Bugs as a Nexus for Emergent Peer Collaborations: Contextual and Classroom Supports for Solving Problems in Electronic Textiles

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Abstract: Few studies have examined the role of failure in more open-ended situations where problems develop as a consequence of designing projects and where collaborations can emerge as an outgrowth of debugging said problems. In this paper, we explore the peer-to-peer collaborations that emerge spontaneously in the context of coding, crafting and design bugs within open-ended design activities, specifically an electronic textiles unit for secondary students taught over 10-12 weeks in introductory computer science classes. Examining observations from three introductory computer science classrooms, we address the following research questions: (1) How and what kinds of peer-to-peer collaborations emerged in unstructured ways, especially around bugs in open-ended projects? and (2) What curricular, spatial, social, and teacher supports allowed these interactions to emerge and flourish? In the discussion, we consider implications for supporting similar types of emergent collaborative learning in open-ended computational making designs.

Introduction

One could argue that failure in its various forms has more often been seen as an impediment rather than a complement to successful collaboration (Barron, 2003). Indeed, failure can lead to stable patterns of discourse in a classroom community with troubling consequences for students' ideas about themselves (DeLiema, 2017). However, the recent success of "productive failure" (Kapur, 2008) has put failure into a different light: it highlights the counterintuitive notion that failure can precede later success in learning. Yet the research on productive failure has generally emphasized tight structures both in collaborative groups and in the sequence of planned ill- and well-structured problems (e.g., Kapur & Kinzer, 2009, Kapur, 2008). Missing in these studies is an opportunity to examine the role of failure in more open-ended situations where problems develop as a consequence of designing projects and where peer collaborations can emerge as an outgrowth of debugging said problems.

Problems that stem from designing open-ended projects, such as those common in most STEM-oriented maker activities (Peppler, Halverson & Kafai, 2016), occur frequently in many situations where groups are not pre-designated. In open-ended maker activities, temporary failures or unexpected bugs are not just hindrances but also opportunities for learning, when and if students reach outside of their immediate work to a wider group of people and resources (e.g., Sheridan et al., 2014). Reaching out can generate emergent collaborations, that occur quite frequently in makerspaces as students help each other, invent uses for technology, and catch ideas from each other (Halverson, Litts & Gravel, 2018). This raises questions about how peers help each other and what attributes of the broader environment facilitate such improvised collaborations, for even spontaneous collaboration does not take place in a vacuum.

In this paper, we explore the peer-to-peer collaborations that emerge spontaneously in the context of bugs (or problems) within open-ended design activities, specifically an electronic textiles unit for secondary students taught over 10-12 weeks in introductory computer science classes (Fields et al., 2018). Electronic textiles (e-textiles) involve programmable circuits hand-sewn onto soft objects like clothing and stuffed animals, with conductive thread, LEDs, digital sensors, and sewable microcontrollers, providing a space for creating personally relevant computational artifacts (Buechley, Peppler, Eisenberg & Kafai, 2013). Making an e-textile artifact involves learning not only about crafting, circuitry and code but also about identifying, isolating, and fixing bugs at the intersection of these domains (Fields, Searle, & Kafai, 2016; Jayathirtha, Fields & Kafai, 2018). Whereas the study of collaboration has often focused on structural supports that teachers or computer environments provide to ensure success, this study focuses on how peers help each other progress through failure and the qualities of the broader learning environment that support these emergent collaborations. The particular context of our study includes three introductory computer science high school classrooms with 69 students where different teachers at separate public secondary schools led an e-textiles unit in which students created a series of four e-textile projects (Fields et al., 2018). In this paper we explore 1) How and what kinds of peer-to-peer collaborations emerged in unstructured ways (i.e., outside of assigned collaborative groupings), especially around bugs in open-ended projects? 2) What curricular, spatial, social, and teacher supports allowed these interactions to emerge and flourish? In the discussion we consider implications for supporting similar types of emergent collaborative learning in open-ended computational making.

