The Discourse of Creative Problem Solving in Childhood Engineering Education

Elise Deitrick, Brian O'Connell and R. Benjamin Shapiro
Center for Engineering Education & Outreach, Tufts University, Medford, MA, USA
Elise.Deitrick@tufts.edu, Brian.O_Connell@tufts.edu, Ben@cs.tufts.edu

Abstract: Researchers and teachers are increasingly in agreement that classrooms should adopt more open-ended, ill-structured, creative problem solving pedagogies (Kapur, 2008). However, we lack sufficient understandings of how to assess the variegated *outputs* of learning activities that afford students considerable discretion over what they will produce, and of the mechanisms through which group work can produce those outcomes. In order to understand how collaborative problem solving discourse shapes the creativity of collaborative products (as measured by the novelty of those products), we analyzed collaborative problem solving talk and the resulting products designed for fictional character by 9 groups of middle-school aged youth. We found that engaged responses to peers' proposed design ideas are predictive of novel solutions.

Introduction

Creativity has been gaining attention in education as an important skill for students in a variety of disciplines. Researchers are beginning to recognize the need to study the role of creativity in learning, and how creativity is related to other important phenomena. Creativity has been directly implicated by prominent theories of giftedness in young students (Renzulli, 2005; Sternberg, 2005). Creativity has been connected with improved performance and retention in mathematics (Van Harpen & Presmeg, 2013; Yuan & Sriraman, 2011), found to be beneficial to science understanding and literacy (Develaki, 2010; Webb & Rule, 2012), and enhances retention in music (Peterson & Madsen, 2010). This excitement extends to policy circles as well: The International Society for Technology in Education lists it first among their student standards and other organizations place similar importance to this desired virtue (ISTE, 2012; Davies et al., 2013). Most recently the Next Generation Science Standards (NGSS) have included engineering design, among other reasons, because "engineering offers opportunities for 'innovation' and 'creativity' at the K-12 level" (NGSS, 2013).

Collaboration among students is another goal – long held by learning scientists – that is receiving broad attention. NGSS (2013) exemplifies this by expecting that students learn about working in a team and developing communication skills, stating, "these skills are likely to be acquired when students engage in projects based on the science and engineering practices and core content." Connections between these values, creativity and collaboration, have been examined in many various studies from collaborative creativity as a desired learning outcome (Sullivan, 2011) to the resources and obstacles found in teacher team creative collaboration (Kurtzberg & Amabile, 2010) to more in depth and wider examinations of the topic (Eteläpelto & Lahti, 2008).

Theory

Researchers have proposed many definitions for creativity (Glück, Ernst, & Unger, 2002; Taylor, 1988). So many, in fact, that many have found it ineffective to narrow the definitions to one that is universally accepted (Saunders & Gero, 2002). This lack of a communal definition made creativity a nebulous catch-all buzz word in research. Instead of focusing on the vast number of concepts creativity could arguably cover, we have chosen a clear *aspect* of creativity often encompassed in these definitions: novelty (Saunders & Gero, 2002; Shah, Vargas-hernandez, & Smith, 2003). Novelty is "a measure of how unusual or unexpected an idea is as compared to other ideas" (Shah et al., 2003).

Researchers have developed two broad categories of instruments for measuring novelty: comparison and selection. When using a selection scale, student work is related to a set scale, as in a rubric. When using a comparative scale, the differences between artifacts are examined and scaled in comparison to one another (Merrill, Charyton, & Jagacinski, 2008). While most grading is currently done on a type of selection scale, e.g., a rubric, a problem arises when trying to do the same with creativity. In a classroom, there is a culture of borrowing and picking up ideas from peers. This may lead to a classroom set of solutions that look remarkably similar and on a selection scale, would be scored similarly. However, on a comparative scale, solutions are scored based on their differences. This means that creativity is scored locally, allowing for students to be assessed on their ideas, regardless of the common features that may have come about from classroom influence.

