Designing Solutions in Middle School Engineering: An Exploration of Epistemic Practices of Engineering in Small Group Contexts (Work in Progress)

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Abstract

Students construct meaning and build epistemic understandings through discourse, interactions, and social practices, which collectively make up epistemic practices [1], [2]. Small group engineering activities offer opportunities to examine collaborative interactions and discourse as students make sense of engineering problems and design solutions. As engineering education evolves, it is important to understand epistemic practices of engineering (EPEs) that promote construction of new understandings, including how students use ideas and materials to construct meaning during small group engineering design activities. This study examined EPEs during small group design activities in a middle school science class.

This study focused on the Museum Security curriculum unit, which was designed to address 6th grade science and mathematics standards as students worked in teams to design a laser security system to protect the artifacts in a traveling museum exhibit. Students were expected to apply their knowledge of the properties of light and geometry to produce a solution to meet the criteria and constraints provided by a fictitious client. Based on transcripts and recordings, we selected significant meaning-making events and moments of rich discourse when members of the group worked together, and where the discourse shaped collaborative meaning-making and knowledge-building related to the engineering design challenge. EPEs identified by Cunningham and Kelly [3] were utilized as an analytical framework. In our work, we operationalized and refined these EPEs in order to use them in the small group collaborative discourse context. Discourse in the form of statements, questions, and group interactions were analyzed during each of the significant meaning-making events. Thus, student discourse, which included talk and actions, was analyzed to identify knowledge-building resources and EPEs used by students. These practices were made visible through small group discourse and interactions with the learning environment (peers, mentors, artifacts etc.), particularly as students designed and optimized solutions within the engineering context. Subsequent rounds of coding based on EPEs enabled central themes to be systematically conceptualized and, subsequently, for findings to be generated.

Preliminary findings reveal that students engaged in various EPEs that highlighted how individual cognitive processes and collaborative meaning-making and knowledge-building are inherently interwoven as students constructed meaning while working in engineering design teams. Students displayed a range of EPEs, including taking into account criteria and constraints during the design process, using test information to make significant changes to move a failed design forward, and evaluating multiple solutions against each other. Findings include how students' use of EPEs supported them in a) pushing beyond the scope of set criteria and constraints to collaborate toward innovation; b) utilizing design failure to better understand the problems in context; and c) contributing as a group to iterative-reflective cycles. Findings contribute to enhancing K-12 engineering teaching and learning with a focus on collaborative problem-solving throughout the engineering design process. Findings of this study also have significant implications related to the structure and design of small group collaborative K-12 engineering learning experiences.

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Current policy documents call for K-12 science classrooms to employ integrated STEM strategies to provide more authentic learning experiences for learners. While there is a lack of consensus on a definition of integrated STEM (e.g., [4] - [6]), there is some agreement on desired learner behaviors and practices related to engagement with integrated STEM education. Integrated STEM instruction should engage learners in solving real-world problems that require learners to apply scientific, mathematical, and engineering concepts to authentic problems [4], [7] - [9]. Learners are expected to participate in design thinking, applying the practices of science and engineering to propose explanations and design solutions [10]. It is expected that learners should develop teamwork, communication, and critical thinking by engaging in integrated STEM activities [4], [8], [11]. Students construct meaning and develop epistemic understandings through discourse, interactions, and social practices, which collectively make up epistemic practices [1], [2]. As integrated STEM and engineering education evolves, it is important to understand epistemic practices of engineering (EPEs) that promote new understandings, including how students use ideas and materials to construct meaning during small group engineering design activities. In particular, small group collaborative engineering contexts offer opportunities to examine interactions and discourse to study how verbal (statements, questions) and nonverbal (actions, gestures) are used as epistemic resources.

In this study, small group engineering activities in a middle school science class provided opportunities to analyze epistemic practices through examination of different types of discourse as students construct meaning as they engage in engineering focused activities [12], [13]. In particular, small group collaborative engineering design activities offered opportunities to examine how interactions and discourse shape epistemic resources. The following research questions guided the examination of discourse in this study, within the context of small group engineering design activities for middle school students:

1. How do students collaboratively participate in epistemic practices while engineering a design solution?
2. What epistemic practices do students engage in during collaborative small group engineering design activities?

Theoretical Framework

Sociocultural learning theories [14] provided a theoretical framework for this study, with a focus on epistemic practices [2], [15] and EPEs [1], [3]. In this perspective, learning is necessarily relational, situated, and dependent on interactions with the learning environment. The learning environment includes individuals (mentors and peers), technology, information, and artifacts. Learning, constructing meaning, and developing transferable knowledge of concepts and practices are viewed as relational processes, shaped and enacted through interactions and discourses embedded in cultural, historical, and social contexts, including students' interactions with each other in the learning environment [2], [16]. A sociocultural lens, therefore, enabled an in-depth examination of interactions and discourse during collaborative small group activities in order to identify cognitive and discursive practices that helped advance how students constructed meaning and developed epistemic understandings [15].