Background

Debugging has long been noted as a productive, if not particularly collaborative, site of learning (e.g., Papert, 1980). As a site of problem solving, debugging is recognized as a key computational thinking practice in engineering and computing that is essential but often overlooked in K–12 classrooms (College Board, 2016; McCauley et al., 2008). Debugging computational issues requires a deep and systematic understanding of the program along with the programming language and environment (i.e., McCauley et al., 2008). The ability to debug or troubleshoot may be especially challenging for novice programmers who lack experience in seeing programs as a whole and systematically identifying, testing, and solving problems (Vessey, 1985). Yet while there is significant research around tools and programming environments designed to support learners through the process of debugging (e.g., Ko & Myers, 2004; Sorva, Lönnberg, & Malmi, 2013), there is relatively little research about other kinds of pedagogical, social, and environmental structures that can support learners dealing with various debugging challenges. Understanding learning environments that support debugging is especially important since the complexity associated with debugging demands not just programming skills but also other skills such as decision-making, emotional intelligence, and perseverance (e.g., Patil & Codner, 2007).

Within the field of computer science education, collaboration is generally understudied even if it is recognized as helpful. Most prominent is the research on pair programming where a team of two learners collaborate on one project, designing, coding, testing and debugging on a single machine with students periodically changing roles as “driver” and “navigator” (Williams & Kessler, 2000). While this model illuminates the social aspect of problem solving in programming contexts, this more formal, structured model of collaboration does not include other possible modes of collaboration when more than a pair of learners attempt to support each other. Further, these formal collaboration arrangements become more difficult to maintain when learners are programming in hybrid computing environments such as robotics and e-textiles. For example, the studies about collaboration in making e-textiles or similarly crafted computational artifacts have shown students splitting up their learning in inequitable ways rather than learning productively from each other (e.g., Litts et al., 2017). Moreover, a focus on only formal ways of pairing up students misses opportunities to explore other more open-ended forms of collaboration and emergent social supports where students can draw help from peers other than their immediate partners.

In this study then, we focus on the nature and contexts of emergent peer learning while debugging in a classroom environment, how it emerged (because of the teacher, peers, or through other means), and how it mattered to individual students. This type of peer-to-peer collaboration has received much less attention in research because most studies have focused on organized small groups, with students taking on various roles or with some students designated as more experienced experts or less experienced novices in situations intended to generate “peer pedagogy” where peers educate each other (e.g., Ching & Kafai, 2008). Yet teachers are already developing environments where more emergent peer pedagogy, not structured in specific groups, can take place. For instance, a prior study on the e-textiles curricular unit for introductory computing classes documented productive teacher practices that supported equity, namely by legitimizing peer expertise and supporting iterative learning (Fields et al., 2018). The researchers observed that teachers modeled their own and their students’ mistakes to the whole classroom, lowering the risk associated with failure and allowing students to provide ideas to solve problems in the projects. Sometimes, especially in situations where the teacher could not give individualized help to each student, the teacher would train one student in a task (e.g., a crafting or computing technique) with the expectation that that student would then share that knowledge with others. These and other practices, structures, and environmental features may support productive peer pedagogy.

The many peer-to-peer learning collaborations that emerged beyond formal partnerships in our study appeared to be highly significant to students’ continued perseverance in the e-textile unit. So, we sought to understand how these specific collaborations emerged, what relevance they had to individual students, and what aspects of the larger classroom environment facilitated these types of interactions.

Methods

Context and participants

Over the course of two years, we developed an e-textiles unit for the *Exploring Computer Science* (ECS) curriculum, a year-long introductory computing course with equity-focused and inquiry-based teaching (Goode, Chapman, & Margolis, 2012). This paper focuses on the second year of this e-textiles unit implementation, where three teachers led the unit separately in each of their respective schools. The e-textiles unit took place over 10-12 weeks and consisted of a series of four projects: 1) a paper-card using a simple circuit, 2) a wristband with three LEDs in parallel, 3) a classroom-wide mural project completed in pairs that incorporated two switches to computationally create four lighting patterns (the only collaborative project), and 4) a "human sensor" project that used handmade sensors to create conditions for lighting effects (see Kafai & Fields, 2018). Each project allowed increasing flexibility in design and personalization in the context of learning challenging new computing concepts. The e-textile projects provided many opportunities for debugging since problems occurred in the code, the circuitry, and the physical designs, requiring students to test and isolate problems, often fixing multiple co-occurring issues that added to the complexity and challenge of the projects (Kafai et al., 2014; Fields et al., 2016; Jayathirtha et al., 2018). The unit also drew on ECS practices such as pair programming during certain coding lessons.

