Re/Thinking the Nature of Technology in Elementary Science Classrooms

Abstract

With increasing technological changes and needs in society, technology and engineering education has received much attention in school science. Yet, technology traditionally has been subordinated to science or simply taken as the application of science. This position has resulted in a limited understanding of teaching technological and engineering education. This study questions the traditional view of technology in school science by examining children's action and learning in the course of designing and building cantilever bridges in science classrooms. We adapt Heidegger's articulation of the four causes known to philosophy in the Greco-Roman tradition—causa materialis (material), causa formalis (form), causa finalis (purpose), and causa efficiens (effect-producing)—to analyze elementary children's technology design activities. The study suggests that children's technology has certain dimensions of knowing-how, i.e., there is an instrumentality that goes beyond scientific knowledge. We suggest that the practice of technology and engineering education, which mainly focuses on children's scientific knowledge, needs to be reexamined and reframed to develop holistic ways of teaching technology.

Keywords: technology, engineering, philosophy, elementary school, science

Introduction

> Invention [engineering] causes things to come into existence from ideas, makes the world conform to thought; whereas science, by deriving ideas from observation, makes thought conform to existence. (Mitcham 1978, p. 244)

Historians have linked economic and cultural development to advances in technology, such as the cultural changes that occurred with the invention of the printing press, power engine, and telecommunication. As a consequence, technology and engineering education have received much attention in school education.[1] In recent years, engineering and technological knowledge and practices have been recognized in the Framework of K–12 Science Education, Next Generation Science Standard, and STEM (Science, Technology, Engineering, and Mathematics) initiatives in science education (Carr et al. 2012; National Research Council 2012; NGSS Lead States 2013; Wendell and Rogers 2013). In Canada, this tendency is also noticeable in the emphasis on STEM literacy for Canada's economic productivity and future suggested by the Council of Canadian Academies (2015).

To integrate the societal emphasis on engineering and technology in the school curriculum, science teachers are encouraged to integrate in their curricula engineering and technological design tasks such as designing and building structures (i.e., boats, bridges, or devices). Such recommendations are often based on the dimensions that science and technology share rather than on those in which they differ (Roth 2001a). As a result, there exists a tendency to prioritize science content knowledge and skills acquired in hands-on technological design (Dohn 2013). In this approach, teachers regard technology and engineering activities as means for developing students' scientific knowledge by emphasizing how certain concepts can be applied and verified in technological designs. Accordingly, educational projects and research on engineering and technology have emphasized the importance of connecting children's technological design activities to science content (e.g., Crismond 2001; Wendell and Rogers 2013). For instance, *Engineering for Children: Structures curriculum* (Roth 1998a), *Learning by Design* (Kolodner et al. 2003), and the *Design-Based Science* approach (Fortus et al. 2004) all emphasize how designing and building technology can be used to enhance children's understanding of scientific concepts. Wendell and Rogers (2013), in their study of a LEGO engineering curriculum,

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[1] It is beyond the scope of our study to distinguish technology and engineering. Instead, we acknowledge technology in our study is discussed in the context of hands-on tasks such planning, designing, making, and building, which could be inseparable from the process of engineering. Thus, we do not differentiate technology and engineering in this work but refer them interchangeably.

emphasized how the engineering curriculum developed students’ science content knowledge. The authors concluded: “students showed greater performance gains when using the LEGO engineering curriculum than when using their school’s typical science curriculum” (p. 153).

There has been much emphasis on enhancing students’ science content knowledge and the application of science in technology and engineering education. Yet already decades ago, concerns were raised about the fact that technology was considered to be only a subservient discipline that applies science (Gardner 1992; Goldman 1990). But the subordination of technology to science disregards the uniqueness of technological and engineering know-how. Such subordination is problematic as there are many examples where technology existed before science, including the technologies of brewing, construction, metallurgy, and aeronautical engineering (McGinn 1991; Sismondo 2004). These technologies were developed without a lot of interaction with science; and they were not the outcomes of adapting scientific theories and explanations but constituted independent dimensions of knowing-that and knowing-how. It is therefore not correct to assume that technology is completely dependent on science; nor is technology merely applied science or a subordinate structure of science (Latour 1992, 1999).

This study was designed to investigate the characteristics of children’s technology- and engineering-related knowing-how by expanding the question of technology through the notions of causality and instrumentality. We offer the modest proposal that children’s technology-related inquiries be suitably understood using the classical philosophical distinction between four causes—material (causa materialis), form (causa formalis), purpose (causa finalis), and effect (causa efficiens)—that Heidegger (2000) takes up to discuss the nature (being) of technology. Case studies from engineering activities in a second-/third-grade science classroom are used to show that children’s technological activities can be investigated in the light of the four causes that together constitute the essence of technology.

