Characterizing Indicators of Students' Productive Disciplinary Engagement in Solving Fluids Mechanics Problems

Ms. Jessica E. S. Swenson, Tufts Center for Engineering Education and Outreach

Jessica Swenson is a graduate student at Tufts University. She is currently pursuing a Ph.D. in mechanical engineering with a research focus on engineering education. She received a M.S. from Tufts University in science, technology, engineering and math education and a B.S. from Northwestern University in mechanical engineering. Her current research involves examining different types of homework problems in mechanical engineering coursework and the design process of undergraduate students in project-based courses.

Dr. Kristen B. Wendell, Tufts University

Kristen Wendell is Assistant Professor of Mechanical Engineering and Adjunct Assistant Professor of Education at Tufts University. Her research efforts at at the Center for Engineering Education and Outreach focus on supporting discourse and design practices during K-12, teacher education, and college-level engineering learning experiences, and increasing access to engineering in the elementary school experience, especially in under-resourced schools. In 2016 she was a recipient of the U.S. Presidential Early Career Award for Scientists and Engineers (PECASE). http://engineering.tufts.edu/me/people/wendell/

Characterizing Indicators of Students' Productive Disciplinary Engagement in Solving Fluids Mechanics Problems

Abstract

Engineering science courses are typically taught with lecture-based pedagogies and routinely assign problems sets comprised of problems authored by the professor or from the course textbook. With the high number of required engineering science courses, students spend a substantial amount of out-of-class effort on these types of problems. Yet, there is little research on how students engage in and learn from these problem sets.

This study examines three groups of students while they work on fluid mechanics problem sets and identifies instances and origins of productive disciplinary engagement. When students disagreed and debated how to solve problems, they engaged in productive disciplinary discussion. Three factors contributed to this active discussion and disciplinary engagement: the nature of the problem, the norms of the class, and the goals of the students. Our findings have implications for designing problem types that include conflicting constraints or require students to debate for a worked out solution.

Introduction

To earn a bachelor's degree in an engineering discipline, students must take 10 to 15 courses in the engineering sciences. These courses are typically taught with lecture-based pedagogies and focus on students learning a particular set of conceptual knowledge such as fluid mechanics, control systems, or thermodynamics. Engineering science courses usually require students to complete work outside of scheduled class time; this homework typically consists of weekly or bi-weekly problem sets comprised of problems from a course textbook or written by the course instructor. Occasionally, these problem sets also incorporate modeling tasks or simulations. In courses with this structure, these problem sets are designed to have students practice the problem solving techniques that are part of the discipline. The number of problems assigned weekly varies by professor but typically the set of problems requires several hours of work (and in the U.S., a 3-credit hour college course assumes 6 hours per week of out-of-class effort). With the high number of these courses required, and the frequency of this type of assignment given, engineering students spend a large amount of their homework time solving problems in these assignments. Considering this substantial amount of time, there has been relatively little research into how students approach and learn from these problem sets. This paper, along with others from our research program, aim to begin to understand when and how students learn conceptual knowledge during these homework sessions.

For our research program on the dynamics of learning in undergraduate engineering courses, we are building ethnographic records of engineering students carrying out homework problems and reflecting on their approaches to learning engineering through these outside-of-class assignments. We have been collecting video of students completing homework assignments in a variety of courses[1] and developing and iterating on an approach to characterize productive disciplinary engagement during homework sessions. This specific paper focuses on students doing homework for a fluid mechanics class taught by a mechanical engineering professor. Analyzing video of three groups of students working on their weekly homework assignment, we ask: (a) when do we see episodes of productive disciplinary engagement? (b) what is the nature of student engagement? (c) what are the factors that lead to these episodes occurring?

Background

Our analysis builds upon work done by[2,3] that looked for instances of productive disciplinary engagement (PDE) in chemical engineering senior design project teams. To identify these instances of PDE, Koretsky and Nolen use a construct from Volet and colleagues[4] to distinguish between two cognitive orientations, *task production* and *knowledge construction*. *Task production* is cognitive talk focused on the completion of an assignment. *Knowledge construction* refers to group talk oriented at deepening their conceptual understanding. Koretsky and Nolen describe how groups navigate back and forth between task production and knowledge construction throughout their work together.