Collaboration, like creativity, does not have an accepted definition in the research world. "The broadest (but unsatisfactory) definition of 'collaborative learning' is that it is a situation in which two or more people learn or attempt to learn something together" (Dillenbourg, 1999). As two people attempt to learn, they share ideas and knowledge that have the potential to be taken up by the group, often after critique or discussion (Soller & Lesgold, 2007). Due to the uncertain nature of collaborative learning, there is "a general concern is to develop ways to increase the probability that… types of interaction [that trigger learning mechanisms] occur" (Dillenbourg, 1999). Dillenbourg (1999) categorizes these catalytic activities into Setup of Initial Conditions, Over-Specifying Collaboration Contract with a Scenario Based on Roles, Scaffolding Productive Interactions by Encompassing Interaction Rules in the Medium, or Monitoring and Regulating the Interactions.

There has been extensive research in the Computer Supported Collaborative Learning (CSCL) community around how to enable or study collaboration. This research examines what kinds of learning environment designs can support changes in the social organization of learning and enable youth to work together to construct new knowledge (Scardamalia, Bereiter, & Lamon, 1994; White, 2006). However, much of this work focuses on problem solving in domains where there are a priori knowable right answers. Learning scientists know relatively little about how collaborative discourse shapes solutions to open ended problems, particularly about how student talk can support the development of creative solutions to those problems.

Collaboration and creativity are two very complicated subjects, made up of a series of observable and unobservable factors whose relations the aforementioned studies have examined to varying levels of detail. What sort of discourse is associated with creative problem solving? Existing work in collaboration has shown engaged responses to peers' ideas can lead to correct answers in group problem solving, but this work has been limited to studying problem solving collaboration around problems that only have a single correct or incorrect solution (Brigid Barron, 2003). In this paper, we build upon Barron's (2003) methods to study problem solving discourse from a hands-on engineering summer camp to examine whether the characteristics of student discourse patterns that lead to success on closed-ended problems also predict more creative solutions in open-ended engineering design projects. Using mixed methods, we examine correlations between key features of students' collaborative discussion and the creativity of their solutions to open-ended engineering problems.

Study Context

We present data from a middle school age summer camp that was part of Integrating Engineering and Literacy at Tufts University's Center for Engineering Education and Outreach. This camp challenged participating youth to brainstorm, design, build, and test inventions that could assist fictional characters in children's literature who face a variety of problems. Three challenges, each based in a different book, were addressed over the span of three days. The camp had a morning session which used LEGO Mindstorms, and an afternoon session which used PaperBots, a newly developed educational robotics kit that was designed to be inexpensive and makes use of paper and craft material as building components (O'Connell, 2013). Each session of the camp consisted of 15 students in 4th through 6th grade, split into five groups of three.

Each challenge began with the participants and their teacher together reading a book. Then, the teacher-researcher asked participants to identify engineering problems within the story, facilitated by the lead instructor. Going back to their groups, participants then chose one of the identified problems and designed a solution to help the characters in the story using a robotics system. The data presented in this paper is taken from their interactions and solutions for the story Muncha Muncha Muncha by Candace Fleming, in which bunnies sneak into a farmer's garden and eat his vegetables at night despite his attempts to stop them. The children identified the problems of trying to help the farmer keep bunnies out of his garden or, alternatively, to help the bunnies get into the garden to eat the vegetables. After these two possible problems were identified, students returned to their groups, where they worked together to decide which problem to focus on. They then brainstormed possible solutions, and iteratively built and tested them. Students' group work lasted 2.5 hours, which was spread over two days. During this time, the teachers and researchers interacted with the groups, prompting them to talk about their ideas and what they were doing while working not to influence decision making. They did emphasize that their solutions had to work for the characters. The groups presented their solutions to the class at the end of the session.

Research Methods

We videotaped each group of students throughout their work, collecting about 115 hours of high definition video. Researchers deliberately avoided influencing solutions but intervened if significant group discord arose.

Computing Solution Novelty

We calculated novelty using a five step process: First, researchers identified *attributes*. Second, we assigned *weight*s to the attributes. Third, we mapped *ideas and features* to the identified attributes. Fourth, we computed *values* for ideas. Finally, we calculated a *novelty score* for each artifact.

