Mapping Disciplinary Conceptions of Engineering Design Processes in Undergraduate Courses

Katherine Drinkwater Gregg, Virginia Polytechnic Institute and State University

Katie Drinkwater Gregg is a PhD candidate in Engineering Education at Virginia Tech. She holds an MS and BS in Mechanical Engineering. Katie researches decision-making in engineering design, peer feedback literacy, out-of-class activities for engineers, and women in engineering.

Cassie Wallwey, Virginia Polytechnic Institute and State University

Dr. Cassie Wallwey is a Collegiate Assistant Professor in the Department of Engineering Education at Virginia Tech. Her research interests center on student-centered and inclusive learning practices and principles including student engagement in learning, feedback and assessment, self-regulation of learning, and student motivation. Cassie got her PhD in Engineering Education from Ohio State University and her MS and BS in Biomedical Engineering from Wright State University.

Dr. Benjamin Daniel Chambers, Virginia Polytechnic Institute and State University

Dr. Ben Chambers is an Assistant Collegiate Professor in the Department of Engineering Education at Virginia Tech, and Director of the Frith First Year Makers program. His research focuses include the interactions of non-humans with the built environment, the built environment as a tool for teaching at the nexus of biology and engineering, and creativity-based pedagogy. He earned his graduate degrees from Virginia Tech, including an M.S. Civil Infrastructure Engineering, M.S. LFS Entomology, and a Ph.D. in Environmental Design and Planning.

Matthew James P.E., Virginia Polytechnic Institute and State University

Matthew James is an Associate Professor of Practice in the Department of Engineering Education at Virginia Tech, where he currently serves as the department's first-year program coordinator. Since joining in 2017, Matt's work has centered on teaching and curriculum development for the general engineering program, with a focus on foundational experiences for first-year students. He holds B.S. and M.S. degrees in Civil Engineering from Virginia Tech and is a licensed Professional Engineer in the State of Virginia. Before moving into academia, Matt worked in land development planning and design, contributing to projects in stormwater management, airport design, floodplain modeling, site development, and construction document preparation. In his teaching, Matt supports a project-based learning approach to help students develop professional and technical skills relevant to engineering practice. He has contributed to scholarship of teaching and learning through research interests that include first-year engineering education, service learning, and international engagement. In addition to teaching and research, he serves as the faculty advisor to several student design teams, including the Virginia Tech chapter of Engineers in Action.

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Introduction

Design is a fundamental part of what it means to do engineering work. Some definitions characterize engineering as a form of design, like Wulf's definition of engineering as "design under constraint" [1, p. 23]. The foundational role of design in engineering is represented in engineering education through ABET student outcome three, which states that all engineering students will develop "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]. After students graduate, their ability to work on open-ended design problems is key to success in industry.

To prepare students to satisfy outcome three and to be successful in their careers, ABET requires that all students participate in a major design experience, typically a capstone course [2]. In recent decades, engineering educators have recognized that design education should begin before a student's final year. First-year and middle-year cornerstone courses are now common infusions of design throughout the curriculum [3]. More opportunities to practice design help students develop important competencies, but this also means more faculty are teaching design. Differences in department, course, or instructor can introduce substantial differences in the design approach taught.

It is well recognized that different engineering disciplines have different foci, practices, norms, and cultures [4], [5]. Disciplinary divides are particularly strong in academia, where college and department structures reinforce delineations that may not exist in the public sector [6]. While these differences are both the source and result of boundaries between disciplines, they do affect how students perceive and develop interest in engineering [7], [8]. Thus, it is relevant to consider how disciplinary culture and identity could impact instruction of similar topics across engineering. Design is one such topic that is taught in every ABET accredited engineering program, so how might design education differ across disciplines?

This study examines the question of disciplinary differences in design education by focusing on engineering faculty who teach undergraduate design courses. Our inquiry is motivated by our roles as instructors for first-year, general engineering courses that teach design to students who have not chosen a major. We attempt to present a conceptualization of design in our courses that can apply to all engineering disciplines, but it is not known how our conceptualization differs from the types of design students will encounter in future courses. Through interviews, we examined faculty conceptualizations of engineering design in their disciplinary undergraduate courses. We sought to answer the following research question: how do different disciplines represent unique and common elements of engineering design in undergraduate courses? By analyzing how faculty define and teach design, we contribute to understanding the differences in disciplinary identity that impact the practice and teaching of engineering design.

