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Conceptualizing First Principles Thinking in Engineering Education

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Abstract

This research paper provides a case study of a large Engineering Science program, with a particular focus on perceptions and practices related to first principles thinking from alumni, faculty and students. As part of a broader project designed to realign program goals, practices and outcomes, this study included semi-structured interviews and focus groups, designed to understand how program stakeholders conceptualize first principles thinking, and how they perceive the benefits or utility of such an approach.

Through the historical analysis of the engineering curriculum, a key tension identified is the focus on foundational mathematics and science, which is contrasted with a focus on professional practice and the applications of engineering work. An interest in emphasizing mathematics and science led to the launch of a number of undergraduate and graduate programs around the world in Engineering Science, Mathematics, Physics and Chemistry, and the persistent inclusion of a comprehensive foundation in mathematics and science in engineering programs.

This foundation has enabled a focus on first principles as part of the teaching and learning discourse in some engineering programs. More recently, first principles thinking has also been discussed in the popular technology discourse as connected to innovation. Here, it is described as a method used to identify and reason from the most fundamental truths in our knowledge base to support problem solving and innovation. While many stakeholders have a vague awareness of first principles thinking as a philosophy of knowledge construct, there is a gap in conceptualizing this in the engineering and education literature.

Thematic analysis was used to identify several key findings. First, while some stakeholders viewed first principles thinking as a learning and problem solving strategy, others tied the practice to the disciplinary knowledge itself, for example, key theories and equations and their derivations. While these two conceptualizations are related, the latter provides less room for transfer to the engineering problem solving process, and stakeholders expressed an interest in building this opportunity to transfer the skill to other engineering contexts. Second, different stakeholders viewed the utility of the approach differently; for example, while alumni articulated the benefits of building first principles reasoning as a skill, students felt that the practice was more tied to a career in research and less useful in other engineering settings. Third, students in particular noted the challenge in maximizing the learning benefits associated with first principles thinking with the heavy workload and knowledge base in engineering.

These results provide some avenues for the examination of first principles thinking in engineering education, particularly in considering the interplay between disciplinary knowledge and learning skills, and the need to balance first principles thinking with other considerations in the curriculum. We hope this work will open the door to future inquiry about the value of first principles thinking in the development of life-long learning and innovation in engineering. Furthermore, reconciling the historical focus on fundamental math and science in engineering with a more contemporary view on first principles thinking should be considered.

Keywords: First Principles Thinking, Qualitative Analysis, Teaching, Learning

Introduction

The composition of the engineering curriculum has been the subject of various inquiries in engineering education, through both work in program evaluation and engineering education scholarship. Through historical analysis of the engineering curriculum, one of the key tensions identified is the focus on mathematics and science (theory), which is contrasted with a focus on the more practical components of the engineering profession (practice). An interest in emphasizing mathematics and science as a way to drive research and add rigour and prestige to the engineering profession launched programs around the world in Engineering Science, Mathematics, Physics and Chemistry.

This tension between theory and practice has been described by [1], who reviewed research on the history of engineering education in the US, Germany, Britain and France. One such inquiry was from [2], who described different visions of engineering, including one held by those who prioritized the relevance of "engineering theory" which included both the natural sciences as well as the complex features of working machines; while another belonged to those who view design as the core of engineering practice. The history of Engineering Science programs also provides a lens to consider this tension and the motivation for a more theoretical approach, for example, [3] argues that war prompted an engineering research space between pure science and industry, influencing the design of undergraduate education. Harwood also examined David Channell's [4] and Ben Marsden's [5] studies of the development of W. J. M. Rankine's conception of engineering, which provided students who had apprenticeship experience – the predominant model of early engineering education in the United Kingdom – with engineering science, to help them link idealized systems with real-world problems, connecting science and practice.

Harwood argues that there have been two general phenomena in the history of engineering education. First, the curricula have varied widely among engineering colleges and universities; with some emphasizing science more than practice, and others emphasizing practice more than science. Second, over time, the curriculum in many institutions has moved from a practice to a science orientation, a process known as academic drift or academisation.

The program under study, a multidisciplinary engineering science program in a research-intensive North American university, differentiates itself from other engineering disciplines by its emphasis on *teaching from first principles.* The program describes taking a more "rigourous" approach to math and science and teaching deductively, working from the general to the specific case. In previous work [6], we adapted the concept of Signature Pedagogies to further understand and learn about the pedagogical choices employed in the program, from the perspective of instructors and program alumni. This work demonstrated the focus on first principles and foundational theories, but also identified some tensions between instructors and alumni in the relevance of this approach to real world practice. For example, while instructors linked the first principles approach to inspiring innovation, this link was not reported by alumni. These contradictory results regarding the utility of the first principles approach, and the emphasis on teaching from first principles throughout the history of the program, encouraged us to attempt to conceptualize first principles more fully, in an attempt to understand its impact or potential for impact in student learning and engineering practice. Specifically, the research questions are as follows:

1. How do faculty, alumni and undergraduate students understand the practice of teaching from first principles?
2. What are the benefits and utility of teaching from first principles as perceived by faculty, alumni, and students?
3. How do undergraduate students experience the practice of teaching from first principles?

