CHAPTER N

BRIDGES AND BARRIERS TO CONSTRUCTING CONCEPTUAL COHESION ACROSS MODALITIES AND TEMPORALITIES: CHALLENGES OF STEM INTEGRATION IN THE PRECOLLEGE ENGINEERING CLASSROOM

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INTRODUCTION

Engineers use science, but distinguish themselves from scientists. They do math but do not identify themselves as mathematicians. They use and invent technology but typically reject the title of technician. As a profession, engineers enjoy a complex relationship with the other STEM fields, having to demonstrate mastery with each of them, yet acting in a manner wholly distinct from any of them.

There are many accounts of professional engineering work, but most are normative and prescriptive, stating what constitutes good and proper engineering, and how it should be taught (ABET, 2010; NRC, 2005). Empirical studies of the engineering process, though few in number, provide great insight to the practices of the profession (Anderson, Courter, Mcglamery, Nathans-Kelly & Nicometo, 2010; Bucciarelli, 1988; Gainsburg, 2006; Stevens, O'Connor, Garrison, Jocuns, & Amos, 2008). In an ethnographic study of structural engineers, Gainsburg (2006) showed how the engineers freely adapt standard mathematical concepts and algorithms into non-routine methods during the course of their work in design and analysis. The study illustrates how engineering practice seamlessly traverses concepts and algorithms in math and physics, design constraints specific to the site where the construction work is to be done (a parking ramp), material specifications regarding load for concrete, and computer simulations. Engineers exhibit something that is mundane to other engineers, but quite remarkable to everyone else: they "see" the math and science in the materials and devices and can thread them through the design and manufacturing processes, thereby constructing conceptual cohesion throughout a project. This chapter examines the degree to which high school engineering students also develop and maintain this type of cohesion during classroom instruction by analyzing the emergence of mathematical and scientific ideas during a project-based unit. This analysis provides a theoretically-informed account of how teachers and students may produce or constrain opportunities for mathematics and science integration in engineering courses.

Literature Review

Engineering education, long recognized as a highly competitive area of higher education, has become more established in the K-12 and even pre-school arenas (PBS, 2011). The 2009 report from the National Academy, *Engineering in K–12 Education: Understanding the Status and Improving the Prospects*, put forth three principles of K-12 engineering education that attempt to align curricula to the professional standards by: emphasizing engineering design; incorporating important and developmentally appropriate knowledge in science, math and technology; and promoting engineering habits of mind, including collaboration, communication, systems thinking, creativity, optimism for improving the quality of life, and ethical considerations for the environment and the general public.

While the purpose of college level engineering education programs can be framed in terms of career readiness, the purposes behind P-12 engineering are more diffuse. One distinction that has been made is whether the emphasis is on incorporating engineering activities and concepts into established content areas, such as science and math, or whether "stand-alone" courses are developed, often within career and technical education (CTE) programs (Burr-Alexander et al., 2006). Program expectations may emphasize the exposure to engineering practices and ideas, such as collaborative, project-based work and the engineering design cycle, following a "technological literacy for all" model packaged for the general student body, or they may serve as highly selective "pre-engineering" programs tailored to students who demonstrate a history of technical excellence, and who are more likely to pursue a STEM field of study (Custer & Daugherty, 2009; Katehi, Pearson & Feder, 2009; Nathan et al., 2011).

One of the central driving forces behind P-12 engineering education is the reauthorization of the Perkins Career and Technical Education Act, which mandated that technical education and academic math and science topics be integrated "so that students achieve both academic and occupational competencies." Substantial funds have been allocated "to provide vocational education programs that integrate academic [math and science] and vocational education" (Perkins Act, 1998). In addition, highly visible initiatives have promoted STEM integration. The National Research Council (2007) report, *Rising above the Gathering Storm* implores the nations' leaders to energize the science, technology, engineering and mathematics (STEM) career pipeline, while "Race to the Top" allocated large state grants to promote STEM education efforts.

In response, commercial curricula have emerged that target this mandate toward STEM education. One of the most widely adopted curricula is from Project Lead the Way (PLTW). As they state in their marketing materials (PLTW, 2009):

> PLTW's premier high school program, Pathway To Engineering™, is a four-year course of study integrated into the students' core curriculum. The combination of traditional math and science courses with innovative Pathway to Engineering courses prepares students for college majors in engineering and E/T fields and offers them the opportunity to earn college credit while still in high school.

PLTW has been adopted by over 10% of US high schools, and is present in all 50 states (Walcerz, 2007). PLTW was singled out as a model curriculum for providing the kind of rigorous K-12 materials needed to improve math and science learning and increase America's technological talent pool (NRC, 2007). Thus, findings based on PLTW have far-reaching implications.

Issues of STEM Integration

According to Sanders and colleagues (in press), STEM integration is the intentional integration of content and processes of science or mathematics education with the content and processes of technology or engineering education along with explicit attention to technology or engineering learning outcomes and science or mathematics learning outcomes as behavioural learning objectives. STEM integration lies at the heart of engineering practice and current curricula, yet fostering robust STEM integration is difficult to achieve in many P-12 engineering courses. One line of evidence comes from studies of student achievement data. If engineering courses are effective at teaching STEM integration, then we might expect to see measurable advantages in "high-stakes" science and math assessments for those taking engineering courses. However, studies of the effect of engineering course enrolment on achievement gains in math and science show equivocal results. Wendell et al. (this volume) show evidence suggesting that elementary students learn science content knowledge from engineering units. Similarly, high school students in some studies show greater gains in standardized achievement tests after taking engineering courses than their peers (Bottoms & Uhn, 2007; Phelps, Camburn & Durham, 2009; Schenk et al., 2011), especially when these students are in specialized STEM programs. However, in other studies high school students from the general population with less specialized technical knowledge or interest showed modest or no advantages on science and math achievement from engineering classes compared to their peers who take non-engineering electives along with the same program of other STEM courses (Nathan & Tran, 2010a, 2010b). Overall, STEM exposure does not always lead to STEM integration.

Analyses of K-12 engineering curricula provide another line of evidence for the challenges of forging STEM integration. Curriculum analyses examine the content and sequencing and the alignment of content to an established set of objectives, such as state and national curriculum standards. Analyses of the three PLTW then-foundations courses (these designations have since changed) -- *Introduction to Engineering Design (IED)*, *Principles of Engineering (POE)*, and *Digital Electronics (DE)* -- showed that while many of the math content standards were present in the curriculum sequence as a whole, far fewer math standards were in evidence in the courses IED and POE that enjoy the largest enrollment. Furthermore, analyses showed that math concepts in IED and POE were rarely called out or explicitly integrated with the engineering activities (Nathan, Tran, Phelps & Prevost, 2008; Prevost et al., 2009, 2010). This lack of explicit integration makes students' transfer of these concepts less likely (Pellegrino et al., 2001).

