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Identifying Signature Pedagogies in a Multidisciplinary Engineering Program

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Identifying Signature Pedagogies in a Multi-Disciplinary Engineering Program

Abstract

This work-in-progress is part of a larger research and evaluation project designed to realign program goals with teaching and learning practices in a large, multi-disciplinary engineering science program at a research-oriented Canadian university. The ultimate goal of this work is to define and develop a set of key teaching and learning practices that reflect program goals and future directions. Drawing from Shulman's work on signature pedagogies, which are defined as the modes of teaching and learning that are unique to a particular discipline or profession, this paper presents the qualitative analysis of a series of semi-structured interviews with program faculty and alumni. Teaching for depth and breadth were found to differentiate teaching in engineering science compared to other engineering disciplines. However, some tensions were identified between instructors and alumni in the use of foundational theories and understanding the significance of it to real world practice. For example, while instructors linked a first-principles approach to innovation, this link was not reported by alumni. This study highlights the tensions and challenges in the process of framing and defining the signature pedagogy for a multidisciplinary program, and sets the stage for further work on improving coherence between program goals, practices and outcomes.

Introduction

Although engineering programs are subject to regular reviews due to accreditation and quality assurance requirements, it is less common that engineering programs take a step back and examine the bigger questions about program goals and teaching practices. As faculty and educational researchers within a multi-disciplinary engineering program, we observed a misalignment between the program's historical roots, its pedagogy, and its recent directions. Add to this a complex program structure, a changing post-graduate landscape and new degree level and accreditation requirements, and a need was identified to understand current views and practices on curriculum and teaching, in service of better program coherence. We took a decidedly academic approach to this process; taking advantage of relevant literature in higher education and curriculum studies, and applying qualitative methodology to our process.

The idea of striving for coherence is a key goal in this work. Coherence has been defined by Tatto [1, p. 176] as "shared understandings among faculty and in the manner in which opportunities to learn have been arranged to achieve a common goal." Hammerness [2] drew upon this definition and defined conceptual and structural coherence, while acknowledging that the borders between these constructs often become indistinct. Conceptual coherence refers to the connections between content within a program, and the relationship between foundational ideas and classroom practice. Structural coherence refers to the structural connections between specific program components, and focuses on the structure of the program and its organization. An example of the latter is sequential building of the courses [2], enabling a coherent organization of the subject matter [3], [4]. In a slightly different framing of coherence, Sullanamma et al [5] described three complementary components: consistency of the intended direction, an integrative approach to teaching and learning, and alignment between objectives, content and assessment.

With respect to professional programs like engineering, it has been noted that it is particularly important that theory and practice are linked; a common critique of professional education is that the theoretical content is often inadequate as a basis for professional practice [6], and this serves as an extension of coherence in the professional context. While there is no measuring stick for coherence in a program, we see it as a value to strive for, and the concept provides a theoretical foundation for the goals of our work.

In previous work [7], we examined Engineering Science as an academic discipline, using higher education literature on the construction of academic disciplines [8], [9], [10], [11], [12]. A multi-institutional workshop, which included representatives from various Engineering Science programs from around the world, elicited a number of key themes: a strong focus on fundamentals and first principles; a multi or interdisciplinary perspective; a focus on non-traditional and rapidly developing subdisciplines; unique approaches to problem solving and design; and a diversity of views on the relationship between science and engineering within Engineering Science. This initial work on defining the characteristics of Engineering Science as a “discipline” encouraged us to take a deeper focus on the specific teaching and learning practices of Engineering Science, to understand how these characteristics are enacted in the program. To do this, we adapted the concept of Signature Pedagogies [13] to further understand and learn about the pedagogical choices employed in Engineering Science, from the perspective of instructors and program alumni. This paper documents the process of interviewing faculty and program alumni, and the analysis of qualitative data from the interviews. Identifying these signature pedagogies will help us in our ultimate goal of better coherence between program goals and practices; and will allow us to build appropriate curricular and instructional strategies.

