Maker Education: Where Is the Knowledge Construction?

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> Context • The construction of a product is fundamental. However, students' having produced something is not enough to ensure that they have constructed knowledge. **> Problem** • The objective of this article is to understand how maker education can contribute to the process of students' knowledge construction. **> Method** • Initially we discuss aspects related to the theory of constructionism, subsequently, using Piaget's notions of conceptualization, we discuss how knowledge can be constructed in a makerspace, then turn to a case study that illustrates our theoretical commentary, and end with conclusions about our main research question: "Where is the knowledge construction in making?" **> Results** • We show that in makerspaces students can develop sophisticated artifacts by using digital technologies, and that besides the product, this process allows for the representation of the actions with these machines, expressed as concepts and strategies used. **> Implications** • The action representation constitutes the "window into the mind" of the learner, allowing one to understand and identify the knowledge used and, with that, help the learner reach a new stage in knowledge construction. However, in order to know whether the student has constructed knowledge, the teacher can use different strategies, such as Piaget's clinical method, analysis of results gathered throughout product testing, and use of simulation software related to concepts involved in the maker activity. **> Constructivist content** • The discussion in this article is based on Papert's constructionist ideas. However, we use Piaget's distinction between success and understanding to discuss how knowledge can be constructed by students in makerspaces. **> Key words** • **Makerspaces, fabrication technologies, constructionism, knowledge evaluation.**

Introduction

« 1 » Makerspaces are being introduced in K-12 education as an alternative to traditional approaches so that students can learn about STEM subjects in project-based fashion, have agency over their school experience, and engage in activities around new topics and technologies. In makerspaces, students learn how to produce artifacts by using traditional objects and materials combined with digital fabrication technologies, which are increasingly present in the contemporary world (Blikstein 2013; Halverson & Kimberly 2014.) These activities are directly or indirectly based on the constructionist approach to learning proposed by Seymour Papert (1986) and are being inserted in education so that learners can develop objects of interest to them and, with this, explore and build knowledge in several domains.

« 2 » Seymour Papert and collaborators developed, in the late 1960s, the Logo programming language, with similar goals: it allowed children to "teach" the computer, an activity that, according to these researchers, would be much more efficient than "passive" strategies used in the traditional classroom. Papert called the approach through which the learner constructs knowledge when she produces an object of interest to her, such as a work of art, a report, or a computer program, *constructionist* (Papert 1986). Papert emphasized the importance of learning through "hands on" and "heads in": the learner is involved in building something of interest to her, and in doing so, is faced with unexpected problems for which there is no pre-established explanation. This belief in the development of an increasingly complex and multidisciplinary problem-solving capacity in students brings Papert's constructionism ideas closer to the current maker movement.

« 3 » A central aspect of a makerspace or digital fabrication lab is the construction of objects using different materials such as scrap, wood, cardboard, electromechanical and electronic components, which can be combined with computer programming activities and the use of fabrication tools such as laser cutters and 3D printers. The emphasis is on promoting engagement and a strong sense of experimentation with media and the materials, while constructing knowledge, collaborating, and building a learning community. Making involves trying to solve a specific problem, creating a physical or digital artifact, and sharing that product with the public. The interaction between participants and the process of knowledge-sharing is often mediated by social media, as well as online repositories of objects, tools, and "how-to" manuals.

« 4 » Despite issues regarding equity of participation and culture mismatch (Blikstein & Worsley 2016), makerspaces have great potential to contribute to progressive education and to create multiple paths for students to learn topics that are more relevant to them. Researchers have been suggesting that making, associated with learning methodologies such as constructionism, can create conditions for students to be creative and critical, as well as able to solve problems and to work in groups (Martinez & Stager 2013; Halverson & Kimberly 2014; Kurti, Kurti & Flemming 2014).

« 5 » In many maker labs, the focus is on building a product, and learning how to operate different machines and devices. However, when something is produced, multiple ideas and concepts that the learner already has are put into action. This knowledge goes beyond technical skills and may involve disciplinary content or can be constructed as learners interact with their objects and machines. However, through trial and error, a product can be successfully constructed without the learner necessarily being able to understand all the concepts involved in the process.

« 6 » Jean Piaget studied the development of certain concepts, which are constructed as the result of the interactions between the learner and everyday objects or people; a process that Papert called "Piagetian learning" or "learning without being taught" (Papert 1980: 7). Other researchers, such as Lev Vygotsky, understood that the construction of scientific concepts does not result from the simple interaction between the learner and objects, nor is it a natural result of the development of "hands-on" activities. The learners' construction of knowledge goes to a certain point, and from then on, no matter how much effort the learner makes, the content cannot be assimilated. The learner needs the help of a more experienced colleague or a specialist, who will assist in the construction of these new concepts (Vygotsky 1986).

« 7 » This article aims to understand educational makerspaces and how these contribute to learning; to discuss the theories underlying knowledge-building processes, especially regarding hands-on activities; to understand how knowledge can be represented, conceptualized and evaluated in makerspaces; and to reflect on the knowledge construction process that takes place in makerspaces. In other words, our main goal is to investigate the tension between making and learning, which is currently being taken for granted by many schools and programs. Our starting point, in agreement with theoreticians such as Piaget, assumes that experiences "out in the world" always impact learners, but also takes a Vygotskian perspective in considering (as Papert did) that not all making experiences are created equal, and that both mediation and social conditions can deeply impact the nature of the outcome of the activity.

« 8 » Thus, we begin the article by reviewing the literature on maker education, and examining the cognitive and pedagogical theories that preceded or inspired it, reconsidering connections between making, facilitation, mediation, and learning. We then turn to a case study that illustrates our theoretical commentary, and end with conclusions about our main research question: "What is the learning in making?"

Makerspaces and education

« 9 » From the point of view of technological diffusion, the idea of "making" has its roots much earlier than commonly believed. For example, some of the same ideas were already present in the Mechanics' Institutes, created in Edinburgh, Scotland, during the beginning of the 19th century, for the provision of technical education for craftsmen, professionals, and workers in general. These institutes have revolutionized access to science and technology education (Holman 2015). With the dissemination of digital technologies, the 1980s and 1990s saw the creation of the hacker movement and hackerspaces, in several cities across the United States and Europe. These were places where technology enthusiasts could work together to invent devices, reuse and exploit new technologies such as low-cost microcontrollers, and were inspired by the open software community (Blikstein 2018). In this context, the term "hacker" does not refer to the transgression of rules, but rather describes the use of existing everyday objects to understand a phenomenon, or for the production of new objects or systems. A classic example is the disassembly of electronic devices and the reuse of their parts for the creation of new appliances.

« 10 » From the educational point of view, the interest in a student-centered or learning-by-doing-based education is not new either. One of the first educators to use this pedagogical approach was Dewey, during the beginning of the last century. This author criticized expository teaching as being old-fashioned and ineffective, and proposed the implementation of hands-on learning situations (Dewey 1916). Other educators and thinkers such as Célestin Freinet (1998), Maria Montessori (1965), and Paulo Freire (2008) have devoted special attention to the relationship between mind and artifact-production as part of the educational process. More recently, during the first decade of this century, new educational, social, economic, and technological trends have contributed to the growth of these movements into formal and non-formal educational environments, such as schools, museums, and makerspaces in communities.

« 11 » The interest in the creation, dissemination, and popularization of makerspaces can be attributed to five trends (Blikstein 2018):

- the greater social acceptance of ideas and principles of progressive education;
- countries' interest in establishing a basis for an innovative economy;
- the growth of public awareness, in addition to the popularity of computer programming combined with the creation and production of artifacts;
- the sharp reduction in the cost of digital information and communication technologies (DICT), as well as digital fabrication technologies (DFT); and
- the development of tools that are more powerful and easier for students to use, along with studies and publications in academic research focused on the effect and impact of these new technologies on learning.

« 12 » Since 2005, makerspaces have gained great popularity as a result of the emergence of the broader "maker movement" (Anderson 2012), the publication of Make Magazine, and the first Maker Faire in 2006 (Dougherty 2013). In addition, these spaces received a great deal of attention from educators and researchers after the former US President, Barack Obama, launched an initiative to promote learning environments that "encourage young people to create and build and invent – to be makers of things, not just consumers of things."[1]

« 13 » Papert's constructionist ideas are the rationale behind the dissemination of making in schools, since, in these spaces, learners can learn from hands-on and "heads-in" experiences. Several researchers and research groups focused on this area of

1| https://www.energy.gov/articles/remarks-president-national-academy-sciences-annual-meeting

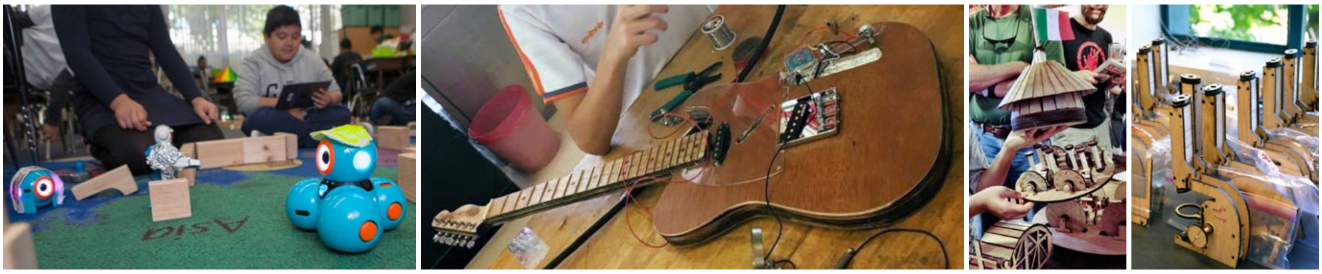

Figure 1 • Examples of students' projects (from left to right):
A robot-enacted theater play, a custom-made guitar, a da Vinci machine, and a microscope.

study have emphasized that students use different concepts throughout the activities developed in these spaces (Martinez & Stager 2013; Halverson & Kimberly 2014; Kurti, Kurti & Flemming 2014).

