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Idea generation and knowledge creation through maker practices in an artifact-mediated collaborative invention project

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ABSTRACT

This investigation involved carrying out interventions that engaged teams of lower-secondary (13–14-year-old) Finnish students in using traditional and digital fabrication technologies to make materially embodied collaborative inventions. By relying on video data and ethnographic observations of the student teams' collaborative invention processes, the investigation focused on investigating 1) how the teams generated and developed their design ideas in their materially anchored making process and 2) what kinds of maker practices they relied on during open-ended invention projects. The study focused on a microanalytic study of three teams of students, and we utilized and developed visual data analysis methods. Our findings reveal the complex nature of the student teams' materially contextualized ideation and the knowledge creation activities that took place within their projects. The findings suggest that open-ended, materially mediated co-invention projects offer ample opportunities for creative cultural participation and practice-based knowledge creation in schools.

1. Introduction

The current article analyzes idea generation and knowledge creation processes in teams of 13–14-year-old students (seventh graders) who participated in a collaborative invention (co-invention) project at a public school in Helsinki, Finland. Many schools have become interested in cultivating practice-based maker pedagogies to inspire students' interest in science, technology, engineering, arts, and mathematics (STEAM) learning (Martin, 2015; Papavlasopoulou et al., 2017; Vossoughi & Bevan, 2014). Maker-centered learning is a form of innovation education (Korhonen & Lavonen, 2017) that enables participation in technology-enhanced co-invention processes in STEAM contexts (Honey & Kanter, 2013; Martin, 2015; Petrich et al., 2013; Seitamaa-Hakkarainen & Hakkarainen, 2017). Investigations have indicated that maker projects are equally motivating for girls and boys (Buchholz et al., 2014; Kafai et al., 2014; Martin et al., 2018; Riikonen et al., 2020a), as well as those who have faced challenges in adapting to traditional educational settings or who come from nondominant backgrounds (DiGiacomo & Gutiérrez, 2016; Sormunen et al., 2020). Furthermore, making and tinkering activities produce symmetrical relations and relational equity among participants in intergenerational learning environments (DiGiacomo & Gutiérrez, 2016; Schwartz et al., 2015). Hands-on working with materials and digital components is characterized as a productive STEM opportunity for children. Paying attention to childrens' rich experiences, and seeing them as capable and competent in STEM is important to design learning ecologies, in which learning is made equitable and consequential for youth from

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nondominant communities (Gutiérrez et al., 2019). In the present study, the teams we analyzed consisted of both boys and girls, as well as of students from different socio-economic and ethnic backgrounds. The open-ended design of the present co-invention project gave every student an opportunity to equally contribute and participate to the project and bring forward their valuable experiences, knowledge and viewpoints that they had accumulated through their diverse backgrounds and interests.

Engaging students in designing and constructing tangible and digitally enhanced objects using various technological resources, including digital fabrication and programming (Blikstein, 2013; Papavlasopoulou et al., 2017), can foster a renaissance of practical thinking at school. These projects are nonlinear, cyclical processes that engage students in sustained efforts to solve open-ended, meaningful design challenges (Härkki et al., 2021). Despite the materially embodied nature of making and tinkering, such activities promote the learning of multifaceted epistemic practices, such as design thinking, knowledge-creating inquiry, and peer collaboration (Hakkarainen & Seitamaa-Hakkarainen, 2022; Martin, 2015). During maker projects, student teams seek solutions to their often self-determined invention challenges by jointly creating and building knowledge and participating in experimenting and prototyping activities. Investigators have revealed different ways in which schoolchildren learn through mediated, collaborative "making" environments (Clapp, 2017; Papavlasopoulou et al., 2017; Parekh & Gee, 2019; Schad & Jones, 2020). Most empirical studies have, however, focused on merely describing maker projects (Schad & Jones, 2020). Some other studies have used pre- and posttest designs to examine the motivational impact of making activity (e.g. Lin et al., 2020;). However, very few studies have analyzed student teams' idea generation processes or the epistemic processes and practices that students rely on when pursuing complex materially embodied design and making activities (Paavola & Hakkarainen, 2014, 2021).

In the current article, we conducted a multiple case study of three student teams' making processes and practices. The present study focuses on the epistemic aspects of complex, nonlinear, maker-centered learning processes. We examine how student teams generated and refined their design ideas and the kind of knowledge that the teams worked with during the co-invention processes. Our research questions are as follows:

1. How did the student teams generate and develop design ideas during the making process? How did these design ideas evolve from preliminary design ideas to final ideas?
2. What kind of epistemic architecture of maker practices did the teams' design process rely on?

In the following sections, we reflect on the theoretical foundations of maker-centered learning as a form of knowledge-creating learning. We examine the epistemic aspects of maker learning involved in the collaborative design process before introducing the present co-invention project and student teams. We then outline the methods of data collection and data analysis. Finally, we present our findings and conclude by discussing the study's implications.

1.1. Theoretical framework: knowledge-creating learning

The present sociocultural investigation is anchored on the knowledge-creating learning framework (Hakkarainen et al., 2004; Paavola et al., 2004), which engages teams of learners in technology-mediated collaborative efforts of using traditional and digital fabrication technologies for ideating, designing, and making complex artifacts that can spark intellectual, engineering, and aesthetic challenges. *The knowledge creation metaphor* of learning was proposed as a response to Sfard's (1998) well-known distinction between *knowledge acquisition* and *the participation metaphors* of learning. The former represents encapsulated school learning that involves externally controlled reproductive efforts to solve closed textbook problems and assimilate pregiven disciplinary knowledge. The participation approach, in turn, examines learning as a process of growing up in a community, moving from initially peripheral to more central participation when learning to master relevant cultural norms and practices and building an associated identity (Hanson, 2015; Holland et al., 1998; Lave & Wenger, 1991). To enable learning more advanced inventive skills, maker pedagogies involve providing young people with expanded opportunities for creative cultural participation (Clapp, 2017; Glaveanu, 2014; Hanson, 2015). The materially and socially distributed resources provided by the maker technologies and practices enable moving from mere participation to knowledge creation at the creative edge of such practices (Paavola & Hakkarainen, 2021; Ritella & Hakkarainen, 2012; Skagestad, 1993).

The knowledge-creating learning framework (Paavola et al., 2004) is inspired by the theories of Peirce (1998), Popper (1972), and Vygotski (1978) and by the educational and organizational theories by Bereiter (2002), Engeström (2015), Nonaka and Takeuchi (1995), and Papert (1980). Together with these investigators, Vygotski (1978) emphasized the importance of learning by constructing artifacts. His well-known method of double stimulation involves confronting a student with a creative learning challenge and proving a potential "neutral" artifact that could be employed to find a solution for the challenge. As suggested by Ritella and Hakkarainen (2012), his approach can be extended to consider expansive stimulation involved in the long-standing iterative pursuit of designing and making artifacts, which may involve a long series of double-stimulation processes. The knowledge creation framework is further anchored on the Vygotskian approach to the intertwining of semiotic (sign-mediated) and material (tool-mediated) activities in practical intellect (Vygotsky, 2004). Semiotic activities involve creating, elaborating, reflecting, and advancing invention ideas. The material activities involve selecting and tinkering with tools and materials, training the required skills, and prototyping and experimenting with the artifacts being constructed. Further, joint invention also requires social organizing of creative processes in terms of creating timetables, distributing work among the team, and reflecting on advancing the process.

Designing and making are mediated by emergent, materially embodied "epistemic objects" (Knorr Cetina, 2001; see also Ewenstein & Whyte, 2009; Paavola & Hakkarainen, 2014, 2021), which entangle the epistemic and material aspects of the artifact being ideated, designed, constructed, and developed by the students. The concept of the "object" has its philosophic roots in studies by Hegel and

Marx, as well as Peirce and Popper, along with psychological roots in activity theory, as developed by Vygotski (1978) and Engeström (2015). Further, posthumanist approaches highlight the dynamic agentic role of artifacts, as well as physical, virtual, and hybrid environments (e.g., makerspaces) in which enacted collaborative activity is embedded (Latour, 1996; Mehto et al., 2020a; Stahl & Hakkarainen, 2021). Epistemic objects are more akin to enactive projections that guide embodied and emergent ideation and making processes than preconceived ideas to be straightforwardly implemented (Malafouris, 2013; Mehto et al., 2020b). Despite being incomplete, constantly defined, and instantiated through a series of successively more refined visualizations, prototypes, and other design artifacts, the envisioned epistemic objects guide and direct the knowledge creation process (Knorr Cetina, 2001). The students' epistemic process becomes materially entangled as the material objects being worked on deeply affect the intertwined generation of ever more advanced design ideas (Mehto et al., 2020b). The creative transformation of ideas into a physically embodied form, such as sketching or prototyping, sharpens and advances initially fuzzy ideas, molding them into refined versions accessible to other team members, even without verbal interactions. A recent study by Riikonen et al. (2020b) revealed the importance of model making, which is building tangible artifacts to test design ideas, such as technical functionality, during the successful completion of the making process. Model making can foster the generation of new, often more detailed, design ideas that can advance the co-invention process. Furthermore, model making gives the proposed solution a concrete form, making it possible to evaluate and accept or reject the prospective solution.

To cultivate the creative capabilities that the invention process requires, both learners and teacher practitioners must 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 prereflectively one's habits and further yet to “thing knowledge” (Baird, 2004) embedded in the design and use of tools and environment. The pragmatic use of relevant fabrication tools and materials presupposes and generates concrete and applicable working knowledge. When designing and crafting artifacts, students harness the “material agency” (Pickering, 1995) of things, as well as accumulate the working knowledge needed to construct an artifact and enable its reliable operation. Arguably, this process involves ascending from abstract conceptions to interconnected concrete implementation in practice (Iljenkov, 1977). Epistemic practices represent generative systems of creative habits, patterns, routines, and 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). Making processes also entail an understanding of the functional requirements of the potential human users' activity. Yet current educational epistemologies do not sufficiently appreciate the epistemic value of such materially mediated thing knowledge (Baird, 2004), instead privileging the conceptual aspects of knowledgeability (Nathan, 2022).

Co-invention projects focus on open-ended creative challenges (as epistemic objects), rely on multifaceted tools, materials, and production processes, and result in unforeseen inventions. As a result, it is neither possible nor desirable to predetermine specific epistemic practices and skills to be employed. Instead of instructing students and their teams to learn fixed tools and pregiven procedures, they are provided with access to three mutually supporting disciplinary domains of knowledge-creating activity: 1) scientific practices, 2) computational engineering practices, and 3) collaborative design practices (Seitamaa-Hakkarainen et al., 2010; Worsley & Blikstein, 2016). The importance of employing design thinking and engineering design as tools for improving students' science learning has been highlighted by recent educational reforms (Martin, 2015; Parekh & Gee, 2018, 2019). Because digital fabrication technologies bring a new computational layer to co-invention projects (Blikstein, 2013), students are guided to employ programmable microcontrollers. We consider *maker practices to be* an umbrella term that combines scientific, engineering, and design practices in the context of collaborative designing, making, and inventing artifacts with the help of both traditional craft and digital fabrication technologies. When productively combined, the three disciplinary domains constitute an epistemic architecture of maker practices wherein the various practices are intertwined according to student teams and teachers' and researchers' preferences.