Background

To further contextualize our study of faculty conceptions of engineering design, this section discusses popular definitions of engineering design, previous work that compares design concepts and practices, and our chosen design process model for this study.

Defining Engineering Design

Studies on engineering design often take either a prescriptive or descriptive approach: that is, an ideal view of how the design process should operate (prescriptive), or a description of the habits and practices of the designers as they occur (descriptive). Many courses in engineering programs are based on ABET's definition, which frames design as a decision-making process, noting the importance of iteration and creativity. This definition breaks design down into a combination of best practices and a series of phases: "identifying opportunities, developing requirements, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks, and making trade-offs, for the purpose of obtaining a high-quality solution under the given circumstances" [2]. This definition is largely prescriptive, framing design as a technique that engineers use to apply technical knowledge in a specific context to achieve a desired outcome. The suggested phases, however, are not organized in any prescriptive order. To organize design phases sequentially, several models with prescriptive approaches have been developed, notably Pahl & Beitz's model that divides design into four major phases: *planning and task clarification, conceptual design, embodiment design, and detail design* [9]. In this model, each phase becomes more nuanced and detailed as the designers work towards a final solution.

On a professional level, several states have adopted a systematic approach to design such as that outlined in the Virginia Construction and Professional Services Manual, which divides engineering design services for publicly funded Capital Projects into *schematic design, preliminary design, and working drawing (construction documents) phases* [10]. Interestingly, in this model, professional engineering designers are largely left out of the initial "big picture" project scoping phase of the design process, with that portion of the work left primarily to state agencies. This model shows that engineers can enter and finish the design process at different stages.

Descriptive design approaches look more closely at the mindsets and habits of engineering designers and emphasize "design thinking" [11]. Osgood & Johnson synthesized relevant literature and interviews with practicing design engineers across several disciplines into the following nine practices of design engineers: *Collaborative, Confident, Creative, Independent, Intuitive, Inquisitive, Motivated, Systematic, and Versatile* [12]. This represents a cognitive approach to defining design by trying to understand the thought processes of those doing the designing, rather than the actualization of their work. Atman et al. [13] also studied the ways that designers approach their work by comparing novices (students) with expert practitioners. Differences between novice and expert designers were organized into a framework of five design themes: *problem scoping, project realization, alternative solutions generation, distribution of activity over time, and solution quality.*

Comparing Design Practices

As our study seeks to compare design conceptualizations across engineering faculty, it is important to discuss extant work that compares design definitions and processes. Relevant literature has compared design practice between engineering and non-engineering disciplines, novice and expert engineering designers, and broader concepts of engineering among faculty.

Design practice exists in many disciplines outside of engineering. Art, architecture, aesthetics, and other fields all practice design. Daly [14] interviewed designers from a wide range of disciplines to identify how their conceptualizations of design differed. She identified six categories of design, from 'evidence-based decision-making' to 'freedom'. Across the six categories, however, there were significant similarities in how designers thought about design. Diving into design practice, Yilmaz and Daly looked at two key activities in design, idea generation and feedback, for students in mechanical engineering, industrial design, and dance [15], [16]. These studies identified both similarities and differences in design practice, but did not address how students were conceptualizing design differently. A similar study by Kuys and de Vere [17], compared the performance of engineering and product design students on two design tasks. Product design students engaged in more iteration than engineering students, but the overall design processes were similar. Across these studies, we can see how students from different disciplines practice design, but little is known about how or where they learned the design process they employed.

A third type of comparative work in engineering design research looks at differences between experts and novices. Foundational works by Atman [18] and Crismond and Adams [19], compared novice and expert designers to identify elements of design expertise and assess the gap between new and experienced designers. More recent works, such as Mazzurco and Daniel [20], apply a similar design to understand expertise in a specific area of design. Their study looked at the consideration of sociotechnical factors in humanitarian engineering. Comparing designers at different levels of expertise is helpful to identify best practices, but it is unclear what influences novices to become expert designers.