In the first section of the paper, a brief history of academic drift in engineering education and creation of the program under study is provided. The second part of the paper documents the process of interviewing faculty and program alumni as well as conducting focus groups with undergraduate students. The results on how various stakeholders conceptualize first principles and their perceptions on benefits of this approach are presented. Identifying the alignment or lack thereof between intentions and outcomes in these and other teaching practices will help us in improving program goals and practices; and will allow us to build appropriate curricular and instructional strategies.

Background

History of Engineering Science

Engineering was taught as apprenticeship in the field or in a machine shop as late as the 1870s [7]. In the late 1880s, engineering schools in the U.S. were created with an emphasis on learning by doing or practice rather than formal learning in science. This teaching strategy was supported by the preference of industrial employers for graduates who "could step right into jobs." The engineering colleges also focused mostly on teaching rather than research. After 1900, there was an increase in research at a few universities, but the research involved materials testing and projects focusing on specific problems facing industries and state government officials. Industry funded research was rare, but when it was, they expected practical results rather than theoretical research [8]. Thus, in the early 20th century, most engineering schools emphasized the *how* rather than the *why* [7].

According to Seely [7], it was only after 1945 when the academic drift of engineering curricula happened, and there was a major increase in research conducted in engineering schools. One contributing factor to academisation was the presence of European-educated Americans who were more focused on math and science, and held a greater interest in the theoretical foundation of engineering work, and the utility of applied mathematics [7]. Another significant factor was the funding from federal government for academic research and graduate programs; this funding was provided to allow scientists and engineers to ask basic research questions, rather than focus on practical engineering applications [9], [10]. Given these funding opportunities, schools realized that in order to grow, they had to support fundamental research programs with an emphasis on engineering science [7]. This resulted in a shift in engineering education; machine shops, surveying and drawing classes were replaced by science and mathematics courses, and more attention was given to engineering science fundamentals. New undergraduate programs or majors built strictly on engineering science appeared to support this academic drift. For example, the University of Illinois and Cornell University created an engineering physics program in the 1940s. Standford University first offered a B.Sc. in Engineering science in 1946, while an honors program in engineering science was offered by Penn State university in 1946 [7]. A rigourous admission policy was common among these programs.

In the early 1950s, the ASEE chartered a committee to "...recommend patterns that engineering education should take in order to keep pace with the rapid developments in science and technology and to educate men who will be competent to serve the needs of and provide the leadership for the engineering profession over the next quarter centry." [11] Key recommendations were made related to providing more emphasis on the basic sciences such as mathematics, chemistry and physics, as it was concluded that engineering graduates were too practically oriented without sufficient training to solve problems by referring to first principles [12]. In 1965, ASEE reported that in the period since 1945, engineering science was at the center of every engineering school that planned to grow, and this focus dominated American Engineering schools [13].

History of Faculty of Engineering at University of Toronto

In January 1871, the Ontario government proposed to create a provincial 'school, or college, of technology' in Toronto, providing advanced scientific studies, similar to programs at Harvard, Yale and Cornell. In this school, students were to take courses in mathematics, sciences, drawing and languages to become ready for professional work [14]. The school or college was envisioned to be practice oriented. However, the plan deviated from the original vision to include not only engineering programs, but also wood/leather workers, carvers in the decorative and industrial arts and applied chemists. Before the plan could be put in place, the government changed, and the new premier believed that this approach to professional education was unnecessary, and instead advocated for a separate College of Technology to function as an evening school for working artisans, rather than providing advanced education for professionals. The college thus opened and offered only two subjects: Chemistry, and Civil Architectural/Mechanical Drawing [14].

In 1873, however, the government again proposed a 'school for practical education in such arts as mining, engineering, mechanics and manufacturers.' This lead to the official establishment of the Faculty of Applied Science and Engineering. According to White [14], the meaning of "practical" remains unclear; it could have been either referring to a useful outcome or purpose, or to engaging students in hands-on work such as laboratories. The school officially opened in 1878. This original school had a broader mandate than strictly engineering, as it offered two other diplomas in addition to engineering: Assaying and Mining Geology, and Analytical and Applied Chemistry. The signs of success of the college were seen in the late 1880s, as enrolments increased, and the graduates were finding positions in industry. The Provincial School of Practical Science was formally affiliated with the University of Toronto in the fall of 1889.

Similar to early research carried out at American engineering schools, the research in the Provincial School of Practical Science initially focused on how things worked, rather than on fundamental physical principles [14]. However, similar to the U.S., the trend of using advanced science and mathematics in research slowly began to dominate the research agenda. The new research agenda focused more fully on science and mathematics, but also on solving problems related to devices, processes and man-made materials. White [14] argues that this is what historians have called ‘engineering science’ - the fundamental science of manmade things. Engineering research in the Faculty no longer involved product development or conducting tests, which resulted in an increase in government research funds congruent with the government research agenda of the time.

In 1934, a new program called ‘Engineering Physics’ was offered by the Faculty of Applied Science and Engineering [14]. Similar to other Engineering Physics programs offered by American universities, this program was designed for academically strong students. The program was a major deviation from the original practical programs offered. First, the teaching was done mostly by Arts Faculty members, who focused on mathematics and physics in their teaching. Second, there were only a few hours of required drawing in first year, and there was no shop or field work in the program, which was a contrast with other programs [14].

