestration varied from highly structured (*Class 2*) to highly flexible implementation (*Class 3*), providing information on effective orchestration practices. In what follows, we describe the main elements affecting the orchestration design and then elaborate dynamic orchestration of the invention projects through the teachers' organization before the lessons and teachers' guidance during the unfolding activities.

Orchestration Design

The orchestration design varied in different class settings according to learning design and support for active student collaboration (Table 10.2).

Learning Design

All projects were pedagogically anchored and were planned to begin with teacher-led ideation activities and continue through sketching to the production of functional prototypes. *Class 1*'s project design was based on maker-centered project-based learning, unlike the others (Sormunen et al., 2020), following a relatively linear and structured process from beginning to end. In *Classes 2*, *3*, and *4*, teaching and learning were based on nonlinear invention pedagogy. They followed the invention pedagogy process model as presented in Chapter 9 of this book.

Teachers in all classes set transdisciplinary learning objectives for the project, integrating science and mathematics, crafts, and visual arts, and four or five transversal competence objectives, depending on the project (Finnish National Agency of Education [FNAE], 2016). Two projects (*Classes 1 and 3*) included also Finnish language objectives, meaning that all students practiced reading, writing, or listening skills during the process. Unlike in other classes, in *Class 1*, the teachers had already considered the students' learning needs at the design stage. They set differentiated learning objectives for each student, especially for struggling students and talented students.

The projects' learning objectives also highlighted socio-digital (information and communications technology, ICT) competence as an object or tool for learning and technology-enriched materials were essential parts of all projects. In the Finnish curriculum (FNAE, 2016), technology education is a multidisciplinary and cross-curricular entity that is practiced in science (e.g., engineering), mathematics (e.g., programming), and crafts (e.g., designing and manual and digital crafting). Teachers included crafting and engineering elements in their project design, but more specific technology content was unclear during the orchestration design phase. However, programming was considered initially because some or many of

Table 10.2 Elements of orchestration design in four different invention projects

Elements	Class 1: Scale model house *Structured orchestration*	Class 2: My invention *Highly structured orchestration*	Class 3: Everyday challenges *Highly flexible orchestration*	Class 4: Smart product *Flexible orchestration*
Learning design	*Pedagogy* Maker-centered project-based learning *Learning objectives* Differentiated content of science and mathematics, crafts and visual arts, Finnish, and transversal competencies. Technology enrichened learning materials: crafting tools, electronics, multimodal learning materials, and digital portfolio.	*Pedagogy* Invention pedagogy *Learning objectives* Integrated into the invention/ design challenge: science and mathematics, crafts and visual arts, and transversal competencies. Technology enrichened learning materials: crafting tools, electronics, robotics, and electronic and maker kits.	*Pedagogy* Invention pedagogy *Learning objectives* Integrated into the invention/ design challenge: science and mathematics, crafts and visual arts, and transversal competencies. Technology enrichened learning materials: crafting tools, electronics, 3D designing, robotics, electronic and maker kits, and digital portfolio	*Pedagogy* Invention pedagogy *Learning objectives* Integrated into the invention/ design challenge: science and mathematics, crafts and visual arts, Finnish, and transversal competencies. Technology enrichened learning materials: crafting tools, electronics, 3D designing, electronic and maker kits, and digital portfolio.
Support for active student collaboration	*Engagement* Possibility to choose an engaging learning task and make a wish for group members *Grouping* Interest-, student- and teacher-led grouping based on students' wishes and intensive teacher-support for teams with struggling students	*Engagement* Possibility to choose an engaging learning task and work independently or collaborate *Grouping* Teacher-led grouping based on students' wishes and teachers' knowledge of students	*Engagement* Possibility to choose an engaging learning task *Grouping* Interest- and student-led grouping based on students' wishes	*Engagement* Possibility to choose an engaging learning task *Grouping* Interest-, student- and teacher-led grouping based on students' wishes and teachers' knowledge of students

the programmable devices were new to the students. In *Classes 2*, *3*, and *4*, the invention challenge directed students to use programmable devices. The teachers designed two to four lessons where students learned the basic skills of these tools. For example, teachers designed the programming lessons at the beginning of the project (*Classes 2 and 3*) or just after students had finished their initial ideation (*Class 4*).

Technology was also designed as a tool for process organizing. The digital learning environment (Office 365) was set up to mediate the process and achievements between students by organizing the process, giving guidelines and setting tasks (*Class 1*), and for reporting the progress of the process after every lesson and sharing it in the digital learning environment (*Classes 1*, *3*, and *4*). In *Class 2*, teachers chose not to use process portfolios. Teachers felt that the students should focus more on practical skills than academic ones to build the invention rather than getting frustrated with academic writing.

Support for Active Student Collaboration

Teachers designed support for active student collaboration by focusing on student engagement, giving them authority over their own learning, and using different grouping methods. In *Classes 1*, *3*, and *4*, the students were required to cooperate, and most of the students worked in pairs or small groups based on an interest-led, student-led, and/or teacher-led grouping. In *Class 1*, before the project, students completed an initial survey that mapped students' interests and asked them to assess which students in the class supported their learning best. Teachers grouped students according to their interests, but they also considered students' personal needs. Teachers planned struggling students' grouping especially carefully because research shows that careful grouping promotes student collaboration during the project and supports the development of social skills (e.g., Jenkins et al., 2003). In *Class 1*, the teachers also agreed on how to support every student team's work.

In *Classes 3* and *4*, teachers supported active student collaboration through interest- and student-led grouping, which took place after the first ideation session. In *Class 3*, the students were allowed to choose the most engaging invention idea and form teams and select team members by themselves. Also in *Class 4*, the students formed teams based on their interests, but the teacher made the final decision on each team's combination. She assessed what would be the team's chances of succeeding, reflecting on previous collaborative learning tasks. After teacher-student negotiation, some students changed teams.

In *Class 2*, the teachers encouraged students to collaborate, but also allowed them to work alone. Teachers based their decision on the fact that working with another student was particularly challenging for some students. Some students' participation was influenced by self-regulatory, socio-emotional, and other skills needed in peer collaboration. The teachers listened to students' perceptions and evaluated the meaningfulness of cooperation based on student knowledge.

Dynamic Orchestration

The teachers' dynamic orchestration that maintained the unfolding process was identified as teachers' organizing and guidance activities (Table 10.3). Each teacher's organizing included work and support prepared for the lessons. This support was based on the students' ongoing process achievements. The maintenance of the process during the lessons was the teacher's guidance. It involved flexible responses to the students' unfolding work and discussion.

The Teacher's Background Organization

In each class, teachers planned how best to support the students' invention process advancement during each lesson. Except in *Class 2*, teachers supported teamwork between lessons in a digital learning environment, in which they could provide multimodal learning materials (*Class 1*). The classes primarily used the digital learning environment to pursue and share student teams' process portfolios (*Classes 1*, *3*, and *4*). After each lesson, teachers went through each team's portfolios (*Classes 1* and *4*) and provided written feedback regularly (*Class 1*) or a few times during the project (*Class 3*). Teachers gave feedback on the content and quality of the process logs. The process portfolio helped teachers

Table 10.3 Elements of dynamic orchestration in four invention projects

Elements	Class 1: Scale model house *Structured orchestration*	Class 2: My invention *Highly structured orchestration*	Class 3: Everyday challenges *Highly flexible orchestration*	Class 4: Smart product *Flexible orchestration*
Teachers' background organization	*Digital learning environment* Checking teams' process portfolios and providing written feedback after each lesson and giving general or detailed instructions to teams for the next lesson. *Physical learning environment* Not addressed *Teacher resources* Dividing guiding responsibilities with teachers. Recognizing certain teams that need intensive support.	*Digital learning environment* Not used *Physical learning environment* Preparing the class with required materials and tools before a lesson. *Teacher resources* Planning how to place students based on previous lesson's student interaction. Dividing guiding responsibilities with teachers.	*Digital learning environment* Checking teams' process portfolios and providing written feedback a few times during the project. *Physical learning environment* Making the scripts for beginning and ending routines. *Teacher resources* Dividing guiding responsibilities with teachers.	*Digital learning environment* Checking teams' process portfolios and anticipating the teams' support needs for the next lesson. *Physical learning environment* Preparing for the next lesson with required materials and tools. *Teacher resources* Not addressed

(Continued)

Table 10.3 (Continued)

Elements	Class 1: Scale model house *Structured orchestration*	Class 2: My invention *Highly structured orchestration*	Class 3: Everyday challenges *Highly flexible orchestration*	Class 4: Smart product *Flexible orchestration*
Teachers' guidance during lessons	*General guidelines* Reminding to check portfolio feedback and to fill process portfolio at the end of the lesson. Following actively and scaffolding teams' work. *Personalized guidelines* Supporting some of the teams to organize their work at the beginning of the lesson. Leading reflective discussion after each lesson to guide students' collaboration skills and promote self-organization at the next lesson.	*General guidelines* Following actively and scaffolding students' and teams' work. *Highly personalized guidelines* Seating students in their places when they enter class. Starting the lesson with general instructions and helping them to organize their work at the beginning of the lesson. Modeling working if needed.	*General guidelines* Starting the lesson by reminding students of the routines and reminding them to fill process portfolio at the end of the lesson. Following actively and scaffolding teams' work. *Personalized guidelines* Supporting some of the teams to organize their work at the beginning of the lesson.	*General guidelines* Starting the lesson by reminding students of the routines. Reminding to take photos during the lesson for the process portfolio. Following actively and scaffolding teams' work. *Personalized guidelines* Helping students organize their work at the beginning of the lesson.

predict what the invention teams would do in the next lesson, what challenges they might encounter, and the kind of support they might need during the next lesson (*Class 4*).

The preparation of the learning space (physical learning environment) and the teaching team's division of labor (teacher resources) were also acknowledged as the teacher's background organization. Teachers supported the independent work of the intervention team by creating posters on the classroom walls that included step-by-step routines for starting and ending group work (*Class 3*). In some classes, teachers brought out the necessary materials just before the class (*Classes 2* and *4*) and arranged workplaces for the teams (*Class 2*) to ensure that students began to work immediately. In this way, teachers could prevent conflicts between students when setting up work (*Class 2*). Also, it was beneficial that teachers discussed each team's need for support and agreed on which of them was responsible for guiding each team before each lesson (*Classes 1*, *2*, and *3*). It also seemed appropriate to anticipatively consider what to do if a student fails to collaborate or make progress (*Class 2*).

Teacher's Guidance during the Lessons

Depending on the class setting, the teacher's guidance between the structured instruction and flexible guidelines varied. The lessons always had a similar start in all classes, and teachers gave explicit instructions for working during the lesson. Teachers also made sure that all students' and teams' work started. If the students had difficulties concentrating or regulating their behavior, the teacher moved on to work with them. In *Class 2*, it was often the case that teachers' support was identified as highly personalized. Typically, a struggling student had challenges, so the teacher worked side by side with a student doing the same task and modeling the desired activity. In *Class 2*, the teaching staff resources were considerable, with three teachers leading the project and another two or three assistants to support the students in each lesson.

In other classes, the organization of work was more flexible, and the goal was to reduce personalized support gradually. Teachers reminded invention teams about the posters on the classroom wall (*Class 3*) or commonly agreed (*Class 4*) routines, to review feedback or instructions that teacher had written on portfolios (*Class 1*), and to work on the portfolio during and at the end of the lesson (*Classes 1*, *3*, and *4*). Particularly in *Classes 1 and 3*, when mainstream students supported the work of struggling students, teachers emphasized the independence of student teams. They sought to personalize the work organization only for some groups by helping them get started at the beginning of the lesson (*Classes 1*, *3*, and *4*). Efforts were also made to increase the independence of the teams through reflective discussions at the end of each lesson (*Class 1*). In these discussions, the teacher aimed to guide students' collaborative skills and promote self-organization in the next lesson. When all invention teams were ready to work, the teachers followed their work and provided scaffolding if necessary. The independent student teams checked the teachers' feedback and instructions from the digital learning environment (*Class 1*). They could plan the lesson (*Classes 1* and *3*), divide tasks (*Classes 1* and *3*), and complete process portfolios (*Classes 1* and *3*) without teachers' support.

Concluding Remarks

This chapter defines the elements present in orchestration when implementing invention pedagogy in classrooms. We focused on the cognitively diverse classrooms, including students who struggle with their learning, to raise attention to the ways of working that help all students' participation. Figure 10.1 summarizes the appropriate orchestration design and dynamic orchestration that teaching teams should implement when guiding and scaffolding the co-invention processes of diverse students. We illustrated how the invention projects orchestration designs were created in different cases by setting learning design and support for active student collaboration. We also defined how the teacher's organizing and guidance activities maintained the processes in practice.

The case examples presented show that orchestration design has a significant impact on the success of a nonlinear invention project. The more diverse student

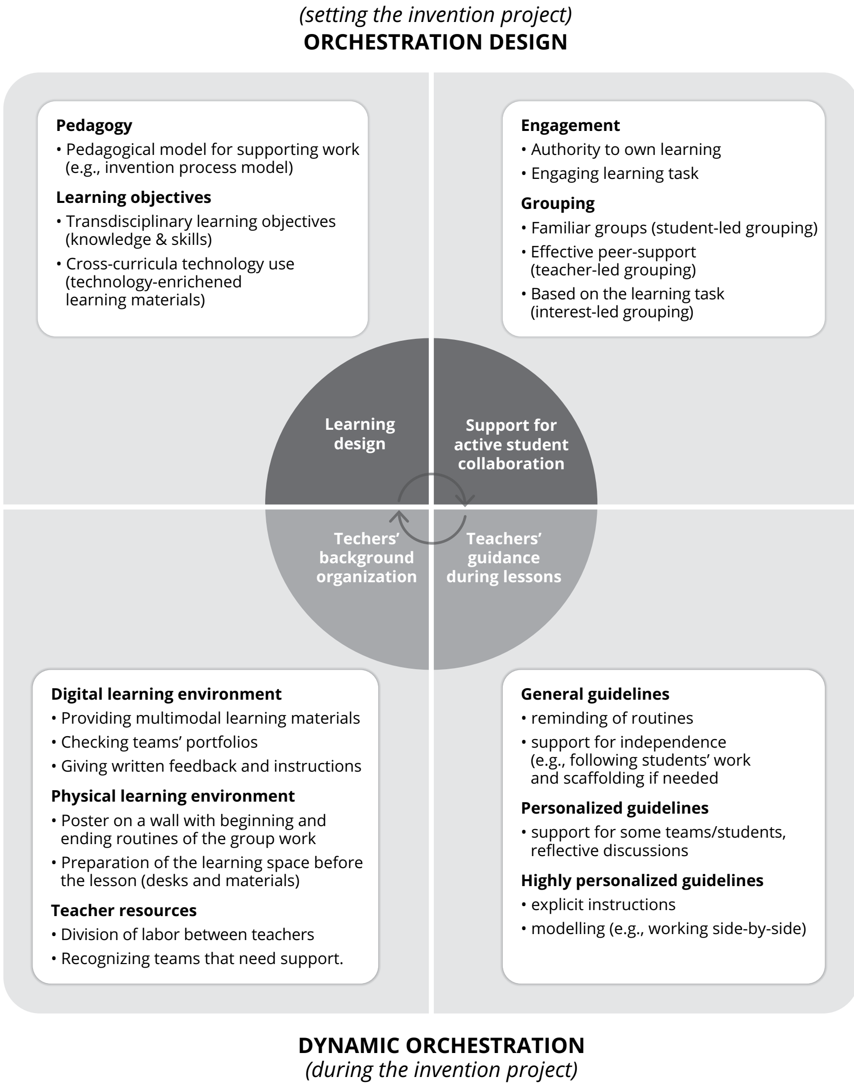

Figure 10.1 Model for orchestrating invention project.

teams are, the more carefully the teacher must plan for orchestration. The projects were settled by defining the transdisciplinary learning objectives raised from the curriculum and formed the content area with which the students worked during the invention process. The pedagogical models and the ideas of invention pedagogy supported the unfolding activities when developing the objects of the participants' processes. It is often perceived that struggling students benefit from a highly structured learning environment. However, our cases show that inventing exercises do not need to follow any strict order. The developing object determines the stages of the process and directs both the activities of the student teams and the guidance of the teacher. Carefully planned but adaptable orchestration design supports not only struggling but all students learning in nonlinear settings where invention activities unfold.

The orchestration design also considered students' participatory roles among the community and teams. The invention processes challenge participants to engage in collaborative discussions and designing. Collaboration and reaching mutual understanding require the skills to negotiate, build further on the discussions and the process, reflect on the process achievements, and make decisions together based on the current status of the invention process. All these skills and processes must be supported. In the present processes, the process design involved engaging learning tasks that gave students authority over their own learning. In addition, the well-planned and familiar groups and effectively constructed peer support helped the students collaborate and design their processes further.

Dynamic orchestration plays a vital role in the success of heterogeneous group invention projects. In the background, the teachers do well when arranging phases of the process, providing tools, and preparing the learning space for the coming lessons. It is also fruitful to comment on the student's processes in the digital learning environment, offer feedback, and provide additional materials to help their work. In most cases, organizing an invention project requires close cooperation between subjects and teachers and collective following of the ongoing process. In this way, different perspectives and a wide range of expertise are included. During the project, the presence of several teachers enables the implementation of flexible and creative teaching arrangements and solutions (see Chapter 11 of this book). However, dynamic orchestration must be planned between the teachers taking part in the project.

During the invention activities, it is helpful to rely on the plans created before the lesson and adapt them according to situational demands. The teachers' role is paramount in cognitively diverse classes for providing support and guidance throughout the process, responding to and sustaining the students' ideas, and advancing the design practices. The teachers should promote the groups' independence and interdependence and provide only as much support and structuring as the students' learning process and inventing requires. In most of the present classes, the students could affect their own learning processes, take responsibility for the process with teachers' help, and let go of it when the work proceeded. The teachers' support varied between the highly personalized guidelines to students' independent work. Some students were able to assume more responsibility earlier than others.

The purpose of this chapter has been to recognize the ways of working that may help the participation of all kinds of students in nonlinear invention pedagogy processes. To conclude, when orchestration works, students can assume more responsibility for their own actions. In successful orchestration, the support responds to emerging needs helping participants feel how their initiatives are highly valued. It creates ownership of the collective process and supports all students' belief in their own strengths.

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11 Team Teaching in Invention Projects

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Introduction

Team teaching an invention project is a pedagogical choice that aims at creating an inspirational and motivating learning experience for students. For teachers, team teaching translates into innovation, collaboration, shared expertise, and teachers' professional development. In Finland, the model of team teaching usually refers to co-teaching whereby at least two teachers teach in the classroom at the same time (Cook & Friend, 1995). Another approach emphasizes the various roles teachers have as a starting point of teaching, and this model consists of three continuum constituted pedagogically motivated stages: the sequential motif, the distinctions motif, and the dialectic motif (Wenger & Hornyak, 1999). In particular, the dialectic motif is in line with the pedagogical aims of invention projects, such as risk-taking, spontaneity, collaborative knowledge creation, and continuous feedback. However, team teaching in this manner is quite complex, especially in turn-taking (Wenger & Hornyak, 1999), and it requires both training and collegial support for teachers to leverage from it (Aarnio et al., 2021).

In Finnish schools, team teaching occurs infrequently, even though the benefits of team teaching in general are collectively recognized, attitudes toward it as a pedagogical approach are positive, and the importance of collaboration is highlighted in the national curriculum of basic education (Finnish National Agency of Education [FNAE], 2016; Guise et al., 2017; Saloviita & Takala, 2010). Moreover, Finnish teacher education does not equip student teachers with adequate team teaching competence (Aarnio et al., 2021), even if the need to push the traditional student teaching toward a more collaborative direction has been recognized (Guise et al., 2017). However, invention projects are student-centered, multidisciplinary, and phenomenon-based; therefore, team teaching can be seen as essential as teachers' diverse expertise is required to manage the project in a pedagogically meaningful way.

In our research projects, many teacher teams were simultaneously learning to teach invention projects and to teach as a team. A large part of the teachers' energy was spent on learning pedagogical approaches and novel technologies. Thus, at the beginning, team teaching practices emerged and developed along with invention projects rather than being specifically designed in detail in advance. For instance, many invention projects were multilocal: teaching occurred simultaneously in

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several classrooms, makerspaces, other internal learning environments, or extramural school premises. Different schools had different facilities, and the teams tailored their team teaching approaches according to their capabilities, ambitions, and available external resources.

Typical for invention projects, teachers' responsibilities, availability, and division of workload influences the design of learning tasks and student assessment. For instance, when done by a team of teachers, student assessment becomes more balanced as teachers can recognize different aspects and nuances of learning (Härkki et al., 2021). However, not only is the availability of expertise likely to be in simultaneous demand by several students, but also the availability of materials, tools, and learning environments need to be considered. All in all, team teaching in invention projects is about sharing one's expertise: knowing the specifics of a disciplinary topic or technology, pedagogical approaches, presentation, and demonstration techniques, promoting constructive interaction, motivating students, supporting student self-efficacy, and organizing supportive learning environments. More importantly, team teaching is about teachers extending their individual skills to become collaborative ones, such as shared orchestration, socially distributed metacognition, and socially shared regulation. Additionally, team teaching and the collaboration of teachers provide a model that shows students how to cooperate, and through that, how to excel in invention projects.

In this chapter, we describe team teaching approaches based on the research literature and our research projects. In the context of invention projects, we discuss how to organize a team and implement essential activities in different project phases to build a well-functioning teaching team. The examples of teachers' experiences come from several research projects. All of these were multiyear, large-scale projects aimed at developing innovative teaching practices in collaboration with teachers. The teachers worked either in primary or secondary schools. Some teachers had long-term team teaching experience, while some teachers generated team teaching practices during the invention projects. The main emphasis is on successfully team teaching an invention project, as an extensive literature already exists on building teams. In this chapter, we also discuss the characteristic activities of a well-functioning teaching team and provide recommendations for further developmental steps.

Blended Model of Team Teaching

While team teaching in general refers to a team of teachers planning, teaching, and assessing together (Thousand et al., 2006), most team teaching models described in the research literature reflect the teachers' roles and activities visible in a classroom. This section describes some of these models that can be applied and blended in invention projects. In practice, variants and dynamic combinations of these models that are applied depend on the invention project specifics, the participating teachers, and the school- or district-level policies.

Based on the teachers' roles and presence in the classroom, White et al. (1998) separated rotational and participant-observer models of team teaching from interactive team teaching. In the interactive team teaching model, simultaneously present teachers have equal roles and participate in discussions. In the rotational team teaching model, each teacher visits the classroom only for the lessons related to their own area of expertise, while a course coordinator is responsible for organizing the course and communication. In the participant-observer model, teachers alternate as lead teachers, while the others observe and assist while also making comments and providing examples.

A range of models assuming the co-presence of teachers focuses on the students' needs and instructional intent. For instance, Thousand et al. (2006) described four main alternatives: complementary, supportive, parallel team teaching, and teaming. In complementary teaching, teachers enhance each other's instruction. For instance, one provides a lecture while the other paraphrases statements and exemplifies note-taking. In supportive teaching, one teacher leads, and the other teacher rotates among the students to provide support when necessary. In parallel teaching, teachers teach the same content but can differentiate their approaches according to the students' needs. Variations of paralleling include splitting the class between teachers, teachers being responsible for teaching stations or experiments, teachers rotating or instructing particular student groups, and supplementary instruction, in which one teacher works with most of the students and the other teaches a smaller group to apply the taught content, to teach more advanced content, or to repeat some earlier content according to students' needs. In teaming, teachers equally share the responsibilities for planning, teaching, and assessing.

When these models are applied in invention projects, they should support the teachers' division of labor according to their special expertise. A typical variation involves teachers teaching in different makerspaces, which means that teachers no longer reside in the same room. Furthermore, station teaching can be used to provide independent learning tasks for students who rotate between stations, while teachers step in only as they notice a need to elaborate or demonstrate some advanced detail.

The teacher teams in the invention projects we studied developed their own blended models of team teaching. These dynamic models included features of the models mentioned previously, but they seldom fully represent any of the models. Teams have different developmental needs and paths, which are also reflected in which team teaching models are appealing. A fresh team can consist of old colleagues who know each other well, colleagues who barely know of each other, or anything in between. Some teams come together for a one-time project, while some continue working together for years; this translates into different developmental paths as a team. Teachers' eagerness to try team teaching is a fruitful starting point, but successful team teaching seldom happens spontaneously. It requires conscious efforts from teachers, as well as resources and support from the school community (Härkki et al., 2021; Thousand et al., 2006). Each team is unique with unique members in unique circumstances. Therefore, team teaching is simultaneously a focus of and a context for teacher learning (Rytivaara et al., 2019). Yet, it is not just the individual teachers who learn and change. Teams are dynamic entities that learn and develop along the different phases of invention projects.