Background

On the Relation between Science and Technology

> Philosophers only interpreted the world differently; the point is to change it. (Marx & Engels 1978, p. 7)

In the opening quotation, the authors distinguish philosophy, the pursuit of which is the understanding of the world, from the power of practice to change the world that conditions human beings. In so doing, so Marx and Engels (1978), human nature coincides with what they produce and how they produce it. This may give technology a priority in the development of human knowledge. Science on the other hand, which has arisen out of natural philosophy, has an orientation towards knowledge creation. It may be that in its very essence, science partially misses the point. Questioning the ontological and epistemological differences between science and technology, some scholars have recognized that the latter has its own unique dimensions of knowing in terms of goals and purpose of knowledge (e.g., McGinn 1991; Sismondo 2004). Other scholars argue along the lines of Marx and Engels (1978) that science is interested in knowledge and explanation but that the purpose of technology is to make things and make them work in practice (e.g., Dohn 2013; Gunstone 1994; Lewis 2006). In the history of science and technology, there are indeed examples of technological tools and devices developed based on scientific knowledge, such as the development of optical lenses (Gardner 1990). Based on the theory of light, lenses were developed for various purposes in life, including the telescope and the microscope. In the particular example, science comes first as the principle and technology is the application thereof, an order and hierarchy perpetuated in school science (Gardner 1990).

The National Research Council (1996) states that the distinct difference between science and technology lies in their respective goals, that is, “science is to understand the natural world and technology is to make modifications in the world to meet human needs” (p. 24). With the different purpose and goal of knowledge and practice, the unique dimensions of technology education has been discussed in terms of trial-and-error and instrumentality (Lewis 2006; Ritchie and Hampson 1996), the influence of societal forces and innovative decision making on design practice (McRobbie et al. 2001), tinkerability and creativity to improvise, adapt and iterate things for new possibilities (Resnick and Rosenbaum 2013), and situated cognition in technological design and problem solving (Guzey et al. 2014; Murphy and McCormick 1997; Roth 2001a). These and other authors suggest that a practice of technology and engineering teaching as application of science might overlook some of the important aspects of technology and question how technology and engineering education can address a unique form of knowing-how emerging from the curriculum.

Teachers' pedagogical content knowledge of engineering and technology teaching was also scrutinized in the considerations of how to implement engineering education in school classrooms (Carr et al. 2012; Rockland et al. 2010). One study investigated teachers' professional development program and practice of engineering lessons in grade 3–6 science classrooms employing *Engineering is Elementary* (EiE) program (Guzey et al. 2014). The teachers in the study were encouraged to produce lessons that develop children's understanding of engineering design, nature of science, and science inquiry. In contrast to the development of a separate technology and engineering curriculum, the integration of engineering knowledge and skills into school science standards has been recommended in STEM approaches (Carr et al. 2012). Science teachers are asked to develop science lessons with engineering tasks to further students' engineering literacy together with science. Yet, the approach of integrating engineering into science might result in a greater emphasis on science than on technology and engineering, especially when teachers do not realize how technology and engineering knowledge and skills could be different from science (Brophy et al. 2008).

When scholars discussed the nature of technology in the 1990s, they examined it in the context of design, artifacts, engineering, and hands-on tools, rather than information technology commonly referred as technology today. In STEM initiatives in the recent years, there has been also much confusion and debate on what 'T' means in STEM between computer-related technology and technology education as an area of interdisciplinary study (Cavanagh and Trotter

2008; Kelly 2010) and how technology and engineering are intertwined in STEM approaches (Harrison 2011). There appears to be a stalemate in the discussion. The exist from this situation, we turn to other ways of thinking about technology and engineering education; these ways have been developed in a long history of philosophy of technology reflecting on the essence of technology.

The Essence of Technology

The Greek word τέχυη (technē)[2], from which the English word technology[3] derives, needs to be considered in two ways to understand its signification (Heidegger 2000): "First, technē is not only the name for the artisanal doing and knowing-how but also for the arts of the mind and the fine arts. Technē belongs to bringing-forth, to ποίησις (poiēsis)" (p. 14). The second even more important aspect is its relation to ἐπιστήμη (epistēmē). The two words together, technē and epistēmē constitute knowing in its largest sense. Particular about technē is that it is a mode of άληθεύειν (alētheuein, from alētheia = truth). This, technē "reveals whatever does not bring itself forth and does not yet lie here before us" (p. 14). Heidegger concludes that technology is a mode of revealing; and it "exists in that realm where revealing and unconcealment, alētheia, where truth happens" (p. 15).

Technology concerns the goals and means of revealing, that is, instrumentality. To understand the complexity of instrumentality of technology in relation to a means and ends of human endeavors, Heidegger grounds his discussion of technology in a fourfold determination of

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[2] Heidegger writes all relevant words in Greek letters; we introduce each word as Heidegger used it but then follow the Anglo-Saxon convention to use Roman transliterations.

[3] Heidegger does not write about *Technologie* (tchnology), (a) the science of the transformation of materials into finished products that makes use of scientific and technical knowledge and (b) the totality of processes required for the production and transformation of raw materials. Instead, he writes about *Technik* (technology + technique), (a) the totality of measures and modes of operation to mobilize scientific knowledge for practical purposes and (b) the mode, method of proceeding, the execution of something.

a thing that can be traced back to Aristotle. He emphasizes that the ancient Greek were not thinking in terms of the present-day notions of cause and effect but in terms of blame [Ger. *Verschulden*, Lat. *causa*, Gr. αἴτιον]. The four causes are modes of blame that belong together. The four causes, exemplified in the object of silver chalice, include: (a) *causa materialis* [material cause]—the material from which a thing is made (e.g., silver); (b) *causa formalis* [formal cause]—pattern, model, structure, or form (e.g., a chalice); (c) *causa finalis* [final cause]—goal, purpose, function or potential (e.g., use of the chalice as sacrificial vessel); and (d) *causa efficiens* [efficient cause]—the means or agency that produces the effect (e.g., a silversmith).

