Destigmatizing Confusion – A Path Toward Professional Practice

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Introduction

This research paper investigates a student team's approach to a task designed to elicit concepts and practices used in professional engineering contexts [1], [2]. This study is part of a broad curricular reform project in 11 core studio courses using assignments that support students' learning of engineering practice [3], [4]. The reform is motivated by research that relates the development of higher-level capabilities such as systems thinking, communication skills, ethical standards, and critical thinking to students' success in the workforce [5]. It also addresses calls for greater emphasis on complex, open-ended design problems reflecting work done by professional engineers [6].

Such tasks contrast with more typical school worksheets that require an algorithmic application of course concepts, with an emphasis on reaching a single correct solution through an instructor-determined solution path [7]. Given a steady diet of such work, students might have difficulty using those concepts in tasks that ask them to reason, debate, or critically examine alternate approaches and designs [7], [8]. Confusion over how to tackle such a novel task might interfere with students' learning. On the other hand, confusion might initiate more creative or exploratory thinking that considers multiple dimensions of the problem and provides space for students with different ideas and perspectives to contribute [9]. We present a case study of a student team working on a studio task that positions them as professional engineers determining whether or not to implement a proposed change in their candy production process. This task is designed to prompt students to use the "big ideas" of their course and social practices of engineers, and to allow for multiple solutions. The case study investigates how students take up this challenge.

Using video records of the team's work, we examine how thinking and engagement shift over the course of the period, paying particular attention to periods of confusion. Although the instructor frames the task in terms of engineers making an important design decision, the team begins by treating the task as typical schoolwork; confusion centers on the nature of a "correct" response to atypical worksheet questions. Activity is dominated by two students. Later, students exhibit a state of engagement that we call "glorious confusion" in which the team comes up with an important question to which there is no immediately clear answer although there are multiple possible solution paths. The term "glorious confusion" draws from work in the mathematics education community and specifically a case where an instructor describes shifting the attitudes of students in learning mathematics, "We talk about how brains learn and how they should expect to move from surface knowledge to confusion to deeper understanding" [8, p.22]. We call this engagement "glorious" because there is increased and more evenly distributed group participation and responsiveness to others, there is an uptake of authority to think and reason for themselves rather than seeking a predetermined correct answer, the warrants for reasoning incorporate the big ideas of the course, and the confusion is grounded in real world concerns.

Using as theoretical framework Productive Disciplinary Engagement [11], [12], we analyze the video data episodically, investigating the group's interactions leading up to and including this "glorious confusion." We argue the state of engagement characterized as glorious confusion reflects real engineering work and develops ways of sense-making and habits of mind that align with the higher-level capabilities needed in practice [13].

In this case study, we investigate the following research questions.

1) How do student teams take up an engineering task designed for them to adopt roles reflective of professional engineers?
2) In what ways might confusion be a productive state of engagement towards forming engineers?

Theoretical Framework

Critiques of engineering curriculum are not new, with Felder (1987) stating "most engineering schools are still going about business as usual," relying on "well-defined problem and single correct answers," but that "this format has never been shown to be effective at producing the critical, innovative thinking skills needed to solve difficult technological problems [7]." Even 27 years later, a study on creativity in engineering departments found that "even the most exemplary engineering courses" are lacking important aspects which foster creative problem solving [8]. It was found that many engineering programs promoted analysis and evaluation skills, yet programs did not foster the development of idea generation, flexibility, and originality, a critical aspect in the professional formation of engineers [8].

While technical skill is important, developing the social components of engineering is also critical [5], [6], [14]. Course-specific, technical knowledge consists of a set of "big ideas," including content (concepts, principles, and theories) and practices (planning and carrying out investigations, analyzing and interpreting data, engaging in argument from evidence) [15]–[17]. In the sophomore Material Balance course studied here, for example, big ideas could include conservation of mass and reasoning with chemistry. Engineering is also inherently sociotechnical, as the technical work performed is for the benefit of consumers or communities [18]. As has been found in studies of the disciplinary language and warrants for reasoning in group-based work (sociomathematical [19] and sociochemical [20] norms), we presume that social norms enable engineering work.

Because we are interested in designs of instructional environments where students engage in disciplinary practices, we use the framework of Productive Disciplinary Engagement (PDE) [11], [12] to analyze students' activity in engineering group work. We follow Ford and Forman [21] in characterizing *disciplinary* engagement in engineering as use of the social, material and rhetorical practices of engineering [22]. *Productive* disciplinary engagement is "when students make disciplinary progress from beginning to end of a particular issue [11]." Conditions for supporting PDE include *problematizing* content, granting students the *authority* and *resources* to address those problems while holding them *accountable* to each other and to disciplinary norms. The studio activity used in this study problematized content by presenting a complex engineering task, situated in a realistic context, which allowed for multiple approaches. Students are granted authority to identify and address various aspects of the task that are problematic. At the same time, they are held accountable to norms for working together and for using their resources (knowledge and tools from within and outside the course) appropriately. By embodying the conditions for supporting PDE in this task, we hoped to prompt students to engage in the kind of engineering activity called for in critiques of engineering schools' "business as usual."