Team Teaching during the Project Phases

The Beginning of the Project

For a successful team-taught invention project, it is essential that all team members have a realistic understanding of the project's goals and practices. In addition to planning the learning goals for students and the necessities of an invention project, teaching as a team needs to be planned. This forward planning requires time and effort, yet it is time well invested. Moreover, it is essential that all members are provided equal opportunities to contribute. Having a kick-off meeting for the project is a good way to start planning and generate mutual trust.

Learning tasks and invention project schedules are dependent on the available expertise and other needed resources, such as the learning environments, materials, and tools. A demand for a specific expertise could be very different in different phases of the project. For instance, students could benefit from a professional designer in the early ideation phase, but in the later phases, experience in materialization techniques could become essential. Or an invention project could start with technological or material explorations, followed by student ideation and grouping to develop their inventions further. Capitalizing on each teaching team member's expertise and availability requires early discussions about the member's strengths, skills, and knowledge, as well as their personal goals for the project and teamwork and their expectations of it. This kind of appreciation for a team member's expertise could result in increased commitment to the team, enhanced motivation, and greater job satisfaction.

Discussing practicalities (lesson plans, student needs, materials, etc.) comes more naturally to teachers than discussing their personal goals of the invention project and teamwork and the teachers' expectations. These goals could include working within certain pedagogical preferences, introducing certain subject-specific (novel) contents or a new approach to support the student groups' agency. Personal expectations could involve professional development needs or job satisfaction and motivational factors. Bringing these topics to the shared planning table should be explicitly encouraged. Through open negotiations and mutual respect, it is possible to reach the best pedagogical result, as one of our elementary school teachers suggested:

> There have always been four adults in it, and those are the perspectives of how to do things. So, it's not just one person's idea, but someone throws an idea and it's discussed, and it's supplemented or the other one throws in a different idea and then we think which is better, and we end up with which one's better. After all, it requires us adults to give space to each other, not just to go with our own mind—to give and take, so to speak.
>
> (Tom, class teacher)

Open discussion about team members' expectations, opportunities, and limitations provides fertile ground for planning the project and for constructive interaction throughout the project. Communication is essential for successful teamwork: who, what, when, and through which channels. Effective teamwork does not happen by chance; it is built by conscious choices, clear roles, and communication. A common challenge for team teaching is the lack of shared planning time during the project (Härkki et al., 2021). Shared language and effective ways to communicate emerge from shared planning time; these can make or break teachers' day and, more importantly, the students' learning experience.

During the Project

During the invention project, things happen because inventing challenges the students' skills. Teachers must be aware of and sensitive to the complex, shifting interactions constantly occurring between and among the students and the instructional activities within their classrooms. Sharing their awareness of students' learning and other circumstances facilitates coordinating the team's efforts to respond appropriately and effectively. Teachers need to consider several limitations—materials, tools, expertise, schedules—every time they instruct students. At times, unforeseen incidents occur, and teachers need to react and change plans quickly. Flexibility is essential.

All the teachers are responsible for informing their team members about relevant issues and potential conflicts. Often, time for communicating is limited; brief exchanges in hallways during a break are frequently used to pass on vital information. As necessary as they are for passing the torch of practical matters and securing smooth(ish) continuation of the students' projects, these fleeting moments are insufficient for building an effective team. Instead, as one of our secondary school teachers emphasized, it is essential to determine the division of labor:

> You really have to share those tasks in such a way that one takes care of this and the other one takes care of that and the third one reminds you of "Hey, now", and then you can have recess meetings saying "Hey, are all things taken care of right now?" Like a clear arrangement. That's what you have to do.
>
> (Susan, subject teacher)

The time reserved for communication is important, as is what is communicated and how it is communicated. In our research (Härkki et al., 2021), three major factors differentiated the teacher teams in terms of successful collaboration: (1) shared pedagogical priorities, (2) commitment to project goals and developing shared teaching practices, and (3) socially shared regulation. The quality, quantity, and content of communication come together in regulation, which refers to the intentional, adaptive response to new challenges, situations, or failures. According to Hadwin et al. (2018), regulation involves self-monitoring and optimizing one's activities and objectives according to changing situations. In socially shared regulation, these activities and goals are intentionally shared and transactively negotiated (Hadwin et al., 2018). A shared mindset and a positive attitude toward team teaching enhance the chances of succeeding and provide a fruitful breeding ground for collaboration, as an elementary school teacher recalled:

> Through experience and reflection, one can immediately find a lot of positive things in it [team teaching]. I see it as a huge positive asset in the work of a teacher for both myself and the children. As for myself, I can share things and I don't always have to reinvent the wheel, it brings out the best parts of both [teachers], and one can patch up one's own weaknesses through the strengths of the other. And for the kids then, there's two adults nearby and they get a different kind of feel for teaching. And I think it enriches [teaching] in that regard too. Designing and planning with the other is sometimes a little challenging in terms of time, but most of all, in responding to such personal chemistries and thought worlds, you have to just fall into those things and principles, and you need to have the same interests, because that person will rise to a pretty big role at that point.
>
> (Peter, class teacher)

Our understanding is that socially shared regulation is the key to successful team teaching. Time and channels for it should be agreed on during the planning phase. Another issue that should be agreed on is how to evaluate the team's performance during the project and after it ends.

Wrapping up the Project

If school days are hectic, term end with the need to submit grades for all the students is even more hectic. However, it is important that the teachers find time to discuss the lessons learned and to evaluate both the innovation project and the team teaching experience. It can be done in a simple and traditional way, as described by a teacher working in a secondary school: "When you get some success, you stop and write down what went well and what went badly. That is what has been done now" (Sarah, subject teacher).

In one of the projects, the researchers interviewed the teacher teams at the end of the school projects. The central idea was to facilitate the teachers' team building and ensure dedicated time for shared reflection, despite the busy term end. Members of one teacher team, subject teachers Vera and Hannah, discussed how to organize extended team teaching in a way that would support transfer of the students' code-writing skills better:

HANNAH: Math teachers taught the basics of coding, two hours. But it felt that students know nothing.

VERA: It is interesting. Because they most certainly did learn coding in math. But the transfer…if students learn something in math, they do not recognize it at crafts. How to organize team teaching…should one of us [crafts teachers] stand there in the math class to make the connection visible? This is an interesting question because this is not the only time this has happened. Students can be like "never heard, dunno what a ruler is, or what to do with one."

HANNAH: Or maybe the math teacher could have come to our classroom to help with coding?

VERA: We need to think about how teaching of coding should be scheduled and organized next year.

Subject teachers Theo and Nita reflected on their long-term teaming experience highlighting the meaning of trust:

THEO: This project has further developed our collaboration. We have done several projects like this, and our collaboration develops all the time. We know that we can work together, and we don't need to think about what the other is doing. We can trust that things are under control. It is really valuable that we can trust each other.

NITA: It would be impossible to work without trust. Maybe it is the trust, you know that the other one wants to do this as good as possible. Personally, this collaboration and doing together is most important.

They also reflected on how they change projects from year to year, based on what they have learned. This time, they noticed that specific learning tasks resulted in an imbalance between the students' needs and the teachers' expertise:

THEO: As usual, we'll make changes, and our next project will be different. This time, the big change will be [the] emphasis on technologies: we'll include coding that both of us can teach.

We also recommend a more formal evaluation of the team's performance. Designing the evaluation criteria and scale could be part of a project's kick-off agenda, but in any case, the team members should agree on the evaluation at the very beginning of the project. How the results are collected and analyzed should also be agreed upon beforehand. Evaluation criteria could include some school-level criteria, some project-specific criteria, and some criteria related to the teachers' personal goals. Moreover, student learning should be reflected in the evaluation criteria. Evaluation could be done as a shared discussion or as an individual task by each teacher separately.

Shared and Extended Expertise as the Backbone of Team Teaching

The learning objectives set for invention projects, the technologies that are used, how the disciplines are integrated, and the teaching methods used can often benefit from expertise not possessed by the core teacher team. Some of this expertise could be needed throughout the project, while some could be required for a limited time at a specific phase of the project. In addition to a more permanent core team, the extended teaching team could include visiting members. Bringing in experts could be highly motivating to students, but also rewarding to the core team teachers, as they could be exposed to new perspectives and the experts' professional practices. As one of our elementary school teachers described, having a group of experts enables large invention projects to be carried out:

> This is a lot easier as a team. You don't always have to do everything by yourself. When four people are involved, four heads forget a lot less. If you had to do all this by yourself, it could be quite a big project or would be a big project to carry out.
>
> (Tom, class teacher)

External experts can include professional inventors and designers, specialists in robotics or material technology, and local community members or policymakers. Involving external experts can also take the form of organized visits to school extramural learning environments, such as museums, laboratories, the workshops of craft professionals, etc., which is encouraged by the national core curriculum. These visits could also provide opportunities for students to become acquainted with various tools, artifacts, and work environments organized to support experts in their work, as well as authentic communities of practice (Hakkarainen et al., 2004).

An example of expert roles in an extended teaching team, teacher professional development, and increased job satisfaction comes from a seven-week-long invention project for seventh graders. The Proto-lab for Redesigning School Environment was planned cooperatively by two craft teachers and a professional service designer, who also facilitated the first two ideation lessons for students. After the ideation phase, the teachers took over, and later, the student groups visited a nearby design museum to collect practical tips on specific constructs. We interviewed Mila, one of the teachers.

> For me, working with several adult professionals was the most valuable experience. I got so many new ideas and food for thought from discussions with Jean [the service designer]. Jean could have some high-flying ideas, which needed to be brought closer to earth and simplified, closer to the students' experience. However, this project offered versatile learning both for the student and for us teachers, which was most rewarding. For me it was important to realize that even if students produce lots of ideas [with the designer], it is not so straightforward to choose and narrow down what we can actually do within the tight course timeframe. In that sense, the teacher has also an important role in designing.
>
> (Mila, subject teacher)

Another alternative to strengthen the expertise of a teaching team is to use students as tutors (Tenhovirta et al., 2021). A refreshing way to empower students and motivate them to pursue their interests is to encourage them to engage with special expertise relevant for the project and invite them to provide tutoring for their peers as expert members of the extended team. Chapter 12 of this book provides examples and describes the advantages and conditions of engaging students as tutors, but as described by an elementary school teacher, it is noteworthy that shared expertise may expand to the teacher-student level: "It's been amazing how some of those kids have in a way risen up alongside us teachers. It has been really great what kind of skills and enthusiasm can be found there" (Amy, class teacher).

However, having expertise in the team is not enough. For a group of experts to function as a team, each member needs two main types of knowledge. The first type involves the team members' expertise and how that knowledge is related to the learning tasks and project objectives, essential for socially shared regulation and shared orchestration of student work and learning. The second type includes situational, emergent knowledge about evolving circumstances and challenges. This situational awareness is essential for a team's success (Jones et al., 2019) and socially shared metacognition, e.g., in collaborative building and maintaining of socio-material learning environment that responds to continuously evolving student needs and facilitates meaningful student participation and learning. This awareness is developed with less effort when teachers are co-located and can see each other's interactions with students; otherwise, it requires good communication and shared time to emerge.

Team Teaching: A Means of Professional Development

Team teaching could provide a safe and fruitful environment for teachers to develop and test pedagogical innovations for teaching novel contents and knowledge practices. In invention projects, teachers co-innovate, co-develop, co-reflect and co-teach. This reflects the very idea underlying Finnish teacher education and national core curriculum: all Finnish teachers have a master's level university degree, which equips them to construe and apply rather than implement the curriculum. Therefore, invention projects are often vehicles of teacher professional development: experimentation and even seemingly small events can initiate meaningful changes in a teacher's thinking, beliefs, and practices (Rytivaara & Kershner, 2012). According to one of our secondary school teachers, team teaching can be seen as a means of professional learning and development: "I feel that it [team teaching] is also my continuing training" (Sarah, subject teacher).

Invention projects involve unexpected twists and turns arising from the students' versatile experiments, which requires teachers to be flexible and sometimes, to improvise. A teacher's role shifts from being an omniscient authority to being a facilitator or even a co-learner. Developing instructional approaches in situ contextualizes teacher thinking in the instructional dialogues and versatile project activities. In this way, the connection between teacher learning and new classroom practices is immediate, unlike in many professional development programs; co-developed classroom practices are not only learning outcomes but part of the teachers' learning process (Rytivaara & Kershner, 2012). Team support can also encourage a teacher to try novel things and thus support his/her belief in his/her capability to carry out an invention project, in general. This is seen in the example provided by an elementary school teacher:

> At least I would have had the anxiety straight away: "Help! What's being sought here, whether I understood correctly and how can I come up with it?" And I would have been distressed by the fact that do I even dare to do this. It would have taken a little courage if I had been alone, and I would have been a little unsure if I would have dared [to carry out an invention project].
>
> (Lisa, class teacher)

Experimentation and reflection are essential parts of the teacher learning process, and learning experiences are unique for each teacher (Rytivaara & Kershner, 2012). However, to teach as a team, teachers need to make their thinking and learning more explicit as they plan activities and discuss student learning. This could be challenging but not impossible, as teachers' practical knowledge is implicit and deeply embedded in classroom practices (Rytivaara et al., 2019). Receiving constant feedback, combined with the teacher's willingness to adopt and enhance his/her teaching practices, can be very rewarding. An elementary school teacher described the professional development happening in this sense:

> I've been saying all along that I'm in a more delicious position than I've ever been in. Two people who are about to leave us and the quiet information they have, I'm the winner in that exchange. I wouldn't have developed this well professionally if I hadn't done it on a team. Since you get feedback from other adults on that team, it also develops your teaching, and you see others' way of teaching. The same thing and you think, "No jokes, you can do that in that way too?" It gives [me]perspective that my way is not the right way, or you can do things in other ways too; with a little "improvement", push it in a better direction.
>
> (Maya, class teacher)

The teaming model, in which co-present teachers co-teach the same student group, provides teachers with opportunities to directly experience and observe each other's teaching styles and pedagogical decisions in an authentic context. However, there is still the need for individual reflection to develop into shared reflection. Shared reflection and open communication are central for a team to develop into an effective partnership (Pratt, 2014), but also for a successful team-taught invention project.

Elements of Well-Functioning Team Teaching

Common challenges for well-functioning team teaching include establishing roles based on the balanced use of expertise and skills, insufficient time for co-planning, communication, evaluation of success in collaborating, and lack of support from the school community (Pratt, 2014; Thousand et al., 2006). According to Härkki et al. (2021), the challenges specific for invention projects also include the physical learning environments, the class student size and integration, teacher competence, and insufficient in-service training (mostly regarding technologies, but also group pedagogy and team teaching). Moreover, having different pedagogical priorities makes it challenging to build an effective longer-term partnership. Instead of focusing on the teachers' personalities, similarities, or chemistry, we recommend keeping the focus on professional practices and priorities: professional courtesy and creating a working environment in which all the central processes, responsibilities, roles, and goals have been agreed upon from the very beginning of the project.

Sustainable team teaching is built on communication, shared decision-making, mutual support, and positive reinforcement (Kodkanon et al., 2018). Seemingly small actions, such as thanking, encouraging, complimenting, nodding in agreement, being courteous, helping with mistakes, praising, and apologizing, showing respect and professional courtesy, and providing a behavior model for students, good communication and professional respect result in mutual trust (Kodkanon et al., 2018; Pratt, 2014), which is crucial for teaming.

A change from individual teaching to a collaborative culture means not only expanding individual teaching skills to collaborative ones but also thorough discussions on beliefs and pedagogical priorities. Working together effectively does not require team members to agree on everything; in fact, different perspectives can complement each other (Pratt, 2014). Good collaboration can also be built by recognizing and respecting differences in the team members' motivations and expectations of privacy (Thousand et al., 2006). However, differences in pedagogical preferences need to be discussed if they are relevant for the planned project; then, careful listening and the willingness to negotiate solutions and compromise are necessary. Ultimately, the aim is to provide an inspiring and innovative learning experience for students.

Invention projects clearly benefit from well-functioning team teaching. However, especially in invention projects, team teaching is a highly situated, dynamically evolving enterprise, necessarily dependent on the participating individuals' objectives, timely capacities, and needs. It requires re-conceptualization of roles and responsibilities (Hackett et al., 2019). According to Härkki et al. (2021), teachers could overcome the lack of external support if they are motivated to team teach and are capable of flexible time management. However, individual teachers' flexibility is neither a recommended nor a sustainable bedrock for organizing teaching. Rather, organizational-level commitment is essential (Takala & Uusitalo-Malmivaara, 2012). We argue that implementing (and later nurturing and further cultivating) team teaching as a beneficial, widely entrenched practice for invention projects requires supportive structures and systematically aligned activities at the national, regional/municipal, and school levels. Our experience of beneficial support structures and skills for team teaching is summarized in Figure 11.1. This listing is not exhaustive nor fully implemented in Finland either.

The outer levels of this contextualized team teaching model (Härkki et al., 2021) facilitate and constrain the inner levels. While the national level focuses on overall aims and policies at all levels of the educational system, regional and school-level policies and support activities provide details, guidelines, and resourcing specific to that level. At the school level, it is best to base team teaching practices on consistent and continuous building of innovative school culture rather than short-term project-based initiatives. Importantly, national, regional, school, and team levels should have frequent opportunities for feedback between them, preferably supported by collectively agreed on performance and quality indicators.

Discussion

Team teaching is an efficient way to respond to the challenges that come with a teaching job: staying abreast of the emerging knowledge and skills needed to be a teacher (Thousand et al., 2006). We recommend starting with a short project and clear objectives. A short invention project provides a good opportunity for teachers to determine whether team teaching is a suitable approach for them and to test the waters with novel learning tasks. A short commitment gives teachers a glimpse of the benefits, and the possible challenges are smaller in a short-term project than in a longer-term project. Clear objectives from the start help each team member set

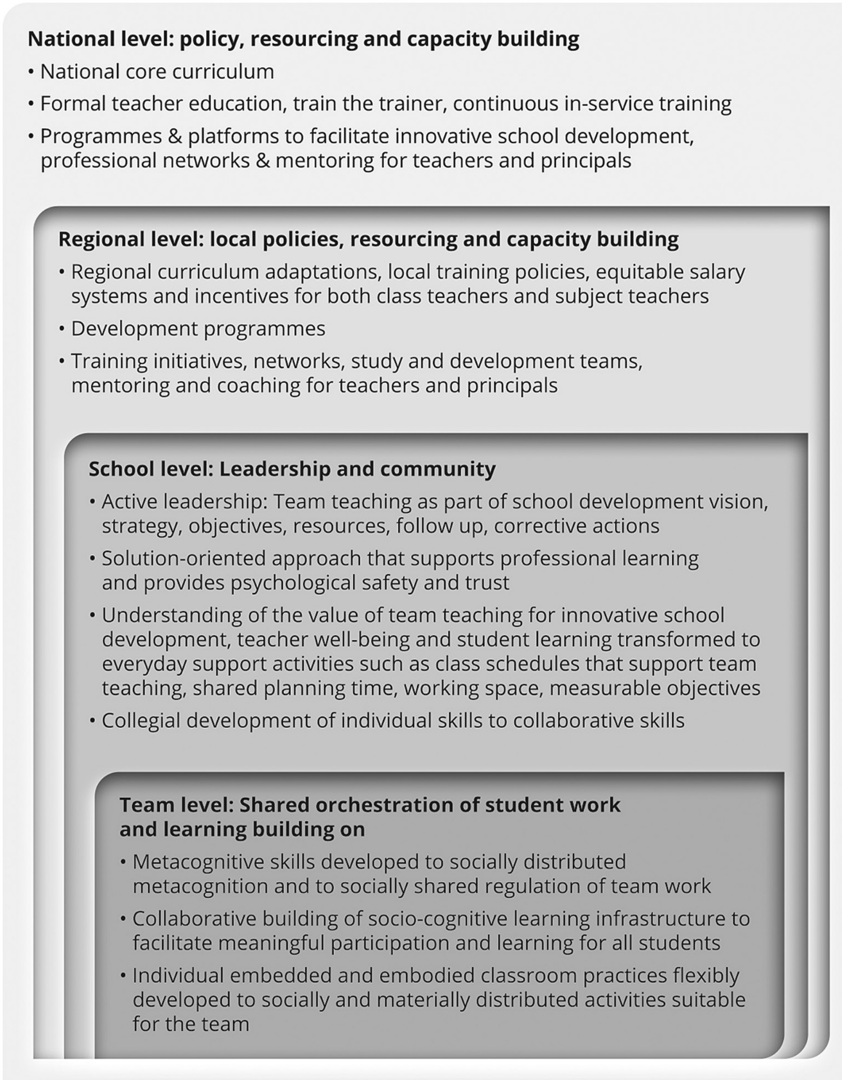

Figure 11.1 Beneficial support structures and skills for team teaching.

realistic yet inspiring personal objectives—and achieve them. This applies to the school-level implementation of team teaching and to the teachers planning a team-taught invention project.

Instead of a set of implemented (or pursued) practices, a team-taught invention project should be seen as a unique learning path taken by a particular team of teachers. The shift from individual teaching to team teaching and shared orchestration of student learning is a major undertaking. When team teaching is initiated by individual teachers who want to develop their classroom practices, it could be characterized as a first-order change. That level of change fine-tunes their work routines but does not challenge their values or the wider community. However, when team teaching is initiated as a school- or (regional/national) curriculum-wide change, it becomes a second-order change. This level of change entails a paradigm shift, confronts fundamental beliefs about current practices, and leads to new goals, roles, and structures, as well as different ways of thinking and working (Marzano et al., 2005). These two levels of change require different supportive structures. In Finland, the 2016 national curriculum initiated a second-order change regarding team teaching. Currently, there are inconsistencies in the ways regions and schools have been building supportive structures that facilitate emergence and further development of team teaching practices. Moreover, structural, dialogical feedback channels between the school, region, and national levels are underdeveloped.

At its best, team teaching serves as the backbone of both short-term and long-term invention projects. Teachers' shared expertise in the design, implementation, and evaluation of invention projects supports the implementation of entities that go beyond subject differences. It requires creative problem-solving and it supports the different needs of groups of students. Working in a team also supports continuous teacher professional development as a part of the day-to-day life of the school's activities. Above all, working in the team facilitates implementation of multidimensional invention projects in ways that support the student groups' activities that are innovative in terms of content and practices.

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12 Fostering Invention Projects through Cross-Age Peer Tutoring

Sini Davies

Introduction

In this chapter, we introduce cross-age peer tutoring, which refers to a pedagogical approach and infrastructure in which older students with technological expertise systematically support their younger peers in invention projects. Cross-age peer tutoring provides valuable support for teachers, especially in long-standing invention processes and in implementing new digital technologies like microprocessors, robotics, e-textiles, and 3D printing. It allows teachers to concentrate on the pedagogical orchestration of the overall project rather than solving technological challenges. Furthermore, it offers opportunities to use more advanced technologies, as teachers do not have to overwhelm themselves with learning to use or even be familiar with them. On the other hand, cross-age peer tutoring provides ample opportunities for the tutor students for personal growth and have far-reaching positive effects on their futures.

Peer tutoring is not a new approach, although it has been implemented and studied more in tertiary education than at the elementary and secondary levels (e.g., Ching & Kafai, 2008; Fields et al., 2018; Morrison et al., 2010; Topping et al., 2017; Willis et al., 2012). It is a point of emphasis in the newest Finnish curriculum (Finnish National Agency of Education [FNAE], 2016). Peer tutoring pedagogies often focus on transmitting basic skills and promoting positive attitudes to learning rather than engaging tutors and tutees in emergent, knowledge-creating problem-solving and learning novel skills and competencies (Topping et al., 2017). Consequently, many cross-age peer tutoring programs are heavily structured, involve pre-planned learning activities, and aim at pre-specified learning outcomes (Karcher, 2005). In our invention projects, we have focused on developing and investigating cross-age peer tutoring in open-ended, maker-centered learning projects based on nonlinear pedagogy and emergent technology-mediated invention activities (Riikonen et al., 2020a; Tenhovirta et al., 2021).

First, we introduce the theoretical aspects of cross-age peer tutoring from the perspectives of learning and pedagogy. Second, we describe a cross-age peer tutoring model at one of our research–practice partnership lower secondary schools. The school already had an established practice of older students serving as tutors for their younger counterparts. Through invention projects, the school aimed at creating a more systematic approach to cross-age peer tutoring, where eighth-grade

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students from a technology-focused class tutored their seventh-grade peers on the latter students' invention projects. Here, we present two perspectives of the cross-age peer tutoring practices developed during the first year that the invention project was conducted in the school: (1) how tutors experienced cross-age peer tutoring and (2) how peer tutoring in invention projects could be to supported and facilitated. Finally, we discuss the opportunities that cross-age peer tutoring offers for schools, students, and invention pedagogy.