The pattern is not unique to the PLTW program, but is also found when one looks broadly across the range of elementary and secondary engineering curricula. A recent report from The National Academy of Engineering examined 22 elementary, middle and high school pre-engineering curricula, including nine high school programs (Katehi et al., 2010). The analysis looked at the goals of each curriculum, the presence of engineering concepts, and how each treated mathematics and science concepts in the context of engineering activities. The report is particularly striking in its remarks regarding the shallow role of mathematics, which is often relegated to little more than taking measurements and gathering and organizing data. Notably, the study found curricula gave little attention to more advanced standards, such as analysis and modeling, despite the great potential for such activities in these rich, project-based units.

Studies of classroom instruction provide a third line of evidence of the challenges of implementing STEM integration. Whereas curriculum analyses contribute to our understanding of the *intended* or idealized lessons, classroom-based research provides empirical evidence of the *enacted curriculum* (Prevost et al., 2010; Porter, 2004), and allows us to investigate the actual learning experiences of students. For example, students engaged in CAD activities to design a new robotic part may need to inscribe a cylinder into a rectangular prism. The analytic geometry concepts are noteworthy, and can be built on earlier math lessons of inscribing circles in squares. However, students often experience this as a series of menu selections and commands to the CAD system, rather than as an opportunity to connect their work to general math concepts and procedures. As with the analyses of the intended curricula, explicit integration of math and science concepts was more evident in advanced courses (Prevost et al., 2009, this volume).

Situated Perspectives and Scientific Practice

The challenges of STEM integration in pre-college engineering can in part be understood through the learning theory of situated cognition. A situated perspective on the nature of learning posits that knowing in a domain involves the adoption and reorganization of appropriate participation practices in social systems of activity (Cobb & Bowers, 1999; Driver, Asoko, Leach, Mortimer, & Schott, 1994; Greeno, 2006). From this view, knowledge of mathematical and scientific ideas is not separable from the practices through which these ideas arise, or the context of the learning environment (Brown, Collins, & Dugid, 1989). The context of an activity system like school includes learners, teachers, curriculum materials, and the physical environment, as well as representational, material, informational, and conceptual resources. Viewing learning as a trajectory of participation in activity systems leads to a conceptualization of transfer as the ways in which participation in a social setting contributes to one's growth as a learner and one's future participation in other activity systems of value (Greeno, 1997).

By focusing on the nature of the practices themselves, rather than solely on knowledge, situated perspectives on school learning have helped to articulate why knowledge acquired through classrooms often does not transfer to the workplace and other out-of-school settings. (e.g., Blumenfeld et al., 1991; Boaler, 2002; Jurow, 2005; Greeno, 1991; Greeno & Hall, 1997; Lampert, 1990; Lave & Wenger, 1991; Resnick, 1987). Learning in traditional school settings may remain inert, heavily procedural, and based on idiosyncratic contextual cues, with students viewing a content domain as a static, certain body of knowledge passed down from authorities like teacher and text (Bransford, Brown, & Cocking, 2000; Schoenfeld, 1988). In response to these concerns, educational innovations like project- and problem-based learning (Barron et al., 1998; Krajick & Blumenfeld, 2006), communities of practice (Lave & Wenger, 1991), cognitive apprenticeship (Brown et al., 1989) and inquiry-based learning (Edelson, Gordin, & Pea, 1999) have become prevalent in the discourse of education, especially in STEM contexts. These innovations accentuate the importance of students adopting mathematical and scientific ways of knowing while participating in some version of authentic disciplinary practices. Indeed, a central tenet of many current reform and project-based curricula is the idea of using applied problems to provide students with a genuine purpose for the scientific or mathematical practices they are learning, an idea forwarded a century ago by Dewey (1916).

In PLTW engineering courses specifically, students engage in projects involving the design, creation and testing of devices, providing authentic venues for mathematical and scientific ideas to arise. Learning and participation are distributed across a variety of settings, contexts, and events that are similar to those that arise in engineering practice, including formal classroom lecture, small-group modeling and design on paper and in interactive software, physical construction of devices in a workshop or laboratory, and testing and demonstration of products for various stakeholders. While a situated perspective recognizes that the adoption of participation schemes in each of these contexts is essential to gaining competence in the field of engineering, in formal education settings, important challenges arise.

Specifically, when students adopt the participation practices of many different physical and social settings, working with a variety of tools, materials, and representations, they may struggle to see how these practices are connected across time and space. In the language of situated cognition, they may not readily perceive how participation in one context overlaps with or is related to other participation in previous or future stages of project work. For example, Wendell et al. (this volume) describe the challenges of implementing a project-based engineering curriculum in elementary school. Critical issues include teachers structuring complex and unpredictable tasks to promote learning, as well as students realizing the underlying concepts in these activities. This becomes especially problematic in formal education, where there are certain socially-established mathematical and scientific ideas that students are expected to recognize on assessments of learning. Since learning in project-based engineering classrooms is distributed across many different contexts with vastly different norms, students may have difficulty seeing how the mathematical and scientific practices that are valued on school assessments are related to these different events. This leads to what we consider a central challenge in STEM education – the problem of context.

THEORETICAL FRAMEWORK

Modal Engagements and Embodied Cognition

As situated perspectives locate learning within activity, we propose *modal engagements* (MEs) as a central organizing concept for STEM instruction. Hall and Nemirovsky (in press) define modal engagements as "a way of participating in activity, with others, tools, and symbols" (p. 5). Activity in engineering classrooms can be viewed as a series of interconnected MEs that occur as students encounter and interact with different material and representational forms, across time, social configurations, and physical settings.

Conceptualizing learning as a trajectory of participation in MEs draws upon embodied views of the nature of cognition, emphasizing the perceptual, physical, actionable, and interactive properties of the concepts to be learned and the representations used to refer to them. Theories of embodied cognition posit that all cognition is rooted in the body's interaction with the world, and thus all cognition inherently involves body-based perceptual and motor systems (Lakoff & Nunez, 2000; Wilson, 2002). The construct of modal engagements brings to the fore the multi-modal, embodied nature of learning that is central to participation in project-based classrooms where students and teachers use gesture, speech, and action to engage with a variety of media.

Locally Invariant Relations

Situated perspectives reject essentialist notions of mathematical knowledge as universal and pre-determined (e.g., The Bourbaki Group, 1950; also see the "romantic view" reviewed by Lakoff & Nunez, 2000) and views of scientific knowledge as based on unbiased observations of the world (e.g., Carey & Smith, 1993; Pomeroy, 1993). Instead, situated knowledge is viewed as a set of socially-constructed practices and norms for participation in different systems of activity (Driver et al., 1994). Using an embodied cognition framework, Noble, Nemirovsky, Wright, and Tierney (2001) further posit that students view mathematical knowledge as a web of "family resemblances" (Wittgenstein, 1958) among their lived-in experiences in mathematical environments. This idea of family resemblance has important implications for understanding how students, who often have very limited experiences "living in" the domains being studied in school, conceptualize these mathematical and scientific practices.