Scientific practices constitute an essential aspect of next-generation standards for science education (Krajcik & Blumenfeld, 2005; Osborne, 2014). Such practices engage students in applying scientific knowledge and principles to investigate complex phenomena and conduct inquiries mediated by questioning, hypothesizing, experimenting, visualizing, modeling results, and building knowledge. Engineering practices, in turn, are needed to find potential solutions for technical problems, determine their criteria, construct and iteratively test model solutions, compare their strengths and weaknesses, and build and communicate results (Krajcik & Blumenfeld, 2005). The tinkering and making involved in such practices provide children with the material, conceptual, and social resources to understand the relationship between science and technology (Blikstein, 2013). Tinkering is an improvisational, bricolage-style problem solving that provides students with an understanding of what technologies are based on and their unique affordances and constraints (Bevan et al., 2015; Parekh & Gee, 2018; Resnick & Rosenbaum, 2013). Such iterative activities nurture various habits of the mind (values, attitudes, and thinking skills) when children begin making sense of complex problems to create solutions (Martin, 2015; Vossoughi & Bevan, 2014; Worsley & Blikstein, 2016). Collaborative design practices (Kangas et al., 2013; Koh et al., 2015) characterize advanced design and technology studies, craft education, and various thematic and creative STEAM projects carried out in school communities. Collaborative designing involves team efforts to find and construct material-laden solutions to a design challenge. Collaboration requires all group members to focus on a shared epistemic object that is being pursued through coordinated invention efforts that involve maintaining and advancing a shared understanding of the co-invention challenge at hand (Damşa et al., 2010). Design researchers (e.g., Cross, 2006; Lawson, 2004) have proposed that the design process consists of several overlapping but iterative phases, as well as problem-framing and problem-solving activities that coevolve at the same time. The design process is iterative in nature; it involves generating initial design ideas, making the ideas concrete by writing them down and visualizing them, refining the ideas by studying users and their needs, analyzing the design constraints, exploring and testing various aspects of design, creating prototypes, obtaining feedback, and constructing the design object. As indicated by Rowell (2002), working with materially embodied physical materials stimulates team collaboration. To conclude, our study focuses on those students engaged in the scientific, engineering, and design practices that support students in a creative way using technologies, applying knowledge, and understanding how things operate.

1.2. Implementation of learning by making in education

Learning by making has a long history in craft education and Scandinavian sloyd education (Seitamaa-Hakkarainen & Hakkarainen, 2017), project-based learning (Krajcik & Blumenfeld, 2005), and computer-supported collaborative learning (Stahl & Hakkarainen, 2021). According to Papert's (1980) notion of constructionism, participating in the learning process by making and creating external digitally enhanced artifacts fosters artifact-mediated thinking and supports in-depth learning. The creation of artifacts opens up creative paths of learning and development based on personal and collaborative improvisational exploration. The maker culture is anchored in Richard Feynman's maxim (quoted by Baird, 2004, p. 114): "what I cannot create, I cannot understand." Maker-centered learning takes place through innovation-driven collaborative interaction involving both epistemic and material considerations; consequently, it is not simply "learning by doing." Such learning is valuable because the artifacts involved in maker-centered learning may become both the internal and external tools of thinking (Papert, 1980; Vygotski, 1978).

Co-invention projects rely on teachers who, in close collaboration with one another, coordinate and provide appropriate help and real-time support for student teams. The pedagogy of maker-centered learning is based on a designer's way of thinking (Cross, 2006), sociodigital competences, and an entrepreneurial spirit, together with an experimental culture of creating, playing, and making for the purpose of fostering students' creative teamwork capabilities (Honey & Kanter, 2013; Martin, 2015). The co-invention projects are 1) multimaterial, including both soft and hard materials; 2) anchored in integrative thematic study projects orchestrated by teacher teams representing multiple subject domains; 3) integrate traditional craft and digital fabrication technologies; and 4) involve holistic processes, including all stages, from design ideation to experimentation and from fabricating to evaluating the final products (Riikonen et al., 2020b; Seitamaa-Hakkarainen & Hakkarainen, 2017).

We have conducted maker-centered co-invention projects in various schools and at different grade levels to offer students opportunities to take part in knowledge creation and the creative use of technology (e.g., Mehto et al., 2020a; Riikonen et al., 2020a; Riikonen et al., 2020b). The co-invention projects engage students in STEAM learning activities that involve working with digital maker technologies and solving various technical and aesthetic challenges. The co-invention projects offer a collaborative way to design and make, as well as a contextual application of knowledge and skills for devising novel and practical solutions to relevant real-world issues and solving associated design challenges (Bevan et al., 2015; Clapp, 2017; Honey & Kanter, 2013, p. 3). When students participate in knowledge creation activities, they acquire learning experiences that promote nonroutine problem solving, creativity, innovation, and teamwork—all of which are essential skills necessary in the emerging innovation society of the twenty-first century (Binkley et al., 2012; OECD, 2019). These knowledge-creating capabilities need to be promoted starting from a young age (Aflatoony et al., 2018; Carroll et al., 2010). Personal and collaborative participation in knowledge creation activity and creating socially recognized tangible inventions provides a strong sense of contribution and supports improvisational building identity as a prospective creator of knowledge (Hanson, 2015; Holland et al., 1998; Honneth, 1995).

2. Research setting

The present investigators organized a collaborative invention project with a public school located in Helsinki, Finland, in spring 2018. A 7th grade technology-focused class, consisting of 18 students in total, aged 13 to 14, participated in the project. The Finnish curriculum for basic education includes compulsory weekly craft lessons until end of grade 7. This enabled us to implement learning-by-making projects as a part of regular curricular activity. For assistance, teachers relied on collegial (co-teaching) resources to negotiate emerging challenges (Riikonen et al., 2020a). We worked with two craft-subject teachers and a visual arts teacher to coordinate the project. Science and information and communication technology (ICT) teachers participated in the project when their expertise was needed. Furthermore, we engaged grade 8 students to work as "digital technology" tutors providing additional guidance to the student participants (Riikonen et al., 2020a; Tenhovirta et al., 2022). The tutor students had themselves participated in a similar innovation project in the previous year. The teachers were familiarized with the digital fabrication technologies in workshops organized before the project and also 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 warm-up session, held by the visual arts teacher and the researcher, they experimented with electric circuits by making postcards with copper tape, simple LEDs, and a coin-cell battery. The grade 8 tutor students arranged the second warm-up session, a microcontroller workshop for the participating class, to familiarize the students with the possibilities and infrastructure of microcontrollers and to promote the emergence of ideas on how microcontrollers can be utilized in inventions (Ching & Kafai, 2008). The actual collaborative invention project began in February. 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."

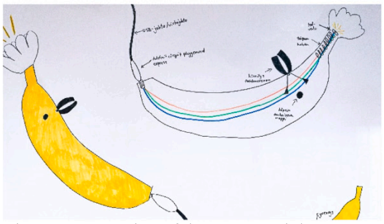
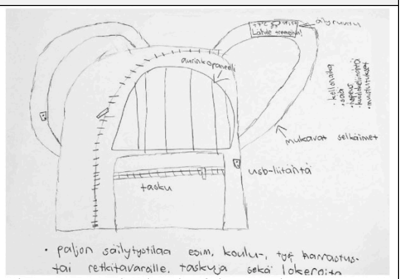
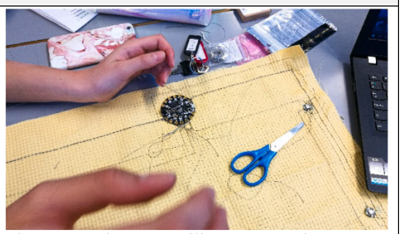
The project involved eight to nine weekly co-design sessions (two to three hours per session) during March, April, and May of 2018. The teams also presented their inventions in a co-invention exhibition, held at the University of Helsinki in May 2018.

3. Methods of data acquisition and analysis

Our analysis relied on video data and ethnographic observations of the student teams' collaborative invention processes (see, e.g., Derry et al., 2010). For this study, we analyzed the video-recorded invention processes of three out of the five teams participating in the project, selected on the basis of the completeness of the video data. The teams were formed at the beginning of the project through a random drawing. Every team's design process was video recorded separately. The video recordings were made using a GoPro action camcorder, placed on a floor-standing tripod, and a separate wireless lavalier microphone. The camera was positioned at a high side angle to capture the team's actions as fully as possible. The first author was present during every co-design session and made observations and field notes to support in-depth analysis of the data. We also collected the sketches and documents created by the teams and photographed the teams' co-inventions and their prototypes. The analyzed teams and the video data for each team are presented in Table 1. In this study, we have named the teams based on their inventions.

To answer the first research question on how student teams developed design ideas, and how these design ideas evolved from initial

Table 1
Analyzed teams and video data.

Banana Light		
Team members	2 girls and 2 boys: Jessica, Carla, Leo, and Ray	 Figure 1A: First prototype of the Banana Light team
Invention	A banana-shaped light that is attached to a laptop lid and lights up the keyboard. Their invention included a lamp with a bendable inner structure and a microcontroller that provided a sensor-based, on-off functionality and automatic light brightness control.	
Workshop sessions	8	 Figure 1B: Drawing of the Banana Light
Analyzed video data	12 hours 40 minutes	
NEObag		
Team members	1 girl and 2 boys: Leah, Roger, and Bob	 Figure 1C: Early sketch of the NEObag
Invention	A smart backpack that utilized a micro:bit microcontroller. The microcontroller provided several functionalities for their backpack, such as a compass and a thermometer.	
Workshop sessions	10	
Analyzed video data	13 hours 15 minutes	
Smart Pillow		
Team members	2 girls and 1 boy: Helena, Jackie, and Darren	 Figure 1D: The Smart Pillow team sewing electronic components
Invention	A smart pillow for improving the quality of sleep. The pillow utilized the Adafruit Circuit Playground Express microcontroller and had several digital functions, such as a night light, relaxing music, and an alarm	
Workshop sessions	10	
Analyzed video data	13 hours and 50 minutes	

ideas to final ideas, we analyzed the ideation processes and evolution of the design ideas though qualitative analysis (Saldaña, 2016) by systematically identified and selected all the ideas that the team generated from the video data (Appendix A). We used the expression of a design idea as the unit of analysis. The ideas were coded directly into the video data using the ELAN multimedia annotator. For every idea, we determined the following factors:

- Possible preceding (parental) ideas
- Theme of the idea
- Whether the idea was included in the final design, that is, whether it was a final design idea.

Then the design ideas were categorized according to four themes that emerged during the data analysis: 1) physical functionality and structure, 2) product quality, 3) aesthetics, sounds, and branding, and 4) digital and electronic functionality. The physical functionality and structure theme includes all the ideas related to the mechanical functions of the invention or its physical structure. For the product quality theme, we applied the product quality model introduced in the ISO/IEC 25010:2011 standard (International Organization for Standardization, 2017), which defines product quality based on eight categories (we then added the additional categories of ergonomics and user experience). Hence, the product quality theme consists of functional suitability, reliability, performance efficiency, usability, maintainability, security, compatibility, portability, ergonomics, and user experience. The aesthetics, sounds, and branding theme as well as the digital and electronic functionality theme are self-explanatory.

By relying on the above analysis, we first created visual displays of the chronological order in which the teams developed their design ideas (Fig. 2). Hence, the ideas were organized in a timeline representing the four design themes explained above. Fig. 2 illustrates how the teams' ideation progressed during the different workshop sessions (which we numbered and separated from one another). In the timeline, we used the same colors for themes as we did in the idea networks (see Figs. 3, 5, 6).

Next, to reveal the evolution of the individual design ideas, from preliminary design ideas to the final ideas, a network graph of all design ideas and their evolution was created for each team using the Cytoscape network visualizing software. The ideas embedded in the networks are numbered in the order they appeared during the ideation process (see Appendix A). In the network graphs, the ideas are linked to each other with arrows that signify an idea being derived from one or many parent ideas. The arrows in the network point from the parent idea(s) to the ideas generated based on or inspired by the initial idea(s). The size of the idea node signifies whether the design idea was included in the final design. These networks reveal the relationship between the main ideas and individual ideas, the order in which they occurred, and which ideas were rejected or accepted during the process. It also reveal the iterative and cyclical process: ideas were adapted, rejected or abandoned. The largest node marks the key idea of a team; for example, for the Banana Light the key idea was number 2: "*A lamp that lights up the keyboard*." The medium-sized node signifies the ideas that were included in the final design, while the small node marks the ideas that were not part of the final design (idea was abandoned). The colors indicate the theme of the idea. The visual elements used in the timelines and idea networks are described in Table 2.

