Designing for Collaborative Creativity in STEM Education with Computational Media

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Abstract

In this chapter, we present the findings of our research about how middle school STEM students engage in collaborative creativity while working with computational media, including robotics and Scratch. The development of these media was based on Papert's constructionist learning theory, and as such, they reify particular constructionist ideals. Our research findings are theoretically rooted in a sociocultural definition of creativity as collaborative dialogic inquiry which accounts for the role of influential voices in the classroom (real and reified) in the collaborative creativity of groups. In this way, we expand the notion of the collaborative group beyond the actual members of the group to include the mediating role of the materials, technologies, and teachers on student creativity. In addition to specific research findings, we report on the overarching factors that bear on students' ability to enact collaborative creativity while problem solving with computational media. These factors revolve around the nature of the activity, the nature of social interaction, and the role of the tools in the environment.

Keywords

Collaborative creativity • STEM • Robotics • Scratch • Constructionism • Dialogism

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Computational Media and Collaborative Creativity

> "As a practice, software development is far more creative than algorithmic." – J. Bradford Hipps (2016).

Our research has focused on the ways in which collaborative learning interactions with computational media (LEGO robotics and Scratch, specifically) enable the development of collaborative creativity in children and youth. In this chapter, we present the findings of our research and we provide recommendations for pedagogical approaches and curricular designs that create the conditions for student collaborative creative activity with computational media. The chapter is organized thusly: we begin with a theoretical explication of our sociocultural view of creativity as collaborative dialogic inquiry; we then present a discussion of Papert's (1991) theory of constructionism as it relates to student learning and creativity with computational media – the design of both LEGO robotics and the Scratch software is rooted in constructionist principles of learning. Next, we present our research findings based on these theoretical constructs. We then present both pedagogical and curricular recommendations for using computational media in teaching and learning for collaborative creativity.

The Sociocultural View of Creativity

From the sociocultural perspective, creativity overlaps strongly with learning in that both are manifested through the coconstruction of new meanings while engaged in collaborative activities (Eteläpelto & Lahti, 2008; Rojas-Drummond, Albarrán, & Littleton, 2008). Sociocultural researchers focus on the situated nature of the learning environment and they view creativity as a potential outcome of collaborative interactions in open-ended, student-directed, learning environments (Barab & Plucker, 2002; Fernández-Cárdenas, 2008). Sociocultural research related to collaborative creativity focuses on the emergence of local practices and the quality of social interactions among members of the collaborative group (Rojas-Drummond et al., 2008; Sawyer & DeZutter, 2009).

Following the Vygotskyan emphasis on the role of language and tools in the development of higher-order thinking (Vygotsky, 1978), sociocultural research about collaborative creativity focuses on the nature and quality of student talk (Fernández-Cárdenas, 2008; Rojas-Drummond et al., 2008; Sullivan, 2011; Vass, 2007) as well as student's collaborative interactions related to available tools in the learning environment (Kangas, 2010; Sarmiento & Stahl, 2008). From the sociocultural viewpoint, collaborative group interactions serve as the basis for the generation and development of creative ideas/solutions/projects. Research findings suggest that productive talk, where children build their knowledge collectively, is the basis of collaborative creativity (Rojas-Drummond et al., 2008; Sarmiento & Stahl, 2008; Sullivan, 2011). Productive talk includes sharing, exploring, and reflecting on one another's ideas (Vass, 2007) as well as elaborating on each other's ideas (Sarmiento & Stahl, Sullivan). It also includes negotiating meaning (Fernández-Cárdenas, 2008; Rojas-Drummond et al., 2008).

In order to establish a productive working relationship, students need to build trust in the group (Aragon, Poon, Monroy-Hernandez, & Aragon, 2009; Eteläpelto & Lahti, 2008; Vass, 2007). Such trust building may come through highly social talk (Aragon et al.) or play and playful talk within the group (Sullivan & Wilson, 2015). Indeed, both play and playful talk have figured prominently in various groups' creative interactions in a number of these studies (Fernández-Cárdenas, 2008; Kangas, 2010; Sullivan, 2011; Sullivan & Wilson, 2015; Vass, 2007). Productive talk that results in coconstruction of meaning may lead to creative solutions to problems (Sarmiento & Stahl, 2008; Sullivan, 2011), creative design of environments (Kangas, 2010), or creative expression as manifested in a multimedia work (Fernández-Cárdenas, 2008; Rojas-Drummond et al., 2008; Vass, 2007) or a performative work (Sawyer & DeZutter, 2009).

This new perspective on studying creativity as an outcome of collaborative interaction has led research efforts in a new and promising direction. However, missing from some of this current sociocultural research is a theoretically based examination of how local practices (e.g., productive talk) emerge on a moment-to-moment basis in a given environment. Our own research addresses this issue. We have developed a thesis of creativity as collaborative dialogic inquiry (Sullivan, 2011). Our thesis focuses on the theoretical basis of collaborative creativity as an outcome of productive talk, as well as the multivocal influence of real and reified voices in the classroom. Our work builds on Wegerif's (2007) interpretation of Bakhtin's (1981) theory of dialogism as it functions in technology-based learning environments, with special attention paid to reified voices. We now present our thesis.

Collaborative Dialogic Inquiry

The view of creativity presented here builds on the sociocultural approach to understanding learning and the development of higher-ordered thinking. It does so by establishing a theoretical argument for the discursive basis of creativity. Drawing on Bakhtin's (1981, 1986) theory of dialogism and Pea's (1993) notion of distributed intelligence, we argue that creativity is an intrinsic element of everyday talk and that the development of a creative idea may be traced through the collective interaction with and interpretation of the discourses present in any given activity context. While a specific individual may voice a creative idea, we argue that the creative idea is formed through the interaction of many voices. These voices may be organically embodied, reified in a tool or artifact, or embedded in the environmental and social structure of the context itself. In this way, the collaborative group is comprised of more than the individual members of the group. Indeed, the group is expanded to include the real and reified voices found in the classroom. Let us now consider, in detail, the theories of dialogism and distributed intelligence as they inform our definition of collaborative creativity.

Dialogism

Dialogism is Bakhtin's (1981) theory of language and communication. Like Vygotsky, Bakhtin was interested in developing a theory that reflected a Marxist viewpoint. Such a viewpoint takes into account the historical, social, and cultural factors that influence human endeavors. While Vygotsky investigated human learning, Bakhtin studied language and communication as manifested in literary works. Bakhtin regarded the spoken word itself to be the most meaningful linguistic unit of analysis (Bakhtin, 1981). In line with the Marxist notion of ascending to the concrete (Lave & Wenger, 1991), it is through historical analysis of language in use, as spoken and written, that one is able to understand how new words come into being and how the meaning of a word shifts and changes over time. The notion of ascending to the concrete refers to the idea that to truly understand what concretely "is" one must attend to the historical development of the given phenomenon. It is only through historical analysis that one may come to an understanding of how social forces shape social realities – such as a national language.