At the same time, however, engineering students bring with them a history of relatively successful engagement with more typical school tasks. By the time they enter their second year of engineering education, they have developed strategies for engaging in group work that is focused on figuring out what the instructor wants them to do (often involving calculations related to current lecture content), dividing the labor either through "divide and conquer" or having one or two group members take control, and producing the correct "answer [23]." These typical (and generally successful) strategies are likely to continue to be applied in similar contexts (other school classes), even, perhaps, when tasks require different approaches [24]. To the extent that tasks challenge students to take up different strategies, they may cause confusion and distress [25]. However, confusion may also lead students to broaden their notion of what it means to do engineering.

Methods

Participants and Setting

As part of the ongoing curricular reform project in these studio courses, video data is collected and reviewed weekly in order to determine student responses to the revisions to these tasks. The video of the team analyzed in this study was originally selected for a faculty development workshop to illustrate an interesting and unusual form of student engagement. Due to the variety of opinions expressed in the workshop, we chose to pursue the analysis reported in this paper.

The participants were a team of second-year undergraduate engineering students at a large public university composed of three men and three women. The video was collected in the seventh week of the 10-week required Material Balances course. Studios in this course are not graded on task completion, but instead on participation and engagement of group members. Two facilitators, a graduate teaching assistant (GTA) and an undergraduate learning assistant (LA), both of whom attended pedagogical training workshops, were present. This research was approved by the Institutional Review Board and all participants provided written consent.

Studio Task

As part of the curricular reform project, studio tasks have been designed according to principles of Problem Based Learning [26], [27] and Model Eliciting Activities [28]. These tasks emphasize the process with which engineering students work together to obtain their solution rather than the product, or solution, itself. Problems are designed to have multiple solution paths where the creative identification and formulation of a path is a critical aspect of the activity[29]. In focusing on the process rather than the product, Diefes-Dux and colleagues argue that engineering students develop higher order understanding of the concepts, thus forming them into better practicing future engineers [28].

The group was assigned a task which positions them as process development engineers working for a candy production company, via a handout in the form of an interoffice memorandum. The memo describes the “current process,” which produces a mixture of glucose and fructose with a single-pass conversion of 20% via the hydrolysis of sucrose in an aqueous solution of hydrochloric acid. The students are not given the stoichiometric chemical equation for this process, but are provided the chemical structures of the reactants and product. The team is then told that they have the opportunity to include an additive to increase the sucrose conversion to 60%, but which will require “an additional separation process and a simple but energy-intensive recovery unit.” The students are directed to address the following sub-tasks, while considering that the “quality we provide to our customers is of utmost importance.”

- Share ideas on how best to work together.
- Sketch fully-labeled process flow diagrams comparing our current design with one utilizing the exciting new additive.
- Brainstorm *specific* engineering questions that need to be answered, then choose at least one and describe how you would recommend addressing it using the scientific process:
    - Hypothesis
    - Research/experiment (details, e.g. qualitative size, concentrations, flows, etc.)
    - Analyze/conclude (e.g. If we see this, then… If that, then….)
- Provide me [supervisor] any feedback you might have on my ethical approach to investigating this opportunity.

Data Collection

Video data of this group was collected with a camera in the corner of the room. The researcher left the room after setup in order to avoid distraction. A microphone was placed on the group’s table in order to better pick up dialogue between the students. Verbal utterances were transcribed, and used in conjunction with non-verbal behaviors observed in the video in order to analyze the manners in which students were engaged with the task. While the studio lasted 50 minutes, this study only reports analysis of the first half. At this point, an interaction with the LA ended the period of engagement of “glorious confusion” in which we are interested.

Analysis and Codes

The video data was coded iteratively in order to develop a stable code list that characterized the group’s interactions. Second-by-second talk time analysis was performed in order to supplement codes developed using the turn-based verbal utterances. For the analysis, the three female students are represented as F1, F2, and F3, and the three male students are represented as M1, M2, and M3. Based on the emergent codes, the video was divided into four episodes for analysis.

Codes were created for three categories: Participation, Authority, and Engagement. Table 1 provides the codes under the Participation category. Codes in this category were applied to the four episodes of the video rather than to individual student turns and refer to the division of talk times and turns of the students in the group. Given that these codes are applied to full episodes in the data set, examples were not deemed appropriate to include in this table.

Table 1. Code list for Participation category

Code Name	Definition
Dominated Participation	The majority (>75%) of the talk time of an episode is distributed between (at most) two of the six students. Other students provide supplementary dialogue, but are not significant in driving the discussion. Not all students participate.
Distributed Participation	Talk time and control of the discourse is more evenly distributed amongst students. All students in the group provide dialogue which contribute to the group's understanding.