Program Context

The program under study is designed, according to program literature, to provide students with an enriched academic experience, utilizing a more rigorous focus on underlying math and science, also described as taking a “first principles” approach. The program has a rich historical context, having started as the Engineering Physics Program, but over time expanded to include a range of sub-disciplines (or “Majors”) as an “Engineering Science” program. The program is structured in a 2+2 model; students participate in a 2-year foundation curriculum that includes a range of courses across engineering disciplines, the sciences, mathematics, design and complementary studies. This is followed by a 2-year specialization curriculum, during which students take one of 8 (at publication time) Majors. Curriculum integration and multidisciplinary thinking are emphasized as program goals.

The Majors have a focus, although not exclusively, on emerging and rapidly developing areas of specialization within engineering. Some of the Majors that are offered within the Engineering Science program are also offered in other institutions/programs (like Aerospace Engineering, Biomedical Engineering and Electrical & Computer Engineering) while other Majors are unique or almost unique to the program (like Engineering Mathematics, Statistics and Finance, and the new Machine Intelligence Major). A unique characteristic of the program is that given the structure of the program, its offered Majors can change relatively quickly in response to industry and research needs, which makes the program quite agile in responding to global trends in technological development.

The program has only a few full-time teaching faculty members; most of the teaching staff and teaching assistants are drawn from other departments and Faculties at the university. This allows for flexibility, but also proves a challenge with respect to emphasizing a set of common goals and practices over time. There is a strong emphasis on research experience in the program, with many students finding summer research placements and a program-wide requirement to do an independent thesis in the final year. Finally, approximately 50% of program graduates pursue graduate studies with the remaining 50% pursuing industry, professional school and entrepreneurship.

Background Literature and Theoretical Framework

In this work, we draw from Shulman's work on Signature Pedagogies [13], which defines them as the modes of teaching and learning that are unique to a particular discipline or profession [13] and through which "future practitioners are educated for their new professions" [13, p. 52]. Signature Pedagogies define the functions of expertise in a field, the locus of authority and the privileges of rank and standing [13].

Shulman describes Signature Pedagogies using three "structural dimensions": (1) Surface Structure, or the concrete operational acts; (2) Deep Structure, or the assumptions and decision-making that takes place in designing educational experiences; and (3) Implicit Structure, also known as the 'hidden curriculum', which describes the beliefs about necessary moral characteristics, values and dispositions, and appropriate attitudes and behavior. Signature Pedagogies demonstrate to students what is accepted as credible knowledge, practice and culture in their future profession. Tingerthal [14] suggests that there is no consensus on the Signature Pedagogy of engineering. In this work, we attempt to apply the concept of Signature Pedagogies to a multidisciplinary Engineering Science program that, despite its engagement with a multitude of more traditional disciplines, holds its own philosophy of teaching and learning.

The concept of signature pedagogies has been used in various disciplines such as teacher education [15], e-learning in higher education [16] and sustainable food systems [17]. Signature pedagogies, regardless of their discipline or field of application, ensures that the thought processes of the students as professionals-in-training are made visible. These signature pedagogies must adapt to changing professional requirements or new teaching methods [18].

In examining Signature Pedagogies, we wanted to understand how instructor and alumni perceptions might differ. Although we will also be using student surveys and focus groups in this project, we decided to start with program alumni as we feel they are uniquely well-positioned to discuss their learning experience in the program with a juxtaposition to their career and graduate school experience, and speak to the relevance of the program's teaching and learning approaches beyond the program itself. Comparing faculty perceptions with alumni perceptions is key in distinguishing between the intended and the enacted curriculum [19], [20].

To engage in this research, we sought previous research on comparing instructor and alumni perspectives. Interestingly, despite an extensive literature review, the majority of studies focus on one of either engineering faculty perceptions OR engineering alumni perceptions; comparative studies tend to focus on perceptions of faculty or undergraduate students. One example of a study comparing faculty and alumni is a study by Stowe and Huh [21] on life-long learning, which demonstrated a link between instructor approaches and alumni perceptions of the life-long learning focus in the program.

Methods

As a first step in working towards an understanding of these signature pedagogies, we have conducted a series of semi-structured interviews with a group of program instructors, who have provided a rich description of how they position the program in the larger engineering landscape, how they describe the learners in the program, and how they construct learning experiences in their courses. We have also interviewed program alumni, who described how they see the program positioned in the larger engineering landscape, and have been asked to reflect back on their own learning experiences in the program and how these experiences impacted their post-graduate careers.