Two central ideas in Bakhtin's (1981) theory of dialogism have special relevance here: heteroglossia and ideological becoming. Heteroglossia refers to the dynamic nature of language that is a result of the tension created by the many social languages that make up a national language. Social language refers to the mode of speaking favored by distinct social groups in society. Social groups may share class status (e.g., upper middle class), ethnic or racial background (e.g., Latinx), or sexual orientation (e.g., heterosexual), they may be comprised of people from the same age group (e.g., youth), or who share a passionate interest (e.g., photography). These social groups will share a social language and their use of a national language (including the meaning of words) will be distinct from other social groups' use of that same national language.

Moreover, the term heteroglossia refers to the idea that the context in which an utterance is made governs the meaning of the utterance. In other words, it is only through understanding the social, historical, and cultural conditions under which a specific utterance is made that one will be able to understand the meaning of that utterance. Meaning is derived from context. As contexts are constantly shifting, so are meanings. In Bakhtin's formulation the meanings of words are not fixed but are dependent on the context, which subsumes the socio-ideological position of the speaker of the words and the social situation in which they are spoken. He describes this phenomenon as the centrifugal forces constantly at work in any language. At the same time, there are centripetal forces that constantly seek to fix the meaning of words in order to create a "unitary language." It is the tension created by these opposing social forces that account for the dialogic nature of language. In other words, dialogism refers to the constant interplay of social forces on the meanings we make of the words we speak.

Dialogism also takes into account the temporal nature of communication. According to Bakhtin (1986), every utterance is spoken as part of a chain of utterances that have come before and those that will come after. All communication is historically situated (words one utters contain the meanings of previous speakers of the words) and are responsive to the anticipated understanding and response of the addressee (we choose our words based on what we know of the person or people to whom we are speaking). In this way, each utterance is multivoiced and temporally dynamic – containing the voices of previous speakers and shaped by the anticipated voice of future speakers. As Wegerif (2007) has noted, dialogism is characterized by an openness to the other "...by taking the perspective of the other in a dialogue..." (p. 52). This happens as a result of considering the addressee and the possible responses of the addressee to one's own utterances. It is this openness that creates a space for dialogue to occur and new meanings to emerge.

While Bakhtin is not a learning theorist per se, his work sheds light on how individual frameworks for knowing and understanding come into being. Bakhtin (1981) refers to this process of framework development as ideological becoming. Ideological becoming is the method by which people appropriate the discourses of others wherein the discourse goes beyond being "information, directions, rules, models and so forth..." (p. 342) to become the basis of one's own ideological development. These appropriated discourses constitute the lens through which experience is filtered. In his discussion of the concept of ideological becoming, Bakhtin has identified two types of social discourse: authoritative discourse and internally persuasive discourse.

According to Bakhtin (1981), authoritative discourse emanates from a hierarchical source and demands to be accepted as it is. Authoritative discourse is monological in nature in that it is not open to the perspective of the other. Authoritative discourse is privileged language that purports to present the "truth" which, from a Bakhtinian perspective, is a suspect concept – particularly given the contextual and shifting nature of the meaning of words. Sources of authoritative discourse may be familial, political, educational, or religious. Authoritative discourse is influential in people's lives. However, when individuals cease to respond to the power of an authoritative discourse, it becomes a "dead" discourse. An example of this may be the dogma of a particular religion that has much influence over an individual's life; however, if that individual decides she or he no longer believes in that religion, the authoritative discourse of the religion ceases to have power. In Bakhtin's view, one does not engage an authoritative discourse; one either accepts it or rejects it.

Internally persuasive discourses, on the other hand, are open discourses. They may be altered, extended, or framed in new contexts. They are discourses that can be creatively developed to take on new meanings. According to Bakhtin (1981), internally persuasive discourse is unfinished and inexhaustible – always open to further dialogic interaction. One assimilates an internally persuasive discourse into one's existing framework, comparing it, perhaps, with other internally persuasive discourses, and in this way, further develops one's own framework.

Bakhtin (1981) argues that internally persuasive discourses are significant elements in the development of individual consciousness. As we come to understand language, we do so in specific social and cultural contexts. Bakhtin argues of a word uttered in an internally persuasive discourse that:

> Its creativity and productiveness consist precisely in the fact that such a word awakens new and independent words, that it organizes masses of our words from within, and does not remain in an isolated and static condition. It is not so much interpreted by us as it is further, that is, freely, developed, applied to new material, new conditions; it enters into interanimating relationships with new contexts. More than that, it enters into an intense interaction, a struggle with other internally persuasive discourses. Our ideological development is just such an intense struggle within us for hegemony among various available verbal and ideological points of view, approaches, directions and values. The semantic structure of an internally persuasive discourse is not finite, it is open; in each of the new contexts that dialogize it, this discourse is able to reveal *ever newer ways to mean* (p. 345–346) emphasis added.

Assimilating and then transforming various internally persuasive discourses that surround one in a given culture is a creative process – giving rise to a specific and unique consciousness: the self. Viewed in this way, creativity is an inherent part of ideological becoming, or the development of consciousness. The conceptualization of creativity as dialogic inquiry emphasizes the dynamic nature of meaning in a living language and its impact on the development of consciousness – conceived of here as learning in one's culture. Creativity then, is an act of learning, and this act of learning occurs through the active engagement with, and transformation of, internally persuasive discourses.

Voice and Distributed Intelligence

A key element in the dialogic theory of language and communication is voice. Dialogism conceptualizes voice as being present in both spoken words and written texts. Kristeva (1986) has coined the term "intertextuality" to describe Bakhtin's "...conception of the 'literary word' as an *intersection of textual surfaces* rather than a *point* (a fixed meaning), as a dialogue among several writings: that of the writer, the addressee (or the character) and the contemporary or earlier cultural context." (p. 35–36: emphasis in the original). In other words, as speech occurs in a dynamic, historically situated context of shifting meanings that features an openness to the perception of the other, so written texts are constructed in relation to other, historically situated written texts and responsive to the perceptions of the readers, and those who are the subject of the text (fictional or otherwise). This same notion of dialogic voices may be found in the concept of distributed intelligence.