The three schools were located in a large metropolitan school district and served a large number of students who came from ethnic/racial groups that are traditionally underrepresented in CS. At the three schools, 54-95% of students were identified as socioeconomically disadvantaged as defined by the state, and were ethnically diverse (40-90% Hispanic or Latino/a, 1-25% White, 4-43% African American, 0-18% Asian, 0-10% Filipino). The classes each included 20-35 students from 9th-12th grade (14-18 years old) and were diverse in terms of and gender ratios (36-66% girls). All teachers received six days of professional development over two years: three days in the first year of the curriculum development focused on design and content learning, and three days in the second year focused on supportive pedagogical practices.

Data collection and analysis

Data for our analysis was drawn from fieldnotes, student artifacts, and interviews across the three classrooms. Two researchers, including the first author who was also a lead designer of the unit, collected weekly field notes in each classroom adding up to 39 fieldnotes. In addition to observational fieldnotes, we collected students' design notebooks, journals, and end-of-unit portfolios where students reflected on challenges and learning during the unit. Further, we interviewed 12 students from each classroom in focus groups at the end of the unit and interviewed teachers before, during, and after the unit. Of note, the original focus our data collection was on students' learning of computational and circuitry concepts, which matched our research agenda. However, we recognized the central role of unplanned peer-to-peer collaborations in students' learning and perseverance in the unit after initial analysis of students' progressions of learning with e-textiles. This led us to analyze emergent collaboration in its own rite.

In analyzing the data, we first sought to identify all examples of emergent peer-to-peer collaboration across our observations. We defined this to include only student collaborations outside of teacher-directed groups (i.e., pair programing lessons) or formal partnerships (i.e., the collaborative pair-work in project #3) that related to student work (i.e., excluding casual banter unrelated to classwork). Drawing from the principles of grounded theory (Charmaz, 2014), two researchers initially coded a set of three field notes (close to 10% of the total), to come to agreement on applications of this definition, and coded a second set to verify consistency. Then one researcher culled all examples of emergent peer-to-peer collaboration in the entire dataset. We then analyzed these moments holistically (Miles, Huberman & Saldana, 2014), often returning to fieldnotes or related data (i.e., portfolios where students reflected on problems), to understand what stimulated those moments of emergent collaboration, the larger context that surrounded them, and their implications on the students. Next, using a two-step open coding analysis (i.e., developing initial codes, analyzing the dataset in full, re-visiting and editing the codes, and re-analyzing the dataset in full), we jointly developed the following categories which we will elaborate on in the findings section:

- *Stimuli for collaboration*: Bugs, verbal exclamations, help other than debugging, stimulus from a lesson, other.
- *Subject of collaboration*: Problem-solving, feelings of camaraderie, extra pair of hands, other.
- *Enabling environmental factors*: Physical proximity, overseeing/overhearing, curricular affordances, teacher practices, distributed expertise, adult brokerage, earlier friendship

Overall, our analysis was similar to Sawyer's work (2012) in that there was a focus on individual actions that was used to identify the events of emergent collaboration, which then guided a deeper sociocultural analysis of the contextual factors around these events.

Findings

We identified five types of stimuli for emergent peer collaboration: bugs (a problem in a project or task); exclamations (students saying something loudly, such as something that went well); general help (including learning a new technique, getting advise on the aesthetics or appearance of a project or completing a necessary task); following through on a lesson-based task that was not intended for group work, or a general "other". Figure 1 shows the frequency of instances in each of these areas as well as the type of collaboration that occurred: solving a problem, building camaraderie between peers, working together not on a problem but on something that required "extra hands" (i.e., holding something), and of course, "other."

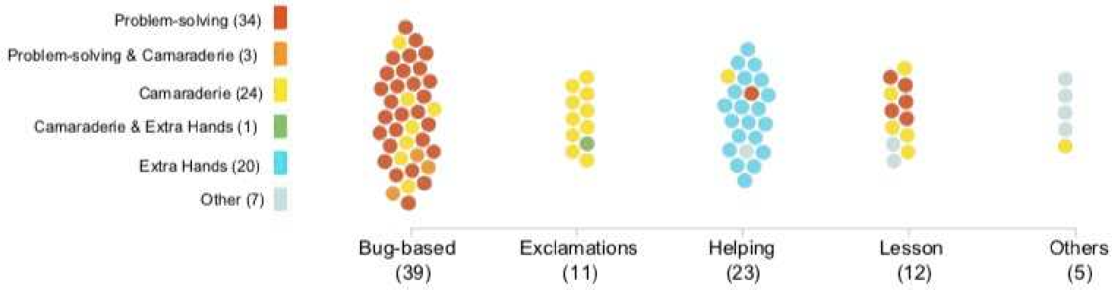

Figure 1. Graphical visualization of all the instances of emergent collaborations across the themes.