Theoretical Aspects of Cross-Age Peer Tutoring

The theoretical foundation of peer tutoring is often linked to the concept of the zone of proximal development, which Vygotsky (1978) defines as "the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance, or in collaboration with more capable peers". Later studies emphasize the educational value of peer tutoring as a process of "learning by teaching," where tutors not only provide valuable support for tutees but also learn themselves (e.g., Duran & Topping, 2019). Although peer tutors are not expected to have the pedagogical competences of their teachers, they may still function as "experts by experience" who share their knowledge while challenging themselves to develop new competencies (Mieg, 2006; Olson & Bruner, 1996; Willis et al., 2012).

Maker-centered collaborative invention projects that rely on nonlinear pedagogy and involve open-ended design challenges, novel technologies, and unforeseen and emergent stages and outcomes can be challenging for teachers to orchestrate (Härkki et al., 2021). Neither teachers nor students may be familiar with the technologies that are slated to be used or may emerge during the projects. However, students who have previously conducted such projects or have developed significant digital competencies through informal activities may be much more familiar with these technologies, so engaging such students in invention projects through cross-age peer tutoring can be a valuable asset (Härkki et al., 2021; Riikonen et al., 2020a).

According to Hietajärvi et al. (2020), students with high creative socio-digital competencies developed outside the classroom may lose motivation and become alienated and cynical at school if their skills are not acknowledged. Through cross-age peer tutoring, skilled students can be provided with an acknowledged role, as supporters of their younger peers' design, invention, and making activities (Ching & Kafai, 2008; Duran & Topping, 2019). Karcher (2008) points out that the competence gap between tutor and tutee in peer tutoring should not be too big, ideally no more than two or three years. However, our projects have provided evidence of highly successful digital technology workshops organized by eighth-grade tutor students for elementary and secondary school teachers and even university lecturers and professors. Peer tutoring has the potential to shake up the traditional role of teachers and academics as the only authoritative holders of knowledge in the school community and even more widely in the academic world. Having their skills and contribution socially recognized not only promotes peer tutors' learning and skill development but also potentially strengthens their sense of belonging and self-efficacy (Bandura, 2006; Barron, 2004).

According to Barron et al. (2009), socio-digitally skilled students often have strong informal social networks, both in real life and on the internet. Forming a functional team of peer tutors requires building an active personal social network within and outside team members and even beyond their existing friends to gain access to the knowledge, tools, and competencies they need (Nardi et al., 2000). Furthermore, peer tutoring is a challenging experience that emphasizes the importance of having a supporting social network. Some students may develop a more active and central role within the social network of the tutor team through their "collective cognitive responsibility" (Scardamalia, 2002), through their efforts to advance the team's joint pool of skills, and by forming active and trusted relationships with teachers. In showcases of our own studies (Tenhovirta et al., 2021), we defined these "key tutors" as those with a cognitively central role in providing advice to other tutors and an agentic role within the whole peer tutoring network. Based on our findings, cross-age peer tutoring provides significant support for implementing practices of maker-centered learning and science, technology, engineering, arts, and mathematics (STEAM) education at school (Tenhovirta et al., 2021).

Developing a Cross-Age Peer Tutoring Model at a Finnish Secondary School

A cross-age peer tutoring model was developed to support invention projects in which teams of seventh-grade students participated. The inventor teams were engaged in creating complex artifacts by using digital fabrication and traditional technologies in a learning project integrating science, technology, engineering, and mathematics (STEM) subjects with crafts and visual arts. The school had already used cross-age peer tutoring in other projects but wanted to develop a more systematic approach to it. Meanwhile, having tutor students as part of the teaching team was considered necessary because of the new technologies used in the invention projects, of which the teachers did not have any previous experience.

The invention challenge given to the inventor teams, "[i]nvent a smart product or a smart garment by relying on traditional and digital fabrication technologies or other programmable devices or 3D CAD", was designed jointly by the teachers and researchers. The same invention challenge was assigned to teams in each of three years, so we had three cycles of invention projects. Following our research–practice partnership principle (Coburn & Penuel, 2016; Riikonen et al., 2020a), the projects were designed in close collaboration between the researchers and the teachers against the background of the practical constraints of regular school activity. Two craft and technology education teachers took on primary responsibility for the project; supported by computer science, chemistry, and physics teachers as needed. The projects were conducted during the spring term of 2017 and involved eight to nine weekly design sessions (90–135 minutes per session). The student inventor teams were formed by the students' own choices in the first year, by draw in the second year, and by teachers' choice in the third year, following our experiences and research findings on invention activities in the teams (Riikonen et al., 2020b).

The first group of cross-age peer tutors was introduced to help in the invention projects in fall 2016. At first, the plan for the school's cross-age peer tutoring model was to have an entire eighth-grade class of 15 students as tutors. They were given two hours of training on the GoGo Board programming tool by the Innokas network at the University of Helsinki. GoGo Board is an affordable, multifaceted digital fabrication instrument based on a visual programming language that involves numerous robotic elements like sensors and actuators for external devices (Sipitakiat et al., 2004). It was intended for use in several future invention projects, and the tutors were encouraged to further explore it themselves. Four students voluntarily began spending their free time practicing and experimenting with the GoGo Board and programming. They quickly formed a team of coordinating "expert" tutors. These tutors who showed exceptional agency were asked to co-plan workshops to introduce the GoGo Board to seventh-grade students. In February 2017, training sessions were organized for each of the school's four seventh-grade classrooms. These workshops proved to be highly effective, so in subsequent years, the tutors in each cycle organized similar events for the new inventor teams.

After the training sessions, the craft teacher invited a few tutors at a time to support the seventh-grade students with their invention projects. During those sessions, tutors worked in pairs to help the inventor teams with problem-solving, troubleshooting, and further developing their ideas, with the expert tutors taking responsibility for organizing the peer tutoring activity. From these first sessions onward, the expert tutors took on more and more responsibility for the tutoring; toward the end of the invention projects, they were the only people who helped the invention teams in the classroom. As their expertise in both the technologies and teaching grew, they also started arranging technology workshops for students in other schools and even for teachers from their own and other schools. The teachers highly valued their expertise and input, and the tutors were soon engaged in all levels of technology-related activities in the school community, from tutoring and advisory roles all the way to having input into school-wide technology purchases.

Although functioning in the role of peer tutor was considered motivating and provided positive pro-social experiences of helping others, most tutors desired more structured and better-supported, peer-tutoring processes. To that end, they took an active role in training the next cohort of tutors, selecting six students from the first tutee group to receive deeper computational training, following which they taught new groups of students together. Slowly, during spring 2018, the coordinator team started to step back, giving the new tutors more space to learn and teach when they entered eighth grade. The third cohort of digital tutors took more responsibility for the entire innovation process in 2019: they were more involved in the teams' designing by sharing their expertise in technology, but also by challenging and encouraging the teams to further develop their inventions. Their motivation was high, and they received more training and opportunities to teach or conduct workshops for teachers and students in other schools.

Throughout their time as peer tutors, the first cohort tutors took an active role in developing the tutoring model in collaboration with the teachers and researchers. Based on their experiences and ideas, a tutoring cycle model was developed (see Figure 12.1).

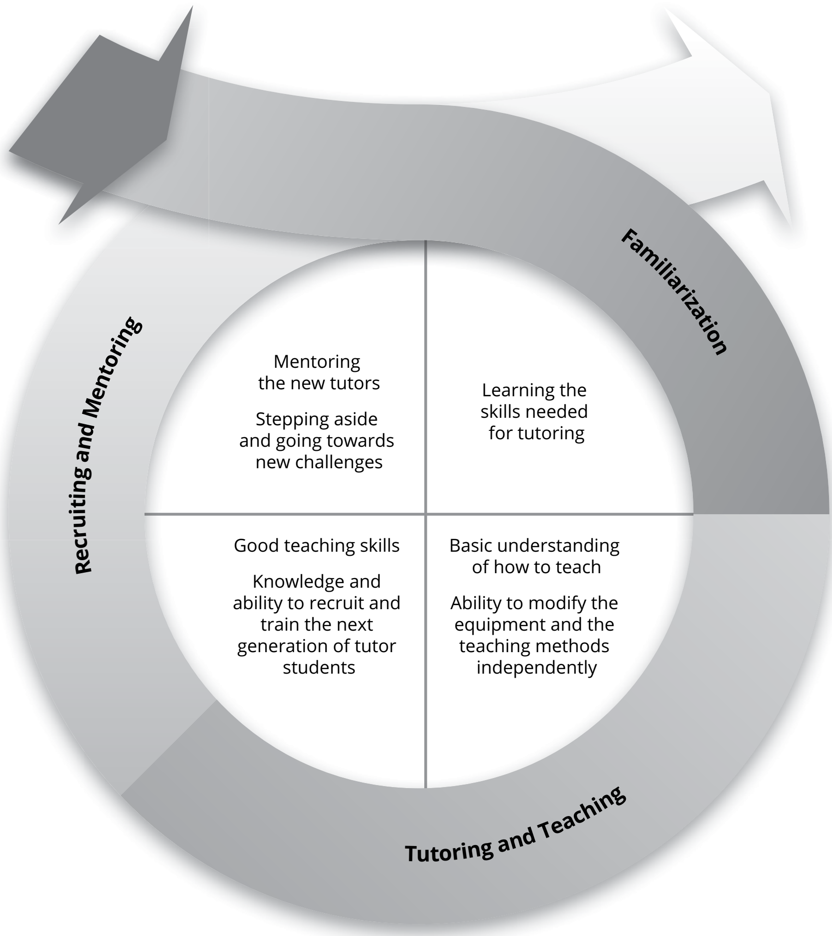

Figure 12.1 Cross-age peer tutoring cycle model.

The cross-age peer tutoring cycle consists of three phases: familiarization, tutoring and teaching, and recruiting and mentoring. During familiarization, the tutors learn and develop basic skills regarding technologies, teaching, and collaborative inventing. In tutoring and teaching, the tutors begin to guide the tutee teams and organizing workshops while they advance their own expertise. Toward the end of this stage, the tutors also begin to expand tutoring outside the classroom, providing their expertise to the whole school community and even outside their school. In the final stage, the tutors recruit a new group of students to become the next year's peer tutors. The advantage of having tutors do the recruiting is that they are part of the school's student community and can more easily find enthusiastic younger students who already are or are keen to become experts in new technologies. Finally, they mentor the new group of tutors, providing them with invaluable support, insight, advice, and information on being a peer tutor.

The effects of this cross-age peer tutoring model on the school's working culture and community extended well beyond the invention projects. The tutor students helped narrow the gap between students and teachers and created a more democratic working culture in the school, especially regarding maker-centered activities. They became an asset to the school's pedagogical team and created mutual respect between teachers and students. As the crafts teacher and school principal put it, the "tutoring model enables students' participation in the school's operation at various levels. It creates a positive, appreciative, heart-to-heart atmosphere in our school".

Tutor Students' Experiences of Becoming and Being Cross-Age Peer Tutors

When developing a long-lasting, cross-age peer tutoring model in a school, the tutor students' experiences of their tutoring journey and its effects on their learning and personal development should not be overlooked. In this section, we present some of the experiences of the expert tutors from the first cohort of peer tutoring; they provide valuable insights into cross-age peer tutoring from their own perspectives. To describe their own cross-age peer tutoring cycle, a time line was created by the author and expert tutor students (Figure 12.2).

According to the findings of our study of the first cohort of tutor students (Tenhovirta et al., 2021), they had to learn and cultivate a multitude of skills to overcome the challenges they encountered as peer tutors. Examples include basic and advanced technical skills, teaching skills like how to explain things to motivate the tutees, social skills (especially regarding collaboration), self-regulatory skills like taking responsibility and exercising self-control, and reflective skills. With only the brief training they received at the beginning of the initiative, they had to actively develop these skills on their own.

Initially, the tutor students felt uncertain of what they should be doing and how to act. They felt that they lacked the skills needed to function successfully as peer tutors; indeed, they did not yet fully perceive what those skills were. They had no

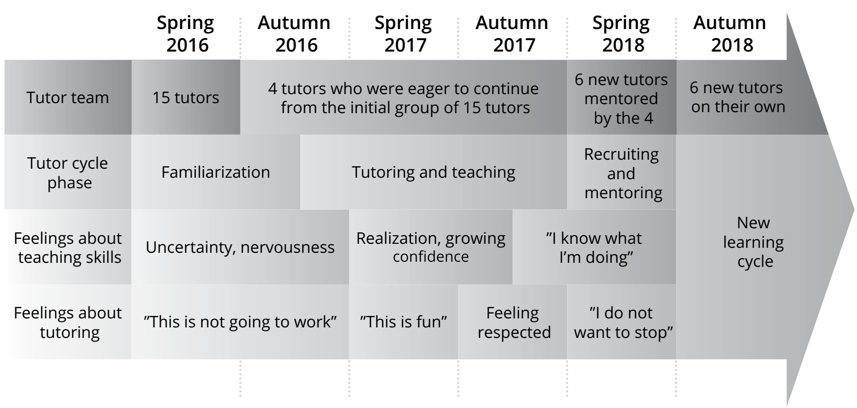

Figure 12.2 The time line of the first cohort of peer tutors.

experience in teaching others and thus felt insecure and nervous. One tutor wrote the following about the early stages: "The start was hard. We weren't sure about what we were doing, and we didn't know what to think about all of it".

The tutor students quickly established collaborative practices that supported the development of their teaching skills. They began to plan and structure the workshops they organized in detail and to systematically reflect on their teaching, especially after the workshops. This process involved making reflective notes and having conversations after the sessions. In the following interview excerpt, one expert tutor describes this approach:

> We wondered how the session should go and what we should show, in what order. And after that, usually after the session, we discussed with Joona [one of the tutor students] how the session went and what I could have done better. There were conversations…of what we had learned in the last session, and it always improved a little.

Gradually, the tutors developed their skills, and uncertainty and nervousness transformed into confidence and joy. The tutor students became a well-organized team, with each having a different role, while working in close collaboration and relying on one another's strengths. Based on our experiences and research findings (Tenhovirta et al., 2021), this team-building process of discovery is very important and may have long-standing benefits for the tutor students' self-confidence. One described this transformation from uncertainty to high confidence and well-organized teamwork as follows:

> We started enjoying what we were doing, finding out new ways of holding the classes, new things to teach, and new challenges.… We had different unspoken roles in the group. I did the talking; then, we had one helping out the students, a coder, and a pessimist who kept our feet on the ground. We all knew what to do, and we felt secure about it. At this point, without our even noticing, this tutor teaching had changed all our suspicions to pure admiration, and we were proud to have the chance to do it. By then, we had developed good teaching methods and equipment and a great attitude toward tutoring.

In both written reflections and interviews, the tutor students described the role of the teachers and the importance of the support they were provided by all parties in the research–practice partnership, emphasizing the independence, responsibility, and respect they were given. They also felt that they became highly respected members of the school's pedagogical team; they also started to respect their teachers even more. This boosted their confidence even further and motivated them to seek to excel in their positions as peer tutors and to develop their skills. One tutor student described the significance of the teachers' role in the following way:

> It is important to mention that during all this time, we weren't on our own. We had the complete support of the crafts and IT teachers, the principal, and the university. In particular, our teachers spent a lot of time with us, but they never tried to act like they were better than we were. Instead, they even

> backed off sometimes and asked our advice. It became a relationship of mutual respect, because we tutors started to appreciate the job they did after trying it out ourselves, and they respected our commitment. I see this as the key. The reason this was possible was our commitment and also our teachers. They supported us by letting us decide on our own. If we had always been guided by one of our teachers, I don't see any way it could have worked.

The first cohort tutor team recruited a new team of tutors from among their younger peers and guided and motivated them to continue their work. The tutors felt that this was an important task and did not want the tutoring model to fade away. This was also an emotional experience for them because they did not want to stop being tutors, but they knew that they had to cede responsibility to a new cohort of tutors and move on with their own studies. Based on our findings (Tenhovirta et al., 2021) and the tutors' writings and interviews, the experience and skills they acquired through their time as peer tutors affected and clarified their future plans and could have far-reaching effects on their futures. This is a very important aspect of peer tutoring from the educational point of view. One tutor crystalized the key effects of peer tutoring on him and his fellow tutors as follows:

> The most important lesson we learned as tutors is to believe. Even if sometimes things do not go as planned or you have a rocky start, it is better to try than to give up. We have also learned to teach and to respect those who teach us. After having the experience of making our own decisions in tutoring, we have learned to take more responsibility, to know our limits, and to have the courage to break those limits.
>
> It has also had a positive effect on our future plans by, for example, clarifying our study paths. For me, it made really clear that I want to follow a path in technological discovery in medicine, and it made me choose to take the scientific and technological class in high school.

Discussion and Conclusions

This chapter focuses on describing the opportunities provided by cross-age peer tutoring for collaborative invention projects, for maker-centered and STEAM learning, and for the tutor students themselves. Over three cohorts of peer tutoring, with the help of the student tutors, we developed a sustained cross-age peer tutoring model for maker-centered learning projects. Our observations and findings indicate that developing a systematic mode of cross-age peer tutoring to support invention and maker-centered learning was a fundamental aspect of the school's pedagogical approach and provided critical scaffolding structures and practices when combined with the teachers' support (Riikonen et al., 2020a; Tenhovirta et al., 2021). The effects of cross-age peer tutoring on the school's pedagogical infrastructure were crystalized through the following four key aspects:

1. Cross-age peer tutoring releases teachers to focus on the overall orchestration of the class and the project, instead of being diverted by technological and practical challenges experienced by individual student teams.

2 More advanced new technologies can be used in maker-centered and STEAM learning when teachers, who already have heavy workloads, do not have to master these technologies.
3 Cross-age peer tutoring promotes a more democratic school community by helping to narrow the gap between students and teachers.
4 For the tutor students, cross-age peer tutoring can offer many opportunities for personal growth and have far-reaching positive effects on their futures.

Authentic invention projects are often nonlinear and engage teams of students in creating unforeseen solutions for ill-defined, authentic, and complex challenges (Viilo et al., 2011). However, these projects can be very challenging for teachers to plan and conduct. Cross-age peer tutoring offers an invaluable asset to support the successful completion of such maker-centered learning projects. With the support of peer tutors, the teacher does not have to concentrate on solving novel and often complex technological challenges, while the tutor students can use their own constantly developing expertise to introduce more sophisticated new technologies into the invention projects. With the help of the tutor students, teachers can take a more comprehensive role in scaffolding the projects and classroom activities. When teachers trust the tutor students and respect their expertise—which often exceeds their own—those students can even be engaged to help plan the procurement of such technologies for the school.

When the school acknowledges the expertise of its students through systematic peer tutoring that can be expanded to many areas beyond technological expertise, it promotes a more equal culture between teachers and students. Based on our observations, even students who do not serve as peer tutors benefit from this building of mutual respect and knowledge exchange. Furthermore, such an open atmosphere of mutual respect could promote the development of a culture of innovation in the school, with the teachers no longer the sole holders of knowledge, and the students no longer passive receivers of it. The educational value of cross-age peer tutoring should not be overlooked in this respect.

Finally, becoming a peer tutor can have long-standing positive effects on students. Cross-age peer tutoring promotes the tutors' self-efficacy and self-image. It also offers them abundant opportunities to learn and cultivate a multitude of skills: technological expertise, teaching know-how, collaboration, taking responsibility, self-control, and reflective skills. Perhaps the most important aspect of self-development among the peer tutor students, based on their own experiences and our observations, has been to believe in themselves and have the courage to take on new challenges. Not being afraid of making mistakes and having the mentality to try again if something goes wrong are some of the more valuable skills to learn in becoming an innovative participant in today's society.

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13 Approaches to Student Evaluation in Invention Pedagogy

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Rationale behind Evaluation

The concept of evaluation refers to the actions which are supportive of the learning process and the actions which are aimed at determining the amount and quality of the learning outcome (Black & Wiliam, 2009). Both types of evaluation are related to the aims of the invention project. When an evaluation action makes a judgment related to the achieving of the aims of an invention project or grade of the performance of a student or a small group of students, the type of evaluation is summative (Wiliam, 2000). In turn, while supporting the invention project or appraising students within an ongoing process, the type of evaluation is formative. These two main types of evaluation require individual or collective interpretation of the learning aims as well as evidence, which is used as the starting point in evaluation.

Evaluation of the invention project might be challenging because the aims of the project are typically set holistically. First, the project supports students in learning core ideas in the domain through engaging them in scientific and engineering practices, collaboration, and constructing of an educational artifact (see for example Chapter 2 of this book). Learning the scientific and engineering practices or skills needed to complete these practices are also aims of the invention project. These practices are practices that are similar to experts in the field, such as asking questions, defining problems, planning and carrying out investigations, analyzing and interpreting data, developing and using models, and communicating information (Krajcik & Czerniak, 2013). An artifact, here the invention, is an object created by students during an invention project.

Second, there are aims related to the characteristics of an artifact. To be considered as an artifact, it needs to be lasting, durable, public, and materially present (Frederik et al., 2011). Moreover, aesthetic aims, such as exceptionality and diversity, ethical aims, and aims related to sustainability, are often emphasized as aims for the artifact.

An invention project is also an environment for the learning of transversal competencies also called key competencies, generic competencies, or 21st-century competencies, such as creative and critical thinking skills, collaboration, and problem-solving skills, skills needed in the use of various tools, such as digital and manual tools (Voogt & Roblin, 2012). Therefore, aims related to the transversal

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competencies in an invention project form the third group of aims, which could be evaluated as a part of the project (Pepper, 2011). However, the development of various skills and competencies through invention or design projects does not easily reach full potential. For example, aims related to the transversal competencies are often not shared with the students (Scott & Yates, 2002). Therefore, self-evaluation and peer evaluation that move learners forward do not focus enough to the learning of transversal competencies.

In an evaluation action of an invention project, the focus is always on both the quality of the learning process (the formative type of evaluation) and the learning outcome (the summative type of evaluation) with a focus on improving students' invention process and outcomes. Therefore, both the teacher and the students use evaluation data to develop teaching and learning, and consequently, the evaluation is called enhancement-led evaluation (Atjonen, 2015; Patton, 2011). Consequently, it is important to support students in using evaluation feedback in the development of their learning process and learning outcome. This type of orientation to the evaluation is emphasized in Finnish education policy and practices and is recognized as an orientation to evaluation in this book because the authors are from Finland. In general, in Finnish compulsory school education, student assessment is the responsibility of teachers who have pedagogical autonomy in the matter, although principles of student assessment and assessment targets are defined in the national core curriculum. Standardized testing has no role in Finnish compulsory education; instead, students are encouraged to design and assess their own learning (OECD, 2020).

A quality learning process promotes students' learning and depends on cognitive activation, supportive climate, and classroom management (Hattie, 2009). The quality of the outcome of the learning process refers to how well the competencies can be used in new situations, such as in problem-solving or in new invention projects (Dixson & Worrell, 2016). The evaluation provides students and the teacher with feedback. There are several other aims of evaluation, such as making the learning process and the learning outcome transparent. The evaluation actions are always based on the verified evidence and graded according to the criteria. The criteria come from the general part of the curriculum, such as the description of transversal competencies and from the subject-specific part, such as the description of engineering and design practices.

The evaluation and the feedback affect how the students learn or work during the invention projects and get excited by the inventing (Weeden et al., 2002). Evaluation with encouragement supports a student's self-concept as an inventor. This type of encouragement and constructive feedback is supportive in the development of students' self-efficacy, in other words, their belief in their capacity to execute behaviors necessary to use their creativity and invention process (Bandura, 1997). Self-efficacy reflects confidence in the ability to exert control over one's own motivation, behavior, and social environment. It influences confidence in how the invention project proceeds and results in the invention which is pleasing to at least its inventors in its newness. Moreover, an invention project has many features known to improve growth or maker mindset (Nadelson, 2021). Therefore, the evaluation actions should indeed be constructive and encouraging during the learning of invention projects: students need to understand the feedback and, according to that, direct their learning and working in the desired direction. The feedback is directed and connected to each student's actions and outputs. The students are directed simultaneously to interpret feedback so that it will be easier for them to change their own way of operating.

Making Evaluation Relevant

The relevance of evaluation depends on a range of characteristics, such as validity, reliability, and objectivity. According to the validity characteristics, the evaluation should focus on the knowledge and skills or competencies that are aimed at learning within the invention project. The evaluation should focus on essential and relevant issues, described in the curriculum as aims for learning. Thus, the starting point for the evaluation should be the aims of the curriculum or the aims emphasized in the invention project.