« 14 » However, before using constructionism as a conceptual basis for the creation of the maker activities, it is relevant to understand the context in which this concept was developed in the mid-1980s. First, researchers believed it was important to introduce an alternative to the uses of computers in education, which at the time were still totally focused on the idea of transmitting information through tutorials, or exercise and practice programs, which Papert called "instructionism" (Papert 1991: 8). Second, for Papert, constructionism builds on constructivist theories: "this happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it's a sandcastle on the beach or a theory of the universe" (ibid: 1). The emphasis was, therefore, on the idea that learning is not only the result of the learner's interaction with objects and people around her, as proposed by Piaget's constructivism, but the result of the learner's engagement in the construction of something of interest to her, which can be done with or without the use of computers. Papert makes it clear that "computers figure prominently only because they provide an especially wide range of excellent contexts for constructionist learning" (ibid: 8). Perhaps when these ideas were proposed it was not as important to emphasize the presence of computers, since they were not yet widely disseminated, and learning was not centered on the "connections between computers and real-world artifacts" (Donaldson 2014). Third, constructionism as a theory required further elaboration. Although the concept is "much richer and more multifaceted, and very much deeper in its implications" (Papert 1991: 1), Papert even went so far as to comment on the irony that

> "it would be particularly oxymoronic to convey the idea of constructionism through a definition since, after all, constructionism boils down to demanding that everything is understood by being constructed." (ibid: 2)

« 15 » The presence of digital technologies as part of constructionism was further elaborated by Edith Ackermann, as she differentiated constructivism from constructionism considering three dimensions:

- The role that external aids play at higher levels of a person's development;
- The types of external aids, or media, studied (Papert focuses on digital media and computer-based technologies); and more importantly
- The type of initiative the learner takes in the design of her own "objects to think with" (Ackermann 2001).

« 16 » Besides the points made by Ackermann we argue that digital technologies become important when they go beyond aiding in the production of a product. They can help to make explicit the actions that one must carry out during the process of developing an object. The ability to explain one's actions to a machine is very different from what takes place during the production of something using traditional objects. It is one thing to be able to produce a sand castle or a vase from a clay slab. Another thing is to provide information so that a robot can produce the same sand castle or vase. In the case of the robot, in addition to the product, one must be able to represent the actions the robot must take so that the product can be produced. These actions are described as concepts and strategies created by the learner using commands that the robot understands. This collection of commands constitutes the action representation, which can be studied and analyzed in terms of the concepts and strategies used and can be improved or debugged for production efficiency. This representation can be seen as a "window into the mind" of the learner, in the sense that it allows one to understand and to identify the common-sense knowledge that was used during the production process and, with that, an educator can help the learner reach a new level of scientifically based knowledge that is a product of a growing learning spiral (Valente 2005).

« 17 » Thus, considering the importance of the digital technologies for the knowledge representation process to create an educational makerspace, it is important to consider, in addition to traditional objects of construction, digital information and communication technologies such as computers and digital cameras, as well as fabrication technologies such as 3D printers, laser cutters and computerized numerical control milling machines. These technologies should not only be part of the makerspace, because they are innovative and part of advanced production processes, but also because of the role they play in making explicit the concepts and strategies learners use to develop the artifacts they produce. For these technologies to function they need to be programmed using concepts from STEM subjects, such as scale, distance, geometry, and programming. Furthermore, the learner must develop different strategies to apply these concepts in the "program." Lastly, as noted by Erin Riley (2015), technologies add precision, scalability, and reproducibility to the students' work, as shown in Figure 1.

« 18 » Riley (2015) showed that the tasks that can be performed in makerspaces, particularly using digital technologies, give learners the possibility of working with concepts from several knowledge areas, such as subjects in standard curricula. While analyzing students' use of fabrication technologies, it was possible to identify that students had the opportunity to develop mathematical concepts such as Cartesian coordinates for the transposition of 2D shapes into 3D figures and vice versa, geometric shapes, units of measure, scale, Boolean operations, etc. The production of artifacts using a combination of traditional materials and digital technologies makes it possible for learners to use concepts from other areas such as science, engineering, and technology.

« 19 » In addition to these concepts, several authors mention that makerspaces promote personal and social development. For example, Edward Clapp et al. (2017) identified the development of agency (a more proactive orientation towards the world) and character building in makerspaces. The learner can take risks, cope with failures to achieve success, and develop a mindset that includes creativity, curiosity, mental openness, persistence, social responsibility, and teamwork.

« 20 » However, the lack of a deeper understanding of constructionism, of the role digital technologies play in these environments, and of a more precise definition of what constitutes an educational makerspace, contribute to several misunderstandings. First, makerspaces set up in schools are quite heterogeneous, varying in terms of size, capacity, and cost. Some schools have understood that simply having a room with tables, traditional materials, and glue guns is enough, while other schools offer spaces with the most sophisticated digital fabrication technologies (Blikstein 2018). It is crucial to understand the role that technologies play in these spaces and to seek a balance between traditional materials and digital technologies.

« 21 » Second, educational makerspaces in schools should be understood as spaces for knowledge production. In this sense, it is important that they are not seen as environments for the development of isolated activities, but activities that are integrated with curricular disciplines. It is not enough to create makerspaces in which learners can be creative and have agency, while curricular subjects are still introduced in a traditional way. Third, for the learner to construct knowledge in the makerspaces, it is important that a series of issues be observed. The elaboration of a product is fundamental, as Papert emphasized. However, the production process and the analysis of representations, which provide the opportunity for one to understand the concepts and strategies used by the leaner, are also important. Thus, the learner's having produced something is not enough to ensure that she has constructed knowledge. The teacher's role is fundamental to mediate processes and product development, to create opportunities for reflection, and to develop the learner's awareness of the concepts and strategies that are used, as observed by Piaget and Vygotsky.

Knowledge construction and hands-on activities

« 22 » In this topic we discuss the cognitive and pedagogical theories that connect making, knowledge construction, and the role of mediation. In terms of knowledge that an individual can construct, Piaget identified three types: physical knowledge (constructed through the direct action of the individual with the object), logical-mathematical knowledge (fruit of a reflection regarding the information collected at a practical level, generating the conceptualization), and social-arbitrary knowledge (constructed through the interaction with other people in society, Matui 1995). However, it is the development of logical-mathematical concepts that has received the most attention from teachers, since these concepts depend on the ability for abstraction and their development must be aided by educators.

« 23 » Vygotsky makes a similar distinction regarding the construction of different types of concepts. He distinguishes spontaneous concepts from scientific ones. The first are developed based on the individual's experience in the world in which she lives, and with the world organization imposed by society, whereas scientific concepts are developed from spontaneous experiences, but fundamentally depend on social interaction and on the presence of more experienced people or the school environment (Vygotsky 1986).

« 24 » Differently from Piaget, Vygotsky was concerned with the study of how to provide the means for the construction of knowledge. He makes an important distinction between development and learning. "Actual developmental level" (Vygotsky 1978: 85) can be understood as all the knowledge the learner has already constructed. Potential developmental level is what the learner can achieve during the teaching and learning process – understood here to be the literal translation of the Russian term *obuchenie*, which involves the learner, the person who teaches, and the relationship between these pairs that are subjects of the educational process (Matui 1995). Therefore, learning is what allows for the transition from actual developmental level to the level of potential development. Between these two levels is the area or zone of proximal development where teaching must take place, since "the only good teaching is what advances to development" (Matui 1995: 121, our translation).

« 25 » Papert adds to Piaget and Vygotsky's ideas the importance of enriching learning environments by incorporating digital technologies, so that subjects can act and construct concepts and ideas that permeate these environments (Papert 1980). The use of these technologies requires logical-mathematical concepts and the interaction with these concepts becomes a way to stimulate "Piagetian learning." However, constructing knowledge about these concepts does not happen without the help of more experienced people, mediating the knowledge construction process as emphasized by Vygotsky (1986).

« 26 » From this brief analysis of the ideas proposed by notable socio-interactionist authors, one can see that the development of spontaneous concepts, or even some kind of logical-mathematical or social-arbitrary knowledge, can be achieved through "Piagetian learning." For learners to be able to develop scientific or logical-mathematical concepts, however, mediation is necessary. One cannot assume that simply providing information or completing a task is sufficient for constructing knowledge. This mediation needs to be done by more experienced people who understand the process of how to promote learning and the content being studied – in other words, there is a need for educators.

« 27 » Considering the activities that can take place in a makerspace, how can we understand that the learners' production process helped them to construct knowledge? In general, the evaluation of teaching and learning processes is still based on the idea that the student has learned a concept if she is able to successfully apply it or is able to talk about the acquired information. However, if the learner succeeds at performing a task, this does not necessarily mean that she understands what was done. Piaget noted that there is a difference between doing something successfully and understanding what was done.