Since the majority of the instances that involved bugs (a little less than half of all emergent collaborations), we focus the remainder of this paper on investigating this area more deeply. Bug-related events might involve realizing a breakdown, identifying a bug, fixing, testing or otherwise debugging a project or celebrating fixing a bug. Collaborations stimulated by bugs included directly helping in problem-solving (red and orange dots in Figure 1) or providing emotional support (i.e., "camaraderie"—orange and yellow) by fostering a sense of camaraderie around making mistakes by encouraging, being comical or even heckling. In order to share the wide variety of technical and emotional supports that students provided to each other, below we explicate three examples of peer collaboration which illuminate the diversity of supports and immediate contextual factors that enabled the collaboration. We also include information about the significance of these moments for students who were involved in these collaborations. At the end we consider the broader contextual factors that enabled these emergent collaborations, including the tools, spaces, classroom and lesson structures, classroom practices, and student and teacher roles.

Observations of emergent collaborations

Initiating peer-to-peer debugging

One way that bugs became a source of collaboration was when students noticed another student's bug and inserted themselves into the debugging process without being invited. For instance, this happened with Andrea, a student who had earlier been identified by her teacher as a 'middle of the class' student who struggled with motivation in the class. Unusually for her (teacher post-interview, May 24, 2017), Andrea was one of the first to finish her final project (the human sensor project) and noticed that a friend sitting at the same table, Maria, was struggling with her project. The collaboration proceeded as follows:

First, Andrea noticed that Maria was having trouble with her project. Andrea shifted her seat to be next to Maria and began to interact with Maria's project. When uploading the code, an error message about the "port" came up, and the girls realized that the USB cable was not working. They switched out the cable and were able to upload the code, but no lighting patterns were triggered when the sensor (two aluminum foil patches) was activated by their touch. Andrea set her computer next to Maria's to check the code. Andrea went line by line through the code with Maria to see if was correct. 'I think it's the 1000 [sensor range]. Mine is set to 900 and it works better; maybe your range is too small,' Andrea said. In this, Andrea identified that the sensor threshold was too high, and the ranges within the conditional statements did not trigger the outputs Maria had programmed. Once they changed the ranges, two of the four patterns in Maria's project worked. Maria then began to debug her own code, identifying some places in her lighting patterns that were not giving the effects she intended. Andrea continued to sit next to Maria for the rest of the time, playing with a fidget spinner and answering questions whenever Maria asked for help (field note, May 18, 2017).

This spontaneous collaboration began with a bug in Maria's project apparent without any requests for assistance. In fact, spotting a simple USB cord problem led to a series of bugs including the more challenging customization of sensor ranges within a set of conditional statements. Notably, both the teacher and researchers noticed a change in Andrea during the e-textiles unit, moving from hesitation about computing and coding to being "way more proud and way more into the work" (teacher post-interview, May 24, 2017). This change was visible in Andrea's confident approach to her friend and tablemate Maria, and in the ways that she both helped identify and fix problems and stood by while Maria continued to debug on her own.

Soliciting help on peer-to-peer debugging

Another type of emergent peer collaboration involved students explicitly soliciting another's help to debug their projects. Many a times students requested help from peers they considered more expert in a specific area, from threading a needle to checking a circuit diagram to fixing code. This recognition of expertise may have come from a teacher or researcher suggesting getting help from a particular student or, more often, from prior knowledge of a student's expertise from earlier in the class, as it did with Jesse below.

During the fourth project, Jesse had successfully sewn and tested his lights and had sewn his sensors patches on but was "terrified" to start the coding of his sensors, which involved reading the sensors and deciding on a set of ranges that would work with different levels of squeezing the two patches (fieldnote, Mar. 07, 2017). To start on the coding, he got up from his seat and went to the other side of the classroom to seek help from Gencio, a student who had already worked through much of his sensor code (with the help of a researcher) and who was known as a very proficient coder in the class. After getting assistance from Gencio, Jesse came back to his table and almost immediately switched roles from being helped to helping, looking at his neighbor Joyce's code and pointing out an incorrectly (or inconsistently) named variable. Joyce quickly corrected her error, but not before the interaction drew the attention of Felix, sitting at the same table, who teased Joyce for not listening carefully.