However, it is useful in school settings to conceptualize commonalities in mathematical or scientific relationships that arise across contexts and events, as these commonalities are often considered important outcomes for instruction. For example, the relationship between the load placed on an object and the resultant forces of tension and compression may be viewed as having some degree of invariance, whether this relationship arises in an idealized software modeling environment or a free body diagram; in the balsa wood sticks of a model bridge with weights placed on it, or in the steel beams of a full-sized bridge as vehicles drive across it. We refer to the common mathematical and scientific relationships that hold across MEs as *locally invariant relations*, and recognize that these often form the core of what students are expected to learn in engineering courses. We accentuate the *local* invariance of these relationships to emphasize that idealized equations for quantities such as force and acceleration will never precisely hold in complex, real world situations where there are countless unmeasured variables. These invariant relations may be broadly construed as what is more commonly recognized as “concepts” or “conceptual knowledge” in educational settings.

Modal-Specific Epistemological Orientations

Focusing on how locally invariant relations become instantiated across the diverse MEs that arise in formal STEM education settings helps to identify how the curriculum can create serious barriers to STEM integration. That is, students may notice or fail to see important commonalities and distinctions in scientific practices across different settings and representations that arise during a project-based unit.

Research on project-based instruction suggests that students are sometimes prone to engage in “action without appropriate reflection,” or that they get so caught up in doing an engaging activity they can fail to see important connections (Barron et al., 1998, p. 274; Schauble et al., 1995). If students are engaged in project-based design units that continuously orient them towards motivating, capstone events like launching a model rocket or breaking a model bridge, this orientation may overshadow other important but less salient MEs, and interfere with forming connections across activities. Further, students may experience what Heidegger calls *skillful coping*, where they act directly upon the world by employing socialized background practices rather than critical reflection. When coping, materials, tools and representations become invisible to students who use them in automatic, unreflective ways that does little to foster learning (Dreyfus, 1991).

As project work unfolds, participants can become fixated on the specific MEs that are present, to the exclusion of the other, relevant MEs that arise within the project unit. Students can exhibit a type of orientation to one focal modality that limits their appreciation of the role this one object or event plays within the larger conceptual structure. As a result, students can have difficulty viewing the specific activities they engage in as related to MEs that came earlier in time and those that are yet to be. Such modal-specific orientations are not unusual (Engle, 2006), and can direct one’s attention to important steps in the project. When they also serve to narrow one’s ability to relate a particular stage of the project to the overall conceptual structure of the curricular unit – as when designing an aesthetic element of a bridge is no longer related to its structural properties in the designer’s mind – this *modal-specific epistemological orientation* serves as a formidable barrier to constructing the conceptual cohesion necessary to foster STEM integration.

Students may also fail to see how co-present, but highly dissimilar appearing forms, like equations and scale models built from materials, can be manifestations of a common invariant relation. Unlike the professional engineer, students may not recognize how formal or abstract mathematical and scientific ideas arise in material form as the class activity becomes increasingly centered on physical objects and devices.

Previous research on students' epistemological beliefs and resources (e.g., Hammer, Elby, Scherr, & Redish, 2005; Hogan & Maglienti, 2001; Pomeroy, 1993; Sandoval, 2003; Zeineddin & Abd-El-Khalick, 2010) relating to scientific practice has not focused on the role that materials and representations play in orienting participants towards certain scientific practices. However, modality is an essential component of students' beliefs about scientific practice, as construction and validation of knowledge often centers around materials and representations (Baird, 2004). In project-based classrooms, teachers and students can display modal-specific epistemological orientations in that they attend to specific, often highly salient, material and representational forms, without integrating ideas and generalizing across the progression of MEs in a project-based unit. These orientations represent a core challenge to STEM integration, as they highlight important issues that arise when teaching engineering practices in the authentic contexts of their use. Past research on the importance of situated perspectives for understanding and designing learning environments has paid insufficient attention to the barriers that inquiry and project-based approaches create to STEM integration, and how these difficulties are negotiated in practice by participants. The primary research question addressed in this chapter is: **How do participants build conceptual bridges across the diverse modal engagements that arise in project-based classrooms, in order to produce and maintain cohesion of the locally invariant relations that are important outcomes of instruction?**

Modality Transition Behaviors

As students design, build, and test devices in engineering classrooms, locally invariant relations become instantiated across disparate settings and contexts. Activity in engineering classrooms takes place in various *ecological contexts*, or venues that involve different physical locations, social norms, participation structures, and sets of available tools, materials, and representations. Students and teachers must navigate *ecological shifts*, or changes in ecological contexts that occur during project work. An example of such a shift would be students moving from a teacher-centered lecture on abstract physics concepts to building devices with raw materials in a workshop. We will argue that constructing and maintaining conceptual cohesion of key invariant relations across different MEs and ecological shifts requires the explicit attention of both teachers and students.

To this end, we have identified *modality transition behaviors* that appear to be especially important cohesion-producing mechanisms in educational settings. First, teachers and students use speech, gesture, and coordinated action with objects to make *projections* forward or backward in time, connecting the invariant relations arising in current MEs with their instantiations in past or future MEs. Explicitly referencing or describing how different stages in a project unit are related can encourage students to see how key invariant relations arise within different MEs across time and space. Second, participants use *coordination*, where they make links between co-present material and representational forms, highlighting how different modalities instantiate common invariant relations. We will show how together, projection and coordination have the potential to foster cohesion of key mathematics and science concepts across MEs, facilitating flexible understanding and STEM integration; and how, in their absence, students struggle to connect elements of the curriculum to the central math and science concepts.

Modal Engagements Analysis

Arising out of this theoretical framework is the approach of Modal Engagements Analysis (MEA). We have described the conceptualization of STEM classroom practice as learning to participate in a web of interconnected MEs that encompass varied **materials** and **representations**. These MEs are distributed across **time**, as project work unfolds and is reflected upon and planned for; across **space,** as students and teachers move between formal classroom settings, workshops, and computer laboratories; and across **social structures and interactions,** as instruction is situated in teacher-centered lecture, small group design and building, and the public presentation of products for various stakeholders. These MEs also involve coordinated action on materials, tools, and objects, with **action** and **gesture** serving as key agents in classroom interactions. Finally, as these MEs are situated in formal educational settings, a need arises to recognize **locally invariant relations**, or mathematical or scientific ways of knowing that can be referenced with some level of consistency across settings, contexts, and events, and that are often viewed as important outcomes for instruction.