« 28 » In 1974, Piaget published two books: *La Prise de Conscience* – translated into English as *Grasp of Consciousness: Action and Concept in the Young Child* (Piaget 1976) and *Réussir et Comprendre* – translated into English as *Success and Understanding* (Piaget 1978). These described the process by which children and adolescents develop what he called "conceptualized understanding" of the concepts involved in a series of tasks, which Piaget asked the subjects of his research to perform.

« 29 » In these studies, Piaget noted that children can use complex actions to achieve premature success, which represents all the characteristics of *savoir faire*. The child can perform a certain task but not understand how it was performed, nor be mindful of the concepts involved in the task. Piaget also noted that the passage from this practical form of knowledge to understanding is done through the grasp of consciousness, which is not a kind of insight, but a level of conceptualization. This level of thinking is achieved thanks to a process of transforming schemes of action into notions and operations. Thus, through the coordination of more complex concepts, the child can move from the level of premature success to a level of conceptual understanding, which takes place in three phases. In the first, the child neglects all the elements involved in the task; in the second, she coordinates some elements, and in the third, she coordinates all the elements involved in the task.

« 30 » Besides this succession of phases, Piaget first observed that it is not the object that leads the child to the comprehension phase. Being able to understand how to topple a sequence of dominoes does not necessarily mean understanding how to make a castle with playing cards. For each situation, the child must transform the action schemas into notions and operations that are involved in a given task. Piaget also noted that understanding is the fruit of the quality of the interaction between the child and the object. If she has a chance to play with objects, to reflect on the results obtained, and to be challenged by new situations, the greater the chance is that the child will be attentive to the concepts involved, and, thus, reach the level of conceptualized understanding.

« 31 » In the case of working with digital or fabrication technologies in the makerspaces, learners can explore, create, and reflect in a very stimulating and innovative environment. However, from the educational point of view, it is impractical to think that they will be able to construct knowledge individually, without being aided by others. First, it would be too costly to construct learning environments involving concepts from all the existing domains so that an individual could act in this environment and construct her knowledge in isolation. Second, as an educational solution this model is not practical, because the time needed to train people with the knowledge already accumulated by humanity would be enormous. In this sense, the idea of knowledge construction can be improved if we have teachers prepared to help students (Piaget 1998) or, as Vygotsky proposes, through mediation by more experienced people who can help formalize concepts that are historically agreed upon (Vygotsky 1986). Without the presence of an educator it would be necessary for the learner to recreate these conventions. However, once the learner has constructed a product in the makerspace, the question is how to evaluate the knowledge she has used in this production. How can the teacher know that the learner has understood and constructed the concepts used in the production of her artifact?

Case study: Evaluation of the construction of knowledge during the maker activity

« 32 » This topic presents a case study based on students' production in makerspaces, describing the data collection process, data analysis and findings. The objective is to illustrate the theoretical approach discussed before and to show how to create conditions in the makerspaces so we can evaluate students' knowledge construction process.

Data collection

« 33 » Students in a public school in California, USA were challenged to create catapults using different resources in the makerspace. In addition to constructing these catapults, the students had to test their productions, verifying how far the catapults could launch a plastic ball. Figure 2 illustrates a few of the catapults students created.

« 34 » In Figure 2, catapult A consists of a spoon attached to a support with rubber bands that create tension, a structure assembled between two wooden supports cut by a laser cutter. Catapult B consists of a pipe attached to two wooden supports that were cut using a laser cutter. At the bottom end of the pipe the student placed a plug connected to a spring that, when activated, launches a ball that is placed within the pipe. Catapult C was assembled on a wooden platform, using popsicle sticks connected to a spoon and rubber bands. The ball is placed on the spoon which, when activated, launches the ball. Catapult D consists of a structure of pipes, which supports an additional pipe diagonally placed. On the lower end of this pipe, the student attached an elbow. When the ball is placed on the upper end of the diagonal pipe, it travels through the pipe and is launched from the bottom end.

« 35 » One of the authors of this article visited the school on the day the students were finalizing their productions and testing, in the school hallway, the effectiveness of their respective catapults.

Data analysis and findings

« 36 » Observing the products created by the students, one can infer that they used a series of concepts and strategies during

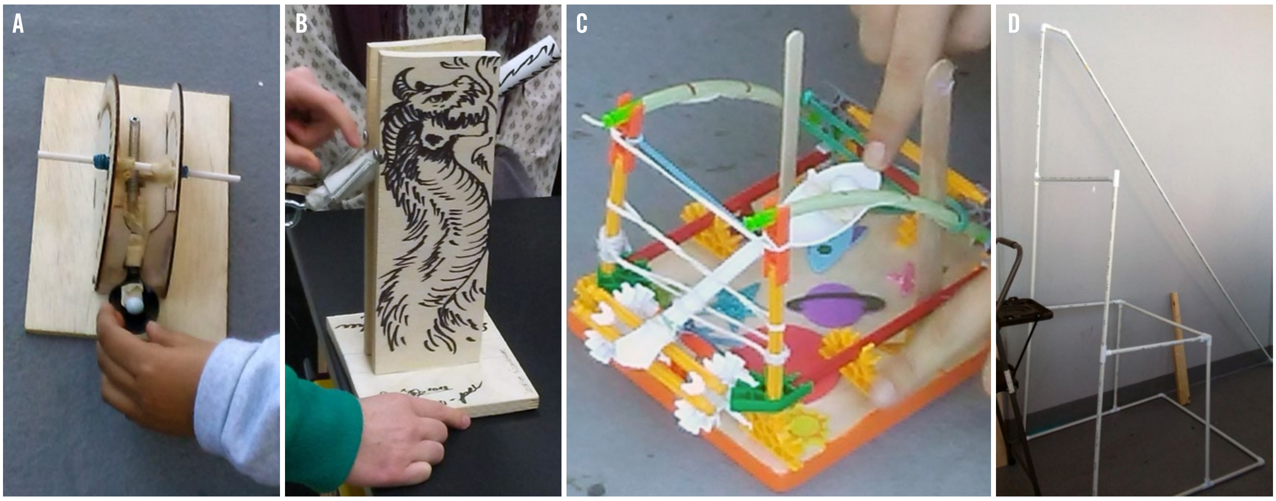

Figure 2 • Examples of catapults using different structures and materials.

the process of constructing the catapults. Analyzing these productions, one can perceive that the distance the ball travels is a function of the relationship between different concepts such as the angle at which the ball is launched, tension on the springs or rubber bands, friction between the ball and the pipe, the ball's initial speed, and the ball's size. In addition, the activity in which students test their catapults can be used to study the ball's curve as it moves in the air, whether the ball's mass interferes in its trajectory and distance reached, etc. Therefore, the question is: are the students conscious of, and can they conceptualize, what they did? Did the process of creating this catapult contribute to the construction of the concepts involved in this activity?

« 37 » In order to answer these questions, it is important to refer back to Piaget's work once again. His conclusions were based on the observation of the results of the activities children and adolescents performed, and by interacting with them, using what Piaget called a "clinical-critical method" (Piaget 1929). This method is based on procedures Piaget used to investigate how children thought, perceived, acted or felt about a given activity they accomplished.

« 38 » The clinical-critical method consists in the systematic intervention by an educator based on the learner's conduct, such as verbal interaction, the manipulation of objects, or an explanation. Thus, the intention is to present the student with a problem situation she must solve – be it a game or an object that is conceptually rich and significant for the student – and observe what she does, seeking to clarify its meaning. Since it is not always possible to understand the learner's behavior, the intervention must aim to clarify the meaning of these actions or the explanations she offers. In order to do so, the educator must formulate a hypothesis about the action's meaning and try to immediately prove it through her interventions (Delval 2002).

« 39 » An important characteristic of Piaget's method, which is generally not described in the studies regarding this theme (Delval 2002; Carraher 1989) or even in Piaget's own work (1929), is the educator's concern with the examination of the problem activity in terms of the concepts involved and their different levels of complexity.[2] The objective of this exercise is to gather information regarding the activity being developed so that the educator can understand the different levels of the student's conceptualization. Based on what is being presented by the learner, the educator can create hypotheses and, therefore, intervene and identify the learner's underlying level of development and her potential level of development, regarding the concept being studied.

« 40 » Piaget developed the clinical-critical method in order to diagnose the level of knowledge of the subjects involved in his study. This method was also used in a study regarding the development of learning situations, one of the few studies by Piaget's group regarding this theme (Inhelder, Sinclair & Bovet 1974). However, the clinical-critical method can also be used in situations of knowledge construction (Ackermann 2003). The educator's questions, and the challenges she poses to her students, if these are within the learner's zone of proximal development, can contribute to the process of elaborating new conceptual relations and of new knowledge being constructed by the learner.

« 41 » Based on Vygotsky's ideas about the development of scientific concepts, and on Piaget's use of the clinical-critical method, one can conclude that the effectiveness of teaching and learning processes, in the sense of helping students construct knowledge, is centered on the interaction between the educator and the learner. During the activities developed within the makerspace, the educator's interaction can take place through the dialogue established with the student regarding the object she created. This conversation must be guided by the educator's knowledge of the concepts involved in the activity, and by the learner's explanations. In the case of the catapults, the teacher

2| Informal conversation with Ackermann, July 2002, in Cambridge MA.

