International Journal of Engineering Education Vol. 36, No. 2, pp. 556–567, 2020
Printed in Great Britain

0949-149X/91 $3.00+0.00

Balancing Curriculum Design Trade-Offs for Larger Learning Goals: A Synthesized Model*

RICHARD J. ALEONG
School of Engineering Education, Purdue University, Wang Hall, 3rd Floor, 516 Northwestern Avenue, West Lafayette, Indiana, 47906, USA. E-mail: raleong@purdue.edu

MOLLY H. GOLDSTEIN
Industrial & Enterprise Systems Engineering, University of Illinois, Urbana-Champaign. 104 S. Mathews Ave., Urbana, IL 61820, USA. E-mail: mhg3@illinois.edu

Engineering educators face a number of instructional trade-off decisions that may be experienced as tensions in curriculum design. To navigate these tensions, we present a synthesized model based on experiential learning theory, novice-expert development, and design learning and practice. Our model highlights how different mechanisms may support students in a back-and-forth movement between learning general engineering tools and that of particular cases that utilize engineering tools. With this model, we focus our attention on students' professional and personal development towards larger system learning goals that encompass engineering formation and students' personal growth. In the context of an introductory engineering design and graphics course, we utilize this model to develop a series of reflection exercises that aim to elicit students' thinking about connections between their coursework and future careers. Two student reflections are presented to illustrate the model and its features for supporting critical reflection and meaning-making of educators' instructional practice. As engineering educators are continually challenged to navigate curriculum decision-making, this paper highlights opportunities for curriculum reframing that balances the need for students' holistic personal and professional formation.

Keywords: curriculum and instructional design; experiential learning; professional formation; scholarship of teaching and learning; student reflections

1. Introduction

In engineering design, making trade-offs is inherent to professional practice. The need to make trade-offs arises from the challenges of designing solutions under constraints, managing diverse stakeholder requirements, and evaluating solutions to meet technical objectives. Specifically, the process of making trade-offs serves to evaluate possible outcomes against their respective benefits and costs in areas such as aesthetics, financial cost, degree of safety, and various performance indicators. In this way, making trade-offs is an effective design practice and part of any successful design process [1].

Similar to design practice, educators in higher education are required to make a number of instructional trade-offs when thinking about the design of learning experiences. At the course level, educators make trade-off decisions when it comes to the selection of course content, the amount of time dedicated to specific activities, types of instructional methods, formats, and technologies, and assessment criteria and weightings. At a program level, changes in program content, structure, and modes of delivery may require a variety of curriculum development solutions ranging from the development of new courses, the initiation of course redesigns, or the addition of new content and teaching methods to existing courses. Evaluating these possible solutions will require consideration of the trade-offs between time, resources, and effectiveness that each solution provides to achieve the desirable instructional goals. Our ability as educators to recognize and navigate these kinds of instructional trade-offs directly impacts our learners in terms of what is learned and how learning takes place.

In engineering education, the need to make trade-off decisions becomes apparent when faculty are faced with the tensions of teaching for diverse educational objectives and learning outcomes. Engineering faculty face tensions of teaching for engineering analysis and engineering design, teaching for technical abilities and professional skills, and teaching with a focus on engineering knowledge and broad student formation and growth. For example, how might an instructor balance the need to teach the subject matter of their course with the engineering professional skills of communication, teamwork, and leadership? How might programs integrate engineering knowledge with larger learning goals of developing individual engineering identity?

In this paper, we call for pause – to step back from wrestling with trade-off decisions and reframe these moments as opportunities for sitting with tension. Here, we reflect on our instructional values and

* Accepted 12 November 2019.

shape our perspective to see various learning goals. From sitting with this tension, we offer a conceptual model for thinking about engineering learning to support a pedagogical approach that focuses on engineering students' larger system learning goals. We will describe the synthesis and generation of our model based on theory from experiential learning, novice-to-expert development, and iterative design processes. Using students' personal reflections from an empirical pilot research study in an introductory graphics and design course, we illustrate the application of our model as a design and analysis tool for students' learning.

2. Background

Engineering educators are continually challenged to address questions such as what counts as engineering knowledge? How should the engineering curriculum be structured? And who does the engineering curriculum serve? These questions call for critical reflection as we sit with these moments of tension and see the potential opportunities for our engineering education system to better support student learning. In the following section, we draw attention to three broad tensions in curriculum decision-making for engineering education:

1. Tension between teaching for engineering analysis and engineering design.
2. Tension between teaching for technical abilities and professional skills.
3. Tension between teaching for engineering formation and personal growth.

As shown in Fig. 1, we frame these tensions as nested and intertwined within three increasing system levels of education: course, degree program, and society. First, at the course level, engineering analysis and engineering design are framed as specific engineering skills. Within a degree program, at the second system level, these engineering skills are in service to the development of students for professional engineering practice – a practice that requires technical engineering abilities and professional skills. Finally, the third system level acknowledges the role of education in society. Beyond students' education for careers in the engineering profession, the engineering education curriculum also serves the goals of higher education, and therefore should also consider students' personal growth as individuals and global citizens.

2.1 Tensions between Teaching for Engineering Analysis and Engineering Design

Engineering analysis and engineering design are two characteristic elements of engineering education. While each term may be open to different interpretations, we use engineering analysis and engineering design in this paper as concepts that broadly refer to the set of knowledge and skills associated with particular activities within engineering practice. Engineering analysis is associated with the use of mathematics and science to analyze, evaluate, and solve engineering problems. This conception of engineering analysis aligns with ABET Criterion 3 Student Outcome #1: "An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics [2]. Engineering design is associated with the process that supports the creation of artifacts to meet specific needs and aligns with ABET Criterion 3 Student Outcome #2: "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors" [2]. With these conceptions, a tension arises at the course level between the need to teach the technical and analytical tools of math and science that distinguish the engineering sciences, while also incorporating adequate engineering design experiences [3].