Participant Selection

Participants in this study included faculty and alumni of the program. Purposeful sampling was employed, to maximize the range of perspectives examined. This is a work in progress study and thus interviews, and their analysis, are still in progress. This paper is based on the perceptions of 10 faculty members and 14 alumni. The roles of these faculty members varied; all had served as instructors; some had also served as Program Chair, Associate Chair or Major Chair. The alumni graduation year ranged from 1971 to 2019. These alumni are currently participating in diverse careers, including entrepreneurship, as employees of engineering firms, academia, graduate studies, business analysis and management consulting, pharmaceutical science and law.

Data Collection and Analysis

Data was collected through semi-structured interviews with faculty members and alumni. The study protocol was approved by the appropriate university research ethics board. The interviews were conducted on Zoom, due in part to the Covid-19 Pandemic, and were subsequently transcribed by the research team. The faculty interviews were analyzed using open coding; codes were developed based on participant responses. Thematic analysis was then completed to form themes. The themes were then categorized using the three categories of signature pedagogies: surface, deep and implicit. The alumni interviews were coded using the themes and codes from the faculty responses, using these as a lens to look for supporting evidence or contradictions in the alumni perceptions.

Results and Discussion

Instructor Interviews

Through a thematic analysis of the instructor interviews, elements of a “deep structure”, which includes the assumptions and decision-making that takes place in designing educational experiences, emerged. The "surface structure", or the concrete operational acts of teaching, was not of a significant focus; this was to be expected, as our focus was on understanding the underlying structures that influence instructor action rather than the concrete actions themselves. An "implicit structure", which according so Shulman focuses on moral characteristics, values and dispositions (and subsequent attitudes and behavior) did not really emerge from the interviews; we will speculate on a reason for this below. Each of the key themes that emerged are explored below.

1. Deep Structure: Teaching for Depth

The most common theme within deep structure was teaching for depth, which included teaching "*fundamental math and science*", "*theoretical foundations of model*", "*fundamental descriptions and derivations*", "*limitations of the equations*", and spending "*a fair amount of time on proofs*". According to the instructors, the know-how requires answering the question of "why" and learning "how you get there" rather than simply using the equation. For example, one of the program instructors shared the following about a "teaching for depth" approach:

"*We derive the equations. We show them where they come from. We show them what the limitations of those equations are and limitations for the physical models […] We are showing them what that is the answer and how to understand whether that's the right answer*."

Another instructor made a comparison with other engineering disciplines:

"*Where we might teach a model for argument to the (other programs), I think for an engineering science class, you might go into the theoretical foundations of that model, right? So instead of just saying, "here's the model", you might go back into the history and also the kind of rationale for that model, and you would do that a little bit more deeply, whereas for the (other programs), I will introduce the model, here's some examples of applying the model*."

Instructors mentioned that they employ this approach because engineering science students have a desire and appreciation for learning the fundamental math and science, and Engineering science students welcome "*a deeper understanding*", as they are "*top students*".

Innovation, at the most rudimentary level, is about doing something different – an idea, product, device or other novelty. It is the process of generating and combining ideas, in the service of a relationship between present accomplishments and past experiences to solve a future problem [22]. The majority of instructors indicated that the engineering science graduates are expected to become innovators, and that the fundamental math and science would help students to be "*better prepared to create new knowledge to work in novel areas to synthesize disparate disciplines*," and "*makes them equipped better for rapidly changing innovation and technology landscapes, because essentially no matter what the future brings the fundamentals never change*".

Looking to the literature, Boh et al. [23] conducted a research study on inventors' breadth and depth of expertise influencing innovation at a company known for sustained innovation. Their results indicated that depth of inventor expertise results in the generation of technically influential inventions, and that these specialists are also competent in problem solving and accurate analysis of a problem. They are also able to understand fundamental principles of a problem, which helps them to make recombination of existing components. Previous research also indicated that depth of expertise helps individuals to interpret the principles and abstractions, which might otherwise not be obvious from the surface presentation of the problem [24]. The instructors' belief that depth is linked to innovation seems to have some grounding in the literature.