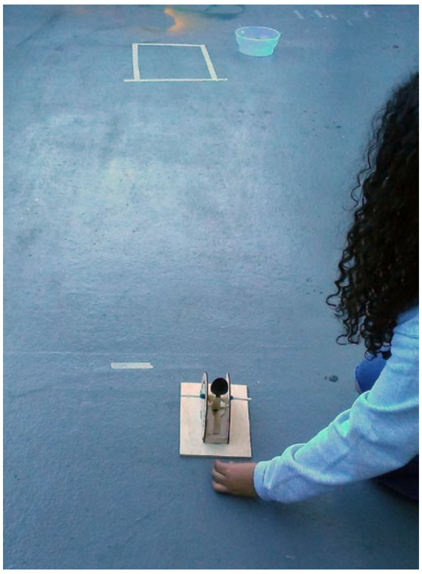

Figure 3 • Student testing her catapult, verifying if the ball lands on the square marked on the floor.

can request that the student explain how the catapult works, how the structure was developed, and whether it is possible to change the distance or angle at which the ball is launched, how the spring's tension interferes in the distance traveled by the ball, etc. In addition to understanding the learner's level of conceptualization, the teacher can help the student understand certain concepts by creating challenges that lead them to seek new information or strategies, and, therefore, not only improve the final product, but increment their level of understanding of what is taking place during the activity.

« 42 » Piaget's and Vygotsky's theories were elaborated in a context that was not permeated by digital objects. Since the student is working in a makerspace, using digital fabrication tools, both the teacher and the student have access to the representation of knowledge used in the production of artifacts, which can be used to substantiate the conversation and interactions between both subjects.

« 43 » Another activity that can be important to create the conditions for the construction of knowledge is to test the developed product. Figure 3 shows a student testing the catapult illustrated in Figure 2A, in the school's hallway. In order to do so, she made a mark on the floor with tape to identify where to place the catapult, and the square where she aimed for the ball to land.

« 44 » However, for the test to be effective and contribute to the process of constructing knowledge, it must be conducted using certain research methods and techniques, for example, making explicit the variables that should be observed and that are related to the concepts being studied; making explicit the procedures to be used during the testing of the product; using the data collected to analyze how they affect the catapult's performance. Based on the analyzed data, the teacher can question the student regarding what she concluded and how the performance of her catapult can be improved, since the student understood the involved concepts.

« 45 » In order to collect data, the student must systematize and record the spring's or rubber band's tension, the angle at which the ball is launched, and the distance traveled by the ball. If possible, it is interesting to photograph or film, using a cell phone, the ball's trajectory, registering its trajectory (there are many apps that can record videos and allow students to "dissect" them frame by frame, and track the speed and location of different objects). Finally, this data must be analyzed, aiming to relate the different variables to the ball's behavior. The objective of this activity is to identify and understand how the different situations experimented influence the trajectory and distance traveled by the ball.

« 46 » Once the results are analyzed, the teacher can pose new challenges, such as altering the size or weight of the ball. How does this alter the catapult's performance? Or the group can consider how air resistance created by wind affects the ball's behavior. Another activity can explore the ball's curve in the air, and try to understand how it can be altered in terms of maximum height and its relationship to the distance traveled by the ball.

« 47 » Certainly, the testing situation presents multiple variations, as a result of the control of different variables. This can hinder conclusions regarding the phenomena, particularly if these variables are related and influence the catapult's performance.

« 48 » In order to make the phenomena "cleaner" and facilitate the understanding of the concepts involved in the launching of projectiles, as in the case of the catapults, it is possible to use simulation software. For example, various themes in science and mathematics can be found through the site PhET,[3] developed by the University of Colorado. Another example is the software NetLogo,[4] which has hundreds of simulations in various scientific fields. In the case of the teaching of physics, in the topic regarding ballistics,[5] the use of simulation software allows for the completion of activities that simulate the catapult's behavior.

« 49 » Figure 4 shows a ballistic simulator, and the different variables that affect this phenomenon and that can be altered, such as the angle between the cannon and the ground, the projectile's weight and diameter, the air's resistance, and the projectile's initial velocity. In addition, the software offers other resources that make it easier to understand the projectile's trajectory, such as the total or decomposed vectors on the horizontal or vertical axis (x and y), for both velocity and acceleration.

« 50 » Once values are set, 5kg for weight, 0.8m for the diameter, no air resistance, 75° angle to the ground, and initial velocity of 18m/s (Figure 4, left), the result of the launch shows that the projectile went beyond the initial target (Figure 4, right). Maintaining the initial values, but only changing the angle to 80°, the projectile hits the target.

« 51 » By altering the variables, one can observe the effects they produce on the projectile's behavior. The student can systematically register, in a table, the value of the given variable and its effects. An analysis of these results can help the student understand how variables affect the projectile's movement and, therefore, she can develop a mathematical representation of the phenomena.[6]

3| http://phet.colorado.edu

4| http://ccl.northwestern.edu/netlogo

5| https://phet.colorado.edu/en/simulation/projectile-motion

6| For examples of side-by-side computer models and physical experiments promoting this kind of sense-making, see the bifocal modeling approach described in Blikstein (2014).

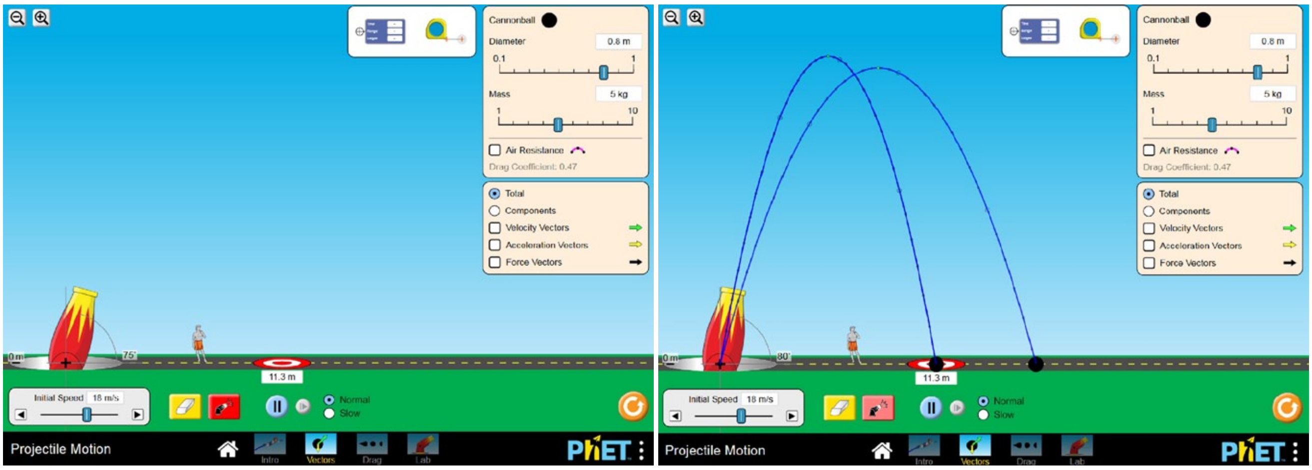

Figure 4 • Left: ballistic simulator, indicating the variables that can be altered at the projectile's launch. Right: launching projectiles for different angles, maintaining all other variables constant.

« 52 » It is only after performing this conceptual exercise regarding how the variables affect the projectile's behavior that the student should come in contact with the mathematical representation that reliably describes the phenomena. Subsequently, she can return to the simulator and "play" with the variables, confirming that they do indeed work according to the proposed formula. In other words, during this activity using the simulator, the process for understanding the phenomena is the exact opposite of what takes place in a pencil-and-paper curriculum. In the simulation case, the mathematical representation is given after the process of experimentation and an understanding of how variables affect the phenomena, and not in the beginning, as part of a definition of the phenomena, as takes place in traditional education.

Discussion: Knowledge construction process in makerspaces

« 53 » Traditional education, based on a "pencil-and-paper" curriculum, follows a relatively standardized sequence of activities, both for the presentation of a theme in a given subject, and the curricula's sequence of classes for different areas of knowledge, as illustrated in Figure 5 (left). When introducing a theme, in general, this takes place by providing a definition of the basic concepts, or the foundation of this theme. Next, teachers provide an interpretation of these concepts, presenting examples of how they are used or can be applied in the resolution of a problem. Based on this interpretation, one hopes that the student will understand and know how to apply these basic concepts. This takes place by asking the student to apply these concepts to the resolution of a series of problem exercises, with the intention of consolidating the conceptualization of this theme. This same sequence characterizes curricula in different areas of knowledge. Initially, the students are exposed to classes, with basic concepts and theories. Gradually, more practical subjects are introduced, and, finally, the student must develop a final project.

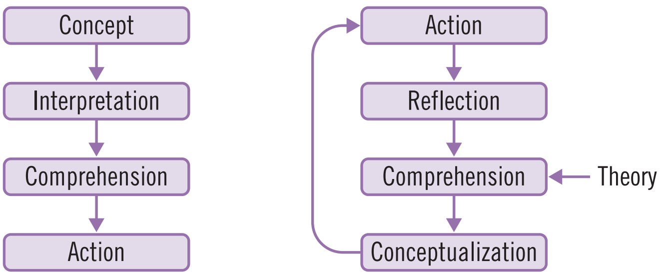

Figure 5 • Left: Traditional education-based pedagogical approach. Right: Makerspace-based inverted pedagogical approach.

