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Productive Disciplinary Engagement in Complex STEM Learning Environments

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Productive Disciplinary Engagement in Complex STEM Learning Environments

Introduction

Researchers have described the advantages of complex, realistic, and challenging science, technology, engineering and mathematics (STEM) learning environments that engage students in the practices of STEM disciplines. Benefits include: increasing students' likelihood to transfer skills learned during school activities to practice, value of the task, and motivation.[1,2,3] Research teams from four universities are currently studying *productive disciplinary engagement* in these types of learning environments. Productive disciplinary engagement occurs when learners use the discourses and practices of the discipline in authentic tasks in order to "get somewhere" (develop a product, improve a process, gain better understanding of a phenomenon) over time.[4,5] Productive engagement in meaningful, authentic activity is essential for motivation and progress toward flexible, adaptive expertise in STEM, but learning systems that support it are complex and difficult to scale. Such systems are usually studied and designed in single contexts (e.g., high school environmental science classrooms, engineering design projects), so the knowledge gained, though rich, is difficult to transfer to new settings. Through collaboration among researchers from the United States (Washington and Oregon), Finland, and Australia who study these systems in different curricular, institutional and cultural contexts, we aim to identify unifying themes and develop *generalizable understandings* about supporting engagement and learning in STEM. We focus on group settings in authentic contexts, where students must integrate and flexibly apply concepts and practices.

The research teams use a variety of approaches, including ethnographic (video and audio) records of students and teachers engaged in STEM projects; design-based research on virtual learning environments, material tools and assessment strategies; and controlled field experiments with in-depth process analysis. Ultimately we are trying to answer the following research questions across projects:

- What supports productive disciplinary engagement in advanced, complex STEM learning environments?
- How do these patterns of engagement in complex STEM environments vary by level (high school, university), discipline (engineering, environmental science, veterinary science) and country (US, Finland, Australia)?
- How can findings from these collaborative analyses inform further design of complex STEM learning environments?

The contexts and levels include: Washington, high school science students; Oregon, undergraduate engineering students; Finland, high school science students; and Australia – undergraduate, veterinary medicine students. More detail of the contexts is provided in Appendix A. In the first year, we developed a common understanding of productive disciplinary engagement and developed systems of analysis that enable cross-project investigation. This poster paper presents a summary of our progress during the second year of the collaboration.

A General Theoretical Framework of Productive Disciplinary Engagement

The research groups described in this paper investigate different educational levels, different students, different teachers, and different cultures. While the contexts are different, an overarching common theory is found in productive disciplinary engagement. Engagement has been defined generally as "active, goal-directed, flexible, constructive, persistent, focused interactions with the social and physical environments."[5 (p. 399)] We use Engle & Conant's term *productive disciplinary engagement*[5] to capture the kind of interaction with people and objects likely to result in deep learning of STEM concepts and practices. Engagement is *productive* to the extent that conceptual or practical progress on a problem is made over time. Finally, engagement is disciplinary when students use the discourse and practices of a specific STEM discipline in their work together.

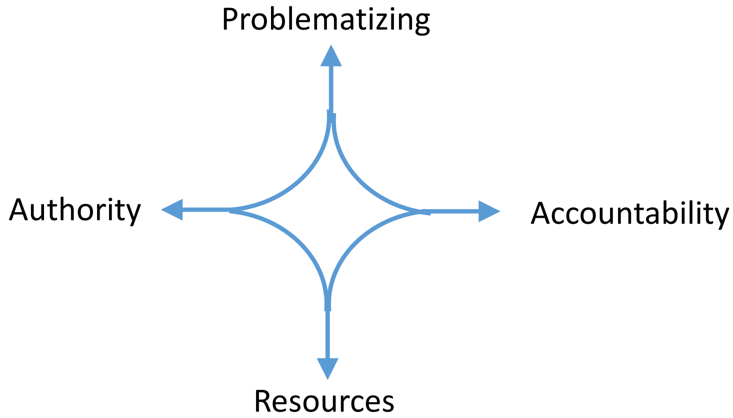

Figure 1. Characteristics of contexts that support PDE (Engle, 2012; Engle and Conant, 2002)[4,5]