Koretsky and Nolen[2] also looked for instances of productive disciplinary engagement, a construct originally proposed by Engle and Conant[5,6]. *Productive* means students are intellectually progressing. *Disciplinary* refers to using the language and engaging in the practices of the academic discipline, as if the students were professionals in the practice. When students are productively disciplinarily *engaged*, they are immersed in the practices of the discipline that result in deep learning. Koretsky and Nolen[2] found productive disciplinary engagement was triggered by productive friction in the group; that is, students' PDE began when constraints and components of the students' design conflicted.

When collaboratively working on problem sets, students could be trying to accomplish a number of goals, including to learn and understand the material, complete the homework as quickly as possible, figure out what the professor wants them to do and earn a good grade, or build or manage relationships with other students. In this paper, we describe factors that cause a student, or a student group, to prioritize some goals over others. This prioritization affects the cognitive engagement of groups; it determines whether they spend more time co-producing tasks or co-producing knowledge. Our analysis aims to understand what factors, such as student epistemologies[7], instructor expectations, course norms, or given assignments, cause students solving homework to prioritize some goals over others.

Methodology

This specific fluid mechanics class was chosen for research after retrospective interviews with fourth-year students (Swenson, in preparation). These interviews indicated that different students in this department perceive the types of questions posed by this instructor to be uniquely productive for the building of their conceptual knowledge. Classroom observations also indicated that this instructor had different, explicitly stated expectations for how he wanted students to go about their work both during class time and outside of class. One of his most insistent expectations was the students write on their homework solution every assumption they made when analyzing a system presented in a problem. A typical class period in this fluids course involved the professor and students working through a number of example problems, and at the beginning of each problem the professor would ask students in the class to name the assumptions. The most typical assumption, for example, was that the fluid was incompressible. Even if these assumptions seemed obvious, the penalty for students' not writing them down on their homework was to have points taken off their homework score. Another problem solving technique the professor encouraged students to practice was to consider whether the solution seemed to be a reasonable answer. This thought process was modeled as a valuable engineering problem solving practice.

Participants

The students in the class were third-year mechanical, environmental, and biomedical engineering students. The lead author made a recruitment announcement during class time to explain that she was conducting an ethnographic study of homework sessions, and students volunteered to participate in the study. Groups of students who typically worked together were identified from the consenting population. Three groups of students were video recorded for one to two homework sessions. Students were contacted by e-mail to determine if their group was working together on the problem set and the time and location of this work. Sometimes participating groups decided to complete the problem set separately and were not recorded. One of the groups was comprised of biomedical engineering students and the other two included only mechanical engineering students.

Data Collection

During the video recording sessions, students worked together on the homework assignment assigned for that week. These problem sets were comprised of problems from the class textbook[9] or modeling problems created by the professor and executed in Microsoft Excel or MatLab. The sampling of what was recorded was determined by the problems the students decided to work on together in the group. Some recorded sessions begin with students having started the problems in the problem set while others work on all four problems from start to finish together. While this is not ideal for research purposes, it captures the authentic ways in which students work and does not require them to do anything out of the ordinary as a participant in this study.

Table 1: Overview of Data Corpus

Group	Assignments	Video Length
Group 1: Emma* & Rachel, Mechanical Engineers	Problem Set 21: 2 book problems, 2 modeling problems Problem Set 22: 2 book problems, 2 modeling problems	1 hour, 10 minutes 1 hour, 20 minutes
Group 2: James, Matthew & Sabina, Biomedical Engineers	Problem Set 21: 2 book problems, 2 modeling problems Problem Set 22: 2 book problems, 2 modeling problems	1 hour Did not complete problems together
Group 3: Ken, Zoe & Grace, Mechanical Engineers	Problem Set 21: 2 book problems, 2 modeling problems Problem Set 22: 2 book problems, 2 modeling problems Problem Set 23: 3 book problems	2 hours (both Problems Sets 21 & 22)** 2 hours

*All names are pseudonyms

**The students were working on and discussing Problem Set 21. It was due two days before the video recording session.

Student Group Profiles

The three groups differed in their behavior, focus, and discourse patterns. Group 1, Emma and Rachel, are mechanical engineers on the same varsity athletic team and work closely together. They were quieter as a group but remained focused on their work. Group 2, James, Matthew, and Sabina, all biomedical engineers, joked throughout their session. In between questions about equations, they talked about popular videos, made sarcastic comments, and laughed at each other. Group 3, Ken, Zoe, and Grace, were very thorough and detailed in their discussions and going about their work. While they didn't always work through problems at the same pace, they checked answers, equations, and use of constants with each other as they did their work. Due to these characteristics, the Group 3 homework sessions generated the longest transcripts and richest episodes of data.