The whole sequence of events demonstrates an example of cascading help that was provided from one person to another. First, the researcher helped Gencio and his partner with coding and debugging the sensors on their projects. Later, Jesse approached Gencio for help. Then Jesse pointed out an error to Joyce, and the whole table became involved in Felix's teasing about Joyce's coding bug. Conversations such as these where students developed a sense of camaraderie by heckling, joking and even encouraging each other were observed frequently as demonstrated in the Dante and Juan's story (see next section).

Peer camaraderie over failure

One other type of collaboration that occurred around debugging included many friendly conversations where peers sympathized about bugs. Often prompted by a student's encounter with some mistake or issue, these conversations became places where students not only shared their individual problems, but also debated their causes and considered possible solutions. Along with promoting a sense of camaraderie and/or sympathy, these moments provided much needed emotional support for one to persevere through moments of frustration and sense of failure. For example, below is a fieldnote record (Jan. 26, 2017) illustrating Dante's experience when debugging his dysfunctional wristband (project #2) led to a spontaneous conversation, inviting his nearby classmate's attention. During this episode, Dante shifted from discouragement to sharing laughter with peers about common mistakes, highlighting the way camaraderie influenced his participation.

Researcher: How's it going?

Dante: I can't sew. Yeah, I keep messing up like 30 times. *(Other students giggle.)*

Researcher: What did you mess up on? *(Others are still snickering.)* Everybody else knows what you're messing up on?

Dante: It's 'cause I didn't pull the string all the way, so I had loops in the back...

Juan: Yeah, but his first mistake was getting that color, though.

Dante: Oh yeah. Yeah, my first mistake was getting this [gray] color felt, so I barely see the [gray conductive] string.

Researcher: Ohhh, it's hard to see!... So that was the first problem, the color?

Dante: Yeah, because I didn't know what I was doing so I was just pulling the strings, and before I knew it, I was pulling apart… *(Points to frayed areas of felt on his project).*

Researcher: Oh, 'cuz you can't tell what's the string and what's the fabric…. (*Juan laughs)* And Juan, why're you laughin' at him?

Juan: 'Cuz I made the same mistake!

(Juan, sitting across the table from Dante, starts to describe how messy the back of his wristband was, after he thought he did a good job stitching and pulling the thread all the way through. He talks on for a minute.)

Juan: Yeah, and when you look at the back… *(Several others laugh, including Dante).*

Dante's visible errors—large knotty clumps of thread with fabric the same grey color of the thread—invited attention and laughter from his classmates, providing an opportunity for Juan to share his own similar mistakes. While the laughter of Dante's classmates may initially appear off-putting, the tone of the conversation implies that the laughter was more in sympathy than in jest, effectively lessening the significance of a single mistake. In fact, Dante joined in on the laughter at the end, sharing a sense of camaraderie over common problems. Although Dante never successfully completed his wristband, this did not prevent Dante from finishing his next two (more difficult) projects. In the end, even creating a fully-functional final project which involved a spatially complex, three-dimensional interactive ball created attaching four pieces of felt.

Designs and supports for emergent collaboration

Analyzing the occurrences of emergent collaboration around bugs (including those above as well as our entire dataset), here we consider the features of the learning environment that supported this phenomenon. Overseeing, overhearing, and close proximity to peers were important features that related to physical aspects of both the projects and the spaces in classrooms. For instance, bugs stood out visibly in the physical *tangibility* of e-textiles. Mistakes such as knotty threads or malfunctioning lights were visible to others within eyesight, effectively serving as "open tools" (Hutchins, 1995) that triggered collaboration and, as seen above with Dante and Juan, commiseration over problems. Further, all three classrooms had *open physical spaces* where students were grouped at tables and could see each other's work. A number of collaborations happened between students sitting next to each other or across the table from each other (e.g., Andrea and Maria). Muttered frustrations or exclamations also led to conversations and collaborations about problems, even when problems were not physically visible.

