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Pedagogical Development for Chemical Engineering PreService Faculty- Foundational Knowledge

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Abstract

Engineering education, particularly chemical engineering education, has done significant work in developing better ways for teaching undergraduate students. With the rise of engineering educational departments and programs over the past decades, there has been an increasing focus cross-disciplinarily on the similarities of educating engineers. Unfortunately, graduate students, particularly engineering graduate students, are under-studied within literature. Graduate school is a time of significant personal development, growth, and apprenticeship into the research world. As such, this presents an excellent opportunity to facilitate pedagogical development. However, there is little scholarship around the pedagogical knowledge or current skills of future engineering faculty. To address this, I performed an exploratory descriptive phenomenological study. The goal of this study was to determine what PreService Faculty (PSF) believe it means to learn and teach engineering. PSF is a term I use to refer to engineering graduate students who are intent on pursuing a faculty role post-graduation.

A descriptive phenomenological analysis was performed on interview data collected with PSF on their views of learning and teaching. This work focuses on PSF who were in Chemical or Biomedical Engineering PhD programs. The four interviews from this study were collected from a larger corpus across multiple disciplines.

Our research questions for this project are:
What does it mean to “learn engineering?”
What does it mean to "effectively teach engineering?”
How, if at all, are these two phenomena connected?

PSF considered learning engineering to involve several key unexpected elements, such as: a necessity for resources to facilitate one’s own learning, a clear physical connection between the topic being learned and the phenomena being described, whether learning was a social or personal exercise, and “learning to get ‘un-stuck’” when faced with challenges.

PSF considered teaching engineering to involve a difference between why an element is being taught, whether that was for conceptual or content coverage, or instead focused upon student learning. Further, their pedagogical decisions were focused upon student learning, while their content coverage descriptions were focused upon the teacher facilitation of the course.

These two phenomena were connected for these participants specifically through their (hypothesized) teaching methods; PSF often would draw upon their own learning experiences to consider how to facilitate similar experiences with other students.

The findings from this disciplinary subset are echoed within the larger dataset, indicating a minimal difference in the views toward learning or teaching engineering cross-disciplines. These findings indicate that disciplinary nuances are often minimal by the time graduate school occurs. While the concepts of a discipline are extremely important, the more integral elements of learning or teaching engineering are not disciplinarily unique, and indeed are often shared across the disciplines. This presents unique potentials for facilitating peer-development. Chemical

engineering education could provide leadership in this way, guiding their peers (or PSF as peers-to-be) in the development of their own pedagogical excellence.

Introduction

Engineering faculty are rarely taught how to teach in the US. Significant scholarship in recent years has established this fact, the difficulties in learning how to teach [1], [2], [3], [4], [5], [6], [7], and the sacrifices many early career faculty must make if they choose to focus upon their pedagogical skills rather than pursuing a research agenda [8]. The rising number of positions for teaching faculty indicate a shift in the academic agenda and institutional recognition of the power of focused pedagogy, as well as the mutual benefit to traditional faculty and students by these newer positions. However, many of these faculty are still relatively under-prepared for their pedagogical skills required by this position; most PhD programs are excellent at facilitating research competencies, professional skills, and grant writing. Rarely do they similarly facilitate excellence in teaching and curriculum development. The presumption that the experiences of being a Teaching Assistant (TA) will provide these necessary skills is unfortunately false, and well documented to be misaligned with the duties of a formal faculty member [9], [10], [11], [12], [13], [14].

Due to the significant competing pressures on early career faculty, it would be better to train the requisite pedagogical skills for curriculum, assessment, course design and delivery, and classroom facilitation within a similar apprenticeship program as is currently facilitated by PhD programs with research skills. A program does exist within the US to provide the extended and guided practice for the development of teaching excellence: the pre-service teacher (PST) preparatory program.

However, the knowledge basis between public school teachers and engineering faculty is significant; there is a large difference in teaching mathematics, literature, or history as compared to an always changing list of engineering courses such as thermodynamics, ethics, senior design, or computational simulations.

As such, to adapt the methods of training from PST to engineering, I need to know the baseline knowledge and instincts for our population. After all, this is the principle behind formative assessments [15], [16], [17], [18]; it is equally frustrating to teach integrals to someone who recently learned multiplication, and vice-versa. Unfortunately there is nearly no scholarship on the knowledge of learning and teaching for graduate students. These future faculty, or PreService Faculty (PSF) as I call them, are understudied from this lens.

This work seeks to address this lack of foundational knowledge, connecting the views PSF hold towards knowledge, learning, and teaching of engineering through the framework of epistemological beliefs to provide the formative knowledge which can be used to develop preparatory programs for building a better generation of future faculty.

Background

Teaching and learning are strongly related topics. These are integral within epistemology [9] and common topics within literature from pre-service teacher training [19], [20], [21], [22].

Teaching-learning conceptions have been related to lifelong learning [23], beliefs about learning and teaching implications thereof [24], the alignment of learning styles and teaching styles [25], and within studies on faculty pedagogical content knowledge [26]. Epistemology is connected to both teaching and learning and has been used to examine the connection between these topics [10], [27], [28].

Considerations of teaching and learning can be examined in cohesion under the lens of epistemology, defined as "an individual's ideas about knowledge" (specifically their ideas about "the nature of knowledge" and "nature of knowing") [[29] pg 119]. Epistemology is also integrally connected to ideas of learning and teaching [30], [31].

Epistemology lens

I define epistemology in this context as the way the PSF define knowledge and what it means to know something, truth and the possibility of an absolute fact, and justification for that knowledge [32]. Epistemology has been used quite often within the context of preservice teacher training [33], [34], [35], [36], [37], [38]. Epistemology has also been considered with several levels of engineering students, ranging from students new to engineering and college [39]to engineering faculty [40], [41], [42].

TA training as Insufficient prep for STEM PSF

Many studies have considered engineering graduate students in the context of being TAs, though the majority of these explore TA training, utilization, or experiences. While these positions do give a student experience in delivery and class management, they rarely provide any experience with the more conceptual issues related to courses such as content development, course progression planning, or learning outcomes [9], [10], [43], [44]. TA preparation is often rather brief, rapid, and focused upon a few basic skills such as classroom management, problem solving tricks, and lab safety [9], [10], [13]. Even when TA training programs are more dedicated and focused, they focus more on content delivery and less on course design [45], [46], [47]. There are some studies on graduate students in TA positions which go beyond the standard model [13], [14], [48], [49], [50], [51], [52], empowering TAs in these contexts with additional responsibilities or learning experiences to better model a faculty position. These studies describe programs which provide TAs a more structured practice. Such studies, while innovative, do not capture what TAs consider to be learning or teaching, which influence most if not all decisions made about what learning looks like within a classroom. Furthermore, while there are some studies which provide more structured or scaffolded practice for TA positions [14], [43], [48], [50], [51], [52], [53], these are not widely implemented.