Questioning the different forms of causality leads us to explore the ways in which human agency is positioned in the relationship of technology, truth, art, nature, life, and values. Heidegger (2000) describes how the silversmith carefully considers and gathers together the three aforementioned ways [material, formal, and final causes] of being responsible and indebted. To consider carefully is to bring-forth into appearance. There is also a deontological dimension that arises from the consideration of causality (Ihde 2010). Thus, for example, the silversmith is co-responsible as that from whence the sacred vessel's bringing-forth and subsistence take and retain their first departure. The three ways of being responsible owe to the pondering of the silversmith for the "that" and the "how" of their coming into appearance and into play for the production of the sacrificial vessel. The final cause (the purpose of a thing) enters into the formal cause of the thing. These causes intricately interact and bring forth the existence of the designed and made thing to the world. To understand the nature of technology, the four causes of a thing, a product, and a practice need to be questioned and analyzed. We exhibit such an agenda in the following study of children in the process of designing a bridge based on the principle of a cantilever, that is, a structure that is supported on one end only.[4]

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[4] A cantilever bridge consists of two halves, each strutting out from opposing points of a river or valley, joined in the middle where no support is required because the cantilevered halves are self-supporting.

Research Methods and Context

Participants

Fifteen children in a mixed second-/third-grade class from an elementary school in an urban area in western Canada participated in this study. There were five second graders (three girls and one boy) and nine third graders (three girls and six boys) in the class. For group work, the children were mixed regardless of grade and gender and often chose their own groupings. The children were English-speaking from middle-class families. The teacher was dedicated to science and inquiry-based teaching. She taught science to second-/third-grade students (the participants in this study) and also to the fourth- to sixth-grade students in the school. Having taught science in informal contexts for several years, including an experience at a nonprofit science learning center for children and various science camps, the teacher was well prepared to teach the curriculum. Her interest and confidence in teaching science was evident throughout the study. During the lessons, different teacher assistants—one at a time—were present. They generally did not have science backgrounds.

Curriculum

The curriculum investigated here took place two hours per week over a four-week period. The teacher designed a unit plan on forces and structures and taught those topics with various instructional methods such as hands-on, reading science tradebooks and story telling, video films, science notebooks, etc. The topics of equilibrium, lever systems (load, fulcrum, and effort), and forces (compression, tension, and torsion) were discussed through various activities such as balancing butterfly, balancing measuring sticks, and bodily experiences of different forces. During the last few lessons, children were engaged to design and build two cantilever structures;

cantilever building and cantilever bridge. The intention of these activities was to provide children with opportunities to come to understand the concepts of weight and balance and build a structure by using those concepts. Throughout the unit, the children were engaged in tasks sometimes individually and sometimes in groups. Even though it was a mixed class with different academic grades, no specific attention was given to differentiating task levels or grouping for group work.

In this study we particularly investigate classroom episodes of children's design and building a cantilever bridge. Before the task of building a cantilever bridge, children built a cantilevered building. The children previously had made a cantilever arm stick out from the support by stacking heavy materials on the end of the arm. The teacher emphasized that cantilever structures mean that there is no support underneath the open end of the cantilever arm and the arm should sustain extra weight such as humans or furniture on the structure (Fig. 1).

«««««« Insert Fig. 1 about here »»»»»»

The teacher asked children to build a cantilever bridge. Different materials and forces on cantilever structure were reviewed in preparation to the construction. The teacher showed several pictures of cantilever bridge and asked where different forces were applied on the bridge. After the introduction, she asked the children to build a cantilever bridge with given materials: two pieces of cardboard paper, one piece of folder paper, two plastic cups, and a windup spring toy car per group. The teacher briefly demonstrated one design by using those materials. When she put some weight in the middle of the bridge, it collapsed. The teacher allowed the children to use other materials available in the classroom.

Data Collection

To investigate the nature of technology in the context of education, we collected video data of classroom activities to examine interactions among children and teachers in the process of designing and building artifacts. Two video cameras were used to videotape events. A researcher was observing and taking notes over the weeks of the unit on forces and structures. All recorded classroom talk was transcribed by a service provider and subsequently verified by the researcher.

Analysis

The four causes of technology were used as analytic categories to classify observed events. To develop a thick description and analysis of children's learning and action, conversation and video analysis is employed in this study (Jordan and Henderson 1995) by adapting the metaphor of zooming in and out to understand complex classroom phenomena at multiple interconnected levels (Roth 2005). As in the case of a biologist, who observes different structures when zooming in and out with her microscope, social analysts can zoom in and out, which yields different but related patterns in the available data.