Attributes were identified that were common between both populations and identifiable as distinct or necessary features of their artifacts by either direct communication by the participants during their final share out or directly observable from their artifacts. Those identified were intention, means, sensor, and body. Intention is the chosen purpose for their robot, or their initial idea. Means is denotes how the artifact fulfilled their intention. Sensor refers to the means with which it senses the state of the world around it. Body is the overall physical embodiment of their final solution. Researchers experienced in working with children on robotics selected these features, and refined through discussion within the research team. Different populations or problems may require different attributes..

Attribute weights emphasize the importance of particularly difficult or design-critical features. Due to the pilot nature of this study and the field's lack of understanding about which parts of robotic engineering are particularly difficult for youth, we assigned all weights equally. Note that f_j is the weight for the attribute j, where $\sum_{j=1}^{n} f_j = 1.0$ (Shah et al., 2003). Since all of the weights must sum to one, we set all our weights to 0.25.

Ideas and features were mapped to attributes based upon observation of the artifact itself and discussion during a group's final share out. More specifically, we identified *intention* based on discussion during final share out, *means* both from discussion during share out as well as observing the artifact itself and both *sensor and body* through observing the artifact.

Values for the ideas were computed using the formula given in Shah et. al (2003): $S_j = [(T_j - C_j)/T_j]\times 10$ where T_j is the total number of ideas for attribute j and C_j is the number of instances for a specific idea in that attribute.

Finally, *Novelty scores are calculated* using a summation of those values, computed from $M = \sum_{j=1}^{n} f_j S_j$ (Shah et al., 2003). Resulting values range from 0 to 8.0 that were then translated to a percent of the possible value to get a Novelty Score out of 100.

In this case, the solutions for the LEGO group and the PaperBots group were scored as separate populations since although they were participating in the same activities; they were using different technologies with unknown difference in breadth of solution possibilities or impact on students' conversations.

Analyzing Collaborative Discourse

A coding scheme described by Barron (2003) was used to classify how students responded to a peer-proposed problem-solving solution. There is a two-part process for coding responses: identifying solution proposals and coding the responses as *Accept, Discuss* and *Non-engage*. A proposed solution was defined as any suggestion that explained how the group would help the designated character in the story. It was counted as an *accept* response if a group mate indicated "agreement with the content of the proposal," a *discuss* response if a group mate acknowledged "the proposal but did not accept them outright or reject them without rationale", and a *reject or ignore* response if a group member rejects "the proposal without a rationale….[or] there is a lack of relevant verbal response." The term *engage* refers to the both *accept* and *discuss* responses, and the term *non-engage* refers to the *reject or ignore* responses (Barron, 2003). In addition to the counts of the types of responses, an Engagement Score, Acceptance Score and a Discussion Score were calculated as the percent of *engage, accept* and *discuss* out of the total responses, respectively

One of the researchers coded all video data available for the Muncha Muncha Muncha. A second researcher randomly chose a group from the LEGO session and a group from the PaperBots session and independently coded their first hour of the activity using the same coding scheme. Agreement between the two coders was 100%.

Comparing Discourse and Solution Novelty

We used Microsoft Excel to calculate a Pearson product-moment correlation coefficient between each of the Engagement Score, Acceptance Score, and Discussion Score against Novelty Score.

Results

The methods described above were then applied to the data collected from the camp to yield the following results. Please note that all solutions were considered. The solutions in the book by the farmer were to dig a moat around his garden and after that failed to keep out the bunnies, build a large fortress wall around it. The bunnies were still able to infiltrate it through cunning though. The absurdity of the farmer's solutions and the anthropomorphic abilities of the bunnies opened up such possibilities that the student solutions, no matter how unrealistic, were considered as long as the students could present their reasoning which they all successfully did.

Solution Novelty

An example calculation: To clarify our process, we present an instance of mapping ideas to an attribute, computing the values for ideas and calculating a group's novelty score.