The validity also includes transparency. The evaluation should be open and transparent, and the participants must know the aims of the invention project and the evaluation practices. Therefore, it is important to pay attention to the aims of the project, including aims for learning transversal competencies, and the expected outcomes of the project at the beginning of the invention project: students and teachers should share the same aims. After sharing the aims, evaluation practices to be used should be agreed upon at the beginning of the invention project. In practice, the students should be invited to be involved in the planning of the invention project and planning its evaluation. It is also important to go through the evaluation criteria with the students' parents. This is because the invention project is different from traditional teaching and learning, and it might be difficult for parents to comprehend all the aims and how they are planned to be achieved during the project. For example, parents should understand that learning to formulate problems is one of the aims in invention pedagogy, and the learning task or design problem is not clear in the beginning of a project.

Validity is also important in the context of enhancement-led evaluation. Enhancement-led evaluation aims to help students to improve their learning process and performance within the invention projects. Therefore, the formative and summative evaluation and the feedback must support the development of the learning process and working in the long run also.

The demand for the reliability of the evaluation includes the fact that the tools of the evaluation do not contain random errors and that every student is given feedback and support according to their needs and process and product are evaluated according to the agreed criteria in the same way. The objectivity of the evaluation includes the fact that the effect of the subjective factors, values, and preconceptions have been removed.

Teacher's Role and Evaluation Tools in an Invention Project

The evaluation gives the teacher's feedback on the success of the supervision in an invention project and on the progress of the project. The evaluation also further directs the development of instruction and supervision practices. The teacher's supervision is multilevel during the project: the operation is directed at the level of an individual, small groups, and the whole group. In the case of a group, the evaluation information will be interpreted by the group members at an individual level.

The teacher can influence the internal division of labor of groups and how this division of labor is realized: the negotiation of the academic and cooperative aims of the groups, roles of the group members, and individual responsibilities. In the evaluation, the teacher considers how the needs of the different students have influenced the personalization of the objectives, process, and outcomes of the project (Jahnukainen, 2011) and the level of support of the different students. This means that the variation in the objectives, invention project, and expected outcome, are taken into account in the evaluation of different students. Therefore, it is central to take the special needs of individual students into consideration already at the beginning of the invention project.

The teacher examines the invention project as a whole and at the same time estimates their own operation. To be able to do a comprehensive evaluation, the teacher needs other tools for perceiving the various groups and individual student invention projects. The invention project consists of many levels of operations, and it is challenging to keep them all in mind and sometimes because of the long-term nature of the project, even impossible. Therefore, other visual evaluation tools such as tables and color codes help a teacher to control the whole project and its evaluation and to facilitate the follow-up. The tools help the teacher to divide the process into shorter periods. The teacher strengthens their own development by anticipating their successes and by thinking what needs to be done better next time.

The teachers do not necessarily have experience with the evaluation criteria and evaluation of long-term projects, so the teachers often face a new data acquisition process and information analysis. The traditional ways of evaluation could be modified to each specific situation, but usually, they should be modified to the group in question in addition to the control of the students' actions.

Evaluation Types and Methods

Evaluation and learning are strongly connected when the diagnostic and formative purposes of evaluation are highlighted. The evaluation methods described in the following sections form the evaluation in an invention project. Invention is not a linear process, so diagnostic and formative evaluation are emphasized during the process. The portfolio evaluation, presented later, includes all three evaluation methods.

Diagnostic Evaluation: Evaluation before Learning

The aim of diagnostic, declarative or planning evaluation is to find the skills and perceptions needed by the students in the invention project. Tools for diagnostic evaluation include various tests, teacher questioning, and observations (Leighton

& Gierl, 2007). The questions posed by the teacher direct the student to look at the invention project from a particular perspective. The student's response tells the teacher what the student thinks about the topic. For example, a review of the "if-then" structure used in coding can begin with the question:

> What different smart processes have you recognized at home? Or in more detail, what automatic processes are typical to house heating or cooking with an electric plate? (An answer: the electric plate heats until the selected temperature is achieved and then the heating stops). Which everyday objects could benefit from smart processes and what kind?

Or: "Tell us about a situation in everyday life in which you have previously acted to decide what to do: if you do—then you do it—otherwise…"

While they are being questioned, the students should be given sufficient time to think about the question. Therefore, it is good sometimes to ask questions on a whiteboard or via an online environment. Students may be asked to discuss the questions in small groups, write or draw an answer, and compare answers between the groups. Answers can also be presented by taking pictures of the environment or during a school trip. Answers, pictures, or thoughts should be discussed constructively—not through negative evaluations.

A test, Kahoot,[1] or Socrative[2] activity could also be used to map the students' conceptions or skills: Which of the processes include the "if-then" structure: (a) listening to music, (b) heating water in an electric kettle, (c) writing a document. Teachers can ask questions that they know to be critical for the success of the students' work: "How are the results reported?", "What keywords did you think you should use in a search?" In a similar way, it is possible to map the way in which the students have understood the aims of the invention project: "What and how we are evaluating in the invention project?", "What sensors/electrical equipment do you think you will need in your project?" The questions help students think about aims of the project.

In the context of diagnostic evaluation, students often respond in an unexpected way because the topic has not yet been studied, and they do not know the concepts or skills needed in the project. Therefore, it is particularly important to provide encouraging feedback to students. After the student's answer, a teacher naturally continues with a follow-up question. If the answer is vague, the student may be given an opportunity to modify the answer. The teacher can repeat or slightly modify the student's answer, for example, by asking, "Do you mean that…" (repeating the answer in your own words), "You bring up perspectives A and B, would there be other perspectives?", "What do you think about C?" The types of feedback given by a teacher can be grouped as follows:

- Encouraging feedback: emphasizing competence
- Evaluative feedback: highlight positive perspectives and ask to look at it from another perspective, for example
- Guiding feedback: how the objectives should be considered in the future

Formative Evaluation: Evaluation during Learning

Formative evaluation was used during the invention project to support the student's invention project and learning. Moreover, peers could be active in giving feedback during the process, such as during the communication sessions. Therefore, it is important to ask students to communicate the phase of the invention project to other students and the teacher after the students have formulated the problem or challenge of the invention project, generated ideas, and selected the most appropriate ideas related to the invention, and after the prototyping.

The feedback provided by the teacher during the invention project, as well as the self-evaluations and peer evaluations help the students to understand their learning and invention project and to identify the development of their skills and knowledge and areas where competencies are not yet sufficient. The students learn to correct their mistakes and develop their working so that the goals set for the project and learning can be achieved. The feedback could be given orally, adding comments to the portfolio or learning diary or with structured forms. Therefore, it is important that at different stages of the invention project, students communicate to the teacher and to each other about the stage and results of the project.

Formative evaluation guides regulate the student's working and learning toward the aims set for the invention project. Its primary function is to help students to discover what they know and how, or are able to do, and what still needs to be learned and in what way (Webb & Jones, 2009). Formative evaluation helps the teacher to focus his or her support and supervision on issues that students do not yet know. Formative evaluation can also support the student's feeling of competence. The need for competence is one of the key basic psychological needs or motivating factors in learning.

Summative Evaluation: Evaluation after Learning

Making the achievement of the aims and learning visible is the evaluation of knowledge and skills which have been learned or summative evaluation. Evaluation of knowledge and skills are based on verified evidence of how well and to what extent the student has achieved the aims set for the invention project (Doran & Tamir, 2002)

The knowledge and skills achieved in an invention project are rarely evaluated by a traditional test. Summative evaluation is done more often by an observation form, a learning diary, a portfolio, or based on a screening test. Documents, reports, blogs, or videos written or produced by the students could also be evaluated. Summative evaluation could be implemented through the evaluation of the invention created in the invention project. A specific evaluation sheet, constructed based on the aims of the project, could be used in the evaluation of the invention. It is common to evaluate the invention base on its usability or functionality and based on aesthetic and ethical criteria.

Self-Evaluation and Peer-Evaluation Methods

Through self-evaluation, the students find out what they have learned, compare their learning to the set aims, and strive to find out what should still be learned.

They can also recall how they have worked during the invention project and how they could work more effectively next time. Self-evaluation is thus like formative evaluation and intended to support the invention project and learning. It helps students to become responsible for their project and their learning. Self-evaluation also supports the development of metacognitive skills, self-confidence, and self-image. In addition to learning, the use of a self-evaluation method develops readiness for further studies and adult life (Andrade, 2019).

It is known that self-evaluation is challenging for students. Therefore, students' self-evaluation should be supported by teacher-led discussion, teacher questioning, or assigning a task. The discussion can be started by asking the student to share their experiences of the project in general. Next, the student could be asked to look at their own activity during the project and to think about what kind of problems they had. Finally, the students could be encouraged to analyze how they can develop their working and learning. The students' self-evaluation could be supported, for example, with a question, "What was the most interesting/surprising/charming thing about the invention project?" This question guides students to evaluate what they have learned during the project. Other examples of questions that guide the self-evaluation process include: "List the three most important things you learned during the project," and "What else would you have liked to learn?" Students can be asked to write the answers on a common page of the project or on other digital platforms. After writing, they can be instructed to compare their responses and discuss each other's experiences. It is important to guide students to evaluate their invention project asking the students, for example, "How have you succeeded in your group in collaboration, idea generation, prototyping, and communication?" "How can you improve your working during an invention project?"

The forms could be used for guiding the self-evaluation. There may be fixed and open-ended questions on the form (see Table 13.1).

The group can also self-evaluate its own activities using other forms or relying on a discussion. As the group evaluates its own activities, group members become aware of how each group member and the group as a whole has worked. In peer review, a student evaluates working or innovation of another student or a group. In

Table 13.1 Example of self-evaluation form of students' activities

What can I do? *(1 = I need exercise, 2 = moderately, 3 = well)*			
1. I am able to search for information related to the invention project.	1	2	3
2. I am able to generate ideas.	1	2	3
3. I am able to evaluate ideas.	1	2	3
4. I am able to make a prototype and test its operation.	1	2	3
5. I am able to work in a group.	1	2	3
6. I am able to communicate during the invention project.	1	2	3
7. I am able to evaluate an invention project.	1	2	3
8. I am able to evaluate an invention.	1	2	3
What was most interesting related to the invention project?			
What else would you like to learn about the invention project?			

this case, it is important to encourage students to be positive in the evaluation and to bring up a number of perspectives. Any criticism presented should be done so constructively. For example, a question about how the robot could be made to work more smoothly could be asked (Brown et al., 2021).

Several views or aspects of evaluation are highlighted while evaluating the invention project. Divergent views are discussed and recognized in such a way that all aims for the invention project are evaluated or the invention project and product are evaluated from different perspectives. These perspectives could be found among the aims of the project, such as the external presentation of the work itself, the layout of the poster or presentation slide, the use of colors, the interest of the work, and the meaningfulness of the results.

ePortfolio—a Method for Knowledge Building, Interaction, and Evaluation

The digital portfolio, a briefcase or a folder, refers to the collection of the displays of student assignments, descriptions of the learning process, and outcomes within an invention project. The display discloses the student's diverse abilities and the reached competence levels depending on the portfolio assignment type: the open assignment type reveals more detailed and unexpected information than the ready-to-fill-in type (Kimball, 2005; Parker et al., 2012). The content of the portfolio, collected documents, consist of the process descriptions, the choices available, and the self-evaluations/the group evaluations and describe success and recognized challenges and objectives for further projects (see Figure 13.1).

Alongside the authentic documentation, the portfolio consists of two more basic elements: reflection and collaboration (Zubizarreta, 2006). (See Figure 13.2). The portfolio develops in the portfolio process from a container to a reflective report and even to a dialog (Kimbell, 2012). The content of the portfolio diversifies as the unexperienced student becomes accustomed to the method and the simplest documenting is transformed into a more diverse holistic or even abstract narration (see also Saarinen, 2021). The collected materials can be processed, reflected, immediately and/or later at an appropriate time.

In turn, the collaboration can be a multifaceted act. It can mean control or communication (of a teacher/with a teacher), producing contents (with peers), or the division of the learning in the first place. When working with the portfolio method, the learner's action develops or is transformed into a critical thinker who has "a dialog" of their own learning by themselves. The highest manifold content relies on a well-developed ability to reflect comprehensively and on student-led freedom to implement activities (Saarinen, 2021). This development or transformation also strengthens the experience of the ownership of the portfolio, which engages the learner to put more effort into their own learning and to make it more meaningful (Kimball, 2005).

The portfolio can contain a range of types of assessment: It can be shared online with the teacher when the process feedback is direct and formative by nature. If the portfolio is shared with peers, the peer feedback can be directed toward content or criteria, and due to its formative nature, it also supports the process. Finally, the contents of the portfolio comprise the material for summative assessment purposes.

Figure 13.1 An extract of ePortfolio in an invention project: Everyday Assistive (Arjen apu) (sixth grade). A burglar alarm that reacts to movement and protects your property and works as a mirror.

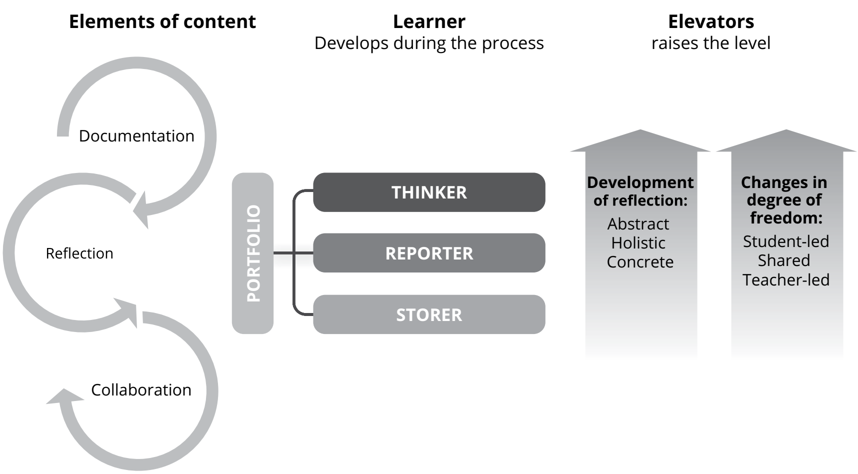

Figure 13.2 The elements of ePortfolio process and the development levels.

(modified from Saarinen, 2021).

One principle of the portfolio evaluation is that the working and the progress of it, the best achievements, and failures and coping with them are stored. One's own development is examined and with the help of the documentation, reflected either to construct a statement or the deepest level of reflective thinking (Kimball, 2005). Then also the mistakes and failures are seen but not emphasized in the same way as for example in the traditional evaluation which is based on the use of summative tests. On the other hand, the examination of mistakes and their corrections show versatile skills and abilities, and therefore it is desirable for the portfolio documentation to contain errors and mistakes. The portfolio evaluation is an attempt to strengthen learning to learn and self-direction, as well as to develop self-esteem.

Discussion

Both, formative and summative evaluation are needed in an invention project, and they can be realized through self- and peer-assessment practices. Both types of evaluation are carried out according to the holistic aims of an invention project. Formative evaluation supports the invention project and students learning during the process. Summative evaluation summarizes the student's invention project and learning outcomes. Therefore, it is more than grading, and a single grade might not be enough for summarizing. In this chapter, alternative evaluation tools, such as self-assessment evaluation, a list of evaluation dimensions, and a collecting ePortfolio method have been introduced. The ePortfolio method enables both the short- and long-term tracking of learning activities and thus gathers the evidence for assessing the process and finally assesses summatively the reached level. The ePortfolio can contain along with self-/group-interpretation views from peers and feedback from the teacher. The collected evidence becomes material for evaluation and gives a broader and authentic picture of the skills and competencies that have been achieved. Also, the transversal competencies, demanding to verify, can be more conveniently traced through the authentic evidence in ePortfolio.

However, the invention project and nonlinear learning model demand new ways of applying evaluation. Evaluation should support the creation of the student's wide-ranging creative competencies and capabilities. These open-ended problems with complex nature settings in invention projects need to be assessed with improvisation and the evaluation accomplished in a way that facilitates the process, like the ePortfolio method. Evaluation should be seen as an ongoing process with several iterations, a co-creation with learners, and as a learning event itself, not a vanishing point.

Notes

1 https://kahoot.com/
2 https://www.socrative.com/

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Part III

Co-developing Inventive School Culture

The principles and practices of invention pedagogy can be expanded to school-level development, in which the aim is to create inventive culture for the whole school community. Invention pedagogy supports schools in co-developing such a culture through creative processes that combine research-based knowledge with teachers' pedagogical experience and everyday school practices. Central to both inventive school culture and successful implementation of invention projects is enabling teachers' transformative professional development in collaboration with other school communities and networks.

The third part of the book explores invention pedagogy from the perspectives of developing learning environments and teachers' transformative digital agency, as well as discusses the pathways toward the innovative school 2.0.

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14 Learning Environments for Invention Pedagogy

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Introduction

Within invention pedagogy, we consider schools to be learning ecosystems composed of the operating culture, collaboration practices and networks, pedagogic practices, digital and non-digital instruments, and learning environments. Further, learning environments can be interpreted to include physical, virtual, and epistemic-social environments (Nardi, 1999; Nonaka & Konno, 1998). One of the aims of invention pedagogy is to create learning environments that provide multifaceted technological (tools) and social (community) resources that enable students to participate in creative practices of inventing and making artifacts in schools. Such environments are usually seen as "makerspaces," distinct from structured, formal learning environments (e.g., Halverson & Sheridan, 2014; Hatch, 2014). Makerspaces (sometimes also referred to as hackerspaces, hackspaces, and fablabs), are creative, do-it-yourself spaces where people can gather to create, invent, and learn. Makerspaces emphasize personally meaningful informal learning and nurture purposeful tinkering and peer-supported inquiry, whereas maker-centered learning in schools tends to be more preplanned, structured, and guided by teachers (Halverson & Sheridan, 2014; Martinez & Stager, 2013; Sheridan et al., 2014). Although many researchers are excited about the educational potential of makerspaces, maker-centered learning often takes place in informal and non-formal contexts, such as museums, libraries, or science centers (Gutwill et al., 2015; Halverson & Sheridan, 2014; Kafai & Peppler, 2011). Our research efforts in invention pedagogy have focused on how learning by making can be integrated into school environments and practices for systematically educating personal and collaborative creativity in formal education.

Finnish schools have had a type of makerspace since the 19th century: craft classrooms. As crafts is a standard school subject in Finland (see Porko-Hudd et al., 2018), each school has dedicated spaces for crafts, usually one classroom for textile crafts and another for technical crafts (Figure 14.1). These typically include basic workplaces and workstations for various craft techniques, such as sewing, seaming, knitting, and printing in the textile classroom and woodwork, metalwork, plastic work, electronics, and machine tools in the technical classroom (Jaatinen & Lindfors, 2019).

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Figure 14.1 Examples of technical and textile craft classrooms.
Photographs: Juha Kokkonen.

In recent years, efforts to expand the craft classrooms with instruments of digital fabrication, such as 3D design and making tools, wearable computing (e-textiles), and educational robotics, have taken place. In addition, some schools have built separate makerspaces or created mobile solutions, such as maker toolboxes or maker vans. Such efforts have been fueled by policies underlining that learning environments should offer "possibilities for creative solutions and the exploration of phenomena from different perspectives" (Finnish National Agency of Education [FNAE], 2016, p. 53) and by research indicating that a holistic makerspace with well-defined areas of working and paths for moving provides students multifaceted opportunities for design and problem-solving (Jaatinen & Lindfors, 2019).

Internationally, research on makerspaces has revealed that there is a wide variety in the composition of makerspaces; the purpose, settings, equipment, users, and management of makerspaces vary considerably (Mersand, 2021). Carefully designed makerspaces have proven to support participants' engagement and innovation (Sheridan et al., 2014) or students' literacy (Nichols & Coleman, 2020), among other things. Further, research indicates that physical re-design of learning environments may facilitate shifts in how, when, and why students engage in learning (Hughes & Morrison, 2020), and that "makerspace design should consider the development of possible encounters between people and things to support unforeseen transformations" (Keune & Peppler, 2019, p. 281). However, both internationally and in Finland, research is still scarce in terms of how to develop well-functioning makerspaces in formal education, considering the essential underlying pedagogical conditions that must be designed, implemented, and addressed to foster students' creative practices of inventing and making.

In this chapter, our aim is to explore the ongoing co-development process of the Innokas FabLearn Lab, a makerspace concept for Finnish schools, through the framework of pedagogical infrastructures, that is, the conditions designed and implemented in an educational setting to support the fundamental learning objectives (Lakkala et al., 2008, 2010; Riikonen et al., 2020). We first provide a background for the co-development of Innokas FabLearn Lab concept. Then, we outline the pedagogical infrastructures, i.e., the (1) epistemological, (2) scaffolding, (3) social, and (4) material-technological infrastructures underpinning the development of the concept. We illustrate the co-development process through a case example, in which a network of technology- and development-oriented teachers co-created a flexible and modifiable concept for designing a multipurposed learning environment. We use direct quotes from their interviews conducted in the fall of 2021. Finally, we provide some conclusions and future directions for the development of environments that support learning through inventing and making.

Co-development of Learning Environments for Invention Pedagogy

Multidisciplinary collaboration by educators, architects, and various experts is needed when designing school learning environments. Educational activities cannot be separated from spaces, and users' active participation in design is important (Daniels et al., 2019; Frelin et al., 2021; Tse et al., 2019). The ownership of design solutions should be shared by the users and supported systemically (Higgins et al., 2005). There is an interrelationship between environments and their users shaping each other through practice and activity (Daniels et al., 2019). A tendency exists to underestimate the effects of physical spaces for learning (Lei, 2010), to give inadequate attention to materiality in learning (Fenwick et al., 2011), and to move into new and more innovative spaces (French et al., 2020). An increased knowledge and understanding of the relationship between architecture and educational practices would help make more informed design decisions and uses of school spaces (Deppeler & Aikens, 2020; Gislason, 2010).

Guiding Principles in the Co-development of Innokas FabLearn Labs

The Innokas Fablearn Lab concept was and still is developed collaboratively in the Innokas Network and is based on the needs and expertise of the members in the network, the Finnish curriculum, and the research on invention pedagogy. The aim is to support inventive activities in Finnish schools, considering their diverse starting points and resources. The Innokas FabLearn Lab is a member of the international FabLearn Lab network (www.fablearn.org/labs/) developed at Columbia University by Paulo Blikstein and his team. FabLearn advocates and supports constructionist, equitable learning experiences for all students. These experiences should be accessible to all students, a force for inclusion and diversity, based on rigorous academic research, and shared globally. Further, FabLearn Labs should include the following principles: activities should be personal, cross-curricular, meaningful, holistic, and process- and product-oriented. The concept and proceeding should be modeled by teachers and developed in each country based on the local curricula, needs, and resources.

The Innokas FabLearn Lab development work is situated in the context of Finnish schools and their curriculum. The work follows the principles of the international network and is carried out as part of the Innokas Network's activities. The development work was originated following the request of several network members when they realized there was a need to develop new facilities or mobile solutions to support invention pedagogy. Pedagogical perspectives guide the communal design of facilities, materials, and tools. The involvement of network actors, user ownership of the design of solutions, and support by systems and behavioral change (Higgins et al., 2005) play a focal role in the development work.

It is essential that the design and co-development of the Innokas FabLearn Labs acknowledge the capabilities and resources of each school to implement learning environment solutions. Adaptivity is considered in the design of space solutions; the culture and identity of the user community, the intended activities, the facilities that are available, and other resources determine the kind of FabLearn Lab model implemented in the school. Some of the network's municipalities design space solutions as part of new schools under construction, some consider how existing facilities could be modified to support invention pedagogy activities, and some design mobile solutions such as tool kits with mobile tools and materials. Innokas FabLearn Labs can thus be separate, purpose-built spaces, combinations of existing spaces, or other material and spatial solutions that support invention pedagogy. The common pedagogical goal of developing learning environment solutions is well described by the following comment by a network member:

> The Innokas FabLearn Lab is a learning environment that stimulates creativity, where technology is utilized, and everyday problems are solved. Working together and leading oneself are highlighted. Central to the FabLearn Lab are problem-based learning, learning by doing, collaborative learning, cross-curricular learning, and entrepreneurship education. School becomes a motivating place for the student as the work connects to real life.
>
> (Teacher 1: Class teacher, deputy director, medium urban school with a separate FabLearn Lab since 2015)

Network- and School-Level Co-development

The community-based development of the Innokas FabLearn Lab is an open process, through which the structure and the grounds of the concept are defined together in the network. The key questions in the beginning of the process are: What basic principles are common to all, and what can be adapted in accordance with the local user community? A team of interested members of the network review and develop common guidelines and practices for the Innokas FabLearn Labs and present them at the biannual network meetings at which the whole community is participating in co-development. The co-development work utilizes the methods of the innovation process (see Chapter 15 of this book). Development work materials can be accessed and commented on openly by all members on a joint online platform.