Complexity of Children's Design Understood in Terms of the Four Causes

This study was designed to investigate children's designing through the lens of the four causes discussed in the Greco-Roman philosophical tradition. Our analysis of children's designing shows how the building of cantilever bridges exhibits the four causes of technology (material, formal, final, and efficient). For each of the four causes that are identified in the children's designing, we provide a brief introduction, then articulate evidence from the classroom observations, and end by discussing the findings in terms of the concerns of technology.

The Material Cause

Introduction

The first of the four causes focuses on the materials that enter technological design. Because of their differing properties and configurations, what is being considered and used in designing has a determinant effect on the quality of the final product. The following shows how designing is shaped by the materials.

Empirical Evidence

To build a bridge, children were given two pieces of cardboard paper, one piece of folder paper, and disposable plastic cups. The teacher's demonstration suggested initial ideas of how they might want to use those materials. As in the teacher's demonstration, the bridges did not stand steady so children tried to add more materials to hold the bridge such as books, masking tapes, play-dough, binders, etc. In one group, Kevin and Jack were putting the papers on the cups. But the paperboards kept falling (Fig. 2a and 2b). Kevin brought marbles to add on the anchor, but the teacher asked him not to use it. Kevin said, "but we're gonna use it for the weight. Then we have nothing for the weight." The teacher gave him a box of play-dough and said "you can stick this inside, on the cups, but this (cardboard paper) needs to be on books to test the car." Kevin tried to put the play-dough on the paper to balance the bridge (Fig. 2c). Then the play-dough did not stick to the paper and he soon asked Jack to bring some books. While Jack was bringing books, Kevin put the cup under the center of the cardboard paper (Fig. 2d) and added a piece of folder paper in the middle (Fig. 2e). Kevin acclaimed, "Wow!" and said to the teacher aid, "And there is no weight!" The teacher aid said, "Nice balancing!" Now Jack put a car on the bridge to test it and it collapses (Fig. 2f).

«««««« Insert Fig. 2 about here »»»»»»

Kevin and Jack started to add books to their structure. They made two piles of books and Kevin took apart the two banks further but the desk was not wide enough to do so. The banks got close and the two cups were placed underneath the cardboard (Fig. 2g and 2h). They tested their final design with a toy car.

Discussion

In this episode, the children’s design was changing as they interacted with materials. The configuration and availability of materials influenced children’s courses of action. The emerging design therefore resulted not from an externalization of thought but in response to the external conditions (availability and nature of materials). When a material was disallowed, new approaches to the design emerged. Play-dough, rather than appearing underneath the paper and on the cup, as per the teacher suggestion, came to find a place on the top of the paper before being replaced by books. The play-dough turned out not to be sticky, thus insufficient to serve an earlier goal. Throughout the process, it was evident that weight was a consideration in the building. As the books entered the ensemble of building materials, the distance between the two cups got shorter. The cup was closer to the end of cardboard paper and supported the balance. The bridge balanced itself without extra weight on the anchor. As shown in an earlier study focusing on art and artifact in children’s designing (Roth 1996a) and the importance of materials literacy in children’s design process (Bennett and Monahan 2013), the process and outcome of the designs in this study were connected to, changed, and developed with the material conditions of the surroundings. This is clear evidence that the available materials contribute to the determination of technological design activity and the ultimate artifact produced.

The Formal Cause

Introduction

The second cause pertains to the pattern, model, structure, or form of the design. The essence of technology is emergent and evolving as the form of some thing changes over time. Technological design does not imitate the form of a thing (in mind) but creates a form that completes its mission (Ingold 2013). Form does not exist as thought but form is born in the *articulation* of thought (Vygotsky 1987). The following episode shows how the form of children’s design reveals certain levels of creativity and ownership in designing activities.

Empirical Evidence

The task was to design a cantilever bridge. To set up the goal, the teacher showed a few pictures of cantilever bridge on the whiteboard and later demonstrated an example by using planned materials. The teacher's model offered children a possible structure for their designs. Most designs (Fig. 2 and Fig. 3) were similar to the model, that is, most groups put the two cups underneath the cardboard paper and connected the paper with the folder paper in the middle as the teacher showed. In this regard, the teacher's demonstration might have limited children's thinking and design to a certain direction. However, once children reached their goals of building a bridge by modeling the teacher's structure, they often started to change their structure and created something new on their own.

«««««« Insert Fig. 3 about here »»»»»»

Two groups of children (groups of Daniel and Cole) working next to each other started to combine their bridges into one long bridge. Daniel asked, "Who wants to join our big bridge? Our giant bridge?" Kevin visited Daniel's group and, back at his desk, took his bridge apart bringing all the materials to Daniel's group. Then three groups made a longer bridge. They started to put the parts together by using masking tape and discussed how cars would run on the bridge and what other parts could be added. They added safety walls (Fig. 4).

«««««« Insert Fig. 4 about here »»»»»»

The teacher's design was available and implemented in children's bridge model in the beginning and extended and transformed into a new bridge. There was creativity and ownership emerged which transformed their ideas, models and structures of bridge into a new form, which emerged rather than pre-existed.