Engle[4,5] describes necessary characteristics of contexts that interact to support PDE, as shown in Figure 1. Characteristics include:

- ***Problematizing***: Engle[4] defines problematizing as "any individual or collective action that encourages disciplinary uncertainties to be taken up by students." It (i) engenders genuine uncertainty (ii) is in some way responsive to learner's own commitments, and (iii) embodies the "big ideas" or some other central aspect of the discipline. We are particularly interested in the way design tasks facilitates problematizing and discuss this aspect below.
- ***Authority***: Students are given authority in addressing such problems. Authority including both: (i) an active role, or agency, in defining, addressing, and resolving problems, and (ii) being publically recognized as stakeholders where students are encouraged to be authors and producers of knowledge, with ownership over it, rather than mere consumers of it.
- ***Accountability***: Students working in teams in complex STEM learning environments are accountable to one another,[5] to disciplinary norms,[5] to nature,[6] and to the instructor.[5] Engle[4] elaborates accountability as "a norm developed within a learning environment that learners are responsible for regularly "accounting" for how their ideas make sense given the relevant work of others."
- ***Resources***: Students have access to sufficient resources to do all of the above. Resources provide access to disciplinary knowledge and practices needed to make progress and can come from multiple sources such as through prior required coursework, through material tools that are integrated into the task, or through library or internet searches. Resources can also include assignments, documents, and interactions with the instructor and other students. Engle[4] includes "… participation structures that serve as resources for supporting students' authority and accountability in ways that make evidence-based persuasion not just possible but necessary" (p 174).

Findings from Year 2

In the second year, we focused the study of PDE on the following:

1. The interplay between authority and accountability
2. School world vs. engineering world production
3. Function of interlocking elements of the learning system to create productive friction which promotes PDE
4. The role of socially shared metacognitive regulation of teams with reference to authority and accountability
5. Identification of common characteristics

Authority and accountability (AERA)

One tension in Engle's PDE framework is between authority to construct explanations or address problems and accountability for those constructions (See Figure 1). Ford[6] argued that recent reforms in STEM education have emphasized granting authority to students while not attending to the necessity of accountability. He argued for at least two kinds of accountability for scientists: accountability to disciplinary norms and practices and accountability to nature. The characteristics of authority and accountability vary in the four learning systems: design tasks differ from knowledge organization tasks, for example. In our AERA paper,[7] we explored the nature of authority and accountability in the engineering design task of the Virtual Chemical Vapor Deposition project. As designed, student teams have the authority to approach the design task in any number of ways, but must work within the constraints of engineering principles and a virtual budget. Once given access to run virtual experiments, students are "held accountable" to iteratively make sense of results produced by their virtual “runs” and use this information to refine or redesign their approach. In addition to this "accountability to nature," students are held accountable to disciplinary practice norms through structured meetings with their "supervisor" and the need to present their approach and justification to peers at the end of the project. At the same time, teams do not check their student identities at the door. Accountability to the instructor (and to teammates) is an inevitable part of the negotiation in a course project. The interlocking components of the design task and the multiple roles (students and process engineers) create tensions between the demands of engineering school (school world) and the demands of a process engineering "fab" (engineering world) that teams must navigate. This aspect was considered in our FIE 2014 paper,[8] described next.