The tension between engineering analysis and design is deeply rooted in the history of engineering as an academic discipline, where disciplinary boundaries were drawn to establish rigor, legitimacy, and professional status [4]. These boundaries have transferred to the teaching of engineering

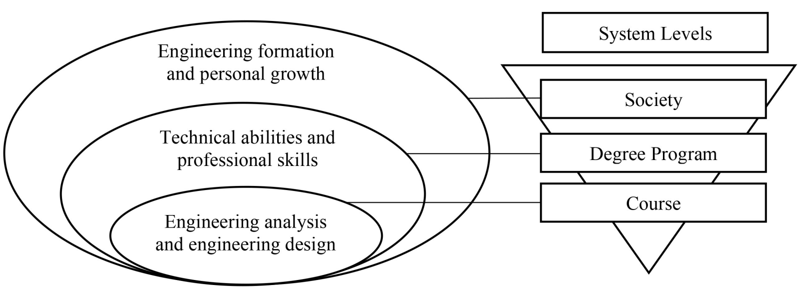

Fig. 1. Nested tensions in the engineering education curriculum across system levels.

analysis and design where students experience a science-based engineering curriculum as the source of their technical competence and rigor [5].

For pedagogical purposes, engineering design may be used to teach engineering analysis – as engineering analysis is applied throughout the engineering design process [6]. Furthermore, engineering design provides an authentic context for supporting student motivation and the application of learning [7]. In line with these pedagogical benefits, engineering schools have introduced design experiences in first year and throughout the engineering education curriculum [8, 9] to complement the culminating capstone senior design experience required of accredited engineering programs [2]. Several authors have argued for the integration of teaching approaches for engineering analysis and design, such that analysis and design are taught as complementary engineering skills [10–12]. However, these efforts for integration in the engineering curriculum inherently position engineering analysis and design as two separate, albeit complementary, skills that support engineering practice. Furthermore, we posit that a focus on engineering analysis and design as skills, adopts an outcomes-based approach that positions these skills as the end goals of engineering education. However, Walther & Radcliffe [13] identified how an outcomes-based approach, focused on knowledge and skills, may be limited in its approach to consider elements of traits, motives, and self-concept that also contribute to competency development. With the view of engineering analysis and design as two separate skills, competing values and priorities among diverse engineering educators will arise. In response to these challenges, the call for integration of analysis and design will continue, thus further supporting the view of analysis and design as separate skills that need to be integrated. However, we adopt a transcendent view to challenge the assumption of engineering analysis and design as the end goals of education. A nested view of the tensions at varying system levels situates engineering analysis and design as two inseparable elements in service of learning for engineering practice.

2.2 Tension between Teaching for Technical Abilities and Professional Skills

The tension between teaching for technical abilities and professional skills is characterized by the need to develop students for engineering professional practice, in ways that extend beyond the skills of engineering analysis and design [14, 15]. Walther and Radcliffe [13] described the competency gap between university and industry, due in part to the goal conflicts between university and industry, and the nature of university education versus industry needs. For example, university focuses on technical skills although industry hires individuals for their traits and practical job skills [13]. Other authors have pointed to the nature of the engineering curriculum as overloaded with technical content at the expense of training and preparation for holistic learning and professional skills (see [16]). Similar to integration approaches for the teaching of analysis and design, educators seek to integrate learning experiences such that technical abilities and professional skills are learned simultaneously. For example, the design spine model [17] has been widely adopted to promote education for engineering professional practice [18, 19]. Other examples of efforts to integrate professional skills with technical learning experiences in the engineering curriculum include social justice and sustainability studies [20], technical communications and engineering [21], and teamwork and leadership development through targeted programs [22].

2.3 Tension between Teaching for Engineering Formation and Personal Student Growth

We refer to students' engineering formation as their development towards becoming future professional engineers and joining the engineering profession. For example, under the NSF Engineering Directorate [23], the Professional Formation of Engineers is described as "the formal and informal processes and value systems by which people become engineers". Walther, Kellan, and Sochaka [24] point to the need of a holistic perspective that acknowledges how "a wide range of education factors interact in a complex fashion to impact students' professional formation on the level of both specific learning outcomes and intangible, attitudinal aspects" (p. 706).

A focus on personal student growth acknowledges the role of higher education in preparing students "for the professional, civic, and personal challenges of adult life" [25, p. 2] that includes employability, civic responsibility, and lifelong learning [26]. Therefore, although students may not pursue professional engineering as a career path, their engineering education should still prepare them for life's challenges in whatever future they choose to pursue. With a focus on adult development, Baxter Magolda and King [25] identified three areas of contemporary college learning outcomes that align with a focus on student growth in areas of cognitive maturity, integrated identity, and mature relationships. Towards this end, they present a learning partnership model that supports student development toward *self-authorship*, defined as the "capacity to internally define a coherent belief system and identity that coordinates mutual relations with others" (p. 8).

Our conception of education for personal student growth encompasses such abilities as civic engagement, lifelong learning, and a sense of self – in line with the learning outcomes of cognitive maturity, integrated identity, and mature relationships [25]. Koshland [27] identified aspects of student personal formation with regards to a liberal education that prepares students who are "ready to pursue a complex career path and a rich post-graduate life with skills in critical thinking, analysis, and an appreciation for the complexity of the society in which [they] live" (p. 54). In a similar way, Bucciarelli and Drew [28] proposed an undergraduate engineering program that is based in the liberal arts to address the need for "more open learning experiences that emphasize teamwork, social context, and creative design as much as instrumental analysis of single-answer problems" (p. 106). Within this tension, we have pointed to the need for engineering education to consider its role in society for preparing future engineers as well as preparing individuals for navigating their future careers.

