Making Meaning through Art-Integrated Engineering

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In recent years, much attention has been paid to a general lack of skilled workers and the lack of diversity in the domain of engineering (e.g., Andrews & Clark, 2016; Mukuni, 2015). Numerous studies have indicated the importance of addressing this issue in K-12 education due to increasingly negative attitudes toward science with age, particularly beginning at the middle school level (Baram-Tsabari, Sethi, Bry, & Yarden, 2006; Sadler, Sonnert, Hazari, & Tai, 2012). Young adolescents in the middle grades often begin to develop their subject area affinities (Kessels, 2011) and embark on programs of study that ultimately determine their career pathways (Hannover & Kessels, 2002). Therefore, providing high quality engineering learning experiences in the middle grades is a critical strategy for increasing and diversifying the future engineering workforce.

As educators seek to enact this strategy in middle schools, many are confronted with the difficult challenge of teaching a subject area in which they have little or no training (Hynes, 2012; Nugent, Kunz, Rilett & Jones, 2010). As Hynes argued (2012), those who teach engineering would ideally be post-secondary engineering degree holders. However, this is largely not the case. The small amount of engineering instruction that exists in the middle grades is commonly embedded within science and mathematics classes (Purzer, Strobel & Cardella, 2014). This means many teachers who teach engineering hold licenses that do not require any significant knowledge of engineering content or pedagogy, in fact, most states do not even have any licensure or certification for K-12 teachers in engineering.

Compounding this problem is the fact that the domain of engineering is broad, multi-faceted, and multidisciplinary. Combined with the lack of licensure-related guidelines, it is difficult to determine what teachers need to know about the engineering content as well as various pedagogical methods in order to provide high quality engineering instruction to middle school students (Hynes, 2012).

The proposed paper explores these under-researched areas by examining data collected over the course of a two-year study, which took place in two urban middle schools in Columbus Ohio. The study was part of a community engaged (O'Meara & Rice, 2005; Boyer, 1996) initiative that united a large land-grant university (The Ohio State University), the two schools, and several community partners (Columbus City School District, Beta by Design (an Ohio 501(c)(3) nonprofit education organization), and the Center of Science and Industry (COSI). Together, the partners compared the impact of a conventional approach to teaching engineering content and skills to a visual art-integrated approach, which was focused on the medium of origami (the Japanese art of paper folding) and the biomolecular subject of DNA origami. As the research team developed the two instructional approaches, a central question related to our teacher partners' perspectives on engineering became central to our overall inquiry. That question was: **What do the teachers need to undertake effective, high quality engineering teaching at the middle school level?**

To address this question, the research team employed a case study approach to analyze qualitative data gathered through semi-structured interviews with the lead teachers on the project (the “smART Project”) at each of the two school sites. In the pages that follow, we describe the study as well as the theoretical perspective that guides it. We situate our inquiry under the sociocultural umbrella (Vygotsky, 1930-34/1978), and describe teacher learning in relation to Lave and Wenger’s (1991) Community of Practice theory. We then describe the data analysis, which led to our findings concerning the teachers’ perspectives on the smART Project’s arts-integrated and conventional engineering approaches to teaching engineering content and the engineering design process. These findings center on how the teachers imagine increasing engineering education in their schools and what they perceive as the role of the university in supporting them to do so. Our art-integrated approach could be applied to any engineering discipline in the future. Initially, the approach using DNA origami was chosen because of the interest and expertise of the collaborating engineering faculty.

Review of Literature

The idea that learning takes place first on the social plane and then on the individual plane (Vygotsky, 1934/1986) provides an important foundation for considering how teachers develop new understandings about both subject matter and pedagogical methods. As research has repeatedly demonstrated, traditional transmission models of teacher professional learning often fail to gain traction or result in any significant change to teachers’ professional practice (e.g., Borko, 2004; Timperley & Alton-Lee, 2008; Clarke & Hollingsworth, 2002). Transition models align with what Freire (1970) criticized as a “banking concept” of education, whereby an instructor narrates information as if it were a set of static truths, “bestowing” knowledge on learners as if it were a gift. Learners are thus positioned as passive receivers of the instructor’s greater wisdom. A Vygotskian perspective positions learners as active agents who participate in their social context as they internalize new, culturally-bound ideas. In this view, the primary role of an instructor is providing appropriate assistance to help the learner accomplish a new skill or task that they have not yet mastered but that lies within the range of their developmentally determined capabilities (Vygotsky, 1978).