Using the LEGO session's artifacts shown in Figure 1 as an example, the *body* attribute had 3 different design concepts; a *single* body where all components were in a single package, a *single-functional* body where all components were in a single package but included some functional components like a cow catcher on the front, and a *tethered* system where the NXT brick was tethered to the functional portion of the robot.

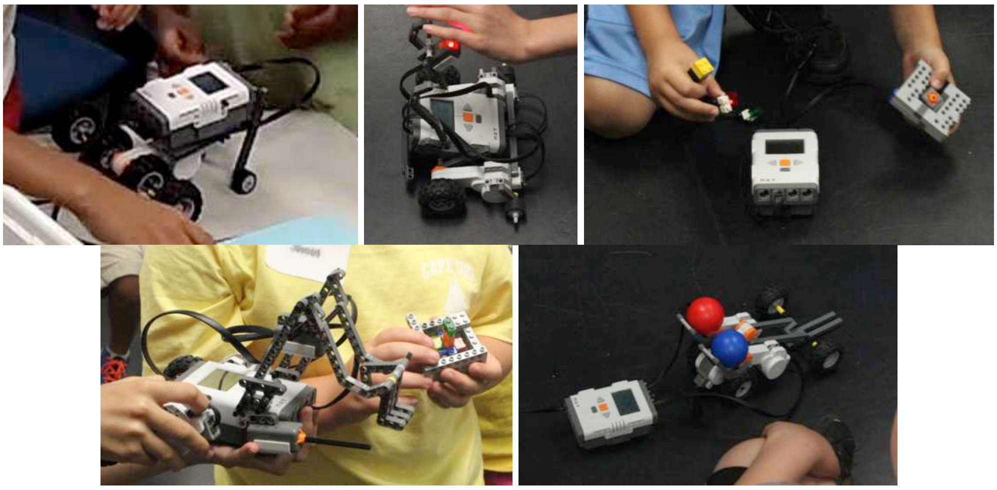

Figure 1. Artifacts from *Muncha Muncha Muncha* activity for LEGO group's A, B, and C in the top row and group's D and E across the bottom.

For the *single* and *single-functional* design ideas, there were two instances ($C_4 = 2$) of each so for a population of 5 ($T_4 = 5$) giving an idea value of $S_4 = [(T_4 - C_4)/T_4] \times 10 = [(5-2)/5] \times 10 = 6.0$. For the *tethered* idea, it was unique among that population ($C_4 = 1$) so it gains a higher novelty value of $S_4 = [(T_4 - C_4)/T_4] \times 10 = [(5-1)/5] \times 10 = 8.0$.

LEGO group C's novelty score comes from adding up all of their idea scores. They had the idea to *warn* the rabbits with a *light* triggered by a *pressure* sensor built into a *tethered* system robot. That would give them a value of 8.0, 8.0, 6.0, and 8.0 for their ideas (values shown in Table 1) and then, with the weights calculated in, a total novelty score of 7.2 (scores shown in Table 2).

Overall: We used the methods described above to compute the novelty of each group's design solution. Table 1 shows the results from computing the values for the ideas as described as step four. None of the attributes have all unique ideas, the intentions of the morning session being the least unique. Table 2 shows the ideas for each attribute by group as mapped in step three as well as their final novelty scores as calculated in step five. Overall, we found that the artifacts in the afternoon were on average more novel then the morning artifacts with statistical significance using a 1-tailed heteroscedastic t-test, which is statistically significant using the conventional 5% cut off.

Table 1: Attribute idea values from *Muncha Muncha Muncha* activity final artifacts and presentation

Lego Group											
Intention			Means			Sensing			Body		
Idea	C	V	Idea	C	V	Idea	C	V	Idea	C	V
Scare	4	2.0	Chase	3	4.0	User	1	8.0	Single	2	6.0
Help	1	8.0	Light	1	8.0	Dark	1	8.0	Sgl-Funct	2	6.0
			Catapult	1	8.0	Pressure	2	6.0	Tethered	1	8.0
						Baited	1	8.0			
PaperBots Group											
Intention			Means			Sensing			Body		
Idea	C	V	Idea	C	V	Idea	C	V	Idea	C	V
Scare	2	6.0	Scarecrow	2	6.0	None	1	8.0	Diorama	2	6.0
Trap	1	8.0	Drop Cage	1	8.0	Baited	1	8.0	Tethered	2	6.0
Help	2	6.0	Launch	1	8.0	Timed	1	8.0	Multi	1	8.0
			Pickaxe	1	8.0	Dark	2	6.0			