Data Analysis and Results

We begin by presenting the method of analysis and a summary of our findings examining all five homework sessions. Our focus then turns to a case study of a single episode of three students engaged in a productive, disciplinary debate over how a system should be modeled mathematically.

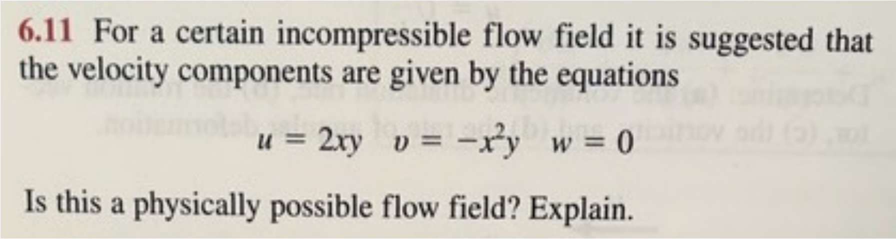
The five homework sessions total eight hours of video across the three groups. We began analysis by examining the transcript line by line to determine whether the group of students was orientated towards task production or knowledge construction[4]. Instances of task production in this data set included conversations about the correct equation to use, how to model and change the settings of one's computer model, and solving mathematical equations with reference to physical variables. We found that these activities made up the majority of the hours of data. Figure 2 shows the approximate number of total minutes each session each group spent task producing, knowledge constructing, or off-topic. Group 3 is the only group to spend extended periods of time constructing knowledge together. In the other two groups, Group 1 and Group 2, a single group member sometimes made a bid for deeper sense making (typically taking 10 to 20 seconds to make such a bid) but if not taken up by the other students, the group would return to task production. An example of a bid is shown in the transcript excerpt below with James and Matthew.

Table 2: Approximate time spent by each group task producing, constructing knowledge, and off-topic

Group	Problem Set	Task Production (minutes)	Knowledge Construction (minutes)	Off-Topic (minutes)
Group 1	Problem Set 21	62.25	0	6.5
Group 1	Problem Set 22	73.5	0	4.75
Group 2	Problem Set 21	46	2.25	4.5
Group 3	Problem Set 21 & 22*	93.25	5.5	13.5
Group 3	Problem Set 23	86	15.5	18.25

*Members of the group were working on finishing Problem Set 21, due two days earlier, as other members were starting Problem Set 22.

To illustrate task production and an unsuccessful bid to shift toward knowledge construction, we present an example of James and Matthew completing a text book problem from chapter six.



6.11 For a certain incompressible flow field it is suggested that the velocity components are given by the equations

$$u = 2xy \quad v = -x^2y \quad w = 0$$

Is this a physically possible flow field? Explain.

Figure 1: Problem Statement

They have just sat down to start the problem set. After a few minutes of off topic talk to the researcher and each other, James and Matthew throw out some ideas of how to start the problem.

1. James: Oh is it all we need to do so we know that these (pointing to his notebook) are equal. We just want to be able to say that (pause) um (pause) d, d^2 psi over dx dy is equal to um the opposite of - or is equal to d^2 psi over dy dx which- and we get those by these (points to notebook) two things.
2. Matthew: So we have to take…
3. James: So we differentiate u with respect to x.
4. Matthew: Ooohh yeah.
5. James: And then v with respect to y cause he showed that on the board right? I didn't write it down now.
6. Matthew: I have that.
7. James: So we don't even have to calculate psi necessarily.
8. Matthew: No we just have to do the same.
9. James: Well we could to make sure that it also makes sense.
10. Matthew: Or we could just take the teacher's word for it.
11. James: It looks like the- it is going to be...
12. Matthew: Wait where is it? I guess I didn't -

Here, in line 1, we see James proposing a way of going about the problem. In line 2, Matthew seems to accept this proposal and begins talking through the steps of the problem. Together, they walk through the math and discuss if they're choosing the right operations based on what the instructor presented on the board. However, in line 9, James also proposes that they could "make sure it also makes sense" but Matthew rejects that bid for sense making. They spend the next three and a half minutes continuing to work on the problem and complete it. Sabina, though present in the room, remains silent.