In 1962, the Engineering Physics program was renamed Engineering Science, due to the availability of a chemical specialization for third-year students, followed by several other specializations that would become available in the program. Thus, the word “physics” was no longer appropriate. The program also became a separate Division in the Faculty, and offered an academically advanced program with specializations similar to most of other engineering courses available, albeit with that stronger focus in science and mathematics [14].

This current structure of the Engineering Science program at University of Toronto still resembles the original program formulation. It still offers a range of specializations (now officially called “Majors”) for students to enroll in. 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 eight (at publication time) Majors. The Majors have a focus, although not exclusively, on emerging and rapidly developing areas of specialization within engineering, with a belief that these areas are best supported by math and science, and that emerging disciplines ripe with opportunity sit at the intersection of science and 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 in Canada to the program (like Engineering Mathematics, Statistics and Finance, and the new Machine Intelligence Major). 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. Approximately 50% of program graduates pursue graduate studies with the remaining 50% pursuing industry, professional school and entrepreneurship.

The program provides students with an enriched academic experience, in part through the volume and breath (and depth) of classes taken, and in part through the teaching and learning practices encouraged. Key pedagogical practices, as described in program literature and by program stakeholders, include the use of curriculum integration and multidisciplinary thinking. Furthermore, the program prioritizes a focus on underlying math and science, which is also described as taking a “first principles” approach.

First Principles and First Principles Thinking

The concept of first principles can be traced back to some of the earliest works in the philosophy of knowledge. Aristotle defined first principles as “the first basis from which a thing is known.” [15]. Descartes, in his *Principles of Philosophy* noted that first principles must possess two conditions. First, “they must be so clear and evident that the human mind [...] cannot doubt of their truth” and second, “the knowledge of other things must be so dependent on them [that although] the principles themselves may indeed be known apart from what depends on them, the latter cannot [...] be known apart from the former” [16].

A study by Cross [17] reported three case studies of exceptional designers to identify the designers’ creative strategies in responding to the problems they tackle. It was found that all three designers used the first principles of basic physics, engineering and design in both the initial conceptual and detailed design stages. More recently, first principles thinking has been discussed in the popular discourse connected to innovation and entrepreneurship. Perhaps the most famous example of first principles thinking is its use by Elon Musk. He has described first principles thinking as follows:

“What I mean by that is, boil things down to their fundamental truths and reason up from there, as opposed to reasoning by analogy. Through most of our life, we get through life by reasoning by analogy, which essentially means copying what other people do with slight variations. And you have to do that. Otherwise, mentally, you wouldn't be able to get through the day," he said. "But when you want to do something new, you have to apply the physics approach. Physics is really figuring out how to discover new things that are counterintuitive." [18]

Teaching from first principles has been a key documented priority in the program under study throughout its history, and seemingly one of the most important characteristics that distinguishes the program from other engineering disciplines. However, based on our review of the literature, there is a demonstrated gap about teaching and learning from first principles, with the study by Cross [17] as a singular finding in the educational research space. Therefore, the aim of this paper was to document and describe how various program stakeholders conceptualize the practice and outcomes of first principles thinking, as a first step in articulating and improving this signature pedagogy in the program under study.

Methods

Professor and Alumni Interviews

As part of a larger program evaluation project, we have conducted a series of semi-structured interviews with professors and program alumni. The professors interviewed have provided a rich description on teaching and learning in the program, and on the position of the program in the larger engineering landscape. Program alumni have offered reflections on their learning experience in the program, and how their experiences impacted their post-graduate learning and working lives. In selecting interviewees for the project, purposeful sampling was employed, to maximize the diversity of perspectives offered from these groups.

This paper is based on the perceptions of 20 professors and 21 alumni. The roles of these professors 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. The 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. It is important to acknowledge that this diversity of post-graduate outcomes may influence the responses, as compared to a group of alumni who pursued a more traditional career pathway to engineering industry. However, this diversity is representative of the program graduates in Engineering Science.

Undergraduate Student Focus Groups

Focus groups with undergraduate students were also conducted to support this research. Initially, a survey was sent to students in years 1-4 at the end of the year. Students were asked to contact the project lead if they were interested in participating in a focus group to share their experiences as undergraduate engineering students. The data for this paper is from four focus groups conducted each with two to four students in the same year for a total of 12 students across all four years. Students were asked about their general experience in the program and specific teaching practices used, to further support an understanding of teaching from first principles and related practices. The names used throughout the paper are pseudonyms.

Data collection and analysis

The study protocol was approved by the appropriate university research ethics board. The interviews and focus groups were conducted on Zoom, due in part to the Covid-19 Pandemic, and were subsequently transcribed by the research team. The interviews and focus groups were analyzed using an open coding process; codes were developed based on participant responses. Thematic analysis was then completed through a cross-comparison of interviews and a process of memo-writing.

The specific questions analyzed from alumni and faculty interviews were:

- In Engineering Science, we often talk about teaching from first principles. What does this mean to you?

In addition to this question, students in the focus group were also asked:

- Have you benefitted- as a learner or otherwise- from this approach of teaching from first principles, or do you think you will in future? Why or why not?