Discourse Markers for Collaboration

To illustrate the coding process, we provide two snippets of transcript and the correlated coding process. The first is from Group A, which had a lower Engagement Score. This could have been due to the fact the one girl, Helen (gender-keeping pseudonyms have been used) seemed as if she did not want to work with her group mates so much as delegate tasks to them. Part of this is evident in the fact that George did not say anything during this active brainstorming session. This created a tension between Helen and Karl who seemed to want to involve George and work as a cohesive team. Despite this greater than normal tension, they are still productive in sharing and discussing ideas.

Karl: *drawing* So we could do- this is the whole vegetable garden. And then this is all the vegetables.
Helen: I have an idea. I could build a paper fence. And then-
Karl: No, because - you know how they tried that and it didn't work? We could do this-
Helen: No no no no no. I mean like a tall paper fence and then *looks at name tag* George- whatever your name is- you could fill the holes with something and then you *points to K* could build some kind of ceiling on it.
Karl: No like, yeah, I was thinking of the ceiling-
Helen: Yeah so you-
Karl: and like a door that you can open and close.
Helen: Um, the bunnies would be able to go through the door.

Table 2: Novelty scores from *Muncha Muncha Muncha* activity final artifacts and presentation

Lego Group	Intention	Means	Sensor	Body		Novelty Score (out of 100)
	Wt = 0.25	Wt = 0.25	Wt = 0.25	Wt = 0.25	Score	
A	Scare	Chase	User	Single	5	62.5
B	Scare	Chase	Dark	Single-Functional	5	62.5
C	Warn	Light	Pressure	Tethered	7.5	93.75
D	Scare	Chase	Baited	Single-Functional	5	62.5
E	Scare	Catapult	Pressure	Single	5.5	68.75
				Lego Avg. Score:	5.6	70
PaperBots Group	Intention	Means	Sensor	Body		Novelty Score (out of 100)
	Wt = 0.25	Wt = 0.25	Wt = 0.25	Wt = 0.25	Score	
Red	Scare	Scarecrow	None	Diorama	6.8	81.25
Blue	Trap	Drop cage	Baited	Tethered	7.8	93.75
Green	Help	Launch	Timed	Multi-functional	7.8	93.75
Yellow	Scare	Scarecrow	Dark	Tethered	6	75
White	Help	Pickaxe	Dark	Diorama	6.8	81.25
				PaperBots Avg. Score:	7.04	85

The solutions in this segment include the fence and the ceiling as they both explain how the group is keeping the bunnies out of the garden whereas the addition of the door does not explain how they are keeping the bunnies from the vegetables. Helen first introduces the idea of a fence on the second turn. Karl's response is categorized as *discuss* because even though he rejects the proposal, he explains that in the story, the character already tried building a fence and it did not prevent the bunnies from eating the vegetables. The idea of the ceiling is presented by Helen on the fourth turn and is immediately accepted by Karl so the response is coded as *accept*.

The second snippet is of group B which had a disruptive group member, Andrew, whom was constantly off task or suggesting inhumane solutions for keeping the bunnies out of the garden. Jane and Alexis who originally tried to include Andrew eventually started ignoring and rejecting his proposed solutions, possibly because they found them counter-productive or viewed them as his way of playing around. The two girls managed to complete the challenge with very limited assistance from Andrew.

Jane: No no no no no. Like, like a net! A net.
Andrew: No, its-
Alexis: But a net could hurt them.
Jane: No you just put it in it, like fish.