Table 2 presents the codes for the Authority category, their definitions, and an example from the transcript. Codes in this category were first applied to individual student turns. Once the turns in a given episode were analyzed, the entire episode was characterized, based on the predominant authority type, and given a single Authority code. The example for Handout/Instructor Authority shows a student relying on explicit language presented in the handout in order to justify a previous assertion. These types of statements are consistent with traditional student roles while completing a worksheet. Using language such as "*it* says" is prevalent in excerpts coded for Handout/Instructor Authority. The example for Student Authority shows a student demonstrating understanding of the process being investigated and raising a concern about the byproduct of a chemical reaction ending up in the edible product. When students take up the authority to raise or answer concerns, "*we*" is used in their dialogue, rather than "it."

Table 2. Code list for Authority category

Code Name	Definition	Example
Handout / Instructor Authority	Authority to make decisions lies in handout or instructor information. Warrants for student reasoning are based on explicit language used in the handout, perceived expectations of instructors, and normal classroom practices.	"It kinda just says it's *in* there. Like in the aqueous solution. It doesn't say it's like *fed* into the reactor."
Student Authority	Students take the authority to make decisions regarding the task. Warrants for reasoning are based on the physical system described in the task, engineering principles, and disciplinary norms.	"Yeah. [points to her paper] But then we have extra chloride that needs to be a product. Where's that going? That can't be going into the glucose-fructose."

Table 3 presents the codes for the Engagement category. Codes in this category describe the way in which students approach their work. These codes are applied to whole episodes, rather than individual student turns, and therefore this table does not include examples. Episodes coded for Worksheeting are characterized by students looking to one another for a "correct" or "appropriate" answer; there is little discussion or group sense-making, other than that related to determining the instructor's wishes. In activity coded Engineering, students discuss approaches and ideas and suggest (and critique) solution paths which rely on both principles from the course and real world experience.

Table 3. Code list for Engagement category

Code Name	Definition
Worksheeting	The primary activity is to complete the worksheet, get the correct answer that the instructor expects, or fill in the blanks. This type of engagement generally assumes a single, correct answer and prescribed solution path.
Engineering	The primary activity is to consider different aspects of the system, identify what is important, and use their knowledge and skills to make progress towards a decision. This type of engagement allows for argumentation for different solution paths based on the merits of a proposed path's reasoning.

Transcribed utterances presented in this paper use the symbol (.) to represent pauses, and parentheses surrounding a number, such as (2), describe the length of pauses longer than 1 second. Words written in brackets, [], describe nonverbal behaviors, such as where a student is looking or pointing. Phrases beginning and ending with <1> </1> represent when two students are speaking at the same time.

Results

Following a description of how the activity was framed by the instructor, we present three episodes of confusion: Teaming Norms, Flow Diagram, and Where does the HCl go? In each section, the episode will be characterized by the codes assigned to it, talk time distribution of students, and select quotations which elucidate the nature of the students' engagement with the task and one another. Table 4 summarizes the codes assigned to three episodes in which the students are speaking. Based on the three codes, we characterize the type of confusion.

Table 4. Summary of coded episodes

Code Category	**Episode 1:** **Teaming Norms**	**Episode 2:** **Flow Diagram**	**Episode 3:** **Where does HCl go?**
Authority	Handout/Instructor	Handout/Instructor	Student
Participation	Dominated	Dominated	Distributed
Engagement	Worksheeting	Mixed	Engineering
Confusion	*Inglorious*	*Minimal*	*Glorious*

Figure 1 shows the relative talk time distribution of team members over time. The x-axis is the time stamp of the video data, divided into 30 second increments. The more an individual student speaks, relative to their group members, in a 30s increment, the taller their respectively colored bar in that increment is. Episode dividers are given by vertical dotted lines.