Methods

This work was conducted under a descriptive phenomenological analysis of previously collected data. IRB approval was extended from the original study to cover this additional analysis. Data were collected from PSF via interviews about their view on learning and hypothesized teaching. The original interview protocol presumed that there would be a clear connection between these two concepts; the hypothesis that the ways one learns informs how one goes about teaching others is rare in literature. Unfortunately this was not the case. While there was influence on the hypothetical or idealized teaching methods, it was unclear and indirectly related to the PSF beliefs about learning.

Subsequent analysis of the data was conducted via a parallel descriptive phenomenological analysis. Within this process, I examined independently what PSF considered to be the phenomenon of '*Learning Engineering*' as well as the phenomenon of '*Effectively Teaching Engineering*' to disentangle the constructs. the 10 participants had widely varied views and beliefs, which are detailed elsewhere [53]. However, the Chemical or Biological Engineering PSF had much more closely congruent beliefs across the two phenomena and more similar to each other than any of the other groupings of data characteristics. This was an exciting opportunity to more deeply investigate the connections between the two phenomena. For more information about the analysis done with the entire dataset, see our previous publication [53].

Participants

10 PSF were recruited through interest and screening surveys among all doctoral students in the school of engineering at one large, urban, northeastern public research university in the continental US. The only recruitment criteria were active participation in a Doctoral program and a self-stated intention to pursue (or consider) a faculty role after graduation. For this specific work, a narrowing of the data was done to focus on the chemical and biomedical engineering engineering students. Detailed demographic information is provided below in Table 1.

Table 1: Participant Demographics

PSF	Gender	Year	Major	Industry	Teaching	Ethnicity	Other facets
Red	M	2	Chemical	N	Expecting to TA	White	
Deepika	M	3	Chemical	N	TA	Asian/ Indian	Low SocioEconomic Status
Janelle	F	4	Chemical	N	TA	Asian	
Morgan	F	4	Biomedical	Y	TA	White	

Phenomenological Inquiry

This specific work uses a modified phenomenological analysis, drawn from various schools within the Husserlian tradition. See our other works at the conference for more intensive details on the construction of this method. Specifically, the interviews were analyzed following the procedures set out for STEM inquiry and leveraging the attitude of bridling. Bridling is presented restraining the biases of the analyzing researcher until the participant knowledge (findings) are solidified, and then engaging the power of an insider researcher (that is a researcher who is themselves a part of the research population). In this case, the lead author is themself a PSF, so their analysis of the beliefs of other PSF should only leverage their personal views and beliefs AFTER conclusion of the initial analysis. For purposes of this work, that means the findings were constructed without considering personal bias, which was then the basis of the discussion sections.

Within this analysis process, I chose to align to a specific analytic process for descriptive phenomenology. The method's development within analytic psychology, along with its significant focus on detailed steps, balances the well-structured nature of STEM with the intuitive and adaptive methods inherent to qualitative research, and especially within phenomenology.

Giorgi's method follows general protocols of phenomenology and is presented below.

A. Listen to each interview repeatedly.

B. Identify key elements or codes within the interview.

C. Only use the participant's words to define those codes.

D. Determine the organizations of those codes, or themes for the interview.

E. Organize the themes within a hierarchy for the phenomenon

F. Repeat this process for every interview, independent of other interviews.

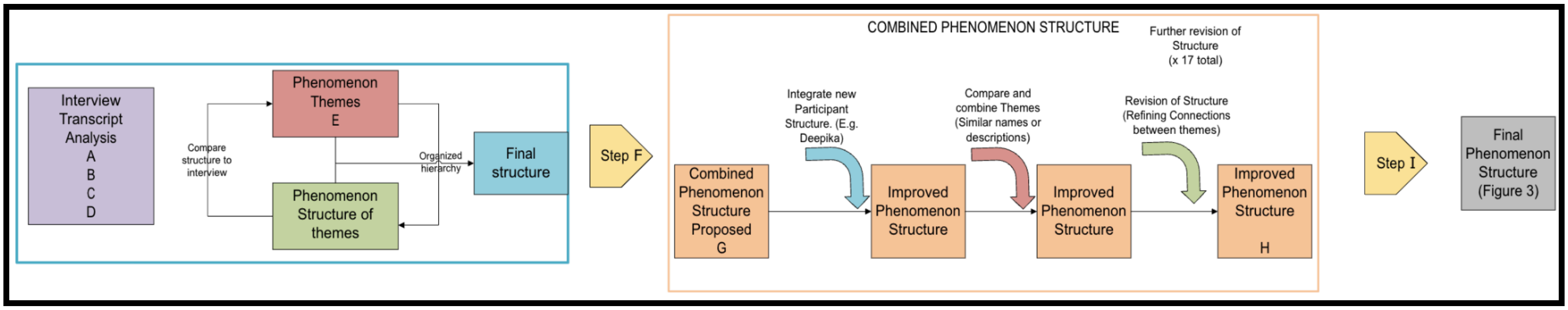
G. Look across all the interviews for consistent themes and hierarchical relations.

H. Determine which of those themes and relations are most important and essential to the phenomenon.

I. Develop the composite phenomenon via those essential themes and relationships. This should take the form of a hierarchy of themes.

This analysis was conducted for each participant individually, then comparing those individual phenomenon structures to develop a composite hierarchy of consistent themes for the entire population.
Figure 1: Cohesive Data Analysis Process

Data Analysis



Each interview was analyzed a minimum of five times following the guidance of Giorgi's process [27]. This process is shown in Figure 1. This began by reading through each interview to remind myself of the content (step A). Then, I read through again noting the key elements or codes of the interview (these codes could be key words, phrases, or ideas) (step B). Next, I read to find the codes and defined them through the use of participant's words (step C). Subsequently I read through to collect all of those codes, and then connect them to identify themes (step D). Finally, I read through using the constructed themes to search for new instances of their presence in the interview (ensuring theoretical consistency).

That is, each participant had a unique set of codes, from their own quotations, and themes within which those codes were classified. I draw operationalized definitions of the thematic elements exclusively from the participant interview data. The codes consisted of key words or phrases, like when Red said he "learned backwards" or when Morgan said that engineering is "an approach or mindset." These codes became themes, for example, Red's assertion for "backwards learning" was classified as *Self-Directed Process* because of how he defined backwards as being application first, then the mathematical theory. This is the example process of doing steps B-D above, which was conducted independently for each interview.