The theory of distributed intelligence (Pea, 1993) extends the idea of intertextuality and voice to include material culture. As D'Andrade, (1986) noted "Material culture – tables, chairs, buildings and cities – is the reification of human ideas in solid medium" (p. 22). Cole (1996) further argues that the historical modifications to a material object as it is put to use in human endeavors provides the object with not only a conceptual but also an ideal aspect. It is this historical modification that is analogous to the idea of intertextuality. Humans encounter tools developed in previous eras, these tools carry with them the ideas of previous generations – the tool may be modified based on current needs, but it remains in dialogue with the previous makers, inasmuch as elements of the previous design are retained. In this way, we, living today, are connected culturally to distant prehistoric ancestors who developed "the flint knife and, later… the wheel" (p. 136) (Wells, 1999). Therefore, it is possible to come into contact with an internally persuasive discourse not only through oral or textual means but also through ideas reified in a designed artifact itself, such as a new technology. Indeed, it may be argued that the mediating power of a material object is derived in part from the accumulation of knowledge of prior generations inherent in the design of the artifact itself (Cole & Engeström, 1993). As Pea (1993) argues:

> These tools literally carry intelligence *in* them, in that they represent some individual's or some community's decision that the means thus offered should be reified, made stable, as a quasi-permanent form, for use by others. In terms of cultural history, these tools and the practices of the user community that accompany them are major carriers of patterns of previous reasoning. (p. 53: emphasis in the original).

It is not only designed artifacts that may convey patterns of previous reasoning, but also designed environments. The design of a classroom environment includes both the physical and spatial aspects of material artifacts found in the room – tables, chairs, desks, chalkboards, computers, etc., as well as the design, or structure, of the lived experience – for example, timed periods, the discreet disciplinary treatment of objects of study, the curriculum, the nature of participation structures, specific discourse norms, classroom routines, and school policy.

These lived experiences are what Varenne (1998) refers to as "School," the always already there social and cultural "facts" that meet students when they enter the school building. Some of these School structures are outside the purview of the teacher to regulate, for example, timed periods, the prescribed curriculum, the disciplinary nature of middle and high school STEM classrooms in USA and school policies that affect students. Teachers, generally speaking, do have control over the enacted curriculum including material resource usage, participation structures, specific discourse norms, and classroom routines.

While many of the social and cultural facts of School in a public setting may be similar across sites and classrooms, others are specific to the teacher herself, and it is this specificity that allows for the teacher's voice to emerge in the environment. From a dialogic perspective, the teacher's voice speaks in relation to other teachers, the voices of the principal, the superintendent, the school board, the voices encountered in their own teacher education programs, and historical discourses related to public education in USA.

The teacher's voice in a designed classroom may be thought of as the dialogized ideas the teacher is trying to convey to the students when he or she sets up the classroom. In this way, the designed environment may overtly convey epistemological and pedagogical beliefs, expectations about the nature of teacher/student relations and student/student relations. It may relate ideas about the importance of specific topics or about the types of lived experiences the students may have as members of the class. The design may intentionally or inadvertently convey ideas about the importance of particular curricular objectives or about expectations related to a student's membership in a particular group (including racial-, gender-, ethnic-, and ability-based perceptions). In other words, the designer of the classroom in terms of both the material culture and the lived experience is speaking directly to the students about his or her priorities as he or she is able to instantiate them within the constraining tones of other, more powerful, voices present in the system.

Viewed through the lenses of dialogism and distributed intelligence, all of the voices in the classroom carry a discourse with which students are either directly or indirectly engaged. The oral and written discourses are the most obvious to identify, yet, as has been argued, the ideas reified in objects and conveyed in structured environments are also active agents in a given activity system; agents that carry the intelligence or voice of the designer, steeped as it is in its own socio-ideological perspective and conveying its own internally persuasive discourse to be engaged, altered and/or extended. *It is through the engagement with these internally persuasive discourses found in the classroom that creative ideas emerge and new meanings are made*. Let us now consider the voices reified in the design of the two computational media we are discussing in this chapter, LEGO Robotics and Scratch. Both of these computer science based-learning technologies have been developed in the Media Lab at the Massachusetts Institute of Technology. Mitchell Resnick and Fred Martin developed the programmable brick used in the LEGO Robotics kit and Mitchell Resnick headed up a team that developed the Scratch program at MIT. The learning theory that underlies the development of these technologies is Papert's constructionism.

Constructionist Learning Theory

Papert (1991), a student of Jean Piaget and an intellectual leader of the MIT Media lab, has stated that the theory of constructionism shares Piaget's (1981) basic view that human cognitive development and learning consists of "building knowledge structures" (p. 1) through interaction with the natural and designed environment. However, constructionist theory diverges from Piaget's constructivism in relation to the hierarchy of stages: most notably the third and fourth stages. Constructionists do not privilege abstract thinking as the pinnacle of cognitive development. Rather, they argue that high levels of understanding may also be reached through proximal interactions with concrete objects (Resnick, 2004; Turkle & Papert, 1991). It is this belief that underlies the design of computational media (such as Robotics and Scratch) as learning objects that support the development of creativity.

While Papert's theory builds on the work of Piaget, a large portion of the theory is derived from empirical research on student interactions with computational media directed by Papert, his colleagues, and students at the Media Lab. Interestingly, Papert (1991) has discussed how his anecdotal observations of students in an art class at a local high school influenced his understanding of learning and creativity. Each time he passed by the art class, Papert noticed the intense focus and engagement of the students in the class. In speaking with the teacher, Papert found that the students were allowed to pursue their own artistic ideas, while still being guided by the art teacher. Papert set out to create a similarly engaging math learning situation for students. He aimed to create a software program that allowed students to play, explore, and create, all while working with mathematical ideas. Hence, at the very heart of the constructionist approach to learning is creativity. As is widely known, Papert and colleagues at MIT developed the LOGO programming language and the mechanical (and virtual) LOGO Turtle that enacts the LOGO program for children.

The LOGO Turtle, a perceptual object, provides immediate feedback to the student on the elements of their LOGO program. As we shall see, the role of the perceptual object (whether physical or virtual) and immediate feedback in the learning environment are central to the theory of constructionism. A perceptual object may be an artifact that children themselves create or it could be an existing objects. Such objects become, in Papert's term, objects-to-think-with; as such, they facilitate children's engagement with ideas that they otherwise would not be able to grasp. According to Papert, objects-to-think-with allow children to materially participate in a meaningful way in their own cultural setting, which then provides them with a connection to others in that setting. Furthermore, these perceptual objects allow children to use their own body knowledge in reasoning about concepts. In this way, Papert's theory of constructionism introduces three important ideas related to creativity and learning: personally meaningful activity, the central role of the social in learning, and the role of one's own body in sense making.