2.4 Focus on Larger System Learning Goals

Educational tensions will need to be continually negotiated as systems of education respond to contemporary needs, challenges, and societal changes [29]. The three tensions that we have identified may be experienced by educators as challenges that require trade-off decisions. With this current frame, approaches to resolve the tensions may be limited. For example, particular skills may be valued as end goals of themselves within the engineering curriculum, resulting in a fragmented learning experience that leaves gaps in students' abilities [13]. Therefore, the challenge of these trade-off decisions calls for critical reflection to guide curriculum decision-making and pedagogical approaches. We reframe the challenge of making trade-off decisions as an opportunity to align our educational values, reflect on our instructional approaches, and evaluate our feedback and assessment mechanisms to support student learning. We focus our approach on larger system learning goals that operate at the societal level within our system of education, that is, learning goals that focus on students' engineering professional development and their personal growth. In this way, the conception of larger learner goals encompasses elements for personal student growth such as the elements identified by [30] as the development of leadership skills and initiative, teamwork capabilities, a mindset of adaptability and flexibility, an awareness of societal impacts, self-confidence, and self-identity.

For this paper, we explore larger learning goals in the context of an introductory engineering design and graphics course. These larger learning goals extend beyond the technical skills that students are expected to develop through regular homework, labs, projects, and assessments. While students will be developing their visuospatial skills while learning a particular modeling software and making hand sketches, students are also understanding the practice of engineering through engineering standards of communication and through the engineering design process. Additionally, this course allows students the opportunity to develop their leadership and communication skills through focused team design work requiring adaptability and flexibility. Moreover, through these challenges students will continue to develop self-confidence in their abilities and refine their developing engineering identities. Specifically for this paper, the targeted overarching larger learning goal was to support students in making connections between their engineering courses and their future careers, in ways that would "encourage students to reflect on their assumptions and their personal ways of meaning-making" [26, pp. 154–155]. We aligned our focus on larger learning goals with two existing course goals:

1. To introduce engineering design methodology, and to demonstrate the role of graphics in the engineering design process.
2. To provide insight into the product design process, in particular as it relates to the architecture and functionality of the product.

For this research project, these two course goals were identified as the most relevant for supporting students in framing their learning of design around larger learning goals for their professional and personal development. Specifically, both of these course goals speak to the embeddedness of particular engineering tools and processes within broader engineering activities. For course goal #1, "the role graphics in the engineering design process" points to the purpose and use of graphics in engineering design, and for course goal #2, the "product design process" is held in relation to designing for "architecture and functionality of the product". We used these two course goals as a starting point for thinking about how our course specific larger learning goal, that of supporting students in critical reflection for making connections between their engineering courses and future careers, could be achieved.

3. Model Synthesis

In response to the three engineering education curriculum tensions previously identified, we present a synthesized conceptual model for thinking about larger system learning goals, and how engineering educators may transcend the different system level tensions. Our model draws on theoretical perspectives from experiential learning, novice-expert development, and design practice, with each perspective offering insight into ways of reframing our educational approach towards larger learning goals.

3.1 Experiential Learning

Experiential learning theory has been used in engineering education in a number of different ways for curriculum development and instructional design (see [31]). For example, opportunities such as client-based design projects, cooperative education and internships, service-learning, active learning, and problem-based learning may all be broadly considered as forms of experiential learning, since the goal of these opportunities is to expose students to authentic learning contexts and direct experience with authentic problems. Through these experiences, learning is possible as "knowledge is continuously derived from and tested out in the experiences of the learner" [32, p. 27].

For this paper, we focus on the elements of experiential learning described by Kolb's experiential learning model that highlights a cycle of four adaptive learning modes: concrete experience, reflective observation, abstract conceptualization, and active experimentation [32, p. 40]. The learning modes are described as "adaptive" because each mode represents a distinct way of "dealing with the world" (p. 29), and learning occurs from resolving conflicts across these learning modes [32]. While students may have a direct experience with a particular problem (concrete experience) or generate some symbolic representation (abstract conceptualization), learning requires that students make meaning of this experience through reflection (reflective observation) and/or testing of these new concepts in the world (active experimentation) [32]. Based on these aspects, Kolb [32] framed learning as "the process whereby knowledge is created through the transformation of experiences" (p. 38).

Against the backdrop of experiential learning, we see engineering analysis and design as creating opportunities for experiences towards authentic engineering practice. This frame focuses on the process of learning and moves away from the view of engineering analysis and design as outcomes of education or skills to be learned (see [32]).

3.2 Novice-Expert Development

For expert functioning, Scardamalia and Bereiter [33] proposed that experts interact between domain knowledge and immediate cases in such a way that "domain knowledge is used to interpret or deal with the immediate case (p. 175). A dialectical process ensues as "the immediate case yields information that may be used to modify domain knowledge" [33, p. 175]. Based on Scardamalia and Bereiter's [33] theory of expertise development, we represent engineering learning by two spaces, referred to as the *general* and the *particular* [34]. The "general" space refers to general domain knowledge of engineering, while the "particular' pertains to specific cases of using engineering to reach a goal. Development of expertise occurs through a back-and-forth process between general domain knowledge and that of particular cases or problems [33, 34]. Therefore, at the course level, the spaces of the general and particular do not distinguish between learning for engineering analysis or engineering design. That is, learning for engineering analysis and design may occur in either the general or particular space depending on the instructional learning objectives. For example, in a graphics course as shown in Table 1, the learning of section views as an engineering tool (general space) may be used in the analysis of an object and to communicate ideas in product development (particular space). Furthermore, translating this concept for larger learning goals in our project involves seeing one's learning from engineering coursework (general space) and how that learning may be connected to other courses and one's future career (particular space).