Then, after the final pass through the interview, I took those themes and organized the themes into a hierarchy which represented the participant's view of the phenomenon of Learning Engineering (step E). That is, I took Red's themes and put them in a hierarchy to see what was most important to Red. I also took Morgan's themes and put them into a hierarchy as what was most important to Morgan. These were done independently of each other (step F). By the end, each participant had their own unique codebook (with the codes defined in their own words) and hierarchy of themes for their interview.

Afterwards, I compared all of those structures of themes and the hierarchy across all participants (step G). Then I combined each participant's distinct hierarchy to determine commonalities and consistent elements across them. This was based upon the author's own interpretations and was not confirmed with the participants. After the final version of the synthesized themes had been formed, I considered what made it unique or distinct (step H).

Finally, the author identified which elements within this hierarchy made the phenomenon uniquely 'Learning Engineering', as opposed to similar phenomena such as: 'Learning', 'Learning Mathematics', or 'Solving Engineering Problems'. These themes make up the most essential components of the phenomenon's structure (step I).

During the process of analyzing the separate phenomena, I discovered that there was similarity between the two phenomena of consideration, ‘Learning Engineering’ and ‘Effectively Teaching Engineering’ for several of our participants who were in Chemical Engineering PhD programs. Given that our original motivation was to test in what ways these two constructs were related, I decided to focus in depth on this sub-population.

Our research questions for this project are:
What does it mean to “learn engineering?”
What does it mean to "effectively teach engineering?”
How, if at all, are these two phenomena connected?

Findings

Given that descriptive phenomenology is a synthesis of the intangible phenomenon from the experiences of multiple participants, I had to perform another analysis refinement with just the limited participants. Below I present sequentially the chemical engineering PSF views of the phenomenon separately followed by the overlapping elements. Each of the constructs will be presented after the visual of the findings, organized by ‘strands’ or connected themes.

A. Learning Construct

For PSF, learning engineering was composed of several distinct strands: a self-directed process, practice, applications, and independent learning. A visual of this construct is shown below in Figure 2.

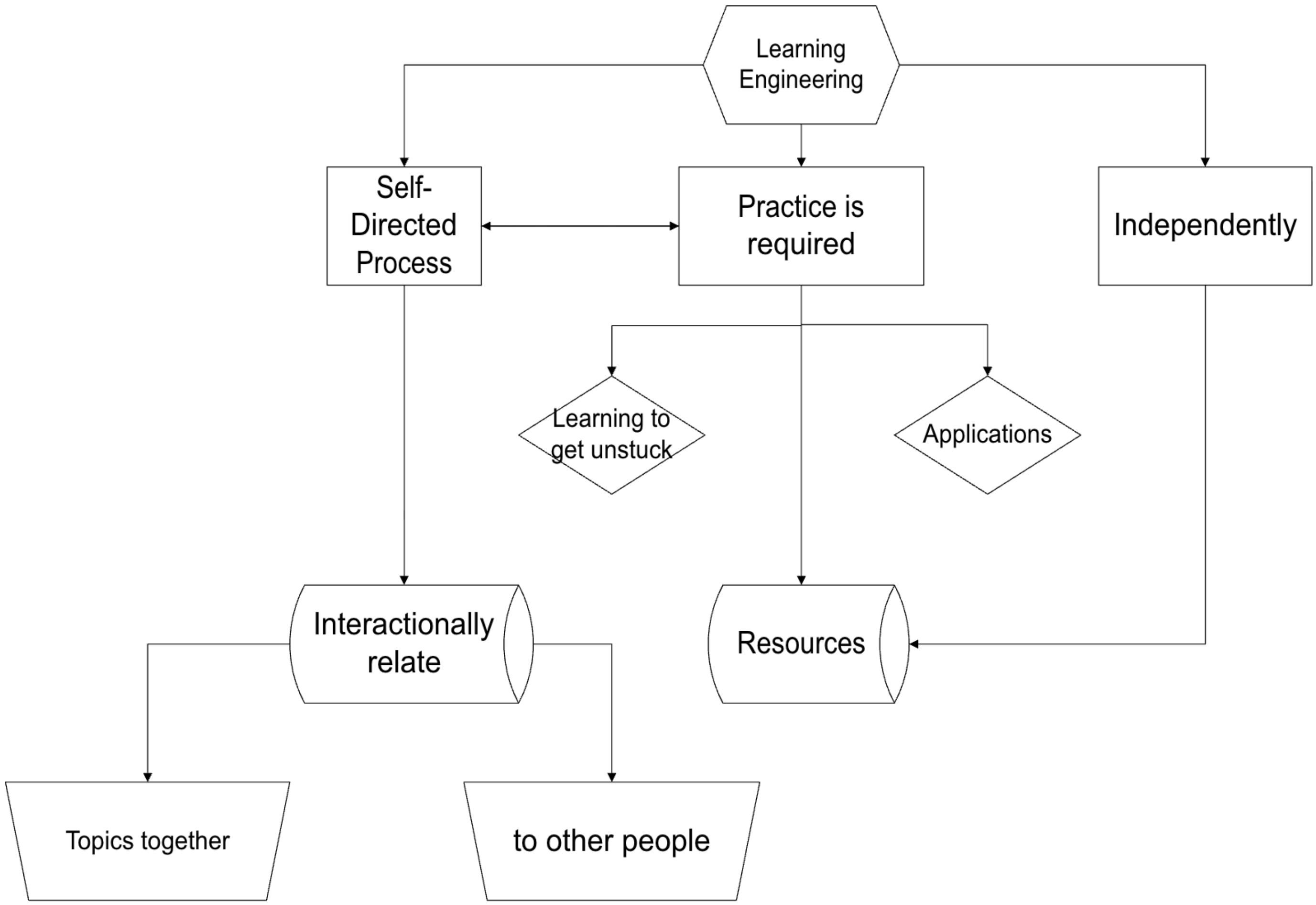


Figure 2: The Phenomenon of ‘Learning Engineering’

Strand 1: Self-Directed Process

The first major component of learning engineering to PSF was the fact that it is a ‘Self-Directed Process,’ which varies by person. While several common strategies, approaches, and techniques may exist, every person’s learning process is unique and must be in charge of it themself. A major component of this self-directed process is the discovery or creation of that process through practice. Deepika describes that self-directed process as “a lot of engineering is about solving problems” and one must “have [an] understanding [of] the concepts to be a better solver.” That is, engineering is solving problems, and an understanding of concepts empowers learners for better solving those problems through enhanced understandings. Morgan also describes how a core part of learning engineering is learning how to learn. She mentions the most important parts of courses as “the connections and networking. And the other part of learning it’s … I gotta learn the processes or whatever. It’s more important to teach [students] how to find information, not what the information is.” She further states that “a big part of undergraduate education is learning how to learn.” All of these are ways that PSF discussed how learning engineering is predominantly understood, grasped, and pieced together or created by themself, or under their own direction.