The second level analysis was conducted to answer the second research question: What kind of epistemic architecture of maker practices did the teams' design process rely on? When analyzing the evolution of the students' ideas, it became evident that the ideas were not isolated but embedded in more profound and contextually relevant engineering, design, and scientific knowledge practices. While the design ideas and their related networks provided answers to the design problems, the complexity of the problems and the knowledge practices needed to solve them often remained hidden. In this round, we identified each team's design problems and qualitatively analyzed the discourses related to solving them. We used one articulated problem and the discussions related to it as our unit of analysis. The analysis was conducted in two phases separately for each team. In the first phase, the themes and phenomena covered when solving each problem were determined by relying on an entirely data-driven approach. In the second phase, the themes were further clustered together according to the knowledge practices that the identified phenomena related to. This analysis resulted in the emergence of four clusters of practices common to all the teams. The epistemic architecture of maker practices consisted of 1)

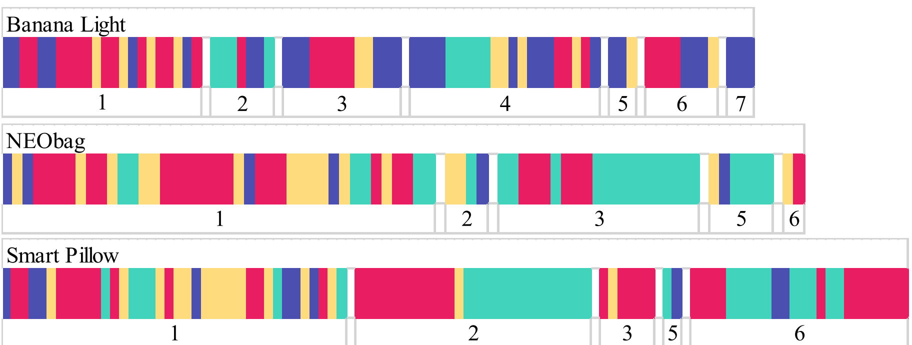


Fig. 2. Chronological order of each team's design ideas. The figure depicts the idea generation flow across the four design themes. The numbers represent the workshop sessions, divided by a gap in time. The main themes of design and making are marked with different colors: 1) physical functionality and structure (blue), 2) product quality (yellow), 3) aesthetics, sounds, and branding (green), and 4) digital and electronic functionality (red).

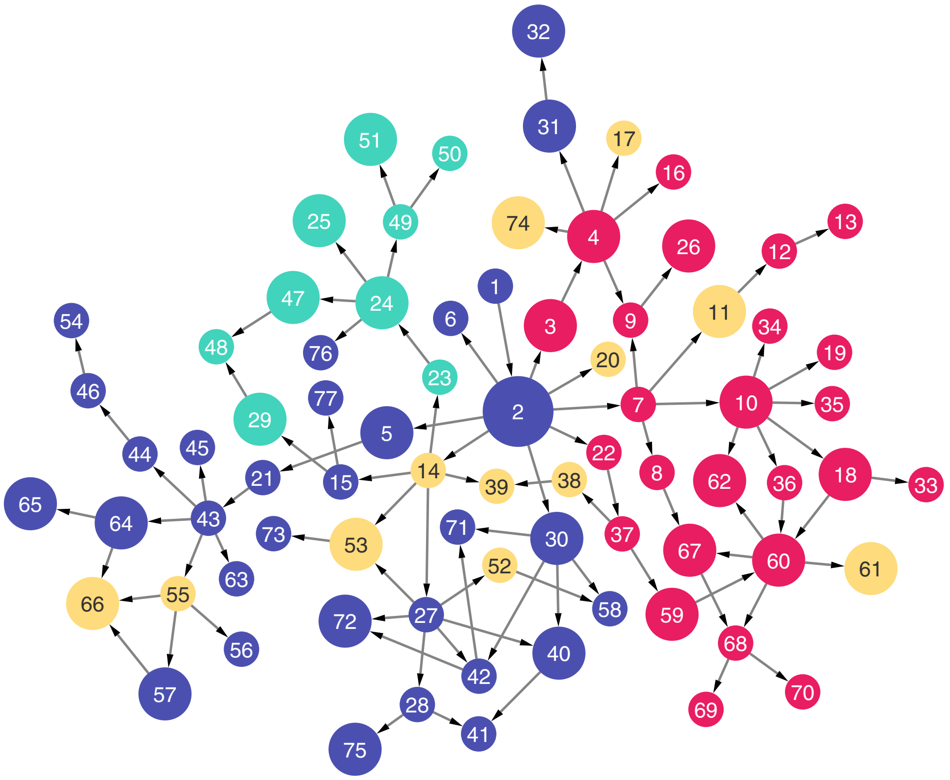


Fig. 3. The Banana Light team's idea network. The colors represent the main ideation themes: 1) physical functionality and structure (blue), product quality (yellow), aesthetics, sounds, and branding (green), and digital and electronic functionality (red). The numbers represent individual ideas, which can be found in Appendix A.

Table 2
Visual elements used in the timelines and idea networks.

Symbols and colors used in the idea networks	
Colors: ideation theme	
	Physical functionality and structure
	Product quality
	Aesthetics, sounds, and branding
	Digital and electronic functionality
Node size: implementation of the ideas in the final design	
	Small node: idea that was not implemented in the final design
	Medium-sized node: idea that was implemented in the final design
	Big node: team's key idea
Numbers and arrows: order and direction of the idea generation process	
17	Numbers signify the order of the ideas generated from first to last
	Arrows describe the direction of the ideation process, pointing from a parent idea to the idea based on or inspired by it.

computing engineering practices, 2) design-process practices, 3) product-design practices, and 4) scientific practices. For practical reasons, design practices were divided into two clusters, with the former being orienting toward the design process (working forward from ideas to the invention) and the latter involving design considerations of the final product (working backward from desired features to the invention). The epistemic aspects covered by each of these *Dimensions of Maker Practices (DMPs)* are characterized in Table 3.

For each team, we constructed the DMP framework that best describes the invention process and the invention from the perspectives of knowledge practices. The DMP frameworks allowed us to capture the complexity and magnitude of the knowledge creation

Table 3
Dimensions of Maker Practices (DMPs).

Dimensions of Maker Practices (DMP)	Knowledge practices covered
Computing engineering practices	• Programming • Programmable technologies (e.g., microcontrollers) • Input components (e.g., sensors and microphones) • Output components (e.g., LED lights and speakers) • Using and implementing software and digital devices (e.g., 3D-modeling, 3D-printing, and vector drawing)
Design-process practices	• Collaborative design • Fabrication techniques • Selecting, evaluating, and working with materials • Sketching and prototyping
Product-design practices	• Functional suitability • Reliability • Performance efficiency • Usability • Maintainability • Security • Compatibility • Portability • Ergonomics • User experience
Scientific practices	• Formal sciences (e.g., mathematics) • Natural sciences (e.g., physics, chemistry, and geography)

effort required for the teams' collaborative invention processes. The idea networks describe the invention and invention process though the development stages of the properties and characteristics of the object being invented, whereas the DMP frameworks describe the inventions and the invention process through the knowledge practices entangled in their creation.

4. Findings

4.1. The development of design ideas

This section provides an answer to the first research question, regarding how the student teams developed their design ideas and how the design ideas evolved from preliminary design ideas to the final ideas. To reveal the idea development process, we created for every team a visual idea timeline (Fig. 2) and an idea network (Figs. 3, 5, 6). All teams generated a substantial number of ideas during their ideation processes, which we divided into four themes: 1) physical functionality and structure, 2) product quality, 3) aesthetics, sounds, and branding, and 4) digital and electronic functionality. Fig. 2 illustrates the ideas generated during each design and making session in chronological order. It indicates that the main ideation themes were thoroughly entangled with one another rather than successively following one another. The teams often focused on intensively working on one theme but then proceeded to work for shorter or longer periods of time with other themes relevant for advancing the overall design and making process. The first session was the most intensive for each team, indicating that the key idea was first invented (a lamp that lights up the keyboard, a smart backpack, a smart pillow) to represent the main product.

The NEObag team had two sessions (session 1 and 3), while the other teams had three ideation-intensive sessions, with other sessions held in between where they generated only a few ideas. Fig. 2 shows that the number of ideas generated during later sessions varied considerably but did not linearly decline from session to session. During these less idea-intensive sessions, the teams moved from abstract concept design to embodied designing with materials and prototyping (for example, session 3 and 5 for the Smart Pillow team). Thus, through concrete and embodied making, they tested the ideas that had been generated during the prior idea-intensive sessions. The making and testing efforts brought forward new design problems in relation to the proposed prototypes and gave the teams grounds to refine the previously generated ideas, leading to more intensive ideation in a later session. This clearly highlights the iterative nature of design processes and the importance of material testing of ideas. All the teams used their final session to build a prototype and did not generate any new ideas (from session 8 onwards for the Banana Light team and from session 7 onwards for the Smart Pillow and NEO bag teams). The NEObag and Smart Pillow teams both held one additional session in between (session 4 for both teams), which did not yield any new ideas. During these sessions, the teams concentrated on building their prototypes and on their presentation material.

The idea networks (Figs. 3, 5, 6), on the other hand, represent the flow of idea development from preliminary design ideas to the final ideas. Once the teams had worked out their key ideas, they quickly generated more detailed ideas based on them. The key ideas also brought the team members together, motivated them, and got them working on the same epistemic object. Fig. 3 illustrates the Banana Light team’s ideation process, which involved a strong focus on physical and digital functionalities. The teams did not advance straightforwardly from their initial to final ideas but instead approached the epistemic object from several zigzagging perspectives. The

Fig. 4. Banana Light team ideating a clip holder.

Banana Light team concentrated mostly on physical functionality and especially on the structure of their invention (blue). They generated 31 ideas on this theme, of which 11 (see medium-sized nodes) were included in the final design.

The Banana Light invention consisted of several mechanically challenging elements, such as how to direct the light to the keyboard and how to attach the lamp to the laptop lid. The following quote conveys the way in which they developed a clip holder that can be attached to a laptop lid, using gesturing, sketching and a prototype to convey and crystalize their ideas (Fig. 4). The discussion demonstrates how the mechanics of the device was fundamentally intertwined with the invention process as well as the open atmosphere created by the team, where ideas could be challenged and discussed, and an awareness of the importance of working with concrete materials. In this discussion, the students were ideating about a mechanical button that could push open a clip that holds the lamp in position on the laptop lid. After the discussion, they tested possible solutions with a binder clip and a clothespin (session 4, idea 45):

> Jessica: Yes, but then it [the clip] has to be pushed from both sides.
> Carla: No, it doesn't, because when the button is pressed we put something there that pushes the clip claws open. Like with a clothespin. When you press from the sides, the pin opens … the same mechanism [draws a sketch].
> 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 [shows the idea and a possible placement of it with the prototype (Fig. 4)].
> Carla: Oh, yes [continues the sketch].
> Jessica: So, could we make two things that press it from both sides?
> Carla: Yes, ok, we can do that.

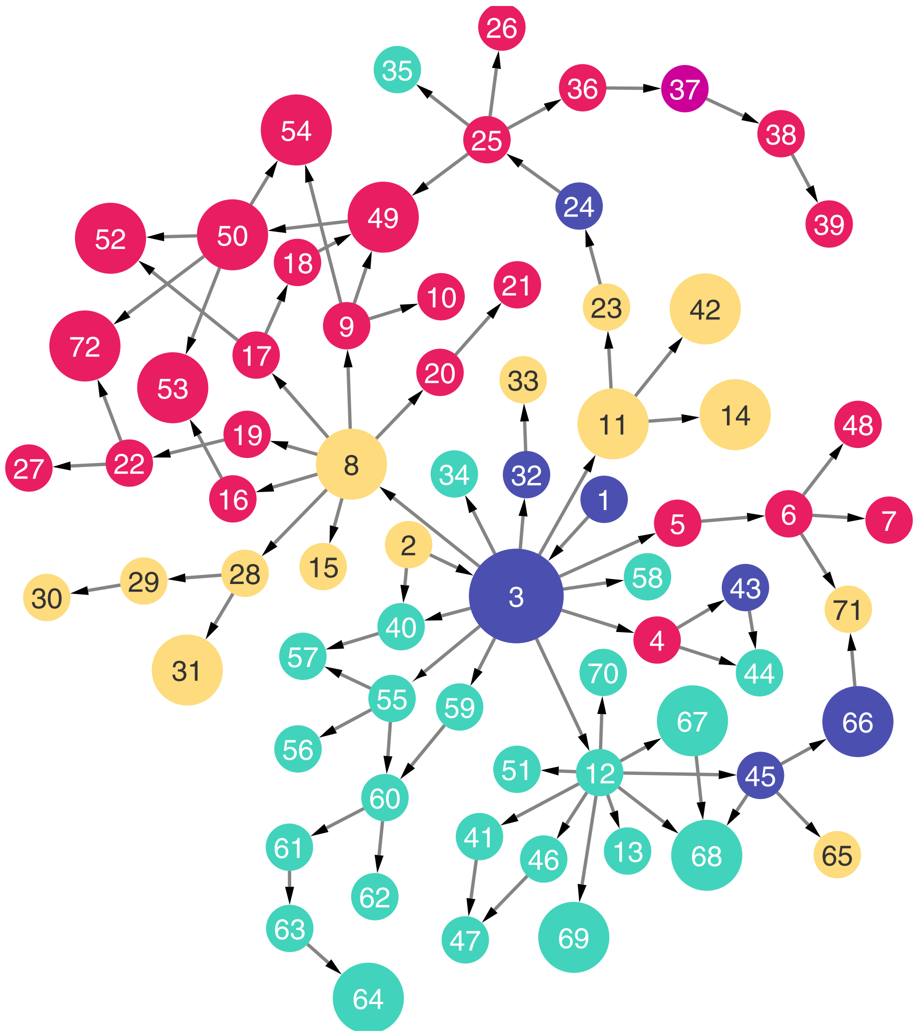


Fig. 5. NEObag team's idea network. The colors represent the main ideation themes: 1) physical functionality and structure (blue), product quality (yellow), aesthetics, sounds, and branding (green), and digital and electronic functionality (red). The numbers represent individual ideas, which can be found in Appendix A.