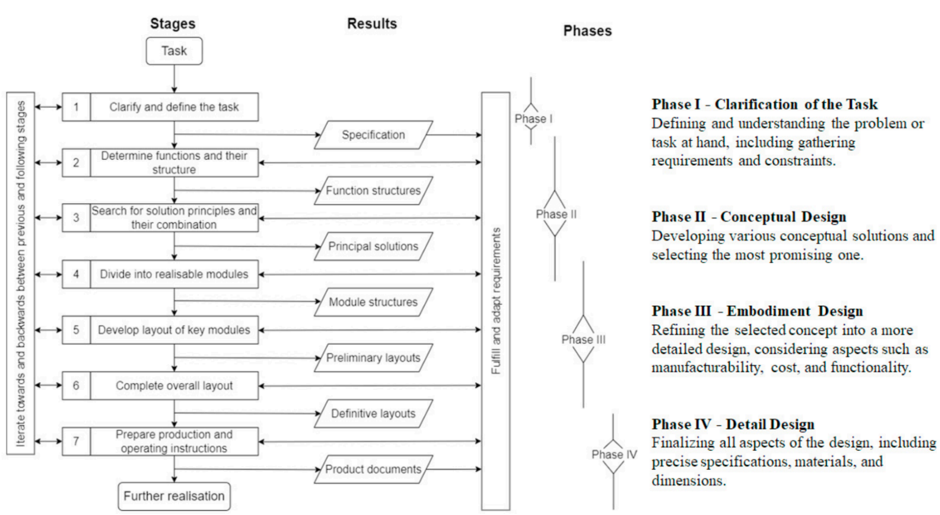
We are unaware of any studies that have interviewed faculty from different engineering disciplines about design. Pawley [21], however, conducted a similar study where she interviewed faculty about their definitions of engineering. Several elements of design arose in the three universalized narratives identified in the study. One narrative, ‘engineers make things’ has many parallels to engineering design. Pawley emphasizes the importance of analyzing faculty narratives because these are the narratives that are communicated and taught to students. It is with a similar motivation that we aim to capture faculty conceptualizations of design.

Our Design Framework

Given the broad range of definitions and models for the engineering design process, we felt it was necessary to ground our analysis in a specific design process model. A generic, widely applicable framework was necessary to accommodate the emergent coding used to analyze the interviews. The framework we selected is the VDI 2221 standard, created by the Verein Deutscher Ingenieure (VDI) [22]. This model is well known and recognized internationally as a prescriptive process model intended to systematize the design process [23]. Figure 1 shows the model’s two parts: phases and stages. The four phases represent main parts of design, but the timing of their beginning and end are not prescribed and can overlap. The seven stages break each phase into specific tasks and results. Iteration exists throughout all stages.

This model was chosen because it is applicable to a wide variety of design problems. The model also refers to the design output as a layout rather than specifying a specific design product. We utilized the framework in analysis to avoid biasing the participants or ourselves toward a particular form of design. The participants were not presented with any information about the VDI 2221 at any point in the interview. For analysis, the design phases were selected as the organizing mechanism for codes because they are specific enough to separate subcodes into different parts of the design process but general enough to be understood by a wide audience.

Figure 1. VDI 2221 Design Framework (adapted from [22])



Methods

Study Context

This study took place in the context of a large land-grant R1 university in the United States. The College of Engineering serves over 10,000 undergraduate students in 14 degree-granting disciplinary departments [24]. Before selecting and entering a degree-granting program, students pass through a two-semester general engineering curriculum. Nearly 3,000 students each year take the two core courses in this curriculum, and gain experience with team-based engineering design through semester-long projects. A goal of these General Engineering courses is to create opportunities for students to get authentic engineering experiences and to explore disciplinary areas of interest. Because of the number of possible disciplinary paths, it is not feasible to give students an opportunity to try each one. Rather, we give them exposure to disciplines and opportunities to self-select and explore different disciplines as part of their course experience. We also seek to create opportunities for our students to experience elements of the engineering design process that can be linked to the way that professionals in a given discipline practice.

Data Collection

Before beginning data collection, a research determination request was submitted to the institution's Institutional Review Board, which determined that the project did not constitute human subjects research. Following this determination, recruitment of participants began by searching Fall 2025 course offerings in the College of Engineering that contained the word "design" in the course title or description. The instructors of identified design courses and other design faculty known by the authors were recruited via email. At least two instructors from every engineering department were invited to participate. Faculty interviews were conducted over a two-week period, with all participants providing explicit consent for their interview responses to be used both for internal continuous course improvement and an ASEE conference paper.