The practices developed and ideated in the developer group and network meetings are tested in schools and further developed based on the needs of schools across Finland. At the school level, FabLearn Labs are designed with the identity and culture of the user community in mind, including the age structure of the community, the emphasis and history of the school, and local strengths, such as potential business partnerships. At the school level, the design of space solutions is also influenced by the needs of school actors; that is, they are designed, for instance, on a project basis, on a user-basis, or based on learning environment development. It is also important to consider whether only internal or also external users of the school use the space.

The starting point for school-level planning is the user-driven definition of practice. It is important that the users describe the projects they would like to undertake and what tools and facilities would be needed to carry out these projects. The versatility of the space designed for FabLearn Lab activities is often important. The space must be flexible for the different stages of invention pedagogy projects, including brainstorming and making, as well as presenting and sharing. The design considers whether the available space is fixed or mobile, open or closed, a separate space, or a combination of spaces. It is also important to consider the relationship of mobile solutions to other teaching facilities in advance.

At the school level, according to the Innovative School model (see Chapter 16 of this book), a range of actors at the school are involved where possible, including students, teachers, and other staff, principals, and partners, such as parents. Participating in the planning and co-development of activities and facilities strengthens the commitment of the actors and the formation of common practices for the users of the learning environment solutions. Collaborative development work is supported by the openness of the process, and practices can be tried out together in joint workshops for parents and students, for instance:

> I have held a 3D printing school for parents and students, student pairs. It involved training so that I didn't have a FabLab at the time, but there was a printer anyway, and the parents and students were trained in 3D modeling and using these devices, and then they implemented these joint plans at home, after which the parents and students brought them into the school, and they were printed.
>
> (Teacher 2: Craft teacher, big urban school with a FabLearn Lab close to craft classrooms since 2020)

Collaborative planning can also mean involving school networks in the planning process. Especially in the design of a new space, the school staff typically collaborates with the architects and the municipal environment services responsible for the design and implementation of the facilities. External expert support is often needed in the planning of pedagogical activities.

Pedagogical Infrastructures in Learning Environments for Inventing

It is essential in invention pedagogy to provide adequate structural support to facilitate students' learning processes and to unleash their full potential during complex and multifaceted invention projects. From the viewpoint of learning environment design, this requires recognizing the underlying pedagogical conditions that need to be addressed in the environment to enhance the desired type of learning. Within invention pedagogy, we have conceptualized these conditions with the help of a pedagogical infrastructures framework, which was first introduced by Lakkala et al. (2008, 2010) in the field of technology-enhanced knowledge-creation learning. The framework was inspired by Bielaczyc (2006), whose research on computer-supported knowledge building highlighted the role of the appropriate social infrastructure around the technical one, that is, the classroom culture and its established norms and social practices as well as the organization of physical and virtual spaces. Lakkala et al. (2008, 2010) identified interrelated technical, social, epistemic, and cognitive infrastructures that simultaneously affect the educational setting. The infrastructures create the background conditions that mediate the intended social and cultural practices of a learning environment but do not strictly prescribe learning activities (Lakkala et al., 2010).

Within invention pedagogy, distinct from more discursive computer-supported collaborative learning, we have developed a slightly modified version of the pedagogical infrastructures framework (Riikonen et al., 2020). While Bielaczyc (2006), Lakkala et al. (2008, 2010), and also others (e.g., Scardamalia & Bereiter, 2006) have underscored the role of conceptual ideas and tools in the learning process, invention pedagogy also highlights the importance of material artifacts and socio-material intertwining (Orlikowski & Scott, 2008; see also Chapter 6 of this book). Thus, instead of "cognitive" infrastructure, we refer to "scaffolding" infrastructure, which includes not only epistemic but also embodied and tangible support. In addition, we have used a broader concept, "material-technological infrastructure," for outlining both the technological and material conditions of the educational setting—the combined non-digital and digital settings that support the invention process. In this chapter, we use the pedagogical infrastructures framework to describe the pedagogical conditions underlying the collaborative development of learning environments for invention pedagogy. An overview of the modified framework is presented in Table 14.1.

Epistemological Infrastructure: Co-creating Knowledge through Inventing

The epistemological infrastructure refers to the operational practices that encourage teachers and students to share and co-create knowledge (Lakkala et al., 2008, 2010). This requires knowledge to be treated as something that can be shared and jointly developed (Bereiter, 2002; Scardamalia & Bereiter, 2006). Creating new knowledge is seen as a process embedded in shared practices ("knowledge practice") that are enacted (Hakkarainen, 2009). A proper epistemological infrastructure enables knowledge creation in dynamic and innovative processes that involve

Table 14.1 Pedagogical infrastructures in the co-development of learning environments for invention pedagogy

Pedagogical infrastructure	*Definition*	*Essential features of the setting*
Epistemological	**Operational practices** that encourage teachers and students **to co-create and share knowledge** through inventing	**Concept of Innokas FabLearn Labs in a school context** for open and shared innovation processes, spaces for co-creation, cooperation, sharing, and presenting. Various users: versatile tools and activities and ways to use the spaces, with options for short and long-standing projects.
Scaffolding	**Epistemic and embodied scaffolding structures** for promoting teachers' and students' capabilities of engaging in invention processes	**Pedagogical support** for the meaningful use of spaces. Invention pedagogy teaching and learning materials for teachers and students. Training sessions and events for teachers and students. Multiple communication channels for pedagogical discussions.
Social	**Arrangements for organizing** students' and teachers' **collaboration**, social interaction, and shared responsibility	**Physical and social arrangements** of spaces for organizing productive teamwork and interaction. Team-teaching and tutor-student practices for supporting invention pedagogy activities within the spaces. Digital arrangements for coordinating the use of the spaces; fixed settings, mobile solutions, external users.
Material-technological	**Organization of appropriate spaces, materials, and technologies** and support for applying them	**Co-created handbook** for designing versatile spaces, places, projects, equipment, and tools.

Modified from Lakkala et al., 2008; Riikonen et al., 2020.

several participants with various backgrounds and skills and mediating artifacts where knowledge is embedded (Paavola et al., 2002). In invention pedagogy, the epistemological infrastructure enables knowledge creation through long-term, iterative designing and making processes, where students' advancement is visible in their design artifacts, such as sketches, prototypes, and final inventions (Riikonen et al., 2020).

The long-term, iterative, and socio-material nature of the invention process, as well as the various participants and versatile activities, need to be taken into account while developing the learning environments for invention pedagogy. Innokas FabLearn Labs are used both during and outside school lessons, and the users can be students and their teachers or others interested in inventing and making. During lessons, a whole class of students with varying levels of motivation and skills participate in the activities. The environment needs to be designed in a way that supports teamwork, such as the building up of team spirit and the co-creation and sharing of ideas. For other users, the space should allow activities included in self-directed personal projects. Different users and their varying needs for the environment impact on the design and implementation of spaces and activities.

> If you think that there are students or teachers who have acquired the basic skills and already know them well and have a lot of interest and innovation to come here to develop something, something that is their own thing, then it is a completely different thing in a way or if you are teaching a group that comes because of wanting to innovate or because of what you can do in a makerspace, then it is a little different than teaching a regular class.
>
> (Teacher 2)

For all users, the learning environment should enable both short- and long-term invention projects. Long-standing projects require time, which should be considered when designing, storage solutions, for example. Ideas, prototypes, and other artifacts created during invention projects should be visible for everyone visiting the space, allowing the users to be inspired by projects created by others.

> The time needed to work depends on the group of students; if the group of students is not familiar to others, then it is worth spending time on those warm-up tasks, probably 45 minutes is suitable. Then, for this initiating or brainstorming, it easily takes a few hours, maybe even more. It may take up to five hours, and then you start making the artifact; so it depends entirely on that artifact, but it may take 5–10 hours and then the marketing and pitches and sorts; then it depends on how you guide the project, but five hours maybe it could count to that, too.
>
> (Teacher 1)

Various Innokas FabLearn Labs have been established in different parts of Finland. In some cities, the Lab is situated in a school, but other schools and nonschool users can use the space as well (Figure 14.2). In many small schools, the most practical solution is to set up the space in a normal classroom to provide a low threshold for invention pedagogy activities. In addition, mobile solutions, such as maker toolboxes, enable invention projects in educational institutions short of space or resources (Figure 14.3).

Scaffolding Infrastructure: Epistemic and Embodied Support Structures

The scaffolding infrastructure includes the epistemic and embodied support structures that promote students' and teachers' capabilities of engaging in the invention process. These support structures involve both conceptual tools, such as guidelines,

Figure 14.2 FabLearn Lab Vuores.

Photographs: Juha Kokkonen.

Figure 14.3 Mobile solution of FabLearn Lab Lohja.

Photograph: Panu Pitkänen.

models, and templates that support students' planning, monitoring, and reflection of their learning (Lakkala et al., 2008, 2010), as well as material and embodied scaffolding that facilitates students' competencies in designing and making (Riikonen et al., 2020). In invention projects, the scaffolding infrastructure consists of design briefs introducing the open-ended invention challenge and related constraints, guidelines relevant for designing and making, and teachers' and tutors' real-time support. The scaffolding infrastructure is often embedded with some other pedagogical infrastructure, and particularly the distinction between epistemological and scaffolding infrastructures is not clear cut (Lakkala et al., 2008).

The establishment of Innokas FabLearn Labs is scaffolded with training sessions and learning materials based on systematic research and the development of invention pedagogy. The training and materials are created through research-practice partnerships (Coburn & Penuel, 2016), through which cutting-edge research supports the design of accessible pedagogical practices tested in the field.

> Our space is intended for use in basic education in our city. In practice, I am currently offering training here, and when we join the Innokas FabLearn Lab, I will be involved, and we will have other teachers actively involved in Innokas, and training will be organized here as well. The aim is to train the teaching staff and students, especially here at our school.
>
> (Teacher 2)

An essential element of the scaffolding infrastructure is the possibility for interaction and pedagogical discussion through multiple channels. Active members of the Innokas FabLearn Lab community share best practices and good experiences through social media and discussion groups. Real-time support for various challenges and questions in the learning environment design has been especially significant for many teachers.

> We had already given a little thought to starting FabLab activities in the Innokas Network, and this device listing was already done. And then, of course, I started asking others for ideas, and because we have a great network, I got a lot of ideas through it.
>
> (Teacher 2)

Social Infrastructure: Arrangements for Organizing Collaboration

The social infrastructure includes the agreements and organizational structures that enable the participants to collaborate and create common ground. It can include the physical and social settings for advancing students' and teachers' teamwork and social interaction, formulating learning tasks in a way that requires shared responsibility for accomplishing them, and sharing the learning process, as well as its outcomes (Lakkala et al., 2008, 2010; Riikonen et al., 2020). As invention pedagogy relies on multidisciplinary team teaching, it is also essential to create a school culture and practices that support teacher collaboration (Härkki et al., 2021; see also Chapter 11 of this book) and co-planning of invention projects (Aarnio et al., 2021), as well as spaces for them.

The premise of Innokas FabLearn Labs lies in collaborative practices: spaces, tools, and activities are designed to support collaborative making. Projects are planned in a way that requires teamwork, and each team member has an essential role in setting up and achieving the goals of the project. Shared responsibility supports the development of students' socio-emotional skills, such as self-confidence, perseverance, and communication skills (see Chapter 5 of this book).

> I believe that the skills learned in invention projects are exactly the skills you will need in the future: working together, creativity, problem-solving, and self-management, that kind of self-directed work, although it is quite difficult, but when supported, it works really well.
>
> (Teacher 1)

In Innokas FabLearn Labs, collaboration is often very visible and tangible, and limited tool resources guide students to create inventions in teams. In addition, establishing the Lab in a space in which the activities can be seen by people passing by can be inspiring for many students, teachers, and other possible future inventors.

> The space is between the primary and secondary schools, and we were able to open it on both sides to have a wall with a window; from there you can see it on both sides in full swing, and it is used by the whole comprehensive school, and we have discussed that of course because the high school is in the same building, so then they will also be able to take advantage of it as well.
>
> (Teacher 1)

Material-Technological Infrastructure: Organization of Spaces, Materials, and Technologies

The material-technological infrastructure involves the organization of appropriate materials and technologies and support for applying them in a way that facilitates students in the invention process (Riikonen et al., 2020). In invention pedagogy, the material-technological infrastructure is multidimensional. It includes the tools and materials for designing, engineering, programming, and crafting the inventions, as well as technologies for documenting, reflecting on, and sharing the process of creating knowledge through making (Kangas et al., 2022; see also Chapter 8 of this book). Sufficiently rich material and technological resources are crucial for sparking students' creative ideas and for testing the usability of ideas and solutions. Furthermore, diverse equipment, machines, and tools enable students to learn by doing and to adopt a responsible attitude toward making (FNAE, 2016).

While developing learning environments for inventing and making, the material-technological infrastructure is usually the first element addressed. In the development of the Innokas FabLearn Lab concept, members of the community started by creating a list of age-appropriate and pedagogically meaningful tools and materials. The key questions in this work were as follows: What kind of learning do we want to support? What learning paths do we want to enable? How can we implement these? What kinds of projects support students' innovative capabilities? Essential in the material-technological infrastructure was to enable creativity, learning by doing, and student agency, as well as understanding technology as both a tool and an object of learning. Low-tech and high-tech tools are equally important for supporting students' understanding of technologies and their development from mere consumers to active shapers and makers of the technological world.

An essential component of the Innokas FabLearn Lab concept is the handbook, which will bring together the technological tools and materials used in different types of FabLearn Labs and thus support the operation of diverse labs planned in different parts of Finland. The handbook will cover all infrastructures of invention pedagogy in a comprehensive way so that practitioners can get an idea of the dimensions of the Innokas FabLearn Labs and consider these factors in the design, implementation, and organization of learning environment solutions.

The aim is that the handbook provides a pedagogical framework for the design and implementation of a range of FabLearn Lab solutions. The needs-based and regularly updated handbook responds to the needs of those planning the activities and working in the spaces: it provides practical tips for the design and implementation of various collaborative invention projects and the use of tools and technologies. The handbook opens up the invention process and contains tips for carrying out the whole process from the ideation stage to the presentation of the final outputs. It provides support material for teachers to carry out activities with students of different ages, as well as tips for training provided by the Innokas Network to support FabLearn Lab activities. The handbook also contains links to other interesting material related to the topic and, for example, to social media groups.

The needs-based handbook considers that schools also want practical support for the implementation of the Innokas FabLearn Labs and the use of digital solutions: What kind of reservation system is needed for the equal use of shared spaces? Who is responsible for maintaining the space? What are the common rules? How can technology be used to guide students and support teachers, for example, in implementing projects or learning to use tools? How can we enable long-term multidisciplinary projects with limited resources? The regularly updated FabLearn Lab handbook is openly distributed to anyone interested in FabLearn Lab activities.

Conclusions and Future Directions

The aim of the ongoing development of the Innokas FabLearn Lab concept presented in this chapter is to bring together the co-created epistemic, scaffolding, social, and material-technological infrastructures that should be considered in the design and implementation of learning environment solutions. The goal is to support schools and other users in carrying out and further developing invention pedagogy practices and activities. Knowledge of physical, virtual, and epistemic-social learning environments (Nardi, 1999) and the integration of these into functional pedagogical entities in a meaningful way with the possibilities of digital technology are needed to create environments that support students' creative activities and future-oriented learning.

Innokas FabLearn Labs are based on the needs of the users; their culture and identities, as well as the importance of facilities for operations, are considered from the beginning of the planning. Diverse spaces serve both short-term and long-term projects and enable ideation, implementation, sharing, and reflection. In some municipalities, entirely new schools and Innokas FabLearn Labs are planned, while some schools consider renovating existing facilities with solutions that support invention pedagogy. For example, the organization and equipment of classrooms for crafts, arts, or physics are modified for better enabling creative and collaborative activities based on invention pedagogy. In addition, mobile solutions are designed to provide possibilities for schools with limited spaces and resources.

So far, the development of Innokas FabLearn Labs has mainly focused on how learning by inventing and making can be integrated into school environments and practices in formal education. However, attention has also been turned to include other user groups as well. After-school and club activities linked to school, as well as collaboration with parents or local businesses, are natural ways to develop the diverse use of the facilities. Moreover, in the future, more emphasis will be placed on inclusion and diversity, that is, designing learning environments that are accessible to all students. More research is also needed on how the pedagogical infrastructures can be used to inform the design and implementation of learning environments. Furthermore, stronger connections with the international FabLearn network would support the wider sharing of experiences and the international co-development of innovative learning environment solutions.

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15 Developing Teachers' Transformative Digital Agency through Invention Pedagogy In-Service Training

Tiina Korhonen, Laura Salo, and Markus Packalén

Introduction

Research on teachers' professional learning and development guides the orientation of national-level teacher education strategies and practices in Finland. Lavonen et al. (2020) synthesized these studies and highlighted four factors supporting teachers' professional development strategies identified in the previous research: the long-term nature of the professional learning (Oliveira, 2010), teachers' active role in their learning (Garet et al., 2001), the connection between learning and classroom or practical context, and collaboration and reflection with colleagues (Avalos, 2011; Van den Bergh et al., 2015). Lavonen et al. (2020) also emphasized that in the Finnish context, teachers are expected to actively regulate their own professional learning by setting goals, reflecting, and self-assessing their own learning processes.

There are various opportunities for professional learning through in-service training for Finnish teachers. National and regional institutions such as the National Agency of Education, universities, and private entities provide professional learning possibilities for teachers. In addition, municipalities are obligated to support teachers' continuous professional learning. Despite these affordances, participation in in-service training is occasional and lacks long-term learning plans and continuity (Husu & Toom, 2016; OECD, 2020). Participation in in-service training is voluntary in Finland, apart from a few obligatory training days a year. Twenty percent of teachers do not participate in any in-service training for various reasons, and participation varies across the country. Barriers to participation include organizing substitute teachers and their funding as well as motivating teachers to undertake continuous professional learning (Ministry of Education and Culture [MEC], 2016). With regard to in-service training in digitalization, teachers have mostly participated in training that covers basic information and communications technology (ICT) skills and the use of specific programs (Tanhua-Piiroinen et al., 2020). Thus, there is need for training that supports teachers' creative use of technology (Korhonen et al., forthcoming) and innovative orientation toward teaching and learning (Lavonen et al., 2021). As solutions to these challenges, it has been suggested that in-service training be developed so that it is tied to the everyday work of schools and utilizes networks and sharing best practices (Lavonen et al., 2021; OECD, 2020).

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In this chapter, we depict how the invention pedagogy approach supports teachers in their professional learning and learning transformative competencies needed in the 21st-century era. We first define the concept and the need for transformative digital agency and draw connections to the aims of the national curricula in Finland. Second, we depict the Everyday Technology in-service training course context and development of teachers' transformative digital agency during the course and through the implemented invention projects with students. Finally, we reflect on the course's impact in the light of Finnish national-level teacher education strategies and practices and theory of transformative digital agency.

Teachers' Transformative Digital Agency

The digital transformation of education and society calls on teachers to cultivate their *transformative agency* (Markauskaite & Goodyear, 2017; Stetsenko, 2017), a term understood here to indicate teachers' proactive pursuit of pedagogical and professional innovations. Transformative teachers do not merely cope with changing environments (Emirbayer & Goodwin, 1994) but invest in deliberate collaborative efforts to exploratively develop professional innovations as epistemic objects (Knorr Cetina, 2001). Integrating novel socio-digital tools with activity requires a developmental process of instrumental genesis (Rabardel & Bourmaud, 2003; Ritella & Hakkarainen, 2012)—that is, active personal exploration with the goal of appropriating the tools as part of a distributed cognitive system and adapt these tools to one's system of professional practices (instrumentation). Teachers explore and try these creative activities that will later engage students. Such "fiddling" has been proven to strongly deepen teachers' level of innovation (Frank et al., 2011). The co-appropriation of novel socio-digital practices and the joint building of an innovation-oriented educational culture develop teachers' professional capabilities (Daly, 2010; Korhonen et al., 2014; see also Chapter 16 of this book). Teachers' self-confidence and experience-based empowerment play essential roles because participation in nonlinear learning processes is challenging for students and their peers. Teachers should provide students the "gift of confidence" (Mahn & John-Steiner, 2002) to assist them in trying out their wings before they have learned to fly.

Lund and Aagaard (2020) highlight the digital dimension's role in teachers' transformative agency. According to them, technology has been traditionally viewed in the educational field as a tool that mediates and serves people in certain contexts and in specific ways. There has been less focus in looking at the change potential that digital technology has and how to change educational settings and practices. Lund and Aagaard found that the impact digitalization has on changes in the environment, social practices, and concept of knowledge and thus to the individual and community, create a special need for teachers and teacher-educators to look at transformative agency through digitalization and the digital realm. They state trends like how phenomena are digitally represented, how communicative spaces emerge, how problem-solving becomes collective and collaborative, how suspending constraints in space and time to explain why digitalization impacts our epistemic practices. Digitalization is here understood as the overall process of moving toward a digitalized society and using digital technology in changing practices (Tilson et al., 2010).

Moreover, Lund and Aagaard (2020) characterize *transformative digital agency* through the competence requirements pertaining to agency. The key issue facing teachers' and teacher-educators' agency is their capability to identify educationally challenging situations and use digital resources to transform these situations into constructive teaching. We argue that from the perspective of teachers and teacher-educators, transformative digital agency plays a central role in recognizing the epistemic changes brought by digitalization. Equally important is recognizing competencies related to digital technology and technology itself, as well as the adaptive competence of using digital technology pedagogically in teaching and interaction. How technology is situated in the goals and aims set for learning and teaching goals is also pivotal. Is technology viewed as merely a tool for learning, or are technology and digitalization also objects of learning? We hypothesize that teachers need guidance and support to understand digitalization and the ubiquitous nature of technology so that they can adapt these elements to their teaching. In this way, they can meaningfully situate both the instruments and content of these elements into their multimodal teaching and interaction.

The Finnish National Core Curriculums for early childhood education and basic education (compulsory education) express two themes that are especially relevant to teachers' transformative digital agency in the 21st century: transversal competencies and multidisciplinarity. Transversal *competencies* refer to globally known 21st-century competencies (Binkley et al., 2012; Trilling & Fadel, 2009; van Laar et al., 2017) that manifest as a set of seven skill areas that prepare students for their future lives and work (for more, see the current book's introduction). These competencies are instructed and evaluated as parts of subjects across the curriculum. In the basic education curriculum, teaching is structured via traditional subject areas, but the renewed National Core Curriculum breaks from this centuries-old tradition and includes transversal competences, as well as multidisciplinary learning modules. Each school is expected to plan and implement a learning module at least once per academic year that connects a compatible set of content from separate school subjects as an interdisciplinary project or entity. These multidisciplinary learning modules are considered good opportunities to teach and learn transversal competencies.

Although both National Core Curriculums for early childhood and basic education are clear on transversal competencies and multidisciplinarity and examine in detail their underlying pedagogical ideals, they do not provide actual examples, scripts, or lesson plans to help with their classroom-level implementation. The Everyday Technology course introduced in this chapter was designed as a platform for teachers to experiment, design, learn and share new school practices for transversal competencies and multidisciplinary learning modules, thus supporting teachers' transformative digital agency. For the participating teacher, the course provided an opportunity to learn about digitalization and everyday technology, how to run multidisciplinary learning modules embedding invention pedagogy and technological content and tools, teach and assess transversal competencies and learn from—as well as remodel—other participants' projects.

The Everyday Technology Course as Teachers' Professional Learning Context

During the 2019–2020 academic year, the national Innokas Network organized the Invention Pedagogy: Everyday Technology—professional development course for early childhood, primary, and lower secondary school teachers. The course was a blended learning experience that included an online course module, two full days of face-to-face workshops, a daycare or school project with participants' students, and a final reflection meeting online. The targeted learning outcome was expressed in a single sentence: "Participants are able to plan, implement and evaluate creative Innovation Pedagogy projects on the topic of everyday technology and understand how the projects are linked to the Finnish National Core Curriculums."

A focal aspect of the training was that during the course teachers received an orientation to digitalization, and they were guided to reflect on the aspects of digitalization in relation to their own professional learning, teaching, and students' learning. Teachers were acquainted with various technologies starting from everyday technologies (e.g., simple machines, structures and electronics) and ranging to programmable technologies (e.g., Micro:bit controllers). More than 200 teachers from schools and daycare centers across Finland participated in the course. Due to the first COVID-19 outbreak in spring 2020, many enrolled teachers faced challenges in completing the course. Seventy-one participants ultimately completed the course and permitted their course materials and questionnaire answers to be used for research purposes (see Table 15.1).

The course was differentiated based on teachers' grade levels as Everyday Technology for primary and lower secondary teachers and Technology Crafts for early childhood education teachers. For both groups, the course's objectives, pedagogical approach, and structure were similar, but the hands-on technological content differed slightly: Everyday Technology included programming with microcontrollers, while Technology Crafts covered simple electric circuits.