A.1.1 Connection to Practice

The practice of trying to learn engineering (skills, concepts, procedures, or standardized assessments) will inform, refine, and leverage that self-directed process. Learning engineering, and specifically the methods of performing engineering, are skills which are similar to artistic execution or physical endeavors; they are learned and refined more through practice than expanding theory or knowledge. As Deepika puts it well, “I think, having an understanding of the concepts that are being used in the problem definitely helps you to solve many of those problems or like it supplements your approach. Because if you don't understand the concept, then I think solving a problem will be very difficult, even if you practice it many times.” Here he is emphasizing the importance of practice, but also understanding alongside replication, and further that this practice is not just problem replication since “I think just having one avenue doesn't work…. it’s kind of a combination of all those practices.”

A.1.2 Learning by Relations

A significant component of this self-directed process is learning how to learn via interactional relations. That is, no concept or person exists in a void, and part of the self-directed process is learning how to leverage those connections. Learning to connect topics, work with others, and draw upon numerous available knowledge sources is one of the essential tasks of everyday engineers; learning this method and viewpoint is essential for learning engineering and one of the better trained skills for the workplace which is facilitated by the academic setting.

Red describes this when he states that “classes teach you the basics, you have to go learn the material.” By this Red means that classes teach the foundations, or the “basics” of topics, the conceptual framework. However, to Red, this is incomplete and needs application or industry experience to finalize. He notes that “you need like a framework of like engineering and like mathematic principles to be able to like do a class” but that “a gap that a lot of classes miss” is “showing me directly how what I learned in the classroom can be applied to industry or like in the real world.”

Red later extends this idea, explicitly and elegantly stating that “academics will like set you up, but you don't really learn, you don't really have the end result without doing something with research or industry. So I think you need a sort of the basis of engineering, with schooling.” By this Red is emphasizing that while he learned concepts and knowledge in the classroom, his classes left him with incomplete learning. Red is seeking the connection between the academic knowledge and the application therein.

A.1.2.1 Conceptual Relations

The interactional relations between different topics can provide powerful nuance and connections and further is where much of the iterative complexity of engineering occurs; it is nearly impossible to design a thermal reactor without an underlying knowledge of thermodynamics, temporal mathematics, material properties, or modeling software. Courses in engineering programs also build upon the conceptual and procedural knowledge of the prerequisite courses, for the subsequent courses; a major element of learning in engineering is learning deeply to allow for long term recollection. Janelle describes this when she says that she learns engineering by “it’s easier to focus on specific things” because “initially I tried to do everything in a problem at once.. And then I figured out I cannot do this, so I went back to stepwise.” Janelle clarifies that as engineers “ I take a lot of classes, so I can build up our foundation, apart from that, I mean sometimes I calculate something” and that “every question is related to like science science, and I learn by… trying to use, something I learn from the lab and then apply that in our life personal life.”

Janelle here is referring obliquely to the fact that most engineering problems are significantly synthetic; they are composed of numerous elements, each of which requires addressing or considering when attempting to solve them. This conceptual intensity and complexity led Janelle to her key emphasis on learning, that “I need to identify the problem first” because “a lot of times [engineering students] want to do something very conceptual and then realize I don’t know how.” Here Janelle is emphasizing the importance of problem labelling or identifying the central topics of a problem.

A.1.2.2 Interactional Relations

Further, engineers work on teams so a major component of learning via this self-directed process is the development of professional skills to interactionally relate to and with people. These can be peers (and most commonly are within learning engineering), learned mentors (like TA or faculty members), with stakeholders, or with interdisciplinary teams. Deepika and Morgan have opposite experiences, yet arrive at the same conclusion that interdisciplinary or group work are important. For Morgan, her core “teaching philosophy is learning through team based experiences from diverse perspectives in a way that always challenging you to think beyond what you know.” That is, learning from and on a team is highly important to engineering. Deepika, in contrast, states that “I really hated group projects. But I don't think I would get rid of them because obviously it really helped to learn how to use the software for engineering plan design and team work. It helps you to work with people… I hated that, but it was obviously [valuable] for a lot of things I learned from that. And so group projects is probably my least favorite but I wouldn't eliminate it, I think sometimes you have to do things that you don't like that you can learn.”

So despite Deepika hating group projects, he agrees with Morgan that learning with and from others (likely peers) is a valuable component of engineering learning.

Strand 2: Practice

Practice is an integral process for learning engineering. PSF made a specific point that this should be using one’s own self-directed process. However, practice will help the learner improve and better understand their own process. So, to learn one’s process, one must use that process in practice. Practice, therefore, will help one understand both the personal learning process, but also where this process is ineffective or inefficient. Deepika emphasizes that

> “I think also… having an understanding of the concepts that are being used in the problem definitely help you to solve many of those problems or like it supplements your approach. Because if you don't understand the concept, then I think solving a problem will be very difficult, even if you practice it many times, and so I think it's important.”

Deepika is emphasizing here that conceptual understanding is integrally important alongside practice of problems. He continues that

> "So solving engineering problems, I think, for me, it's just been doing as many as possible for a given class. You have to learn how to solve a specific problem so the more similar problems that you solve by looking at others. [F]irst of all start looking at examples, you look at them, see how they did it and copy that, see if you could approach it that way. And then… the more you practice that, at least for me [the] more I practice it, the more I'm able to solve problems and another way is also having a defined approach for how to solve problems. [S]o having a predefined approach and then practicing a lot kind of helps you to get an idea of how to approach problems and solve them least for me."

Deepika is specifically connecting practice of problems with learning. For him, learning engineering requires practice on the skills, approaches, and concepts in problems. He solves problems to learn how to solve problems like that, as a vehicle for facilitating conceptual growth. That is, seeing the concept used in the problem and solving that problem helps him understand the underlying concept better, though both conceptual growth and procedural fluency are important.

A.2.1 Learning to 'Get unstuck'

A major portion of this practice (with the self-directed process) is learning how to 'get unstuck' as Morgan put it. That is, the entire experience of finding an unexpected issue/problem within the practice, learning about, discovering, identifying, and trying a solution until the problem is addressed, is essential. This is the core of engineering as a field, the identification and addressing of problems, yet students are more often aware of this process on the macro-scale of design problems. To PSF, a major component of practice is practicing the necessary skill of learning how to get out of a feeling of being stuck, and identify new avenues to proceed.