MEA is an approach for analyzing and understanding a central challenge to STEM integration: maintaining cohesion of locally invariant relations as they arise across MEs and ecological shifts in rich, project-based classrooms. Teachers and students in STEM settings must negotiate this complex, ever-changing web of activity, while attempting to meet established curricular goals. MEA incorporates an explicit focus on the challenges of integration as well as on the ways in which participants in these settings work strategically to build and maintain cohesion throughout these project-based units.

Drawing on methods of conversation analysis (Goodwin & Heritage, 1990; Schegloff, 2007) and gesture analysis (Duncan & McNeil, n.d.), MEA emphasizes temporality, social interaction, and the manner in which communicative demands are negotiated through speech, embodied action, and social norms. However, MEA also focuses on the role of materiality (Latour, 1996; Law, 1992; cf. Gal'perin's theory, Arievitch & Stetsenko, 2000), using the organizing construct of modal engagements with others, tools, and symbols (Hall & Nemirovsky, in press). In this way, MEA is also related to actor-network theory (Law, 1992), which describes the semiotic and material relationships that arise as agency is distributed across a network of activity, which includes the participants, tools, and the ecological and historical context of the interaction.

METHOD

Data Sources

Video data was collected from the high school engineering classes of one teacher. Participants were enrolled in *Principles of Engineering*™ at a Midwestern urban high school using the *Project Lead the Way* (PLTW) curriculum. The school was 51% Caucasian, 26% African-American, 11% Hispanic, 11% Asian, and 1% Native American; 49% of students received free or reduced lunch, and 14% were classified as English as a Second Language (ESL). During the year of the study, 64% and 65% of 10^{th} graders at the school passed the state science and mathematics standardized assessments, respectively. The teacher had been teaching technical education classes at the school site for 8 years, and had taught 15 different areas of technical education for grades 9-12. The teacher held Bachelor's degrees in industrial arts education and architectural design and building construction, and had previously worked in industry. *Principles of Engineering*™ is the second engineering course in the standard PLTW sequence, and is usually taken after the *Introduction to Engineering Design*™ course.

Curricular Unit

In Unit 5 of the *Principles of Engineering*™ curriculum, *Statics and Strengths of Materials*, students participate in an extended activity where they build and test balsa wood bridges. Students learn to mathematically analyze the forces on a structure with the goal of building a bridge that supports the greatest amount of weight per gram of mass. Students learn about the different forces that act upon a bridge, and how to use free-body diagrams to identify and combine different vector forces. Students also investigate how stresses, strains, and displacements occur as a solid body is subjected to a load. Using these concepts, students are expected to be able to predict how materials will react when placed under stress, the relative strength of different designs, and to model the relevant forces in a computer-aided system (PLTW, 2004). Central to the analysis presented here are the invariant relations on forces of tension and compression. A structure is under *tensile force* or *tension* or when it is expanded, stretched, or lengthened as a result of the acting force. A structure is under *compressive force* or *compression* when it is pushed together or shortened.

Data Analysis

MEA utilizes multi-modal analyses (Alibali & Nathan, in press; McNeil, 1992) of classroom discourse episodes, focusing on how contextualized speech, gestures, inscriptions, and actions work in conjunction to build and maintain cohesion of invariant relations as teachers and students participate in diverse MEs. Central to these analyses is how the modality transition behaviors of projection and coordination are instigated by teachers and students to make meaningful connections across ecological shifts and other MEs.

These “case studies” are then complemented by an analysis of the related MEs that occur as connected sets of activities that take place over days or weeks, situating specific episodes within the larger sequence of a STEM project. Identifying key MEs in this sequence, and then analyzing how they are connected by participants as they enact projection and coordination, allows for a broader conceptualization of how students may perceive the connectivity of classroom events over time. An analysis of how MEs are linked both temporally and through modality transition behaviors shows how cohesion is maintained or misplaced by participants as their activity on a project unfolds. Thus MEA illustrates how invariant relations central to STEM education can be threaded through settings, contexts, materials, and representations.

Conducting MEA on a data set has several stages. First, video footage is transcribed, and divided into clips of MEs that take place during the project. Modal engagements are the primary unit of analysis in MEA, and clips are separated such that each shows the interactions of the teacher and students around a single concept, idea, or procedure, making use of materials and representations in a specific social configuration and physical location. While MEs can be conceptualized on many different scales of time, the unit of analysis described here is particularly well-suited to STEM formal education settings where there are explicit goals related to the communication and adoption of certain concepts and procedures. Each clip is coded for the modalities (i.e. material and representational forms) that arise during the ME, and the modality transition behaviors (projection and coordination) enacted by participants. Clips are also coded with the concepts or procedures (locally invariant relations) being discussed. Clips are organized temporally, and grouped according to the ecological context (physical setting and social organization) in which they take place. Clips that are important to the analysis are further transcribed to include detailed descriptions of gesture and action (see episode transcripts, next section). Clips with key instances of modality transition behaviors are used for case study analyses of individual classroom events. The entire set of clips is also mapped (see Figure 1) to illustrate how invariant relations become threaded through MEs that are connected by a web of projection, coordination, and ecological shifts.

Modal Engagements Analysis of the Bridge Case

Classroom activities related to bridge design, simulation, building, and testing are complex, and involve many MEs with different materials, representations, tools, and social and physical settings. Some of the key MEs that occurred during the first day of the video footage include: a demonstration of a software program that models forces of tension and compression, a lecture about how these forces will be visible as bridges are tested, students working on building their bridges with raw materials, and group discussions about upcoming bridge testing procedures and tools. During the second day, key MEs included students: weighing their bridges, stressing their bridges with weights, making predictions about how their bridges will break, analyzing broken bridges, and comparing strength-to-weight ratios.

We describe three episodes, one that occurred during the teacher's lecture the day before bridge testing, and two that occurred on the day of bridge testing, as the first group prepares to stress their bridge. Classroom interactions demonstrate both the potential and the pitfalls of threading mathematics and physics relations through different ecological contexts, as a class orients itself towards the exciting capstone experience of breaking their bridges.

RESULTS

Episode 1: Tension and Compression Lecture

During a classroom lecture prior to bridge testing, the teacher observes that many of the students' model bridges have a "shear problem," – i.e., they are designed such that beams will slide past each other when placed under a load – and he uses this observation to initiate a discussion of structural forces. The transcript of this final portion of the lecture, which lasts 36 seconds, is shown below. Video frames are included to show the temporal progression of speech and gesture; this technique is similar to Goodwin (2003). The boxes show the part of the speech during which the gestures occurred (from gesture preparation through retraction), while overlaid arrows show the direction of movement in the gestures.