3.3 Design Learning and Practice

Theories of design learning and practice place the first two theories in the context of engineering. Experiential learning theory [32] and theory of expert functioning [33] supports the back-and-forth movement that is characteristic of learning. In order to develop design expertise, Adams, Turns, and Atman [34] draw on the theory of expert functioning [33] to emphasize how students should engage in "repetitive cycles between the general and the particular" [34, p. 18]. There are a number of

Table 1. Examples of the general and particular space of learning

	Graphics Course (at course system level)	**Larger Learning Goals** (at society system level)
General – as engineering tools	Sketching and section views	Learning from engineering coursework
Particular – as specific case for use of engineering tools towards a goal	Communicating ideas in product development	Seeing connections between courses and connections to future careers

design practices that describe a general back-and-forth movement [34]. For example, iteration as a design activity involves feedback loops, moments of reflection to monitor progress, the use of design strategies multiple times, and the improvement of design ideas whereby designers are "cycling back to upgrade their understanding of the problem" [1, p. 769]. Oher activities related to learning and design such as reflection [35, 36], and testing and experimentation [1], are particularly applicable in illustrating the important of the back-and-forth movement that promotes learning. Schön [36] described the "reflective conversation" that occurs between designers and the design situation, as designers construct and reconstruct their environments to determine the objects and relationships that are part of the design situation. Testing and experimentation as a design practice involves conducting investigations that help designers "learn quickly about design variables, users, and materials, to understand how things work, and to optimize the performance of the prototypes" [1, p. 765]. In the context of design, Kokotovich and Dorst [37] describe a similar back-and-forth movement as "stepping back", where designers "demonstrate a capacity for stepping into an exploratory development cycle which moves from mentally modelling very concrete levels of abstraction to higher levels of abstraction" (p. 80). Similar to the experiential learning process, Kokotovich and Dorst [37] call attention to the nature of experience and abstraction in design:

> "As we move through the world of objects, relationships and events, we develop experiential knowledge that allows us to think about the experiences we have had, and aids in developing abstractions, that is, general interpretations in relation to them." [37, p. 81]

As demonstrated through the cyclical process of experiential learning [32] and through various design practices, we have demonstrated here how this back-and-forth movement is a characteristic feature of learning and design practice (see [34]). In the next section, we integrate insight from the three theoretical perspectives to offer a model for thinking about engineering learning.

4. A Synthesized Model for Thinking about Engineering Learning

The synthesized model for thinking about engineering learning focuses on three key frames for thinking about curriculum and instructional approaches across the three system level tensions (Fig. 2): (Frame 1) systems of learning and their interactions (Frame 2) engaging general and particular spaces of learning and (Frame 3) the role of reflective thinking for making meaning of experiences. Within Frame 1, we see engineering analysis and design as one system – one process, one mechanism, one tool – in support of engineering formation and to prepare students to face the challenges of contemporary society. These mechanisms and systems may take the form of engineering concepts and tools, pedagogical approaches, assessment methods, and instructional strategies. For Frame 2, the model highlights the spaces of the *general* and *particular* and challenges us to consider what instruction for the general and particular spaces may look like across systems level goals. We align our instructional approach to focus on ways of creating opportunities for students to learn in the general and particular space for larger system learning goals. Finally, Frame 3 focuses on the need to engage students in the back-and-forth meaning-making process between the general and particular space that is consistent with learning and design practice. Through these three frames, curriculum challenges that appear to require trade-off decisions, can be reframed to focus on larger learning goals of engineering education across system level tensions. For

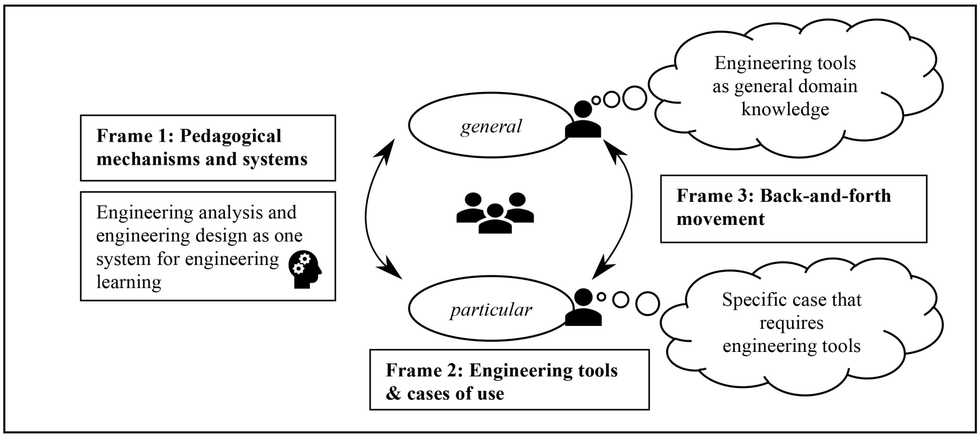

Fig. 2. A synthesized model for thinking about engineering learning.

example, the tension between teaching for engineering analysis and engineering design is reframed such that engineering analysis and engineering design are one system that mediates the back-and-forth movement between the general and particular spaces of learning.

In thinking about our curriculum and instructional approach for larger learning goals, our model prompted us to ask reflective questions about our practice (see [26, pp. 114–116]) within the three frames:

Frame 1: Pedagogical mechanisms and systems that work together to support students' learning

- What mechanisms and systems are facilitating students' learning?
- How are these mechanisms and systems interacting to support students' learning?
- Why are these mechanisms and systems important for students' learning?

Frame 2: General and particular spaces highlight engineering tools and specific cases of use

- What general and particular spaces do we want students to explore?
- How are these general and particular spaces related to our instructional goals?
- Why are these general and particular spaces important for our instructional goals?

Frame 3: Back-and-forth movement for making meaning of experience

- What back-and-forth movements do we want students to experience?
- How are we supporting students in engaging these back-and-forth movements?
- Why are these back-and-forth movements important for our instructional goals?

These questions are not intended as a prescriptive list, but allow us to think critically of our teaching practice and examine our personal views as a scholarship of teaching (see [26, pp. 114–116]). Additionally, while our focus has been on supporting larger system level learning goals, responses to these questions will depend on the instructional goals that are unique for each learning situation.