Personally meaningful activity refers to allowing children to follow their own interests and questions in a particular domain of learning. This is a very important aspect of constructionism that directly supports student's creativity. Amabile (1983) has demonstrated that choice is an important element in creating the conditions that support creativity. When people are allowed to follow their intrinsic interests, through choosing which activity they will undertake, people develop more creative ideas and/or products. One of the reasons for this may be because choice emphasizes the affective aspect of learning and doing. As Kafai and Resnick (1996) have noted, "In constructionist learning, forming new relationships with knowledge is as important as forming new representations of knowledge" (p. 2). In order to become involved in personally meaningful activity, the learning environment must be materially and conceptually rich enough to allow for student exploration and discovery.

Papert (1993) argues that a computer-based environment provides access to such material and conceptual richness.

Social aspects of learning refer to two notions for Papert. The first is that, through using objects in the environment to think with, children materially participate in their own cultural milieu and this helps them connect to adults in their environment who also are in touch with these objects. In a sense, the objects are an aspect of shared material culture that opens paths of communication between children and adults. These paths of communication become paths to learning for students. The second notion is that as children engage in personally meaningful activity, they become excited about this activity and naturally wish to discuss it with others. Hence, in a materially rich classroom (one that has computers, for instance) where open-ended student interaction is encouraged, much topical, social interaction will occur among students and between students and the teacher. This topical, social interaction spurs student learning and creativity.

In terms of using one's body to learn, Papert argues that computational media that use perceptual objects, such as Scratch and LEGO Robotics, offer students the opportunity to consider the movements of the object from their own bodily perspective and, in so doing, are enabled to reflect more deeply about how to program the object. In essence, the child can imagine her body in place of the object and may then reason, from a physical perspective, about how to program it. Indeed, we have observed this behavior in our research with students solving robotics problems (Sullivan, 2008). In our study, students used their hands as proxies for the robotic vehicle as they simulated the proposed movement of the robot and considered how to program that movement. Such simulation allows students to use their own bodies as a creative tool of exploration and reflection.

From the constructionist perspective, then, reflection is a key aspect of learning with computational media. The movement of an object-to-think-with, such as a Scratch Sprite or a LEGO Robot, provides immediate feedback to the learner. This feedback functions to stir reflection in the student that leads to the practice of debugging. When students encounter programming results that are inconsistent with their expectations, they are spurred to develop explanations of why this is so, which improves causal reasoning (Legare, Gelman, & Wellman, 2010). In essence, computational devices have the potential to spur metacognitive or reflective thinking, diagnostic reasoning, conditional reasoning, and problem solving as part and parcel of the activity itself.

In terms of computational media, then, the reified voices in the robotics and Scratch technologies that work to support and enable student creativity speak to the following ideas: (1) creativity is supported through engagement in personally meaningful activity; (2) creativity is supported through collaborative dialogue spurred by the perceptual nature of the media; (3) creativity is supported through embodied simulation; (4) creativity is supported through the reflection, explanation, and problem-solving activity that is promulgated by the immediate feedback mechanism of computational media. It is this intellectual activity, based on interaction with the perceptual object, that leads to student understanding of higher-level concepts and to creative expression.

Collaborative Creativity Research

Having presented our thesis on creativity as collaborative dialogic inquiry, and discussed the theoretical basis for the development of constructionist computational media, we now discuss the results of two prior research studies we have conducted on the development of collaborative creativity with these computational media (Sullivan, 2011; Sullivan, Hamilton, & Foley, 2012). These prior studies illustrate how collaborative creativity is enabled through curricula that use computational media. We begin with a case study of the collaborative development of a creative solution in a robotics context. We then present a case study focused on collaborative creativity in a Scratch learning environment.

Robotics and Collaborative Creativity

As previously noted, the LEGO Mindstorms robotics kit is equipped with Resnick, Martin, Sargent, and Silverman's (1996) programmable brick, a small microcomputer, encased in plastic featuring a visual display, power and menu selection buttons, and numerous ports for connecting sensors and motors with cables. The microcomputer is about the size of two decks of cards resting horizontally upon one another, so it fits easily in older children's hands. Generally speaking, the first activity children take part in when working on a robotics project is to build up the microcomputer into some sort of robotic device using the motors, the sensors and the LEGO pieces that come with the kit. Typically, a vehicular robotic device is assembled, though many other types of robotic structures could be created, for example, vending machines, automatic doors, or robotic arms.

In my case study on collaborative creativity (Sullivan, 2011), I followed three focal students (Esteban, Janice, and Yolanda (pseudonyms)), as they worked together to develop a creative solution to a programming challenge that required the use of a light sensor to solve. The study took place in a 6th grade science classroom in a small, economically depressed, city in Western Massachusetts. The study was conducted over a 2-week period. Robotics challenges were used to introduce students to physics-based elements of a light and heat energy unit. The curriculum for this study was cocreated by the first author, a physics professor and four middle school science teachers. The three focal students who took part in the study were all of Latina/o descent and each was 12 years old at the time of the study. The school they attended served students who demonstrated need of a high level of support from the school. More than 80% of the students received free lunch (an indicator of low socio-economic status in USA), and 38% of the students in this school were English language learners. Moreover, the school was, at that time, designated a level four school by the state of Massachusetts, indicating that the students performed at a failing level on the state's standardized tests.

My research with this group of students proceeded from my theoretical view of creativity as collaborative dialogic inquiry, which is to say, I collected and analyzed student interactions with the spoken and reified voices in the classroom. Data collection consisted of audio and videotaping all of the focal group's collaborative interactions, their interactions with the teacher and with other students in the classroom. I also interviewed the teacher at the end of the first and the second week of the robotics unit. The challenge given to the students in this case study was to program a robotic vehicle to perform the following tasks:

- Move forward until a black line (that reflects less light) is detected
- Make a 90-degree turn, then
- Back up slowly for one foot, and
- Repeat forever

The goal of this particular unit was for students to develop their knowledge of how the light sensor worked. A light sensor is a computerized device that functions to trigger an event, given certain lighting conditions.

The challenge was for the students to program the robot to respond when a black line was detected. The triggering source for this challenge was pieces of black paper provided by the teacher. These pieces of black paper were set on a grey carpet in the front of the classroom. The focal group initially approached the problem by taking light readings of the surface of the black paper only; they did not take a light reading of the grey carpet surrounding the black paper. At this early juncture, the students were using the light sensor not as a computational device, but as a measurement device, akin to a ruler or a measuring cup.