Discussion

This episode shows that the formal cause (form, pattern, structure and design) is enframing and enframed by the materials and the goals of the task. The form of bridge initially resembled what the children were shown. But then the form was changing over time, in and through the relations between groups. The emergent forms were determined in part by dilemmas that became salient in the process: between designing for the curriculum goal and designing for real world problems. Compared to other designs in the Fig. 3, the design of Fig. 3d exhibits a cantilever structure in the way described in the planned curriculum. But that original design did not take into account the windup-spring toy car that was to move across it. In other designs, books held the bridge; the design in Fig. 3d, however, exhibits a concern for the aesthetics of the curricular product (how the design looks). The former design was focusing on instrumentality and creativity and the latter oriented itself towards scientific knowing-that.

The Final Cause

Introduction

The third cause pertains to the finality of a design: its goal, purpose, function, or potential. In the analysis of mundane consciousness, this cause is integral to how craftspeople orient to their work (Heidegger 1977). In school science and engineering, this dimension is not normally found, and students' products tend to be abandoned and thrown away once a task has been assessed. However, education does not have to be without final cause, such as when students contribute to environmental activism or when they create green spaces in a city that are subsequently used by its inhabitants (e.g. Roth and Barton 2004). The goal of children's design is often confused with curriculum goals. For example, the goal of designing a bridge is to apply scientific knowledge, not the goal of bridge in the given problem contexts. Expanding the goal of design from a curriculum focus to instrumentality in practice could bring forth the connectedness of technology to life contexts. This aspect of the final cause may be found in schools when tasks address realistic design problems—e.g., fourth-graders' designing software to teach mathematics to peers and students in lower grades (Harel 1991)—or when classroom talk addresses the potential uses of designs by society at large.

Empirical Evidence

The teacher had planned curriculum to allow children to learn scientific knowing-that in and through technological design tasks. In the classroom, however, we observed a different intention manifest itself: an orientation to making the bridge stand up and allowing a car to cross it. Thus, an orientation to the final cause of technology—a working bridge—predominated over the planned curricular products—scientific knowing-that concerning cantilevers. In the following question | reply sequence, the stated challenge was one of making the bridge do what it is supposed to do rather than one concerned with knowing the scientific principles underlying the cantilever design.

> Teacher: What are some of the design challenges that you had when you were putting bridges together?
> Kevin: Trying to get them actually work and stay on the (cup), but they're like kept on falling.

Another topic of the talk concerned the difficulties of safely sending cars over the bridges. Even the teacher found herself initiating sequences that emphasized the pragmatic issues and the final causes rather than at the curriculum outcomes that she had aimed at initially.

> Teacher: What are some safety features you wanted to do? Did you ever find your car drove off the side of bridge?
> Children: Yea
> Jason: Yea, sometimes that happens.
> Teacher: what is something that you can add that you might see a real bridge would be a safety feature? Alexia? Guard . . . ?
> Alexia: Rail.
> Teacher: Railing on the side so you can have part on the side of it. . . When the car started off the drive, then push it back to the center.

The talk concerned toy cars that had been falling off the bridges and the means that could make the bridges safe by using wires, bolts, and nuts. The goal of design and engineering was focused on the safety of the bridge in the real situation of cars crossing it. In one contribution, the teacher talked about a cantilever bridge in Quebec that had collapsed and caused many fatalities.

There was a discussion of the importance of the responsibilities of engineers to make a structure safe. The goal of a bridge design (the final cause) was expanding from the narrowly defined curriculum outcome to the real lifeworld contexts beyond the immediate bridges to those that populate the out-of-school world. In the latter case, the safety of bridge ranges among the responsibilities of engineers (efficient cause).

Discussion

This episode exhibits two important issues around children's engineering in science classrooms. First, the goals of engineering activity seem to be perceived differently by the teacher and the children. The teacher's goal of design in this study was to develop children's scientific knowing-*that* pertaining to cantilever structures (balance, weight, the concept of lever). But the children's goal was towards making things work. It was clear that the teacher expected children to use their previous knowledge to build a cantilever bridge; but children became more interested in building bridges according to their own emerging designs. The teacher implemented the design activity as application of science knowledge but children's design was on and from instrumentality of technology, that is, how to make things respond to the surroundings.

The episode also shows how the classroom talk expanded the goal of design activity toward lifeworld contexts and responsible engineering actions. The classroom talk highlighted the responsibilities and consequences of a thing, like the cantilever bridge, into final cause of technology. The real life context of designing provided children opportunities to reflect how engineers' knowledge, decision making and actions could affect the safety of technology and others' lives in the community.

The Efficient Cause

Introduction

The fourth cause refers to the means or agency that produces the form. In school science and engineering activities, children, engaged in designing/making, are the agents. Agency is often approached by considering how children apply existing scientific knowing-that in the design process. However, as per the position Marx and Engels (1978) described above, there is learning that occurs not in the direction of the object-orientation of design but orthogonal to it (Ingold 2013). Participation, as Lave (1993) notes, is itself a form of learning.

Empirical Evidence

In this study, children's courses of action were influenced by the configuration and conditions of materials and the interactions with other subjects in the classrooms. As children reviewed and built a cantilever structure in the previous lessons, it was expected that they would use their knowing-that and knowing-how of the cantilever principle to build a cantilever bridge. The materials and demonstration were provided to children to help them learn from applying particular forms of knowing-that into their designs. However, the anticipated goals of materials and demonstration were influenced by and transformed into new interests, new directions, and new designs. The process of design was not a linear process, but, as an earlier study theorized (Roth 2001b), is better understood as an unfolding distributed process in which new, unforeseen and unforeseeable possibilities emerge.