Andrew: Yeah, well what about like um like what about like a nuclear bomb? That won't hurt them.
Alexis: No
Jane: The bunny catcher.
...
Teacher: It's just going to drive around?
Alexis: It will go around- it will go around
Andrew: How is that suppose to scare them? Wait, no, it will drive around and then they exterminate them with like giant lasers-
Jane: If we could we would make it high speeds of running around
Teacher: Ok
Alexis: Yeah, we could scare the bunnies because a lot of animals if you get too close to them they get scared.
Teacher: They'll run away.
Alexis: Yeah, so we're just going to scare them away.
Andrew: These are radioactive bunnies

Table 3: Student Engagements from *Muncha Muncha Muncha* Activity

Group	Accept	Discuss	Non-engage	Total	Engagement Score (out of 100)	Acceptance Score (out of 100)	Discussion Score (out of 100)
A	5	3	7	15	53	33.33	20
B	2	6	4	12	67	16.67	50
C	3	6	1	10	90	30	60
D	2	2	2	6	67	33.33	33
E	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LEGO	12	17	14	43	67	27	40
Red	2	2	1	5	80	40	40
Blue	4	10	2	16	87.5	27.78	62.5
Yellow	7	5	0	12	100	57.14	42
Green	1	7	2	10	80	10	70
White	2	3	2	7	71.43	28.57	42.86
Paperbots	16	27	7	49	86	32	54

The solutions proposed in this segment are a net, a nuclear bomb, and giant lasers. The idea of a net is introduced in the first turn by Jane and Alexis responds with concern for the bunnies being hurt by the net without accepting or rejecting the idea which means the response is categorized as *discuss*. A new proposal is brought to the group by Andrew at turn five for a nuclear bomb where he assures his group mates that it would not hurt the bunnies, however he is flat out rejected by Alexis which is coded as *non-engage*. Later, when Jane and Alexis are explaining to the teacher their current solution of a robot that drives around and scares bunnies, Andrew proposes giant lasers. This idea is not addressed in six turns, thus it is considered being ignored and categorized as *non-engage*. The results of the discourse coding are summarized in Table 3.

Collaborative Discourse Predicts Solution Novelty

Each group's Novelty Score was charted and regressed against their Engagement Score (Figure 2), Acceptance Score and Discussion Score. Because one video file was lost, we only had enough video to code nine groups.

Our regression value (R) of .90 for *Engage* responses is statistically significant ($p < 0.00042$), indicating a strong correlation. However, when Accept and Discuss scores were charted against Novelty score, there was not a significant correlation ($p < .13$ and .08 respectively), indicated by the low regression values of 0.40 and 0.50.

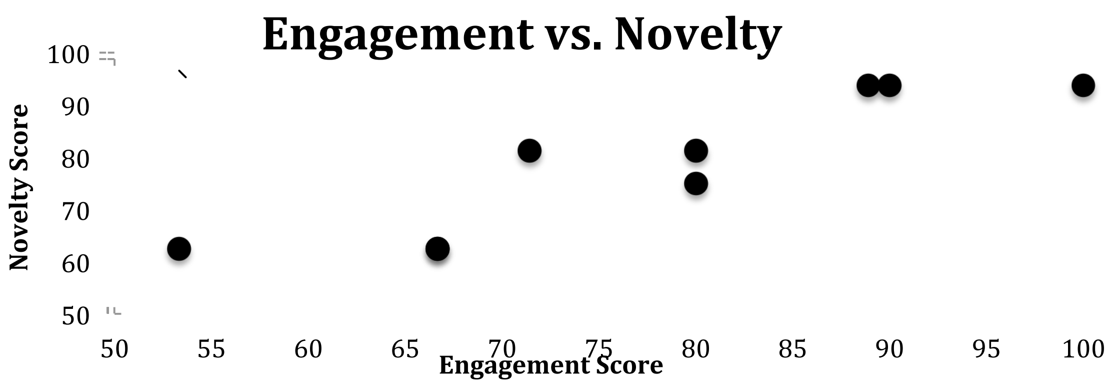

Figure 2. Engagement versus novelty

Discussion

Our results show that there is a strong correlation between number of *engage* responses and novelty in the students' final artifacts. Engaged responses in student discourse predict novel solutions. There has been other research that shows there are ways to teach this type of discourse to students (Demetriadis, Egerter, Hanisch, & Fischer, 2011). Further, we have demonstrated the possibility of novelty assessment being used in a classroom-like environment using only observations, share outs and pictures of final artifacts.

