Epistemic Objects and Knowledge Creation in Invention Projects

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Introduction

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

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

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

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

Knowledge-Creating Learning and Epistemic Objects in Invention Projects

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

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

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

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

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

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

Invention Project and Data Gathering

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

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

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

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

Methodology and Analysis

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

Figure 3.1 Prototype of the Banana Light.

Photograph by the author.

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

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

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

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

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

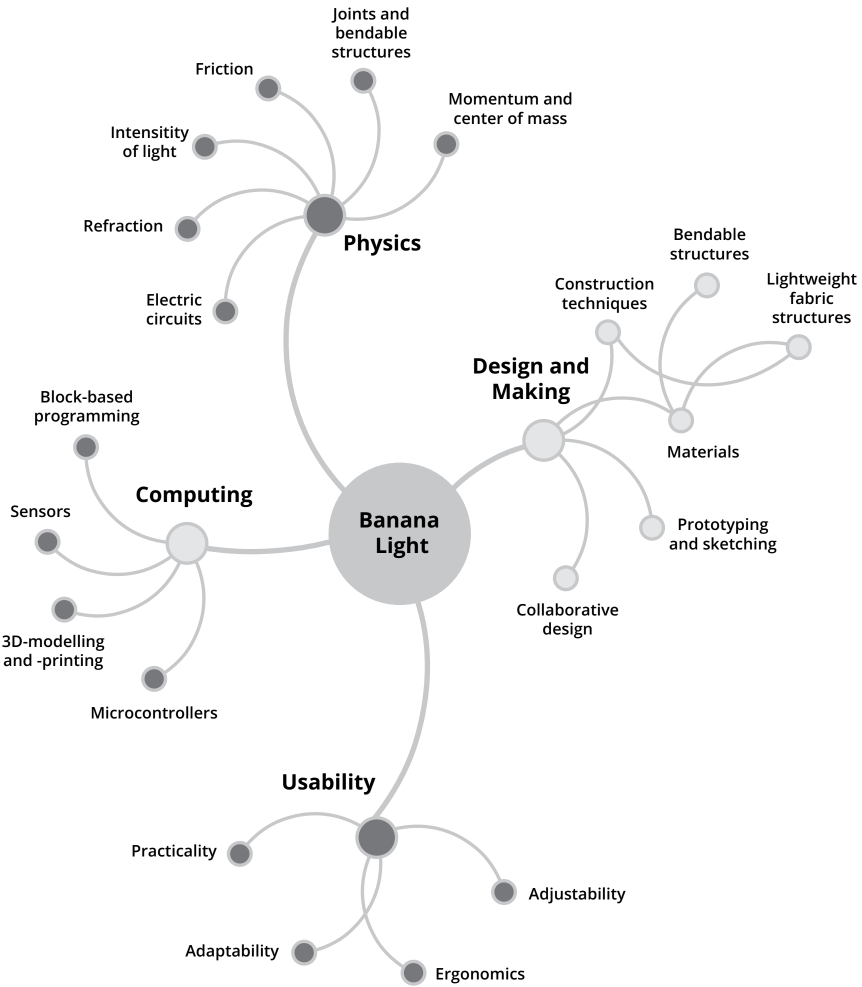

Figure 3.2 Model of the knowledge dimensions and themes of the Banana Light team's epistemic object.

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

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

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

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

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

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

CARLA: Oh, yes.

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

CARLA: Yes, okay, we can do that.

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

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

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

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

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

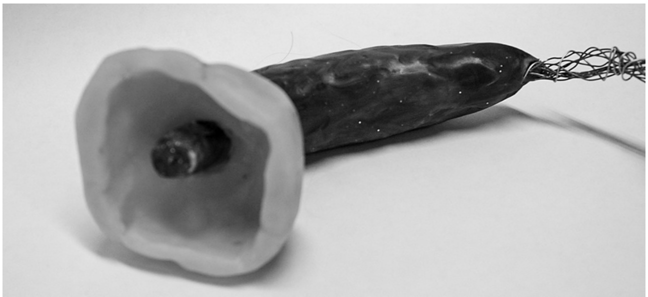

Figure 3.3 Early prototype of the Banana Light.

Photograph by the author.

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

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

Discussion and Conclusions

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

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

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

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

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