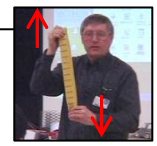
In the transcript, the teacher uses gesture, action, coordination, and projection to demonstrate how invariant relations of tension and compression will be threaded through the future ME of bridge testing. In lines 1-6 ("Look at your bridges, like I put up here, did you see the tension and compression?") the teacher makes a backward projection to the computer simulation software that was previously on the screen, encouraging students to think about their own bridges in terms of principles of statics. The teacher uses beat gestures, which can serve meta-narrative functions such as emphasis (McNeill, 1992), when saying the words "tension" and "compression"; these gestures accentuate the centrality of these invariant relations to students' work on the project.

In lines 7-8 ("I want you to see it happening as it starts coming apart") the teacher makes a forward projection to the future, imagined ME of stressing the bridges. The teacher uses coordination with projection, creating a link between the long foam block he is pulling on, and a beam of an imagined bridge being stressed. The large size and elasticity of the foam block, along with the grid markings that exhibit clear deformation as the block is stressed, makes the effects of the forces visible in a way that would not be possible with the wooden beams.

In lines 10-16 ("When we replay the tape, we can slow it down one frame at a time, and you can actually see the action happening") the teacher makes a forward projection to another future ME, watching video of the bridges breaking. In lines 17-30 ("Is the bridges going to twist? It is gonna, is it gonna cave in right in the middle? Is it gonna shear off at the ends, and the whole bridge is gonna go straight down?"), the teacher enacts forward projection and coordination, simulating different possibilities for how the students' bridges will behave under stress, using a model bridge and iconic gesture. This directs students' attention to observable ways in which the invariant relations being discussed will become visible during bridge testing.

T: Look at your bridges, like I put up here,
Teacher makes deictic gesture, pointing to projected computer screen.

T: did you see the tension and compression?
Teacher makes 2 beat gestures with finger, accentuating "tension" and "compression."

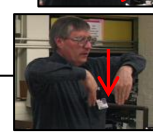


T: I want you to see it happening as it starts coming apart.
Teacher pulls on both ends of foam block.

T: When we replay the tape
Teacher makes deictic gesture, pointing to camera

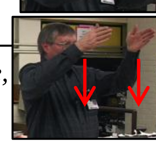
T: we can slow it down one frame at a time,
Teacher makes iconic gesture, simulating frames flashing by with hand.
T: and you can actually see the action happening.

T: Is the bridge gonna twist?
Teacher uses iconic gesture, rotating open hand around model bridge in twisting motion.



T: Is it gonna, is it gonna cave in right in the middle**?**
Teacher makes iconic gesture, placing hands horizontal with fingers touching, then points fingers downwards.

T: Is it gonna shear off at the ends,
Teachers uses deictic gesture, indicating one end of the bridge.



T: and the whole bridge is gonna go straight down?
Teacher makes iconic gesture, moving open vertical palms straight down.
T: Can you see what's gonna happen to your bridge? An engineer has to have vision.

Finally, in lines 31-32 ("Can you see what's going to happen to your bridge? An engineer has to have vision."), the teacher ties the discussion together by referencing the role of *professional vision* in engineering, i.e. "socially organized ways of seeing and organizing events" (Goodwin, 1994, p. 606). The teacher also uses this closing comment to tie in noticing or imagining strain on a solid body subjected to a load, one of the goals of the unit.

The teacher invokes several different materials, representations, and body movements in this episode – the computer simulation diagrams, a wooden model bridge, a foam block representing a bridge member, iconic gesture, and the abstract concepts of tension and compression themselves – to show students what might happen to their bridges as they become stressed. The teacher bends the foam block, makes twisting gestures around the model bridge, and forms a bridge with his hands that he "caves in" by drawing his hands downwards, using gesture enactment to demonstrate each of the ways the bridges can break. Here, gesture and action seem to be a particularly important component of projection. While it may not be feasible for the teacher to show actual model bridges breaking, by using forward projection, gesture, and action around different representational forms, the teacher *simulates* this future ME in an attempt to build cohesion of the invariant relations across this new, upcoming event. This episode demonstrates how action, gesture, projection, and coordination act in concert to provide tools for teachers to build cohesion across different ecological contexts.

However, the transcript also demonstrates the challenges of maintaining cohesion across the diverse modalities and temporalities that arise in engineering design projects. In the space of about 30 seconds, participants listening to this lecture must keep track of projections made to past temporalities (computer simulation software) and future imagined temporalities (stressing bridges, watching videos of bridges breaking), and coordinate these projections with different representational forms (foam block, model bridge, iconic gesture) and tools (camera, computer screen). While to an expert, it may be transparent how invariant relations of tension and compression become instantiated across these diverse modalities and temporalities, for a novice it can be difficult to maintain the cohesion of these concepts. In order to see how concepts are ultimately realized by students as they engage in bridge testing, we present two additional episodes.

Episode 2: Bridge Testing Discussion - "Spreading Out" the Weight

T: Alright, let's put the bridge on.
S2: Is the paper really necessary?
S: Sure why not?
S1: It makes it stronger.
T: If it was glued to it, it would of given it a skin
S2: Yeah it would've given a little extra weight… spread out the weight.
T: If the paper was on there and glued to it, would it improve the tension or compression?
S: Yeah.
S2: It would spread out the weight.
T: What?

S1: Tension.
S2: It would spread out the weight.
T: What's your other answer?
S: Compression.
T: Thank you.
T: Think about it, it's pointing down, remember the beams I showed you yesterday, what happens?
S1: Ohh I was thinking that it would be under tension.
T: Alright, let's start loading it up.

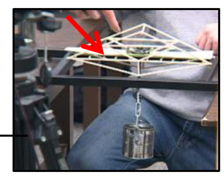
In the second episode, it is the next day and the class has arrived at the much-anticipated event of testing their bridges. As the first group prepares to stress their bridge, a student makes a comment about a piece of paper that is lying flat on the base of the bridge (line 34, “Is the paper really necessary?”). In line 36, a different student offers a conjecture (“It makes it stronger”) which is refined by the teacher in line 37 (“If it was glued to it, it would have given it a skin”). In line 38, another student offers a conjecture about why the paper might be beneficial (“Yeah it would have given it a little extra weight… spread out the weight”). Then in lines 39-40, the teacher takes this opportunity to directly invoke invariant relations by making a projection to a hypothetical situation (“If the paper was on there and glued to it, would it improve the tension or compression?”). This move encourages students to think beyond the local, present situation, and focus on the larger context of the bridge project and its various instantiations of tension and compression. The students initially fail to give the desired response to the teacher’s question, with one student continuing to claim the paper would spread out the weight (lines 42 and 45), and another stating that the paper would improve the tension (line 44).