By identifying a type of student discourse that supports novelty, we began research that we hope will ultimately inform teachers how to better foster creativity in the classroom. The method utilized in this paper is a quantitative way of defining the type of student discourse but in classrooms, in the moment, discourse must be observed and the most beneficial discourse be fostered. "It's clear that the classroom teacher plays a critical role in establishing and modeling practices of productive group learning processes and conversations. Observing a group's interactions can provide teachers with valuable insight" (Barron & Darling-Hammond, 2008) but only if they know what they are looking for. CSCL research has explored how a facilitator can influence discourse. One example is having a tutor sustain and deepen inquiry through well-timed refocusing (Lakkala, Muukkonen, & Hakkarainen, 2005). It has long been taught that group members shouldn't say "types of comments that indicate competition, premature judgment, or failure to listen in group discussion" (McKendall, 2000). Our research supports this long-held idea and extends it to teachers actively supporting engaged responses in student discourse.

This study also illustrates the use of a creativity assessment instrument, specifically the method of assessing novelty described by Shah et. al (2003), in a classroom-like environment. The prescribed novelty assessment allows teachers to grade projects after-the-fact either by looking at the physical artifacts, pictures or video, depending on their preferences and resources. This is a vast improvement over other instruments that advocate identifying the provenance of an idea, not something that can readily be applied in a classroom, though advancements in learning analytics may change this (Blikstein et al., 2012). The methods used in their current form are unrealistic for timely use in classrooms but the novelty measure and others like it in the works of Shah et al (2003) may be useful for assessment as part of an application that organizes the student works and their features and takes care of the calculations. Despite the small sample size, the implications of a quick and easy way to measure even an aspect of creativity after-the-fact are clear. Teachers who have been able to intuitively tell that one solution is more original than others will finally have a way to measure and support that sense. In the future, systematic assessment creativity could even become a more effective way to measure teamwork effectiveness than current methods of asking groups to report on the other members or scattered observations.

Conclusions

Open-ended and group problem solving have been shown to lead to more robust individual understandings (Kapur, 2008). While teachers are constantly pressured to increase test scores, they are also expected to promote teamwork and creativity through engineering design projects (NGSS, 2013). This study suggests that it may be possible to combine methods from the learning sciences, art, and engineering education research to better analyze creative problem solving, and ultimately to develop classroom-practicable techniques for assessing creativity.

References

Barron, B., & Darling-Hammond, L. (2008). Teaching for meaningful learning: A review of research on inquiry-based and cooperative learning. *Powerful learning: What we know about teaching for understanding*, 11-70.