Based on their understanding of the relationship of the color spectrum to the reflection and absorption of light, the students expected the black pieces of paper to absorb more light than the grey carpet. However, each of the pieces of black paper provided by the teacher reflected different amounts of light due to the texture of the paper, and in two out of three cases, the black pieces of paper reflected more light than the grey carpet. This was a confounding variable which complicated the problem for the students. Over time, and through the process of collaborative dialogic inquiry, the students discovered that the reason they were having trouble solving the problem was because the grey classroom carpet was reflecting less light than the black construction paper meant to trigger the light sensor, hence their light sensing program was not working. This discovery is what Koschmann and Zemel (2009) call an *occasioned production*. It is a discovery that the students did not know they needed to make prior to the moment they made it. This occasioned production occurred as a result of their problem-solving effort the feedback they were getting from the various trials they were performing, their own discussions of the problem, and their interactions with the teacher; it represents their changing understanding of what the problem actually was. Indeed, once the students understood the variable nature of reflected light readings and the important role of the grey carpet in their calculations, they enacted a creative solution to the problem. This *creative solution was to repurpose the black cables* provided in the robotics kit to serve as the black source that would trigger the rest of the light sensor program.

The students' arrival at a creative solution was supported by their deepening understanding of the problem represented by three key, interrelated realizations. First, they came to understand that they needed a light reading of the approach surface (grey carpet) as well as the target surface (black paper), and that the function of the light sensor was not only to take a reading of the amount of light reflected off of various surfaces (sensor as measurement tool), but also to discern between the two light readings (sensor as computational device). Second they realized that not all similarly hued entities reflect the same amount of light. For example, the laminated black paper reflected more light than the black construction paper, due to the texture of the laminating plastic. And third, they reframed the given problem as one in which the light sensor is programmed to simply react to a black (or darker) surface, to an understanding that any number of environmental variables may serve to confound the process (Sullivan, 2008); and, therefore, these variables need to be identified and taken into account. This reframing of the problem is part and parcel of the creative activity engaged in by the students, it reflects the students deepening understanding of the complex nature of the problem and, as the students were better able to identify the variables bearing on the problem, so were they able to develop a creative solution. Dorst and Cross (2001) refer to this as the coevolution of the problem and the solution, which is a typical creative activity in design situations. The better one understands the problem, the more likely one is to develop a creative solution to the problem. Let us now consider how the voices (real and reified) in the classroom contributed to the students' creative solution.

Classroom-Based Internally Persuasive Discourse

As previously discussed, the sociocultural approach to understanding creativity focuses, in part, on the discursive interactions among people. (Rojas-Drummond et al., 2008) in their research on collaborative creativity in the language classroom have developed a good explanation of how idea generation works in a group:

> Among the common acts present in all the [discourse] data were: joint planning; taking turns; asking for and providing opinions; sharing, chaining and integrating of ideas; arguing their points of view; negotiating and coordinating perspectives; adding, revising, reformulating and elaborating on the information under discussion and seeking of agreements. These data, taken together, suggest that the children engaged in diverse processes of 'co-construction' of meaning and knowledge to achieve their goals. . . (p. 186).

The evolution of a creative idea, then, rests in part on an interactive process in which students draw on their own prior knowledge (internally persuasive discourses) and experience to generate ideas and contribute them to the group; these ideas may then be acted upon by others in a number of ways including evaluation, elaboration, clarification, or refutation.

In keeping with our theory of creativity as collaborative dialogic inquiry, we argue that in addition to idea generation in collaborative group interactions, ideas are also generated from interaction with other voices that are present in the environment itself. For example, in this case study, we found that in developing a creative solution to the robotics challenge, our focal group of students relied on ideas generated from three different sets of voices in addition to their own, including: (a) the teacher's voice, (b) the curriculum designers' voices (as reified in the designed activities), and (c) the technology designers' voices (as reified in the designed robotics technology).

The teacher's voice was present in the classroom not only through the words he spoke but also through the spatial arrangements of the room. Indeed, the classroom environment was designed by the teacher to support a student-centered, project-based, inquiry approach to learning. The student desks were arranged in clusters of four. Students sat facing one another during class time. In this arrangement, the students were oriented to one another, as opposed to all students facing forward, oriented towards the teacher, as is commonly found in more traditional seating arrangements. The classroom north wall featured student posters reporting on a recently completed inquiry project devoted to making functional model boats from various materials. There were two tables set against this wall that displayed the student completed model boats themselves.

The internally persuasive discourse embedded in the classroom environment as designed by the teacher reflects the teacher's epistemological belief in a collaborative, student-center, project-based, inquiry approach to the teaching and learning of science. This interpretation is validated by the teacher's own comments. In response to an interview question about his teaching style, he states:

> [My approach is] more [of an] inquiry-based situation where I challenge the kids with a question or problem, and then they have to attack it by some sort of process that they devise based on what we're learning. I pretty much give them full freedom because I think that they have the ability to move about the classroom and do what they're supposed to do, like the light scavenger hunt today. They were able to do that. They were then able to answer the questions about what we had in the review. I really think that the kids learn better that way, because they take the control of it for themselves.

Hence, students' ideas are influenced by the physical and spatial arrangements of the class itself in that they are allowed to pursue their own lines of inquiry. They are free to speak to one another and to move about the classroom. In essence, this teacher provides conditions for "freedom of intelligence," which Dewey (1938/1997) notes is the most important freedom we have. This freedom sends a message to the children. The message is "I trust you" and "I believe you can learn from interacting with one another." The teacher's voice thus reified has a strong impact on student idea generation. Students were free to think, explore, and create.

Likewise, the voice of the curriculum designers is reified in the content and the activities of the robotics unit. The curriculum for this study was developed by four middle school science teachers from the local area. The curriculum consisted of eight activities. The first two activities were prescribed, utilizing a hints worksheet for identifying and labeling the pieces and blueprint instructions for building the robotic vehicle. The remaining activities were open-ended; students were given minimal instruction as regards the completion of the remaining activities, they were expected to develop their own approaches to solving the particular robotics challenges utilizing the resources available to them including the written challenge itself, a ruler, the robotics vehicle, the touch, light, and temperature sensors, the Robolab programming software, members of the small group, other classmates, and the teacher. The curriculum designers' voices are reflected in the choice of open-ended, inquiry-based activities to be undertaken by the small groups. In this formulation, students direct their own group activity in solving the robotics challenges. They are free to move about the room to test their programs, free to discuss their programs with other students beyond their small groups and free to call on the teacher if they reach an impasse. Here, the curriculum designers' voices reinforce the voice of the teacher, which sends a message of openness and trust to the students in a spirit of collaborative inquiry.

Meanwhile, the technology designers' voices were reified in the robotics technology devices themselves. As noted earlier in this chapter, the Mindstorms kit was created based on constructionist learning principles. At the heart of the Mindstorms kit is the Programmable Brick. In discussing the design of the Brick, Resnick et al. (1996) have this to say:

> The Programmable Brick makes possible a wide range of new design activities for children, encouraging children to see themselves as designers and inventors. At the same time, we believe that these activities could fundamentally change how children think about (and relate to) computers and computational ideas. . .The Programmable Brick gives users the power to create and control. . .The Programmable Brick is explicitly programmable so that users can continually modify and customize its behavior. In this way, the Programmable Brick fits clearly within a constructionist approach to learning (p. 443–444).