Kelly [1] describes epistemic practices as “specific ways members of a community propose, justify, evaluate, and legitimize knowledge claims within a disciplinary framework” (p. 99). Epistemic practices have also been characterized as interactional, contextual, intertextual,

and consequential [3], [17]. In K-12 classrooms, as students engage in epistemic practices, they continually shape their knowledge-building and problem-solving experiences. This study focuses on EPEs, which are rooted in action-oriented approaches, where knowledge-building is integrally connected to discipline-specific discourse and practices toward a goal of designing a solution or creating a product or process [18]. Cunningham and Kelly [2] identified 16 EPEs for education in four broad categories: engineering in social contexts, using data and evidence to make decisions, tools and strategies for problem-solving, and finding solutions through creativity and innovation. These practices are made visible through group discourse and interactions with the learning environment (peers, mentors, artifacts, etc.), particularly as students design and optimize solutions in small group engineering design activities. The engineering design context, consequently, is replete with opportunities for students to draw on a variety of epistemic resources as they collaboratively build knowledge of concepts and practices.

Design

This study utilized a qualitative case study design, which Merriam [19] described as ideal in order to understand a particular bounded phenomenon that is explored, described, interpreted, or evaluated. The heuristic quality of a case study illuminates understanding of a phenomenon by allowing discussion and evaluation of alternatives not chosen, as well as explanations of why an innovation worked. Therefore, the objectives of this study, with respect to examining interactions and discourse to identify epistemic practices, align well with a qualitative case study design. In this study, a group of four learners working together represented the case, and events of meaning-making represented the units of analysis.

Study Context

The study was situated in the final year of a five-year, NSF-funded research project that provided professional development (PD) related to integrated STEM education for in-service science teachers (grades 4-9) in the Midwestern United States. In the final year of the project, teachers participated in a one-week summer PD where they learned about integrated STEM instruction. The PD engaged teachers as learners using a STEM curriculum of their choosing, and teachers were supported in implementing this curriculum in their own classrooms the following academic year.

This study focused on the Museum Security unit, which was designed to address 6th grade science and mathematics standards as students worked in teams to design a laser security system to protect the artifacts in a traveling museum exhibit. Students were expected to apply their knowledge of the properties of light and geometry to produce a solution to meet the criteria and constraints provided by the fictitious client. Students participating in this study are engaged in collaboratively designing a laser security system to prevent a robber from stealing artifacts from a traveling museum, a dialogic activity consisting not only of performing physical tasks, but also of proposing ideas, arguing, and contradicting one another. A focus on epistemic practices through collaborative discourse in this study, therefore, enabled examination of the subtle processes of learning that occurred within the context of small group learning during the engineering design activity. This approach allowed us to examine small group learning in support of integrating engineering in K-12 learning, as well as to shed light on how that learning can unfold (or fail to unfold) as students talk and work together.

Data Sources

Audio and video recordings of each lesson in the curricular unit provided data for this study. Data also included student worksheets and journals collected at the end of the unit. The lessons were implemented over the course of 21 days, and each class period was 45 minutes in length. Of the full 21-day unit implementation, 11 days focused primarily on engineering, which was the focus of this study. Data were collected for three groups of students in the teacher's classroom, and this study focused on one group of four boys: Alex, Ben, Cameron, and Daniel (pseudonyms).

Data Analysis

Transcripts and recordings were carefully examined in order to identify meaning-making events or moments of rich discourse. We selected events when members of the group worked together and where the discourse shaped collaborative meaning-making and knowledge-building related to the engineering design challenge. Discourse in the form of talk and actions were analyzed during each of these meaning-making events. We also considered the multiple modes of discourse people use to make and interpret meaning [20], examining students' gestures, facial expressions, intonation, and use of physical materials.

Cunningham and Kelly [3] identified 16 EPEs for education. In our work, we operationalized and refined these epistemic practices in order to use them as an analytical framework in the small group collaborative discourse context. For example, we removed the epistemic practice of "seeing selves as engineers," as it was not possible to observe internal affirmations of identity. Because we focused solely on small group collaborative activities, we eliminated "working effectively in teams" from our set of codes because some level of teamwork (whether effective or not) was inherent in all of the activities. Fourteen EPEs (see Table 1) were used to deductively analyze discourse as students solved engineering design problems related to the Museum Security unit. This analysis resulted in the identification of emerging themes. Subsequent rounds of coding enabled central themes to be systematically conceptualized and, subsequently, for coherent theories and findings to be generated.