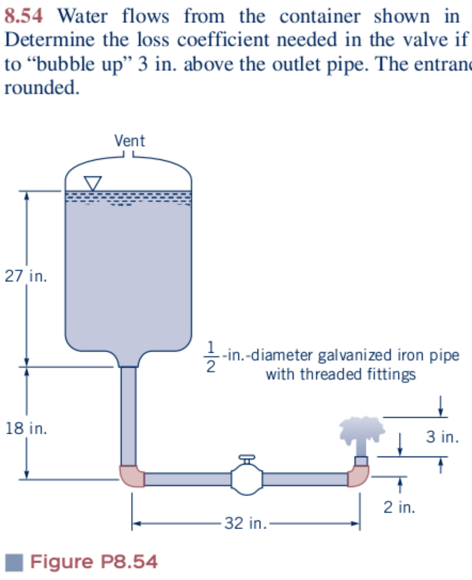
We characterize this as an instance of *task production* because the students' main focus is figuring out the mathematical steps and manipulating equations without making sense of the physical variables represented by the equations and numbers. In this case, James even makes a bid to the group to ensure their math makes sense ("well we could to make sure it also makes sense"), but his proposal is rejected in favor of continuing to work through the problem ("or we could just take the teacher's word for it). Throughout the corpus of data, there are many other instances of students focusing on finding and manipulating equations without reference to the physical phenomena modeled by the equations. Due to the high number of computer-based modeling problems in the data set, there is a large amount of talk on inputting formulas, correct syntax, and parameters of data sets into Microsoft Excel (task production), and little talk focused on understanding and interpreting the models (knowledge construction). The only exception is a short discussion by Group 3, Ken, Zoe, and Grace, about which parameters they should use when modeling a stream flowing around a circle.

Instances of *knowledge construction* in this data set included conversations with students making sense of equations, connecting variables to real life scenarios, and discussing how to translate perceived behaviors of stream flows to computer models. These instances of knowledge construction were closely analyzed for evidence of PDE. While we found both eleven instances and bids for PDE, in this report we provide an in-depth recount of one instance of productive disciplinary engagement in order to understand how the event was triggered and the nature of the engagement.

Instances of PDE are often identifiable by the increased amount of disciplinary talk, as well as passionate engagement of the participants[6]. The following transcript stood out in our analysis because of the sustained, active participation by all three students as well as their fluency to jumping between pieces of evidence and translating the fluid mechanics model into an analogous kinematic system. The following case study provides evidence how emphasized classroom practices may have sparked a disagreement that led to PDE.

Case Study

Three students, Zoe, Grace, and Ken, are working on a book problem together at tables in an engineering school computer lab. They are given the following system and asked to find the exit velocity of the fluid at the end when it shoots out into the air three inches high.



8.54 Water flows from the container shown in Fig. P8.54. Determine the loss coefficient needed in the valve if the water is to "bubble up" 3 in. above the outlet pipe. The entrance is slightly rounded.

Figure P8.54

Figure 2: Diagram from Homework Problem

Zoe and Grace are trying to figure out how to solve the problem when Ken interjects with his answer. In response, Zoe questions his answer. This disagreement turns into a sustained fifteen minute debate about how to solve the problem and reach a logical answer.

Ken begins by declaring his answer and explains how he calculated the problem. Zoe expresses her doubt in the validity of the answer – her reason being that that's way too fast to be realistic. She explains her reasoning by transforming the model into projectile motion instead of thinking about it as a moving fluid.