We collaboratively developed a set of structured interview questions intended to elicit how engineering design and the design process are conceptualized, taught, and operationalized within different disciplines. The interview questions are included in Table A1 in the Appendix. The research team documented the interview with detailed field notes. Researchers standardized their field notes using a spreadsheet that recorded interview answers by question. Field notes were also debriefed in research meetings, which allowed the interviewer to answer questions from the research team and add to field notes. We conducted 15 interviews with faculty from 11 engineering disciplines. Table A2 in the Appendix provides a full list of participants.

Data Analysis

Interview analysis was conducted using a two-stage, interactive coding process. In the first round, one researcher inductively coded the interview notes holistically, examining the complete set of responses for each participant. This initial coding focused on identifying characterizations of the engineering design process, engineers/designers, successful design education, and challenges in design education. The preliminary codebook was then reviewed and refined collaboratively by the research team. In the second round, the inductive codes were synthesized and organized into broader categories. For these categories and characterizations of the design process, the team drew on major design stages outlined in the VDI 2221 framework to guide categorization. The revised codebook is organized into two themes. Each theme has codes (larger categories) and subcodes (original codes from stage 1) organized under it. Using this revised codebook (found in Tables A3 and A4 in the appendix), interviews were deductively coded as a whole, with each code applied only once per interview to maintain consistency.

To facilitate cross-disciplinary comparison, the coded data were transformed into matrices representing the presence or absence of each code (rows) across disciplines (columns). These matrices provided a clear visual representation of whether specific codes were mentioned within each discipline. The matrices were then grouped by category, enabling the research team to identify patterns and contrasts in how design concepts and challenges were discussed across different fields. These matrices can be found throughout the Findings section (Tables 1-2).

Limitations

This exploratory work is limited in its scope and breadth of perspectives and contexts covered. Despite asking participants about their professional experiences, the educational context in which we interviewed faculty may have excluded industry perspectives about what design looks like. Additionally, the participants of this work are all located at the same institution, which limits the perspective even further. We were also not able to recruit from all degree-granting engineering programs at the university, so some disciplinary perspectives from within our own college were not included. We recruited at least two faculty members from every engineering department at our institution, but we were not able to interview faculty from Biomedical, Civil, or Chemical Engineering. We cannot know how the inclusion of these disciplines would have affected our findings, but future research should focus on including all major engineering disciplines.

Findings

This section organizes our findings by theme and code. Subcodes are discussed within the section of their parent code. Two major themes arose throughout coding and analysis: Elements of the Design Process and Characteristics of Designers. Both themes address our research question, ‘how do different disciplines represent unique and common elements of engineering design in undergraduate courses,’ but they provide complimentary perspectives on elements of engineering design. The first theme discusses *what* activities designers engage in to create design solutions, while the second theme addresses *how* designers go about design activities.

Theme 1: Elements of the Design Process

The codes and subcodes encompassed by this theme answer the question, ‘what are the activities and processes of engineering design?’ The codes were largely informed by the design phases of the VDI 2221 framework (i.e. clarification of the task, conceptual design, embodiment design, detail design), however some interviews addressed design activities that extended beyond these phases. As such, we created three additional codes: characteristics, final product, and communication. The added codes described activities that characterize the entire design process, rather than a stage or part of it.

Problem Definition

The first phase of the VDI 2221 design process is Clarification of the Task. We broadened this to Problem Definition to accommodate codes that were not task-specific. This code was the most commonly coded phase, with 32 total code occurrences separated into five subcodes. Every interview except for Participant M in Mining Engineering had at least one code in this phase, indicating that there is some consensus that this phase is an important part of engineering design. The most popular code was ‘define design criteria/requirements,’ followed closely by ‘define constraints.’ A very strong emphasis was placed on defining the problem in terms of criteria and constraints. Four participants mentioned that quantifying measures for criteria was another key element of problem definition. Several participants highlighted that well-defined criteria and constraints are essential for success later in the design process.

The other two codes in this phase are concerned with the boundaries and details of the design problem. The ‘define scope’ subcode refers to delineating boundaries of the problem. The participants who mentioned this kind of scoping were representing disciplines that deal with large, complex systems (Biological Systems Engineering, Industrial & Systems Engineering, and Engineering Education). In these cases, it is important to understand which parts of the system are included in the design space and which are constraints. The last code in Problem Definition is ‘understand client needs.’ This was the third most popular subcode, and was mentioned as a key method for information gathering in problem definition. If you do not properly understand what the client wants, as expressed by Participant N, your design will never successfully solve the problem.