« 54 » However, learning outside of this academic context does not follow this sequence. The things we learn in life, for example, to crawl, speak, socially interact, date, kiss, raise children, etc. do not take place by first learning a concept, then its application in practical situations. In these cases, learning first takes place with an action, as illustrated in Figure 5 (right). Based on the obtained results, the learner can reflect on what took place and try to understand what is being done. In order to gain this understanding, in some situations, someone's help is necessary, for this person will provide information for understanding to take place, or the theory behind the theme being studied. Finally, the last action is conceptualized understanding, as proposed by Piaget (1976, 1978). As the learner comprehends and conceptualizes what she is doing, she can revisit her actions so as to perfect them and, therefore, improve her level of reflection, comprehension, and conceptual construction.

« 55 » By observing the sequence of activities illustrated in Figure 5, one can note that they are inverted. The development of makerspaces in schools has the consequence of inverting traditional pedagogy, in which the student is a "receiver" of information transmitted by the teacher. In these spaces, the learner should be active, carry out actions for the development of an artifact, using digital technologies, and therefore creating opportunities in which she can reflect, comprehend, and conceptualize what she is doing.

« 56 » However, as was discussed throughout this article, in general, the activities taking place in makerspaces within schools are becoming restricted to the action of creating an artifact, without there being an incentive for other activities to take place, such as reflection, comprehension, and conceptualization. Thus, there is a need for the teachers acting in these contexts to be conscious of the importance of going beyond this initial building phase, so that they may incentivize their students to carry out these other activities that are fundamental to the process of constructing knowledge.

Conclusion

« 57 » There is a great interest in introducing maker activities in K-12 education, so the students can have more agency, engage in project-based learning, and be generally more active in the learning process, learning to produce artifacts by using traditional and digital materials. This article argues that it is possible to create learning environments that are based on constructionist ideas using activities in which the learner can develop objects of interest to them and, with this, explore and construct knowledge about various curricular concepts, especially those related to STEM.

« 58 » The analysis of constructionist ideas indicates that Papert has emphasized the production of objects as a way for learners to express their ideas. However, as proposed by some researchers, production should take place using digital technologies, which besides generating a product, also allows for the visibility of the actions provided by learners to these machines. These actions or instructions are registered as the concepts and strategies the learner used, which can be analyzed and debugged. These representations constitute a window into the learner's mind allowing teachers or a more experienced person to help the learner construct new knowledge.

« 59 » As the learner is working with digital technologies in the makerspace, this allows the representation of the action she is using or hers knowledge, in addition to the creation of the product. This means that digital technologies play an important role in makerspaces. Furthermore, since the makerspace is created in the school, it is important to integrate activities students develop with other curricular content. It is also important that the production process is used for the students to reflect upon what they have done and the concepts used in the production process, so as to be able to comprehend and conceptualize them. What we observe in these makerspaces is that, in general, the activities are restricted to *product construction*, and the students are not engaged in activities that are important for the *construction of knowledge*.

« 60 » In line with Piaget and Vygotsky's ideas, it is important that makerspaces take into account the need for teachers or more experienced persons to act as mediators, challenging students, creating conditions that promote interaction with objects being produced, and helping students understand the concepts and strategies used. Through these interactions with the students, teachers can help students construct new knowledge, as well as reach a higher level of comprehension about what they are doing.

« 61 » However, for this type of setting to take place in a school it is necessary to change the relationships taking place in the learning environment and to determine new roles to be assumed by the different professionals who work in the school. This means implementing changes in the relationships between people, and the quality of the students' interactions with the objects and activities performed. As observed by Piaget, if the learner can make an artifact or can successfully arrive at an answer, this does not necessarily indicate that knowledge was constructed. *The learners must also be able to conceptualize what was produced, which allows for the transformations of their mental schemas.*

« 62 » To incentivize and prioritize deep understanding, educators should use rich objects, activities, and tasks that provide opportunities for students to explore, creating the conditions for the teacher to challenge the student and, thereby, increase the quality of the interaction with the product. Also, as proposed by Vygotsky, the learner needs to get help from more experienced people. Without this type of support the learner must recreate knowledge and conventions that are already available. However, for teachers to be able to support and help the student in the makerspace, it is necessary that they receive training not only in terms of how to use technologies, but also regarding how to integrate the activities the students are developing with the disciplines in the curriculum. The analysis of literature on makerspaces has shown that this integration has not fully happened yet – we still have a long way to go in the process of creating makerspaces in schools for knowledge construction.

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Open Peer Commentaries

on José Armando Valente and Paulo Blikstein's "Maker Education: Where Is the Knowledge Construction?"

The Roles of Teachers in Makerspace Learning

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> Abstract • Valente and Blikstein raise what I believe is an important criticism of the under-specification of learning in makerspaces and in the maker movement in general. Based on a synthesis of Piaget, Vygotsky and Papert, they suggest that an important part of the answer is to emphasize the role of teachers in the learning process. I fundamentally agree with their propositions, but raise three questions about the resulting challenges to teacher training and professional development.

« 1 » The maker or makerspace movement has received increasing attention over the span of the last decade and a half. As Paulo Blikstein (2018) notes, there are good reasons for this, relating to increased access to better makerspace technologies, a wider acceptance – at the very least, superficially – of progressive learning principles, and a focus at the level of governments on training the workforce of the future.

« 2 » While the maker movement was, at first, not explicitly tied to *learning*, the potential for learning experiences was discovered relatively quickly, and makerspaces with purposeful learning goals were established in community centres and after-school programmes, similarly to how the early Computer Clubhouses ran. Paulo Blikstein founded the FabLab@School initiative in 2009, and put FabLabs inside schools with the explicit focus of supporting educational goals (Blikstein & Krannich 2013). FabLabs have since then spread to schools across the world.

« 3 » The move of FabLab/makerspaces from outside of school to *inside* schools raises new challenges, and creates a wide range of interesting research areas, some of which have received more attention than others. Among those areas that have received the most attention are questions relating to defining what *making literacy* or the *maker mindset* is (Blikstein 2013; Buechley, Peppler, Eisenberg & Yasmin 2013; Chu, Quek, Deuermeyer & Martin 2017), how to design inclusive maker spaces that welcome a diverse group of young learners (Holbert 2016; Vossoughi, Hooper & Escudé 2016), how to design new and fun low-threshold maker technologies (Buechley, Eisenberg, Catchen & Crockett 2008; Buechley et al. 2013; Sentance, Waite, Hodges, MacLeod & Yeomans 2017).

« 4 » However, some much more fundamental questions remain relatively untouched. The first is how do the activities associated with making and makerspaces contribute to learning, and what is even learned? The assumptions across the literature on makerspaces seem to be that learners *will* learn something from having made something, or, at the very least, that their experiences of enjoying working with technology will result in decisions later in their lives to go into STEM-careers. While neither of these assumptions seems unreasonable, they still leave us without a fundamental theoretical framework for understanding learning as it is connected to learning activities.

« 5 » The second question that emerges from the inclusion of makerspaces in formal education in classrooms is what is the role of teachers in facilitating maker- or fabrication-based learning? Unlike makerspace facilitators outside of schools, teachers are highly trained professionals who know their students' personalities and dispositions, general performance-level, and the social dynamics of their classroom. A lack of understanding of their role in maker education is at best wasted potential, and at worst a hurdle to a successful implementation of fabrication-based learning.

« 6 » In their target article, José Armando Valente and Paulo Blikstein take, first, a theoretical approach to answering these questions, and then an empirical approach to support their answers. This is an important and correct step in the right direction if we want to take learning while making seriously.

« 7 » Synthesizing primarily Jean Piaget, Lev Vygotsky, and Seymour Papert, the authors hone in on their principal claim: that students can be engaged in successfully *constructing* artefacts without necessarily having *learned* anything, *and* that learning necessitates the active participation of "more experienced people who understand the process of how to promote learning and the content being studied" (§26). This leads them to ask what I understand as the Big Picture question underpinning the target article: what is the specific contribution of the making process to the learning process, and by which criteria should teachers in makerspaces evaluate whether this learning has taken place or not?

« 8 » In doing so, they claim that educators must be part of this process in order to make sure that learning happens by diagnosing students' thoughts and conceptual understanding and by proposing directions for the students that are within their zone of proximal development. I do not disagree with this statement by and large, but as someone who works with teachers, though not in makerspaces, I am left with questions about the authors' thoughts on the role of the teacher.

« 9 » First, the caption to Figure 5 suggests that there is something *specific* to makerspaces about this inversion of the pedagogical approach, but is this not a general trend in inquiry-based or problem-based learning activities? (Q1)

« 10 » My second question is a follow-up question, but should apply, regardless of the answer to Q1. Is there anything different about the kinds of artefacts that learners build in makerspaces *in contrast* to artefacts produced in traditional learning activities (e.g., written essays, or maths problems, etc.) that pose new challenges to what teachers should be able to attend to in order to "diagnose" learners' knowledge? (Q2)

« 11 » If so, an optional question arises: What kind of training or professional development do the authors imagine that these new challenges necessitate to prepare teachers to take on these new roles? (Q3)

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Interactive Objects in Physical Computing and Their Role in the Learning Process

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> Abstract • The target article discusses the question of how educational makerspaces can become places supportive of knowledge construction. This question is too often neglected by people who run makerspaces, as they mostly explain how to use different tools and focus on the creation of a product. In makerspaces, often pupils also engage in physical computing activities and thus in the creation of interactive artifacts containing embedded systems, such as smart shoes or wristbands, plant monitoring systems or drink mixing machines. This offers the opportunity to reflect on teaching physical computing in computer science education, where similarly often the creation of the product is so strongly focused upon that the reflection of the learning process is pushed into the background.