The aim of the course was to familiarize participants with the concepts, methods, and tools of invention pedagogy presented in this book's introduction. Technology competence development was supported during the online learning period by using a variety of independent study and communication platforms (e.g.,

Table 15.1 Participant summary (*n* = 71)

Background variable	*Groups*	*n*	*%*
Gender	Female	59	83.1
	Male	10	14.1
	Unavailable	2	2.8
Grade level	Early childhood education	31	43.7
	Primary and secondary school	40	56.3
Region	Metropolitan area[a]	22	31.0
	Southern Finland	6	8.5
	Western Finland	11	15.5
	Eastern Finland	6	8.5
	Northern Finland	26	36.6

[a] *Metropolitan area*: The capital of Finland, Helsinki, and its surrounding municipalities, Espoo, Vantaa, and Kauniainen.

an e-learning platform and videos) and by focusing on everyday technologies during the hands-on meeting. The technological environment surrounded us, and invention pedagogy was approached through video and supplemental materials about maker culture, the history of technology, crafting and tinkering, curriculum reflections, innovation education theory and practice (see more in Chapter 16 of this book), and 21st-century competencies. Additionally, hands-on workshops included programming and computational thinking. Teachers could then apply their learning, in a pedagogically relevant way, to their own teaching.

Another central aim of the course was to introduce teachers to the innovation process model (Figure 15.1), which teachers can use to organize multidisciplinary invention projects and employ everyday technology tools in their classrooms. The model relates to the pedagogically oriented invention process models introduced in Chapter 9 of this book and was co-developed with Innokas Network teachers. During the hands on part of the course, participating teachers formed small teams and were guided through the innovation process step by step. They selected a problem, practiced creative techniques to generate ideas, designed a solution, built a prototype, and presented it to the other teams. Many participants later observed in their learning diaries that this practical exercise was the most fruitful part of the course. It provided a model with which they could start building their own multidisciplinary learning modules, and it offered a chance to reflect on and understand the process from students' perspectives.

Another important part of the course was participants' planning, implementation, and sharing their multidisciplinary projects. Project plans were presented and discussed among course groups. During the reflection session, implemented projects were presented and reflected on. Later, they were published as professional learning material for all teachers via the Innokas website.

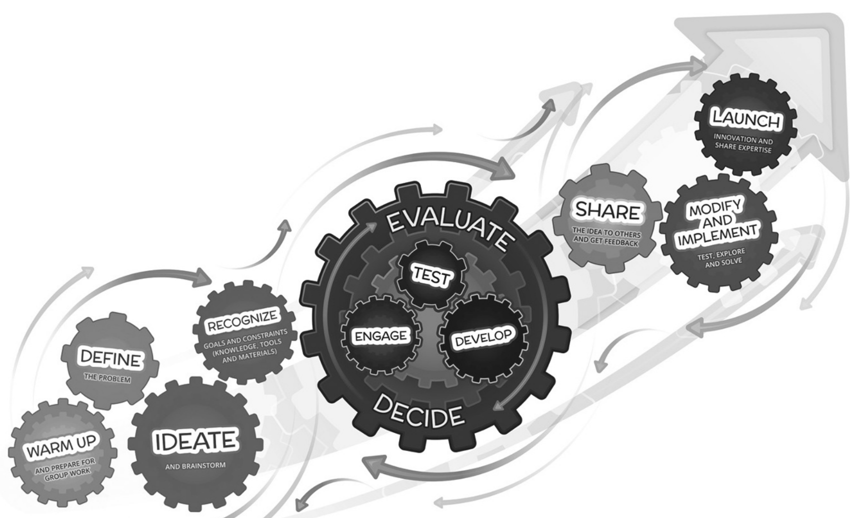

Figure 15.1 The innovation process in basic education.

Development of Teachers' Transformative Digital Agency during the Course and through Implemented Invention Projects

Participating teachers responded to surveys about their competence and needs at the beginning and end of the course. Additionally, teachers wrote structured learning diaries during the course. These diaries were used to map teachers' thoughts and competence development from the course's themes. Teachers were also asked to reflect on invention projects that they had implemented with their students. In the next subsection, we discuss teachers' development from four perspectives: technological and invention pedagogical awareness, technological competence, implemented adaptive practice, and teachers' reflection. Our discussion is based on a qualitative content analysis (Saldaña, 2016) of teachers' learning diaries and augmented by the quantitative analysis of our survey results.

Technological and Invention Pedagogical Awareness

Participating teachers depicted and reflected on transformative digital agency as an increased sense of technological awareness. An essential component of this development was the course's support and guidance regarding the definition of *technology* as a concept and understanding the ubiquitous nature of digital technology. Teachers also described developing an interest in technology during the course. Some reported having always had an interest in technology but no time to pursue it meaningfully. Some also mentioned that they had not previously understood the broad definition of *technology* to have a meaning in their own and their students' technological awareness. Several teachers mentioned that the course materials, which were pedagogically formulated, guided and motivated them to consider the challenges holistically and opportunities of digital technology and digitalization in everyday schoolwork:

> The more you did the assignments, watched videos, and read about it, the more you got into the technological world and thoughts started to form. I felt motivated to think about the impact of digitalization in my own everyday life and read about other participants' thoughts about it.
>
> (Teacher 18)

Teachers reported that the course content clarified how invention pedagogy supports the realization of curricular goals. Participants got to revise familiar processes and learn new content. Problem-solving was approached through the innovation process, and teachers learned how to use programming and robotics tools in invention projects. Teachers' technological and invention pedagogical awareness grew. Moreover, teachers found clarifying parallel concepts related to invention pedagogy and the innovation process important:

> The most motivating thing was to revise the concept of maker education and related concepts, such as STEAM [science, technology, engineering, arts, and mathematics], the innovation process, and invention pedagogy. Thinking about

> making from the perspective of my own work was also especially fruitful, and I got an idea for the spring semester activities from the course assignment.
>
> (Teacher 33)

This increasing technological and invention pedagogical awareness presented various options and dimensions to participants. Practical examples of multidisciplinary learning modules and projects embedded with developed technological awareness increased teachers' competencies in realizing invention pedagogy's possibilities and dimensions. Several teachers also observed that their increased awareness of the aims, methods, and implementation of invention pedagogy made them reflect on their previous practice:

> The content about learning by doing and innovation education were a good reminder for me about how the aims and schedules should be presented openly. Naturally, I have gone through them with the students at the beginning of the course, but they could also be visible as a reminder in the classroom throughout the process. Equally important is to have work samples on display.
>
> (Teacher 35)

Technological Competence

Teachers describe in their diaries that the course had supported the development of their technological competencies. The support was needs-based and augmented each participant's competence gaps. As with technological awareness, teachers here also brought up the relevance of developing epistemic knowledge. Introducing new ideas and content to teachers such as health technology innovations or artificial intelligence supported the development of their technological awareness and competencies.

Teachers' academic, artistic, and computational digital competencies were surveyed at the beginning and end of the course (Table 15.2). Here, *academic digital competencies* refer to basic technological knowledge-processing and knowledge-building practices, such as word processing, multimedia presentations, joint knowledge-building, and communication. *Artistic digital competencies* refer to using creative and visual technologies or software, such as image processing, video editing, or animation. *Computational digital competencies* encompasses creative problem-solving and designing and implementing complex technological systems and artifacts, such as building devices in invention projects that use programming, robotics, and automation.

To examine the extent to which the participants' self-reported digital competencies developed during the in-service training, paired samples t-tests were used to compare the post-questionnaire's digital competence components one by one with the pre-questionnaire's competence components (see Table 15.2). The survey results show that teachers found themselves to have already been proficient in academic digital competencies before the course but reported the lowest proficiency in computational digital competencies. There were statistically significant

Table 15.2 Teachers' academic, artistic, and computational competencies before and after training on a proficiency scale from 1 to 5 (1 = not at all; 5 = very fluently)

	Pre-questionnaire		*Post-questionnaire*		*t*	*df*	*r*
	Mean	*SD*	*Mean*	*SD*			
Academic digital competencies	4.17	0.76	4.33	0.64	2.90**	62	0.82***
Artistic digital competencies	3.03	1.01	3.16	0.97	1.48	62	0.76***
Computational digital competencies	2.15	0.99	2.50	1.05	4.66***	62	0.83***

*p < .05 **p < .01 ***p < .001

changes ($p < .01$) in both perceived academic and computational digital competencies during the course. All mean levels of competencies grew with computational digital competencies growing the most.

Pearson's correlation coefficient (r) was used to enable the assessment of rank-order stability. The correlation for all competencies were strong, indicating that the participants' relative level of competence did not change much. This finding may indicate a homogeneous competence development trajectory.

The teachers' learning diaries also told a story of competence trajectories. Digital academic and artistic competencies were mentioned in a few diary entries, but computational digital competencies and a lack of programming and robotics skills relevant to invention pedagogy were mentioned the most. Participants felt that the course's material and content supported their learning, helping them better understand the connections between computational digital technology and curricular aims and concepts. Also, participants found the hands-on guidance on combining technology competencies with invention pedagogy and multidisciplinary learning modules to be the most valuable. This guidance was realized through the course's hands-on activities, project examples, and collaborative work:

> The Innokas hands-on meeting was very productive, and I got a lot of tools for my own work from them as a teacher-educator. Especially visual programming with Adafruit was so interesting and fun.
>
> (Teacher 33)

Bravery and courage were also mentioned in participants' learning diaries. Participants noticed that, by following other teachers' work and hearing examples from other classes, other teachers faced similar challenges in computational digital competencies. By revealing teachers' varying competence levels, the course encouraged teachers to consider computational digital competence development as a step-by-step process for themselves and their students:

> Programming is interesting. Directions and guidelines were clear, and through that, I was increasingly excited. I still can't write hard and complicated command sequences, but I take small steps forward. It was truly great to see different innovative solutions that teachers had made. They reflected teachers' own previous know-how and motivation. It is great that the teachers' projects were of different levels. It gave confidence that this can also be started with small things with students.
>
> (Teacher 35)

Technological awareness, competence and epistemic knowledge about digital society established a foundation and motivated teachers to ponder the need for continuous learning about technology. Teachers recognized that, during the course, they established a strong foundation on which to develop their technological competence and that, after internalizing the basics it would be important to develop their digital competence independently:

> It was especially important to get motivation and courage to familiarize working with Micro-Bit and Arduino independently, now that the basics of programming are somewhat mastered.
>
> (Teacher 11)

Adaptive Practice

During the course, teachers conducted projects with students using invention pedagogy and the innovation process. These projects varied in duration from a few hours to several months, and they related to challenges that arose in students' daily lives, such as their learning environment, well-being, sustainable development, or home activities. Some projects dealt with specific themes, such as climate change or safety. Other projects were purely based on play or fantasy, and some derived their content from a specific school subject. All these projects used the innovation process that participants had become familiar with during the course. Teachers also targeted multidisciplinarity and crossing subject boundaries when planning and implementing these projects.

During these projects, and in line with the innovation process, students produced tangible artifacts such as scale models or miniatures, toys, games, computer models, escape rooms, or prototypes related to the themes of their projects generally. These artifacts were either advanced tangible products or product designs in nature. Students used the technological dimensions described in Chapter 8 of this book to document their processes and design and implement their artifacts. They used technology in both designing (3D printing), engineering (levers, cranks, cogwheels, syringes), programming (Micro:bit, Adafruit, Lego-robots, Bee-Bot, and Scratch), and making products by crafting (electronical components, recycled materials, craft materials). Cloud services and video production served as a means to document and share during this process. Several teachers also considered evaluating activities when planning these projects. During these projects, teachers guided students in self-assessments and peer assessments. A few projects used portfolios as evaluation tools (see Chapter 13 of this book for more detail). In all projects, teachers conducted continuous assessments.

Through their projects in schools and daycare centers, teachers described understanding the practical preparation required for multidisciplinary invention projects and the way in which students are guided during the innovation process. Equally, the understanding of the scope of the projects and the size of the target group also expanded: the experiences shared by the teachers about the projects led the teachers to understand that multidisciplinary learning entities can vary in scope and duration depending on the teaching objectives and students' level of competence. Also, the project does not always have to be aimed at the whole group to be taught, but can also be tailored to smaller groups as needed.

From a pedagogical perspective, these projects' innovation process, implemented with children and students, also supported participants' technological awareness and technological competence development during the course. For example, having the courage to try was mentioned in this learning diary entry: *"Electrical engineering is not rocket science. It can be easily mastered if you just dare to try."* The use of low-threshold materials is also highlighted. In addition to planning and leading the innovation process, some teachers described pondering student learning and specifically the skills students learned during their project. Alongside content knowledge, participants discussed teamwork skills, problem-solving, and teaching students thinking skills.

Guiding the development of thinking and creative problem-solving skills was also reflected in the teacher survey results. Even before participating in the course, participating teachers reported having guided students toward inquiry-based activities, learning by doing, creativity, and expressing ideas on a weekly basis. To examine the extent to which the participants' invention-pedagogy-related adaptive teaching practices developed during the in-service training, paired samples t-tests were used to compare the post-questionnaire's teaching practice components with the pre-questionnaire's teaching practice components (see Table 15.3). All mean levels of teaching practices grew slightly with encouraging students to share their ideas and be creative growing the most ($p < .05$). After the course, the teachers reported they encourage their students' sharing of ideas and creativity daily as opposed to weekly before the course.

Pearson's correlation coefficient (r) was used to enable the assessment of rank-order stability. The correlation for all practices was moderate, indicating that the participants' relative teaching practices did change and there was varying development among participants.

Reflective Practitioner

In the survey conducted at the end of the course, teachers pondered the course's impact on their previous practice and considered issues related to teaching methods, teaching situations, tools and materials, and collaboration. They rated items based on perspectives implementation and perceived importance (Table 15.4). Almost all responding teachers felt that they were allowed to develop teaching and teaching methods during the course, and they reflected on their past activities.

Table 15.3 Teachers' invention-pedagogy-related adaptive teaching practices before and after training on a scale from 1 to 5 (1 = less than monthly; 5 = several times a day)

	Pre-questionnaire		*Post-questionnaire*		*t*	*df*	*r*
	Mean	*SD*	*Mean*	*SD*			
I guide students toward inquiry-based activities	3.30	1.02	3.41	0.99	1.02	63	0.64***
I use the principle of learning by doing in my teaching	3.70	0.94	3.81	0.87	1.21	63	0.69***
I encourage students to share their ideas and be creative	3.77	0.94	4.02	0.93	2.12*	63	0.49***

*p < .05 **p < .01 ***p < .001

Table 15.4 The implementation and perceived importance of transformative digital agency during the course

Item	*I was able to do this (% of "yes" answers)*	*I felt this was important (% of "yes" answers)*
I developed my teaching and teaching methods	98.4	100.0
I pondered and reflected on my previous practice	96.9	98.4
I solved problems relating to new teaching situations and tools	90.6	98.4
I used new tools and materials	87.5	95.3
I collaborated with other teachers	75.0	85.9
I supported other teachers	68.8	85.9

Both the implementation and importance perspectives were viewed positively (100% and 98.4%, respectively). Teachers were able to solve problems in new teaching situations and use new tools. Moreover, teachers felt that their ability to use these new tools was important. Cooperating with other teachers and supporting other teachers were also considered important, but they had been carried out slightly less than other transformative activities (75% and 68.8%, respectively).

Teachers also considered the themes presented in Table 15.4 in their diary entries. They reflected both on their conception of teaching versus earlier conceptions and their ways of developing their teaching and related emotions. Respondents described their transformative role through their enthusiasm and desire to learn (or desire to learn more), and they identify factors that supported transformations during the course.

Changes to teachers' conceptions of teaching were influenced by both their newfound or strengthened epistemic awareness of technology and of invention pedagogy, as well as related theory and practice (including practical examples). Teachers' thinking was particularly influenced by the nonlinearity of invention pedagogy and its permitting trial and error:

> I also recall (the idea of) a non-linear working process from the videos, as I had never heard of that term before. I understood it to mean a process of working that is unique and no one can know the exact result in advance. From the examples given by others' projects and the views shared by the professor, it is possible to draw ideas and thoughts about teaching in general and not only about projects and multidisciplinary learning entities.
>
> (Teacher 18)

The course's practical examples of multidisciplinary learning entities prompted several teachers to consider the opportunity to implement the entities they had previously found to be too challenging in their own schools. Daring to try and a playful attitude were mentioned in this discussion. The course content related to invention processes made participants reflect on their own teaching concepts and methods, contributing to hesitation as to whether their own skills and courage to try something new would be sufficient to incorporate similar projects in their own teaching:

> Maker culture seems inspiring and interesting. The internet seems to be full of materials, but at the same time, I am struck by being spoiled for choice and the fear that my own skills might not be enough to guide the students. It seems that such an experiment would require the ability to just dive into it and not think about the end result, as well as tolerate the fear of failure.
>
> (Teacher 36)

Teachers also described their doubts about increased awareness and sharing experiences from a perspective based on students' skills or schools' operational structures. Some teachers wondered whether students' competencies would suffice to work on the artifacts that were an essential part of the course's invention projects. Issues were also raised related to the structure of school activities, such as adapting a subject-based syllabus to multidisciplinary, multihour, or longer-term projects or allowing teachers time for joint planning. Participants also discussed the evaluation of multidisciplinary learning modules using invention pedagogy. Teachers wondered how to build encouraging feedback that supports learning into their process so that students have opportunities to reflect on their own activities and at the same time, receive feedback from their teachers that can guide and develop this learning process.

The course also led teachers to reflect on their own teaching methods, practices, their development, as well as how to apply the knowledge and skills they learned in new ways across different contexts. Good examples of this reflection were given in a wide range of subjects; adapting and brainstorming were not only related to STEAM subjects and interdisciplinary learning but also to physical education, religion and ethics, and special needs education. Increased epistemic awareness of technology—and applying this new awareness and competence to one's own students—was also discussed. The experience of defining things previously taken for granted during the course made one participant consider their own teaching activities from the same perspective:

> Defining technology—understanding what is being done. When considering the definition of technology, I found that, in many cases, it can be surprisingly challenging to define / explain exactly the obvious. This is also good to remember in teaching. It is easy for a teacher to assume that students understand something that is difficult for the teacher themselves to define or explain.
>
> (Teacher 46)

During the course, and as part of the invention projects, several teachers reflected on tolerating uncertainty, failure, and trying by mirroring their own transformative agency. Diving into new challenges and the permission to fail were viewed from perspectives based on both teaching situations and students' skill development:

> The teaching situation must be seen as a training ground where there is an opportunity for failure. You can't learn something new without trying it, in comparison to a children's soccer practice, in which a player who avoids mistakes minimizes their own involvement and learns nothing.
>
> (Teacher 34)

> A reminder of how throughout my career, I have already been ready to dive into the new and unknown; this needs to be maintained, and the promotion of children's thinking and creativity needs to be more boldly integrated into every lesson.
>
> (Teacher 26)

Collaboration with other teachers and peer learning rose to occupy a special position in participants' learning diary entries. According to these teachers, the organized sharing of competencies with peers or colleagues during the course played an essential role in their development of transformative agency. Discussions about course content and the projects implemented in schools and daycare centers, as well as the joint planning sections of the course projects and the encouraging feedback received from fellow participants, deepened teachers' epistemic knowledge, self-efficacy, and ability to direct their own activities. The joy of working together and the importance of successful experiences were also mentioned as factors that influenced participants' desire to learn something new and develop their own teaching activities:

> The joy of working together, sharing information, and discussing what you learn really deepens learning.
>
> (Teacher 46)

> In the smallest steps, both the instructor and the student start in cooperation with the teachers. Doing things together and helping others, sharing information, these things accomplish a lot. Students in our schools have a lot of competence, as long as it is presented in a meaningful way, all the while inspiring and supporting the student.
>
> (Teacher 29)

Conclusions

The implementation of the Everyday Technology course and teachers' experiences of this training reflect the factors presented in the introduction of this chapter and support professional development of teachers: the long-term nature (Oliveira, 2010) and teachers' active role in their professional learning (Garet et al., 2001), the connection between learning and classroom or practical context, and collaboration and reflection with colleagues (Avalos, 2011; Van den Bergh et al., 2015). Teachers also regulated their own learning by setting goals, reflecting, and assessing their own professional learning process (Lavonen et al., 2020). The course was designed as a long-term entity emphasizing teachers' own agency and teacher interaction, alternating between course content and jointly planned classroom experiments. Participants' experience revealed that interaction and peer learning, organized discussions, and hands-on co-development—as well as the opportunity to plan projects at schools and daycare centers with colleagues—were important factors supporting teachers' professional development.

Additionally, teachers' awareness of digitalization, technological development, technology itself, and invention pedagogy as a method were important factors that supported participants' innovation orientation and professional development. The increased awareness and increased competence in innovative technologies inherent to invention projects led participants to reflect on their epistemic knowledge and capabilities as instructors in invention projects. Some teachers expressed having the courage to try and developed a new or strengthened sense that they were also allowed to fail and, through failure, learn something new. Some participants, in turn, reflected on their own and students' competence levels, considering whether their own skills or their students' skills were sufficient to carry out invention projects.

Teachers' course experiences (recorded in their learning diaries), hands-on project experiences, and reflections on teaching, self-efficacy, and student competence seemed to reflect Lund and Aagaard's (2020) main goal for transformative digital agency: *the ability to identify educationally challenging situations and utilize digital resources to transform these challenges into constructive situations*. The survey results, for their own part, supported these results. They also strengthened our view of digital and epistemic knowledge's relevance to teachers' transformative agency. Ever-evolving digital technology and digitalization require teachers to have a strong awareness of both technology's development and its impact on our actions. It appears that epistemic knowledge of digitalization is among the factors that enable teachers' transformative digital agency while simultaneously serving as a cornerstone of invention pedagogy. Awareness and competence development will enable teachers to understand the relevance of invention pedagogy projects from the perspective of both curricular objectives and necessary skills for the 21st century and will support them conduct invention pedagogy projects.

Finnish teachers are viewed as autonomous implementers of the curriculum who make independent decisions about teaching methods and tools. Some boundaries are set at the municipal level, but implementations vary extensively (Lavonen et al., 2020). Teachers' experiences with the Everyday Technology course reinforced our earlier understanding that autonomous and highly educated teachers need more tailored, participatory training that includes embedded, practice-oriented activities alongside guidance in understanding digitalization and invention pedagogy's opportunities to support students' 21st-century learning.

However, the teachers who participated in the course and provided data for this chapter represent a very small sample of Finnish teachers. We need more extensive research into factors that influence the development of teachers' transformative digital agency. From the educational equality perspective, we should find ways to motivate the teachers who are less eager to participate in training in invention pedagogy or technological competencies to also develop their innovative orientation toward teaching and learning. Through a comprehensive study of educational institutions' entire teaching staff, we will obtain more information on factors that hinder the development of teachers' transformative digital agency, and this information will enable us to target support measures for teachers more effectively. Our aim is to give Finnish students more equal opportunities to learn 21st-century skills by supporting teachers and inspiring their participation in invention projects.

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16 Toward an Innovative School 2.0

Tiina Korhonen, Leenu Juurola, and Laura Salo

Introduction

In this chapter, we expand invention pedagogy to include the systemic development of schools. We depict the theoretical background and characteristics of the Innovative School Model and innovation education developed in the national Innokas Network in Finland. The model is a result of 20 years of development work with Finnish schools. As a case example, we portray the work done during 2019–2021 in a project focusing on the development of the Innovative School Model and practices with eight schools from several parts of Finland. At the end of the chapter, we reflect on the Innovative School Model and co-development process with the schools and envision the next version of the model, Innovative School Model 2.0.

The multifaceted nature of the systemic and innovative development of schools is well illustrated by the complex adaptive systems theory (CAS). The theory helps build an understanding of the complexity of the school system and the relationships between the factors influencing it. The nature of systems is characterized by emerging consequences that are formed from the relationships between the system's structures (Morrison, 2002). "Emergence" can be described as an internally led change and adaptation process that is realized through self-organization and the formation of a new order. An emergent and unanticipated new order can be formed at the macro-level through collective micro-level interaction. This new order cannot revert to its founding parts. It can be thought that the new order present at the macro-level is a new model, way of thinking, or working culture that is formed in the process and is present throughout the system. The emergent result is described to be more than the sum of its parts (Mitleton-Kelly, 2006; White & Levin, 2016). In school practice, this means, for instance, a new and established way of acting and being in interaction. Here, we speak of a new school culture that is being built.