School World vs. Engineering World production (FIE)

We contextualize students' engagement as occurring in two *figured worlds*[9] – *School World* and the *Disciplinary World*. A figured world is a social system of identities, relationships, and positions, as well as a network of meanings constituted by practices, words, symbols, and actions of its members. In one of the learning systems investigated here, the task aims to have students work in *Engineering World* where teams of three students use industrially-sized virtual equipment in a social environment intended, as much as possible, to mimic industry.[10] However, this project is also delivered in the context of a class in school, and therefore promotes other, *School World* forms of engagement. Students are given their project assignment by a course instructor and expect to be graded on products delivered. The kinds of skills and approaches that lead to success in *School World* only partially overlap with those of practicing engineers. In this kind of "hybrid" learning context, the extent to which students demonstrate PDE is one way to evaluate the extent to which the learning environment helps students learn to think and act like engineers.

Furthermore, we distinguish between two orientations of cognitive engagement during this project - task co-production and knowledge co-construction.[11]In a typical *School World* collaborative learning activity, task co-production refers to talk orientated at the completion of the set work that is prescribed by the instructor (tangible outcome or product). In that same world, knowledge co-construction refers to talk directed at making meaning, trying to build connections between ideas and understanding, and answering how and why questions related to the knowledge underlying the task. In *School World,* instructors often assume that student groups will engage in co-construction of knowledge while completing their prescribed task but there is evidence that if deep-level understanding is not perceived by students themselves as necessary to complete the task, many engage in task co-production with minimal knowledge co-construction.

We extend these concepts to consider production in terms of the *Engineering World* elicited in the VCVD project.[8] When engineering professionals engage in an authentic task, at its essence, it is an act of production, i.e., the tangible outcome is either to make a product or to develop a process. Task production in *Engineering World*, therefore, contrasts with production in the *School World,* where it is often associated with "getting in the assignment" but not necessarily with understanding. To capture the legitimate, yet quite different meaning of production in both environments, we distinguish between task co-production (i.e., "doing") that corresponds to engagement in the *School World* or the *Engineering World*. Thus, tasks with a design objective, incorporate within them, a legitimate outcome of production.

Interlocking components and productive friction (FIE)
We seek to identify the pivot points when students shift from task co-production to knowledge co-construction or vice versa. We seek to identify why students shift from one to the other with the hopes of being able use that information to carefully design and scaffold learning environments to encourage students to engage in co-construction. Such pivot points are observed to bring a team into or take them away from PDE.

PDE is triggered when teams experience productive friction from interlocking components of the learning system. Such interlocking components elicit students to coordinate or reconcile conflicting information, conceptualizations, and/or values. This coordination activity both creates conflict and provides means to resolve it. The interlocking elements can be part of the intentional design (e.g., the design meeting and memo or the virtual reactor in the VCVD project) or from other sources (e.g., prior knowledge or data from the virtual reactor). We relate the interlocking components to the four characteristics of contexts needed for PDE, as shown in Figure 2. For example, the design meeting and memo has many characteristics of the contexts Engle identifies for PDE. It is a *resource*, provides a scaffolded environment for *problemitazing*, provides *accountability* to the disciplinary community as represented by the coach, and allows *authorship* from the student team. Reference 8 provides three examples from transcript data that illustrate the claim that PDE is triggered when team members must coordinate interlocking components of the learning system to resolve friction among components or among team members' conceptions of those components.