« 1 » Educational makerspaces are described as an alternative to traditional education in which the pedagogical approach is inverted and starts with student action (the construction of objects) instead of concept explanation by the teacher. This is more related to learning as it happens in contexts outside of formal settings, which usually takes place in spontaneous interaction with the environment. As the authors have shown in much detail, in consistence with Jean Piaget's idea of constructivism, learning means building networked knowledge structures by interpreting new information (acquired, for example, through playing with things, reading books or listening to people) in relation to existing knowledge and experience (Ackermann 2001; Ben-Ari 1998). Additionally, according to the constructionist learning theory, learning is most effective in contexts where learners construct knowledge and develop competencies from their *own initiative* and for a *personally relevant purpose*, when being *consciously engaged* in *creating visible artifacts*

(Papert 1980; Papert 1991; Resnick 1996). Edith Ackermann, when reflecting on Piagetian constructivism and Seymour Papert's constructionist theory of learning, highlights Papert's view that "[…] 'diving into' situations rather than looking at them from a distance, that connectedness rather than separation, are powerful means of gaining understanding" (Ackermann 2001). This is exactly what happens in makerspaces and also during physical computing activities – at least that is what we aim for.

« 2 » Physical computing is the creative design and implementation of interactive objects or installations, which are programmed, tangible artifacts that communicate with their environment using sensors and actuators. In physical computing, methods and concepts of embedded systems and interaction design are used (Przybylla 2018). The learners have to "teach" their object to behave in the intended way by constructing and programming it appropriately. In designing and creating their interactive objects, learners dive into the role of inventors (Stager 2009). They are connected with their artifacts, even physically, as they can see them, but also touch them, play with them and share them with their peers. Finally, through making their objects, they construct and constantly reconstruct knowledge: As Gary Stager puts it, in physical computing projects "knowledge is constructed and the best way to ensure learning is through the deliberate construction of something shareable outside of one's head" (Stager 2009: 3). In creating their interactive objects by tinkering and prototyping, learners create knowledge gradually and become acquainted with powerful ideas that can be used as "tools to think with over a lifetime" (Papert 1980: 76):

> "The journey from the concept of the project to realization is seldom one-way. The technical skills you develop along the way will inform and change the concept. After you develop some fluency with the tools, ideas often come concurrently with the making of the project, not necessarily before." (O'Sullivan & Igoe 2004: xxviii)

« 3 » With physical computing, constructionist learning is raised to a level that enables students to gain haptic experience and thereby concretizes the virtual. Students create interactive constructions applicable for the purposes of embedded systems design and thus learn in authentic contexts (Martinez & Stager 2013; Stager 2014). Such learning is described as highly interactive because both digital media and the tangible object immediately reflect learning success and problems and thus allow each learner to learn at their own pace based on individual learning goals.

« 4 » However, in many physical computing activities in class, teachers face similar problems to the ones described by José Armando Valente and Paulo Blikstein in the target article: In §5 it is reported that often, in makerspaces, the focus is on machine operation and product creation and that from the mere construction of an object it cannot be inferred that the learner – who may have achieved their goals by trial and error, or worse, by following step-by-step manuals without thinking much about it – fully understands all the concepts involved. Similarly, in physical computing activities, teachers often struggle in finding the right balance between too narrow guidance and complete openness. In our studies, it was clearly visible that both extremes can lead to motivation loss over the course: too narrow guidance very often results in low self-efficacy and a lack of help or helpful material frequently ends in frustration (Przybylla 2018a). Thus, I fully agree with Valente and Blikstein in their conclusion that there is a need for experienced educators (§26), who are able to identify the right moments to help the students reflect on their achievements, to challenge them with new situations and, this way, support them in gaining a deeper understanding of the underlying concepts. However, I sometimes observe in classrooms that teachers are unfamiliar with this role of mediator and in extreme cases are either helpless and cannot assist with specific problems or think too rigidly and give learners concrete steps to follow that may deviate from their own creative ideas (Przybylla 2017). Thus, I cannot help but wonder: How can we prepare those teachers better to take the role of an expert mediator? (Q1)

« 5 » When physical computing is taught in computer science courses, teachers also often struggle with another problem: assessment and grading. First, the question is raised of how the teacher can know whether the learner has learned what he or she was supposed to learn if, from the product alone, this cannot be inferred? Second, the interdisciplinary character of the process makes it often hard for teachers to evaluate the knowledge used in this product: Is a well-working interactive object, which uses only a few lines of code but is very complex in its mechanics and outer shape worth less than an interactive object that uses many lines of code, but is maybe not very appealing in its design? Our investigations showed that, on the one hand, teachers feel uncertain about grading and assessing student work that involves a lot of creative design and wish to have transparent criteria (Przybylla 2017, 2018). For students, on the other hand, grades are an important element of teaching, which cause them to feel pressured but also give them a feeling of pride when they are rewarded for their efforts. In Richard Ryan's and Edward Deci's self-determination theory, however, pressure and tension influence intrinsic motivation negatively and are predictive of a lack of autonomy and self-determination (Ryan & Deci 2000). Therefore, ways must be found for the school context to reconcile the extreme positions and to carry out the necessary performance evaluations in a way that, on the one hand, clearly examines the competencies gained, but, on the other hand, does not impair student motivation too much, as this would interfere with constructionist learning. Thus, another task for future research in the domain of physical computing for computer science education is to investigate possible means of evaluation, grading and assessment. In §41 the authors of the target article raise a similar question and suggest using the clinical-critical method in order to find out whether students have gained a deeper understanding of the intended concepts. This idea of making explicit the activities of reflection, comprehension and conceptualization might help teachers who have difficulties with mediation. However, I wonder what Valente and Blikstein would suggest concerning the above-mentioned problem of grading creative works and specifically what they think about what the quality of the programs says about a student's understanding: Would they assume that these programs are a "window into the learner's mind" as mentioned in §58? (Q2) I would argue that, from a computer science perspective, these programs are just part of the products, which – standing alone – do not say much about the genuine understanding of the learners and even more so do not reveal anything about the learning process. Thus, my final question to the authors would be: What role should these products play in the evaluation of students' performance – are they just by-products of learning or should we grade our students based on the performance, functionality, look, etc., of their interactive objects? (Q3)

« 6 » As a final thought I would like to add that I see a high value for computer science (and general) education in the implementation of projects in which pupils, for example, aim to build and network a Smart City from LEGO bricks or to equip the school with interactive Halloween decorations, although this results in concrete products. It is not a question of no longer developing products in educational settings, but of supporting pupils on their way to their final products in such a way that they become aware of the learning process, externalize knowledge and concepts and "[…] reach a new level of scientifically based knowledge that is a product of a growing learning spiral," as Blikstein and Valente put it (§16).

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Applying the Practices of Makerspace in Other Educational Settings

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> Abstract • Makerspaces, if enriched with mediation and reflection as well as social interaction with experienced learners, can be used as a model for designing learning environments for researchers' education at all stages of their development.

Introduction

« 1 » In primary and secondary education, the ideas of Seymour Papert's constructionism became widely accepted and disseminated by the "maker movement" for the reasons well summarized in §§10f of José Valente and Paulo Blikstein's target article. Still, using this learning methodology to build conditions for developing research abilities and problem-solving minds at the level of PhD studies seems unusual. Yet the relation between making, learning and mediation (facilitation), problematized by Valente and Blikstein, as well as their discussion of the role of digital representation and teacher (or expert partner) in the learning process, is relevant for a wide variety of educational environments, including post-graduate education.

« 2 » A research environment (either a laboratory or an archive of artifacts) is very similar to a makerspace: the researcher is a learner who interacts with objects, uses digital information and communication technologies and digital fabrication technologies, and is not necessarily aware of all the concepts and scientific knowledge that can be employed to construct new knowledge, especially in interdisciplinary or innovative investigation. If we re-interpret research practice as makers' activity from the perspective of constructionism, then the concept of using digital technologies as a "window into the mind" (as suggested in §16) for knowledge representation in a "growing learning spiral" gives us a new perspective on how to design learning environments for producing innovative knowledge both as a part of training and in research. Procedures for testing hypotheses and initial assumptions with representation in digital modelling are now gaining more and more popularity both in the natural and the social sciences.

« 3 » Considering the growing significance of transferrable skills and developing personal effectiveness in postgraduate education, the link between social development and character building in makerspaces (emphasized in §19) gives even more arguments for using this type of educational space in higher-education institutions. Empowering agency in learning is also important from a perspective of developing entrepreneurship skills and the ability of self-evaluation for lifelong learning.

Mediation and Reflection

« 4 » The obvious benefits of "hands-on" learning often create the illusion of simplicity in the implementation of constructionism, therefore Valente and Blikstein reconsidered cognitive concepts of Jean Piaget and Lev Vygotsky to clarify the aspects of agency in knowledge transformation. This is a very important point for consideration in the context of the development of scientific concepts in research. In §26 the authors insist that "mediation" is necessary for learners (researchers) to be able to achieve development (as opposed to going through the "learning process," according to Vygotsky as cited). This brings a new horizon for envisioning the role of supervisors and experienced researchers as constructors of the "zone of proximal development" for the effective functioning of research groups.