In the observed curriculum, there were instances when knowing-that manifested itself, such as when Kevin indicated that there was no weight in his design; knowing-how was exhibited when he showed where to put the weight. Also, Jason made a model the stretched arms from the anchors by using tapes to hold torque and his bridge shows good understandings of cantilever arm and anchor point (Fig. 3d). Daniel in his team design used masking tapes to attach the cardboard on the book and explained, "And this one, what we did was we put a lot of tape, and the tapes on the books represent the heavy weight, the weight, holding it down." These examples show that children understood that cantilever bridge involves weight on anchor point to hold the weight of cantilever arm and how weight and balance could be related in cantilever structure.

Yet, as apparent in the section on the material cause, human agency did not entirely account for the nature of the designs that emerged—consistent with theoretical approaches that recognize agency of the natural world (e.g., Callon 1991). In actor networks, human and non-human forms of agency come together (e.g., Latour 1988). One example of this is seen in Fig. 2, where the design represents a translation of the cantilever structure that had appeared in the whole-class discussion (e.g., Fig. 2a) to the midpoint of his design process (saying, “And there is no weight!”) and later the books became part of the design. Through this process, the non-human agency of papers, play-dough, or books made human agency of constructing a cantilever structure unnecessary because the books made the structure stand by itself without extra weight on the anchor. In this episode, designing is better understood as a distributed process, involving human and non-human agency. Another example is apparent in the transformation of design solutions and design interests that arose out of and emerged from the design process—despite of, and not requiring, intentions. In this case, their design completed the task of a bridge that allowed the toy car to safely cross it. Because the new materials solved a previously identified problem, the design process immediately turned to the testing phase.

Discussion

The efficient cause is concerned with agency. In our study, the design process and design product cannot be understood from the perspective of human agency alone. Instead, there are agential aspects that arise from the material world, including from materials and material tools. This is consistent with one study of cognition in an engineering curriculum to take a look at events through the perspective of a tool, a glue gun, and how it influenced design processes and products (Roth 1996b). In the way engineers take into consideration the availability of materials, costs and expense, and social values of given task, children’s interests were changing in response to the situation at hand.

In the traditional take on technology, the efficient cause—the means or agency that produces the form—has been attributed to human agency (Ingold 2013); its attributes, goals, knowledge, and skills, are thought to enframe and being enframed in the technological products. However, the episodes of children's technological design clearly show that technology is emerging from the inevitable relation between human and non-human agency, which suggests that researchers need to take a different approach to understanding the efficient cause of technology. As has been pointed out in other studies (e.g. Roth 1996b), agency of technology needs to be understood as contributing to the emergent nature of situated cognition, which always adapts to the unforeseen contingencies that arise from the mix of human and non-human agency.

Rethinking Technology and Engineering education in Schools

The analysis of the episodes suggests meaningful ways of understanding technological and engineering knowledge and skills in elementary classrooms. Thus, children's designing and building process can be understood in terms of the four intertwined causes of technology. Children, as the agent of technology, could be seen as the primary cause of the action to influence and determine the goal of design, material choice, and forms of design. However, they are interlocked with, and also determined by, other agencies and causes. Thus, we observed how all four causes were working together to bring out a thing into presence (Waddington 2005). The complexity of the four causes expands children's technology learning beyond the application of scientific knowledge. Based on the findings, this section examines the visions and practice of technology and engineering education in school science classrooms.

The process of children's designing and building a bridge exhibited a certain degree of dis/connection of scientific knowing-that. Some parts of their design and explanation evidence scientific knowing-that applied in the design process. For instance, the teacher and children reviewed and demonstrated together how cantilever structure could be designed with the materials provided and accordingly, children's initial design resembled what they reviewed with the teacher. Children also explained the role of masking tape to anchor and balance the cantilever arms. When children were challenged to send a car across, the concepts of cantilever were not distinctively important or present in their discussion and action but the concerns of safety and stability of the bridge. They used the two cups as supporting beams to enhance stability, which was not a cantilever structure. Children focused more on the functional purpose of a bridge rather than on exhibiting scientific knowledge in their design. Thus, the focus of children's designing moved from how to build a cantilever bridge to how to build a bridge that affords the crossing of a toy car, that is, functional and structural purpose of bridge.

Our case study exemplifies that nature of technology lies in the complexity and interconnectedness of four causes, questioning the needs, forms, functions, and consequences of technological products, not conceptual explanations of the products (Dohn 2013). Children's designing process also requires and develops the knowing-how of materials, needs, situations, functions, and outcomes. In classroom practice, the tension between technological design as applying science and as working with instrumentality is seen in children's actual design and teacher's curriculum expectation. The goal of applying science as stated in the intended curriculum was not the priority enacted in the designing process. For the teacher, the bridge-building task was a vehicle for enhancing children's knowing-that and knowing-how; but for the children, the final cause was to build a steady and safe bridge to send a car. Through the dynamic relationships among the four causes, the understanding and presentation of cantilever bridge became less evident in their design and children's creative, authentic ways of problem solving were developed. Whereas children's activities were developing around the instrumentality of technological problem solving, the teacher's intention on developing science concepts got debilitated. For the instrumentality of bridge, the final cause was the safety and efficiency of structure for transportation. The changes and transformation of formal and final causes might not be considered as successful in terms of application of knowing-that. The gap between curriculum intention and children's actual design is summarized in Fig. 5.