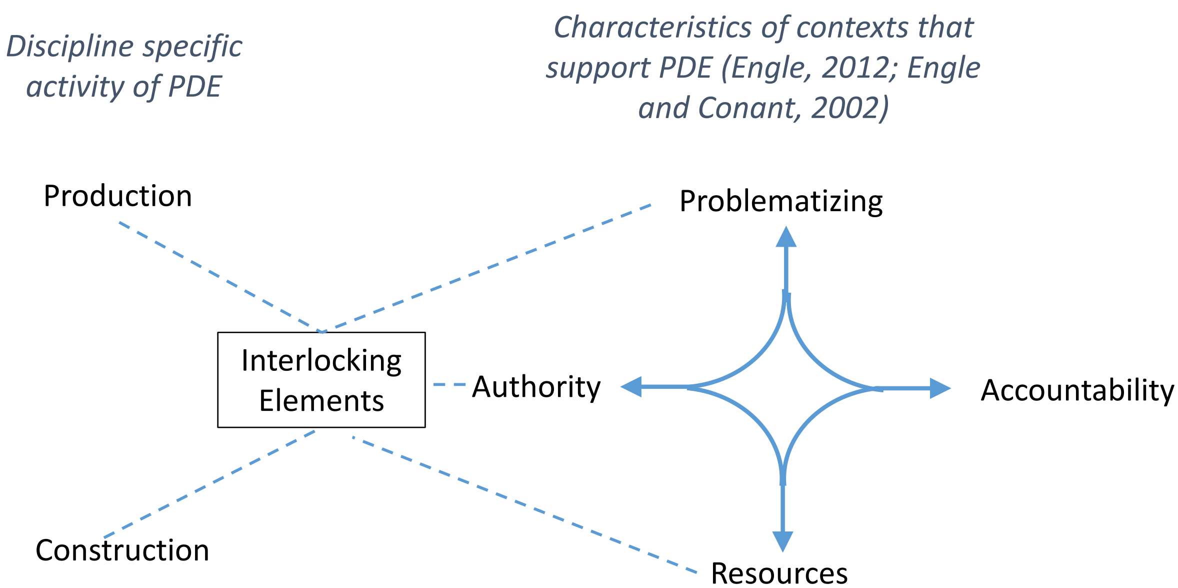

Figure 2. Productive friction from interlocking elements of the learning system leads to production and construction in the disciplinary world characteristic of PDE.

Socially shared metacognitive regulation

Leveraging the previous work of the Finnish and Australian researchers, interaction data from all four learning systems are being examined to identify common patterns (and differences) in the ways student teams co-regulate their project work. Using methods originally developed in Finland for examining Socially Shared Metacognitive Regulation (SSMR),[11-13] we are seeking to establish the nature of group PDE in regulating their co-construction of knowledge and understanding of the task and its underlying scientific content. We are capitalizing on data from four research sites to establish the value of the construct of SSMR, and applicability of the derived coding system across tasks, year levels and learning systems. Preliminary analyses have revealed group differences in SSMR of cognitive activity at different levels of engagement, which were related to meaningful differences in learning outcomes. We are also exploring how individual students take on different roles in regulating their team activity over the course of complex projects, and how these roles influence the progress of the task and the teams' PDE. How these roles contribute to the negotiation of intra-group authority and accountability to peers are also examined, as shown in Figure 3.

Figure 3. Role of socially shared metacognitive regulation in managing the tension between authority and accountability

Identification of Common Design Characteristics
Five common design characteristics have been identified across the four learning systems. While more research is needed to evaluate the necessity of these characteristics, they appear to be important to fostering PDE in complex STEM learning environments. The five characteristics are:

- Challenging problem - Each of the projects presents a problem challenging enough to require multiple students to be engaged over time in order to solve it. This level of challenge is seen as required because it promotes collaboration. However, it is important to note the problem should not be so difficult that the students perceive it as unsolvable. This is consistent with Engle's assertion that problematizing and resources must be balanced.
- Iteration - While the students are engaged in a project, the process requires some form of looping or iteration. For example, in projects where students collect dynamic data, the iteration may be in their experimental strategy, i.e., students modify their strategy based upon new data. In projects like the veterinary project, iteration may come in the form of identifying a possible diagnosis, evaluating it against the case information and modifying the proposed diagnosis depending on that evaluation.
- Real world constraints - All of the learning environments include some form of real world constraints, such as limitations on resources, the need to consider multiple and sometimes competing characteristics of "good" designs, and the types of data available on which decisions can be based.
- Realistic data - Similar to the real world constraints, access to realistic data has been identified as a potentially key aspect of learning environments, providing both resources and accountability to nature.
- Roles - The roles students play while engaged with the learning environment, and the extent to which these roles (rather than "student" roles) are taken up, appear to be crucial in fostering PDE. Following Nasir & Hand,[14] we find that students need access to integral roles that they can identify with and that are clearly part of the discipline they are learning about.