The results of these emergent processes that shape schools' working cultures can be compared to the unpredictable results of the innovation process. Innovation processes are also associated with unforeseen and undefined creative processes. Schools' working culture is examined from the perspective of innovation processes by innovation-driven theories such as the theory of the diffusion of innovations (Rogers, 2003), the theory of educational change (Fullan, 2015), and the Innovative

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School Model (Korhonen & Lavonen, 2017). The Innovative School Model (Figure 16.1) builds on the theories outlined by Fullan and Rogers and brings them to practice through development work with Finnish schools aimed at systemic change. In the Innovative School Model, all actors in the school context are viewed as participants and innovators: students, teachers, principals, parents, and other stakeholders. Collaboration is encouraged at all levels with peer-to-peer learning among students, teamwork between teachers, and in home and school collaboration, and within various partnerships. The model is supported by research indicating that participant involvement in innovation implementation and reinvention increases the probability of the continued use and development of the innovation. The creative and versatile use of technology in learning and teaching is a leading and cross-cutting theme of the model. The model extends the notion of innovation from hands-on learning innovations typical for invention pedagogy to operational innovations renewing school-level practices, such as teaching practices, school-day structures, and teacher collaboration (Korhonen & Lavonen, 2017). As CAS theory points out, the probability of change can be strengthened through smart system regulations by either changing the system, removing parts of it, or co-development (Mitleton-Kelly, 2006; White & Levin, 2016).

The design and co-development of the Innovative School are approached by applying design-based research (DBR) and by being aware of the elements impacting the school's systemic development under CAS theory: interactions between stakeholders, the structures of joint practice, and circumstantial opportunities and

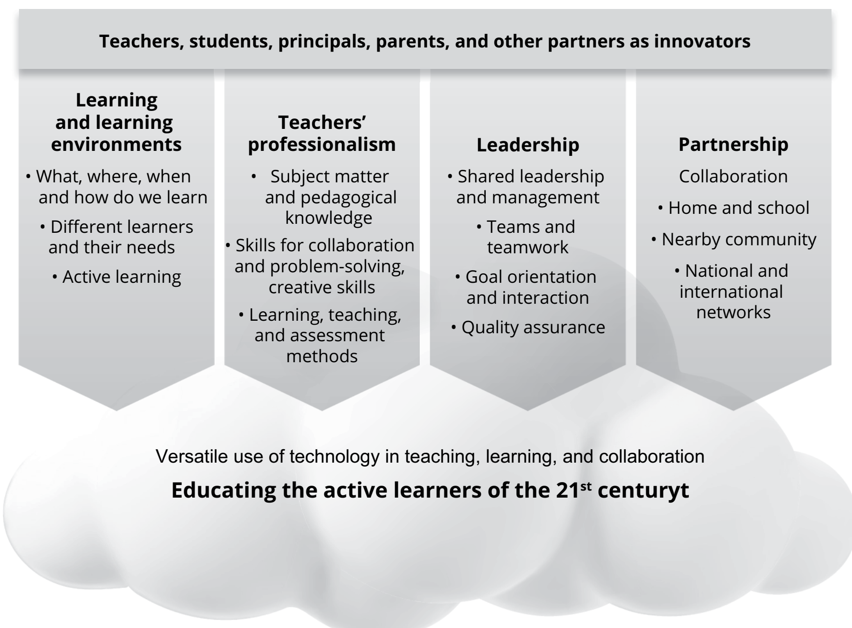

Figure 16.1 The Innovative School Model.

(adapted from Korhonen et al., 2014)

limitations, as well as factors affecting the organization and formation of a new order of each school's interests and epistemic spaces (Mitleton-Kelly, 2006; White & Levin, 2016). A key principle in applying DBR is that Innovative School actors and researchers collaborate through research-practice partnerships (RPP, see more in Chapter 1 of this book), identifying the best practices and the challenges of the Innovative School. The development work is iterative, following cycles that cover the design, implementation, and evaluation (Edelson, 2002; Plomp & Nieveen, 2013) of the model and process activities. Co-development produces three types of outcomes: knowledge of Innovative School activities, knowledge regarding iterative co-development processes, and knowledge of successful design solutions, that is, educational innovations (Edelson, 2002).

The key guiding principle in co-development is Dewey's idea of a shared activity. In a shared activity, all participants have the same interest in the accomplishment of the activity (Dewey, 1916/1980). "Shared activity", in the context of educational DBR, means that school actors and researchers design, implement, and evaluate educational innovations together. This requires interaction and building shared knowledge and understanding between school actors and researchers. Biesta and Burbules (2003) characterize communication not as a process in which school actors simply react to a researcher's movements and vice versa but as a process of the mutual coordination of action. Dewey's thoughts are connected to this with the concept that successful coordination requires school actors to react to what the researcher intends to achieve with their activities, just as the researcher reacts to what school actors intend to achieve with their activities. Successful coordination requires that the interacting partners try to anticipate the other's actions (Biesta & Burbules, 2003). By engaging in shared design, by being exposed to similar experiences in the learning environment, and by anticipating each other's intentions, school actors and researchers can reach a stage at which they experience a shared world. New knowledge concerning teaching and learning is constructed through reflections with others who share the same world.

The central concepts in the systemic development of innovative schools are 'educational innovation' and 'innovation education'. Innovations, especially educational innovations, are formed through emergent processes, which support 21st-century school education. Here innovation is understood broadly: it is the product of a creative process that is new to the innovating person or community. A characteristic of the creative process is combining previous knowledge in a new innovative way (Fisher, 2005). Educational innovations are purposefully designed innovations aimed at developing school practice (Nicholls, 1983). Creative processes result in solutions that can be further combined and evaluated to form a feasible innovation that enriches teaching and learning, collaboration as well as the whole school.

The aims of innovation education in the Finnish and invention pedagogy context are twofold (Korhonen & Lavonen, 2017). On one hand, the aim is to guide and inspire children and youths to learn 21st-century competencies by developing tangible *learning innovations* through invention pedagogy. On the other hand, a focal dimension of innovation education in our model is that it also guides all school stakeholders to develop *operational innovations* that renew school practices and structures with all school stakeholders: students, teachers, staff, parents, and partners. The Innokas approach has a similarity to Shavinina's (2013) characterization of innovation education, the aim of which is to promote societal actions preparing children to become adult innovators. Our approach highlights all students as innovators, whereas Shavinina's model focuses more on the education of gifted students as future innovators. In addition, innovation education in the Finnish and invention pedagogy context views all school actors as innovators and aims at systemic change at the level of the whole school.

Co-creative Development of the Innovative School

The development of the Innovative School Model started at the beginning of the century at a single school in the metropolitan area of Finland. The model has since expanded and been developed through the years in collaboration with researchers and various schools in the Innokas Network (Korhonen et al., 2014; Korhonen & Lavonen, 2017). A central working method has been co-creative development: collaboration between schools and researchers in an RPP. In an Innovative School, development is viewed positively, and it is seen as a continuum and part of everyday schoolwork in a digitalizing society. The idea of school stakeholders as innovators and inventors is central to the practices of the Innovative School and at the center of the Innovative School Model is the courage to think and act differently. The subjects of development are learning and learning environments, teachers' professionalism, leadership, and partnerships (see Figure 16.1).

The Innovative School Model was purposefully developed further in the Innovative School project in 2019–2021. The project was organized by the national Innokas Network, and eight Finnish schools of varying sizes from several parts of Finland participated in the project (see Table 16.1). The schools' activities were guided and supported by the project coordinator in collaboration with local network coordinators. Teams consisting of two to six teachers and the principal were responsible for school-level activities. The project's aims were an RPP with the project's schools to (1) develop the ways innovative schools operate, (2) reflect on and develop the Innovative School Model, and (3) wrap up the developed operations of the innovating school and development process for dissemination.

The schools' activities were guided by DBR methods. The development work was initiated with a status and needs survey targeting teachers and principals in the fall of 2019. The analysis of the questionnaires formed the basis for the development work at schools. The questionnaire was built around the principles and practices of the Innovative School Model. The results of the questionnaires were presented to the school staff and reflected on with them. Based on the results and collaborative reflection discussions, each of the school teams chose a development project to work on.

In all schools, teachers' teamwork and technology utilization in developing and sharing teachers' digi pedagogical competence were raised as core themes of development. In five of the schools, this development work was tied to ongoing or recently initiated processes or upcoming changes in learning environments, such as new school building projects that required a change in working cultures. In

Table 16.1 Schools and development projects of the Innovative School project

School	*Number of students*	*Grade levels*	*School-specific development project*	*School size and area*	*Region*
1	650 + 210*	0–10	A model for developing digital competencies	Big Urban	Central
2	730	0–9	A technology-oriented multidisciplinary learning module for secondary school	Big Urban	Eastern
3	627	1–9	STEAM learning path	Big Urban	Northern
4	588	1–6	Student agent activities	Medium Urban	Eastern
5	500	1–9	Implementing the steps for digital skills and a digi passport	Medium Urban	Capital
6	450**	7–9	Space and ways of working for maker education	Medium Urban	Western
7	240	1–6	Co-planning and competence-sharing principles for teachers	Small Rural	Eastern
8	160	0–6	A collaborative model for sharing innovation and project learning	Small Rural	Western

* Three school units, the project unit with 210 students

** 450 until August 2021, 900 after August 2021

addition, based on the results of the survey and conversations, each school chose one or more specific themes for development. In schools 3 and 5, a consistent learning path was developed ranging from the first school years to the end of lower secondary school. School 3 had an emphasis on students' STEAM (science, technology, engineering, arts, and mathematics) skills, and school 5 had an emphasis on digital skills. At two of the schools (schools 4 and 5), the students' role as peer mentors for digital skill development was the focus. In these schools, a group of students took the role of either tutor students or so-called digi agents. In four of the schools (schools 1, 2, 7, and 8) teachers' competence development and knowledge sharing formed the core of the development work. At school 6, the focus was developing a makerspace and related practices.

After the initial need surveys, analyses of the surveys and selection of the development project plans were altered by the COVID-19 outbreak in spring 2020. Schools moved to distance education, and this period in Finland lasted from March to May 2020. The changed circumstances significantly impacted the development work done at school and the teachers' opportunity to take part in the work.

The project plans were altered under the new situation. Some of the planned supportive measures, such as workshops for teachers and a joint project meeting scheduled for the spring, were canceled. Distance meetings and interviews were organized for each participating school to map the situation.

Schools returned to face-to-face teaching in fall 2020, and the project work resumed accounting for the new circumstances. The schools' development work was supported by local regional Innokas Network coordinators and researchers. Co-development was supported during 2020–2021 on multiple levels: (1) among project experts and project teams in school-specific meetings, (2) among school teams, (3) among the whole school staff and students in joint training or development days, and (4) among all project stakeholders in joint development meetings.

Supportive measures targeting all project stakeholders included joint project meetings, training, and shared project tools such as a project plan template and a checklist for a successful development project. During the joint project meeting, the focus was the schools' subprojects, allowing for sharing competence and experiences, sparring, and co-development among all stakeholders. School-specific meetings focused on the development of each subproject with the aid of the project experts. In these meetings, schools were given practical guidance in using project tools, strengths and challenges were identified, and solutions were sought together. In the meetings, the teams ideated supportive measures such as training for the whole school staff. The work of the project teams was built according to the structures of each school.

In the final project year, during joint meetings, project teams were guided to recognize the developments made: the processes, practices, and needed structures and resources. Based on reflections, the school teams planned and produced videos depicting their schools' work on the different dimensions of the Innovative School Model. The videos served as a tool for sharing expertise, as well as modeling and disseminating project results.

At the end of the project in fall 2021, the school teams and Innokas Network regional coordinators were interviewed. In the interviews, the experiences of the Innovative School Model and project were gathered from the perspective of both the schools and the project activities. Additionally, the interviews sought to find ways to further utilize the developed models and practices in schools beyond the project's lifespan. Schools were encouraged to keep up with development work by further working on structures that support competence development in everyday school practices.

Experiences of the Innovative School Model and Development Process

Teacher and principal interviews administered at the end of the project illuminated the project's development process and the dimensions of the Innovative School Model in practice. In the following sections, we describe the experiences of teachers and principals in the Innovative School project by mapping the main elements of the schools' development themes and by building on reflections of previous knowledge from research and development work related to the Innovative School Model (Korhonen et al., 2014; Korhonen & Lavonen, 2017). We elaborate on the experiences from the viewpoint of the four main stakeholder groups: students, teachers, principals, and partnership networks.

Students as Active Co-creators

Our previous research and development projects have shown that in an innovative and inventive school, student participation and agency have a central role in the development of an Innovative School (Korhonen et al., 2014; Korhonen & Lavonen, 2017). In an Innovative School, students work as co-innovators in collaboration with teachers and other stakeholders. In addition to making learning innovations, they are encouraged to influence the whole school by developing needs-based operational innovations such as the practices of their own class, grade level, or even the whole school. Student innovations include recess clubs, recess tool rentals, tutor-student activities, and internships within the school. The innovation skills learned in actual invention projects are geared to a more abstract level through operational innovations.

Promoting students' participation was the developmental focus in three Innovative School projects. In all three schools, a version of student peer-to-peer teaching aimed at sharing student expertise through newly developed structures and practices was developed. These structures included designated teachers and resources for tutor-student activities, time allocated for collaborative work, student training solutions, and student tutoring scheduling systems. In addition, attention was paid to motivating and committing students to activities through making a tutor-student pledge, designing a shirt, or giving a diploma, for instance. For example, students designed a logo for tutor students and participated in building a digital passport with steps for competence development (see Figure 16.2). In one school, the backpack hooks on students' desks were not working properly, and new hooks were designed and manufactured with a 3D printer as a collaborative effort between students and teachers.

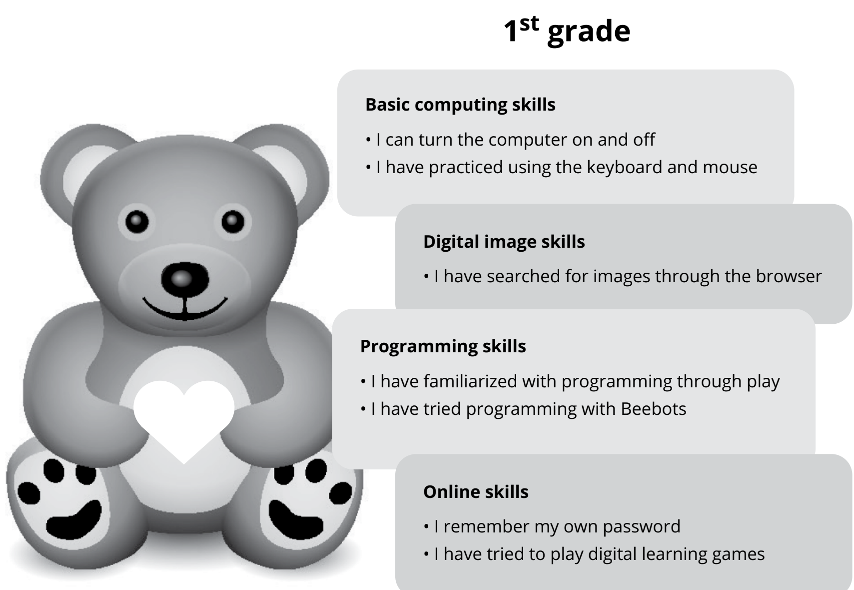

Figure 16.2 First graders' digital passport (school 5).

Team Structure and Teaching as a Backbone for School-Level Collaboration

Instead of weekly meetings common to all teachers, many innovative schools hold team meetings according to grade level, subject group, or theme areas. For example, in team meetings, the implementation and evaluation of cross-curricular invention projects are planned so the expertise of all teachers in the team is utilized. It is essential for the development of a systemic school that teamwork is designed on a structurally sustainable basis and as part of the school's daily activities. Key questions from the perspective of a functioning team structure include which need-based themes the activities of the teams are built around, how the activities of the teams are built into the system of the operation and development of the school, and how the activities of the teams are scheduled. The aim of the activity is to establish common teamwork methods that utilize technology and to make operations transparent.

In addition, it is important to decide where the questions and decisions that have emerged from the teams should be presented: For example, is the leader of each team part of the management team, or are the practices developed shared in pedagogical cafés? There is also a need to consider how teams will be evaluated and developed. When these questions are answered collectively and with the commitment of the work community, so-called pseudo-teamwork is often avoided, in which the goals and structures of the teams' activities are unclear. Jointly planned and goal-oriented team activities serve the objective of an inventive, Innovative School (i.e., to support students' learning and growth and, at best, also the endurance of teachers).

The development of practices related to team structure and team teaching also became one of the areas for development in all schools of the Innovative School project. For example, at one school a team outlined the tasks for their STEAM team members and another team constructed a process model for purchases in a new school (see Figure 16.3). Teamwork was already familiar to some of the schools in the project but less familiar to others. Five of the project's schools were offered team teacher training tailored to their wishes and needs, which supported the schools in developing team-teaching practices through research-based knowledge and experience from previous development work. Among other things, the training dealt with the models and structures of team teaching and the factors that challenge and enable it. An essential role in the training was the teachers' reflective discussion about team structure and teaching in their own school and the mapping of developmental needs and ideas.

Collaborative discussions with other project schools and training affected the development of teamwork in schools to varying degrees. At some schools, the structures and operating models of team teaching became increasingly supportive of the school's overall activities during the project. However, at some schools, the importance and potential of team teaching were better identified as a component of holistic school development activities but did not yet lead to changes in ways of working. The results of the development activities were also influenced in part by the attitude of the school management to team teaching.

In the interviews, the teachers at a few schools considered the future of team teaching, continuous competence development, and sharing after the end of the

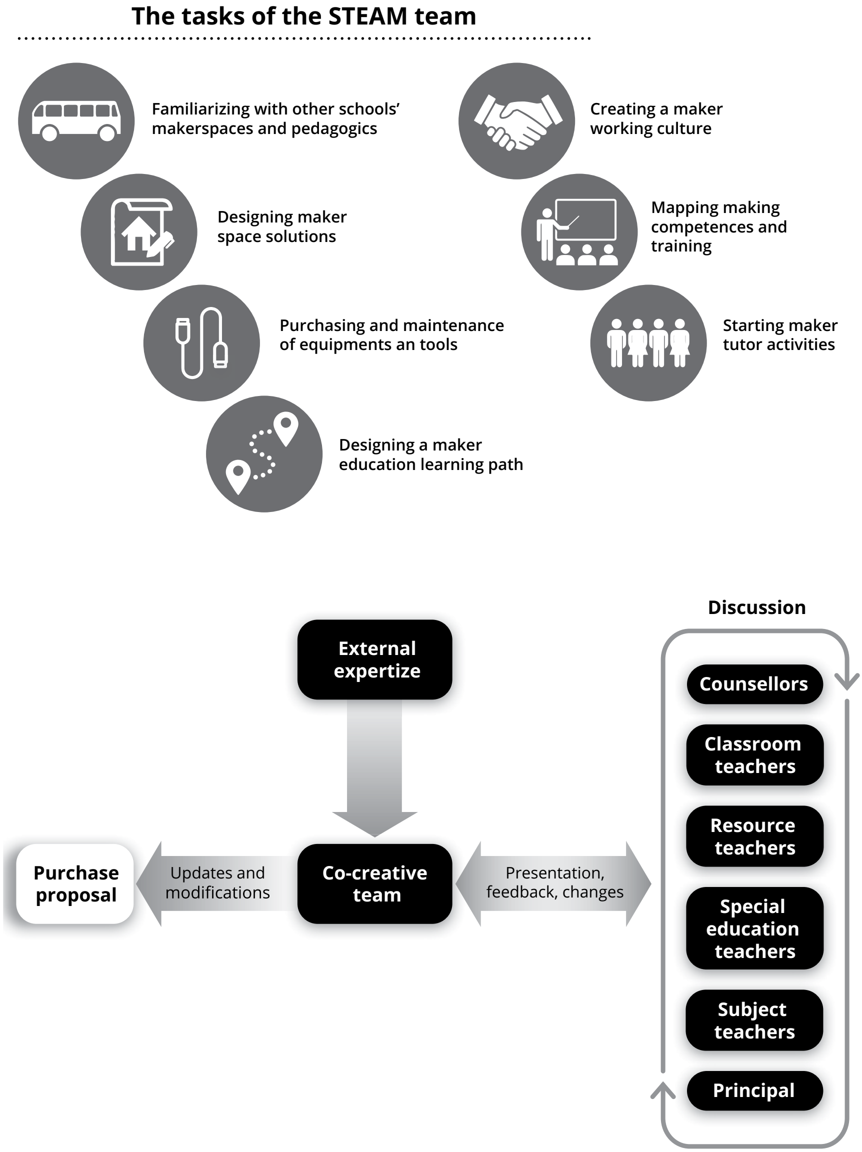

Figure 16.3 The tasks of the STEAM team members and a process model for purchases (school 7).

project. At the end of the project, their schools had begun to consider supporting a continuum of holistic development, and it had been decided that the Innovative School project team could continue to support the joint development of the school's activities as a permanent team after the end of the project. It is also important to consider personnel changes in securing the continuity of team activities. One of the project teachers described the challenge posed by staff exchanges well:

> There have been difficult times when we have felt that we [with the other project teacher] have been trying to run things together. Now, we see the light at the end of the tunnel again because a new person has been recruited to the team.
>
> (Subject teacher, School 2)

Using technology in the development and sharing of competencies, which has been the subject of development in all schools, also came to the fore in connection with the activities and sharing of the competencies of the teams. One of the school's six teachers describes the options for using technology from the perspective of a large school:

> We have started using Google Tools and have introduced Google Classroom to all the sharing activities we do. Now that we have a new school, it is easy to say that this is how things will proceed and these are the ones we'll try at first. New school, new tricks. So now we'll test electronic platforms—how to get things done together and share work.
>
> (Subject teacher, School 6)

Leaders as Co-creative Enablers

Developing the elements of an Innovative School Model as part of everyday school activities requires strong and participatory leadership. The school principals and management team, through their own actions, enable the operation of an Innovative School. The change in ways of working and the commitment of actors to community activities require a clear vision built with stakeholders and long-term support. From a leadership perspective, the most important factor is to identify and recognize the strengths of the actors at the school and give them equal opportunities to implement development activities. In most cases, enabling holistic invention at various levels requires leaders to have the courage to act in new ways and share their own responsibilities. Working in a team also gives leaders the opportunity to practice the skills required by teachers and other actors.

Principal teams or management teams can be considered good operational examples of leadership innovations. In them, the tasks related to the management of the school are divided among people so that each handles the school's participatory development activities. For example, one member of the leadership team may be responsible for teacher teamwork and participatory practices for students. In practice, that member of the management team directs those activities within the bounds of resources as part of the school's daily activities.

In the Innovative School project, the management of all schools was involved during the initiation phase of the project and, to varying degrees, during the project. At three schools, a member of the management team was closely involved in the project work throughout the project, while at two project schools, more emphasis was placed on trust in the self-direction of the project team. However, in the final interviews, all project teachers in the schools stated that management support had been obtained for the development work.

> A big thank you [goes out] to the management for making it possible for us to start such a job. Without the involvement of management, this would not be possible in any way. Yes, time and resources are needed to develop this.
>
> (Project teacher, School 3)

The principal of one project school pointed out that the new technologies for competence sharing introduced during the project strengthened self-direction and reduced traditional top-down leadership, transforming the school little by little into a learning community. Information is equally accessible to all, and the information produced by different teams can be used more easily and flexibly, which, in turn, increases the efficiency and transparency of activities. Simultaneously, the activity becomes more communal.

> The courage to act and take a stand has increased. Things have become more agile, and decision making has become easier.
>
> (Principal, School 7)

The principal also emphasized the role of the project as part of the design and construction process of the new school building underway at that school. The project had been a natural part of the change process in the school; it had been implemented considering the skills of the teachers and workload. Thus, the project has become successful and "looks like us [the school]". The principal of the school in question was particularly interested in co-development as a working method of the project. The principal felt that the activities of the project supported his activities as a leader at both his own school and the municipal level.

> The project has also supported my work, and I have been able to develop things not only at the school level but also at the municipal level.
>
> (Principal, School 7)

Network Actors as Collaborative Partners

The Innovative School as an inventive community also pays special attention to partnerships. The most important partners of the school are the parents. An essential role in the activities of an Innovative School is the opportunity for parents to participate in and influence activities, for example, through class committees and the parents' committee. New ways of working together are ideated with students and parents. For example, a traditional parent–teacher meeting can be turned into a Saturday school day: Parents take the role of students in class activities as students, together with teachers, guide parents through the evaluation phase of an invention project. Building trust between home and school through inclusive practices that consider the diverse backgrounds and situations of parents is one of the cornerstones of an Innovative School.

The Innovative School project activities were visible to parents at several schools through development activities related to students. Several schools also communicated about the project to homes as it started in the winter of 2019–2020. For example, students' enthusiasm for the new role of digital agent received delighted feedback from parents. Project activities were also reflected in homes through school social media channels. However, the involvement of parents in the actual development work did not materialize at the project schools. This was because of the crisis communication to homes caused by COVID-19 in the early phase of the project in spring 2020. At that time, crisis communication became more emphasized, which shifted the focus away from other communication and cooperation between home and school.