In this case study, I argue there is an alignment among the teacher, the curriculum designers, and the technology designers' voices. The technology designers have created a technology that gives children "power to create and to control," it encourages children to see themselves as "designers and inventors." The technology design itself positions children affirmatively as regards their role in their own learning and creativity, just as the teacher's arrangement of the classroom and the curriculum designers' selection of open-ended assignments. Taken together these "voices" create an environment where students are empowered to generate ideas and pursue creative solutions to the robotics challenges.

Indeed, I found the interaction of these voices contributed to the emergence of three critical aspects of the enacted curriculum, which influenced the development of the key understandings and the creative solution pursued by the focal group, including: (1) an open-ended, goal-oriented task, (2) teacher modeling of inquiry techniques, and (3) provision of tools and an environment that allowed students to move between dual modes of interaction: seriousness and play.

Curricular and Pedagogical Design Implications

In this case study, students were working with a robotics challenge *in an open-ended, goal-oriented way.* Their activity was constrained by the parameters of the challenge, and therefore structured, but they were given much freedom in pursuing their solution. Furthermore, the *teacher modeled modes of inquiry*, which included investigation and reasoning (close examination of the functioning of the robot in a neutral setting), as well as playfulness and *bricolage* (demonstrated in an episode where the teacher used the tip of his black shoe to trigger the students' light sensor program). Levi-Strauss (1966) defined bricolage as the repurposing of items that are "ready-to-hand" in the environment. The students' creative idea of repurposing the black cables was an act of bricolage that reflected the teacher's use of the tip of his black shoe to trigger the program. While playfulness and bricolage are not generally considered modes of inquiry in science, they may well be important modes of inquiry as regards the development of creative ideas. If this is so, it points to the *importance of providing tools and an environment that allows students to move between dual modes of interaction: seriousness and play.* In this class, the students had a serious purpose, which was to solve the light sensor challenge, but they were allowed to move between modes of seriousness and modes of play by the teacher. Indeed, in 15 years of research into student learning with robotics, I have consistently observed that middle school students approach robotics as they would approach a toy; they always begin by playing with the robot. Play is also at the heart of the collaborative creativity displayed by two boys featured in the second case study, to which we now turn.

Scratch and Collaborative Creativity

Scratch is computational media that allows students to create interactive animations, music videos, video games, and other media genres. Scratch is a constructionist technology that promotes an iterative design cycle that includes imagining, playing, creating, sharing, and reflecting (Resnick et al., 2009). Scratch creations can be shared in the online Scratch community space and others can view the program or run it online. Scratch is an excellent environment for teaching young learners how to program (Lee, 2011). Recent research on student engagement with Scratch emphasizes the motivating role of youth popular culture as the content base of activity (Peppler & Kafai, 2007). We developed an after school club that featured Scratch, engagement with the Scratch web site, and student-directed animation development, thereby providing students the opportunity to pursue their own popular culture genre interests while learning how to program with Scratch (Sullivan et al., 2012). As will be demonstrated below, we found that students' collaborative creativity was stimulated by the shared genre interest of video gaming and jointly playing a video game that someone else had developed with Scratch.

The middle school students in our study were enrolled in an inner city K – 8 school serving predominantly Latino families with low socio-economic power. A high proportion (38%) of the students enrolled in the school where we conducted our study identified as limited English proficient students. Fifteen students participated in our Scratch Club; however, our data analysis focused only on the core eight students who maintained consistent attendance patterns across most sessions. Of these eight students, three were female and all but one identified themselves as Hispanic or Latino.

The Scratch Club met for approximately 90 min twice a week over a 16-week term. A similar schedule was followed across all sessions: 15 min of community sharing, 20–30 min of a mini-lesson on a particular computer concept, 30–40 min of independent (or collaborative) work, and 10–15 min of project sharing and reflection. The community sharing time was designed to foster social collaboration between students. The mini-lessons were based on ideas generated from the students' project work. During independent work time, students utilized the online Scratch community website to view, play, and remix downloaded animations created by others, they worked with in-class resource files such as the MIT-provided Scratch cards, engaged in discussions with instructors and classmates, and designed and programmed their independent projects. Project share time included "gallery walks" in which students viewed and discussed each others' projects.

While a number of measures were used to collect data in this study, the most salient for our discussion here are the participant observer field notes we collected. We collected notes for 23 of the 31 sessions (notes were not collected for four special events and the four sessions where the primary activity of the students was completion of the other measures). Data collection and analysis utilized methods described by Bogdan and Biklen (2007). Notes were compiled independently at the end of each session. These notes include recollection of specific utterances made by participants. Our data analysis indicated that student social interactions as related to the technology manifested itself in two forms: (1) as interaction revolving around shared genre interests and (2) as a desire to share one's accomplishments with others. Furthermore, the first type of interaction appeared to have been influenced by the classroom seating arrangement while the latter did not.

As previously noted, the Scratch program allows individuals to create interactive animations, music videos, video games, and other genres. We found that each student showed a preference for a particular genre (Sullivan et al., 2012). For example, four students were interested in downloading, playing, remixing, and creating video games; two students were primarily interested in downloading, remixing, and creating music videos; and two other students were interested in cartoons and/or animated, interactive stories. At times, these shared genre interests became a focal point for student interaction, learning and creative activity. For example, two boys, Mauricio and Raul (pseudonyms) whose primary interests were video games engaged in much discussion and collaborative problem solving related to remixing video games that they found on the Scratch website. These boys who were seated next to one another in the computer lab, downloaded, played, and remixed a chase and shoot video game.

Over the 32 sessions of the after school session, Raul and Mauricio devoted approximately 10 sessions to just playing video games. While, initially, this seemed like a waste of time to us, we eventually realized that through repeatedly playing the chase and shoot video game, the boys were informally studying how the game functioned. Later in the term, when one of the boys wished to create a classic arcade video game in which the characters chase and eat yellow dots, he received help from his friend in thinking about how to program the functionality of the game by reference to their prior shared experience with the chase and shoot game. Below is an excerpt from our field notes in relation this exchange:

> While I was working with Raul, Mauricio began asking me how he could make his maze game into a chase and eat video game. He could make one of his characters move around the maze with the arrow keys, but he couldn't figure out how to make the other character chase

> the first one. I suggested that he think about how one would track someone in real life, I said "You would have visual cues to where they were, right? There would be some way to trace the person." I then asked him what happens in the well-known chase and eat video game, he said the character ate up the yellow dots. I asked him to think about what kind of a trace the first character could leave that would allow the second character to chase it. Raul then suggested that Mauricio look at the chase and shoot video game they had played in prior weeks because the characters chase each other in that game. Mauricio opened that game and selected a zombie character and Raul said "No, pick a soldier 'cause they move." So, Mauricio clicked on a soldier sprite (Sullivan, field notes 3-17-11).