«««««« Insert Fig. 5 about here »»»»»»

The instrumentality, creativity, and diversity of designing process in realistic contexts bring out nonlinear outcomes and deviation of curriculum goals and intention where children respond and adopt complex and adaptive procedures to the authenticity of problems (Carr et al. 2012; Murphy and McCormick 1997). The authenticity of real world problem solving contexts inherently brings forth interpretive flexibility and creativity (Resnick and Rosenbaum 2013; Roth 1995). Children's decisions and actions are influenced and bounded by constraints and conveniences of causes and functions of design to solve given problems and the outcomes are often nonlinear and messy (Lewis 2006). In this process, the goal of applying scientific knowing-that may not be the main concern for students. The challenge then is to assist teachers in creating problem-solving tasks that provide authentic and necessary contexts for knowledge application and in assisting students to recognize the necessity of knowledge in design for intended science curricula. Without the necessary context of certain design aspects, children's decisions and actions may be easily influenced by the convenience and configuration of materials and social interactions. In this study, it was convenient for children to build another type of bridge. If there had been given a challenge with a certain width of a river or bridge, creating a cantilever structure might have been necessary for children—as seen when Soviet psychologists changed a design task from simply building aircraft to building aircraft that successfully flew a determined distance (Leont'ev 1983). Without the necessary societal motive of activity, it was convenient to ignore the scientific knowing-that and focus on the functional goals of the bridge. We therefore conclude that it is critical to examine classroom tasks in relation to the efficiency of materials, contexts of problems, and the level of students' procedural knowledge if teachers intend to enhance scientific knowledge through technological problem solving.

We also acknowledge that the practice of science-centered technology and engineering education often misses something critical in children's learning such as creativity and adaptability to solve problems and create new possibilities. The emergence, nonlinearity and innovation of interpretive flexibility and creativity around four causes are hard to be dealt with in traditional approaches to teaching and learning science. Because technological design and engineering tasks could create disconnections between stated learning outcomes and the enacted curriculum, science teachers tend to feel uneasy with the constraints of science standards and assessment (Brophy et al. 2008; Murphy and McCormick 1995). Another challenge in implementing technology and engineering curriculum in schools is the lack of effective assessment programs that evaluate the diverse dimensions of children's learning. Recent practices of assessment in technology and engineering education mostly focus on retrieving factual knowledge or applying procedures that often rely on scientific knowledge on standardized tests (Brophy et al. 2008). These authors also emphasize that the existing standards of science and technology do not include enough engineering contexts and engineering problem types and methods to develop students' understandings of what engineering is and what engineers do. Without the emphasis of engineering contexts, problems, and methods in curriculum standards and assessment, teachers might aim to teach science through engineering tasks as seen in the traditional approach of technology education. This tendency could prevail because engineering standards and practice are most found in science standards in current U.S. curricula (Carr et al. 2012) and this tendency is not much different in other places. This means, unless children participate in special programs of technological design and engineering, they learn technology and engineering only through science classrooms, which was the case in this study.

As observed and discussed above, technology education not only provides children with opportunities to apply and learn scientific knowledge but also brings opportunities to understand and improvise unique practices in situated contexts. Understanding the complexity of children's designing by means of the four causes could allows us to overcome the limited views and practice of technology education in school science. Thus, effective engineering education could be able "to break down the ideology, inculcated by scientific education, that design is essentially an applied science in which application of the scientific method will allow a *best* solution to emerge" (Welch, 2007, p. 87, original emphasis). This means that the idea of science as the primary discipline and technology as a secondary and subservient discipline needs to revisited and reexamined.

In this study, we make the modest proposal to rethink the nature of technology in elementary science classrooms. To rethink and develop a new approach of technology education would need to be supported by the reformation of curriculum standards with assessment plans and teacher's pedagogical knowledge around the nature of technology. Further research needs to be done on the purpose of teaching technology and engineering in science classrooms, especially in the current STEM initiatives and practices in schools.

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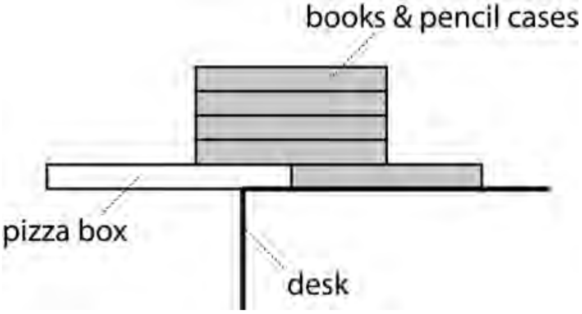

Fig. 1 An example of children's design of cantilever building in the previous class