The goal of almost any engineering problem is to solve an issue or improve a process. So, learning how to have strategies to "get unstuck" when there is no clear idea of how to proceed.

Morgan describes how students of engineering have to "learn how to get unstuck" by which she means that a part of learning engineering is learning how to work through places where the path forward is unclear. As engineering is problem solving, and to Morgan it is "more a set of approaches" and "a mindset" rather than a set of concepts, learning the mindset of pushing through setbacks or places you don't know how to proceed is important.

This is particularly important to Morgan given that learning is highly self-driven and directed, so that mindset of engineering which she mentioned is directly focused on solving problems using the set of approaches taught by engineering. Rather than accepting failure or discomfort or lack of knowledge, the engineering mindset Morgan envisions faces these as challenges to be overcome, learning yourself how to get out of those "stuck" places in a solution process.

A.2.2 The importance of Resources

One major way of getting un-stuck is through the usage of resources. Practice facilitates learning, and practice with finding and using resources is essential to understanding how to evaluate and leverage those resources. These resources can be provided, located, or determined. Even more important is the dual skills of learning how to evaluate those resources for accuracy, validity, and trust. Additionally, many times those resources are peers or other knowledgeable parties and this is a professional skill which needs to be nurtured; what is the necessary information and how to locate it, and once located, how to verify that it is as accurate as possible.

Deepika describes this process well, emphasizing the importance of learning through the use of personal resources. He describes “I felt like the times I learned was when I actually read the textbook before coming to class” because “I could understand what the professor was talking about.” He continues that “I felt like the lectures weren’t effective if I wasn’t doing the readings, as there were gaps in my knowledge along the way.”

Deepika recalls that he often used the textbooks for learning, as “the most effective way for us to learn [was problem sets] because you’re struggling and trying to solve and figure out, and so you go to the textbook and example problems” which he characterizes the entire process as “enjoyable, fun, but very difficult and rigorous.” Deepika elaborates that his ideal learning experience was

> “reading on [the topic] from a textbook, then watching videos to supplement specific concepts, … and then being able to ask an expert specific questions about the topic… I want an expert so when I have a question I can get an answer, not a full lecture.”

Here Deepika is characterizing his learning of a topic or concept in engineering, at least in his most ideal format, as entirely self-directed. Through the usage of a variety of types and modalities of resources, he holds the entire autonomy and efficacy. Deepika chooses when to engage with which resource or topic. Regardless of the form of that resource (e.g. an expert, a peer, reading, video, online search, or something else), Deepika uses them similarly to build his understanding of the topic, in his idealized learning format.

Strand 3: Applications

Applications are an essential part of engineering; this is one of the most commonly stated distinguishing factors between engineering technical research and science or mathematics. As such, it was unsurprising that PSF emphasized that a major component of learning engineering was through applications. The application of a concept will massively help contextualize, retain, and inform the accurate usage of said concept. The same is true for procedures and processes; seeing a process in usage and understanding how, when, where, and why it would be used in real-practice are essential.

Red views applications as highly necessary to cement his learning of a topic, and can show how classroom topics connect to real world ideas, industry topics or prospects, and exist beyond a book context. Red goes on at length about this example, one lengthy project in an advanced course, stating that he truly learned from “the trial and error I guess” and that because it was an open ended project, “you’re not trying to get a right answer, you’re trying to get as good as possible but there isn't like an objectively correct answer" and later asserted that "this felt like something I might actually do in industry… it felt like showing me directly how what I learned in the classroom could be applied to the real world."

Morgan also reveals this when she discusses how

> "because you can learn something conceptually from a book, but if you don't understand how it's applied it doesn't really sink in… that application of science was really important."

Red shows this when he describes "showing the application of a lot of classes is really important" further emphasizing that one class in particular "showed me how much better I retain information [via applications] than just quizzes and tests." Red also asserts that he really enjoyed this process, project, and entire class because "mostly just the applicability" or the fact that what he was learning he could clearly understand and view it as relevant, real-world connected, but mostly that he had an understanding of an application of concept he was learning. This helps Red understand and recall the concepts or topics significantly better, as well as helping him learn faster and more enjoyably, which he notes is "significantly important for student morale."

Similarly, Morgan emphasized a key learning experience from her undergraduate journey in a class with a professor of practice from industry. In reflecting on why this was so meaningful to her Morgan also mentions how she found a consistent trend in topics or classes she enjoyed and learned well within, how "they were just directly applicable" and followed up on this idea with an assertion that applications are similar to teaching others, "until you apply that knowledge you don't realize how much you still [understood] or [had to learn]." She described that one of the key ways to verify your learning was to try and teach another person or explain it to a peer, but the examples or demonstrations of applications was the most powerful way to do that and most essential to learning something in engineering.

Both Red and Morgan elaborate at length how important an application for the knowledge being taught is. What is interesting about their harmony is that Morgan is a non-traditional student who has industry experience, while Red is a traditional student with only a few internships. Despite this, they both spoke strongly and similarly about the necessity of an application for knowledge.

Strand 4: Independent Learning

For PSF, learning engineering is done primarily independently through numerous methods and strategies which vary individually, though all PSF consistently spoke about the usage of resources. Morgan goes on at length about this necessity, how "undergraduate programs teach a rigid 'if I do this I will get this' [attitude] and, instead, what I really want to do is to teach them 'if I do this I could get any of these things.'"

Morgan continues, enunciating her teaching philosophy that

> "I don't want any students to regurgitate information. I want them to take all the information and synthesize it and make their own decisions… that's really the type of thinkers that I need in our society; [information] is not regurgitated if people that take everything, feel confident that they have the right amount of information to make an

> informed decision, and then recognize the limitations in whatever it is they're saying…. I need to do is recognize how much I know and don't know and therefore how strong our opinion really is. [W]e should not have an opinion that I are complete authority on it when all we've done is look at one new source for 30 minutes… [W]e have to recognize where our own limitations are. Now that's a lot harder to teach but if I can just unlock the students to get them to start synthesizing and forming their own unique opinions, instead of regurgitating information I think at the undergraduate level that would be a great start and then teaching them the components of recognizing their limitations."

Morgan later clarifies that this attitude is due to her own recognition of the value of "learning through team based experiences. From diverse perspectives in a way that always this challenging you to think beyond what you know" because in reflection those were the settings which prompted her own most impactful learning moments.

A.4.1 Resources for Learning

These resources may be provided, self-selected, or determined and located through the process of learning. A major reason for the necessity of independent learning is the process of learning how to find, use, determine, and leverage those resources. As Morgan put it, "a big part of [a design project] was… where to find the resources that they need and and how to ask the right questions." Here Morgan is emphasizing the importance of both knowing what information the engineer needs, as well as how to locate it and how to ask the specific questions of the resource to get the actual item of information necessary. Morgan further clarified that this can be actual research or knowing "who to go to for those types of questions and resources" because a resource is not just an item of information but can be a learned other.