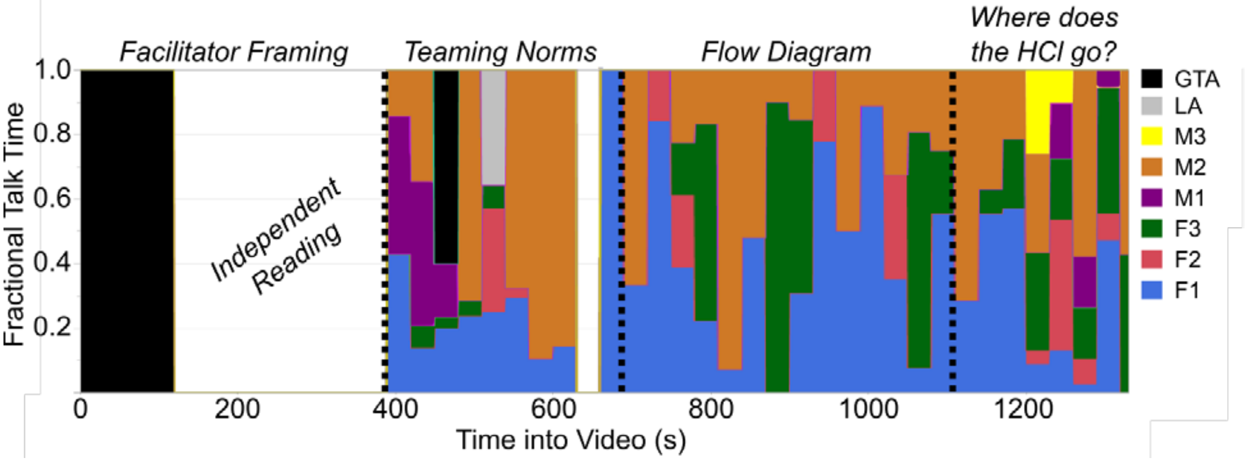

Figure 1. Talk time distribution of group members over the course of the analysis.

As the group progresses through the task, their authority shifts from handout/instructor to student, and their engagement from worksheeting to engineering. The group's participation shifts from dominated, as shown by the lower number of students participating in the second and third episodes, to distributed, where all six students are participating in the final episode. The state of glorious confusion is characterized by the latter of all three code categories, thus answering research question 2. The students shift from a state of inglorious confusion while working on teaming norms, to minimal confusion while in school practices, to glorious confusion while in the final episode. The following sections will describe the analysis for each of the four episodes.

Facilitator Framing

In the first episode, the GTA frames the task for the groups in the studio section. This episode is different from the other three, in that the GTA is the only speaker. Consequently, the episode was not coded but rather used to provide context. The GTA speaks to the entire class for one minute and fifty seconds while walking around the room. He attempts to situate the students as engineers who must make a decision about changes in a process. The framing begins by stating that this task will be “a little bit different” than previous tasks they’ve worked on. Because traditional engineering school tasks focus on solving for a single, correct, numerical value, the GTA urges students to “please, please, please” not try to “solve a mass balance.” The GTA attempts to shift students’ habitual approach to position themselves in a vague and open-ended problem space. Interestingly, the GTA does not mention the teaming norms, the first bullet point in the task, while describing the activity to the class. This omission may suggest to the students that this social aspect of the activity is not of the same level of importance as the technical aspects, described by the GTA in detail.

While the GTA is speaking, students in the group occasionally glance up at him, suggesting that they are paying attention. However, much of this time is spent with their heads down, presumably reading the handout. After the GTA finishes speaking, the students begin to individually read the handout, without dialogue, from minute 2:15 until minute 7:11. This time is likely spent by all group members familiarizing themselves with the nature of the task, as well as what they are asked to do.

Teaming Norms

The teaming norms episode lasts from 7:11 until 11:33 and is coded as Dominated Participation, Handout/Instructor Authority, and Worksheeting. The group addresses the first bullet point in the handout, “share ideas on how best to work together,” which is intended to provoke sense-making around the often-ignored, social aspect of engineering practice. After reading the handout silently, M2 and M1 reading pieces of the handout aloud. F1 makes a regulatory move, asking the group “how to work best together?” M2 responds in a joking manner with, “I think sharing ideas is a good idea,” his gaze moving over the other group members while smiling. M1 echoes M2’s response, evoking laughter from all group members. Following this interaction, the GTA addresses a separate, nearby group and offers several suggestions as to how to think about this first bullet point. The group members in the study all look over and listen to the GTA’s suggestions. After listening to the GTA’s advice, M1 laughs to his group and states, “Well that didn't really help.” The group laughs, then goes back to writing independently before F1 asks, “Are you guys writing actual stuff or just generic teamwork things?” M2 responds with a “pretty generic idea” about brainstorming. The group finishes this episode by completing this bullet point independently.

In this episode, the team appears confused about how to comply with the bullet point indicated by F1's puzzled "how to work best together?" Further evidence of their confusion is their attention when the GTA gives advice to a neighboring group and the study group's response that it "didn't help." The episode was coded as Dominated Participation as F1 and M account for 28% and 47% of the talk time, respectively (Figure 1). F1 behaves as the regulator, bringing the group together after periods of independent work. M2 provides suggestions on how to answer this bullet point. Other group members occasionally contribute, but their suggestions are not considered by the dominating students. By listening to the GTA's suggestions to another group regarding the teaming norms, the group is not only showing their uncertainty regarding this aspect of the task, but also appealing to instructor authority for assistance. This manner of working on the task is the reason this episode was coded for Handout/Instructor Authority. The laughter and joking language used also suggest that the team does not value of this part of the task, but are simply complying with instructor by filling out the worksheet (Worksheeting). When collaborative efforts of the group fail to resolve this confusion, the group members resort to independent work in order to complete this section. The confusion, locus of authority in the handout/instructor, and the fact that group members work independently to simply complete this bullet point and move onto the presumably more comfortable, technical work led us to categorize the episode as "inglorious confusion."