In this example, Raul scaffolded Mauricio's development of a chase and eat type video game he was creating by suggesting that Mauricio study an example provided in the chase and shoot video game. Here, we can see there are several voices coming together to influence the creative development of Mauricio's chase and eat type game. First, and perhaps, foremost, there is the voice of Raul, pointing out the resource that Mauricio could use, second, there is the voice of the designer of the chase and shoot video game, reified in the design of the game itself. Third, there is the voice of the Scratch technology designers who not only created the interactive program but also created an easy way for Scratch developers to share their work and learn from one another. In many ways, the online Scratch community resembles an open source software community, where people work collectively to create the tools they want and need. Finally, there is the voice of the designers of the after school club who provided students the freedom to study and make what they wanted, and the freedom to move about the room and work with any other student in the room. This type of collaborative interaction was also facilitated by the students' shared interest in the video games genre and their shared history of playing the chase and shoot video game.

Curricular Considerations and Pedagogical Approaches

In considering the design characteristics of curricula and pedagogy that support the development of collaborative creativity, our research, and the research of colleagues, has led us to consider three main aspects: the nature of the activity as it unfolds in the classroom (enacted curriculum), the nature of social interactions as enabled through the pedagogical approach (including interactions between the teacher and the students, and among the students themselves), and the role of the tools in the activity.

The Nature of the Activity

To support collaborative creativity in students in STEM learning environments, teachers must attend to the nature of the activity. Three types of activities lend themselves well to the enablement of creativity including design activities, problem-solving activities, and project-based, inquiry learning types of activities. From a pedagogical standpoint, these three activities overlap in various ways. As far as creativity is concerned, the structural overlap that is most significant is the open-ended nature of each of these activities. Open-endedness refers to the notion that there is more than one correct approach to engaging in the activity and there is more than one acceptable outcome for the activity. Let us briefly consider each type of activity.

Design Activities

Design activities are those in which the students are actively designing a functioning device (in the case of robotics) or a functioning program (in the case of Scratch). One of the main creative elements of design is problem setting (Schön, 1983). Problem setting is the act of naming and framing a problem to be solved through the design of a device or a program. While engaged with this activity of problem setting, students develop a deeper understanding of a problem through research, and in so doing, they begin to develop creative solutions to the problem. As noted earlier, Dorst and Cross (2001) refer to this as the coevolution of the problem and the solution.

Developing a design solution to a problem is aided by specific creative techniques such as combination, mutation, analogy, and first principles (Cross, 2004). Combination refers to creating a new design through combining elements of existing designs, while mutation refers to changing one or more aspects of an existing design. Analogy refers to creating a design by making an analogy between an existing design that solves a particular problem to a new design that solves a structurally similar problem. Finally, first principle regards designing from the characteristics of the activity for which one is designing. For example, if one is designing a table, then one characteristic of the design will be a flat surface upon which things may be lain. These techniques, used in combination with a deepening understanding of the problem, will lead to creative activity on the part of student designers.

Problem-Solving Activity

Problem-solving activity can be approached creatively, especially in terms of idea generation and the invention of strategies. Indeed, as noted above in our research on robotics, students first developed a new understanding of the problem through creating a deeper understanding of the functioning of the light sensor (problem reframing), they then generated various ideas for solving the problem, one of which was to re-purpose the black cables in the Mindstorms box to serve as the source of black in their challenge solution. Moreover, in a prior study of problem solving with robotics, we found students developed their own heuristic methods for understanding and solving the problem. One such method included using ones' body to simulate the movement of the robot (Sullivan, 2008). Such a strategy, while hypothesized by constructionist theorists, is still an instance of the development of an invented strategy when students develop the idea through interaction with the device.

To enable creativity in a problem-solving activity, it is important the problem be ill-structured (Jonassen, 2000). Ill-structured problems have specific characteristics that allow for student creativity to unfold. These characteristics include the partial nature of the initial problem state – not all of the pertinent information that bears on a problem is known; also, in ill-structured problems, there are many routes to solutions, and there are many acceptable "correct" answers. When working with ill-structured problems, students must work to define the problem (problem setting) and they must adopt a discovery orientation to the work (Dilon, 2003). Indeed, Sawyer and DeZutter (2009) have argued that collaborative creativity is supported when the outcome of a groups' work is unpredictable, rather than scripted. In other words, the results of a groups' work may be new to the teacher, as well as to the students themselves.

Project-Based, Inquiry Learning

A third pedagogical approach that features open-endedness and supports creativity is project-based, inquiry learning. The roots of this approach lie in the progressive education movement of the early twentieth-century championed by William Heard Kilpatrick (1918) and pragmatist philosopher, John Dewey (1938/1997). The focus in a project-based, inquiry learning approach is on a driving question, as it is developed by the students themselves (Krajcik & Blumenfeld, 2006). Pedagogically speaking, allowing students to develop and pursue their own interests improves student motivation to learn in the activity. It supports "freedom of intelligence" which Dewey defines as consisting of ". . .freedom of observation and of judgment exercised in behalf of purposes that are intrinsically worthwhile" (p. 61). The driving question grounds the learning activity in the lived experience of the children; this grounding allows children to bring their prior experience and knowledge to bear on the project. Often, a project-based, inquiry learning activity will result in the creation of an artifact. Developing such an artifact requires generative thinking on the part of the students and aids in the development of their creativity, particularly as it is related to both idea generation and problem framing.

These three activities, designing, problem solving, and project-based, inquiry learning are very well suited to learning in the STEM disciplines. And, through the open-ended nature of the activity, students are able to engage in a number of practices that enable the development of creativity including: problem setting, using design techniques such as combination, mutation, analogy, and first principles, idea generation, invented strategies, and utilizing their freedom of intelligence to create artifacts that are personally meaningfully. All of these elements support students' free expression of ideas, autonomy, and initiative.

The Nature of Social Interactions

Another element a teacher must attend to when creating the conditions for student collaborative creativity is the nature of social interactions. Here there are two main aspects, first, the role of play and playful talk in a collaborative group context and, second, there is the importance of creating a less hierarchical atmosphere in the classroom, which includes devolving authority from the teacher to the students and supporting student-student interactions. Let us now turn our attention to consideration of the role of social interactions in the enablement of creativity.