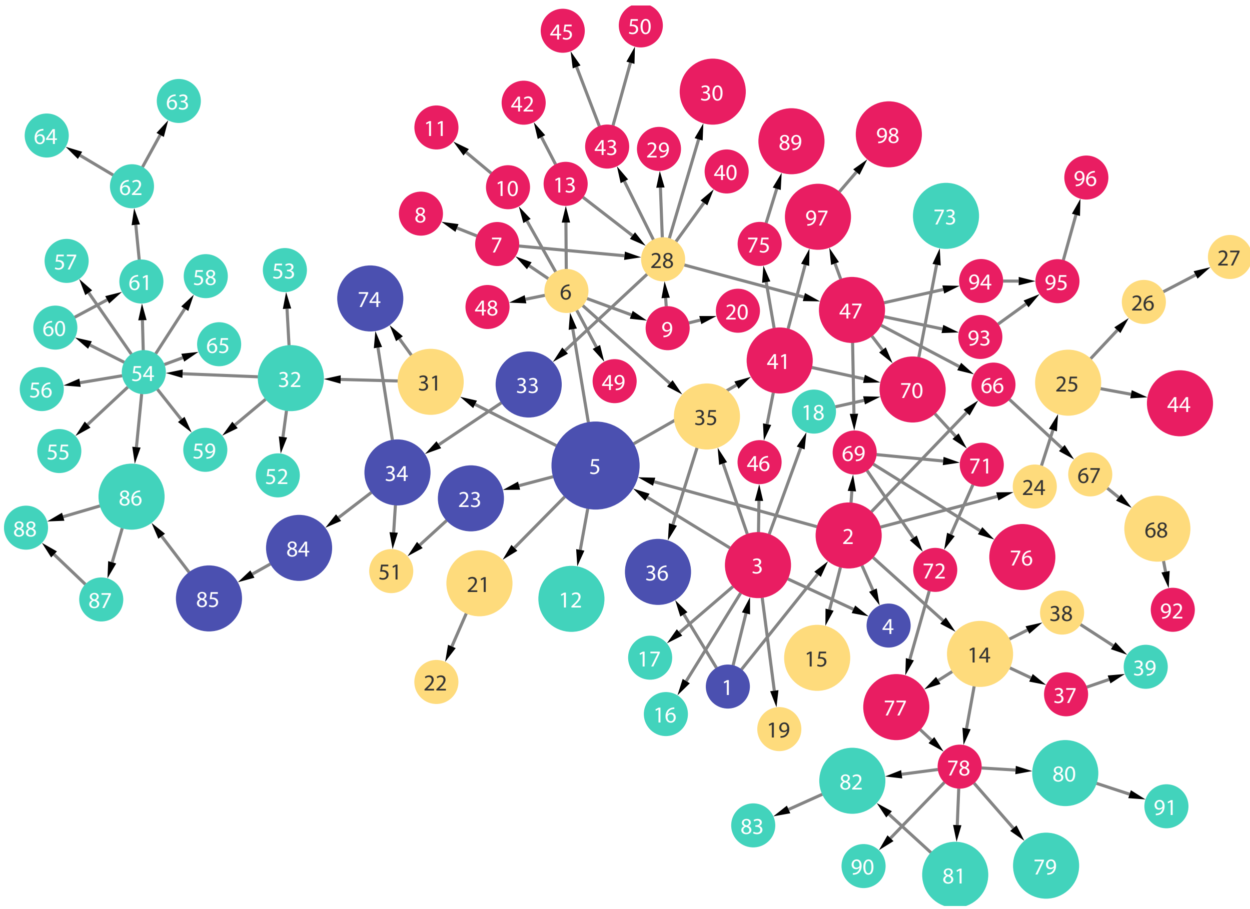


Fig. 6. Smart Pillow team's idea network. The colors represent the main ideation themes: 1) physical functionality and structure (blue), quality (yellow), aesthetics, sounds, and branding (green), and digital and electronic functionality (red). The numbers represent individual ideas, which can be found in Appendix A.

Fig. 5, in turn, illustrates the Neobag team's ideation process, which emphasized aesthetics and digital functionality. The following quote, where the NEObag team found their key idea, shows how the whole team immediately became engaged with and excited about it (session 1, idea 3):

Roger: Think about how cool a smart backpack would be…
Leah: That would be so cool!
Bob: Ooh … that's totally "perfecto!"

Although the key idea of the invention emerged fairly early in the process (i.e., the backpack, number 3), the team had to put considerable effort into elaborating different aspects of their invention. The digital and electronic functionality as well as aesthetic aspect of it were frequently considered, whereas ideas related to its physical functionality and structures did not receive so much attention in their process.

The ideation process of the Smart Pillow team was the most intensive (Fig. 6), heavily emphasizing digital functionality (red). During the Smart Pillow team's ideation process, the placement and functionality of the LED lights guided not only their ideas about the electronic functionality of the pillow but also its physical structure, aesthetics, and usability.

The following quote conveys the way in which the team discussed where to place the lights (session 1, ideas 24 and 25). The discussion shows how they had to simultaneously consider the physical structure and changes to the shape of the pillow when in use. Fig. 7 shows a sketch quickly drawn during the discussion, while fig. 7B shows how the students used gestures to convey their ideas. The discussion and Fig. 7B also show how Darren was reserved at the beginning of the project and the girls tried to draw him into the collaboration. Later in the project, especially when the electronic components were sewn on to the pillowcase Darren became a very active and enthusiastic team member (see Mehto et al., 2020a).

Helena: But where could the lights come from?
Jackie: From the corners, I think.
Helena: You know, if this is the pillow, like this [starts sketching (Fig. 7)]. Your head is here, so I think they could come from somewhere over here [points to the edges of the pillow on the sketch].
Jackie: But not pointing up.
Helena: Yes, the lights point to the sides. [shows, with her hands on the sides of her head, how the lights would point to the sides of her head (Fig. 7B)].
Helena: Do you, Darren, have some ideas about what it could look like?
Darren: The lights could come from a little bit lower down.
Jackie: Oh yes, because if the pillow is like this thick [shows the approximate thickness with her fingers], then the lights would not come straight from the edges.
Helena: Yes, because when you put your head down on the pillow, the edges raise up a little bit [shows, with her hands on the sides of her head, how the lights would then point in the right direction].

Altogether, the timeline and idea network development activities reveal that all the teams began their projects with an intensive ideation session. Based on the idea networks, we were able to spot the ideas that were central in the ideation processes, triggering and inspiring their invention process. These key ideas were often vague but fundamental to the design process because they directed the students' ideas and their design of the final invention. The emergence of the key ideas engaged them in the task and triggered the ideation process. At the beginning of the projects, all the teams concentrated on the physical functionality of their inventions, on

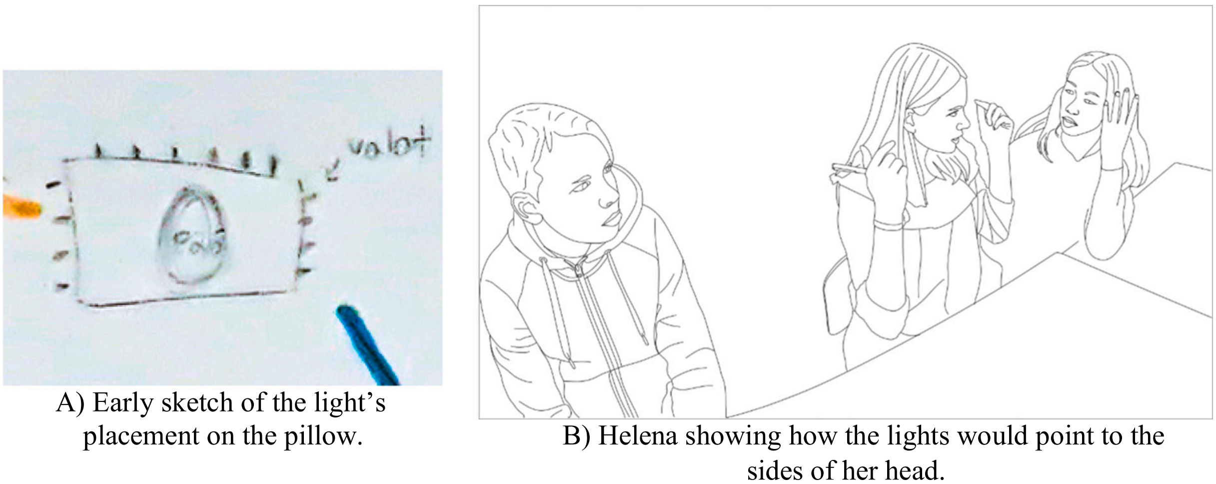


Fig. 7. A: Early sketch of the light's placement on the pillow.
B: Helena showing how the lights would point to the sides of her head.

product quality and, from early on, also on the electronic and digital functions of their inventions, alternating between different ideation themes. Ideas related to the quality of product often preceded moves from one theme to another. In the later stages of the project, the teams generated more consecutive ideas on one theme before moving on to another theme, with ideas related to product quality being an exception to this pattern and occurring more randomly. The idea networks revealed that product-quality ideas were often parented by ideas generated for another theme; on the other hand, those ideas in turn often parented ideas that related back to the main theme. Further, the idea networks show that all teams engaged in a complex, iterative ideation process where new ideas were generated based on previous ideas and then merged with one another to form more new ideas. Generating new ideas did not always mean that the previous ideas were rejected; teams sometimes returned to and developed the same idea later. However, they also abandoned some ideas and did not include them in the final design. In many cases, the design ideas and combination of design ideas, as well as the overall characteristics of the teams' inventions, challenged the teams to develop ideas on several themes simultaneously.

In total, the Banana Light team generated 77 individual ideas, the NEObag team 72 ideas, and the Smart Pillow team 98 ideas during the invention processes, of which the Banana Light team included 30 ideas in their final design, the NEObag team 17 ideas and the Smart Pillow team 34 ideas. Table 4 describes the quantitative proportions of ideas for each team with respect to the different ideation themes.

All three teams concentrated heavily on the digital and electronic functionality of their inventions. For NEObag and Smart Pillow teams, this was the theme that generated the highest number of ideas. The Smart Pillow team generated 40 out of a total of 98 ideas related to this theme and included 12 such ideas in the final design. The NEObag team, on the other hand, generated 26 ideas on this theme, out of a total of 72 ideas, and included six of them to the final design. The NEObag team generated all its ideas on the electronic and digital features of the invention in the late stages of the ideation process. Based on our ethnographic field observations and analysis of the video data, the NEObag team’s strong desire to build a finalized product constrained their ideation process in this regard. They ended up rejecting their early ideas as too time-consuming or difficult to implement.