5. Research Design

To explore the use of our model in curriculum and instructional development, we conducted a pilot research project aimed at facilitating students' thinking about their engineering formation and personal development. Specifically, our model was applied to support students in seeing larger learning goals of their development and how it relates to their coursework and their future careers. The research question that guided this project was as follows: In what ways do students make connections between the course content and their broader engineering learning goals and careers? In this paper, we draw on empirical data to illustrate the frames of the model and how the model may be used to explore aspects of engineering formation and personal development.

5.1 Participants & Classroom Context

This research took place at a large Midwestern University in an introductory engineering design and graphics course in the Spring of 2019. Students (n = 97) in this 100-level course were predominantly first-year students from majors including Aerospace, Agricultural & Bioengineering, Electrical, Industrial, Materials Science, Pre-engineering, and Systems Engineering. Approximately 25% of the students are female in this semester.

In the course, students completed individual lab assignments of sketching and computer modeling. A large component of the course centers around a team project in which teams of four to five students work with a physical consumer product (such as a manual coffee grinder, hand mixer, toy quadcopter, or Da Vinci clock) to understand and model the product's mechanical movement. Students dissect and dissemble the product to re-engineer and model the product, and use engineering tools of function decomposition diagrams, computer aided design (i.e. Autodesk Inventor), and a beginning finite element analysis. Student teams are also challenged to think about opportunities for product improvements. Teams participate in three design reviews to receive guidance and feedback regarding their technical progression and design process.

5.2 Data Collection

We used our conceptual model to design a series of reflection exercises to elicit students' thinking in the general and particular spaces applicable to our larger learning goals. The reflection activities were completed outside of class and were collected through the course electronic platform with reflection #1 assigned in week 2, reflection #2 in week 13, and the final reflection in week 15 of a 16-week semester. With the reflections spread throughout the course, we expected students to base their response on their introductory expectations of the course and their previous experiences. As the course progressed, we hoped to see students develop a more informed understanding of the course and their learning trajectory. As shown in Table 2, the first reflection explicitly targeted an understanding of connections students may make between the course

Table 2. Reflection exercises for eliciting students thinking

Reflection #1	**Reflection #2**	**Reflection #3**
As engineers, we often think in terms of systems to see how parts are related to wholes. Your instructor encourages you to think about how this course is a part of your broader engineering learning. Please respond to the following questions: 1. How might your learning in this course help you in your undergraduate engineering studies? 2. How might your learning in this course help you in your future career?	Your instructor is interested to understand how you connect your learning about engineering graphics in this course with what it means to do engineering work. Think about the activity on Section Views that you completed recently. 1. How does your ability to draw and interpret Section Views relate to your development of spatial visualization skills? 2. What role do you anticipate your spatial visualization skills having in your upcoming engineering coursework?	This course aims to help you learn and grow as a future engineer, so that you have the appropriate "tools" to solve engineering problems. For example, these "tools" may be knowledge of math and science to analysis the strength of materials, or the critical thinking skills to assess a situation and make an informed decision. 1. What kind of "tools" have you developed so far in this course? 2. What do you feel is the most important aspect of these "tools" that will help you in your future engineering studies?

content and their undergraduate engineering studies, as well as between the course content and their future careers. The second reflection focused on eliciting connections between a specific class topic (i.e. section views) and the course goal of developing spatial visualization skills, and the connection between these spatial visualization skills and upcoming engineering coursework. The third reflection prompted students to consider the kind of engineering tools they have developed in the course and the qualities of these tools that will be most important in their future engineering studies.

5.3 Data Analysis

We performed a content analysis to systematically categorize students' open-ended responses to each of the three reflection activities. The analysis was iterative, moving from inductive to deductive states so that themes would emerge from the data [38] and would allow us to link back to our conceptual model. Our goal was to understand students' trajectory in the class rather than at one stand-alone time, so reflection responses were analyzed together. Our conceptual model provided a lens for categorizing and interpreting students' connections. Two examples with pseudonyms are presented in this section to illustrate our conceptual model for engineering learning presented in Fig. 2 and to provide empirical data for richer context of our model. Each of the two examples (5.3.1 through 5.3.2) will first show the data from the first reflection before explicitly demonstrating how this data illustrates the conceptual model. Then, the example will continue with the second and final reflection data to show connections to the model.

5.3.1 Reed – A Retrospective Perspective to see the usefulness of Engineering Tools

> "As a senior, I have always wanted hands on opportunities to apply the things I have been learning to real life. By taking CAD, and with the help of 3D printing, this will become possible in many new ways I couldn't have imagined previously. Additionally, I think this course will help with my general spatial reasoning, which is useful and widely applicable throughout engineering."

> "I personally am interested in electronics, and while the CAD software we will learn doesn't specifically apply to electronics, it may be used for the housings or support, or in general product design. Not only so, but the general principles learned in this course will most likely be applied no matter what field I end up in."

Reed's reference to "hands on opportunities to apply things" is indicative of **Frame 1: Pedagogical mechanisms and systems**, where hands-on opportunities may provide a mediating mechanism between learning in the classroom and "real life" applications. He links the utility of spatial reasoning skills (as engineering tools) with connections in "general product design", pointing to **Frame 2: Engineering tools & cases of use** in the general and particular spaces of learning respectively. Reed also compares his personal interests in electronics with the use of CAD software in the course. This statement is indicative of **Frame 3: Back-and-forth movement** as Reed makes meaning of the relevance of the course material although the software learned "doesn't specifically apply to electronics". Reed further illustrates aspects of **Frame 2: Engineering tools & cases of use** as he shares his view that "general principles" from the course may be applied more broadly despite his chosen career field.

> "My spatial visualization skills have improved with my ability to draw and interpret section views. Drawing section views helps me visualize complex shapes and their intricate details without seeing the real part in 3 dimensions. Interpreting the views is still a challenge, but that allows my visualization skills to continue to improve."