Conceptual Design

The second phase in VDI 2221 is Conceptual Design. This is the phase where concepts are generated and evaluated. The converging and diverging patterns within conceptual design are well represented in the subcodes. Two subcodes directly address creating and selecting ideas, while the third subcode references the role of existing solutions. Subcodes in this phase were not widely mentioned by participants; each code occurred in fewer than one third of interviews. Large and diverse disciplines, such as Engineering Education, Electrical & Computer Engineering, and Mechanical Engineering, account for most of the codes in Concept Selection. Some disciplines may place less emphasis on divergent ideation in design. It is interesting that Participant O in Ocean Engineering mentioned ‘adaption of existing solutions’ as a part of concept selection. This could support the notion that some disciplines rely more heavily on established solutions than others.

Embodiment Design

Embodiment Design is a transformational phase where a design truly takes shape. For this reason, many subcodes are organized under this code. Similarities and differences between disciplines are evident in the embodiment practices mentioned in our interviews. Testing was the most commonly occurring code, with seven mentions across disciplines. Interestingly, testing was more popular than physical prototyping, even though a prototype is likely necessary to complete physical tests. There was a relationship between the two codes, as all four interviews that mentioned prototyping also mentioned testing. 'Modeling/calculation,' was another popular code, which is not a surprise from engineering faculty. Many interviews stressed the importance of using simple calculation and modeling to make preliminary decisions in embodiment design. The simulation code is similar, but this code specifically refers to the use of computer-based tools. Disciplines with large, complex designs, like Aerospace, Mining, and Industrial, mentioned the importance of calculation and simulation. In general, calculation/modeling and simulation did not co-occur with prototyping and testing. This could suggest that disciplines lean toward modeling for difficult-to-build designs and lean toward building when feasible.

Detail Design

Detail Design is a phase of design that courses do not always reach, as this phase is concerned with final verification of the design and transition towards commercialization. However, subcodes in this phase revealed elements of engineering design that are important to engineering faculty. Two of these subcodes address standards and regulations which govern engineering practice. The most popular code in this phase, although only occurring five times, was 'disciplinary standards.' Faculty who mentioned these standards discussed a broad range of resources, from informal industry norms to professional standards to field specific specifications. Across all examples, awareness of applicable standards–even when not legally required–was seen as essential for a successful design. The discussion of 'legal regulations' was similar, although only two participants explicitly mentioned laws. 'Both the 'business/economic consideration' and 'validation/verification' codes were not very common in interviews, but the faculty who mentioned them were adamant about their importance. While not all courses address these topics, it appears to be an important part of the ones that do.

Communication

This code was added to organize the many types of communication that participants discussed during the design process. Each of the four subcodes under this code occur throughout the process, so the subcodes did not fit within the VDI 2221 design phases. Two subcodes address communication outside the design team, and two subcodes address internal communication. For internal communication, interviews often mentioned the importance of good documentation and the need to work with other engineers. 'Documentation' was mentioned by several different disciplines, and could include internal record-keeping or communication to other people working on the problem. ‘Work with other engineers’ was mentioned by Computer Science, Electrical & Computer, Engineering Education, and Materials Science faculty. All of these fields create components (e.g., software, educational materials, materials) that are used in larger projects. In these cases, it is very important to communicate with the other designers working on the problem.

The two subcodes that referenced communication outside the designers were ‘external communication’ and ‘stakeholder interactions.’ Disciplines that do a lot of project management, including Construction Management and Industrial & Systems, were likely to mention this subcode. External communication differs from stakeholder interactions because the audience is typically technical in the former and less technical in the latter. External communication can refer to communicating with a supervisor, professor, mentor, manufacturer, or someone who may have subject-matter expertise. Stakeholders also have specific expertise, but it often relates to the problem context rather than technical knowledge. This distinction between types of communication was an interesting finding from the interviews, as different faculty emphasized some kinds of communication over others.

Final Product

This additional code was added to capture the different kinds of design products that were discussed in the interviews. We realized that a relevant difference in the design processes of disciplines is the form of the outcome from the process. This outcome was deemed the ‘Final Product,’ and five types of final product were identified in interviews. Not all participants mentioned specific final products, while other participants spoke as if their discipline was defined by the types of products they create. Aerospace and Ocean Engineering are two disciplines that design specific products for air or water travel. These two disciplines felt strongly that the final products they design are integrated systems of smaller systems. Larger disciplines (e.g., Electrical) can have design projects with many kinds of final product, and some disciplines may not have a physical product (e.g., Engineering Education). A few codes have only one occurrence, and these mark disciplines that differ from ‘typical’ models of design. The final product for a Materials Science Engineer is often selecting an appropriate material for a specific use case. This is very different from other disciplines which focus on building a device or product.

