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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.

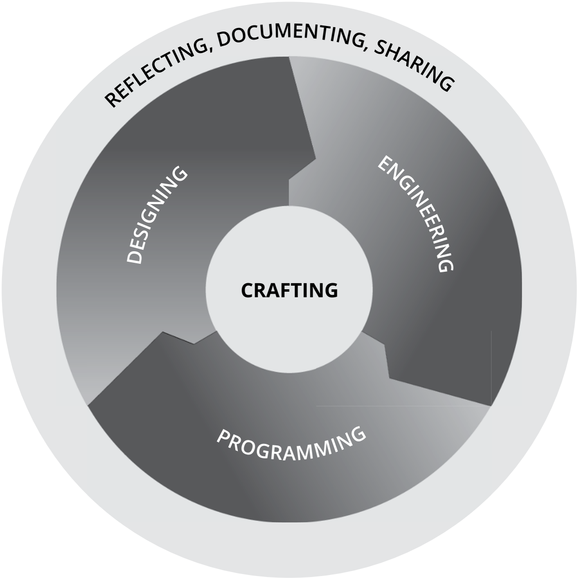

Figure 8.1 The framework for technological competence in invention projects.

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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