> "As a senior, I wish I had taken this class earlier, as it would have helped my understanding of many mechanical concepts that I have encountered throughout my college experience. Any improvement in my ability to solve problems strategically and understand complex situations improves my ability to function as an engineer."

In his second set of reflections, Reed continues to link the class to other engineering topics with his retrospective approach that looks back on his time in the program: "I wish I had taken this class earlier". In **Frame 2: Engineering tools & cases of use,** he links the general engineering tools (i.e. section views) to the specific case for use of the engineering tool towards a goal (i.e. visualization skills for seeing a part). He uses the reflection for his own personal meaning-making, aligned with **Frame 3: Back-and-forth movement**, by identifying personal challenges with "interpreting the views" and the opportunities for growth that come along with this challenge. In **Frame 1: Pedagogical mechanisms and systems,** Reed sees his problem solving skills as contributing to his formation of engineering by connecting to his "ability to function as an engineer".

> "I have further developed my problem solving skills, and have added the ability to discern what design aspects are critical and nonessential. Additionally, my spatial reasoning has certainly improved during this course so that I can better perceive and think through engineering problems and designs."
>
> "These tools come with a wide range of applicability and perseverance that will help me for the foreseeable future in my engineering career."

In his final set of reflections in the second to last week of class, Reed discusses the tools he has developed over the course of the semester. Rather than focus on particular tools such as the modeling software, he discusses broader abilities such as problem-solving skills, "the ability to discern what design aspects are critical and nonessential", and spatial visualization skills (**Frame 2: Engineering tools & cases of use**). He also related his improvement of these skills with the overarching need to "perceive and think through engineering problems and designs", pointing to his connections for making meaning (**Frame 3: Back-and-forth movement**). By recognizing the "wide range of applicability" of the tools and the identification of perseverance in his experience, he points to elements of the tools and of his experience that were part of his learning (**Frame 1: Pedagogical mechanisms and systems).**

5.3.2 Brook – A Big Picture View of Communication and Visualization

> "I have found that my opinion on the philosophy of learning varies quite starkly from most of my peers in engineering. I have always held the belief that being competent in areas of study outside of your own is an integral part of one's education on the whole. This being said, I feel that the principles of design and knowledge of a prevalent design software are two keys to success in engineering, in spite of the outmoded notion that STEM and art are not in any way correlated. Besides the obvious benefit of learning a new software, I feel that [this course] will help me develop how I think through solving physical problems and thus strengthen my communication skills as an engineer. It will help bridge the disconnect between having a personal understanding of how to solve and approach engineering-based questions and thus help me translate into diagrams to create a coherent message."
>
> "In any modern career, an understanding of any type of software correlating to one's field of study is important as society is continually making strides towards a completely digitized world. This will thus serve as a skill that future employers will deem important and may be a point for which I could be hired one day. In addition, having the skills to communicate visually will prove to be important when presenting ideas and solutions to peers and executives to further clarify our discussion. Having a sense of design and space is also important when making estimates out in the field and when designing products and projects with the user in mind. Overall, [this course] will help develop my approach to design and creative thinking and reasoning."

Brook demonstrates a systems view to see the big picture of engineering education as being broader than engineering skills alone. This systems view is representative of **Frame 1: Pedagogical mechanisms and systems**, where she alludes to the importance of a multifaceted education in her reflection: "being competent in areas of study outside of your own is an integral part of one's education on the whole". Brook sees the value of the course in helping develop her thinking to solve physical problems and communicate. Specifically, indicative of **Frame 2: Engineering tools & cases of use**, she mentions two different applications of communication skills to "translate into diagrams to create a coherent message" and to "communicate visually . . . when presenting ideas and solutions to peers and executives to further clarify our discussion". Moreover, in recognizing that her views may be different from her peers and by offering her critique of "the outmoded notion that STEM and art are not in any way correlated", we see Brook offering her voice and making meaning as she states how this course will help "bridge the disconnect between having a personal understanding of how to solve and approach engineering-based questions" (**Frame 3: Back-and-forth movement**). Throughout her reflection, we see Brook place a focus on knowing the design software (as an engineering tool in the general domain knowledge) and articulate the meaning of this knowledge as a marketable skill that may be attractive to future employers (**Frame 3: Back-and-forth movement**). We further see meaning-making of Brook's experiences (**Frame 2: Engineering tools & cases of use and Frame 3: Back-and-forth movement**) through the second portion of this first reflection as she connects the value and use of "a sense of design and space" (general) to "making estimates out in the field and when designing products and projects with the user in mind" (particular), and extended to broader elements of visual communication, creative thinking, and reasoning.

> "At first, I found visualizing section views to be rather difficult. It requires translating a rather cryptic, oversimplified expression of a three-dimensional object, something that I never really had experience doing. That being said, this ability to use context clues given in the multiviews given has really allowed me to practice and overall become much better at spatial visualization. Section views are especially useful because of their level of complexity added to visualization: visualization of what lies beneath the surface."
>
> "I feel that in any sort of design challenge in which a part or object must be made to fit a specific requirement, imagining the space it needs to occupy in relation to other working parts is especially important. I have had an opportunity to practice the aforementioned challenge in my job in research as a lab assistant at the [Sciences Building]."

In this second reflection, Brook discusses the difficulty in section views (i.e. a general content of the course) to her broader understanding of spatial visualization (i.e. a particular goal of the course) (**Frame 3: Back-and-forth movement**). Brook offers her own take on the affordance of visualization as "visualization of what lies beneath the surface" (**Frame 3: Back-and-forth movement).** In another articulation of her learning in the general space of the course and a particular use case, Brook relates a specific design challenge (and high-level goal of the course) with her current professional work (**Frame 2: Engineering tools & cases of use and Frame 3: Back-and-forth movement**).