Results and Discussion

A number of themes emerged from the data related to the teaching, learning and utility of first principles. These themes are outlined and described in this section, organized in three main groupings: (1) five conceptualizations of first principles thinking from the participants; (2) the benefits and outcomes of first principles thinking, and (3) barriers to effective teaching of first principles, as articulated by student participants. These themes are organized in Figure 1, below:

Conceptualization	Benefits and Outcomes	Barriers
1.Fundamental theories in math and science 2.Building from most fundamental knowledge 3.Deriving and understanding equations 4.Emphasis on the why 5.An approach to solve problems	Faculty 1.Deeper conceptual understanding Alumni 1.Systems intuition 2.Problem solving 3.Transfer to new domains Students 1.Problem solving 2.Fundamental knowledge 3.Research	1.Time on other tasks 2.Minimize focus on practical applications 3.Gap in assessment 4.Lack of consistency across courses

Figure 1. Summary of Themes

The Five Conceptualizations of First Principles

Drawing from the data from all three participant groups, five conceptualizations of first principles as a teaching and learning practice were constructed, as outlined in Figure 1. These conceptualizations are described below.

1. First principles as fundamental theories in math and science

Participants referred to foundational theories or principles, specifically math and science in their discussion of first principles. For example, a few instructors mentioned that first principles include "*fundamentals of math and science*", or "*underpinning of the science part*" as part of their response. One professor described how first principles are "revealed" across courses:

"*To try to reveal to them that they've seen these concepts, the same concept shows up in different places. […] so I'd say like first principles approach is to reveal the, you know, the underlying principles, the principles that undergird all these disciplines*."

Another professor mentioned that the first principles approach is consistent with the word "science" in the program. He further commented that too much emphasis on science could result in scientism, which he described as follows:

"*(Scientism is a) term from philosophy on the assumption that basically we can use science to solve all the world's problems, that's simply not true. It's, it's, it indicates a lack of understanding of the understanding of how complex the world.*"

The alumni also associated "*depth in math and physics*" and "*technical math bucke*t" with first principles. One alumnus specifically indicated that this includes depth in math and physics, but not chemistry, reflecting a traditional view of physics as the only "real" science, and the close relationship between physics and mathematics.

A couple of students in the focus groups also raised the emphasis on basic theories and math and science as part of their explanation of first principles. For example, Gregory (4th year) mentioned:

"*So being in engineering physics, it's like getting down to the really basic theory guiding things […] so the courses we take are very, very like the pure basic theory behind it all.*"

Jane (1st year) made a note that even though the program is considered "applied science", there is an emphasis on pure science, and differentiates the program from others on the basis of fundamental theories:

"For example, in calculus you learn delta epsilon and that's really nowhere else on the calculus course...I love it, I love the fact that we sort of get to delve into a lot of the science, but like even though we're getting an applied science degree we still get to delve into a lot of physics and the math that goes behind creating engineering rules of thumb engineering practices"

The results clearly demonstrate the academic drift or emphasis on science which is rooted in the creation of the program, and described earlier in the paper.

2. First principles as building up from the most fundamental knowledge

A common theme among instructors was the emphasis on building everything upon fundamental or foundational knowledge, and moving from the general to the specific in first principles thinking. One professor noted:

"*I think it means to start with fundamentals of what we know, like basic knowledge, and then grow and build up from there.*"

Similarly, another professor suggested:

"*to talk about a first principles approach implies a kind of starting at the lowest level of foundational knowledge and moving up from it.*"

This perspective was echoed by an alumnus who described first principles thinking as where "*You kind of explain the basic building blocks of a concept and you build it up.*"

One professor mentioned developing theories based on basic knowledge, while providing a more detailed description of the process of building up from fundamentals:

"*We're starting from some axioms and then if we can all agree that those are true, then we can try to see what the implications of those are And, and, you know, if it's not mathematics, it's physics, we can start from something like Newton second law and then sort of work out step by step what we can say about different types of systems just starting from those very basic first assumptions like Newton's law. So like you can work out an entire theory of fluid mechanics, starting with not much more than even second law*."

This response emphasizes first principles as being "*true",* drawing from the philosophy of knowledge and echoing Descartes' explanation. [16]

Building conceptual understanding from fundamental knowledge was also mentioned by a few undergraduate students. For example, Roger (2nd year) mentioned that this is how he learns content:

"*So, to me, first principles mean a lot, because I, the way I feel like I understand a content, I learned content is building on top of each other, like, these are numbers, then you can add number, you can multiply numbers and this building layer on layer on layer. Now you have, you can differentiate number, you can integrate. So that's how I learned and so it all starts with the first principle that I can agree with […] the first principles are something that I can, that my gut agrees with when I hear about it, when I see it, when I hear about like if someone tells me one plus one is two I will agree, because now that, for me, is more of a first principle because it's been used so long, but why? I cannot answer that.*"

Interestingly, this student puts an emphasis on starting from something which we can agree on, and thus echoing Descartes' definition, but also describes the tension in lacking an ability to prove these most fundamental principles.

Finally, Trevor, a second year student, compared teaching from first principles to a design and research process:

"*It aligns with the design process and the research process that you would be doing in practice. So you start from a hypothesis or theory or an idea design idea, and you explore all the facets of that idea and just and then study what could go wrong or what other interesting things you can think of when it comes to that topic or idea or hypothesis* […] *I also say that linear algebra certainly did this, where you would start from these very basic theories and then build and build and build until you can actually use the theories to apply to other things, and I think that's very similar to testing and doing other things in practice*."