1. Ken: but it (the exit velocity) is going 48.15 inches per second
2. Zoe: 48…
3. Ken: point 15 inches per second
4. Zoe: and it's only going 3 inches (high out of the end of the pipe)?
5. Ken: Well I found out from the outlet to that height both pressures are the same the difference in height and the velocity at the top of the like water stream is pretty much zero cause that's like aaahhh (raises his arm a small bit and brings it down about three inches quickly) and it falls back down so I found out what the velocity exciting the pipe is-
6. Zoe: It can't be that fast because you're losing something to energy but also if you were going that fast and only (unintelligible) inches like I don't know it would be like cause like you're saying the flow is going for less than a second I mean not less than a second cause I feel like 48 inches per second is really fast and like the water would have to be dropping a lot faster than it's going and also I feel like if you use projectile motion if you're like exiting that fast like you'll do something like that (traces a parabolic arc with her finger) you don't just like crash after 3 inches.

In this transcript we see Ken stating the assumption he used to solve the problem - that both the exit and the top of the spot are at atmospheric pressure (line 5)– lead his calculations just to be about velocity and height. In response, Zoe tries to interpret this answer as reasonable or not and struggles with the fact that if the water is going 48.15 inches per second, and the water is only going 3 inches in the air, "the flow is going for less than a second." She calls on her knowledge of kinematics, relating the water particles to projectiles, making a parabolic trajectory of water particles up from the pipe and falling back down. The discussion continues.

7. Grace: maybe that's what's supposed to be if there was no loss of friction. You haven't accounted for that right?
8. Ken: I mean I don't have to. I know that the pressure at the outlet's zero and the pressure at the top of the stream is zero and there's the only thing that matters is the velocity being transferred as like

Grace proposes that maybe there is an unstated assumption, but Ken rejects this proposal, re-explaining his process. Zoe considers his approach.

9. Zoe: you're using Bernoulli's equation without friction just not formally using it but that's like what you're saying right now. No cause you're saying that since the density is the - wait what - since the pressure is the same and then you are using the change in height to find the final velocity that's just like another way of using Bernoulli's equation cause like that's what Bernoulli's equation is that's like pressure velocity but the thing is Bernoulli's

unless you're accounting for the loss in friction because there is some loss in friction here then you can't

10. Ken: but even with the loss of friction going through the pipe it's still going to leave with some velocity to be able to-

Zoe contends with Ken's equation choice, trying to reason how he might have incorporated the loss of friction. Ken sticks to his argument that there is no need to consider friction; he is only considering the system outside of the pipe. Zoe is still not satisfied and resorts back to her kinematics reasoning.

11. Zoe: Yeah but it's not going to be that velocity. Because okay so if you have something that's going like exiting at 48 inches per second it won't just go up 3 inches because even think of a projectile motion, but you're like kicking an initial velocity of 48 inches per second. It's not just going to do like bloop (makes a small arc off the table with her hand). It will be like waaaaaaaaa (makes a large sweeping arc with her arm). You know? Just like if it's not water just something that you're initially kicking at 48 inches. Especially if you're like kicking straight up like 48 inches per second that's a lot of initial velocity.

Zoe once again uses her knowledge of kinematics to consider the speed of the water. She asks the group to think about what kind of parabolic arcs an object would make going 48 inches per second and gestures to illustrate it for the group. Ken tries to meet her reasoning.

12. Ken: when I come down to it, it just comes into like potential energy verses like kinetic energy masses cancel the only thing left is height and gravity
13. Zoe: but then you have to account for friction because like we don't live in a frictionless world, right? It's like even in the energy equation you still use friction.

We see Ken now leveraging his kinematics knowledge to try to address Zoe's concern about the answer making sense.

14. Ken: are you saying friction between the air molecules or friction between the pipe that doesn't matter. Cause when it exits the pipe there's no friction anymore.
15. Grace: no but the whole point is that like it goes through a friction-ful system
16. Ken: yeah but it's still leading with a velocity like I'm only looking at this section once it leaves
17. Zoe: I-
18. Ken: and then once it reaches the top yeah it can have a higher velocity over here and it slows down but when it leaves here to get to three inches up in the air doing this math with Bernoulli's it has to have some sort of velocity to reach that height.
19. Zoe: Okay I disagree with you and-
20. Grace: You're only looking at the end?
21. Ken: Yeah so this leaves at some distance here is velocity needed to reach a height of three inches. So I want to find out what velocity this leaves at.