Flow Diagrams

The Flow Diagrams is coded for Dominated Participation, Handout/Instructor Authority, and both Worksheeting and Engineering. This episode runs from 11:33 until 18:09, and begins with the students considering the second bullet point in the handout, "sketch fully-labeled process flow diagrams comparing our current design with one utilizing the exciting new additive." F1 continues to hold the role of regulator, bringing the group back together from independent work, by asking the group for clarification on the process. M2, as before, acts as a source of information, responding to F1's questions. After a brief period of independent reading, F1 asks the group how HCl enters into the reactor, which F2 begins to address. F1 speaks over F2, justifying her understanding of the flow diagram by appealing to the explicit language in the handout, stating "It doesn't say (.) it's like (.) *fed* into the reactor," rather than the HCl being present as an extra feed stream, which M2 agrees with. This is followed by M2 reasoning through which streams enter the reactor, due to the presence of a recycle stream after the reactor. There is no discussion with the group, however, with F1 simply agreeing with him. Two, brief clarifications about streams are then made by F3 and F1, neither of which prompts discussion. The final segment in this episode starts with M2 asking if acid comes out of the reactor, which instigates a period of argumentation. M2 states that he doesn't think it's reacting, with F1 justifying her agreement with "the unreacted sucrose is like the same thing. It's with the acid." M2 states that he thinks so too, but asks if "the acid is like the catalyst?" F2 suggests that "one is like the limiting reactant," which F1 disagrees with. F1 ends the episode reasoning that "we don't need to know limiting reactants or anything," because "they don't really give us a (.) chemical equation (.) I hope that we don't have to do that. Cuz that because I feel like that's gonna be (.) a lot."

This episode was coded for Dominant Participation, as F1 and M2 hold 46% and 30% of the talk time, respectively. While F1 still maintains a regulatory role in the group, she also spends more time offering up ideas for the group to consider in order to make progress, as well as critiquing other students' suggestions. F2 and F3 speak slightly more than the previous episode, with M1 and M3 not participating (Figure 1).

When M2 attempts to determine the nature of the acid in the chemical reaction, F2 follows up possibly suggestion it is a limiting reactant rather than a catalyst. F1 suggests that they wouldn't need to know that information, reasoning that because it is not presented in the handout, they shouldn't need to consider it. Such types of reasoning are characteristic of students working on a school task, rather than professional engineers using reasoning grounded in the physical system or scientific principles, leading to this episode being coded for Handout/Instructor Authority. While it is expected that students use the handout to scope out the task, this student uses it as a source of authority rather than reasoning through this physical system would look and what it would take to mix in HCl into their streams. While the language the students use in this particular instance seem to suggest the students have positioned themselves as engineers working on a task, they are simply reading off information provided on the handout. While this episode shows students behaving as students, rather than taking up the framing presented in the handout and by the GTA, the group does make progress on the technical task of sketching the process diagrams. The students are engaging with one another in order to determine the nature of the process and where particular components of the system go, therefore leading to this episode being coded for both Worksheeting and Engineering. Because the confusion is minimized or explained away by invoking the expectation that anything they need to know would be included in the handout, we coded it Minimal Confusion. When questions are raised which cannot be answered by information in the handout, F1 uses this type of reasoning to keep the problem simplified.

Where does the HCl go?

The final episode is coded for Distributed Participation, Student Authority, and Engineering. This episode runs from 18:09 until 22:36, the end of the analyzed segment of the video. During this episode, the students are still working on the second bullet point in the handout, however, it starts with F3 asking, "then is HCl going (.) into our product?" The ethical concern raised here is not immediately taken up by the rest of the group, however. F3 justifies her belief that the acid could end up in the product by reasoning that if the separator "recovers 95% of the unreacted sucrose," that it maybe "only recovers 95% of the HCl as well." M2 minimizes this by stating that the handout "doesn't even talk about HCl," but F3 persists, asking "so where does it go?" F1 continues with her line of reasoning from the previous episode, that "the sucrose is the same thing (.) as the acid." But then M2 takes up F3's concern, reasoning that they will have "acid in both of our streams." F1 and M2 try reasoning through how the separation process affects the acid streams, before F1 states "we kinda don't really have to worry about it." M2 asks if they should even "include it in our (2) in our (.) diagram?" Seeming to reconsider her previous assertion, F1 references the inclusion of the acid concentration in the handout, then states she doesn't "know if that's just like to throw us off, or if we are actually gonna need it for some sort of conversion." This prompts M2 to ask the group what the hydrolysis reaction actually does. At this point, the group members pair up and begin discussion the chemical reaction, pulling on outside resources and their knowledge of hydrolysis in order to determine what the HCl is doing in the reaction. All group members participate. F3 brings the group together again, asking "where's that chloride going?" M2 explains the chemistry of the reaction, which F3 agrees with, then stating "But then we have extra chloride (.) that needs to be a product (.) Where's that going? That can't be going into the glucose-fructose." F1 responds, stating "I mean it must be. I mean if it's coming out of the reactor, it has to be going with the final product. We could maybe say that it doesn't leave the reactor but I don't think we could say that." F3 and M2 agree with this assertion, then stating that they don't understand what's happening with the chloride since "you can't eat it." The episode ends when the LA walks by and the group members ask him for assistance. He responds that they don't need to worry about the acid in this process, thus ending the group's glorious confusion.