Some of these specific innovation skills also resonated with the instructors' responses when discussing the expected skills of graduates as a result of teaching for depth. For example, an instructor mentioned that graduates should be able "*to think about a problem, provide a solution, coming back to you know, a fundamental understanding of the science behind the engineering*", while one of the major chairs mentioned students should be able "to *examine their way of analyzing the problem [..] and figure out where the limitations are, what is going to work well, when is it not going to work well, when do they need to maybe think about different ways of doing things*". There is some evidence here that understanding the fundamentals and foundations could help students become effective problem solvers, leading to innovative practices.

2. Deep Structure: Teaching for Breadth

Although not as common as teaching for depth, teaching for breadth also emerged as a theme from the instructor interviews. In this case, breadth refers to the importance of students gaining and using knowledge across various disciplines, and getting "*some background in chemistry, biology and physics*" and also in "*fluid mechanics, thermodynamics electromagnetism and structures*".

Teaching for breadth was also mentioned as a contributing factor toward the development of innovation skills; a former Chair and instructor noted "*The fact that they've got the science there, so to be able to draw ideas maybe that they've seen in biology or chemistry or physics, whatever to bring those to bear on solving a problem or looking for novel solutions to problem*". Further, he specifically suggested that multi-disciplinary capstones would be a useful opportunity for students to tackle a problem across disciplines as it could mimic multi and cross disciplinary R&D:

"*it's like combining domain specific experts from different fields and making a team and then because of the shared first two years they have a language for communicating with each other effectively and working together as a team, but they also have their domain specific expertise that they bring to the table*".

Placing value on the multidisciplinary perspectives was echoed by other instructors, for example:

"I really think the right role for multidisciplinary character in the curriculum is in the first couple of years where, again, they're building their breadth right and so that you know that even if you end up taking the ECE major you've taken more you know, chemistry maybe than a typical electrical computer engineer, that's, that's one way that you give them an advantage and being able to conduct multidisciplinary R&D throughout their career"

Boh et al. [23] further argue that breadth of inventor expertise is related to the generation of many inventions. Though these inventions may not be the most technically influential, they are still important as deep expertise alone can pose limitations, such as difficulty in integrating innovation from other fields [23]. This is similar to a concept called design fixation, a barrier to innovation which produces an unintentional adherence to a set of ideas or concepts limiting the output of conceptual design [25]. Engineers may become "fixated" on existing standard solutions or variants of existing solutions; this can be triggered by limited knowledge of related fields of study, cognitive blocks, difficulty in identifying new applications, and familiarity with known solutions [26].

Having breadth of knowledge, on the other hand, can encourage individuals to integrate multiple domain components [27], and to look at a problem using different lenses [28]. It has been found that knowledge breadth tends to align with a greater exposure to diverse perspectives, which increase one's ability to recombine knowledge [29], [30], [31], [32]. Spanning different knowledge domains helps individuals see problems from a different perspective, increasing the likelihood they will identify and consider new linkages between domains and schemas [32], [33], [34]. Moreover, diverse knowledge can stimulate individuals to reconfigure existing knowledge schemas and domains, loosening up their internal structure and increasing flexibility [35], [36].

One instructor noted that exposure to various subjects can train students "*specifically well for interdisciplinary areas where knowledge of various subjects needs to be brought together*" and are then able to "*draw on sort of a broader foundation*". Furthermore, an instructor mentioned that providing engineering science students with all the extra background should "*let them take the next step in something as opposed to just design things the way they used to be designed*" and thus, perhaps overcoming the design fixation.

3. Deep Structure: Approach to Design

Building on the relationship between breadth, depth and design, instructors mentioned that design prepares students "*for some of the practical realities of being an engineer*" and provides an opportunity to "*use a knowledge of math and science technical knowledge to create some new product*" while experiencing "*open-ended questions*". Design was also mentioned to be a vehicle to enhance other skills such as teamwork, communication skills, persistence and planning a large project in stages. Instructors who teach design were explicitly asked to comment on the role of design in engineering science vs. in other, more traditional engineering programs. No clear difference was observed in the responses. In response to role of design in engineering generally, one of the instructors mentioned:

"*Engineering involves the development of a product or something where design is going to be needed. So understanding something about that design process, even if you're going to end up in R&D is extremely important […] You got to understand that design is a bit of an open-ended problem […] It's a complicated problem that requires a very windy path to go from start to finish.*"

Being exposed to open-ended problems, however, was also mentioned in this instructor's response when commenting on the role of design in engineering science specifically. Another design instructor spoke about the fundamental role of design in engineering in helping students use their knowledge to create something:

"*Design is the core of engineering. So the purpose of an engineer is to use a knowledge of math and science technical knowledge to create some new product or service that someone is willing to buy so that adds value to society.*"

When this instructor was asked specifically about the role of design in engineering science, no clear distinction was made:

"*If you believe that engineering science is an engineering program, then, I think talking about engineering design is absolutely fundamental and again I talked earlier about a shift from the idea that we're creating academics […] to (creating) people that may be doing a lot more entrepreneurial work […] The are all very entrepreneurial now. They are very design focused*."