Characteristics of Design

This final code contains the most overarching and abstract subcodes about design. Many of the descriptions of design we encountered in our interviews addressed the nature of design holistically rather than specific design activities. These characteristics are key to understanding how engineering faculty think about what design is, so they were grouped into this code.

When we asked participants how they would define design, the most common one-sentence answer was something like ‘design is creating a solution to a problem.’ This kind of answer is represented in the ‘solution to a problem’ and ‘open-ended/divergent’ codes. Many faculty discussed design in the form of a problem/solution relationship, where the design product is the solution. Interestingly, only one interview explicitly characterized design as a positive improvement, although most faculty implicitly discussed the impacts of design products in positive terms. The most common code was ‘systematic/methodical.’ This aligns with how we think about engineering design and supports our decision to organize codes based on the phases of a design process. A related code, ‘multiple steps,’ communicates a similar idea that design is an organized process of different kinds of activity that are specifically arranged in time. Two codes that had relatively few occurrences each were ‘sociotechnical’ and ‘interdisciplinary.’ Despite many mentions of stakeholder interactions and client needs in the design phase codes, only one interview explicitly characterized design as a sociotechnical endeavor. Similarly, the faculty who teach interdisciplinary capstone courses were some of the only participants to characterize design as interdisciplinary.

Table 1. Theme 1 Code Occurrences

	A	**B**	**O**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
	Aero		**Ocean**	**BSE**	**CM**	**CS**	**ECE**		**Eng. Ed.**			**ISE**	**ME**	**Mine**	**MS**	
Problem Definition	1	1	1	3	2	1	4	2	5	1	3	3	2	0	4	33
define design criteria/requirements		X		X		X	X	X	X		X	X	X		X	10
define constraints	X		X	X			X		X		X	X			X	8
define scope				X					X		X	X				4
understand client needs					X		X		X	X			X		X	6
quantify measurements for criteria/constraints							X	X	X						X	4
Conceptual Design	0	0	1	1	0	0	2	0	2	2	1	3	2	0	1	15
adapting existing solutions			X				X									2
downselection/ refinement									X	X		X				3
ideation/divergence									X		X	X	X			4
Embodiment Design	2	3	1	1	0	1	2	5	0	2	0	2	2	2	2	25
modeling/calculation		X						X				X	X	X		5
physical prototyping							X	X		X					X	4
simulation	X	X						X						X		4
systems integration	X	X	X					X				X				5
testing				X		X	X	X		X			X		X	7

Detail Design	1	0	1	1	0	1	1	0	0	1	2	0	3	2	1	14
business/economic consideration													X	X	X	3
disciplinary standards			X				X				X		X	X		5
legal regulations	X			X												2
validation/verification						X					X		X			3
Communication	0	0	1	1	2	1	3	0	1	1	1	1	3	0	2	17
Documentation			X				X			X			X			4
External communication					X		X						X		X	4
Stakeholder interactions				X	X				X			X	X			5
Work with other engineers						X	X				X				X	4
Final Product	1	1	1	0	0	2	0	3	0	0	0	1	0	1	1	11
code/software plan						X		X						X		3
component selection								X								1
integrated systems	X	X	X			X		X								5
material selection															X	1
process												X				1
Characteristics	1	1	0	2	2	2	1	1	1	3	3	3	4	1	2	27
difficult								X								1
interdisciplinary		X			X					X	X					4
iteration				X			X			X		X	X		X	6
multiple steps											X		X		X	3
open-ended/divergent	X			X			X			X			X			5
positive improvement												X				1
sociotechnical					X											1
solution to a problem				X		X				X		X	X			5
systematic/methodical						X			X		X	X	X	X	X	7

Note. BSE: Biological Systems; CM: Construction Management; ISE: Industrial & Systems; MS: Materials Science

Theme 2: Characteristics of Designers

The second theme that emerged though our analysis were the characteristics of designers. Distinct from the characteristics of design processes (although related), the codes under this theme answered the question, “what are the knowledge, skills, and attitudes that good designers have?” Since this theme was emergent in our analysis, the codes are not organized by a framework. The subcodes were sorted into codes through an iterative upcycling process. Overall, the codes in this theme show less consensus than the Elements of the Design Process theme. The following sections describe similarities within codes and occurrences of each subcode.