More subtle than visible and audible awareness of bugs, the *curricular structures* of the e-textile unit further enabled emergent collaborations. The design constraints for the projects meant that each student had to learn similar concepts (i.e., coding conditionals for human touch sensor patches in project #4) while allowing for personal customization (Kafai & Fields, 2018). This combination of constraints and personalization meant that students could legitimately learn from each other and even copy techniques of code, circuitry, or craft while still making something unique. For instance, looking at a peer's code served as a stepping stone for students like Maria or Jesse to debug their projects. Further, the curriculum suggested regular formal collaborations in certain lessons, including pair programming, a collaborative project (project #3), and whole class discussions. This provided precedence and practice for students to work together, and many students either returned to earlier partnerships or used knowledge about peers' expertise gained from class discussions to seek help.

The social structures promoted in the curriculum combined with prior *social networks* in the classes to facilitate emergent collaborations. Adding to the formal collaborative pairings and discussions, students used their own prior networks of friendship in providing help, seeking assistance, and sympathizing over problems. Many emergent collaborations took place between students who had been long-time friends, as was the case of Andrea and Maria. In addition, some students like Dante stated that they developed new friendships during the unit more than at any other time of the school year, expanding social networks.

Finally, *teachers' practices* and *classroom management* played both indirect and direct roles in emergent collaborations around bugs. For instance, unspoken classroom rules allowed for the *mobility* of students and for *informal conversation* about problems. Though students were expected to be on task, this did not mean that they had to sit silently at their own seat as they might be expected to in other school contexts. In addition, teachers often intervened more directly to support peer-to-peer learning by brokering help between students. Further, as we found in our study of teacher practices in the unit (Fields et al., 2018), teachers frequently legitimized students' diverse and developing expertise, highlighting students' knowledge from their earlier mistakes in classroom reflections and sharing of "tips and tricks". This supported the idea of turning to students, not just teachers, as sources of knowledge. Open physical spaces, tangible artifacts, project constraints, formal collaborations, informal social networks, combined with classroom practices to facilitate emergent peer collaborations around bugs.

Discussion

In this paper we described unplanned peer-to-peer collaborations that emerged around problems, or bugs, in students' open-ended e-textile designs. Though others have pointed out the collaborations that happen around idea-generation and technique diffusion in makerspaces (Halverson et al., 2018), in our study problem-naming, fixing and helping were a nexus for emergent peer collaboration. Student-to-student collaborations around bugs resulted in just-in-time assistance with troubleshooting, encouragement, and even humor that helped students' progress and persevere through problems. In doing so students took up roles of leadership and expertise while developing friendships in the class and inserting humor into an often-frustrating design process. Unlike the engineered moments of "productive failure" scenarios (e.g., Kapur, 2008), there is an ample supply of bugs in e-textile designs that arise without structured planning. Together these findings not only refine our understanding of student collaborative experiences in the face of failures but also highlight some of the key contextual factors that turn these moments into productive ones.

In discussing various environmental features that support emergent collaboration, we considered the roles of physical, curricular, social, and teacher attributes. Tangible artifacts and open spaces combined with social norms that allowed movement, conversation, and improvisation afforded opportunities for students to see, hear, and converse with each other over challenges. In settings where making or constructing are the focus and where the teacher is not the only expert in the room, it is important to highlight the more tacit qualities of learning environments and classroom practices that facilitate learning. We do not assume to have captured all environmental aspects that support emergent peer collaboration. Rather we hope that this study provides a starting point for exploring bug-focused collaborations and contextual factors that support emergent collaborations. Much more awaits further study, such as potential relationships between types of problems and the collaborations that emerge around them, the role of different tools and representations in the problem space in inviting collaboration (or not), and further environmental supports (structures, spaces, norms, practices) that facilitate or constrain peer collaboration. More work is also needed on the social-emotional qualities of emergent collaborations, for instance the "camaraderie" identified in this study, which played an important role in making "failure" and bugs more socially acceptable to students like Dante and Juan, facilitating not just problem-solving but emotional robustness and overall perseverance during the course of the unit.

Much work in computer supported collaborative learning has focused on designing direct scaffolds for participation, whether in the form of group roles, group structures, on-screen or in-class scaffolds, or tasks that facilitate collaboration. One of the challenges with such fixed arrangements is that they provide little agency for students to develop their own competencies in dealing with frequent unforeseen challenges that occur while making computational artifacts outside the structured settings. Emergent peer collaboration provides a means to acknowledge and support student agency, expertise, and creativity. Designing environments for emergent collaboration, including in relation to more formal collaborations, may open up even greater opportunities for student learning and development.

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