4.2. Epistemic architecture of maker practices

To answer the second research question regarding what kind of epistemic architecture of maker practices did the teams' design process rely on, we investigated their knowledge creation process using the DMP framework. As stated in the introduction, maker projects involve employing various kinds of knowledge practices to solve design problems. After analyzing the design challenges that the team members addressed, we clustered the DMPs for each team. Four dimensions were based on qualitative data analysis that emerged from each team’s video data. The intertwined DMPs employed by each team were as follows: 1) scientific practices, 2) computational engineering practices, 3) design-process practices, and 4) product-design practices (i.e., practices involving reflective assessment of product quality). The maker practices for each team are presented in Figs. 8, 10, and 12.

The Banana Light team employed scientific practices related to mechanics, such as momentum, center of mass, and friction, through material experimentation. They explored their design ideas by making bendable items with metal and chicken wire, like a bendable ruler, revolute and spherical joints, as well as structures that were hybrids of bendable and solid structures. Center of mass and friction were fundamental elements in their design of how the lamp could be attached to the laptop lid. They adopted product-design practices that allowed them to reflectively assess their experiments and prototypes from the perspectives of functional suitability, usability, and other quality considerations. Fig. 9 shows their early prototypes of possible groove structures for the lamp mountings. These prototypes provided them with an understanding of how center of mass, friction, and the mounting design must be considered in the overall design.

Computational engineering practices enabled the Banana Light team to use 3D-modeling, a micro controller, and sensors when making their invention. For example, the Banana Light team had to actively build knowledge about how to use 3D-modeling software and experiment with different ways of creating 3D-models and modifying ready-made models to suit their needs. Also, the NEObag team’s computational engineering practices involved using vector drawings, which they had not been familiar with before. In the NEObag team’s ideation process, the concrete making of the item and the scientific practices related to geometry and mathematical problem solving were deeply entangled. Their DMP framework is illustrated in Fig. 10.

Fig. 11A shows a digital drawing of the NEObag team’s design. It shows how plane geometry was a fundamental part of the design process. Later, the team members had to learn the design-process practice of patternmaking to transform the two-dimensional fabric

Table 4
Proportion of the ideas generated across the four ideation themes.

Theme	Banana Light		NEObag		Smart Pillow	
Physical functionality and structure	31	40 %	6	8 %	10	10 %
included in the final design	11		2		8	
Product quality	12	16 %	16	22 %	17	17 %
included in the final design	5		5		7	
Aesthetics, sounds, and branding	9	12 %	24	34 %	31	32 %
included in the final design	5		4		8	
Digital and electronic functionality	25	32 %	26	36 %	40	41 %
included in the final design	9		6		12	
Total number of ideas	77	100 %	72	100 %	98	100 %
Ideas included in the final design	30		17		35	

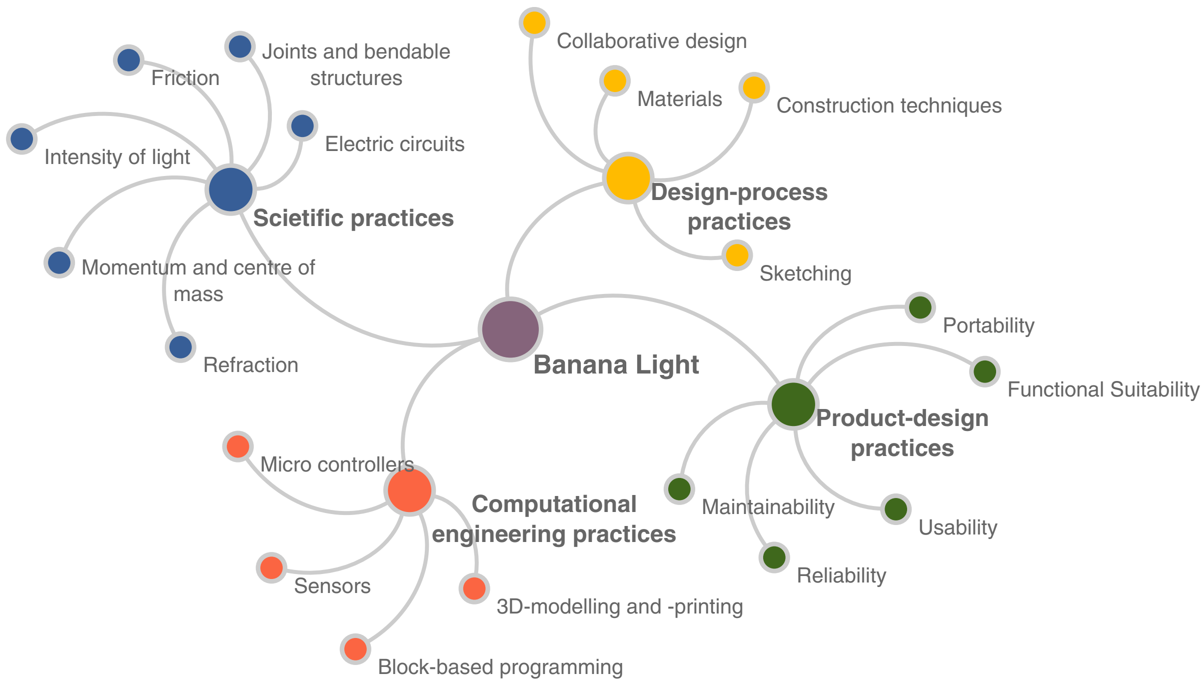


Fig. 8. Banana Light team's DMP framework.

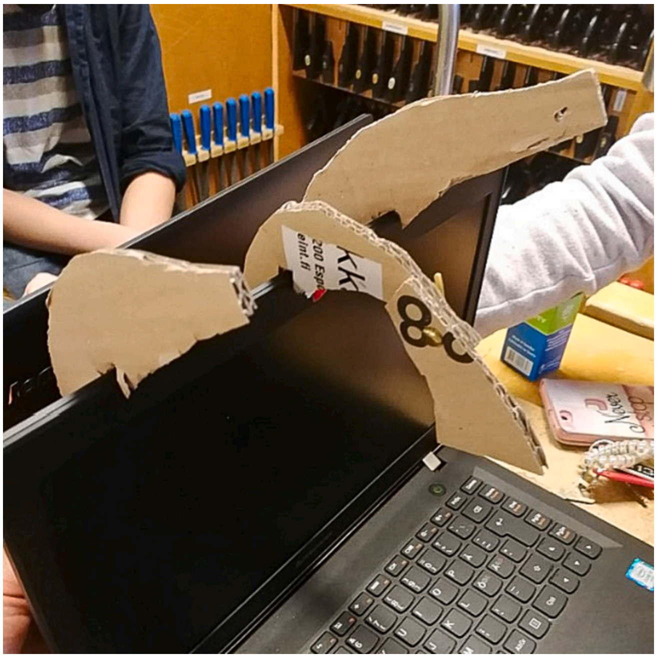


Fig. 9. Banana Light team's prototypes of a possible lamp-mounting structure.

into a three-dimensional backpack and deepen their understanding of the relationship between plane and solid geometry. When making the NEObag, it also became necessary for them to consider how and in what order to sew different parts of the backpack together (i.e., construction technique). Fig. 11B shows the front of a pocket from the backpack, showcasing the complexity of the sewn structures. The pocket consists of three pieces of fabric and a zipper. The students needed to sew all pieces together in a specific order, while simultaneously considering how the front piece could be further attached to other pieces in later stages.

Similar to the maker practices of the NEObag and Banana Light teams, the Smart Pillow team employed various scientific practices

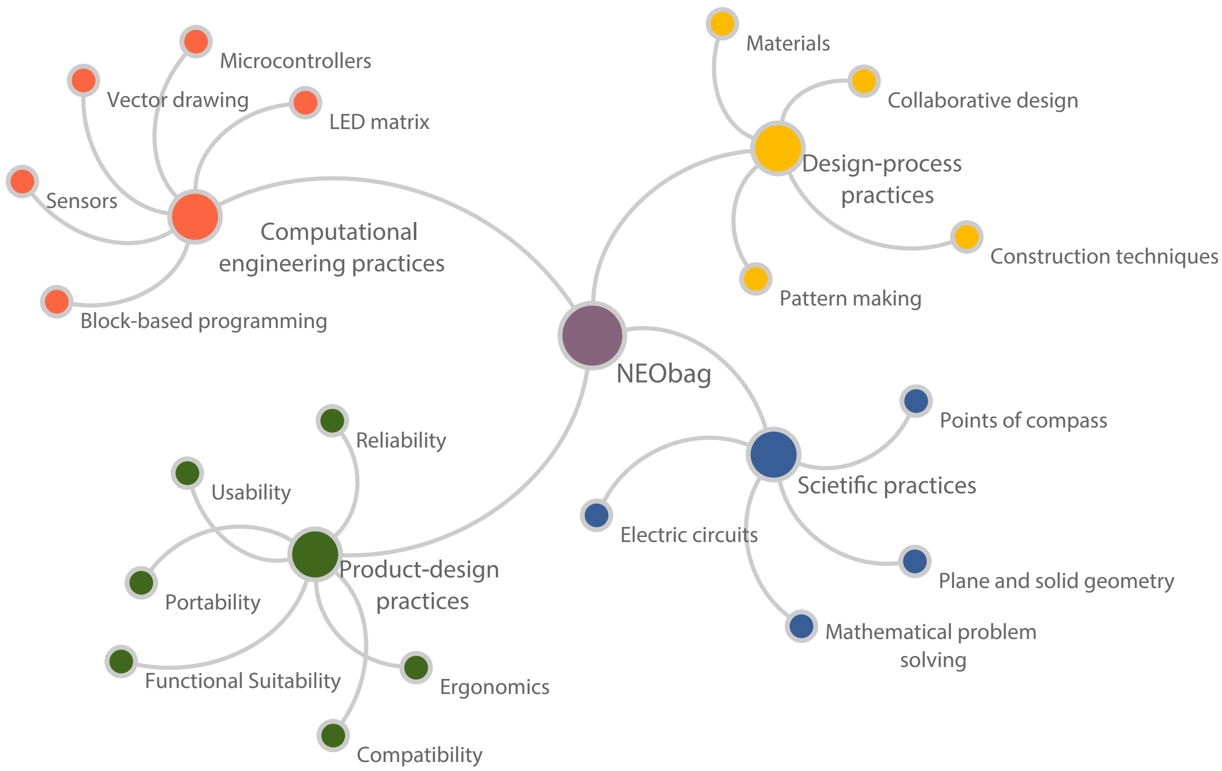
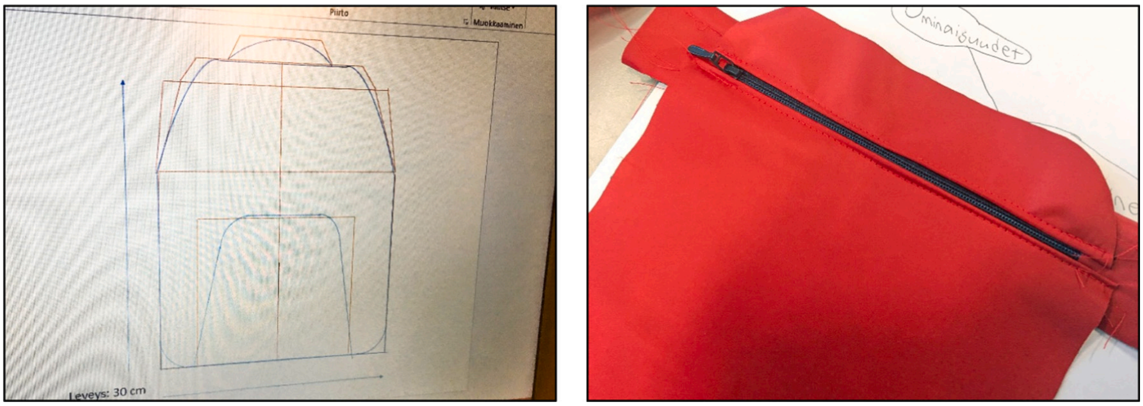


Fig. 10. NEObag team's DMP framework.



A) Vector drawing of the NEObag. B) Front pocket of the NEObag.

Fig. 11. A: Vector drawing of the NEObag.
B: Front pocket of the NEObag.

in the context of concrete making activities. The Smart Pillow team's DMP framework is presented in Fig. 12. The Smart Pillow team members employed especially the knowhow they had acquired about electric circuits in the warmup session for their invention and challenged themselves to build more complex circuits and explore different conductive materials, such as conductive threads and fabrics, and their properties. The Smart Pillow team had to learn, through experimenting and searching for information, how short circuits work and how to plan and protect conductive thread wiring to prevent them from short circuiting. They also put a great deal of effort into adopting scientific and product-design practices, while considering the biology of sleep and how to design their pillow to promote better quality sleep.