While Vygotsky developed his sociocultural theory in relation to children's learning, its applicability to adult learning has been widely explored (e.g., Darling-Hammond & McLaughlin, 1995; Rogoff, 2003; Johnston, 2004; Wells, 1999). One important outgrowth of Vygotskian theory is Lave and Wenger's (1991) Communities of Practice (CoP) theory, which explains that as individuals become bound together through a shared concern, endeavor, or domain, they co-construct the culture of the group. As that unique culture is shaped, the knowledge, and ultimately, expertise of the group members develops in a mutually inflecting manner. As new members enter the CoP, they are gradually apprenticed from the periphery of the group to the center, becoming experts over time in a process that aligns with Vygotsky's (1978) theory of learning.

In the realm of teacher learning and professional development, Rogoff (1990) has conceptualized this sociocultural movement from the periphery of understanding to the center (i.e., becoming an expert) as an "apprenticeship in thinking". However, learning is not simply a matter of an expert influencing a novice in a unidirectional pattern. Rather, the novice also contributes to the expert's construction of their own knowledge (Rogoff, 2003; Ash, 2003; Goodwin, 1997). In this way, the novice also has a role in apprenticing the expert.

Framing teacher learning as a multi-directional apprenticeship facilitates a radical departure from the unidirectional banking model of professional development. The former provides not only a pathway away from ineffective, top-down professional development, but also an equity-based orientation that honors the expertise of teachers. Thus conceptualized, teacher professional development holds the possibility of becoming a more collaborative endeavor between professional development providers and classroom teachers. In the case of the smART Project, the research design originally focused on student learning. However, it became clear that the classroom teachers were significantly impacted by participating in the intervention. This led the research team to view the project as a form of professional development and to inquire into the nature of the teacher learning about engineering that transpired over the course of the project.

smART Project Background

This study took place in two middle schools located in Columbus, Ohio. The first school, Metro Early College Middle School, (MECMS), has a student body of 300. MECMS, a semi-public, non-charter STEM school, is open to all students in the state, but most reside in the city where the school is located. The school is administered by a governing body comprised of representatives from school districts throughout the state, this study's university partner, and industry collaborators. The socio-economic demographics of the school's student body are described in Table 1.

Table 1: MECMS Student Demographic Data

	# Students	% Student Body
Female	161	51%
Male	154	49%
Caucasian	154	49%
Black/African Descent	87	28%
Latino/Hispanic	15	5%
Asian	32	10%

Native American	0	0
Multi-Racial	27	9%
Free or Reduced Lunch	84	27%
ESL	0	0

The second school, Hilltonia Middle School (HMS), is part of the largest school district in the state and is attended by 500 students. The district itself is comprised of more than 50,000 students, 69% of whom receive free or reduced meals and are classified as low SES according to federal guidelines. The district's student population is racially diverse, with approximately 74% representing a non-white population. 13.2% have limited English proficiency, and over 100 languages are spoken. (See Table 2.)

Table 2: Columbus City Schools Student Demographics

	Black	White	Hispanic	Asian	Native American	Hawaiian/ Pac Island	Multi-Racial
Total No.	28,650	13,429	4,448	1,481	99	3	2,760
Percentage	56%	26%	9%	3%	0.2%	0.006%	5%

Source: Columbus City Schools, Dept. of Human Resources, Data & Systems

The smART Project was implemented in MECMS for two years as a weekly after-school club. In the first year, approximately twenty students participated in an art club in which engineering design processes and the subject of DNA origami was taught through arts-based materials and methods. Approximately seven students participated in a traditional engineering club where the content and methods aligned with conventional approaches to engineering education. In the second year, the focus and the curricula of the two clubs remained largely the same as year one. However, approximately fifteen students participated in the art club and twenty students participated in the engineering club. The clubs were both led collaboratively by university researchers, undergraduate and graduate engineering and education students, classroom teachers, and representatives of a community-based arts education organization.

At HMS, the art and the engineering instruction took place in year 2 only. Due to challenges associated with transportation and neighborhood safety, the two programs were offered during the school day, rather than after school. Therefore, approximately thirty students were assigned to a weekly art class focused on origami and DNA origami, and approximately 30 students were assigned to a weekly conventional engineering class. The classes were taught by the university researchers, students, and representatives of the community-based arts organization. At both schools, a classroom science teacher served as the school-based project facilitator and teacher leader. Because of their similar positions and their additional commitment to the project, these two teachers were chosen to serve as case studies in this line of inquiry about the impact of the project on teacher learning.

At MECMS, Anna is an experienced teacher, having taught for twelve years in several charter schools in addition to the three years she has been employed by this semi-public STEM school. She is licensed to teach math and science at the middle school level and often teaches summer school, summer camps, and extra-curricular classes, not only in math and science, but also in Japanese culture and origami. This latter experience, combined with her identity as a Japanese American, drove her to self-select as a teacher participant and teacher leader of the MECMS portion of the smART Project.