This episode was coded for Distributed Participation, with F3 not only taking the lead by raising her concern, but also becoming a more major contributor of talk time, while F1 and M2 fell back. F3 constituted 25% of the total talk time in this episode, while M2 and F1 each contributed 26% of the talk time. The other three students, while not speaking as much as the former three, still contributed to the sense-making process in this episode (Figure 1). F3 is troubled by the fact that hydrochloric acid would be going into their candy product and sent to consumers. While this was not an intended facet of the task's design, the "real-world" feel of the problem allowed for F3 to position herself as a process engineer, considering the ramifications of the product she is making. Importantly, from the previous interactions, F1 shifted her engagement with the task. Throughout this and the previous episodes, F1 has tried to ignore the acid by relying on wording present in the handout, whether explicit ("It just kinda says it's *in* there") or implicit ("because they don't really give us a (.) chemical equation"). However, in this final episode, F1 is using reasoning based on the physical system they were tasked with designing, saying that "it wouldn't just hang out in the reactor on its own, right?" This critical shift in engagement, from a student completing an assignment, to an engineer working on a design task, is the type of progress we hope to see as instructors. This shift in warrants for reasoning and uptake in personal authority lead this episode to be coded for Student Authority and Engineering. This question, and confusion, of where the acid goes is based on the "big idea" of the Material Balances course, conservation of mass. The chloride ion was not used in the reaction, and F3 reasons must therefore still be in the process stream. M2 bolster's F3's initial concern, thus bringing F1 into this line of reasoning as well. Due to the authority the students take up, their reliance on disciplinary norms to sense-make, and invocation of the big ideas of the course, the confusion exhibited in this episode was dubbed Glorious.

Discussion

In this study, we characterize the approach and engagement of a group of second-year engineering students completing a task that situates them as process engineers. Throughout the task, the students engage in various states of confusion. We argue that confusion can be productive towards professional formation when the students take up authority to answer questions, when they hold themselves accountable to engineering disciplinary norms, when the participation allows for equitable input, and when reasoning and sense-making processes use big ideas from their courses.

Framing practices are important to student engagement, and regularly the social aspect of engineering is addressed in ways that are disconnected to technical work. We argue the lack of GTA framing, and student unfamiliarity of practicing social aspects of engineering lead to the group's first state of confusion. It is not that the students are ignorant of teaming norms; however, a lack of situated practice of these norms in engineering tasks may have left them unable to do more than independently write down "general teamwork things" rather than engage in sense-making around teaming norms activities. As instructors and activity designers, we must consider ways to show how these social and professional skills fit into real engineering work, rather than focusing solely on the technical aspects of engineering. The importance of these skills in the professional workplace should be addressed in a more holistic manner, discussing them in lectures and practicing them in situated, group environments. This case study showed the danger of incorporation of these professionally situated tasks without proper framing, leading to a generally unproductive confusion in students.

When the group shifts to the Flow Diagram episode, they appear to be in more familiar work mode where confusion is minimal as they continue "worksheeting." Betts describes worksheeting as changing an activity from "a living, interrupting, surprising exploration to a dull, predictable one fully subsumed in the grinding routine of classroom days," in which "infinite possibilities are destroyed in favor of one possibility, which one person chooses for everyone else [30]." This language implies minimal confusion and authority, as the infinite possibilities become one, students do not expect to be confused, instead identifying a proper, instructor determined algorithm will lead them to the proper solution. Working in this manner, the students are not learning how to be engineers, but rather how to complete a worksheet. While the group still makes progress on the handout, students do not get the chance to practice important skills [31]. While worksheeting, students engage in big ideas, but they implement the big ideas of the course in a manner where they depend on the language of the handout to direct them (e.g., "It tells us"). In a professional setting, however, there are no worksheets. While such worksheeting provides opportunities to engage in the big ideas central to the course, we argue that the reliance on the authority of the worksheet makes it unlikely students will be able to operationalize these big ideas in more realistic engineering work.