Regarding computational practices, all the teams employed block-based programming, microcontrollers, and a variety of electronic components, such as LEDs and sensors. For example, the Banana Light and Smart Pillow teams focused extensively on using sensor data to trigger the on-off functionality of the lights and control their brightness and color. The NEObag team, on the other hand, used the

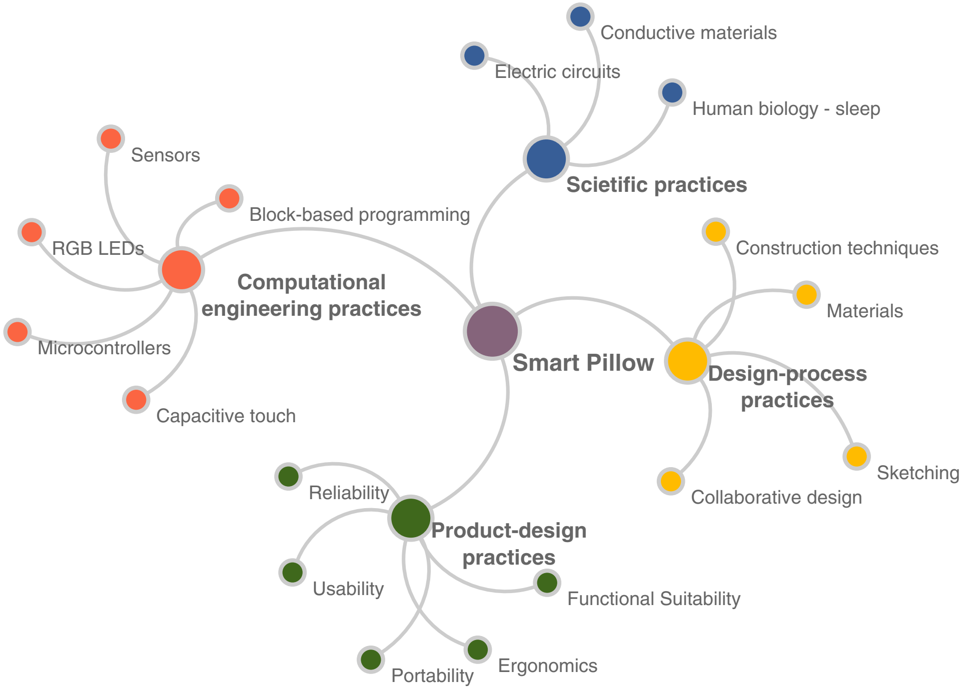


Fig. 12. Smart Pillow team's DMP.

sensors in the microcontroller to provide information to the end user. Experimenting with different sensors especially provided them with ample opportunities to employ computational engineering practices. All three teams had to use conditional if statements and familiarize themselves with functionality and using the event functions in block-based programming. Regarding design-process practices, all the teams learned and experimented with a wide range of design techniques, such as ideation and sketching. Each team learned to pursue collaborative design, which in itself is a valuable skill, one not often acquired in a school setting. They had to organize the overall process, divide tasks, consider each other's ideas, and build on them. Traditional craft techniques also had a fundamental role in all the teams' design processes. The importance of using traditional craft and prototyping techniques cannot be overlooked from the standpoint of knowledge creation because, through concrete making activities, the teams were able to handle and materialize complex conceptual knowledge.

The teams employed product-design practices when assessing various quality features of their designs and making improvements to them. They often evaluated their ideas from an envisioned user's point of view, which promoted further development of the designs and also shaped other dimensions of their making practices. The making process induced knowledge creation on a wide variety of subjects, ranging from understanding shapes and the movements of the human body for ergonomic design to analyzing the differences in possible usage situations and environments to improve their invention's adaptability. When solving problems, all the teams often simultaneously handled many aspects of the DMPs at the same time. For example, when the Smart Pillow team was designing where to place the microcontroller and LED lights on the pillow, they had to consider several aspects of product quality (e.g., ergonomics and usability), the design process (e.g., construction techniques and materials), science (electronic circuits and conductive materials), and computing (e.g., the components and placement of sensors to correctly capture data). They had to constantly account for how these different aspects affected each other and what kind of constraints they created, alone and in relation to each other. Such multi-faceted, making-practice architecture was clearly present throughout all the teams' processes.

5. Discussion

The purpose of the present study was to examine multifaceted knowledge creation processes that involved student teams engaged in highly complex design and making activities. Little previous research exists regarding the kinds of knowledge practices that students rely on when participating in maker-centered learning and cocreating inventions. The current study focused on examining how students' design thinking, as well as scientific and engineering practices, come "alive" through maker-centered learning. Because we have earlier analyzed video data of material mediation of students' making processes (Mehto et al., 2020b), as well as their efforts at prototyping and model making (Riikonen et al., 2020b), the current study focused directly on their ideation process as an epistemic practice. The study should not, however, be considered as mere conceptual in nature because a) students' ideation was anchored in their materially embedded making, b) the ideas were driven by the students' epistemic objects (their invention in making) rather than represented in curricular contents as such, and c) the analysis revealed that the students' emerging ideas were not random but could be clustered according to an emerging architecture of epistemic practices. The findings are aligned with Vygotsky's position, according to which practical activity and creative imagination are intertwined (Moran & John-Steiner, 2003; Vygotsky, 2004).

We analyzed three student teams' collaborative invention projects from two perspectives: 1) how the student teams generated and developed design ideas across their materially mediated making process from preliminary design ideas to final ones and 2) the emerging epistemic architecture of maker practices that the teams relied on during the design and making process. Toward this end, we analyzed students' making processes through video data and ethnographic field observations while utilizing visual representations. The visualized timelines and networks of ideas revealed the multifaceted and iterative nature of the teams' idea generation processes embedded in their materially mediated making processes. Ideas were generated, analyzed, and, ultimately, either accepted, abandoned, or rejected during the ideation processes. The ideas evolved through an iterative process of articulating, modifying, and integrating design ideas with materially embodied efforts of prototyping, testing, and further refining inventions. The concrete-making component was essential for both promoting new and refining existing design problems, which helped engage the students to further develop their inventions. Although the teams' inventions may seem relatively simple, creating them required intensive epistemic efforts to combine science, engineering, and design practices in the context of collaborative making, which relied on both traditional craft and digital fabrication technologies. Finalizing the design ideas required several cycles of ideation and testing that involved multiple themes, which we called the epistemic architecture of maker practices, the intertwining of the various skills, and using the practices needed for constructing the invention. It is remarkable that the epistemic architecture of making practices emerged bottom-up from the student teams' object-driven design and making actions and tools and technologies used, instead of being explicitly dictated, directed, or shaped by teachers or interventionists.

Knowledge creation through maker practices in the teams' co-invention projects began to surface in the ways in which their ideas evolved. Through a second level of data analysis, one that combined their ideas with discussions of design problems, we identified four design and making practices (DMPs) that the teams employed to create knowledge: 1) computational engineering practices, 2) scientific practices, 3) design process practices, and 4) product design practices. Furthermore, the themes that the teams used for the contextual creation of knowledge were versatile and included skills, material, and conceptual knowledge. Our findings are in line with previous research in which scholars have found that maker-centered learning promotes a variety of thinking skills and creativity (Honey & Kanter, 2013; Martin, 2015). The epistemic architecture of maker practices emerged in part spontaneously from the student teams' efforts to solve the open-ended co-invention challenge rather than being deliberately introduced and fostered. The only constraint was developing an "intelligent" product that included digital features. To facilitate computational engineering practices, the students received training in using and coding microprocessors and sensors. Otherwise, the students pursued their own ideas in a diverse range of co-invention projects involving various scientific and design practices. Furthermore, we identified DMP practices through data-driven qualitative analysis. Hence, it must also be noted that the teams took on epistemic challenges beyond what was required of them or absolutely necessary. It certainly would have been possible to more deliberately engage students in scientific practices, and this is something we will consider exploring in the future.

Many investigators—from Dewey (1986) to Vygotski (1978) and from Papert (1980) to Blikstein (2013)—have noted the importance of practical experiences and productive making-like activities for learning. In accordance with Vygotsky's (2004) and Papert's (1980) approaches, our results highlight that concrete making and prototyping play an important role in stimulating and enabling ideation and knowledge creation. Throughout our analysis, we observed a wide variety of ideas emerging through making and working with physical materials. The ideas were not random or fragmented; their generation was driven by the student teams' epistemic objects, here as represented their envisioned inventions and constituted by mutually supporting epistemic practices. Nevertheless, little attention has been paid to how such materially mediated learning occurs and how materials in the environment interact with and are embedded within ideas over time. The teams tested various scientific concepts by creating prototypes. Through concrete-making activities, the teams were able to examine and simultaneously consider aspects from more than one of the four DMP themes. This supports the findings of previous research (Mehto et al., 2020a; Vossoughi & Bevan, 2014).

To conclude, the open-ended design and making challenge set the stage for practice-based knowledge creation. Envisioned epistemic objects and design problems triggered the knowledge creation process, leading to new ideas through the application of maker practices. During the co-invention process, the initial ideas gave rise to novel ideas, assisting in solving emerging design challenges. Hence, working with concrete materials enabled the teams to test their ideas, create new ones, and build an understanding of the scientific and computational practices related to their invention. Thus, we conclude that open-ended, materially mediated co-invention projects offer plentiful opportunities for practice-based knowledge creation and multifaceted learning in schools, an argument supported by the findings presented in our previous studies (Mehto et al., 2020a; Riikonen et al., 2020b).

The present study has certain limitations. As a multiple case study, it addressed only three student teams' processes and practices. That being said, the content-rich video data enabled a detailed level of analysis and revealed similarities across the cases. Because we have earlier examined the interrelations between discursive and materially embodied activities (such as prototyping and model making; Yrjönsuuri et al., 2019; Mehto et al., 2020a, b; Riikonen et al., 2020b), we focused this analysis on student teams' ideation processes, which were, however, embedded in their simultaneous making and fabrication process. The analysis revealed that ideation and materially mediated activities were thoroughly intertwined so that there definitely were not separate initial conceptual planning and subsequent material implementation stages; the design and making were totally entangled and the invention process progressed in a recursive manner. The present study focused only on examining the student teams' activities without considering the teachers' guiding role, which was covered in our earlier investigations (Viilo et al., 2018). Maker-centered learning relies on a nonlinear pedagogy in which the epistemic objects, stages, and final productions cannot be known at the beginning. The teachers worked as a team because nonlinear projects are rather difficult for a teacher to successfully orchestrate because co-inventions may go in different directions when it comes to the relevant technologies, production procedures, and disciplinary principles. Yet teachers' contributions are crucial for assisting students to learn relevant skills, understand principles, and integrate various dimensions of maker practices.

Furthermore, identifying the shared themes of the teams' DMP framework could offer opportunities for developing evaluative methods for open-ended invention projects. Further research is needed to reveal and confirm the findings of the present multiple case study. More longitudinal and design-based research is needed to investigate how co-invention projects can be further designed to offer the best possible setting for knowledge creation during such projects. Creating a continuum of innovative education could offer students a path to learn the skills of co-invention, collaboration, and cocreation—the widely recognized key competencies needed to meet the challenges of the twenty-first century (e.g., OECD, 2019).

Funding

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Declaration of competing interest

None.