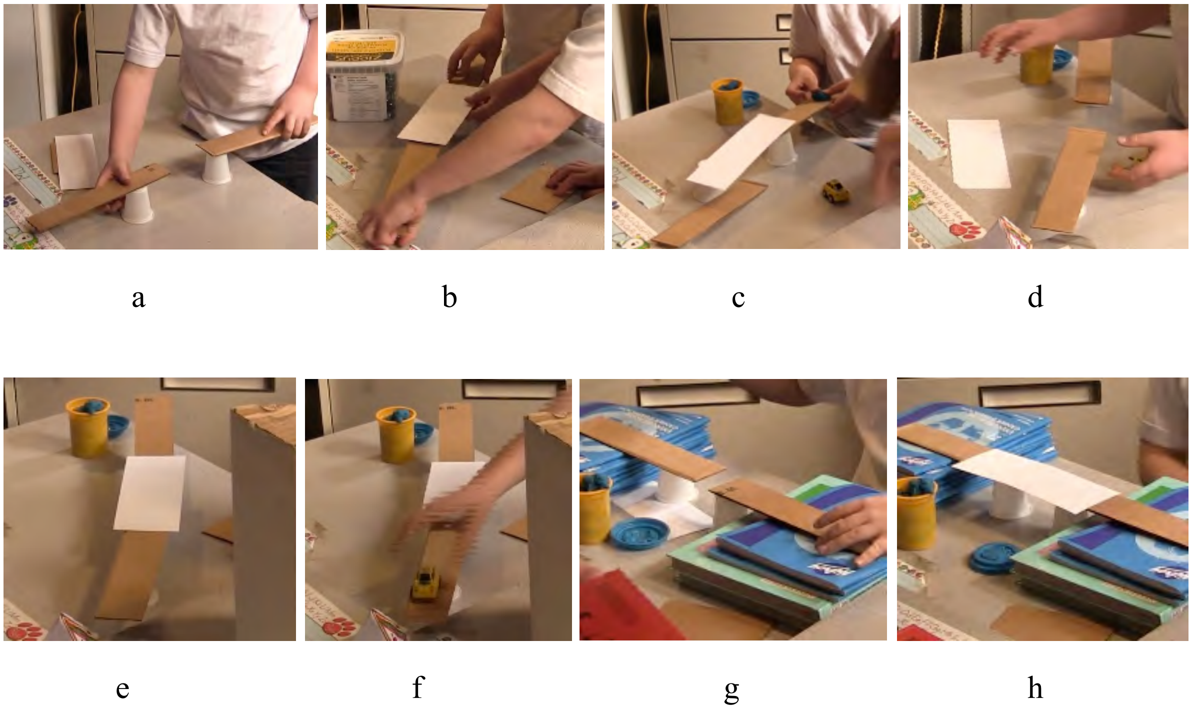

Fig. 2 Kevin and Jack’s design of cantilever bridge

a b c d

Fig. 3 Children’s different designs

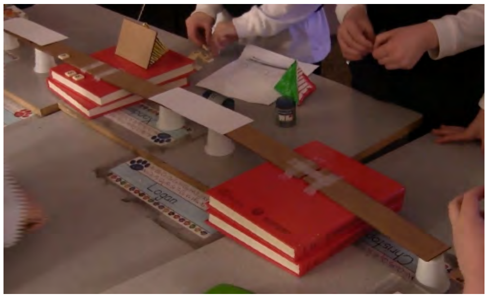

Fig. 4 Building a long bridge

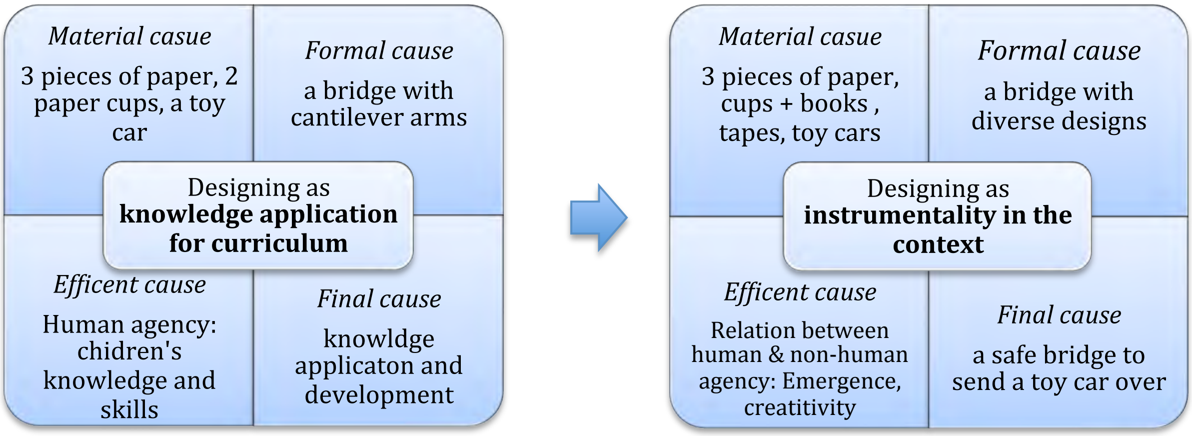

Fig. 5 the Gap between Curriculum Goal and Children’s Design