In lines 49-50 (“Think about it, it’s pointing down, remember the beams I showed you yesterday, what happens?”) the teacher appears to notice that the students are having difficulty understanding concepts of tension and compression in this new ecological context (i.e., bridge testing), with different material forms (i.e., a bridge with a paper skin). To build cohesion, the teacher makes a brief projection to the previous day’s lecture. However the teacher does not re-invoke any of the action or explanation given previously – he simply mentions the connection, using the rather weak criterion that downwards forces (always) correspond to compression. From an expert’s perspective, the relationship between the teacher’s lecture where he stretched and pushed a large foam beam, and the current question of how tension and compression would be affected by the paper, may seem obvious. However, this episode shows that novices do not readily see the same connections across disparate material and representational forms. The teacher’s question on line 46 (“what happens?”) remains unanswered, and the class moves on without addressing the comment in line 51 (“Ohh I was thinking that it would be under tension”). Though students now know the answer to the teacher’s original question, they appear to be left without a conceptual basis for differentiating tension and compression and applying these concepts to bridge design.

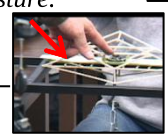
This transcript shows evidence of students' modal-specific epistemological orientations – i.e. an orientation towards ways of knowing associated with particular material and representational forms. Students in the transcript remain focused on the immediately present material form – the model bridge being tested – and have difficulty conceptualizing how this form relates to the previous MEs (i.e., deforming foam beams, manipulating equations, running computer simulations) used to demonstrate the concepts of tension and compression. The teacher's move to build cohesion of the centrally organizing concepts using backward projection to overcome the ecological shifts is ultimately not taken up by participants, and may have been insufficient to add to their understanding. In order to see how students' epistemological orientations continue to unfold as the first bridge is tested, the previous narrative is continued in a third episode transcript.

Episode 3: Making a Prediction – Tension or Compression?

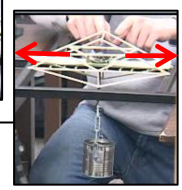
T: Okay, prediction, what's gonna happen?
S: Break -
S: Gonna snap.
T: Keep half? Okay, you think it's gonna hold about half of them.
T: Is it gonna fail at the ends?
S2 adds first 500g weight to the bridge.
S: Yep.
T: Is the floor going to pull through?
Teacher indicates center of bridge with deictic gesture.



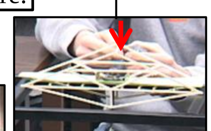
S: Yeah.
S1: No, it's gonna fail in the center.
T: Or the truss gonna fail?
Teacher points at center of bridge, slightly lower.



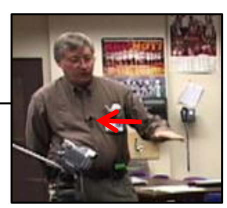
S2: That's gonna be the floor and the ends.
S2 points two index fingers at the middle of the bridge,
then sweeps fingers outwards to point at ends of bridge.



T: Now watch, is it gonna be a tension or is it gonna be compression component?
S2: We designed it so that it would compress in this middle bar here.
S2 points with both index fingers to the middle bar of bridge



S2 adds a second 500g weight to the bridge.
S3: We did, put one in the middle.
T: Is there more strength on the bottom side -
S: Yeah four pounds.
T: - of the flat, of the flat surface?
Teacher gestures with palm outstretched flat.



T: Or stronger on top?
S2adds third 500g weight to the bridge.
S1: No I guess it's only, it's only one point five.
S3: So right now he is at like one, one and a half kilo.
S3: Wh- what do we get if we win?

The third episode occurs immediately after Episode 2; the first student bridge has been set up, and the group is about to begin adding weights. On line 53 ("Okay, prediction, what's gonna happen?"), the teacher asks the students to make projections to the imagined future event of the bridge breaking. The teacher elicits students' prior knowledge, such that the subsequent events will either support or unravel these initial understandings (i.e., Minstrell, 1989). The initial responses (Line 54-55, "break," "snap") are quite shallow. Encouraged by the teacher (Lines 56-57), the students offer a variety of more analytical predictions (lines 63-68) about which portions of the bridge will break (e.g. "No, it's gonna fail at the center.") and how much the bridge will hold. The students' predictions are disparate and inconclusive; they are tied explicitly to the current model bridge being tested, rather than to a conceptual analysis of bridge behavior. In response, the teacher invokes the invariant relations on line 69 ("Now watch, is it gonna be a tension or is it gonna be compression component?"), again attempting to call upon the invariant relations and build cohesion within this new ecological context.

In lines 70-71 ("We designed it so that it would compress in this middle bar here."), a student takes up this move to build cohesion, making a backward projection to the group's design activities, and explicitly describing the role of invariant relations in this phase of the project. Here we see an important instance of a *student* making a move to build cohesion of concepts across different MEs, supporting his prediction with gesture. On lines 74-78, the teacher continues to question the class about the structure of the bridge ("Is there more strength on the bottom side of the flat surface?"). However, his question is not taken up by the students, who are already focused on keeping track of how much weight has been placed on the bridge (lines 75, 80, and 81). The conversation then shifts to a short discussion of the reward for building the "winning" bridge (line 82).

This transcript suggests that during engineering projects like bridge building, teachers and students may have different orientations. We see the teacher making an attempt to "thread through" the invariant kinematics relations, and push students critically analyze the structure of the bridge being tested in terms of these central concepts. However, the students become more interested in figuring out the current "score" (i.e., how much weight the bridge is supporting), and determining a winner. Further, this transcript shows students' tendency to focus on the local, present, salient material and representational forms rather than seeing them along a cohesive progression of instantiations of the invariant relations. When making predictions, students focus on the model bridge currently being tested and the addition of weights to that bridge, again exhibiting modal-specific epistemological orientations. The students' predictions (e.g., "Gonna snap") are also in "lay terms" rather than engineering terms, reflecting a non-analytical account (especially since it was already established at the outset of the unit that every bridge will be broken in order to measure maximum load). The teacher directly invokes the invariant relations using projection in an attempt to build cohesion over the arc of the lesson. In response, we observe a student enacting projection and coordination by connecting his prediction to the activity of designing the middle span of the model bridge, threading the concept of compression through each of these MEs. However, this contribution is not expanded upon by the teacher, and may be a missed opportunity for further cohesion-building.

Summary of Transcripts

In all three transcripts, the teacher seems to perceive an issue with cohesion of the invariant relations based on student action and speech, and responds by using projection and coordination in order to meet pedagogical and communicative goals for the interaction. In the first episode, the teacher uses projection and coordination to address an issue he has noticed with students' bridge designs, i.e., the presence of sliding beams that are likely to shear under low load. In the second episode, the teacher uses projection to remind students of his lecture on tension and compression as students confound these two forces when confronted with a question about bridge strength. And in the third episode, the teacher and a student enact coordination and projection in response to disparate and unsupported predictions made by the class. These data show how projection and coordination are powerful and frequent methods for producing and enforcing cohesion, and overcoming modal-specific epistemological orientations. However, in the episodes presented here, projection and coordination have only limited effectiveness for addressing students' difficulties tracking locally invariant relations across disparate forms and events. The final two transcripts in particular show missed opportunities for participants to make deep and meaningful connections across MEs and representational forms.