Appendix A. List of teams' ideas and their numbers. Bold text indicates the ideas that were included in the final design

	Banana Light	NEObag	Smart Pillow
1	A peripheral for a laptop	Clothing (theme)	Relaxation and sleep
2	**A lamp that lights up the keyboard**	Sports (theme)	**Night light**
3	**Electricity from the laptop**	**Smart backpack**	**Relaxing sound**
4	**Plugs into USB**	LEDs	Smart quilt
5	**The lamp will be attached to the laptop lid**	Four USB ports	**Smart pillow**
6	Fan to cool the lamp if it becomes hot	Ability to charge a mobile phone	Quality of sleep
7	The lamp recognizes when hands are on the keyboard	Large battery on the bottom of the backpack	Recording of sounds during sleep
8	Voice control	**Screen on a shoulder strap**	Recording speech
9	Switches off when unplugged from the USB	Time and date	Duration of sleep
10	**Sensors for the lamp**	Notification when you have to go to, e.g., school	Recognizes getting up at night
11	**Delay feature will switch it off when hands are removed from the keyboard**	**Comfortable**	Weight sensor
12	Length of delay determined by the user	Modern appearance	**Smart Pillow (name)**
13	Application for controlling the lamp	Oval shape	Temperature control
14	Something that directs light to the keyboard	**Lightweight**	**Ability to change light color**
15	A shade	Screen attached with a magnet	**Ability to change light brightness**
16	Connection with Micro USB connector	Weather	Piano sound
17	Wiring behind the laptop lid	Map	Nature sounds
18	**Sensors operated with a microcontroller**	Speed	Meditative music
19	Motion sensor	Android	Calm sounds
20	Could also function as a table lamp	Music	Sleep duration measured by button clicks
21	A holder for the lamp	Headphone jack	**Size the same as a normal pillow**
22	Small LED tube as a light source	Connected to user's mobile phone	Slightly larger than a normal pillow for added comfort
23	Curved	Self-adapting material	**Soft but not too thin**
24	**Banana shape**	Massaging	Lights in the corners
25	**Banana Light (name)**	Physiological sensors	**Lights on the edges**
26	**Button as an on-off switch**	Blood pressure	Lights from under the pillow
27	Bendable structure	Phone screen duplicated with the screen on the backpack	Lights could be reflected onto a wall
28	Metal wire as the bendable material inside the lamp	Waterproof screen	External device and screen to display the information
29	**Flower-shaped shade**	Cover on top of the screen	Phone connected to micro:bit
30	**3D-printed**	Protective film	**Battery-powered**
31	**Wiring inside the lamp stem**	**Waterproof fabric material**	**Pillowcase**
32	**Hollow structure**	Water bottle holder	**Colorful**
33	GoGo Board-operated motion sensor	Magnet that catches the bottle	**Wiring inside the pillow**
34	A switch on the holder for the lamp (automatic on-off)	iBackPack (name)	**Wiring and sensors protected to prevent damage**
35	Automatic brightness control	MindBackPack (name)	**Helps you fall asleep**
36	Vibration sensor	Ability to identify the user	**Shoulder massage**
37	Spot LED light	Prevent theft	Color changes every 30 s
38	3 LEDs to give enough light	Fingerprint sensor that unlocks the zipper	Possibility to choose a specific color
39	3 LED light bulbs pointing in different directions	Fingerprint sensor turns the screen on	Red, blue, green, yellow, and lilac
40	**Bendable structure, not 3D-printed**	SportBackPack (name)	Switch
41	Chicken wire as the bendable material inside the lamp	Black, gray, and white colors	**Alarm**

(*continued on next page*)

(*continued*)

	Banana Light	NEObag	Smart Pillow
42	3D-printed spherical joint	**Comfortable shoulder straps**	Manual cooling and warming selection
43	A clip	Reflectors	Remote control
44	A clip that opens and closes with the click of a button	Reflectors and/or LEDs as decorative elements	**Three lights on both sides of the pillow**
45	A clip opened by squeezing from both sides	Pockets	Phone as a remote control through infrared feature
46	A clip operated by springs when a button is clicked	Yellow or orange	Small speaker
47	**Size roughly two-thirds (=10 cm) of the first prototype**	Black, gray, orange, and blue	**Adafruit Circuit Playground Express**
48	The lamp shade just big enough for three LED bulbs	Solar panel	Motion sensor
49	Yellow	**Microcontroller**	Movements during the night detected from sound
50	Neon yellow	**Micro:bit**	Remotely connected via USB
51	**Warm yellow**	Modernipack (name)	Microcontroller in a fabric pocket, to make it softer
52	The banana will bend in the middle	**Compass**	Pillow itself is white
53	**Bendable structure at the lamp's tip**	**Temperature**	Green pillowcase
54	Buttons will move sticks that push the clip open	**Timer**	Pattern or embroidery on the pillowcase
55	Padding inside the clip jaws	OneBackPack (name)	Flower pattern
56	Felt	SmartOne (name)	Elephant pattern
57	**Rubber**	OneSport (name)	Star pattern
58	Top part of the stem is bendable, the bottom part is 3D-printed	Äppu (name)	Peppa Pig pattern
59	**Neopixel LED, which is very bright**	Xpack (name)	Many pillowcase models with different colors and patterns
60	**Adafruit Circuit Playground Express**	XPackOne (name)	Lama pattern
61	**Circuit Playground placed on the bottom of the banana, behind the laptop**	OnePackX (name)	Screen- or sablon-printed
62	**Light sensor to control the brightness of the LED bulb**	Xone (name)	Electronic components form a part of the pattern
63	Screw clamp	OnePack (name)	Lighthouses
64	**Groove**	**NEObag (name)**	Silhouettes of people
65	**Banana's body leans to the back of the laptop lid and supports it**	Raised pocket	Naive style
66	**Padding inside the groove**	**Flat front pocket**	Light sensor turns lights on and off
67	**Clapping hands twice turns the light on and off**	**Red and black**	Lights come on when bedroom lights are turned off
68	Switch on and off by taping the board	**Pockets as contrast details with different color**	**Lights turn off after certain amount of time**
69	Switch on and off by snapping fingers	**Curved top**	Lights turn on and off by shaking the microcontroller
70	Tapping the board twice to turn the board on and off	Egg-shaped	**Microcontroller plays music**
71	The joint 3D-printed, and the lamp body printed with another manufacturing method	Charging socket in the front pocket	Music turns on and off by shaking the microcontroller
72	**Bending material on the top of the lamp instead of the joint**	**Bluetooth connection between micro: bit and a phone**	Lights turn on and off by tilting the microcontroller
73	Simple hinge that enables the lamp head to turn		**Twinkle, Twinkle, Little Star**
74	**Possibility to plug into a phone**		**Waffle cloth as the fabric for easy sewing with conductive thread**
75	**Flexible curve ruler as the bending core material**		snooze alarm (wake up after one hour)
76	Styrofoam as the body material		**Lights turn on and off by shaking the pillow**
77	Rectangular shade for the lamp		**The color of the LED lights change by tilting the pillow**
78			Two color choices
79			**Pink**
80			**Orange**
81			**White / bright**
82			**Two color choices plus white**
83			Green
84			**Fabric that is safe with electricity**
85			**Upholstery fabric**
86			**Fabric with a ready-made pattern**
87			Gray
88			White stars on gray base
89			**Alarm after 8 h**
90			Violet
91			Yellow
92			Lights on for ten minutes
93			Separate touch screen
94			Separate buttons to control alarm and lights
95			Capacitive touch
96			Conductive fabric touch pads

(*continued on next page*)

(*continued*)

	Banana Light	NEObag	Smart Pillow
97			**Neopixels display the alarm time**
98			**When the alarm starts ringing, the lights turn on**

References

Aflatoony, L., Wakkary, R., & Neustaedter, C. (2018). Becoming a design thinker: Assessing the learning process of students in a secondary level design thinking course. *International Journal of Art and Design Education, 37*(3), 438–453. https://doi.org/10.1111/jade.12139

Baird, D. (2004). *Thing knowledge: A philosophy of scientific instruments*. University of California Press.

Bereiter, C. (2002). *Education and mind in the knowledge age*. Erlbaum.

Bevan, B., Gutwill, J. P., Petrich, M., & Wilkinson, K. (2015). Learning through STEM-rich tinkering: Findings from a jointly negotiated research project taken up in practice. *Science Education, 99*(1), 98–120. https://doi.org/10.1002/sce.21151

Binkley, Erstad, O., Herman, J., Raizen, S., Ripley, M., Miller-Ricci, M., & Rumble, M. (2012). Defining twenty-first century skills. In *Assessment and teaching of 21st century skills* (pp. 17–66). Springer Netherlands. https://doi.org/10.1007/978-94-007-2324-5_2.

Blikstein, P. (2013). Digital fabrication and 'making' in education: The democratization of invention. In C. Büching, & J. Walter-Herrmann (Eds.), *FabLab: Of machines, makers and inventors* (pp. 203–222). Transcript.

Buchholz, B., Shively, K., Peppler, K., & Wohlwend, K. (2014). Hands on, hands off: Gendered access in crafting and electronics practices. *Mind, Culture, and Activity, 21*(4), 278–297. https://doi.org/10.1080/10749039.2014.939762

Carroll, M., Goldman, S., Britos, L., Koh, J., Royalty, A., & Hornstein, M. (2010). Destination, imagination and the fires within: Design thinking in a middle school classroom. *International Journal of Art & Design Education, 29*(1), 37–53. https://doi.org/10.1111/j.1476-8070.2010.01632.x

Ching, C. C., & Kafai, Y. (2008). Peer pedagogy: Student collaboration and reflection in a learning-through-design project. *The Teachers College Record, 110*(12), 2601–2632. https://doi.org/10.1177/016146810811001203

Clapp, E. (2017). *Participatory creativity: Introducing access and equity to the creative classroom*. Routledge. https://doi.org/10.4324/9781315671512

Cross, N. (2006). *Designerly ways of knowing*. Springer.

Damşa, C. I., Kirschner, P. A., Andriessen, J. E. B., Erkens, G., & Sins, P. H. M. (2010). Shared epistemic agency: An empirical study of an emergent construct. *Journal of the Learning Sciences, 19*(2), 143–186. https://doi.org/10.1080/10508401003708381

Derry, S. J., Pea, R. D., Barron, B., Engle, R. A., Erickson, F., Goldman, R., Hall, R., Koschmann, T., Lemke, J. L., Sherin, M. G., & Sherin, B. L. (2010). Conducting video research in the learning sciences: Guidance on selection, analysis, technology, and ethics. *Journal of the Learning Sciences, 19*(1), 3–53. https://doi.org/10.1080/10508400903452884

Dewey, J. (1986). Experience and education. *The Educational Forum, 50*(3), 241–252. https://doi.org/10.1080/00131728609335764

DiGiacomo, & Gutiérrez, K. D. (2016). Relational equity as a design tool within making and tinkering activities. *Mind, Culture and Activity, 23*(2), 141–153. https://doi.org/10.1080/10749039.2015.1058398

Engeström. (2015). *Learning by Expanding: An activity-theoretical approach to developmental research* (2nd ed.). Cambridge University Press.

Ewenstein, B., & Whyte, J. (2009). Knowledge practices in design: The role of visual representations as `epistemic objects'. *Organization Studies, 30*(1), 7–30. https://doi.org/10.1177/0170840608083014

Glaveanu, V. (2014). *Thinking through creativity and culture*. Routledge.

Gutiérrez, K., Higgs, J., Lizárraga, J., & Rivero, E. (2019). Learning as movement in social design-based experiments: Play as a leading activity. *Human Development, 64*(1–2), 66–82. https://doi.org/10.1159/000496239

Hakkarainen, K. (2009). Three generations of technology-enhanced learning. *British Journal of Educational Technology, 40*(5), 879–888. https://doi.org/10.1111/j.1467-8535.2008.00873.x

Hakkarainen, K., Paavola, S., & Lipponen, L. (2004). From communities of practice to innovative knowledge communities. *Lifelong Learning in Europe, 9*(123445), 74–83.

Hakkarainen, K., & Seitamaa-Hakkarainen, P. (2022). Learning by inventing: Theoretical foundations. In T. Korhonen, K. Kangas, & L. Salo (Eds.), *Invention pedagogy: The Finnish approach to maker education*. Routledge.

Hanson, M. H. (2015). *World making: Psychology and the ideology of creativity*. Palgrave Macmillan. https://doi.org/10.1057/9781137408051

Härkki, T., Vartiainen, H., Seitamaa-Hakkarainen, P., & Hakkarainen, K. (2021). Co-teaching in non-linear projects: A contextualised model of co-teaching to support educational change. *Teaching and Teacher Education, 97*, Article 103188. https://doi.org/10.1016/J.TATE.2020.103188

Holland, D., Lachicotte, W., Skinner, D., & Cain, C. (1998). *Identity and agency in cultural worlds*. Harvard University Press.

Honey, M., & Kanter, D. E. (2013). *Design, make, play: Growing the next generation of STEM innovators*. Routledge. https://doi.org/10.4324/9780203108352

Honneth. (1995). *The struggle for recognition: the moral grammar of social conflicts*. Polity.