« 5 » The authors describe the process of learning in makerspaces as starting from the action phase (Figure 5), then they claim that there is a need for reflection, comprehension and conceptualization (often omitted in many makerspaces) with the assistance of the teacher. "Action" is similar to the experimental or modelling phase in research, but in the postgraduate educational environment, the reflection could be mediated not only by the conceptual thinking of a more experienced researcher, but also by the assistance of the peer group, i.e., by structured "peer-led activities."

« 6 » The opposition between "product construction" and the "construction of knowledge," well described in §59, in application to research will illuminate the need for more interaction between researchers and technology to represent stages of reflection on the way to new knowledge. The practice of reflective communications following the creation of the designed research object with either a senior researcher or the peer group, provide the structure for a more effective evaluation of the preliminary results of research and knowledge conceptualization.

« 7 » Thus, in the discussion about structured PhD education as opposed to the individual research-based model, one could refer to makerspaces experience and argue that "just doing experiments" would not be enough for reaching the stage of innovative research. Here, we can also use Piaget's distinction between "success" in performing desired activities and "understanding" to support the need for a reflective (learning) phase in any research practice.

« 8 » One might object that we could not apply the concepts Piaget and Vygotsky initially developed for explaining the process of cognition in childhood and adolescence to research. However, both a child and a researcher at the beginning of experimenting stay in the same zone of pre-knowledge and go through similar stages of knowledge construction and both need social interaction to get to the level of conceptualization.

Conclusion

« 9 » Many of the valuable observations discussed in the target article, related to makerspaces, could be reapplied to the research environment since both educational settings aim at creative and active creation of knowledge instead of repetition or duplication. The digital revolution made learning a part of the research process not only within structured doctoral education, but also in the lifelong professional development of a researcher.

« 10 » The authors encourage educators to reflect on the makerspace activities to support the initial objective of constructionism of developing learners' problem-solving capacity. A makerspace learning environment empowered with reflective practice should be very effective at establishing a risk-taking mindset, though the potential of Papert's constructionism in lifelong learning needs further investigation.

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Authors' Response

Professional Development and Policymaking in Maker Education: Old Dilemmas and Familiar Risks

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> Abstract • Maker education is a new instantiation of the decades-old project of project-based, constructionist, inquiry-driven learning. However, unlike other past implementations, it offers many unique characteristics, makes possible novel educational outcomes, and challenges policy makers and teachers with new infrastructural needs. In this response, using examples from school and district-wide implementation, we address three categories of questions raised in the commentaries around maker education: the uniqueness of makerspaces and the artifacts produced within them (and how they differ from projects and artifacts produced in other educational environments), teacher professional development for this novel type of school environment, and new approaches to assessment. Our conclusions point to recommendations that could be useful for policy makers, teachers and educators working on the implementation of maker programs.

« 1 » The fast dissemination of makerspaces in pre-college education is one of the most noteworthy events in the history of educational technologies – comparable to teaching machines, educational television, and the Logo language. It brings familiar issues and dilemmas that have concerned educators and designers for decades: How much open-endedness should we allow in schools? How to integrate these new spaces within the current school infrastructure? How to do assessment? How to prepare teachers to use those technologies? What learning goals can be uniquely achieved within these novel environments?

« 2 » These recurring dilemmas come back for a reason: despite the vast advances in educational theory and research in the last 50 years, one fundamental issue still divides the world of education like no other: the infamous dilemma of instruction versus construction. While traditionalists have insisted on direct instruction for decades (Engelmann & Carnine 2016; Mager 1988; Kirschner, Sweller & Clark 2006), every progressive educational reform promises to bring openness, authenticity, inquiry, and personally meaningful curricula to classrooms (Dewey 1916; Montessori 1965; Papert 1980; Freire 2008). This dilemma percolates through the entire educational ecosystem and its components, such as national standards, curricular design, and teacher preparation.

« 3 » In our target article we have primarily discussed one crucial aspect of this divide: when classrooms move towards more progressive approaches and project-based learning, how do we reframe what students are learning? Is the mere execution of a project evidence, or a proxy, for learning? We have argued that "doing" or "making," while certainly powerful as tools to promote engagement, do not necessarily lead to learning. Such a statement could be taken as trivial, but a brief analysis of the current discourse around maker education (Blikstein & Worsley 2016) will reveal that such a view – that merely making something equates to learning about the scientific and engineering concepts within the artefact – is quite prevalent. We have, thus, proposed to bring back the classic constructivist lens into maker activities, with students' action a key point in the design and implementation of learning activities.

« 4 » The three commentaries identify a host of cascading questions deriving from this discussion. These questions can be approximately grouped into three main categories: the uniqueness of makerspaces as learning environments, professional development, and assessment and the nature of students' artifacts.

The uniqueness of makerspaces as learning environments

« 5 » **Arthur Hjorth** asks whether there is something specific about maker education that allows for the "inversion" of traditional pedagogical transactions, placing "action" even before conceptual exposition. He is concerned with what is unique about makerspaces (Q1) and the artifacts that students develop in them (Q2). One of the distinctive characteristics of makerspaces or digital fabrication laboratories ("FabLabs") is their variety of tools and possible activities, which is a consequence of the history of the movement (Blikstein 2018). Even though the original FabLabs were relatively uniform in terms of equipment, most contemporary makerspaces and digital fabrication spaces can be very different in terms of infrastructure. This generates challenges, but it also creates numerous "entry points" for children. Whereas in a "classic" robotics club or a Logo computer lab there were few types of activities and objects produced, an artifact created in a makerspace could range from a programmable robot to an "analog" art piece. This diversity enables students to engage in the "action" phase (Figure 5 in our target article) in different ways: building an art installation, an e-textile project, a sensor-based science experiment, or an invention to solve an everyday problem. This diversity of tools also makes it easier to design activities that engage with more content areas and take advantage of "teachable moments" – even in the humanities. Finally, it affects designing activities and the orchestration of the classroom: students can easily transition between group and individual work, alternate between low- and high-tech, and combine projects inside and outside of the school walls. These possibilities are not unique to makerspaces, but they are much richer and flexible in those spaces.

« 6 » These characteristics are also reflected in the artifacts created in makerspaces, as opposed to more traditional ones such as essays or math problems, as **Hjorth** highlights in Q2. Many of the technologies present in makerspaces are not new (robotics, 3D printers, laser cutters, craft tools, art materials, etc.), but their availability in one single physical space makes the artifacts produced there potentially much richer, offering multiple entry points into their construction. A student who enjoys art can start a robotics project with the props and decorations to the robot, then move on to the mechanical construction and coding – and teachers can design such customized paths based on students' previous interests (Blikstein 2008). The interdisciplinarity of the projects also offers teachers and students possibilities to mix and match techniques and learning goals, adapting the activities to different contexts. The "OmniAnimal" activity, for example, which was developed in the context of Blikstein's lab, offers multiple levels of engagement. The goal of the activity is to create exotic, imaginary animals from laser-cut pieces. For short, one-hour workshops, students receive a basic set of pieces and have to design a few new ones, which are cut by a facilitator for time efficiency. For longer workshops, students get to learn how to use the laser cutter and cut their own pieces. When even more time is available, we have added several options: using a vinyl cutter to design decorations for the animals, creating algorithmic designs and engraving them onto the animals, adding LEDs and simple circuits or incorporating full-fledged robotics with motors and sensors. These possibilities use very different types of tools and engage students in diverse ways, which would be challenging outside of a makerspace. These new "maker" artifacts thus offer possibilities that were not present in previous types of environments, such as computer labs or robotics clubs.

Professional development

« 7 » The second category of questions from the commentaries is about the types of professional development needed for maker education, raised by **Hjorth** (Q3) and **Mareen Przybylla** (Q1). Given this flexibility and diversity of tools and activities, how can teachers possibly thrive in the space when they were prepared to inhabit very different environments? To answer this question, it would be useful to bring some additional data from the schools described in the original article. The implementation of the project in these schools was somewhat unusual, but it points to a route that has been successful in many school systems, in the US and abroad. The "unusual" approach was to convince school systems that each makerspace needed its own dedicated teacher. This was, at first, a surprise to the school district, but an argument was made based precisely on the technical and pedagogical complexity of running a makerspace. Even though this idea is often met with resistance from policymakers, no one would question the need for the hiring of other types of specialized teachers. If a school wants to start a sports program, the need for a coach or physical education teacher is obvious. To have an art program, a school needs art teachers.

« 8 » In several implementations around the world, we have observed that the tasks involved in running a maker program are just not compatible with the amount of time available to regular teachers. A makerspace needs constant cleaning and organization, well-organized management of consumables, careful design of lesson plans, special after-school support for students, and technical maintenance. Makerspaces offer many benefits, and diverse and flexible tools – but those come at a price. The need to hire specialized teachers brings up the familiar argument about the lack of funding in public schools. However, we have found that it is quite important to educate policymakers about the cost of their choices – if they want a functional makerspace, they have to invest in the teachers that will run it, as opposed to simply purchasing equipment and leaving teachers to their own resources.

« 9 » There are countless examples of educational technology implementations that fail because they focus on buying equipment, with the hiring of specialized teachers an afterthought. Thus, in places where there is a specialized maker teacher in place, such as the school described in the target article, the work is done in pairs: a science, math, or art teacher co-designs and co-teaches an activity with the maker teacher. The teacher preparation is done differently for the two audiences. Disciplinary teachers will get training mostly geared towards understanding the pedagogical possibilities of the machines and technologies, with less focus on their operation. We focus on techniques for lesson plan redesign, pedagogy, different forms of classroom orchestration, and assessment in project-based environments. The maker teachers would get more in-depth training on the technologies, often spanning several weeks and tens of hours. Both groups would be prepared to work together as a team, both for activity design and delivery.