3. First principles as deriving and understanding equations

Teaching from first principles was also defined in relation to deriving formulas, proofs and understanding formulas and equations. Deriving formulas specifically was a common theme across professors and alumni, whereas only two undergraduate students briefly alluded to "proofs" as part of their response. One professor noted:

"In principle, what that means is that you have that foundation in science, so that you can prove things."

An alumnus compared the program to other engineering disciplines, and indicated that deriving formula is not required in other engineering disciplines:

"*In order to build a bridge, you need certain tools, knowledge […] You don't have to learn how to derive that formula in order to do your job. And whereas I think this program focused on how do you actually derive that formula.*"

Understanding the equations rather than memorizing or just knowing how to apply them was also a common theme across participants. Specifically, some professors mentioned that first principles means understanding not only how to use the formulas/equations but also understanding where the formulas come from. Thus, first principle tries "*for a deep fundamental understanding as opposed to an operational understanding of how. It's where equations come from not just how do they work and how are they applied".*

Understanding formulas was also a common theme in alumni responses. An alumnus working in industry noted:

"*Instead of using a formula as a given, for example, like we're talking about calculus or we're talking about like physics instead of using a formula as a given, talk about how the formula came to be and, like what each part of the formula means, how it was developed.*"

A few undergraduate students also talked about understanding formulas and understanding where the formulas come from as part of their response to conceptualizing first principles. For example, Alexis (2nd year) differentiated between understanding formulas vs knowing how to use them:

"I think without first principles, what you gain is an ability to memorize like a formula and know the situations to apply it to rather than an understanding of what that formula is trying to mean and what it represents, so I think first principles is kind of how you understand where we got to the formulas."

Jane (1st year) compared this engineering program to other engineering disciplines and mentioned that other engineers only need to know the "how":

"*(the structures and materials course) is a great example of being taught first principles […] We were supposed to be looking at the science behind how civil engineering is done. Civil Engineers that are in industry and probably practicing civil engineering, they probably don't really get to have to think about that all that often because I mean they have sort of their list of how to apply civil engineering principles into actually creating a building, but for us, we actually got to see how some of those principles came about.*"

This theme partly demonstrates conceptualizing first principles as content such as deriving formulas, but also includes conceptual understanding, an understanding of relevant formulas, and an ability to assess assumptions and evaluate the reliability of results based on a deeper understanding of the mathematical expression of engineering concepts.

4. First principles as emphasis on the why

Perhaps similar to understanding the equations was this emphasis on understanding the why or "*the endorsement of the ability to say why*." One professor mentioned:

"*You know why things are a certain way, and I think that's, I think that's one of the foundational ideas behind [this program] is that you actually know the underpinnings about why certain things are the way they are.*"

Another professor indicated the connection to validation and question assumptions:

"*we're not just showing students how to get an answer. We're showing them why that's the answer and how to understand whether that's the right answer and questioning, always questioning the assumptions that were made in coming to those answers so that they can decide how accurate that answer is in the more fundamental principles.*"

Similarly, an alumnus emphasized developing an intuition to evaluate results:

"*Not just be given like a load flow analysis software tool and just be able to use it, but you need to know like what's going on, like mathematically in that software, how is the solution driver working so when you like encounter issues with the answers you're getting like you can tell like do these makes sense, like [am I] just going to assume it's right because that's the answer that computers given me like does this intuitively makes sense.*"

Similar to professors, alumni emphasized understanding the why in their responses. An interesting comment from an alumnus was that the emphasis on the why was what attracted him to the program. He also suggested that many engineers do not need to ask why:

"*I was always a person that needs to, you know, I kept asking why, why, why, and I was always frustrated with someone would say because, and I think this kind of goes to the transition point of what is it that you want out of the program. If you just want to be an engineer, if you want to build bridges. You don't need to know, you don't need to ask why,why, why. And it's actually going to be a very expensive proposition, you're going to be learning a lot of things that you may not necessarily need to build the bridge. So yes, so the short answer is yes. Definitely selling point for me. But I think in retrospect, probably the wrong thing to buy.*"

5. First principles as an approach to solve problems

A few participants connected first principles or theories to application and problem solving. For example, one professor noted:

"*First principles approach would be a science based explanation for why engineering problems should be solved in certain ways. Sometimes those first principles are mathematical ones or logic ones. Sometimes they are empirical one saying, well, we know from science, the following things happen, the following ways.*"

Another professor also made a connection between getting back to the basics when faced with a problem, while emphasizing solving novel problems. He further indicates that this is the approach he personally uses:

"*When you have these problems that have never been solved before, you have to back off right […] This is something that nobody ever done before, then you have to back down until you get to the point okay, where I can start […] It is that sort of basis that's key to this ability to solve problems that nobody's ever solved before […] When I'm thinking about when I'm solving problems I've always you know, taking back to these basic rules. Often I'm saying okay, how is this thing is supposed to work well you know energy is conserved or I know I know the circuit is closed, whatever the basic principles is because I can't remember all these all these things I look them up, obviously, often when I do, but often I'm just trying to work it up in my head.*"

A few alumni also explicitly made a connection between theory and application when talking about first principles. An alumnus response also resembled the engineering science definition by emphasizing on using science to solve practical problems:

"*When we use it [first principle] and reference it to Engineering Science, I think we mean solving application-based problems using a conceptual understanding of the underlying mathematical and scientific principles.*"

Another alumnus suggested a connection to a reductionist approach, in that first principles thinking is "*like breaking down the problem into the most basic form like what is the most primitive way to interpret the information so that you can solve that problem*."