Play and Playful Talk

Play and playful talk within the group are integral aspects of the enablement of collaborative creativity. For example, prior research has shown that creativity in collaborative groups is supported when the group itself grounds their interactions in playfulness (Kangas, 2010; Vass, 2007). Play and playful talk are features of the affective climate of the group that have an effect on learning and creativity within the group. Indeed, Vass (2007) has argued that it is the emotional content of play that can serve as a generator of ideas within a collaborative group. Meanwhile, Wegerif (2007) has shown that the notion of playful talk includes verbally "playing" with ideas that may then become the basis of a design, solution, or project element. Moreover, Aragon, et al., (2009) found that the online socio-emotional discussions engaged in by collaborators was a key aspect of two different groups' abilities to work creatively together. Finally, a collaborative group that engages in a high amount of playful talk may well be using that genre to accomplish important affective work within the group. For example, in our own research (Sullivan & Wilson, 2015), we found that a group of students solving robotics challenges used the playful talk genre as a means of regulating the functioning of the group vis-à-vis creating opportunities to learn for all of the members of the group.

Non-hierarchical Teacher-Student Relations

A second, vital, aspect of the role of social interactions in supporting collaborative creativity is the establishment of a nonevaluative environment for the exploration of ideas. As such, the role of the teacher must, necessarily, become less authoritative. Social cognitive research has clearly established the negative impact of evaluation on student creativity (Amabile, 1983; Hennessey, 1995). While this proposes a problem for teachers who must assess student learning, it is not an insurmountable one. For example, it is possible to work collaboratively with students, discussing their ideas with them, providing suggestions where appropriate, and generally encouraging students to develop their ideas. Evaluation and assessment may then occur at the end of the unit. In this way, the teacher enables freedom for students to try out new ideas and to make mistakes while learning. We may think of these actions as being very close to an authentic mode of learning, coming to know and transforming reality through interaction and experience; a practice that is more spontaneous and intuitive and less reproductive or reactionary. Beyond that, the teacher should provide minimal instruction regarding the tools and how they are appropriated to the creative action of the students.

Role of the Tools

Bruner (1973) has argued that there are three representational modes that support the development of higher order thinking in individuals, the enactive (physical interaction), the iconic (perceptual interaction), and the symbolic (linguistic or other sign system interaction). Moreover, while the developing child passes, over time, through a progressive and sequential process of learning to reason from the enactive, to the iconic, and finally the symbolic mode, an individual continues to use these three representational modes for learning interchangeably throughout a life time.

When children work with robotics they are working at all three levels of representation, which increases the pathways to understanding and meaning making available to the child. As we have discussed at length elsewhere (Sullivan & Heffernan, 2016) robotics devices are computational manipulatives. As such, they provide students the opportunity to both physically and virtually interact with the tools. Traditional manipulatives are concrete referents to abstract concepts, for example, using Cuisenaire rods to develop knowledge of mathematical concepts and relationships (Manches & O'Malley, 2012). According to Fishkin (2004), interaction with manipulatives engenders analogical reasoning and embodied cognition. When children use traditional manipulatives, they are often working at the enactive and iconic representational levels.

Computational manipulatives add the symbolic mode to the representational level students are working at; in robotics, students work with a physical device that they can see and manipulate, and they work with one of several programming languages to program a robotics device. While the physical robotics tools serve the traditional purpose of enabling analogical reasoning and embodied cognition, the computational aspect results in a feedback loop that engenders a number of cognitive processes associated with the habits of mind of scientifically literate people including but not limited to reflection, evaluation, hypothesizing, experimenting, measurement, collaborative discussion, and the development of specific, context-based heuristics for problem solving (Papert, 1993; Sullivan, 2008, 2011).

In terms of collaborative creativity, the enactive representational mode has an important role to play. As we found in our prior research, playing with the physical robot serves two important functions. First, it allows students to imagine the robotic device in terms of their own life world. For example, in much of our work with students and robotics, the first thing that happens is students make analogies to objects or entities in their own life, "it looks like a race car," "it looks like a dog," "look, I can make it into a purse." These comments help the students identify with the materials and the activity of robotics. We have found that identification with the activity is an important aspect of creating opportunities to learn with the materials, and that is especially true for girls (Sullivan & Wilson, 2015).

In addition to the identification function, the device and the robotics materials, in general, lend themselves to bricolage. As noted above, bricolage is a means of repurposing materials in one's environment to fit one's specific needs. Students play with the Lego pieces and the other elements of the robotics kits to help them solve the robotics problems in creative ways (Sullivan, 2011). The bricolage function is very much related to the notion of tinkering and experimenting with materials.

While computational media have an important role to play in STEM education, especially when the goal is to promote collaborative creativity, it is important to bear in mind that the tools may also be used in noncreative ways. In other words, just because the tool lends itself to creativity, does not mean everyone will pick up the tool in a creative way. For example, in many cases, new computational technologies may simply be used to reinforce the didactic, transmission-oriented ways of teaching and learning. In order to inspire collaborative creativity, it is important to not only provide the tools but also the social context that supports creativity.

In our view, it is necessary to adopt tools that afford more opportunities for students to collaboratively create in the STEM teaching context. In our research, we utilized two distinct computational tools: LEGO Mindstorms robotics kits and the Scratch program; both tools have the same goal, to give students the power to create and control things in the physical and virtual world, respectively. Resnick (2008), the creator of these computational media, has designed them to be, above all, easily handled by children and young students. He highlights that the main characteristics of the tools are to support creative thinking, arguing that these tools should open space for exploration, with low thresholds for entry, yet, high ceilings for participation (Resnick & Silverman, 2005). Moreover, these tools allow many paths for many styles, supporting collaboration and the open interchange of ideas (Resnick & Silverman). The role of the tool, then, is twofold, both cognitive and affective. It is both a powerful object-to-think-with operating on all three levels of representation, and it is a playful device inspiring both the identification and bricolage functions in children who are allowed to play and learn with them.

Conclusion

From our perspective, collaborative creativity is the wave of the future. Interdisciplinary teams, working over networks to creatively solve the urgent social and scientific problems of today are now and will continue to be the norm. For example, teams that work on environmental issues where many factors need to be taken into consideration may include biologists, geologists, atmospheric scientists, computer scientists, economists, and statisticians. Whereas teams that work on social problems may include doctors, nurses, public health officials, law enforcement, and elected officials. These interdisciplinary teams may use the internet, shared documents in the cloud, mobile phones, and other networked communications to plan and manage their collective work.

In our research, we seek to understand the pedagogical and curricular factors that best support students' ability to engage in collaborative creativity with one another, aided by robust computational media. For, it is not only the robust tools that matter but the conditions of their use. To truly support collaborative creativity, teachers and curriculum designers must create classroom conditions that support freedom of intelligence, choice, play, dialogic inquiry, identification, and bricolage. Here we have provided some insight, gained from our research studies, as to how such conditions may be established in the classroom.

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