Synthesis – Design Tasks as PDE-Supportive Contexts
Our current work examines the specific ways that complex design tasks, as contrasted to other learning tasks, instantiate the four characteristics of contexts that interact to support PDE. As Engle[4] noted, design tasks problematize the discipline for students, as "it is often unclear exactly what the final design should look like or how to go about creating or justifying it (p 169)." Engle goes on to state, however, that the nature of problematizing in PDE has not been as fully developed as authority and accountability. To investigate the problematizing part of contexts supporting PDE (Figure 1) and its relationship to the other dimensions, we are comparing the affordances of design tasks. We are analyzing design tasks from the OSU (engineering) and UW (environmental science) research sites and comparing the ways in which the affordances of these design tasks differ from those of a previously-analyzed open-ended learning task involving a product from the Murdoch (veterinary program) site. This analysis builds on our preceding work on authority and accountability, production in the figured worlds of engineering and school, and how the interlocking components of the learning system prompt iterative cycles of co-construction and co-production. Our initial findings show that in design tasks in which students take on disciplinary roles, snags in co-production lead teams to co-construct an understanding of

problems, leading to co-construction or identification of resources which, in turn, enable co-production to continue. These patterns are characteristic of interaction in both the high school and undergraduate contexts, though the resources available at these different levels differ. Engineering students do more co-construction from their pooled prior knowledge of first principles garnered from engineering coursework, while high school students who are novices in environmental science require more scaffolded resources. The results of this ongoing analysis will be described in a paper submitted to the 2015 REES conference.

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Appendix A: Description of the Four Complex Learning Systems in this Project

While each team's learning environment centers on project-based and simulation approaches to teaching complex disciplinary practices, they span educational levels (secondary, post-secondary) and scientific disciplines (environmental science, biology, engineering), and national contexts. This diversity provides a unique opportunity to develop potentially transformative and generalizable new understandings of engagement and how to support it in STEM. The secondary contexts include urban, poverty-impacted schools in the US and high schools in Finland with significant numbers of immigrant students. The post-secondary contexts are targeted at capstone students in professional programs (engineering and veterinary) who may be at risk for disengagement from their respective discipline. Our collaboration should yield important insights into increasing the participation and retention of students in STEM. Table 1 provides a summary of the four sites and they are described in more detail below. In the following subsections we provide more detailed descriptions of each of the research team learning environments.

Table 1. Summary of contexts at different research sites.

Site	**Student Background and Preparation**	**Learning Environment Description**	**Discipline and Student Roles**
Washington	High school students enrolled in an advanced placement project-based learning course	Students learn to evaluate problems and design proposed solutions in real-life or simulated environmental projects (reducing their ecological footprint, designing sustainable farms, etc.)	***Discipline:*** environmental science ***Roles:*** citizens, scientists, farmers, and representative at global summit
Oregon	Senior-level undergraduate students that have four years of engineering courses and perhaps an internship or two in engineering	Students are tasked with optimizing a new manufacturing process in the semiconductor industry. The students work on teams and meet with a supervisor to get authorization on their experimental design and to get feedback as the project proceeds. They run experiments on virtual equipment that provides them with real-world data. Students submit their final parameters, a final report, and present their results at the end of the project.	***Discipline:*** chemical, biological, or environmental engineer ***Roles:*** process engineer optimizing a process
Finland	High school students that have had some science and are taking science, but they don't have an entire, role-based curriculum prior to project	A marine scientist laboratory in which students work on teams, submit a research proposal, then engage with a virtual laboratory to carry out experimentation testing the influence of different marine ecosystem factors.	***Discipline:*** science ***Roles:*** doctoral students, different types of scientists (e.g., marine biologists, chemists)
Australia	Second year undergraduate students in a veterinary medicine program. This project provides their first exposure to real-world case material.	The project was a clinical case-based group assignment within a unit on physiology. Students self-select into teams of five or six members and are randomly assigned a real-life clinical case. Each team has a different case and must set their own learning objectives for the project. They present their findings at the end of the six to seven week period.	***Discipline:*** veterinary medicine ***Roles:*** veterinary doctors diagnosing an animal