The shift into glorious confusion is not instantaneous, but rather a process, occurring after a non-dominant student, F3, raises an ethical concern that hydrochloric acid is getting into their candy product. M2 and F1 respond by attempting to worksheet a solution, however the task's design does not allow for this to yield satisfactory results. F1 maintains her student role until M2, the other dominant student, suggests the group reason through identifying the chemical reaction, thus instigating a distributed period of participation among all group members, and eventually adoption of engineering roles by all students. It was not that the design of the task alone ensured students take up its framing and elicited engineering behaviors, but rather that its realistic nature provided students with opportunities to engage in these practices. In this state of glorious confusion, students take up the authority to raise and answer questions elicited by the task. In attempting to resolve these questions, students invoke the big ideas of the course *as needed* to address these concerns, reminiscent of the work done in professional engineering settings [13]. Thus, we argue that these practices will be more transferable to a professional context than those skills developed while worksheeting a task [24].

Some faculty and graduate students who watched this episode in a professional development context have argued that F1's characterization of the acid concentration information as the instructor including "something to throw us off" was productive since engineers often need to use heuristics to limit the scope of their work. We acknowledge the use of heuristics is an important professional practice for engineers; however, the language F1 uses does not suggest she is questioning the relevance of information based on engineering merit, but rather on a school "gaming" notion of instructor trickery. We argue that this practice is not one has limited transferability to engineering work [24]. Likewise, faculty have suggested providing the stoichiometric chemical equation in the memo would prevent confusion and allow the group to more efficiently get the answer. This suggestion followed a discussion where some faculty were clearly uncomfortable watching these confused students. We conjecture that many instructors see confusion as generally unproductive and believe effective educators should reduce confusion as much as possible. Further, some assert that the confusion often induced by assigning complex, realistic problems is inefficient and reduces student learning. On the contrary, we argue that confusion can provide students opportunities to sense-make through complex, real-world problems faced by professional engineers. In this case, their sense-making involved utilizing the big ideas of the course. Further, in navigating such problems they engage in and develop the technical and social processes that are needed in professional practice.

In "Where does the HCl go?" the period of glorious confusion was characterized by group members taking up the authority to answer the problem, participating in meaningful ways, using warrants for reasoning which rely on engineering principles, such as conservation of mass, and are based in the physical system they were tasked with designing. The facilitator's framing of this activity, as well as the language and structure of the handout, provided opportunities for students to adopt sociotechnical roles resembling professional engineers. However, students do not simply fall into the complex role of "engineer," and may actively resist it. "Worksheeting" is a habitual approach so ingrained in student engagement with school activities that even thoughtfully-designed, professionally situated tasks do not automatically induce students to take up engineering roles. In the present case, it was only when worksheeting could not provide satisfactory answers to all questions raised in these tasks that activity shifted. Careful framing by instructors may allow students to begin to adopt these professional engineering roles, thus prompting a period of engagement which is not only productive, but allows students to implement the big ideas of the course and adopt roles, language, and reasoning more resembling that of professional engineers. However, sustained practice with complex problems over time is likely needed to shift students' habitual patterns

Confusion comes in many forms; not all are good, but not all are bad. We call it "glorious" confusion when students engage in these complex and realistic problems in ways which afford them the opportunities to participate in sociotechnical disciplinary practices, to operationalize the big ideas from their current and other courses, and to leverage their knowledge and experiences from the real world. In this example, the ethical consideration was not designed to be part of the problem, but due to the complex and real-world nature of the task, students saw this as an important aspect which had to be resolved in order to make progress – just as we hope professional engineers would.

References

[1] W. G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*, First Edition, Thus edition. Baltimore, Md.: Johns Hopkins University Press, 1993.

[2] R. Stevens, A. Johri, and K. O'Connor, "Professional Engineering Work," in *Cambridge Handbook of Engineering Education Research*, A. Johri and B. M. Olds, Eds. New York: Cambridge University Press, 2013, pp. 119–138.

[3] M. Koretsky, D. Montfort, S. B. Nolen, M. Bothwell, S. Davis, and J. Sweeney, "Towards a Stronger Covalent Bond: Pedagogical Change for Inclusivity and Equity," *Chem. Eng. Educ.*, vol. 52, no. 2, pp. 117–127, 2018.

[4] M. D. Koretsky, "Program Level Curriculum Reform at Scale: Using Studios to Flip the Classroom," *Chem. Eng. Educ.*, vol. 49, no. 1, pp. 47–57, Jan. 2015.

[5] American Society for Engineering Education, "Transforming Undergraduate Education in Engineering—Phase I: Synthesizing and Integrating Industry Perspectives," Washington, D.C., 2013.

[6] N. A. of Engineering, *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*. 2005.

[7] R. M. Felder, "On creating creative engineers," *Eng. Educ.*, vol. 77, no. 4, pp. 222–227, 1987.

[8] S. R. Daly, E. A. Mosyjowski, and C. M. Seifert, "Teaching Creativity in Engineering Courses: Teaching Creativity in Engineering Courses," *J. Eng. Educ.*, vol. 103, no. 3, pp. 417–449, Jul. 2014.