The teacher leader at HMS, Kate, is a career public school, urban educator, having spent more than 25 years in the classroom. Kate holds a Bachelor of Science degree in Education and a Master of Science degree in curriculum, instruction, and assessment. She is a state-certified master teacher and is also National Board certified. In addition to teaching middle school science, she also teaches social studies and often provides professional development to other teachers. She currently serves as her building's teacher union representative and is accustomed to serving as a liaison between teachers, administrators and outside organizations.

Methodology and Methods

This qualitative study is located within the interpretivist tradition, using primarily ethnographic fieldwork and interviewing to collect data from Anna and Kate and to understand how they made sense of the smART Project (Travers, 2001). This approach allowed the research team to understand in-depth the teachers' perspectives on engineering, its role in school-based settings including their own classrooms, and what they need in terms of support to achieve the aim of providing high quality engineering education to more students. To analyze the data collected through semi-structured interviews, we used a theme discovery approach (D'Andrade, 1995), paying particular attention to *in vivo* codes (Strauss, 1987; Strauss & Corbin, 1990). The constant comparative method (Charmaz, 2001; Glaser, 1978 Glaser & Strauss, 1967; Strauss, 1987) was used to determine and test patterns emerging across the data sets. Recurring themes were related to teachers' preferences for addressing practical details over theorizing, their desire for more robust, engaged, and reciprocal relationships with the university, and an inclination to exercise their own pedagogical creativity as they attempt to cultivate their students' engineering-related growth.

Findings

Anna's *View: Designing Possibilities and Confronting Constraints*

Conversations with Anna, whether they took place in curriculum planning sessions or in the context of reflecting on the smART project, were characterized by overflowing ideas. She often responded to planning questions by offering new ideas, and when students undertook many of the art-infused engineering projects, she would propose new, related projects or ask for advice on how she could implement similar activities in her science classroom. She was often interested in how origami, an art form with which she had prior experience, could be used to teach other content, such as mathematics. The following statement was typical of the kind of idea generation she often engaged in:

> If I wanted to do more geometry, I could do origami with geometry, because there is math in origami. But if I could teach a geometry course, I could totally use it to do bisectors and areas of sectors. I have kids who have issues with visualizing something and deconstructing it into areas of shapes. I think I could use origami to help kids understand that. For the art part, if I was teaching chemistry or physical science, I could teach different mediums and why they fold the way they do. That would be about the physical and chemical characteristics of things.

In addition to indicating Anna's penchant for imagining possibilities for implementing engineering-related activities from the smART Project into her classroom, this statement also points to how she conceptualizes the organization of knowledge into discrete disciplines. For example, geometry is separate from paper engineering. In fact, origami is simultaneously a tool to achieve the aims of mathematics at the same time that mathematics exists as a discrete phenomenon or entity within the art of origami. Going on to describe the “art part” further indicates a conceptualization of the various disciplines existing within boundaries that intersect without blending into each other. In this sense, Anna did not engage with the engineering or interdisciplinary content on a metacognitive level, but rather on the more granular level that would help her address her immediate classroom needs. This perspective reinforces boundaries between the different disciplines (rather than their blending) and results in the domains being viewed for their instrumental, rather than intrinsic, value. In such cases, the discipline that is positioned as instrumental can be understood as subservient to the targeted discipline (Bresler, 1995).

Anna’s focus on her immediate classroom needs carried over into how she described her engineering-related professional development needs. When asked if she felt equipped to teach engineering (whether in her science classroom or in an alternative setting), she responded that she would need both professional development on core engineering concepts and on-going help within the classroom during lesson implementation. She stated:

> I don’t think we do as much engineering as they [school administrators and policy makers] would like us to do. We have to do design challenges for the fall semester, and that’s probably the closest to what we’d call engineering. I would need a lot of training and professional development to actually teach middle school engineering. And the problem is it’s never free. I feel like if I had a core base on what you’d want kids to know about engineering at the middle school level I could do it, but when I think about what Deb [a member of the research team] does, my eyes go cross-eyed. My head can’t even do it.

In expressing these thoughts, Anna pointed to one of the most significant barriers to instituting high quality engineering instruction in schools: the lack of teacher capacity (Hynes, 2012). She also pointed out an important barrier to overcoming the lack-of-knowledge barrier: lack of funding. Given that high quality teaching in a subject area requires not only subject area mastery, but also curriculum and pedagogical knowledge related to that subject area, large investments of time and resources are likely necessary to equip science teachers like Maria with the ability to facilitate the kind of engineering learning that students need. In continuing to reflect, she point out an additional pathway to developing her engineering professional practice. That pathway involves a commitment by both university and industry partners to engagement in a reciprocal relationship with classroom teachers. Anna stated,

> We need more people to come in and help us. [Company A] is supposed to be a partner with our school, but I've never seen one of their employees come into our school and volunteer in our science classrooms. When I think of a relationship, I think of more hands-on things, not just, "oh, we're going to back this thing with money." They're not much of a partner if we're not able to access all their services. Same is true with the university. It shouldn't be just one direction. If I see one more standard about real-world experiences without help . . .