Ken tries to understand Zoe's model of friction and tries to clarify to the whole group he's only considering the system when it leaves the pipes (line 14). He continues trying to find an explanation to convince them his answer is correct, but Zoe is still not convinced.

22. Grace: I think you multiplied by twelve when you were supposed to divide. You want to cancel out the units here.
23. Ken: inches, inches per foot, dealing with inches, inches per second squared, inches squared over second squared, inches per second
24. Grace: okay
25. Ken: I want to run kinematics on like thinking like a ball to see if it comes out roughly the same as like a sanity check

Grace, clearly frustrated, looks at Ken's paper and comes to the conclusion there must be a math error. Ken walks her through his units to assure her it's correct. He then decides in order to prove it to them he's going to use kinematic equations.

They continue to circle back to the same issues – whether or not friction has an impact on the system and if Ken is using Bernoulli correctly. Zoe is relentless in the answer not making sense. She adds more evidence by recalling the professor solving a problem in class and after finding an answer, checks and concludes he used the wrong method. They finally agree to disagree, but a minute later Ken asks Zoe how she's going to solve the problem. She proposes a method and Ken exclaims that's the method he used. Finally, at the end of fifteen minutes Zoe and Grace realize they were misunderstanding how Ken used pressure in his equation. They agree and finally get Ken's answer.

Discussion

The instance of productive disciplinary engagement was characterized by the intensity of the argument as well as the variety of disciplinary evidence used in the argument. Zoe, Grace, and Ken were highly engaged as they all made "substantive contributions to the topic under discussion" [6], attended to each other's comments, were sustained in the discussion for a long period of time, and were passionate in their contributions. Their arguments centered on choices of how to best model the system; a fundamental disciplinary practice. The argument encompassed three points: was Ken's answer valid, was Ken using the correct equation, and should friction be used to model the system.

Zoe's arguments considering the validity of Ken's answer were driven by a discrepancy between his result and a system in her head. She repeatedly asks her classmates to think of a ball moving or someone kicking at Ken's suggested velocity of 48.15 inches per second (line 11). Something going so fast, she reasons, would not only have a height of three inches.

Zoe and Grace together make the argument the Ken's velocity must be that fast because he's negating friction. Ken claims the fluid, once exiting the system, does not have any friction acting on it and therefore he doesn't need to consider it in his equation. Finally, because Zoe and Grace believe Ken should have friction in his equation, they therefore don't think he should be using Bernoulli's equation.

These arguments arise from problem solving practices modeled by the instructor. Zoe's discrepancy between Ken's solution and her kinematic models echoes the instructor's practice of reflecting on the validity of the answer at the end of each problem. The argument about including friction in the model is a disagreement about initial assumptions made of the system. Again, this practice echoes their problem solving practice in class.

Like the examples of PDE found in Engle and Conant[5] and Koretsky and Nolan[2], this instance of PDE was triggered by disagreement. Like students in prior studies, this argument created a discipline-rich discussion where students debated assumptions and considered alternative models of reasoning. This study highlights an unstudied type of problem solving; this was not a design problem with conflicting constraints or a problem the students themselves choose to pursue. Instead, it was a narrowly defined problem with a single answer.

Conclusions & Implications

Koretsky and Nolan make the claim that "standard, linear textbook and laboratory tasks provide a narrower, more sequestered context with fewer opportunities for productive friction." Our data agrees with that for the most part; the conditions of textbook problems create few opportunities of conflict that can spark moments of PDE. This, as well as past data[1], demonstrates students are mostly engaged in task production while completing problem sets. We do not claim task production activities such as learning how to create a computer models or solving mathematical equations are things students should not be practicing as budding engineers. We believe using mathematics to solve problems is an essential part of an engineering education. Yet, we believe homework sets need to provide more opportunities for productive disciplinary engagement.