"A*ppreciating the messiness*", "*understanding that there are multiple approaches to design*" and "*conscious informed decision making*" to resolve a gap, or a problem were among roles of design in engineering curricula mentioned by an instructor with major focus on design teaching in the program. When the instructor was asked to describe the role of design in engineering science, she noted the following:

"*I think it's the space where the relationships between what they're learning in the other courses and the world as it is starts to come together. Where we can start to show possible application […] You're not experiencing calculus or you know programming in isolation. You're now starting to see the possible places where you can take that and plug it in and apply it to doing other things*."

There is a slight distinction here in that the instructor is noting the importance of applying theory to the real world; and bringing a practical bent to a highly theoretical focus. This instructor went on to mention that when teaching design to engineering science students, she goes much deeper in helping students to discover their own design process:

"*I will go much deeper into discovering who you are with eng sci students […] which I think is quite different than how I teach design in (other engineering programs), which is much more about following the tried and true. And partly that's a scale problem, like engineering science is my small class. But I will push them very much to figure out their own process. And from a perspective of there is no correct answer, there are answers that are better, there are answers that are worse, and you need to be able to argue and defend each of them. Whereas in the (other engineering programs), I will teach, this is the process, there are other processes, this is just one of them, so you know, not fully kind of convergent. But we're going to follow this process."*

A possible theme emerges here in that even in the highly practical space of engineering design, students in the program are encouraged to work from (their own) first principles and adapt the design approach to the context where necessary.

4. The Absence of Implicit Structure

Shulman's Implicit Structure focuses on moral characteristics, values and dispositions, and the subsequent attitudes and behaviors informed by these characteristics, values and dispositions. Shulman acknowledged the importance of these entities in professional education (and the professions more broadly). In our work so far, we noted an absence of these implicit structures in the instructor discussions of the program, despite the importance of ethics, equity and the impact of engineering on society and the environment – and the notion of professionalism – all of which relate to the concept of implicit structure.

One of the interview questions asked instructors specifically how ethics/equity and impact of engineering on society and the environment should be taught in Engineering Science. Responses varied to some degree between instructors. When talking about ethics and equity, a few participants mentioned that they expect the students to be ethical, and that it starts with faculty members as students "*do model themselves to some degree*" on their instructors. The Engineering and Society course, a required course in second year of the program, was mentioned by many as the course aiming to teach the moral aspects of engineering such as ethics/equity and impact of engineering on society and environment, but these competencies did not appear to be present in the pedagogy or practice of the instructors interviewed. The majority of the instructors did, however, mention that design courses are the best place to include a discussion of the implicit structure and they, in the perspective of one instructor, "*are the right vehicles for further cementing those notations*". For example, one instructor mentioned:

"*So if the idea of ethics and equity could be integrated, you know, I think (ESC)203 is a really valuable course because it brings all those issues and makes it the central part of that course. But in third and fourth year, then it needs to be part of their technical curriculum, you know, and capstones or projects are kind of the obvious placed to do that.*"

A few other instructors also mentioned that these items should be addressed by "experts" and not the engineering faculty, which is worth investigating further. For example, a course instructor indicated:

"*I mean maybe it shouldn't be taught by engineers. I mean there's people who do this for a living, right? And there is philosophy department I assume at [name of the university]. And again, speaking about multidisciplinary I think that would be a good opportunity to bring in some people from the humanities and give the students exposure to those people*"

Alumni Interviews

Through a thematic analysis of the alumni interviews, and a comparison with the instructor interviews, we were able to elicit some interesting agreements and tensions between the perception of the instructors with those of the alumni. In some cases, the alumni have agreement with the instructors on the signature pedagogies, but perceive their effectiveness and utility in a myriad of ways.