Another alumnus linked theories with applications, and emphasized that the fundamentals will allow one to solve unknown problems:

"*You learn the methodology for developing solutions to problems and that's where the first principles comes in. You, you don't learn that if you're doing a semiconductor you use this error function, instead you learn, you learn Fick's law, you learn the differential equations, and you learn how to solve it in this geometry, and then you're thrown a different geometry, and you go I've seen that problem before and so that's, that's what first principles is to me, that it, it prepared you to solve problems that you, you've never seen before, but you're seeing them up in the fundamentals, that you can model it and get a first order solution.*"

Interestingly, he makes a distinction between operational understanding (i.e., using an error function for a semiconductor) and fundamental understanding of theories (i.e., Fick's law, differential equations). This theme is discussed further in the next section.

The theme of using first principles to solve problems was not a common theme in the student focus groups, and only a few students made the connection. For example, Heather (4^{th} year) described it as the ability to apply the building blocks to solve problems in different context, which remarkably resembled one of the alumnus' responses above:

"*I internalize it more as transferable skills, so if you understand the underlying principle and you're able to follow those principles to a solution in one specific case, be able to transfer that knowledge to another problem, like how do you use these building blocks and be able to execute* *on the next thing, so I think, I don't know, maybe not so much from the ground up building, but so much as understanding the process of how to use these tools is how I internalized it more.*"

The lack of connection between first principles and application in most of the student responses could indicate that there are not many opportunities for students to learn and practice first principles thinking. In other words, even though students are taught to build from lowest level of knowledge, they are perhaps not being explicitly taught about approaching and solving problems using first principles. This could be because historically, the aim of the program was to teach from first principles from a content perspective rather than first principle thinking; this is a distinction worthy of further exploration.

Design courses, which present a key opportunity for problem solving, were largely missing from undergraduate student discussion. In fact, one student participant specifically mentioned that design courses are not the ideal courses for teaching first principles. One alumnus, however, made a connection between first principles and design courses:

"*If you're looking at a subject like (design) and the first principles point of view, would be instead of taking a (design document) as a given, looking at all the different sections...and being like what purpose does this serve...why are you asking this question to the client and what information are you trying to gain and that's kind of where I see it, is the asking the why behind what's there*."

The Benefits and Outcomes of Teaching from First Principles

In discussing the benefits of first principles, faculty suggested that first principles knowledge "*might give (students) a deeper understanding, some more confidence in what they do.*" and that students "*understand much better and I found you can actually teach them a lot more if they have a better understanding, right from the beginning*". Overall, the focus of instructors was on using first principles to enhance conceptual understanding, which is reflected in the Five Conceptualizations above.

Interestingly, alumni put more emphasis on the benefits of first principles as a transferrable learning skill. Alumni noted benefits of first principles thinking as including problem solving skills, having a better understanding of the problems, the ability to transition from one discipline to another, and stronger systems-level understanding. An alumnus working in the energy sector provided a more detailed description when asked how first principles have benefitted her on the job, suggesting that first principles help one to develop an intuition for how systems work, and the ability to evaluate results:

"*We deal a lot with different simulation technologies, so load full software and energy simulation software...but also market dynamics. So needing to know like how the inner workings of those systems work and also like having that intuition or being able to troubleshoot or like test out when that simulation spits out something for you. Is it right? Does it make sense?... You can study things to like the nth degree, you can look at every single permutation of what that power system is going to look like. And you have the tools, now that you could maybe do that in a reasonable amount of time, especially if you've got like six computers you can run stuff on. But* *that's never the way it was done like 50 years ago...they really had to have that intuition, for how the system's behaving, how it's going to respond to different stressors. And I think that's what we really try to instill in in staff and that I found kind of natural coming out of our program"*

Another alumnus who works as an entrepreneur mentioned that first principles thinking is valuable in understanding how technology and approaches can apply to particular contexts:

"*I think the reason it's valuable is often, if you don't think from first principles and you just blindly apply somebody else's experience or rule or something, it is very likely it would backfire, and like, it could be a process change, it could be a design, there are typically reasons behind those designs, and the fact that they work in the past, doesn't mean they will work in the future, or the fact that they work in a specific company might not mean you work in a different company […] The ones that can think about first principles […], they understand the why, and they can apply that and think about hey does it apply in this new world or hey maybe I have to change it because now we're trading, we would rather be trading off something else.*"

A couple of alumni indicated specifically that first principles as an approach is more important than first principles as content. For example, an alumnus mentioned that the approach of learning and understanding basic underlying concepts is helpful when learning new domains. Interestingly, he also alluded that this is not unique to this program:

"*Generally, I think it's probably like the general like approach or way of the thinking about things, and I can also see that, like that's not necessarily particularly unique to Engineering Science, like you know, having observed some other like undergrad programs, or like just generally what an engineering education kind of is,[…] I do think like there is something of value of being able to start basically without knowing essentially anything about a particular topic and figure out how to learn kind of the basic ideas and like what will translate well into. Right now in my job, like I probably have to learn like four or five, ideally, I would sort of know more about four or five different programming languages or systems or something like that. And kind of understanding the basic underlying concepts are key questions to ask to like kind of set oneself on the right path. I think, is, I think, is a useful skill that I think you know I learned at least partly from [the program].*"

When it came to the benefits of learning from first principles, undergraduate students had various opinions. Heather, a 4th year student, thought that the benefits of a first principles approach would depend on the career stage, and it would be much more useful later in her career, working with broader, "high level" problem solving:

"*It's good to keep these first principles in mind, but I'm not actively thinking about, and I think, especially in the work that I'm doing, a lot of stuff to like progress faster and more deeply doesn't really require that so much...but eventually, where I want to go in, like in this big high level kind of thing merging multiple fields, I think it will be very important.*"

Trevor (2nd year) mentioned that the approach would be helpful in future problem solving:

"if you sort of can start from the theory when you're approaching a problem then you have like sort of a handbook that you can look at and all these different answers and ideas are there, and if you get lost, you can always refer back to those principles."

The student is framing the benefits of first principles thinking in their utility to the problem solving process, and in particular, accessing foundational knowledge in novel problem-solving situations. Sebastian (1st year) differentiated between understanding and memorizing, and indicated that first principles would allow "*you to take full advantage of what you know and apply it in ways that, basically haven't been done before […]. Because when you understand something, it is my belief that when you understand something again, you are less inclined to forget about it or perhaps make a mistake related to that learning.*"

Interestingly, there was a common agreement across many students that the first principles are more beneficial in a research setting than a practical or industry setting, as it can make them a "*better researcher*" and helps them to "*ask better questions*". For example, Alan (3rd year) thought that first principles are not as useful for engineers as to scientists:

"*The idea of thinking through first principles seems more cumbersome honestly, the idea of building everything out from the groundwork is very elegant, it's...something you expect for a mathematician but for engineers sometimes it's too much to think about transistor level logic when you're building a computer.. I guess you got a better understanding of the systems you're working on, but it wouldn't be as useful as just learning a concept outright I don't think*."

Heather (4th year) acknowledged first principles as an approach to solving problems, which some people might want to use it and others might not:

"*but I think it's also like an approach, some people want to go through that understanding everything and i'm i'm okay with like setting aside a few black boxes and just i'll come back to them later"*

Gregory (4th year) echoed the same idea and thought understanding all basic theory seems "*a bit unnecessary for like industry per se. It helps us provide, it helps provide us with that deeper understanding which some people may appreciate, especially if you're going to go into academia afterwards*." Alexis (3rd year) also commented that this approach is helpful for research, "*where you're posing questions and you're trying to answer*."

Overall, the responses indicate that though some students acknowledge that the first principles help with solving problems, they don't necessarily perceive the utility value in industry or in practical settings. This may indicate that there is a lack of examples provided by professors to demonstrate the benefit of such approach, and a lack of opportunity for students to learn and apply the practice.

There seems to be common agreement among students and alumni that the first principles themselves might not be as useful as first principles thinking. This theme combined with lack of associating the utility value of first principles with a practical setting and conceptualizing first principles as mostly content-focused, suggests that there might be a need to change the approach in teaching from first principles. The emphasis on first principles dates back to the creation of the program. However, one must also consider the conditions which resulted in such a decision in 1934. The Faculty was moving towards conducting more research and perhaps an understanding of science and math was necessary to train researcher-engineers, which led to creation of such program. Given the results though, maybe it is time to steer away from the original vision and provide more opportunities for application and developing first principles thinking as a skill.

Student Perception of Barriers to Learning from First Principles

Through the discussion on first principles practices, students identified a number of barriers to the successful implementation of a first principles approach, namely: (1) the side effect of a minimized focus on practical applications; (2) the time on other tasks in a crowded curriculum; (3) gap in assessment practices and (4) lack of consistency across courses.

Some students mentioned that too much time is spent on first principles as content, and perhaps some of that time should be reallocated to teaching other things. For example, Alexis suggested that some of the time spent on first principles should be spent on "*applications, or how...these concepts can be used in people's careers that they might be choosing*."

Steve (3rd year) thought that the instructors should explain why they are teaching from first principles as it will help with motivation to learn in this way:

"*It would have helped even more if the purpose like the why we're approaching first principles was stated more clearly. Like we're going to teach you this because we want you to get that mentality in your mind to ask why? to go look for the fundamental reason why we're doing something. I think if that was explicitly stated it would help one motivate the students and to help us like centralize our brain, help us like align our thoughts and our efforts into like understanding that part and applying it later more effectively."*

Sebastian (1st year) indicated that learning from first principles requires time, and too much content in a limited time becomes stressful. He further suggested that perhaps only the most important parts should be taught from first principles:

"*The less important things that don't really require that much use, those don't necessarily have to be done from that perspective because learning from the [first] principle inevitably takes more time to do but time is limited, and if you try to pack in more stuff on, it would be more stressful and students would probably end up worse off*."