Anna's statements in regard to university and industry support indicate two key beliefs: that both organizations have something relevant and valuable to offer classrooms in terms of "services" and relationships between schools and community partners should be mutually beneficial. Anna's belief that the university and industry partners should provide schools with tangible help aligns with current equity-oriented theories on community-engaged scholarship, which emphasize “genuine *collaboration*: that the learning and teaching be multidirectional and the expertise shared. It represents a basic reconceptualization of faculty involvement in community-based work” (O’Meara & Rice, 2005, p. 28). It is worth noting that over the course of her interviews, Anna did not speak about what she, her students, or her school offered the university or the industry partners in return. However, we regard their willingness to participate in research projects seeking to address the needs of post-secondary engineering education and future industry employers as a service or contribution that is implicitly understood.

Kate’s View: Reciprocity with Student Learning as the End Game

Like Anna, Kate was a tireless and enthusiastic partner in the smART Project. She was an active logistics problem-solver, leveraging her history in her school building and her role as a teacher union leader to facilitate relationships between the research team and other HMS teachers as well as students and their parents. Several times over the course of the year, the project encountered scheduling difficulties that threatened to undermine students’ participation. Each time, Kate found creative solutions that simultaneously met the needs of participating teachers, students, and building administrators. Her strategic thinking capacities were apparent when brainstorming how to systematize some of the innovations that emerged from both the art-infused and the conventional approaches to teaching engineering in HMS during the regular school day. Like Anna, Kate proposed professional development opportunities that would allow middle school science teachers to increase their understanding of engineering content and methods. However, indicating another facet of reciprocity, Kate noted that such opportunities could help university researchers enhance their knowledge of the K-12 context. One typical statement along these lines was as follows:

> If we could work together, maybe during the summer, on creating a semester-long course as an elective for next year, then we could figure out how to take the engineering activities the students are now doing only once a week and build them into daily experiences that are more consistent. I really like a lot of the engineering design challenges and they help meet standards. But, with a whole week in between meetings, it's hard for the students to retain things. So, we could develop a curriculum that links each lesson on a daily basis and also links more closely to what we're doing in science class. I'd learn more about how to teach engineering and you guys could learn how we'd reinforce and develop the concepts in our classrooms with our students.

In this statement, Kate spoke specifically about the reciprocal nature of the professional learning opportunity she envisioned. She clearly conceptualized it as a collaborative, co-constructive experience that would benefit the teachers (including her), the university researchers, and ultimately the students. Kate's suggestion are indicative of her long history as a teacher advocate as well as her extensive background as both a recipient and provider of teacher professional development. Moreover, her proposed scenario is tightly aligned with a CoP (Lave & Wenger, 1991) and an apprenticeship (Rogoff, 1990) model for professional learning.

Concluding Thoughts

We began this paper by **asking what teachers participating in two different approaches to engineering education—one art-infused and after-school, and one conventional and school-based—need to enact effective, high quality engineering teaching at the middle school level.** By focusing on two key teachers who were similarly situated as lead teachers in their respective schools, we discerned several noteworthy patterns that emerged from our data. First, both Anna and Kate were active and creative problem-solvers who were interested in having a strong relationship with the university partner on the smART Project, increasing the parameters of the relationship, and finding ways through the partnership to increase students' access to high quality engineering education. While Anna's perspective focused on discrete, more granular level of day-to-day problem solving and Kate's focused more on systems-level improvement, both teachers expressed a desire to form a collaborative CoP with the university's engineering faculty. Given the current lack of contexts for preparing both teachers and students for high quality engineering experiences that cultivate the next generation of the STEM workforce, Anna and Kate provided a glimpse into the kinds of creative structures that could increase those opportunities. At the core of the data pertaining to both women is the desire not only for direct classroom support by engineering experts but also the desire to actively co-construct new solutions to this challenging problem. Given the sociocultural perspective on learning and the greater likelihood of teacher learning when top-down professional development models are rejected, Anna's and Kate's suggestions for increasing engineering in their schools point to the importance of forming university and school reciprocal partnerships that lead to

Communities of Practice focused on engaging in K-12 engineering education. As mentioned in the introduction, the arts-integrated approach used by the team can be applied to any engineering discipline, which may be undertaken in the future.

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