Barron, B. (2003). When smart groups fail. *The journal of the learning sciences*,*12*(3), 307-359.
Davies, D., Jindal-Snape, D., Collier, C., Digby, R., Hay, P., & Howe, A. (2013). Creative learning environments in education—A systematic literature review. *Thinking Skills and Creativity*, *8*, 80–91.
Demetriadis, S., Egerter, T., Hanisch, F., & Fischer, F. (2011). Peer review-based scripted collaboration to support domain-specific and domain-general knowledge acquisition in computer science. *Computer Science Education*, *21*(1), 29–56.
Develaki, M. (2010). Integrating Scientific Methods and Knowledge into the Teaching of Newton's Theory of Gravitation: An Instructional Sequence for Teachers' and Students' Nature of Science Education. *Science & Education*, *21*(6), 853–879.
Dillenbourg, P. (1999). What do you mean by collaborative learning?.*Collaborative-learning: Cognitive and computational approaches.*, 1-19.
Eteläpelto, A., & Lahti, J. (2008). The resources and obstacles of creative collaboration in a long-term learning community. *Thinking Skills and Creativity*, *3*(3), 226–240.
Glück, J., Ernst, R., & Unger, F. (2002). How Creatives Define Creativity : Definitions Reflect Different Types of Creativity. *Creativity Research Journal*, *14*(1), 55–67.
Kapur, M. (2008). Productive Failure. *Cognition and Instruction*, *26*(3), 379–424.
Kurtzberg, T. R., & Amabile, T. M. (2001). From Guilford to creative synergy: Opening the black box of team-level creativity. *Creativity Research Journal*,*13*(3-4), 285-294.
Lakkala, M., Muukkonen, H., & Hakkarainen, K. (2005). Patterns of scaffolding in computer mediated collaborative inquiry. *Mentoring & Tutoring: Partnership in Learning*, *13*(2), 281–300.
McKendall, M. (2000). Teaching Groups to Become Teams. *Journal of Education for Business*, *75*(5), 277–282.
Merrill, J. A., Charyton, C., & Jagacinski, R. J. (2008). CEDA: A research instrument for creative engineering design assessment. *Psychology of Aesthetics, Creativity, and the Arts*.
NGSS. (2013). *Engineering Design in the NGSS* (pp. 1–7).
O'Connell, B. (2013). PaperBots: An Inexpensive Means for Engineering Education. In *120th ASEE Annual Conference & Exposition*. American Society for Engineering Education.
Peterson, C. W., & Madsen, C. K. (2010). Encouraging Cognitive Connections and Creativity in the Music Classroom. *Music Educators Journal*, *97*(2), 25–29.
Renzulli, J. S. (2005). The Three-Ring Conception of Giftedness: A developmental model for promoting creative productivity. In R. J. Sternberg & J. E. Davidson (Eds.), *Conceptions of giftedness* (pp. 246–279). Cambridge University Press.
Saunders, R., & Gero, J. (2002). How to study artificial creativity. *Proceedings of the 4th conference on Creativity & …*, 80–87.
Scardamalia, M., Bereiter, C., & Lamon, M. (1994). The CSILE Project: Trying to Bring the Classroom into World 3. In *Classroom lessons Integrating cognitive theory and classroom practice* (pp. 201–228).
Shah, J. J., Vargas-hernandez, N., & Smith, S. M. (2003). Metrics for measuring ideation effectiveness. *Design Studies*, *24*, 111–134.
Soller, A., & Lesgold, A. (2007). Modeling the process of collaborative learning. In *The Role of Technology in CSCL* (pp. 63-86). Springer US.
Sternberg, R. J. (2005). WICS: A Model of Positive Educational Leadership Comprising Wisdom, Intelligence, and Creativity Synthesized. *Educational Psychology Review*.
Sullivan, F. R. (2011). Serious and Playful Inquiry : Epistemological Aspects of Collaborative Creativity, *14*, 55–65.
Taylor, C. W. (1988). Various approaches to and definitions of creativity. *The nature of creativity*, 99-121.
Van Harpen, X. Y., & Presmeg, N. C. (2013). An investigation of relationships between students' mathematical problem-posing abilities and their mathematical content knowledge. *Educational Studies in Mathematics*, *83*(1), 117–132.
Webb, A. N., & Rule, A. C. (2012). Developing Second Graders' Creativity Through Literacy-Science Integrated Lessons on Lifecycles. *Early Childhood Education Journal*, *40*(6), 379–385.
White, T. (2006). Code talk: Student discourse and participation with networked handhelds. *International Journal of Computer-Supported Collaborative Learning*.
Yuan, X., & Sriraman, B. (2011). An exploratory study of relationships between students' creativity and mathematical problem-posing abilities. In *The elements of creativity and giftedness in mathematics* (pp. 5-28). SensePublishers.

Acknowledgements

This project is funded by the National Science Foundation DRK-12 program, grant # DRL-1020243, as well as by LEGO. Any opinion, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the NSF or LEGO. We thank Merredith Portsmore, Elissa Milto, Dan Wise, Joe Sanford, and Chelsea Andrews for their assistance.