Teaching Construct

PSF varied more in the descriptions of the phenomenon of teaching, however the common elements were surprising: an explicit consideration of the topics/concepts being taught, the core focus of student learning, the role and responsibility for motivation, and the specifics for the course. A primary component to PSF was the dichotomy experienced within teaching; while there is significant autonomy and flexibility within the classroom setting, there is notably less autonomy within the curricular content of a course and within the conceptual topics which a course covers. A visual of this construct is shown below in Figure 3.

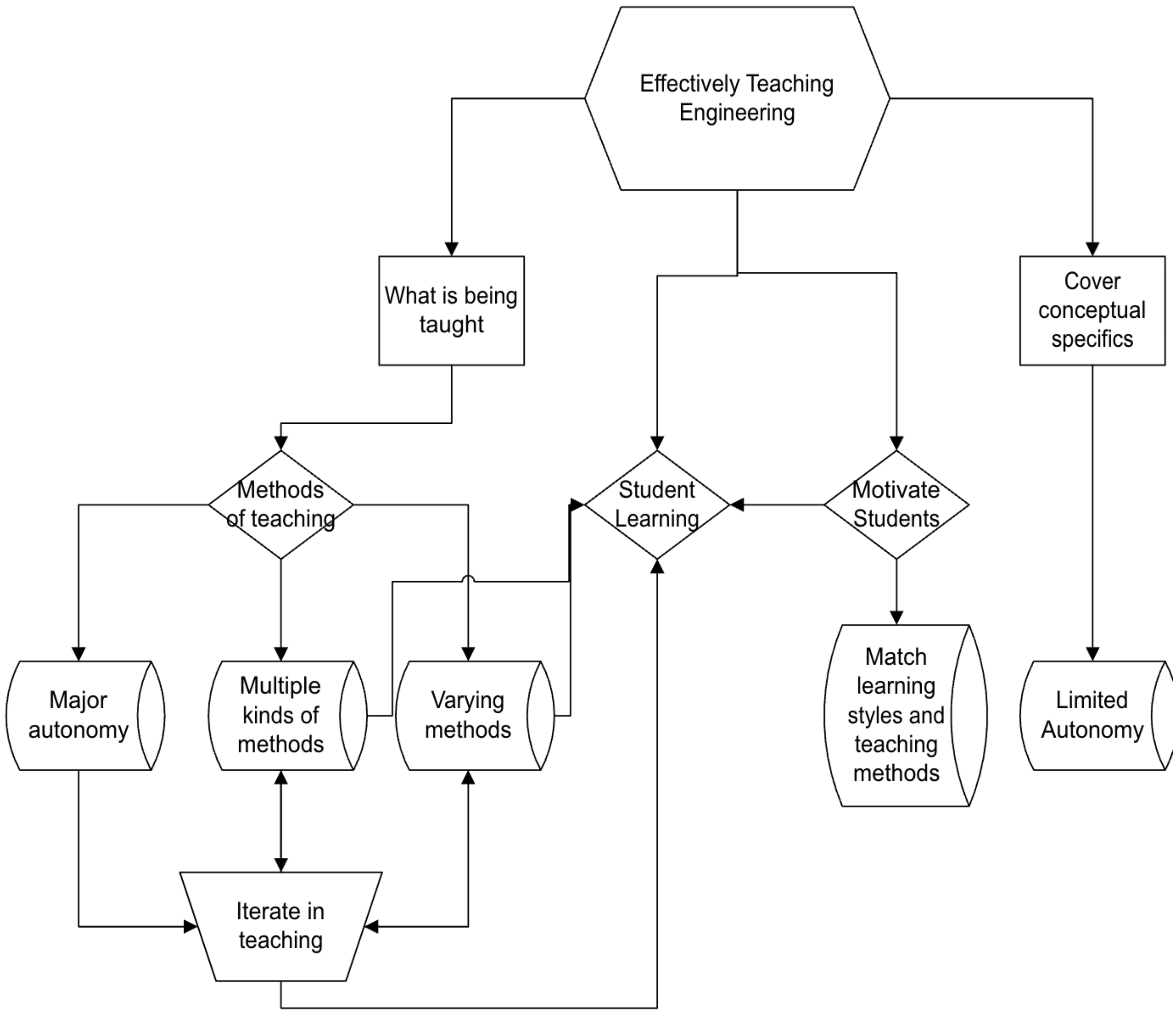


Figure 3: The Phenomenon of 'Effectively Teaching Engineering'

Strand 1: What is being taught (concepts and topics)

The first strand in this construct is how PSF consider the classroom and leverage the setting, layout, and opportunities therein. That is, a major consideration in the effective teaching of engineering is how teaching occurs. The mechanisms by which teaching is facilitated are a major consideration of our PSF. When asked to design their ideal class setting, very rarely did they discuss mechanics or layout or materials unless prompted; more often they detailed how they would leverage elements for their desired teaching methods. Janelle says that "I feel like the most important thing is that I want them to learn this one thing they can remember after taking this course" emphasizing that she wants the course to have something memorable for students, and that she will facilitate this through “this activity thing, then there are theories. They [do] project, and try to encourage them in different parts of my class, that's why one of the reasons why like I want different things than was in my class.” Here Janelle is emphasizing using a mix of methods to teach because she has that flexibility, contrasting that with “boring lectures” or long derivations because “like equations, the theories are useful.” However, she wants to make sure to be “avoiding that [experience] because I know if I throw like 2000 equations they may like stop thinking after the third or the fourth one.” Janelle also notes that it is “important to keep them involved in the class and then make connections like between theory and then example to keep having a connection, that would be how I design as a most areas and how to make them have a connection.”

B.1.1 Selection of Teaching Method(s)

It is the role of the instructor to decide what methods are leveraged to teach the foci of the course; what teaching strategies, what assessments, and what activities to utilize. The foci can be anything from a conceptual topic to a specific problem-solving paradigm to a habitual mindset to ethics, but the instructor has the responsibility to identify the focus and then decide what methods to use to facilitate this focus learning. Red has an interesting take on this, asserting that “teaching is like a strong dictatorship, but where you listen to the voices of the people you're ruling over. You have to like understand the needs of the people that you're controlling and you have to meet those needs.” Red later elaborates that “I need to have unconditional power in the classroom but at the same time, I have to use that to try to help foster their learning, that's my role.” So he believes he needs to have full control of the classroom environment so that he can accomplish his responsibility of facilitating the student’s learning.