> "I think I have developed a tool in the use of Inventor, and even further than just the application itself, a more structured approach to learning a new computer software. I also think I have developed a skill in spatial reasoning from sketching."
>
> "I feel that the most important aspect is the process of approaching learning in a structured way."

In her final reflection of the semester, Brook begins by talking about engineering tools, the modeling software Inventor, and sketching (**Frame 2: Engineering tools & cases of use).** She relates these general tools to their particular spaces that requires these engineering tools (i.e., "a more structured approach to learning a new computer software" and spatial reasoning) as an indication of meaning-making in **Frame 3: Back-and-forth movement**. She summarized her most important aspect of learning the tool in the course as an understanding of "the process of approaching learning in a structured way" (**Frame 1: Pedagogical mechanisms and systems).**

6. Discussion and Implications

The reflection exercises aimed to provide the opportunity for students to reflect on their experiences and begin to see ways where they may direct their own learning by making connections within their coursework and future careers. The sets of reflections suggest the value of reflective thinking for meaning-making as these two students make their values for learning and connections between classroom learning and future practice explicit.

The two examples of students' reflections illustrate the three different frames from our model that students may experience. Students may recognize mechanisms in support of their learning (Frame 1: Pedagogical mechanisms and systems), identify aspects of the general and particular spaces of learning (Frame 2: Engineering tools & cases of use) and make meaning through the movement between the general and particular spaces of learning (Frame 3: Back-and-forth movement). Through our analysis, we aim to bring attention to elements that exist in the frames and to foster critical reflection on how these elements may be further elicited and supported in students' development. In addition, we have shown how these three frames offer one way for reframing approaches to balance curriculum design trade-offs arising from system level tensions between teaching for (1) design and analysis, (2) technical and professional skills, and (3) engineering formation and personal growth.

Although the model may be broadly applicable for use in any engineering course and for diverse learning objectives, we have focused our application towards supporting students in thinking about their engineering and personal formation in the context of an introductory graphics and design course. We encourage instructors to consider the ways that students may be experiencing the back-and-forth movement between the general and particular spaces of learning, when it comes to the instruction of technical subject matter, professional formation, and personal growth. In this way, our model aims to support instructors in identifying and developing an articulation of the general and particular spaces of learning that may be applicable and appropriate to their learning objectives. Our model also offers instructors ways of thinking about how their course may be situated in a broader learning system and how connections between courses may begin to form in students' learning. For example, through Frame 1, different mechanisms, concepts, or tools, may be used to connect across courses. With Frame 2, common elements may be used in the general and particular spaces of learning that offer students with consistent frameworks or integrative experiences for making meaning of their learning.

Moreover, for educators who experience the tension of teaching for technical abilities and professional skills, these findings show how a series of intentional and guided mini-reflections offers opportunities for students to make connections between technical and personal learning.

The model we have presented is highly context dependent, and its interpretation and use will vary based on an individual faculty's instructional objectives. In this paper, we have used our model to illustrate instructional approaches towards larger system learning goals and as a means for navigating the system level tensions. Future work to develop examples of the model for a variety of learning objectives will further support the application of the model. Therefore, the model is not meant to be prescriptive, but offers ways that instructors may consider the larger learning goals of their course, and how the values of the instructor, department and degree program, and university align across curriculum system levels.

7. Conclusions

In this paper, we offer an approach to navigate instructional design decisions and trade-offs through the development and exploration of a conceptual model that targets larger system learning goals. The application of the model to think about curriculum decisions and instruction has prompted us to consider our values as engineering educators, and how we may think of larger system learning goals for students' professional formation and personal growth. Navigating these curriculum and instructional trade-offs is challenging to do alone. We are grateful for collaborative partnerships that support the sharing of ideas from different perspectives, and the critical evaluation and feedback of our teaching practices that comes from our own reflective practice.

Acknowledgements – We are grateful to the students who shared their reflections as part of this study.