The school's other partnerships with nearby actors such as libraries and kindergartens, experts, or companies in various fields also support the operation of the inventive school. In the Innovative School project, the development of invention pedagogy played a significant role at several schools. The theme is naturally linked to entrepreneurship education, and local companies were a natural partner at some schools:

> When we got companies involved in the first year, it brought a slightly different perspective when we started to get information from elsewhere as well. And that is certainly too what the students have been longing for.
>
> (Subject teacher, School 2)

All the schools involved in the project also had other existing networks, such as a regional tutor network or other regional partnerships. The development work based on the Innovative School Model, therefore, encouraged the identification of existing networks and their better and more diverse use as part of the school's daily activities. Most of the project schools already had plans to utilize networks outside the school. Although the implementation of these plans was interrupted during the COVID period, network cooperation was not completely abandoned; rather, the implementation was postponed.

> We have succeeded very well in the goals of the project, in that we have involved all the actors in our own school. All the teachers are positive, and the students like this. The outside-school activities are, of course, not yet realized due to COVID. I am holding a larger meeting for vice principals and other schools that want to join in the future.
>
> (Class teacher, School 8)

In the final interviews, most teachers and principals found that one of the best outputs of the collaborative work with other project schools (networking) was the realization that the challenges schools faced were similar and that the solutions found were applicable and useful regardless of the school type or area. The support provided by the Innokas Network was also emphasized in the project work. During the project, the schools could take advantage of both the research-based support provided by the university and the support of the regional coordinator in their area.

I've asked the regional coordinator many things and the coordinator has always had time to respond. The coordinator has been our biggest support in daily life.

(Class teacher, School 1)

From Projects to Everyday Innovative School Co-creation Practices

The cyclical and iterative nature of DBR activities of the Innovative School project guided the school actors to co-develop both in their own schools and in cooperation with other project schools. All interviewed project stakeholders emphasized the importance of the participatory RPP process and novel shared activities between practitioners and researchers. Participants found that committing to a recurring, scheduled, and joint planning time built into the school's timetable when co-creating was crucial for the development work. In the final interviews, it was brought up that the project schedule and yearly time line influenced the work of the project teams significantly. The scheduled joint meetings and related tasks set important deadlines for the school-specific teams, and during the joint meetings, the participants were forced to present and depict their own development work to others. The financial resources available through the project also enabled the allocation of human resources and the purchase of equipment and software to support the development of the school's activities.

Project activities and results often live for some time as part of school activities. However, without the identification and recognition of enabling and challenging factors influencing development activities, the operational innovations achieved during the development work and then the continuation of the development work as part of school life may end. One key goal of Innovative School work is to achieve results that transfer to everyday practices. With that in mind, in the last phases of the project, we directed schools to think about the future of day-to-day development work beyond the life span of the project in their schools. In the following, we summarize our previous research work and experiences from Innovative School projects with the elements that support the holistic development in everyday school life as observed in the project during 2019–2021.

Co-creation Structures. To ensure the continuity of development work, it is useful to create permanent participatory structures for schools. It is important to consider and design permanent structures tied to the school's yearly plan for iterative competency development cycles and evaluations guiding development work in collaboration with all school actors. It is also good to think about in what situations and when development work needs are mapped, how co-creation is organized, how and when its results are presented, and how they are communicated to actors. Well-thought-out structures make development work part of everyday life, so one need not reinvent the wheel whenever a new development theme starts. It is essential to include the evaluation of development work in the structures. Both the development process and the results of the work should be evaluated systematically, and the results of the evaluation should be taken as a natural part of development work.

Giving space, time, place, and appreciation to presenting the innovations developed, and the challenges also plays an essential role in the process of co-development and the sharing of competencies. Invention fairs, team meetings, pedagogical cafés, or Saturday school days with parents are examples of knowledge sharing enabled and implemented within school structures. These regular and inclusive meeting opportunities for the different actors in the school are needed to form an inclusive community. The communal presentation of developed learning and operational innovations also serves as a stimulus for innovations as a continuous part of school activities.

All actors as innovators. An essential role in the planning of development work as part of the school's everyday activities is how the involvement of all school actors is considered in the needs assessments, in the activities themselves, and in the evaluation that guides the activities. The idea of all actors as innovators should be regularly opened to school actors through practical examples in a variety of contexts. In this way, new participatory approaches gradually become known, while enabling co-development and innovation in the freshest and most creative way possible. Both the results of our previous research before the COVID-19 period and the results of the Innovative School project suggest that in the future it will be important to co-create and share even more operational innovations for promoting student and parent participation as part of the practices of the Innovative School. Enabling and increasing the participation of students and parents also guides teachers and principals to new ways of working. It is important to discuss and decide among the work community who takes the responsibility for developing these participatory activities. Meanwhile, it is useful to note that leading and organizing these activities and truly being sensitive and open to students' and parents' ideas and needs require a time and a place in school structures.

Shared responsibilities. When starting development work, it is important to consider how the work is to be organized and to agree on the people to be responsible. In connection with the needs assessment, it is good to map not only the development needs but also the competence and willingness of teachers and other actors in the school to lead the development. Using existing expertise and recruiting those interested in development work to be responsible for change creates opportunities for an inclusive and inspiring development spirit. In several innovative schools, the areas of development are divided among responsible teams, with each team having responsibility for a certain part of the development work. It is also significant to consider the diverse skills of team members, their interests, and disparate roles. For example, it is often useful to involve both classroom and subject teachers or special education teachers in development work, ensuring continuity and considering different learners.

Continuous support. School actors need support and tools to involve Innovative School actors in development work. New, creative, and technology-based ways of engaging play a key role. The toolkit must include tools that motivate and are easy for the actors in the school to use, reducing rather than increasing the workload. Diverse and regular support tailored to the needs of the school is crucial. Some of the support directly targets the development team and resembles job coaching. Support can also directly target students, a specific group of teachers, the whole school staff, or school management. Notably, besides experts and researchers, other innovative schools, their development teams, and experts and networks from their own schools can provide support. Development work often helps to better identify the school's competencies. Moreover, new, innovative practices for sharing competencies within one's school emerge during the development work. Participating in national and international networks, either as a listener or as a presenter of innovations, also broadens the perceptions of both students and school staff about the opportunities and importance of developing school activities and sharing knowledge. Activities outside the school or municipality help people to understand the activities of an innovative, inventive school through new perspectives and spark the development of one's own school community.

Reallocated resources. The lack of time and financial resources is often perceived as an obstacle to the development of operational innovations in an Innovative School. Leaders at several schools have set out to plan the use of the school budget and the planning time traditionally allocated for joint meetings of all teachers in new ways. Considering the use of the school's annual budget in collaboration with teachers, such as by enabling grade-level teacher teams to use their own budget has often made it possible to make different purchases than before. Time spent on joint meetings has been cut to once a month, and the other time slots freed for weekly teacher team activities. It is also possible to consider what opportunities the school must finance, for example, a mentor teacher for one day a week to support the activities and development of the whole school.

Versatile use of technology. In the Innovative School project, most schools focused on developing new solutions to use technology as an object of and support for learning. However, it is also good to consider the role of technology as part of the organization of school activities, the interaction of school actors, and support for development work. New solutions utilizing technology at two Innovative School project schools were also reflected in both the school's internal communication and the ways teachers' knowledge was shared. In sharing these solutions and good practices as part of the day-to-day running of an Innovative School, it is important to learn to make extensive use of technology and to dare to bring new technological solutions to different levels of school activity and increase opportunities for all actors' participation.

Building the Innovative School 2.0

The joint development of the Innovative School Model and activities in cooperation with eight Finnish primary schools strengthened our understanding that the development of schools is a complex and multidimensional emergent process (Mitleton-Kelly, 2006). Identifying the complex dimensions in the systemic development of schools of various sizes and cultures and utilizing the identified dimensions to support school activities require a strong commitment to DBR, RPP, and shared knowledge co-creation from both school actors and researchers.

The development work with the project schools brought to life the Innovative School Model we have developed over the years. The operational innovations developed by project schools related to students as co-creators, team teaching and structures, leaders as co-creative enablers, and network actors as partners are examples of needs-based co-development in schools. These operational practices that guided the learning of digital technology and supported the cooperation and sharing of knowledge between teachers are artifacts that are characteristic of DBR development work (Edelson, 2002; Plomp & Nieveen, 2013).

We are on our way to an Innovative School Model 2.0. In version 2.0, we are moving from describing the activities and operational innovations of the Innovative School Model to asking what factors enable all actors to be innovators and implement both learning and operational innovations. Essential factors in enabling innovation and iterative needs-based development activities are based on this development and research work: the co-creation structures of development work described in the previous section, shared responsibilities, continuous support, reallocated resources, and the versatile use of technology. Innovative School 2.0 builds on the school's actors and the basic elements of its activities to the elements that guide and enable activities. These recognized and overlapping elements relate to the factors that guide self-organization in CAS theory: interactions between stakeholders, the structures of joint practice, circumstances, and each organization's interests (Mitleton-Kelly, 2006; White & Levin, 2016) that in turn influence the organization of joint activities and the new order of the Innovative School.

Adapting CAS theory to the Innovative School Model and invention pedagogy: In self-directed, innovative schools, systemic development can be seen as a design challenge that requires the same skills to work as to create inventions. The design challenge is an open and complex problem that takes shape and becomes more precise as solutions evolve. Actors' development needs can be contradictory, and the level of competence and motivation of the actors varies. Indeed, the ability to manage ambiguity and the courage to create something new are key characteristics of an Innovative School actor. Persistence also plays an essential role; that is, the development of ways of working in each school in a step-by-step organized manner, regularly identifying needs and evaluating the results of the development work.

We will continue the work of developing the Innovative School in collaboration with schools through DBR-based research and development. Our aim is to support schools to be innovative communities that see continued development work as part of their daily practice in the 21st century. The ideal situation is that the school, as an inventive community, develops its activity with curiosity, following its time and considering the challenges and opportunities of the digitalizing society. The school encourages innovation from all stakeholders at various levels. At their best, working with challenging invention and innovation processes, school actors are filled with excitement, grit, and drive while learning to take responsibility for their environment and community.

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17 Conclusions

The Cornerstones and Future Directions of Invention Pedagogy

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The Four Cornerstones of Invention Pedagogy

In this book, we introduced invention pedagogy, a Finnish research-based approach to maker education, in which students and teachers engage in nonlinear, multidisciplinary, creative technology-enhanced design and making processes in formal educational settings. In the book, the pedagogical approach has been explored from three perspectives: learning by inventing, facilitation of the invention process, and co-development of inventive school culture. Invention projects are emergent and socio-material in nature and focus on knowledge-creating learning through sustained and iterative generation of shared epistemic objects. Facilitation of this kind of learning is based on careful and dynamic orchestration of the invention process as well as on teachers' transformative agency. The focal features of invention pedagogy can also be used for the school-level development of inventive culture—that is, reconsidering the infrastructures and practices of the school in a way that enables and supports the inventive activities of the entire school community.

The invention projects presented in this book vary in their contents and implementation; however, they all share certain key elements, which we introduced at the very beginning. Such invention projects (1) require and develop an inclusive innovator mindset, (2) are based on multifaceted real-world phenomena, (3) call for co-creation of knowledge and artifacts, and (4) use technology-enriched tools and materials. These key elements have been identified as being central to students' knowledge-creating learning (Paavola & Hakkarainen, 2021) and the facilitation of such learning. At the same time, they are also important in the school-level development of inventive culture, which provides the necessary backbone for established-yet-emergent inventive practices throughout the school (Korhonen & Lavonen, 2017). Thus, the four key elements of invention *projects* also form the cornerstones of invention *pedagogy*, each functioning in conjunction with the others and cutting across the various levels of the pedagogy. The intertwined and cross-level nature of the four cornerstones is illustrated in Figure 17.1, which depicts the cornerstones at the levels of learning by inventing (inner circle), facilitation of the invention process (middle circle), and co-development of an inventive school culture (outer circle).

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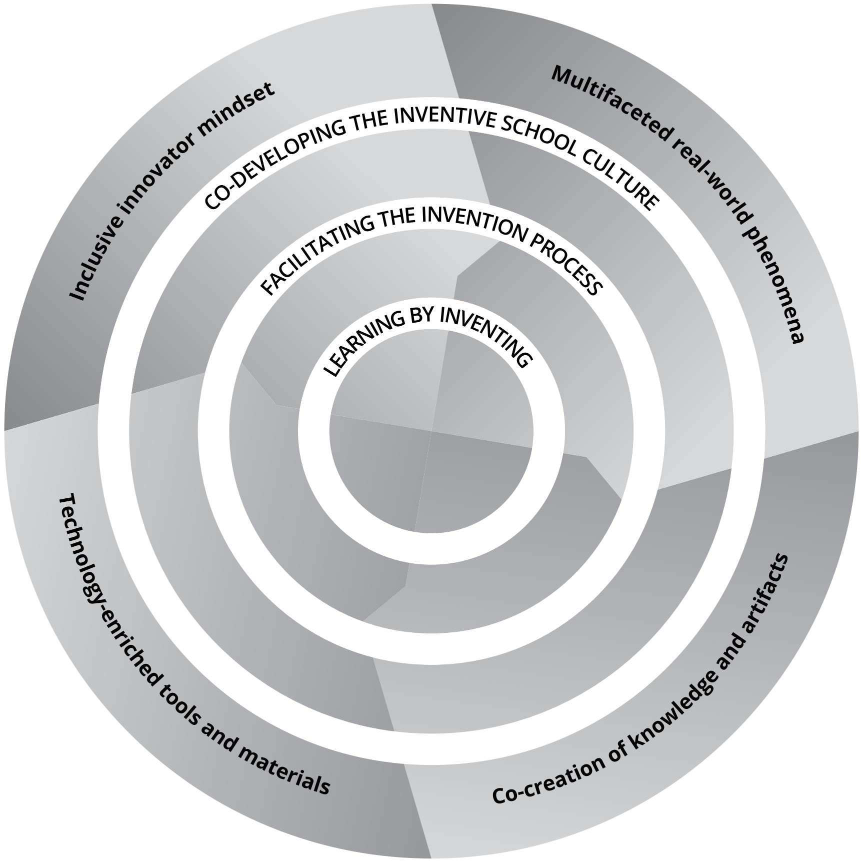

Figure 17.1 The four cornerstones of invention pedagogy across the levels of learning by inventing, the facilitation of the invention process, and the co-development of inventive school culture.

Inclusive Innovator Mindset

Invention pedagogy requires and develops a certain type of mindset in students, teachers, and the other actors in schools. From the perspective of learning, an inclusive innovator mindset is needed from the students for them to be able to create innovative solutions to open-ended challenges; work with others who may have varying perspectives, competencies, and backgrounds; and see themselves as active creators of the future world. Such a mindset has mainly been studied in relation to students (e.g., Chu et al., 2015), but recent research has highlighted that teachers' development of this mindset is essential to the successful implementation of creative learning activities (Jones, 2021). Facilitation of an invention process requires tolerance of the partly unpredictable and ambiguous nature of nonlinear learning, courage to create and test new ways of teaching and learning, and trust in every student's creative potential.

At the school level, an inclusive innovator mindset considers all school infrastructures, practices, and resources as something that can be improved. Thus, in invention pedagogy, mindset is not considered to be something that exists only inside an individual's mind; instead, it emerges and develops through social relationships mediated by the material–technological environment and regulated through cultural traditions. In that sense, it is related to the "makerspace mindset" (Thestrup, 2018), which complements and extends the maker mindset by underlining the culture of the makerspace and acknowledging the opportunities and challenges associated with working with others (Culpepper & Gauntlett, 2020). In invention pedagogy, which is situated in formal education, such a mindset is committed to the continuous and joint development of a school culture that promotes inventive activities.

Multifaceted Real-World Phenomena

In invention pedagogy, the starting point for learning is multifaceted real-world phenomena that are approached through students' own questions, co-creations, and solutions. Therefore, learning objectives or activities cannot be fully determined beforehand, as the goals, contents, and methods of an invention project evolve as the questions and solutions become more defined. New knowledge and skills are applied to the phenomenon, questions, or solutions at hand; thus, they have immediate utility value that is evident in the learning situation. This kind of learning supports students in gaining comprehensive understanding and deeper knowledge of the phenomenon under study (Silander et al., 2022). Although invention pedagogy is situated in formal education and binds to curriculum objectives, its emphasis is on developing students' and teachers' capabilities to navigate in undetermined contexts and utilize the affordances of those contexts rather than focusing only on reaching predetermined goals.

However, invention projects are not characterized as unconstrained exploration (see Sawyer, 2021); rather, they are carefully guided through facilitation that constantly seeks a balance between openness and structure. Facilitating an invention process means giving students the freedom to construct their own ideas and expertise within the boundaries of carefully formulated tasks and with appropriate constraints and materials (Sawyer, 2018; Seitamaa-Hakkarainen, 2022). The underlying phenomenon is formulated, and the invention process is structured in a way that enables student-centered creative pursuits but is not too overwhelming for the students. Teachers provide purposeful structures and address students' emergent needs in parallel (Beghetto et al., 2015; Sawyer, 2021), providing opportunities for all students to flourish and learn. Dealing with multifaceted real-world phenomena also extends beyond individual projects and classrooms to school-level development. Reconsidering and recreating school structures and practices is a similar process of navigating in the unknown; the developers of an innovative school culture determine questions and create innovative solutions related to school-level phenomena.

Co-creation of Knowledge and Artifacts

Inventing something new is a complex and multifaceted process that may go in directions that are unfamiliar to both students and teachers. This is likely to be very challenging and requires collaboration of several people with varying competencies and expertise and systematic joint efforts for externalizing ideas and constructing various types of intangible and tangible artifacts (e.g., Paavola et al., 2004). Whether students are creating inventions in teams, teachers and tutors are collaborating in the facilitation of an invention project, or actors are participating in school-level development work, all participants need to be committed to the shared goals, activities, and division of labor that supports the collaborative achievement of those goals.

Invention pedagogy follows and extends the line of research conducted in the fields of arts and design education (e.g., Davis, 2008; Hetland et al., 2013; Sawyer, 2018) and STEAM (science, technology, engineering, arts, mathematics) education (e.g., Daugherty, 2013; Sousa & Pilecki, 2018), suggesting that creative approaches to education have their own learning heuristic. In art and design, as well as in invention projects, experience-based practices are used for problem-solving, investigation, discovery, and learning. Such practices include envisioning mentally what cannot be directly observed or imagining possible next steps, expressing ideas or personal meanings, exploring playfully without a prestructured plan, and embracing mistakes as learning opportunities. This kind of learning relies on co-construction of epistemic objects that guide and direct the process (Knorr Cetina, 2001; Ewenstein & Whyte, 2009). An epistemic object in an invention project can be described as a cluster of concepts that gradually unfolds through questions and ideas generated by the team members (Mehto et al., 2020); similarly, the development of school-level inventive culture leans on the questions and ideas raised in the community. Experience-based practices enable participants to engage in, persist in, and commit to a project. Furthermore, they promote empathic intelligence (Arnold, 2005), that is, a sustained system of psychological, cognitive, affective, social, and ethical functioning, which enhances participants' connectivity, emotional engagement, and ability to relate to others. Emphatic intelligence is becoming increasingly crucial as the ethnic, cultural, and linguistic diversity in classrooms, communities, and workplaces continues to grow. Furthermore, it enhances academic and labor market prospects, as jobs that require empathic intelligence are less likely to be replaced by technology (see Organisation for Economic Co-operation and Development [OECD], 2019).

Technology-Enriched Tools and Materials

Working with and around various high- and low-tech tools is at the heart of invention pedagogy; technologies are regarded as both objects and tools of learning, depending on the context. The focus of learning is on how to use technologies for creative and academic purposes, for developing students' and teachers' invention competencies, and for narrowing down the "creative participation gap"

(Jenkins et al., 2009). In invention projects, technological tools provide students with the means to externalize and experiment with their ideas, to transform their initially vague ideas into more clearly articulated solutions and artifacts (Kangas et al., 2022; Riikonen et al., 2020). Various technological activities related to designing, engineering, programming, crafting, and documenting both constrain and enable students' inventive activities; furthermore, they provide diverse access points for students to become interested in and inspired by the possibilities provided by technologies. Learning to use technologies for creative purposes follows "the developmental trajectory of creativity," which Glăveanu (2013) describes as "first becoming able to observe and make use of affordances in the surrounding environment and then mastering this use and altering affordances, adapting what already exists and creating new artifacts with new affordances" (p. 76).

Such a trajectory concerns not only students but also teachers facilitating the invention process and all other actors participating in the development of an inventive school culture. Creative use of technologies changes the underlying social and cultural systems in schools. For example, teachers and principals innovate new ways of using technology in organizing school practices and interaction with partners, such as parents and networks. Invention pedagogy underlines teachers' transformative agency (i.e., the proactive pursuit of pedagogical and professional innovations). Teachers' professional development and continuous learning are fostered through appropriating and creating novel technological practices together with colleagues and students and the joint development of an inventive school culture (Korhonen et al., 2014).

Research–Practice Partnerships Supporting the Continuous Development of Invention Pedagogy

The classroom- and school-level invention pedagogy principles portrayed in this book have required both researchers and practitioners to build a joint understanding of the various methods of co-development and to commit to improving teaching and learning in partnership with each other. This development is done not only from the point of view of developing invention pedagogy practices but also of developing research–practice partnership (RPP) processes. In accordance with characterizations of RPPs (Coburn & Penuel, 2016), our collaboration with teachers and schools has been built over several years and through multiple projects, and it has involved co-creation among researchers and practitioners. It has focused on a variety of problems related to practice, the joint testing of solutions for improving teaching and learning and achieving systemic change at the school and municipality levels. We have worked on several invention pedagogy initiatives, from single-classroom cases to school-level development, bringing these developments into discussion and decision-making also at the municipality level.

As researchers in collaboration with school practitioners, we have found RPPs to be a promising path through which we can develop novel ways of working. Simultaneously, we recognize that we must further learn from and study RPPs to realize their full potential. By reflecting on Henrick et al.'s (2017) dimensions of RPP effectiveness, we recognize that we have found routines for collaborating that work well in the Finnish educational context. We have also learned the meaning of shared expertise, through which the viewpoints and competencies of each partner are valued. Additionally, research results have been reflected on with practitioners in a way that suits the needs of everyday school practice (e.g., mode of presentation, scheduling in accordance with school timetables, and presenting key findings in a clear manner). Finally, the dissemination and sharing of the results has been organized on the school partnership level as well as on a broader, national or international level.

Despite having identified well-functioning ways for organizing and realizing RPPs, we recognize several issues pointed out by Henrick et al. (2017) that can be further developed. The comprehensive use of RPPs as a mechanism for educational improvement is still a relatively new phenomenon in Finland. Through our research and development work with schools, we have found that collaboration could be strengthened through a more balanced negotiation of goals and strategies relating to both practice and research on all levels. Furthermore, it is essential to study RPP processes, organizations, and interactions as a whole to gain a holistic understanding of the circumstances and interconnections through which the co-development of invention pedagogy is realized. This would support practitioners and researchers in recognizing RPPs as a strategy for continuous professional learning through collaboration that can lead to sustainable ways of teaching and learning 21st-century competencies.

Our book depicts invention pedagogy practices in RPPs in the Finnish K–12 educational context. At the classroom level, the aims of invention pedagogy are similar to those of global maker education. The Finnish approach to maker education is unique in that it is situated in the formal education context and developed holistically, in addition to the classroom, school, and municipal levels. It strives to use RPPs to build a multilevel process in which the complexities and related aspects of teaching and learning are considered. This means that all actors, teachers, principals, and administrators are guided toward understanding the goals and cornerstones of invention pedagogy, enabling them to support initiatives for development and implementation. The Finnish classroom- and school-level invention pedagogy approaches presented in this book have been developed for over 20 years and have made an impact on how invention pedagogy is manifested in schools and classrooms. In the future, more effort will be needed to build municipal-level partnerships to solidify these educational practices further and provide equal opportunities for students across Finland to participate in inventing and being empowered through innovation.

Another aspect of our work that should be explored further is the research and development in invention pedagogy through global partnerships—making connections, sharing classroom practices across countries, and deepening the understanding of our practices in the global context. These initiatives could include multinational teacher and student partnerships in developing teaching practices to educate global citizens and innovators of the future. This could include developing competencies that reach beyond inventing and extend to working together with participants from other backgrounds and nationalities. These endeavors can build on and draw from established local and global networks, such as the Fablearn network, the European Schoolnet, Nation of Makers, and Innokas Network. We suggest that when developing these practices on a global level, the principles of RPP processes should be taken into consideration in the development and research of global inventive maker initiatives.

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