Table 1

Epistemic Practices of Engineering (based on Cunningham & Kelly [1])

Practice	Code	Observable characteristics
Problems in context	CTXT	Taking criteria and constraints into account during design process
Trade offs	TOFF	Optimizing design by comparing criteria against constraints
Assessing a design solution	ADS	Assessing whether solution meets set criteria
Communicating effectively	COMM	Using domain language to communicate
Learning from design failure	LFDF	Using test information to move a failed design forward
Evidence-based decisions	EBD	Using evidence to make decisions based on available data
Iterative design refinement	IDR	Refining ideas through iterative-reflective cycles
Applying mathematics and science knowledge	MSKNOW	Using math/science concepts or principles to propose, test, or explain design solutions

Evaluating multiple solutions	MSOL	Proposing and evaluating multiple solutions against each other
Considering materials and their properties	MTRL	Testing, exploring properties of materials, and connecting these to design problem
Systems Thinking	SYST	Considering how component parts of a system work together and over time
Developing models and prototypes	MODL	Developing a plan before building or testing a prototype before scaling up; includes physical, mental, virtual models
Envisioning multiple solutions	ENVSN	Brainstorming different possible solutions
Innovating processes, systems, and designs	INNV	Pushing boundaries; applying creativity with respect to materials or design elements

Preliminary Findings

Through collaborative interactions and discourse in small groups, students engaged in various epistemic practices largely independent of facilitation or scaffolding by teachers. We use the following EPEs to illustrate selected findings: a) pushing beyond the scope of set criteria and constraints, leading to innovation; and b) utilizing design failure in iterative-reflective cycles.

Pushing Beyond the Scope of Criteria and Constraints

As students sought to design their laser security systems, key criteria shared by the client included protecting artifacts in the museum from a robber, the robber having to cross the laser beam at least three times between the entrance and the artifacts, and the use of mirrors and lenses to reflect and refract the light. As students engaged in the epistemic practice of envisioning multiple solutions, they were able to bring real world contexts into the engineering challenge, imagining a net, for example, that would be triggered by the laser and trap the robber as he moved toward an artifact. Similarly, during small group evaluation of design solutions, students often pushed beyond the scope of criteria and constraints set up by the client and occasionally contemplated additional criteria that led to a greater diversity of outcomes. For example, Cameron's questioning of Ben's design led to Ben considering the size and other defining characteristics of the artifacts, criteria not mentioned by the client (see Table 2).

Table 2

Cameron Questioning Ben's Design

Speaker	Discourse	Code(s)
Ben	No, no, no, but you have to agree that this one (<i>pointing to his own design</i>) is pretty good though. You can't basically get through; you have to go through three times before you get to the artifacts because it sits in the back corner.	MSOL, ADS-cc
Cameron	But we can only protect one, with this one (<i>points to Alex's design</i>) you can protect five.	MSOL, ADS-cc, INNV
Ben	You can protect five right here (<i>points emphatically to the corner with artifacts</i>)	MSOL, ADS-cc
Cameron	Sure, but you can walk around there...	CTXT
Ben	You can protect five in the corner, look - one, two, three, four,	CTXT, IDR-diag

	five (<i>draws on paper</i>)	
Cameron	Well, how big are they?	CTXT
Ben	They could be diamonds bro, just saying. (<i>continuing to draw</i>)	CTXT, INNV

Utilizing Design Failure in Iterative-Reflective Cycles

As students took turns communicating their envisioned possible solutions for the Museum Security challenge, verbal and nonverbal interactions among group members often resulted in more opportunities for EPEs related to engaging in iterative-reflective cycles to refine ideas and generate better solutions, particularly following a design failure. For example, as Ben described his design, he evaluated his design against the set criteria and realized that it did not meet the criterion of the robber having to pass through the laser beams three times (see Table 3). Cameron then quickly moved to refining the design, suggesting a way to manipulate the mirrors to fulfil the criteria. The interaction was instrumental in utilizing the failed design toward collaborative iterative improvements. All members of the group actively contributed to a new understanding generated as they collectively engaged in epistemic practices of testing solutions through iterative-reflective cycles.

Table 3

Cameron Refining Ben's Design

Speaker	Discourse	Code(s)
Ben	Okay, here's my other one [design on paper]. He walks in, he has to stay here because here's lasers protecting... oh wait, that only goes through two times.	MSOL, ADS
Cameron	Wait, you can join mirrors. Dude, no, just put a mirror here (<i>draws on Ben's paper</i>).	CTXT, LFDF

Conclusion and Implications

By examining discourse during small group interactions against the backdrop of engineering design activities in a science class, this study provides important preliminary findings about how students participate in EPEs. The analysis revealed that students engaged in various epistemic practices during interactions with peers, where the interactions were largely independent of facilitation or scaffolding by their teacher. Findings also emphasize how individual cognitive processes and collaborative meaning-making and knowledge-building are inherently interwoven, especially as students construct meaning while developing new understandings toward refining and redesigning solutions in engineering design teams.