References

1. D. P. Crismond and R. S. Adams, The informed design teaching and learning matrix, *J. Eng. Educ.*, **101**(4), pp. 738–797, 2012.
2. ABET, *Criteria for accrediting engineering programs, 2019–2020*, Baltimore, MD, 2018.
3. S. D. Sheppard, The compatibility (or incompatibility) of how we teach engineering design and analysis, *Int. J. Eng. Educ.*, **17**(5), pp. 440–445, 2001.
4. E. T. Layton, *The revolt of the engineers: Social responsibility and the American engineering profession*, Cleveland, OH: Press of Case Western Reserve University, 1971.
5. C. L. Dym, Design, systems, and engineering education, *Int. J. Eng. Educ.*, **20**(3), pp. 305–312, 2004.
6. W. Neeley, S. Sheppard and L. Leifer, Design is design is design (or is it?): What we say vs. what we do in engineering design education, in *Proceedings of the American Society for Engineering Education*, 2006, p. 16.
7. C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey and L. J. Leifer, Engineering design thinking, teaching, and learning, *J. Eng. Educ.*, **94**(1), pp. 103–120, 2005.
8. S. A. Ambrose and C. H. Amon, Systematic Design of a First-Year Mechanical Engineering Course at Carnegie Mellon University, *J. Eng. Educ. Vol.*, **86**, pp. 173–182, 1997.
9. D. S. Strong, An approach for improving design and innovation skills in engineering education: The multidisciplinary design stream, *Int. J. Eng. Educ.*, **28**(2), pp. 339–348, 2012.
10. C. D. Pionke, E. Seat, and J. R. Parsons, Analysis vs. design: Why the versus?, *Int. J. Eng. Educ.*, **20**(3), pp. 440–446, 2004.
11. J. A. Shaeiwitz, Teaching design by integration throughout the curriculum and assessing the curriculum using design projects, *Int. J. Eng. Educ.*, **17**(4 & 5), pp. 479–482, 2001.
12. B. Linder and W. C. Flowers, Integrating engineering science and design: A definition and discussion, *Int. J. Eng. Educ.*, **17**(5), pp. 436–439, 2001.
13. J. Walther and D. F. Radcliffe, The competence dilemma in engineering education: Moving beyond simple graduate attribute mapping, *Australas. J. Eng. Educ.*, **13**(1), pp. 41–51, Jan. 2007.
14. S. Sheppard, A. Colby, K. Macatangay, and W. Sullivan, What is engineering practice?, *Int. J. Eng. Educ.*, **22**(3), pp. 429–438, 2006.
15. E. F. Redish and K. A. Smith, Looking beyond content: Skill development for engineers, *J. Eng. Educ.*, **97**(3), pp. 295–307, Jul. 2008.
16. Grasso and Burkins, Eds., *Holistic engineering education: Beyond technology*, New York, NY: Springer, 2010.
17. S. D. Sheppard, K. Macatangay, A. Colby and W. M. Sullivan, *Educating engineers: Designing for the future of the field*, San Francisco, CA: Jossey-Bass, 2009.
18. B. Frank, D. Strong and R. Sellens, The professional spine: Creation of a four-year engineering design and practice sequence, *Proc. Can. Eng. Educ. Assoc. CEEA*, Jun. 2011.
19. K. Lulay, H. Dillon, T. Doughty, D. Munro and S. Vijlee, Implementation of a design spine for a mechanical engineering curriculum, in *Proceedings of the American Society for Engineering Education*, Seattle, Washington, 2015.
20. D. Riley, Pushing the boundaries of mass and energy: Sustainability and social justice integration in core engineering science courses, in *Proceedings of the American Society for Engineering Education*, Seattle, Washington, 2015.
21. A. G. Eggleston and R. J. Rabb, Technical communication for engineers: Improving professional and technical skills, *Proc. Am. Soc. Eng. Educ.*, 2018.
22. K. Hunter and J. Matson, Engineering leadership and teamwork development through experiential learning, in *Proceedings of the American Society for Engineering Education*, Albuquerque, NM, 2001.
23. National Science Foundation, Research in the formation of engineers, *National Science Foundation*, 2019. [Online]. Available: https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503584&org=ENG. [Accessed: 31-Mar-2019].

24. J. Walther, N. Kellam, N. Sochacka and D. Radcliffe, Engineering competence? An interpretive investigation of engineering students' professional formation, *J. Eng. Educ.*, **100**(4), pp. 703–740, Oct. 2011.
25. M. Baxter Magolda and P. M. King, *Learning partnerships: Theory and models of practice to education for self-authorship*. Sterling, VA: Stylus Publishing, 2004.
26. C. Kreber, *Authenticity in and through teaching in higher education*. New York, NY: Routledge, 2013.
27. C. Koshland, Liberal arts and engineering, in *Holistic Engineering Education: Beyond Technology*, D. Grasso and M. Burkins, Eds. New York, NY: Springer, 2010, pp. 53–67.
28. L. L. Bucciarelli and D. E. Drew, Liberal studies in engineering – a design plan, *Eng. Stud.*, **7**(2 –3), pp. 103–122, Sep. 2015.
29. N. Noddings, *Philosophy of education*, Boulder, CO: Westview Press, 2016.
30. K. T. Deahl, E. Walz, R. l. Korte, V. Werpetinski, L. D. Hahn, J. A. Sunderman and J. B. Litchfield, Knowledge, skills, and attitudes acquired through engineering student experiences abroad, in *Proceedings of the American Society for Engineering Education*, Atlanta, GA, 2013, p. 19.
31. P. C. Wankat and F. S. Oreovicz, *Teaching engineering*, 2nd ed. West Lafayette, IN: Purdue University Press, 2015.
32. D. A. Kolb, *Experiential learning: Experience as the source of learning and development*, Upper Saddle River, NJ: Prentice Hall, 1984.
33. M. Scardamalia and C. Bereiter, Literate expertise, in *Towards a general theory of expertise: Prospects and limits*, K. A. Ericsson and J. Smith, Eds. New York, NY: Cambridge University Press, 1981, pp. 172–194.
34. R. S. Adams, J. Turns and C. J. Atman, What could design learning look like?, in *Design Thinking Research Symposium*, University of Technology, Sydney, Australia, 2003.
35. D. A. Schön, *The reflective practitioner: How professionals think in action*, New York, NY: Basic Books, 1983.
36. D. A. Schön, Designing as reflective conversation with the materials of a design situation, *Res. Eng. Des.*, **3**(3), pp. 131–147, Sep. 1992.
37. V. Kokotovich and K. Dorst, The art of 'stepping back': Studying levels of abstraction in a diverse design team, *Des. Stud.*, **46**, pp. 79–94, Sep. 2016.
38. M. Q. Patton, Qualitative research, in *Encyclopedia of Statistics in Behavioral Science*, John Wiley & Sons, Inc., 2005, pp. 1633–1636.

Richard J. Aleong is a PhD candidate in the School of Engineering Education at Purdue University. His research interests are in interdisciplinarity, faculty development, and the scholarship of teaching and learning in higher education. His dissertation work aims to understand the practices of interdisciplinary collaboration that leverage multiple perspectives. Richard is committed to designing holistic educational experiences that support learners' personal and professional growth. He earned his MASc and BScE in Mechanical and Materials Engineering from Queen's University, Kingston, Canada.

Molly H. Goldstein is an engineering design educator and researcher at University of Illinois, Urbana-Champaign. Molly earned her PhD in Engineering Education at Purdue University. Molly's research focuses on student designer trade-off decisions through the study of their design actions and thinking. She earned her BS in General Engineering (Systems Engineering & Design) and MS in Systems and Entrepreneurial Engineering, both from the University of Illinois, Urbana-Champaign. Prior to pursuing her PhD, she worked as an environmental engineer, influencing her focus in engineering design with environmental concerns.