[9] D. S. Cordray, T. R. Harris, and S. Klein, "A Research Synthesis of the Effectiveness, Replicability, and Generality of the VaNTH Challenge-based Instructional Modules in Bioengineering," *J. Eng. Educ.*, vol. 98, no. 4, pp. 335–348, 2009.

[10] I. S. Horn, *Strength in numbers: collaborative learning in secondary mathematics*. Reston, VA: National Council of Teachers of Mathematics, 2012.

[11] R. A. Engle and F. R. Conant, "Guiding Principles for Fostering Productive Disciplinary Engagement: Explaining an Emergent Argument in a Community of Learners Classroom," *Cogn. Instr.*, vol. 20, no. 4, pp. 399–483, 2002.

[12] R. A. Engle, "The Productive Disciplinary Engagement Framework: Origins, Key Concepts, and Developments," in *Design Research on Learning and Thinking in Educational Settings: Enhancing Intellectural Growth and Functioning*, 2012, p. 40.

[13] E. Manz, "Designing for and Analyzing Productive Uncertainty in Science Investigations," in *Rethinking Learning in the Digital Age: Making the Learning Sciences Count*, London, UK, 2018, vol. 1, pp. 288–295.

[14] J. Trevelyan, "Mind the Gaps: Engineering Education and Practice," p. 9, 2010.

[15] C. Chalmers, M. (Lyn) Carter, T. Cooper, and R. Nason, "Implementing 'Big Ideas' to Advance the Teaching and Learning of Science, Technology, Engineering, and Mathematics (STEM)," *Int. J. Sci. Math. Educ.*, vol. 15, no. 1, pp. 25–43, May 2017.

[16] W. Harlen, *Principles and big ideas of science education*. Hatfield, UK: Association of Science Teachers, 2010.

[17] National Research Council, "A framework for K-12 science education: Practices, crosscutting concepts, and core ideas," Washington, D.C., 2012.

[18] J. Trevelyan, "Reconstructing engineering from practice," *Eng. Stud.*, vol. 2, no. 3, pp. 175–195, Dec. 2010.

[19] E. Yackel and P. Cobb, "Sociomathematical Norms, Argumentation, and Autonomy in Mathematics," *J. Res. Math. Educ.*, vol. 27, no. 4, pp. 458–477, 1996.

[20] N. Becker, C. Rasmussen, G. Sweeney, M. Wawro, M. Towns, and R. Cole, "Reasoning using particulate nature of matter: An example of a sociochemical norm in a university-level physical chemistry class," *Chem Educ Res Pr.*, vol. 14, no. 1, pp. 81–94, 2013.

[21] M. J. Ford and E. A. Forman, “Redefining Disciplinary Learning in Classroom Contexts,” *Rev. Res. Educ.*, vol. 30, no. 1, pp. 1–32, Jan. 2006.

[22] M. D. Koretsky, E. Nefcy, S. B. Nolen, and A. B. Champagne, " Affordances of computer and physical laboratory-based design projects for engaging student teams in engineering practice," Cogn Instr, 2009.

[23] K. A. Smith, “Cooperative learning: effective teamwork for engineering classrooms,” in *Proceedings Frontiers in Education 1995 25th Annual Conference. Engineering Education for the 21st Century*, 1995, vol. 1, pp. 2b5.13-2b5.18 vol.1.

[24] D. L. Schwartz, C. C. Chase, and J. D. Bransford, “Resisting Overzealous Transfer: Coordinating Previously Successful Routines With Needs for New Learning,” *Educ. Psychol.*, vol. 47, no. 3, pp. 204–214, Jul. 2012.

[25] E. G. Cohen, *Designing groupwork: strategies for the heterogeneous classroom*, Third edition. New York: Teachers College Press, 2014.

[26] D. R. Woods, *Problem Based Learning - how to gain the Most from PBL*. Waterdown: W L Griffen Printing, 1994.

[27] D. R. Woods *et al.*, “Developing Problem Solving Skills: The McMaster Problem Solving Program,” *J. Eng. Educ.*, vol. 86, no. 2, pp. 75–91, Apr. 1997.

[28] H. A. Diefes-Dux, T. Moore, J. Zawojewski, P. K. Imbrie, and D. Follman, “A framework for posing open-ended engineering problems: model-eliciting activities,” in *34th Annual Frontiers in Education, 2004. FIE 2004.*, Savannah, GA, USA, 2004, pp. 455–460.

[29] A. Pickering, *Science as Practice and Culture*. University of Chicago Press, 1992.

[30] S. Gerofsky, N. Sinclair, and B. Davis, “Mathematics and the Arts,” in *Report of Working Group A*, Kingston, Ontario, Canada, 2002.

[31] E. G. Cohen, R. A. Lotan, B. A. Scarloss, and A. R. Arellano, “Complex Instruction: Equity in Cooperative Learning Classrooms,” *Theory Pract.*, vol. 38, no. 2, pp. 80–86, 1999.