Washington. At the University of Washington the Washington team's *Knowledge in Action Project* (http://www.edutopia.org/knowledge-in-action-PBL-research) studies learning and engagement in an advanced, project-based environmental science course (AP-PBL Environmental Science) in poverty-impacted urban high schools. With projects as the primary context for learning, students engage in the varied practices of environmental science by taking on the roles of people solving real-world problems: from reducing their family's ecological footprint to taking the role of international representatives negotiating a global climate accord. Student work is sometimes independent but often collaborative, making use of technological tools but interacting face to face. In classrooms of up to 35 students, teachers must support student engagement in unfamiliar disciplinary practices in real time, as students are working to solve complex problems with multiple possible solutions. This requires teachers to have both the adaptive expertise to know how and when to intervene in students' collaborative work without short-circuiting their' disciplinary thinking, and effective tools for formative assessment.

Oregon. At Oregon State University the Oregon's team uses the Virtual Chemical Vapor Deposition (CVD) Project (http://cbee.oregonstate.edu/education/VirtualCVD/) to provide opportunities for student groups to develop and refine solutions to an authentic, industrially situated engineering task through experimentation, analysis, and iteration. This project is described in more detail elsewhere.[10] Students work in teams on to determine the best (optimal) input parameters to a industrially sized virtual CVD reactor, which deposits thin films on polished silicon wafers. The experiments student teams design are performed virtually, through a computer simulation. Thus, student teams are provided opportunities to practice the complete, iterative cycle of experimental design where they develop and refine their solution based on analysis of experiments. Integral to their success is the ability to develop and operationalize models and identify appropriate strategies. This project has most commonly been delivered as part of the senior-level capstone engineering projects course, but also has been implemented in high school (chemistry, engineering, physics, and biology), community college, engineering cornerstone, and graduate university levels. Senior-level engineering students are the participants of focus in this collaboration.

Finland. At the University of Turku, the Finnish research team employs the Acid Ocean Virtual Laboratory platform (http://www.letstudio.gu.se/studio-3/virtual-marine-scientist/) to help students learn about complex ecological processes, where students become virtual scientists to study the impact of ocean acidification on sea life. Students conduct real, up-to-date climate change experiments, and learn basic principles of experimentation. The data the students analyze are real data gathered by scientists conducting cutting-edge research on global ocean and local Baltic Sea acidification. The study takes place in three high schools in Finland as a part of selective biology and social science courses. Regular curriculum in the target schools generally only includes occasional small projects. Although students learn in the context of the discipline of biology, the whole course in biology is organized as inquiry-based projects and deeply integrated with the environmental policy course in social sciences. The course consists of face-to-face collaborative work and virtual seminars. Students carry out virtual experiments and measure carbon dioxide emissions in their own environments. The biological are then used in environmental policy projects. The point of this work is both to make students familiar with scientific work, and to teach them about the environmental impact of their own activities and in their own society.

Australia. At Murdoch University, the Australian research team's project employs a clinical case-based approach. The project is given within a unit on physiology. Second-year undergraduate veterinary medicine students self-select into groups of five or six members and are randomly assigned a real-life clinical case. When examined by expert veterinarians, some of the cases have multiple appropriate diagnoses, which makes the cases challenging for the undergraduate students. Each group has a different case and must set their own learning objectives for the project. They present their findings at the end of the six to seven week period. The students get feedback and guidance from their instructor in two face-to-face meetings held three to four weeks apart. The instructor often guides students in the formulation of case relevant, concise learning objectives. The meetings also offer a way for the instructor to monitor group progress.