Iljenkov, E. (1977). *Dialectical logic: Essays on its history and theory*. Progress.

International Organization for Standardization. (2017). ISO - ISO/IEC 25010:2011 - Systems and software engineering: Systems and software quality requirements and evaluation (SQuaRE) — System and software quality models. https://www.iso.org/standard/35733.html.

Kafai, Y. B., Fields, D. A., & Searle, K. A. (2014). Electronic textiles as disruptive designs: Supporting and challenging maker activities in schools. *Harvard Educational Review, 84*(4), 532–556. doi:10.17763.

Kangas, K., Seitamaa-Hakkarainen, P., & Hakkarainen, K. (2013). Figuring the world of designing: Expert participation in elementary classroom. *International Journal of Technology and Design Education, 23*(2), 425–442. https://doi.org/10.1007/s10798-011-9187-z

Knorr Cetina, K. (2001). Objectual practice. In K. Knorr Cetina, T. R. Schatzki, & E. von Savigny (Eds.), *The practice turn in contemporary theory* (pp. 175–188). Routledge. https://doi.org/10.4324/9780203977453.

Koh, J. H. L., Chai, C. S., Wong, B., & Hong, H. Y. (2015). Design thinking for education: Conceptions and applications in teaching and learning. In J. Koh, C. Chai, B. Wong, & H. Hong (Eds.), *Design thinking for education: Conceptions and applications in teaching and learning* (pp. 1–131). https://doi.org/10.1007/978-981-287-444-3

Korhonen, T., & Lavonen, J. (2017). A new wave of learning in Finland: Get started with innovation! In S. Choo, D. Sawch, A. Villanueva, & R. Vinz (Eds.), *Educating for the 21st century: Perspectives, policies and practices from around the world* (pp. 447–467). Springer. https://doi.org/10.1007/978-981-10-1673-8_24.

Krajcik, J., & Blumenfeld, P. (2005). Project-based learning. In R. Sawyer (Ed.), *The Cambridge handbook of the learning sciences (Cambridge handbooks in psychology)* (pp. 317–334). Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511816833.020.

Latour, B. (1996). On interobjectivity. *Mind, Culture and Activity, 3*(4), 228–245. https://doi.org/10.1207/s15327884mca0304_2

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge University Press.

Lawson, B. (2004). *How designers think: The design process demystified* (4th ed.). Elsevier.

Lin, K.-Y., Hsiao, H.-S., Williams, P. J., & Chen, Y.-H. (2020). Effects of 6E-oriented STEM practical activities in cultivating middle school students' attitudes toward technology and technological inquiry ability. *Research in Science & Technological Education, 38*(1), 1–18. https://doi.org/10.1080/02635143.2018.1561432

Malafouris, L. (2013). *How things shape the mind: A theory of material engagement*. MIT. https://doi.org/10.7551/mitpress/9476.001.0001

Martin, Dixon, C., & Betser, S. (2018). Iterative design toward equity: Youth repertoires of practice in a high school maker space. *Equity & Excellence in Education, 51*(1), 36–47. https://doi.org/10.1080/10665684.2018.1436997
Martin, L. (2015). The promise of the maker movement for education. *Journal of Pre-College Engineering Education Research, 5*(1). https://doi.org/10.7771/2157-9288.1099
Mehto, V., Riikonen, S., Hakkarainen, K., Kangas, K., & Seitamaa-Hakkarainen, P. (2020b). Epistemic roles of materiality within a collaborative invention project at a secondary school. *British Journal of Educational Technology, 51*(4), 1246–1261. https://doi.org/10.1111/bjet.12942
Mehto, V., Riikonen, S., Kangas, K., & Seitamaa-Hakkarainen, P. (2020a). Sociomateriality of collaboration within a small team in secondary school maker-centered learning project. *International Journal of Child-Computer Interaction, 26*. https://doi.org/10.1016/j.ijcci.2020.100209
Moran, S., & John-Steiner, V. (2003). Creativity in making: Vygotsky's contemporary contributions to the dialectics of development and creativity. In R. Sawyer, V. John-Steiner, et al. (Eds.), *Creativity and development* (pp. 61–90). Oxford University Press.
Nathan, M. (2022). *Foundations of embodied learning: A paradigm for education*. Routledge. https://doi.org/10.1080/00131857.2022.2074833
Nonaka, I., & Takeuchi, H. (1995). *The knowledge-creating company: How japanese companies create the dynamics of innovation*. Oxford University Press.
OECD. (2019). OECD Learning Compass 2030: A Series of Concept Notes. 149. https://www.oecd.org/education/2030-project/contact/OECD_Learning_Compass_2030_Concept_Note_Series.pdf.
Osborne, J. (2014). Teaching scientific practices: Meeting the challenge of change. *Journal of Science Teacher Education, 25*(2), 177–196. https://doi.org/10.1007/s10972-014-9384-1
Paavola, S., & Hakkarainen, K. (2014). Trialogical approach for knowledge creation. In S. Tan, H. So, & J. Yeo (Eds.), *Knowledge creation in education* (pp. 53–73). Springer. https://doi.org/10.1007/978-981-287-047-6_4.
Paavola, S., & Hakkarainen, K. (2021). Trialogical learning and object-oriented collaboration. In U. Cress, C. Rose, S. Wise, & J. Oshima (Eds.), *International handbook of computer supported collaborative learning* (pp. 241–259). Springer. https://doi.org/10.1007/978-3-030-65291-3_13.
Paavola, S., Lipponen, L., & Hakkarainen, K. (2004). Models of innovative knowledge communities and three metaphors of learning. *Review of Educational Research, 74*(4), 557–576. https://doi.org/10.3102/00346543074004557
Papavlasopoulou, S., Giannakos, M. N., & Jaccheri, L. (2017). Empirical studies on the maker movement, a promising approach to learning: A literature review. *Entertainment Computing, 18*, 57–78. https://doi.org/10.1016/j.entcom.2016.09.002
Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. Basic Book.
Parekh, P., & Gee, E. R. (2018). Zooming into a tinkering project: The progression of learning through transitional objects. *Interdisciplinary Journal of Problem-Based Learning, 12*(2). https://doi.org/10.7771/1541-5015.1751
Parekh, P., & Gee, E. R. (2019). Tinkering alone and together: Tracking the emergence of children's projects in a library workshop. *Learning, Culture and Social Interaction, 22*(60). https://doi.org/10.1016/j.lcsi.2019.04.009
Peirce, C. S. (1998). In *, Vol. 2. The essential Peirce: Selected philosophical writings* (pp. 1893–1913). Indiana University Press.
Petrich, M., Wilkinson, K., Bevan, B., & Wilkinson, K. (2013). It looks like fun, but are they learning? In M. Honey, & D. Kanter (Eds.), *Design, make, play: Growing the next generation of STEM innovators* (pp. 68–88). Routledge.
Pickering, A. (1995). *The mangle of practice: Time, agency, and science*. The University of Chicago Press.
Popper, K. R. (1972). *Objective knowledge: An evolutionary approach*. Clarendon Press.
Resnick, M., & Rosenbaum, E. (2013). Designing for tinkerability. In M. Honey, & D. Kanter (Eds.), *Design, make, play* (pp. 181–199). Routledge.
Riikonen, S., Kangas, K., Kokko, S., Korhonen, T., Hakkarainen, K., & Seitamaa-Hakkarainen, P. (2020a). The development of pedagogical infrastructures in three cycles of maker-centered learning projects. *Design and Technology Education: An International Journal, 25*(2), 29–49. https://ojs.lboro.ac.uk/DATE/article/view/2782 https://ojs.lboro.ac.uk/DATE/article/view/2782.
Riikonen, S., Seitamaa-Hakkarainen, P., & Hakkarainen, K. (2020b). Bringing maker practices to school: Tracing discursive and materially mediated aspects of student teams' collaborative making processes. *International Journal of Computer-Supported Collaborative Learning, 15*(3), 319–349. https://doi.org/10.1007/s11412-020-09330-6
Ritella, G., & Hakkarainen, K. (2012). Instrumental genesis in technology mediated learning: From double stimulation to expansive knowledge practices. *International Journal of Computer-Supported Collaborative Learning, 7*, 239–258. https://doi.org/10.1007/s11412-012-9144-1
Rowell, P. M. (2002). Peer interactions in shared technological activity: A study of participation. *International Journal of Technology and Design Education, 12*(1), 1–22. https://doi.org/10.1023/A:1013081115540
Saldaña, J. (2016). *The coding manual for qualitative researchers* (3rd ed.). SAGE.
Schad, M., & Jones, W. M. (2020). The maker movement and education: A systematic review of the literature. *Journal of Research on Technology in Education, 52*(1), 65–78. https://doi.org/10.1080/15391523.2019.1688739
Schwartz, L., DiGiacomo, D., & Gutiérrez, K. (2015). Designing "Contexts for Tinkerability" with undergraduates and children within the El Pueblo Mágico social design experiment. *International Journal for Research on Extended Education, 3*(1), 94–113. https://doi.org/10.3224/ijree.v3i1.19583
Seitamaa-Hakkarainen, P., & Hakkarainen, K. (2017). Learning by making. In K. Peppler (Ed.), *The SAGE encyclopedia of out-of-school learning* (pp. 421–424). SAGE. https://doi.org/10.4135/9781483385198.n164.
Seitamaa-Hakkarainen, P., Viilo, M., & Hakkarainen, K. (2010). Learning by collaborative designing: Technology-enhanced knowledge practices. *International Journal of Technology and Design Education, 20*(2), 109–136. https://doi.org/10.1007/s10798-008-9066-4
Sfard, A. (1998). On two metaphors for learning and the dangers of choosing just one. *Educational Researcher, 27*(2), 4–13. https://doi.org/10.3102/0013189X027002004
Skagestad, P. (1993). Thinking with machines: Intelligence augmentation, evolutionary epistemology, and semiotic. *The Journal of Social and Evolutionary Systems, 16*(2), 157–180. https://doi.org/10.1016/1061-7361(93)90026-N
Sormunen, K., Juuti, K., & Lavonen, J. (2020). Maker-centered project-based learning in inclusive classes. *International Journal of Science and Mathematics Education, 18*(4), 691–712. https://doi.org/10.1007/s10763-019-09998-9
Stahl, G., & Hakkarainen, K. (2021). Theories of CSCL. In U. Cress, C. Rose, S. Wise, & J. Oshima (Eds.), *International handbook of computer supported collaborative learning* (pp. 23–43). Springer. https://doi.org/10.1007/978-3-030-65291-3_2.
Tenhovirta, S., Korhonen, T., Seitamaa-Hakkarainen, P., & Hakkarainen, K. (2022). Cross-age peer tutoring in a technology-enhanced STEAM project at a lower secondary school. *International Journal of Technology and Design Education, 32*, 1701–1723. https://doi.org/10.1007/s10798-021-09674-6
Viilo, M., Seitamaa-Hakkarainen, P., & Hakkarainen, K. (2018). Teacher's long-term orchestration of technology-mediated collaborative inquiry project. *Scandinavian Journal of Educational Research, 62*(3), 407–432. https://doi.org/10.1080/00313831.2016.1258665
Vossoughi, S., & Bevan, B. (2014). In *Making and tinkering: A review of the literature* (pp. 1–55). National Research Council Committee on Out of School Time STEM. July.
Vygotski, L. S. (1978). *Mind in society: The development of higher psychological processes*. Harvard University Press.
Vygotsky, L. S. (2004). Imagination and creativity in childhood. *Journal of Russian and East European Psychology, 42*(1), 7–97. https://doi.org/10.1080/10610405.2004.11059210
Worsley, M., & Blikstein, P. (2016). Reasoning strategies in the context of engineering design with everyday materials. *Journal of Pre-College Engineering Education Research, 6*(2), 58–74. https://doi.org/10.7771/2157-9288.1126
Yrjönsuuri, V., Kangas, K., Hakkarainen, K., & Seitamaa-Hakkarainen, P. (2019). The roles of material prototyping in collaborative design process at an elementary school. *Design and Technology Education, 24*(2). https://ojs.lboro.ac.uk/DATE/article/view/2585 https://ojs.lboro.ac.uk/DATE/article/view/2585.