Further, episodes 2 and 3 are also the *only* occasions during the testing of the bridges where the central invariant relations of tension and compression are explicitly invoked. Although the transcripts show overt actions taken by the teacher to thread the concepts through this contextually rich project, these pedagogical moves are not made consistently, and are rarely used after the first bridge is tested. Thus, as students engage in the highly-anticipated capstone event of testing their bridges, the mathematics and physics concepts that are critical for developing STEM integration are nearly forgotten, overshadowed by the more salient events as bridges are stressed and broken.

Results of MEA of Bridge Case

Modal Engagements Analysis illustrates how invariant relations morph across the array of materialities and temporalities that arise in a typical engineering design project. This methodology allows for explicit identification of the *what* of the science – the key physics concepts and relations that are invariant across contexts, representations and material forms – and the *where* of the science – the all-important skill of tracking these invariant relations across ecological contexts, and understanding how they retain their structure even as their presentation drastically changes with different physical and semiotic instantiations.

Bridge Building Case Study

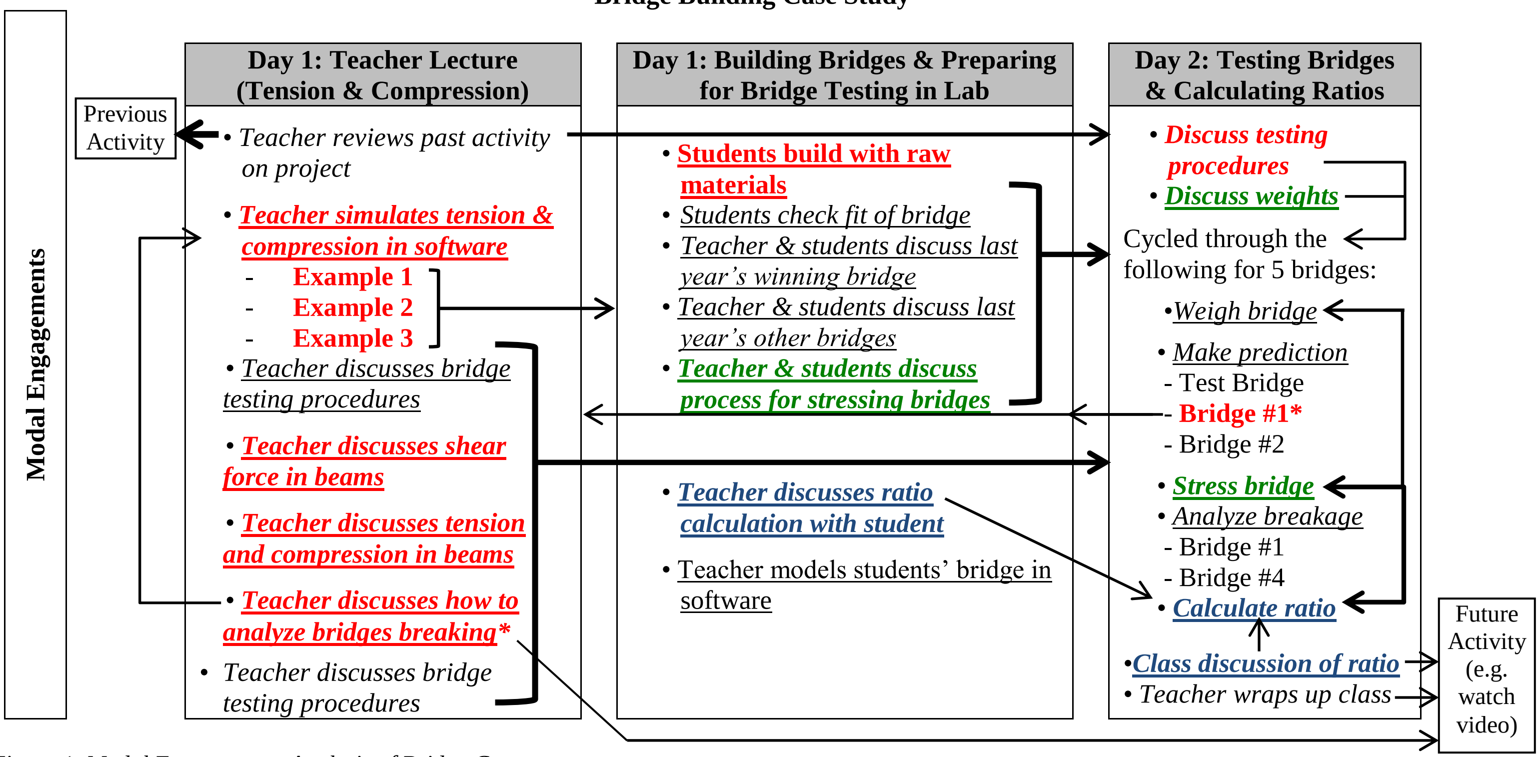


Figure 1. Modal Engagements Analysis of Bridge Case

Boxes show the ecological contexts that activity was embedded in, bullets show the main modal engagements, arrows show projections made between modal engagements.

Italics = *Projection*, Underline = Coordination, *Italics & Underline* = *Projection+ Coordination* (*indicates the modal engagements discussed in the transcripts given in chapter)

Locally invariant relations invoked: **Red = Tension & Compression**, **Blue: Strength/Weight Ratio**, **Green = Live/Dead Load**

Figure 1 shows an analytic summary of the MEA for the two days of the bridge activity discussed in this chapter. Arrows show some of the key projections made by participants, with the weight of the arrow corresponding to the number of projections made. Colors are used to identify locally invariant relations (tension and compression, strength-to-weight ratio, dead load) that were “officially” invoked by the teacher or the students using proper terminology.

Figure 1 makes several important aspects of the bridge project salient. First, the instruction is largely forward-driven, with many projections being made to orient students to future MEs, particularly regarding what to look for during the final event of testing and destroying the bridges. The high proportion of arrows going into and emanating from this capstone event underscore how the anticipation, planning, and reflection of testing the bridges drives nearly all of the efforts of constructing cohesion for the unit. Accordingly, around 40% of all projections made by students and the teacher during the two days relate to the event of stressing a bridge.

Calculating the strength-to-weight ratio also seems to be important to students, as it incorporates competition between groups and is a mathematically-accessible procedure. Around 16% of all projections made during the two days (10% of projections made by the teacher, and 25% of projections made by the students) relate to the ratio calculation. This orientation towards the strength-to-weight ratio calculation is especially interesting, given that this mathematical concept is barely acknowledged in the curriculum materials for PLTW’s bridge building unit, and is never invoked by the teacher as part of the “official” content of the project.