B.1.2 Varying Methods

Within this consideration of methods is the understanding that these methods can (and likely should) vary depending on the day, the component of that focus, the students, and the contextual factors. The usage of varying methods allows for demonstrating to students the variety of approaches which can be used, but also different methods may be more effective at conveying different topics; rarely is this known until it is tried. Deepika notes that he would work to provide not just one way to learn because “I mean that people lean one way when learning content while other students lean another way. Some people might be reading, some people might be watching YouTube videos, although there was a seminar where a professor went in and he said the best way was to have active learning and give them supplementary learning videos. So I'm thinking maybe a lot of people were having kind of an interactive learning environment in the class and then later on these supplement.” Here Deepika is talking about shifting his methods between different learning experiences so that students can both learn and discover what works for them.

B.1.3 Multiple Methods

Furthermore, instructors should use multiple kinds of methods within teaching. This allows both for students to observe many different kinds of approaches, but also allows for more opportunities for a student to effectively engage with the material and facilitate a ‘click’ light bulb moment of comprehension. Morgan elaborates that she would teach by “providing as many mediums of stimulus of learning as possible [to allow] them to capture their learning style. I will want to employ as many of those in my assignments, and optional assignments or group work that I do, and also my lecturing methods of sorts, but then also making sure that whatever [methods] I didn't use and providing resources so that people know what to [look back on] if my methods didn't work for them that day." By this Morgan is emphasizing that students learn in many different ways so she would try to provide something for everyone, through the course of the semester.

B.1.4 Instructor's Major Autonomy in Methods

A major reason for this is because instructors have significant autonomy in the methods they utilize in their course; this is one of the hardest skills to learn and refine: to develop the pedagogical instincts, repertoire, and fluency with different techniques. However, as is noted in the literature for PST [18], [54], [55], [56], [57], this is never accomplished on the first try; common parlance holds that the third iteration of any innovation is the first time it is (likely) to resemble the form desired upon original implementation. As Janelle states, "if i'm teaching a class and then like half of them are sleeping in the class, I would think to try another way of teaching. Maybe just play some video I mean there are some interesting like videos that are related to engineering or to heat transfer even. yeah i'll try to change a way to to to draw their interest and then motivate [them]." Here Janelle is emphasizing a complete paradigm shift in her classroom teaching, demonstrating that she assumes she can overhaul the methods of delivery entirely.

B.1.4.1 Iterating Methods

As such, it is important for instructors to always keep in mind that they can iterate on their methods. These methods should vary and use multiple types, but should always be improving. Engineering is about iterations in search of a more effective/efficient solution, engineering teaching should be the same. Deepika clearly states that he works to " finding the best way to teach students and I'm hoping that, by the way my method for teaching evolves over time, but currently I think it's about teaching students and doing that in a way that's most efficient for students to learn the material. So I think that's my philosophy, it's been using that multi pronged approach that to communicate concepts and learn material, because I think that's the objective of going to school." Here Deepika is emphasizing the core goal of teaching engineering is to facilitate student learning, but he is doing that through constantly evolving methods.

Connection to B.2: Student Learning

The core goal of teaching (what makes it effective) is to ensure student learning, so the variations in methods used, as well as the responsibility to create an environment that students can learn within. The goal of any course or program is to develop learners as such any methods used should be focused on facilitating that student learning, should vary and use multiple methods, which are iterated upon to always improve the learning of students.

Strand 2: The core goal of student learning

As the role of the instructor is to facilitate student learning, effective teaching is evaluated by the student accomplishments. Our PSF demonstrated unusually strong, explicit, and unexpectedly strong student-centered learning beliefs. They understood the administrative difficulties, but described their idealized teaching in ways that are rare to see in engineering classrooms and dreamed of by researchers [58], [59], [60], [61], [62], [63], [64]. To our PSF, a significant portion of this role is the motivation of students. This is both a value and a necessity of learning; effective learning without motivation is rare, and motivation is reinforced by effective learning. As Deepika states, the role of the instructor is "to communicate concepts and learn material, because I think that's the objective of going to school." Janelle says along similar lines that she wants students to "remember one thing from this course" emphasizing the role of deep learning over casual recall for repetition. PSF further emphasized that everything they did in the classroom was focused on student learning, because as Deepika states "if they're not motivated and if they don't understand 'why am I taking this course, why is this relevant to my future career,'then they're not going to learn, it's going to be a waste of time for the both of us." This is emphasizing that the time spent in the classroom and course is 'a waste' if the student doesn't learn.

Strand 3: Motivation for students [and connection to Strand 2]

Effective teaching should consider what can serve to motivate students. As previously mentioned, motivation reinforces resolve, focuses students on the learning, and is difficult to get learning moments without. This motivation is ideally intrinsic and student-generated, but the instructor can assist in this. Or, in lieu of this, extrinsic motivation (through grades, mandatory participation, or other strategies) can attempt to persuade students. Red stands apart from his peers in this regard. Red states that "I might give encouragement, I might give advice. But I don't think my goal would ever be to motivate students; I think if you're in college and you're not motivated you probably shouldn't be in college like if you're not motivated to do what you're doing." He contrasts that with public schooling "I think when you're in just school, motivation is good. And I think positive and negative are good in those, but I think in college it's different because you're an adult and you have that base level of education and I think that if you don't have the motivation, while you're in college, you probably shouldn't be there." Here Red is saying that while grades and reminders can assist students, he wouldn't seek to motivate them, because if they don't have a source of internal motivation then the program is probably not a good fit for them. Janelle, in contrast, emphasizes trying different teaching methods to "draw their interest and then motivate them." Both of these statements recognize that motivation is intrinsic to the student; though the instructor can assist, the student has to be the one who is motivated.

B.3.1 Motivate by Matching Learning and Teaching Styles

One of the major ways this is accomplished or facilitated from the instructor side is by matching learning styles (of students) and methods of teaching. As different methods are differently effective for different students, leveraging multiple methods to try and match learning styles is emphasized by our PSF. Though the entire premise of learning styles is contested and more of a buzzword in modern education research, the intention is reasonable. You can't know what every student needs in a classroom of more than perhaps 30, but knowing the likely trends, probable to be effective methods, and majority preferences can help an instructor tailor their methods so that 'every student gets something'. Morgan captures this, asserting that she would incorporate "diverse set of ways to learn the material and then assessing that material with ways to self correct. that's a lot of work for the teacher, but I do believe that that's the best way to be inclusive, for all learning styles." She continues that

> "I really learned by association, but someone else might learn better by memorization. And I personally believe that association and understanding how something works allows you to apply knowledge from one domain to another better than memorization. But for some people's brains that just doesn't work, so another way is somebody might learn really well or reading the textbook another person might learn really well by doing. Khan academy videos instead or just paying attention and lecture one person might do really well but taking notes another person just needs to watch it happen once and they've got it down. And so, providing as many mediums of stimulus of learning as possible allows them to capture their learning style."

