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

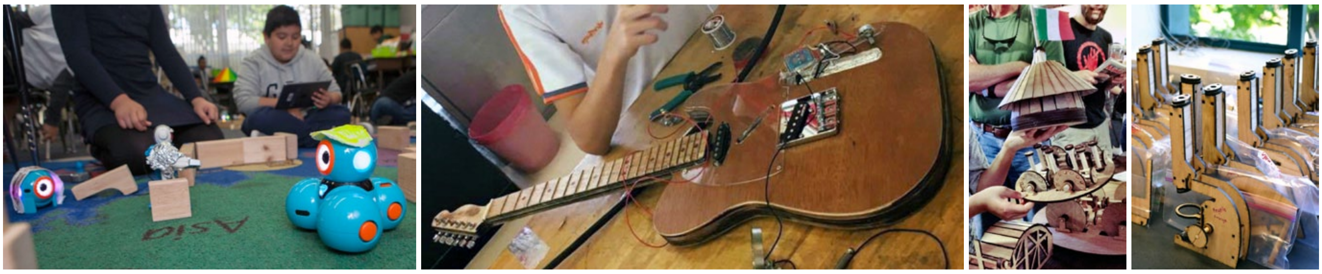

Figure 1 • Examples of students' projects (from left to right):
A robot-enacted theater play, a custom-made guitar, a da Vinci machine, and a microscope.

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

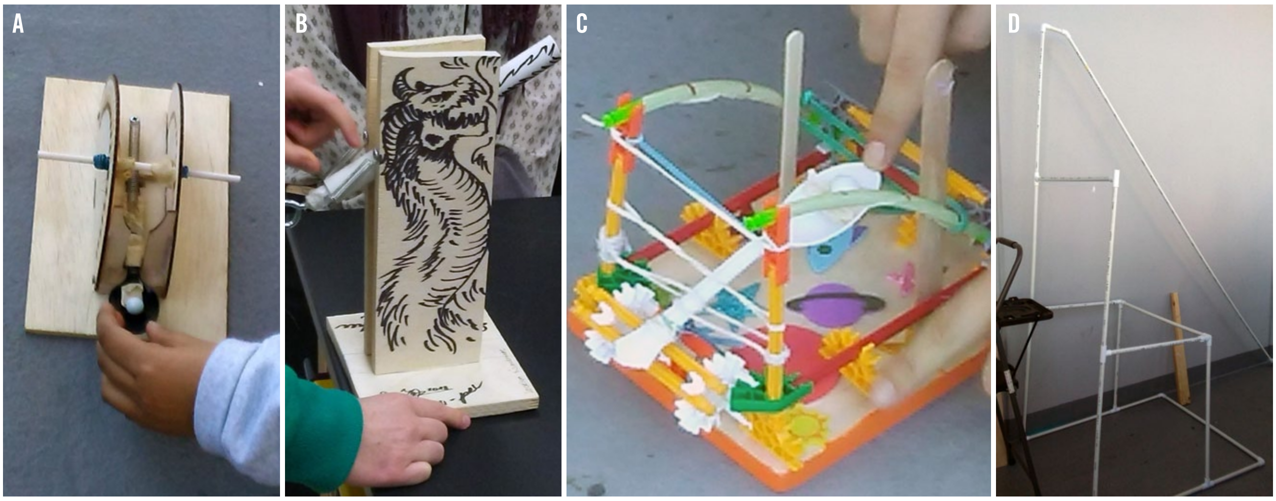

Figure 2 • Examples of catapults using different structures and materials.

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.