« 10 » We found that this combination had a number of advantages compared to the traditional approach of only designing professional development for the disciplinary teachers. First, it was an enormous relief for regular teachers to know that they would not be burdened by extensive technical training, given that not only are they busy with their regular work, but they might not enjoy such training or feel prepared for it. A particularly striking case was of a teacher who resisted implementing any maker-related activities in his science class for months. There were many justifications for his refusal, from lack of time to claiming that it would not benefit students. However, this teacher had never quite understood that he would not be alone when implementing activities. When he finally understood that there would be another teacher helping him deliver the redesigned unit, and in charge of all the technical aspects, he not only agreed to try the new lesson plan, but became an enthusiast of the project.

« 11 » Second, by focusing the training of the regular teachers on pedagogy and lesson plan redesign, we give them tools to not only use the new technologies but to create sophisticated new educational designs, achieving new and ambitious types of learning goals. At the same time, we are able to provide in-depth technical training to the maker teachers in a much more cost-efficient way, since there is just one of those per school.

« 12 » Third, the lab teacher automatically becomes a trainer and evangelist in her own school, promoting lab visits, workshops, training, outreach activities, etc. Over time, new teachers are brought to the fold and become part of this community of practice.

« 13 » Indeed, as **Hjorth** (§10) and **Przybylla** (§4) state, the types of tasks and practices needed in makerspaces are quite different from the ones in traditional classrooms. We often believe that teachers will, overnight, spring into a completely new paradigm of work, facilitating project-based learning, assessing complex artifacts, and establishing dialogical relationships with children, automatically abandoning their "old ways." We know that such transitions require extensive amounts of time in practice, and that localized, short training sessions without regular follow-up will simply not generate the expected changes. We have found that placing a maker teacher in the school can accomplish many of those goals since the school becomes less dependent on the implementation team, and local training can be increasingly taken over by the maker teacher. If this teacher is appropriately trained, she can be a constant force for change, following up with teachers, organizing regular professional development sessions, writing up lesson plans, creating new types of assessments, and accumulating exemplars of students' artifacts.

« 14 » At the same time, the maker teachers often might be more radical than what the school system allows for, or simply have a very simplistic and naïve view of schooling. In that case, the regular teachers would help them understand the system, its dynamics, leverage points, and limitations, and together find productive entry points and pathways for the implementation of new practices. Also, the regular teacher can establish the dialog between the concepts used in the product or project development and the curriculum. The maker teacher may not know how curriculum activities are discussed and approached in the classroom.

« 15 » The need to hire an additional teacher in every school to manage and teach in the makerspace could sound unfeasible for public schools. Nevertheless, many schools and secretaries of education spend vast amounts of funding on equipment and facilities, while with better resource allocation it would be possible to have functional, lower-cost makerspaces and at the same time hire specialized maker teachers. This combination of a well-trained lab teacher and a regular disciplinary teacher has proved to be the key to the success of many maker education programs around the world (Martinez & Stager 2013; Halverson & Kimberly 2014; Kurti, Kurti & Flemming 2014; Riley 2015; Clapp et al. 2017). Arguably, being upfront about the overall costs of a maker program (including extra teaching staff) could be helpful for policymakers to communicate to city councils and elected officials the exact resources needed for successful implementations of the programs. Often, the resources exist, but policymakers need a good justification to make use of them.

Assessment and the nature of students' artifacts

« 16 » The third cluster of questions revolve around assessment, and the nature of artifacts developed by students. For example in Q3, **Przybylla** is concerned with the assessment of creative works and artifacts and whether the examination of these artifacts in isolation is appropriate, i.e., whether students should be graded based on the performance, functionality, and look of these interactive objects. **Liudmyla Kryvoruchka** (§7) interrogates us about the difference between "'success' in performing desired activities" and understanding, and makes parallels between makerspaces and work in post-secondary education. She suggests that research laboratories might generate artifacts that are, in nature, quite similar to those generated in makerspaces, since both are places for interdisciplinary experimentation and innovative investigation. In previous work, we have discussed the compromise between product- and process-based assessments (Blikstein & Worsley 2016). In product-based assessments, teachers look at the final artifacts produced by students and employ some rubric to assess it. In process-based assessments, teachers and peers attentively track the development of a project and apply rubrics not only to a final result but to intermediary milestones. Even though product-based assessment could work in some limited cases, it often generates undesirable unintended consequences. In search of a better final result, students often split the labor based on their current abilities, which ends up reinforcing inequalities in the classroom. The students with more experience in engineering end up doing the technical tasks, and the less experienced wind up doing less complex manual tasks. In other cases, a good final product might obfuscate a poorly designed process or very little learning. Process-based assessments, conversely, allow for teachers to establish several project milestones, and different criteria for success. If an important learning goal is collaboration or a particular curricular topic, the process rubric can include it. If the teacher is particularly concerned with equal group contribution, that can also be part of how groups will be assessed. Frequently, a final product that looks unfinished or even not functional, can be the result of a very rich learning experience – especially for novices with ambitious goals.

« 17 » This issue connects with **Przybylla**'s Q3 on assessment, and Q2 on whether maker programs can be a "window into the learner's mind." First, she asks if we can we take students' artifacts in isolation and assess their functionality. It seems that, in maker education, the appearances of flashy artifacts can be deceiving. Having access to the extensive repositories of resources and premade objects on the Internet, as well as the machines in a makerspace, it is arguably easy to produce objects that are relatively sophisticated without any deep understanding of how they work. Our article discusses how making and understanding are not automatically linked, but the issue is even more problematic in an environment where there is an ever-growing disconnect between the quality of the products and the effort put into making them. There are new maker machines being launched on the market every other month, each more capable than the other. In a few years it will likely be possible to 3D-print objects embedded with electronics and mechanical parts – at that point, how would we distinguish students who designed their own circuits and robots, and the ones who simply downloaded the entire project from the web and printed it with the click of a button?

« 18 » If we set the standard in makerspaces to be about the production of objects, it will be on increasingly shaky assessment ground in years to come, as students devise new ways to produce objects with less effort. If the production of objects and the learning goals are not tightly connected in our curricular and assessment designs, we risk trivializing maker education to the point where makerspaces would no longer be a place for invention but a mere production facility of cool and curious contraptions. Investing in robust process-based and formative assessments is our insurance policy against the rapid development of maker technologies. Let us take as an example the constructions of simple circuits and analog electronics. To make an LED blink in the 1980s, a student would need a degree in electronic engineering and tens of hours of work, between printed circuit board design and soldering. In the 2000s, the same could be accomplished in a couple of hours using a microcontroller board. Today, using some of the more modern physical computing kits, a student could accomplish the same in a few minutes. Przybylla's Q2 on maker programs being a possible "window into the learner's mind" is also relevant. There is great potential to "open" such a window and gain a deeper understanding of students' cognition while creating objects, in the same way that the Logo language was used to gain unprecedented insight into mathematical and computer-science reasoning. However, makerspaces comprise many more tools and types of activities, so visibility into students' cognitive moves is challenging. For example, there are ways to compensate for lack of knowledge about hardware construction in software (and vice versa), with the exact same functional result. The lens into students' cognition, thus, has to be embedded in carefully designed activities, process-based assessments, and project milestones.

« 19 » We should focus considerable attention on these process-based assessments, and not look at products in isolation, but consider how hard it is to generate those products relative to the types of toolkits available for children. This relates to the main argument of our article – the relationship between learning and making. The establishment of learning goals should always precede the definition of technologies or activities to be done with students. If a teacher is interested in Newtonian physics, as in the example in the target article (§§43ff), the quality of the catapults produced should not be the main assessment item – it should be only one of the elements. The catapults should be part of a larger lesson-plan design on Newton's Laws that includes scientific inquiry, statistical calculations, and experiments with different materials.

« 20 » That is not to say that traditional approaches to curricular design have to be the main driving forces in makerspaces, "schoolifying" and trivializing maker education. Granted, as we place the production of maker artifacts within larger disciplinary contexts, there is a risk of switching back to old approaches and models and forgetting that there is enormous richness in the process of construction of interactive objects and artifacts. Not all of maker education should be in the service of learning traditional disciplinary knowledge. At times, perhaps there could be a maker activity only concerned with the design of the most spectacular catapult, with no concern for the scientific experiments that can be performed with it. Teachers should be aware of that compromise and make informed choices about their specific goals.

Conclusion

« 21 » The dissemination of makerspaces in pre-college education is indeed one of the most noteworthy events in the recent history of educational technologies – but it is not automatic that it will also be a learning revolution. Over the last decades we have seen technologies come and go without delivering the promised learning outcomes. By now, we have understood that technologies by themselves do not deliver learning: it is the intentional insertion of technologies within a productive context that delivers results. It is all too easy to design technocentric solutions, which focus on equipment and technology training, just to later blame technology for the failure to deliver the expected learning outcomes. Maker education is just one more chapter in our quest to expose children to the most powerful ideas humanity has created. As we develop more sophisticated knowledge and techniques, more complex forms of schooling, classroom orchestration, curriculum design, and assessment are necessary. It is impossible to teach all the new content topics that the 21st century is producing if we are not generating new formulations for learning environments, new approaches to professional development and new modes of participation in schooling. Those have a cost, but they also have incommensurable benefits.

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