Both students and the teacher consistently orient themselves towards certain MEs during their participation in the bridge activities. But what does this mean for the physics concepts central to this project, and the cohesion of these invariant relations across ecological contexts? Figure 1 shows that while invariant relations of tension and compression (red) are central during the teacher lecture, as the project progresses these concepts are rarely invoked as the bridges are constructed and tested. The figure also makes clear that few backward projections are used to build cohesion of invariant relations across previous ecological contexts. Earlier work (Nathan et al., 2011) shows how backward projections are used to foster *reflective thinking* about the concepts. The paucity of backwards projections in this case suggests missed opportunities for students to deepen their understanding of the science and mathematics that populate this engineering unit. The MEA depicted in Figure 1 also illustrates the frequency with which participants relegate the key scientific concepts of tension and compression to the specific material forms, objects and representations -- the modal-specific epistemological orientations -- that serve as barriers to STEM integration.

DISCUSSION AND CONCLUSION

Modal Engagements Analysis (MEA) reveals how the multi-modal learning environment of the project-based engineering classroom presents barriers to STEM integration and a contextualized understanding of science and math concepts. We focused on pre-college engineering courses as a critical site to accomplish STEM integration – as part of students' high school program, these courses offer rare opportunities to enrich and promote integration of mathematics and science with engineering design and analysis. MEA also provides insight into ways teachers and curriculum designers can foster cohesion of core concepts, building pedagogical "bridges" as ways to understand physical ones, as students encounter the central science and math concepts across diverse representations, settings, social configurations, and materials.

By providing a concise temporal analysis of the nature and interconnections between modal engagements and the attempts to foster cohesion through projection and coordination, MEA shows places in the activity sequence where opportunities for "threading" key math and science concepts through modal engagements are unrealized. This helps to identify the missed pedagogical opportunities for encouraging reflection and integration. The analysis also shows how participants leverage opportunities to build cohesion and invoke key invariant relations, using projection and coordination in conjunction with gesture and action. Thus MEA is a powerful tool for analyzing the complex discourse structure during project-based instruction and tracking how cohesion of central curricular concepts can be produced or fractured across the range of modal engagements that arise in engineering design lessons.

MEA identifies modal-specific epistemological orientations, which represent a substantial barrier to STEM integration. Novice participants have a tendency to confine their speech, action, and gesture to immediately present, salient forms of core concepts, rather than engaging in reflection and integration of ideas across the range of modal engagements in an engineering design activity. Further, students can struggle to see how co-present, but highly dissimilar appearing forms, such as symbolic representations and materials, can be manifestations of common invariant relations. These challenges to STEM integration are often implicit in classroom activity. MEA brings them to the forefront by combing micro-analyses of discourse and gesture (Episodes 1-3) with macro-analyses (Figure 1) of how different classroom events are connected by participants across time and space.

Analyses of pre-college engineering curricula (Nathan et al., 2008; Prevost et al., 2009, 2010), engineering classrooms (Prevost et al., 2010, this volume) and standardized test scores of students who take engineering courses (Nathan & Tran, 2010a, 2010b) suggest that STEM integration is both precarious and rare, and that the curriculum itself can create formidable barriers to establishing cohesion. We provide a theoretically informed analysis to suggest why such integration may be difficult to achieve. Although the analysis highlights the challenges of integration, we have also identified that modality transition behaviors like projection and coordination are important means for establishing the cohesion that is necessary for STEM integration to be realized.

Transfer of learning may be fostered when teachers make moves to build *intercontextuality* by making explicit links across learning contexts, including temporal connections that describe how different events are related (Engle, 2006). We provide an account of how both teachers and students use such projections to build cohesion, and suggest that there is a strategic aspect of this behavior related to overcoming modal-specific epistemological orientations. The STAR Legacy Cycle (Schwartz, Lin, Brophy, & Bransford, 1999), a challenge-based approach to instruction based on research from the Learning Sciences, also directs students to both look ahead to and reflect back on project activity. In this way, students may benefit from opportunities to understand where project activity is leading, and how invariant relations will be instantiated in future stages of the design cycle. Students also may benefit from reflecting on previous stages of project activity, integrating mathematical and scientific ideas across the classroom's lived history of modal engagements. This may be especially important as participants become increasingly oriented towards motivating and highly salient capstone events, and risk getting caught up in "activity for activity's own sake."

Beyond making temporal connections between different settings and events, we also suggest that intercontextuality and cohesion may be enhanced when coordination is made between different material and representational forms. Representational objects can preserve different relationships between the *representing* and *represented* worlds (Palmer, 1978), and research on meta-representational competence underscores the importance of students being able to compare, critique, explain, and understand the purposes of different representations (diSessa, 2004). This account suggests that students may need support to understand the relationship between different instantiations of invariant relations, such as formal mathematical equations and designed objects. Students may also have a tendency to favor concrete, salient representations of concepts, which can be problematic on standardized assessments of learning where students must often recognize invariant relations in abstract or decontextualized forms. Blumenfeld et a1. (1991) accentuate the importance in project-based classrooms of students creating artifacts that are both explicit and concrete such that they can be shared. Here we provide an account of why such concrete, explicit products may not always be sufficient for promoting the learning and transfer of abstract relations. However, as varied MEs become central at different stages of project work, asking students to explicitly compare how they instantiate different aspects of key invariant relations may foster cohesion, helping to overcome modal-specific epistemological orientations.

An important focus for future research in engineering education will be continuing to explore how modal-specific orientations can be overcome through interactional moves and curricular designs that encourage students to build a well-developed understanding of STEM content and practices. Once promising constructs (like projection and coordination) are identified, it will be important to relate them to student learning to investigate their effectiveness for promoting conceptual understanding of the abstract relations that are essential for gaining expertise in engineering fields. Our research suggests that situated, multimodal analyses based on Learning Sciences research can be highly effective for this type of work, due to the socially-constructed and embodied nature of engineering practice. Indeed, developing research programs in engineering education that leverage recent advances in the Learning Sciences is critical to moving the field forward (Johri & Olds, 2011).

Professional engineers demonstrate a mastery of the full range of STEM content. The emerging field of P-12 engineering education must share the same goal. To achieve this, we argue, cohesion and integration across modal engagements must be accomplished in order to develop the competencies and pre-requisite knowledge to engage in effective engineering practices.

AUTHOR NOTES

The authors would like to acknowledge the valuable contributions of Mathew Felton-Koestler, Rich Halverson, John Bowin, and members of the Tangibility for the Teaching, Learning, and Communicating of Mathematics project at San Diego State University, University of Wisconsin-Madison, and Vanderbilt University's Peabody College. This work was made possible through the financial support of the National Science Foundation (DRL-0816406).

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