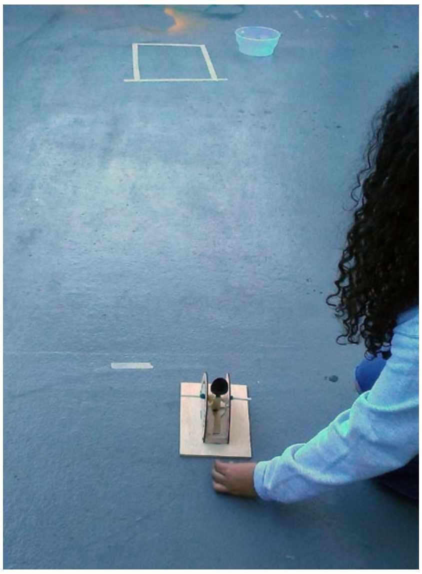

Figure 3 • Student testing her catapult, verifying if the ball lands on the square marked on the floor.

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).

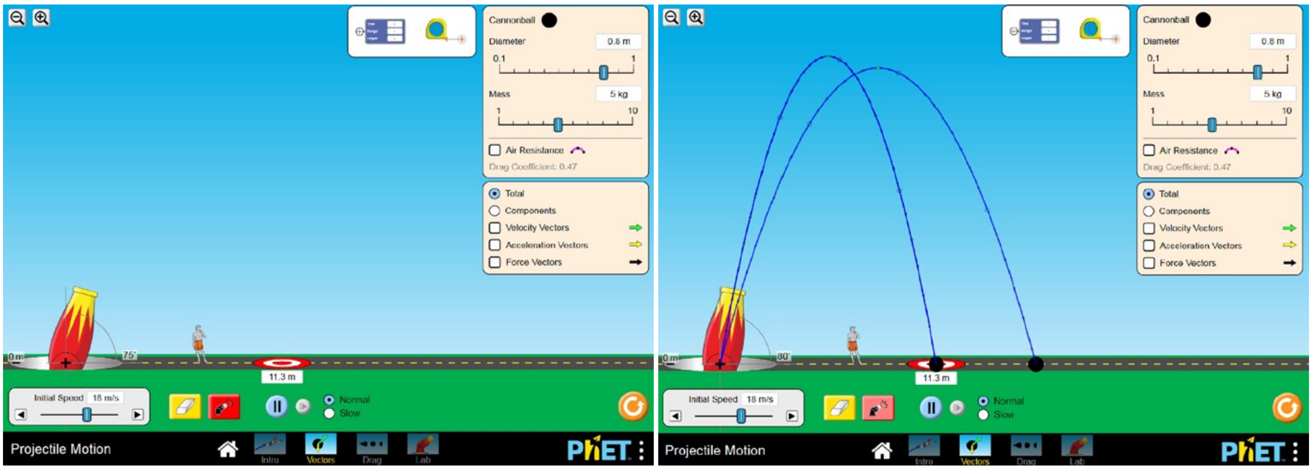

Figure 4 • Left: ballistic simulator, indicating the variables that can be altered at the projectile's launch. Right: launching projectiles for different angles, maintaining all other variables constant.

« 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.

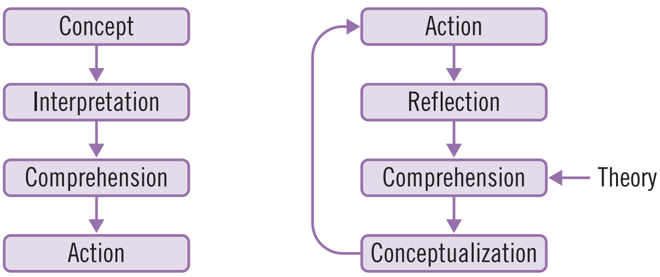

Figure 5 • Left: Traditional education-based pedagogical approach. Right: Makerspace-based inverted pedagogical approach.

« 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.

Acknowledgements

This work is supported by *Conselho Nacional de Desenvolvimento Científico e Tecnológico,* (*CNPq*), Brazil, grant 306320/2015-0; by the Lemann Center for Entrepreneurship and Educational Innovation in Brazil at Stanford University, and by the Transformative Learning Technologies Lab at Teachers College, Columbia University, USA.

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Received: 21 January 2019
Accepted: 29 April 2019