1. Deep Structure: Teaching for Depth

Teaching for depth was also acknowledged by alumni as a key approach in engineering science, and they used similar terms to instructors to describe this, such as "*building blocks of formulas*", "*solid foundation of theories*", and "*peeling back the layers of abstraction.*" However, there were mixed opinions with respect to alumni perceptions in terms of effectiveness of learning fundamental knowledge.

Some alumni saw this approach as an advantage with respect to the mindset developed rather than the content learned; in fact, a few alumni mentioned that they have either forgotten the content related to foundational theories or they rarely use them as they are not practical in industry. However, the approach was mentioned as a skill still being used to solve problems. A common theme across many alumni was that they use first principle approaches to learn in new domains, and that understanding the fundamentals helps with acquiring new knowledge. For example, an alumnus working in the AI field indicated:

"E*ven now I feel very uncomfortable with anything, any topic if I can't go back to the first principles […] if I can't get the basics, I just feel lost*".

while another alumnus working at a large technology company commented:

"b*eing able to learn new things and learn things kind of from first principles or at least from the level of depth that is necessary in order to do something effectively, I would say is useful*".

The "*deep dive*" was also mentioned as a differentiating skill, as you "*know something a lot better than most people in the market and then you can definitely make a lot of money that way because you're really getting paid for your specialist knowledge*". An alumnus working for an energy company echoed the competitive advantage offered by this approaching, noting "*In engineering you have to somewhat learn on the job so what's really important more so is the fundamentals […] whereas other people would have to start from the basics on the job and then learn from there*".

However, other alumni indicated that the deep understanding of fundamentals was not achieved (i.e., in terms of content), even if they indicated they use the approach. For example, one graduate student noted:

"*I feel like I never really achieved it (deep understanding of the underlying theory). It was like one of these like, elusive and lofty ambitions of the program*".

Another alumnus spoke to the issue that fundamental understanding was lacking due to the pace of content presented, stating "*I didn't learn too many things in depth because it was so much and so fast […], It was like always hanging on with my fingertips.*" A few other alumni mentioned that even though they learned the deep fundamentals, there was a lack of understanding the significant of mathematical foundation in the real world, lack of understanding the application or lack of integrating it with hands-on experience. One noted "*it's a far distance between the integrals of the math and the calculus you study to what do you actually end up doing in majority of the cases*" and that the fundamentals are not "*as practical when you get into the industry*".

Learning from first principles is a key priority in engineering science. However, given that the alumni who found utility in this approach indicated that it's about the mindset/approach rather than the content itself, we might ask whether there is a more effective way of teaching this skill. This will be further investigated in future steps of the research project.

While innovation and the generation of innovators was a common theme in instructors' perspectives, connected to "teaching for depth", it was not widely observed as a skill gained from engineering science in alumni perspectives. Only two alumni shared this perspective. One alumnus, an entrepreneur, indicated that while graduates of other engineering disciplines can improve things which are already established, "*they're not sitting there thinking of (a) crazy next idea that makes those technologies obsolete, and well, that's where the engineering science level of thinking comes in*". Another alumnus, who is a Faculty member at another university, noted:

"*If you study civil engineering, you really want to understand […]when you graduate you want to be able to, you know, after you go work for your first company, second company eventually want to be able to design a bridge or a structure or a building or a tunnel or what have you. Whereas I think engineering science should be more about, we don't know yet what those things are going to be designed. We don't know what those systems will be because they're going to be created, they're going to be new. But what is clear is that they're going to rely on fundamentals, because that is how the design process is done.*"

2. Deep Structure: Teaching for Breadth

In contrast to the mixed reports on teaching for depth, teaching for breadth was observed as a positive outcome for the majority of alumni interviewed. For example, one alumnus mentioned that the breadth of knowledge in engineering science has provided "*metaphors to draw on when I'm trying to understand a new domain*", while another mentioned that the breadth of knowledge "*broaden(s) your scope of knowledge*" and gives cross disciplinary perspectives which is useful as "*somebody needs to be the person that bridges all these different things together into something useful*". The majority of alumni interviewed connected breadth of knowledge to multidisciplinary skills as the result of taking various courses. One alumnus who graduated from the Energy Systems Major made this connection:

"For example, like if I went into electrical engineering, I wouldn't generally understand how the generator works in terms of how the fuel was burnt, and like the heat transfer side of things, and so I think the fact that we're able to take courses from all of the different disciplines was really, really useful, especially for something like energy, because the field is so interconnected and multidisciplinary"

Another alumnus, the graduate student, had a different perspective when it came to multidisciplinarity and teaching for breadth. He defined it as "*being comfortable or familiar to switch between almost like, a different like languages or mental models or like frames or assumptions of different disciplines*" which he noted was "*almost entirely implicit*" in engineering science curricula and "*was not deeply woven into practice*". This view is interesting and worth further investigation as more emphasis on explicitly using and integrating various subjects during the program might be needed to enhance multidisciplinary.

Teaching for depth and breadth was also mentioned by a few instructors to lead to "*fearlessness*" or "*perseverance*" from graduates so that they "*are not afraid to have to step into a new field, start from scratch, learn the fundamentals and apply them*." This outcome was also shared by many alumni. For example, one alumnus mentioned that after completing engineering science "*there is nothing that someone can throw at me, that I cannot do. I will preserve. I will survive. I will figure it out*". Similarly, another person indicated that pursuing MBA after engineering science "*wasn't intimidating at all […]. I can easily do this. I survived engineering science, I can survive this program*". Being resilient learners who invest significant effort in learning and persist in the face of challenges are among the competencies we hope instructors will encourage in the students. Based on our interviews, it appears that the engineering science program may act as an intervention in building resilience. One alumnus specifically mentioned that engineering science "*is the one place that taught me that I can't actually know everything and I'm going to fail at stuff.*"

In addition to becoming resilient learners, both faculty and alumni mentioned developing metacognition skills, or knowledge and regulation of cognition [37], [38] as a result of teaching/learning for depth and breadth. Specifically, a few instructors indicated that if necessary, engineering science graduates are equipped to learn new material even if they don't have the background. This was echoed by a few alumni, with one noting that "*you have the confidence to kind of figure things out yourself and kind of systematically learn*", and that engineering science provided a good broad spectrum of knowledge and thus "*I have learned how to learn. I can potentially, if I want to become an electrical engineer in the current industry, I know where to go where to start and learn stuff*". One alumnus pursued molecular pharmacology after graduating from engineering science, which requires an entirely different knowledge and skillset. She specifically mentioned that development of metacognition skills in engineering science made this transition easy because "*I could just pick up any textbook, and new topic and learn it within a week kind of thing. I had the skills set to do the quick learning*".

3. Deep Structure: Approach to Design

The majority of the alumni interviewed had positive opinions about design courses. One alumnus, working at a large Aerospace company, vividly described her experience in a design course:

"We picked an aircraft design and every group had to design an actual model aircraft that flew[...]and the professor brought a professional pilot who could manage the remote and that guy flew every one of our aircraft and they gave us points as to how good it fly, how high it went, how maneuver it was. So it was very, very I guess [a] real course"

Similar to instructors, developing teamwork skills was mentioned by most alumni as an advantage of design courses, which was also cited in helping to understand the importance of other perspectives. Showing skills as designers, appreciation of design work, and integrating knowledge from other courses were among some of the advantages of design courses mentioned by alumni which were mostly echoed in instructors' perspectives as well. For example, an alumnus working as an analyst mentioned:

"*I think it also gave me a better appreciation for a lot of the design work that happens in the real world. Because you realize how many different decisions have to be made about things as small as like designing a doorframe."*

One noteworthy comment given by two female alumni referred to gaining a sense of competency and confidence as the result of design courses, which was not observed in instructors' perspectives. The alumnus working in an aerospace company described the benefits of her design education:

"*Makes you more competent to begin with and that competency drives confidence [...] Whenever you have tested something, you've seen something in action, it's definitely easier to talk about it and talk about it competently [...] I think that would be the most defining impact that those courses would have: the confidence that it brings.*"

4. Perspectives on Implicit Structure

The alumni were also asked to comment on approaches to teach ethics/equity and the impact of engineering on society and the environment. Common themes were not observed in alumni responses. The majority of alumni only emphasized the general importance of learning/teaching these concepts and talked about their own experience about this implicit structure rather than providing suggestions on how this should be implemented in engineering science. Even then, the responses varied, which could be because there was a diverse range of graduating years, and this aspect of the curriculum has changed over time. Similar to instructors, a few recent alumni mentioned the Engineering & Society course as an effective learning experience to learn about these concepts. They also mentioned that this implicit structure is integrated within the design courses.