Here Morgan is asserting that the instructor is responsible but also has a beneficial tool in seeking to match student learning styles with their teaching actions or approaches.

Strand 4: What is being taught in the course specifically

In direct contrast to the methods of teaching, the role of any course is to teach some thing(s). These can be conceptual, procedural, methodological, solution paradigms, or attitudes. Not unique to engineering, but of significant emphasis, is the need of each course to cover specific concepts. Red explains that "you don't really have control over [what is being taught] so the teachers have control; there's actually a list and then a sub list. The main list is what the teacher was told they have to teach, so that's like a necessity, like you have to get through that list, the sub list is more with the teacher thinks is necessary to like fill in the gaps." Red here is emphasizing that each course is part of a distinct curriculum with prerequisite and subsequent courses. Because of this the instructor for any course has "no flexibility in terms of what they're going to [teach] for the class."

B.4.1 Instructor has Limited Autonomy

PSF noted specifically that this is one of the areas where they have significantly more limited autonomy. This can be due to the position of the course in the curricular sequence, the parallel courses, and the highly integrated nature of engineering concepts. Deepika states that what a teacher covers in a course "depends on the university's rules that they might have. They might say you have to teach entire material from like Chapter one chapter 10 to other students… So hopefully whichever university I go to I'll have the freedom to be able to decide, you know how I'm going to teach the students, what I'm going to teach the students." Deepika here asserts a belief that the instructor has little to no flexibility in what they teach in a course, that it is mandated by the university at large. Red believes similarly, but states that the constraints come from the departmental level.

Connecting the two Constructs

Though rudimentary, this sub-group of PSF were the only participants to draw connections between the two phenomena; the ways they considered learning influenced the ways they described teaching, which was not the case with the rest of the interview data.

Table 2: Summary of Construct Elements

Learning	Teaching
Self-Directed Process	What is being taught
Practice is required	Cover specific concepts
Independently	Limited autonomy
Resources	Motivate students
Learning to get unstuck	Match learning and teaching styles
Applications	Student learning
Relate topics	Methods of teaching
Relate to people	Multiple methods
	Varying methods
	Major autonomy
	Iterations on methods

C.1 Self-Directed Learning and (Personal) Motivation

Students need to be motivated for learning BECAUSE it is independently and self-directed. The teacher tries to motivate and facilitate, but the student does the learning. Learning must be facilitated by the student independently through a self-directed process, which makes sense given that much of chemical engineering is learning procedures, solution methodologies or paradigms, and is highly context dependent.

C.2 Practice in Learning through Applications

Teaching course contents to our PSF was described through the usage of applications and opportunities for students to practice. That is, since PSF themselves learn better with an application, they describe providing one for students, as a way to practice using the content being learned in a specific, function-oriented setting.

C.3 Teaching Methods Chosen to Facilitate Student Learning

The methods of teaching differ and vary in order to help students learn. To effectively teach is to help students learn; within learning engineering this requires conceptual growth, attitudinal shifts, and perspective adjustments. These include from our PSF :

1. When and how to use resources
2. To get unstuck in problem solving
3. Interactionally relating topics (to each other and with peers).

As such, there are connections between strand 2 of teaching and all the strands of learning engineering. This makes sense, because as Morgan so eloquently states, "a major part of learning engineering…. is learning how to learn."

Implications and Future Work

This is foundational research and not directly connected to any external innovations as of yet. However, PSF currently demonstrate significantly more advanced pedagogical instincts than would be expected. PSF were surprisingly eloquent on what constitutes learning, demonstrating far more nuanced epistemological beliefs than anticipated. In fact, their beliefs are more analogous to tenured faculty [41], [65], [66] than their undergraduate peers [65], [67], [68], [69], [70], [71]. These beliefs are also indicative of engineering norms of the field, such as lifelong learning and a value on solution oriented procedures.

The clear connection made by these participants is not echoed in the remainder of the dataset, which leads to the question: why not? Why aren't these obviously connected phenomena more clearly and directly connected for engineering PSF? And what happens to these instincts? Why are they not nurtured into pedagogical competencies?

Regardless, this aligns with the findings from early faculty; many more faculty are student-centered in their beliefs, merely do not have the time, resources, space, or support to implement these skills and thus default to the teacher-centered, if less effective, methods like lectures [8], [59], [61], [62], [63], [64].

This foundational literature has established the beliefs of PSF around learning and teaching engineering, however a more careful analysis will be required to align these beliefs with those of PSTs for development of a preparatory program. The findings here do provide some useful avenues of engagement and improvement, however, most notably for PSF themselves or mentors.

For Educators

I encourage other educators to conceptualize and write down or verbalize their teaching-learning connections. Answers to such questions can be enlightening and provide numerous areas for engagement. Further, the chemical engineering education community is at the forefront of ASEE disciplinary fields in terms of student-centeredness, wellbeing, and innovative teaching methods. Often early-career faculty cite a lack of support for implementing the methods they want to, and a community of peer-mentors can provide this structure. Faculty development is a well established field, and highly effective. Still, consider your own practices: what are you hoping to convey to students? How do you do that? Is it effective? How do you know?

For Mentors

Consider how you are providing PSF opportunities to consider their own learning and teaching. PST literature says that scaffolded and mentored practice is the most effective method for facilitating pedagogical excellence; provide your students with these opportunities alongside feedback. Further, consider how you can present your mentees with a more detailed awareness of how teaching is effectively constructed; results from this work indicate that PSF have a constrained view of the autonomy of an instructor, particularly in terms of the content selection which may not be consistently true.

For other Students

Consider your own career goals; ask for opportunities to engage in the pedagogical complexity that is teaching. Find an opportunity to be an apprentice instructor [72]. There are numerous quality but isolated examples of programs that developed more effective pedagogical preparation than typical TA trainings; refer to one of these for inspiration on developing skills to be just as prepared for teaching as the PhD program makes one for research [11], [14], [47], [49], [73], [74], [75].

Conclusion

This work presents exciting new opportunities for research. More clearly connecting or disentangling why and how PSF epistemological beliefs and teaching practices/intentions are related is one such avenue; another avenue is expanding on the disciplinary focus of this work. Are chemical engineering PSF more distinct and explicit in their beliefs? Or was this a result of lucky recruitment? Finally, how do I use this information, as a field, in thinking about preparing our future faculty to teach?

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