In this paper, we see instructor-normed expectations in solving problems prompt Zoe and Grace to question the assumptions and equation choices made by Ken. These questions cause the disagreement about how to model the system that triggers PDE. To encourage more of these instances, instructors could take more time to emphasize problem solving practices needed for the real world. In our retrospective interviews with fourth-year students (Swenson, in preparation), students stated that problems based in real-world scenarios prompted deeper disciplinary thinking and a more authentic use of their conceptual knowledge. Like Engle and Conant[5] and Koretsky and Nolen[2], conflict triggered this instance of PDE. Problems, for either in-class work or problem sets, could be designed to include conflicting constraints and require students to argue their assumptions and decisions. One possible problem type is Model Eliciting Activities (MEAs)[10,11]. MEAs are real-world, client-driven problems that require students to deepen their conceptual knowledge and apply it to create a generalizable mathematical model. These more complex problems that demand students revise and test provide more opportunities for conflicting requirements that may spark PDE. Another problem variation could be providing two or three proposed solutions to a textbook problem and asking students to write an argument for which solution they believe solves the problem best. This would take the focus off mathematical operations and instead zoom in on actively choosing how to model systems and evaluate solution types.

This study was limited by the number of cases examined and is not necessarily representative of the wide range of fluid mechanics courses. We selected this course because of the unique teaching practices of this instructor at this university and because we wanted to understand how the conditions of his classroom affected the dynamics of student work. Other limitations include the population studied was self-selecting and we were limited in the amount we were able to capture due to decisions made by the student groups. While obtaining an identical data set for each group would be preferable, we as researchers aim to capture authentic student homework practices and choices. There is very little data capturing student work in this way, and we believe a fine-grained examination of these homework sessions that are intrinsic to the undergraduate engineering experience is vital for understanding student learning.

Acknowledgements

We'd like to thank the students for their volunteering their time to participate in this study. We'd also like to acknowledge the on going support of our lab group at the Center for Engineering Education and Outreach as well as the Department of Mechanical Engineering. This research was supported by NSF grant DRL 1623910 and NSF grant EEC-1444926.

References

1. Swenson, J., & Wendell, K. (2016, October) A case study of students' engagement in a control systems homework problem. In *Frontiers in Education Conference (FIE), 2016 IEEE* (pp. 1-4). IEEE.
2. Koretsky, M. D., Nolen, S. B., Gilbuena, D.M., Tierney, G., & Volet, S. E. (2014a). Productively engaging student teams in engineering: The interplay between doing and thinking. In *Frontiers in Education Conference (FIE), 2014 IEEE* (pp. 1-8). IEEE.
3. Koretsky, M., Nolen, S.B., Gilbuena, D.M., Lehtinen, E., Vauras, M., Tierney, G. and Volet, S.E. (2014b) *Studying & supporting productive disciplinary engagement in STEM learning environments.* In: 121st American Society for Engineering Education Annual Conference & Exposition, Indianapolis, IN.
4. Volet, S., & Vauras, M. (2013). *Interpersonal regulation of learning and motivation: Methodological advances*. Routledge.
5. Engle, R. A., & Conant, F. R. (2002). Guiding principles for fostering productive disciplinary engagement: Explaining an emergent argument in a community of learners classroom. *Cognition and Instruction*, *20*(4), 399-483.
6. Engle, R. A. (2011). The productive disciplinary engagement framework: Origins, key concepts and developments. *Design research on learning and thinking in educational settings: Enhancing intellectual growth and functioning*, 161-200.
7. Lising, L., & Elby, A. (2005). The impact of epistemology on learning: A case study from introductory physics. *American Journal of Physics*, *73*(4), 372-382.
8. Swenson, J. (in preparation) Examining the Effects of Students' Epistemologies on Approaches to Engineering Coursework
9. Gerhart, P., Gerhart, A, & Hochstein, J. (2016) Muson, Young, and Okiishi's Fundamentals of Fluid Mechanics, 8th edition.
10. Diefes-Dux, H., Follman, D., Imbrie, P. K., Zawojewski, J., Capobianco, B., & Hjalmarson, M. (2004, June). Model eliciting activities: An in-class approach to improving interest and persistence of women in engineering. In *ASEE Annual Conference & Exposition*.

11. Moore, T. J., Miller, R. L., Lesh, R. A., Stohlmann, M. S., & Kim, Y. R. (2013). Modeling in engineering: The role of representational fluency in students' conceptual understanding. *Journal of Engineering Education*, *102*(1), 141-178.