Some of the noteworthy suggestions included teaching ethics as "*grappling with the ambiguity of it*" rather than as a checklist to memorize; provide real life examples and guest seminars on the topic; and presenting ethics as fundamental topic taught by experts. For example, an alumnus working in the AI field suggested the following: "*I think an ethics course that suggests that ethics can be like a set of bullet points about, like a checklist to go through when you're doing engineering isn't reflective of the reality of the messiness of ethics."*

Another alumnus working as a pharmaceutical scientist shared their perspective on ethics:

"*They did have course on ethics, which I thought was reasonable, just to kind of introduce that concept and bring awareness to the importance of ethics in engineering. I think at the time of my studies there wasn't too much focus on that environmental factor. And I know now there is more which is really great […] just bring more real life examples, I think again, kind of echoing what I said before, it could be a special session, does not have to be a whole course on it but you know just guest speakers, or you know, guest seminars on the topic.*"

Interestingly, two alumni indicated that these topics should also be taught from first principles which a dedicated course could achieve, and then should be applied in design courses. One recent alumnus further commented "*But I think we don't talk about the evidence of why we should support equity […]. That principle of let's understand the first principles and then dive into the applications also applies here*", demonstrating a transfer of the "first-principles approach" beyond the math and science.

Conclusions and Future Research

The use of Signature Pedagogies as a theoretical framework encouraged the examination of a few interesting themes from the perspective of instructors and alumni, particularly with respect to the layer of "Deep Structure" in the program curriculum and pedagogy. Most notably, "teaching for breadth" and "teaching for depth" emerged as important programmatic elements, but the ultimate outcomes and perspective on utility of this approach varied between the instructors and the program alumni.

In particular, the instructor link between "first principles"; "breadth" and "innovation" is worthy of further exploration. While teaching for breadth and depth was mentioned as equipping students to become innovators by the instructors, this was not widely observed in the alumni responses. This is not to conclude that graduates will not become innovators, but that these may not be the pedagogical strategies that support that path. The majority of alumni indicated that they use the "first principle" approach (or deep learning approach) as a skill when learning in new domains, or to move between disciplines (or fields) more effectively.

Further exploration is also needed in understanding how program breadth leads to life-long-learning and working across disciplines in post-program careers and education. Alumni spoke favorably about this experience, but we need to learn more about whether it was simple exposure or specific pedagogical practices that lead to these positive outcomes. Alumni seem to connect metacognitive skills and life long learning to their experience in the program, but understanding the specific ways that these skills are developed and reinforced post-graduate will require further exploration with all stakeholders.

While the reflections on design between instructors and alumni did not demonstrate any particularly powerful themes or contradictions, there were a few notions raised – the application of theoretical knowledge, and taking a first-principles approach to design frameworks – worthy of further exploration. Some of our future work will look specifically at the design stream in the program, and our attempt to understand the nature of design within the unique context of a multidisciplinary program.

The absence of a focus on the implicit structure was noted as an important theme in the work. Although this is speculative, it may be that Engineering Science lacks common artifacts and processes that require a certain approach to safety and ethics (and the values that underlie these). Finally, it's also noteworthy that, as evidenced by the career pathways of the alumni interviewed, many graduates do not actually pursue professional engineering jobs. Thus, more research is required to either re-define the type of professionals the engineering science program trains and/or to assess the applicability of using signature pedagogy with respect to engineering science.

One limitation with respect to the methodology is related to the use of signature pedagogies as the theoretical framework. The framework was used as a lens to analyze interview data; but the interview questions were not originally rooted in this framework, and therefore the interviews may have missed opportunities for engagement in this framework. Another limitation that should be acknowledged is that in interviewing alumni, we are unable to measure their experience in the program, but their recollections of it. The choice to interview alumni was purposeful, as we aimed to draw connections between learning in the program and their post-graduate careers, and these connections offer enormous value. Incorporating the views of current students in later components of the project will address this potential gap.

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