Similar to this, Jon (3rd year) indicated that instructors with industry experience are better at distinguishing what should be learned from first principles and what should be memorized:

"younger professors who work in industry and have recently graduated. I think that they do a good job of differentiating between first principles and something that you should just memorize and just know it should be something like that's written on your hand, for example"

A lack of time to absorb all the material and to find balance between learning and doing well on assessments was also mentioned by a few students. Heather, for example, mentioned that the workload inhibits full understanding of the material:

"*But I think the way it was executed, because you have so little time and they want to give so much of a broad foundation that it ends up being like more drill like.*"

Jane (1st year) indicated that it is hard to balance learning the first principles with getting "*enough practice so that I can do well on my exams*." She further commented on a calculus course and how the lectures focused heavily on theory, but the practicing was up to students, which was difficult to do because of high workload.

"*I guess with courses like calculus learning from first principles is great, but […] the way he approached it is just that he would show us the first principles concepts in class, but then leave the practicing sort of up to us, and I mean it it does make sense. But it just didn't really work out in terms of like, given the fact that we have five other courses to also be practicing for it just I just don't think it really worked up like our lectures for me at least.*"

Students also thought that there is a misalignment between content taught and content assessed. In other words, they indicated that even though a lot of time is spent on teaching first principles, the same attention is not offered to assessment. For example, students noted "*it's a shame, when the testing environment doesn't completely match up with first principles*", and "*it is very hard to motivate the learning of the first principles when your assessments don't line up with that approach.*". Another student noted that he would "*gloss over the first principles*" because it would not really get evaluated on tests/exams.

Another student, Elizabeth, noted a distinction between meaningful engagement with first principles, and a simple interpretation of patterns:

"*We didn't need to know how to derive something most of the time or how something works, we just needed to understand the pattern and then apply the pattern to our problems, I think [it] discouraged first principles understanding.*"

Furthermore, students agreed that not all courses were effective in teaching from first principles. The second-year biology course and the first-year materials course were specifically mentioned by a few students as courses which were not taught using first principles. Elizabeth (4th year) indicated that in the biology course:

"*You really couldn't do first principles, I think, a large part of that was because bio was not very connected to our other courses, the same thing with our molecules and materials course like there wasn't enough time to give us a foundation and also teach us something. And also go into the specifics like we really would have had to have had like a pure like foundational chemistry course to have a first principles approach and all those materials and similarly with bio likely. We were taught very specific type of bio that was applicable to the biomed specialization students I wouldn't say at all that we were given the first principles or foundational approach to biology.*"

Overall, students described a set of key barriers that impacted the efficacy of first principles teaching. Namely, a lack of time in a crowded curriculum with a high workload, a misalignment between content and assessments, and lack of consistency between courses were cited by the students. Furthermore, some students questioned the utility of the approach, and what is missed through a focus on first principles, while others questioned whether they were actually applying the practice of thinking from first principles, or simply experiencing a surface level approach.

Conclusions and Future work

Teaching from first principles is cited as a key teaching practice in the Engineering Science program at University of Toronto. However, as the data suggests, there is a lack of common understanding among stakeholders as to what exactly this practice entails. For example, instructors seem to gravitate towards an understanding of first principles as content, through a focus on the fundamental theories in math and science and the practice of identifying and building up from foundational knowledge. On the other hand, alumni were able to describe first principles as a thinking approach that could be applied to the development of systems intuition and a more diverse set of problem solving contexts. Even some of the students saw the potential for first principles thinking in a problem solving context, albeit to a more limited extent.

This distinction, between first principles as a thinking strategy versus a way of understanding disciplinary knowledge, is a key finding that opens the door to further inquiry and pedagogical development in the space. Alumni, through graduate programs and career-based learning, may be extending their ability to apply first principles thinking. There is an opportunity here to work with faculty to build a better process for teaching first principles as a thinking practice, that can be applied to a broader set of problem solving contexts. Furthermore, for students, justifying its utility beyond the research environment was found to be an important consideration. There are many thinking skills that benefit both research and industry contexts, and helping students to understand these “cross-over” skills should be a consideration.

In further considering the way that alumni frame the role of first principles thinking, questions are raised about how we might combine first principles thinking with engineering practice and practical skills. While first principles thinking is often connected to the underlying math and science, as articulated by the results in this paper, at its core, it could be used to examine the fundamentals of any skill, practice or knowledge base. For example, expansion of the work conducted by Cross [17] could better connect first principles with design thinking and the engineering design process.

The results of this project indicate that there needs to be a better alignment between the teaching of first principles and assessments. Lack of time, work overload, lack of relevant assessment practices and lack of consistency across courses discouraged some students from delving deep into first principles and first principles thinking.

We feel that this work – an attempt to better understand a long-held teaching practice in the program – is of critical importance as part of a broader effort to continually evaluate and improve program teaching and learning. In particular, the practice of first principles thinking, rooted in the history of engineering science, academic drift and a focus on pure research in the university, should be re-evaluated in the context of today’s engineering landscape.

Future work will include a more detailed instructor survey to document teaching practices in the program, including those related to first principles and first principles thinking. Furthermore, we plan to engage with those in the learning sciences and other related research communities to further examine the teaching of first principles and first principles thinking in different disciplines and educational contexts.

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