The role of epistemic practices in shaping how students construct meaning during collaborative design activities with peers, and with minimal pedagogical interventions or facilitation by adults, remains vastly unexplored, particularly within engineering contexts. Addressing this knowledge gap holds the potential for significant insight into how pedagogical approaches can enhance collaborative meaning-making with a focus on dialogic processes during small group learning in K-12 engineering and integrated STEM education. This study's findings also have significant implications related to the structure and design of small group collaborative learning experiences, where epistemic practices must be integrated meaningfully into curricula and instruction, so that students are able to develop generative, innovative ways of integrating disciplinary knowledge toward optimal design solutions in real world contexts.

References

- [1] Kelly, G. J. (2008). Inquiry, Activity, and Epistemic Practice. In R. Duschl & R. Grandy (Eds.), *Teaching Scientific Inquiry: Recommendations for Research and Implementation* (pp. 99-117; 288-291). Rotterdam: Sense Publishers.
- [2] Knorr Cetina, K. (1999). *Epistemic cultures: How the sciences make knowledge*. Cambridge, MA: Harvard University Press.
- [3] Cunningham, C. M., & Kelly, G. J. (2017). Epistemic Practices of Engineering for Education. *Science Education*, 101, 486-505. doi:[10.1002/sce.21271](https://doi.org/10.1002/sce.21271)
- [4] Brown, R., Brown, J., Reardon, K., & Merrill, C. (2011). Understanding STEM: current perceptions. *Technology and Engineering Teacher*, 70(6), 5.
- [5] Bybee, R. W. (2010). Advancing STEM education: A 2020 vision. *Technology and Engineering Teacher*, 70(1), 30.
- [6] English, L. D. (2016). STEM education K-12: Perspectives on integration. *International Journal of STEM Education*, 3(1), 1-8.
- [7] Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education*, 3(1), 11.
- [8] Kennedy, T. J., & Odell, M. R. L. (2014). Engaging students in STEM education. *Science Education International*, 25(3), 246-258.
- [9] Sanders, M. (2009). STEM, STEM Education, STEMmania. *The Technology Teacher*, 68(4), 20-26.
- [10] National Research Council. 2010. *Standards for K-12 Engineering Education?* Washington, DC: The National Academies Press. <https://doi.org/10.17226/12990>.
- [11] Honey, M., Pearson, G., & Schweingruber, H. (Eds.) (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. Washington, DC: The National Academies Press.
- [12] Crismond, D., & Adams, R. (2012). The Informed Design Teaching and Learning Matrix. *Journal of Engineering Education*, 101(4).
- [13] Moje, Elizabeth & Collazo, Tehani & Carrillo, Rosario & Marx, Ronald. (2001). "Maestro, what is 'quality'?" Language, literacy, and discourse in project-based science. *Journal of Research in Science Teaching*. 38. 10.1002/tea.1014.
- [14] Vygotsky, L. S. (1934, 1978). *Mind in society: The development of higher psychological processes*. (Cole, M., John-Steiner, V., Scribner, S. & Souberman, E., Eds.) Cambridge, Mass: Harvard University Press.
- [15] Sandoval, W.A., Bell, P., Coleman, E., Enyedy, N., & Suthers, D. (2000). Designing knowledge representations for learning epistemic practices of science. Paper presented at the annual meeting of the American Educational Research Association, New Orleans, LA.
- [16] John-Steiner, V., & Mahn, H. (1996). Sociocultural approaches to learning and development: A Vygotskian framework. *Educational Psychologist*, 31(3-4), 191-206.
- [17] Kelly, G. J. (2016). Methodological considerations for the study of epistemic cognition in practice. In J. A. Greene, W. A. Sandoval, & I. Braten (Eds.), *Handbook of Epistemic Cognition* (pp. 393-408). New York: Routledge.
- [18] Schyfter, P., Frow, E., & Calvert, J. (2013). Synthetic biology: making biology into an engineering discipline. *Engineering Studies*, 5(1), 1-5, DOI: [10.1080/19378629.2013.763647](https://doi.org/10.1080/19378629.2013.763647)
- [19] Merriam, S. B. (1998). *Qualitative research and case study applications in education*. San Francisco: Jossey-Bass.
- [20] Bezemer, J., Diamantopoulou, S., Jewitt, C., Kress, G., & Mavers, D. (2012). *Using a social semiotic approach to multimodality: Researching learning in schools, museums and hospitals*. National Centre for Research Methods.