Professional Behavior

This code contains a variety of characteristics that participants expressed as relevant to professional engineering design work. Many subcodes reference competencies that are required in ABET student outcomes (e.g., ethics, sustainability, collaboration). Most subcodes were only mentioned a couple times, but all subcodes except ‘can productively disagree’ occur more than once. This provides a valuable form of corroboration for the subcodes. The code ‘collaborate with others,’ addressed effective teamwork, which is essential for effective design. Project management was a code mentioned by three participants, despite many more comments from participants about students’ lack of good project management. Several subcodes were left intentionally broad, including ‘are ethical,’ ‘are professional,’ and ‘are sustainable,’ as participants often noted that these characteristics were important without specifying their definition of ethical, professional, or sustainable.

Technical Knowledge

The three subcodes contained under this code each speak to the importance of designers’ technical knowledge, but each subcode references a different source of technical information. The first subcode, ‘apply disciplinary technical knowledge to the design problem,’ refers to abstract technical knowledge that a designer already possesses. They just need to recognize its relevance to a specific part of the design problem. ‘Collect and analyze data’ refers to technical information that comes from the problem context, whether from problem scoping, simulation, or testing. The third subcode, ‘source new information to fill knowledge gaps,’ refers to a designer’s ability to find and learn new technical knowledge. Co-occurrences were relatively uncommon in this code, as nine participants only discussed one kind of technical knowledge. The distribution of codes across nearly every participant might suggest that these subcodes all address part of the same idea: engineering designers must wrangle with problem-specific technical information.

Decision-Making

Across nearly every interview, the importance of decision-making in design was emphasized. The myriad of decisions embedded within a design process is somewhat obscured in a process model like the VDI 2221, but decision-making skills emerged as a prominent code in this theme. The most popular subcode across all codes in the Characteristics of Designers theme is ‘use evidence to make and justify decisions.’ It is easy to see how this skill can apply to all disciplines. A related and similarly popular subcode is ‘evaluate trade-offs,’ which is essentially what designers are doing when making decisions. Evaluating the trade-offs of various design choices with evidence is essentially the core of decision-making. The other two subcodes in this code are skills that compliment designers’ ability to make good decisions. Participants often talked about creativity and how thinking unconventionally can help designers consider all the options for a particular decision. Ambiguity is inherent in the open-ended design problems that engineers encounter, so the ability to handle unknowns with reasonable assumptions is paramount. Participants talked about this skill as a form of decision-making; designers must decide what assumptions are reasonable for their problem.

Table 2. Theme 2 Code Occurrences

	A	B	O	C	D	E	F	G	H	I	J	K	L	M	N	
	Aero		Ocean	BSE	CM	CS	ECE		Eng. Ed			ISE	ME	Mine	MS	
Professional Behavior	1	0	0	2	1	2	1	0	1	2	2	3	4	1	2	15
are ethical								X						X		2
are professional		X	X								X		X			3
are sustainable				X											X	2
can productively disagree										X						1
collaborate with others		X	X						X	X		X				4
effectively manage their project						X			X				X			3
Technical Knowledge	0	1	1	0	0	1	0	0	2	2	0	1	1	0	0	15
apply disciplinary technical knowledge to the design problem							X			X	X		X	X		5
collect and analyze data				X		X						X	X		X	5
source new information to fill knowledge gaps	X	X	X											X	X	5
Decision-Making	1	1	1	1	0	1	1	0	0	1	1	1	2	2	2	21
are creative				X	X				X	X					X	5
deal with ambiguity								X	X				X			3
evaluate trade-offs	X							X		X			X		X	6
use evidence to make and justify decisions								X		X	X	X	X	X	X	7

Note. BSE: Biological Systems; CM: Construction Management; ISE: Industrial & Systems; MS: Materials Science

Discussion

To answer our research question, how do different disciplines represent unique and common elements of engineering design in undergraduate courses, we conducted 15 interviews with engineering design faculty from 11 engineering disciplines. By analyzing the interviews, we identified two key themes that capture how participants talked about elements of engineering design: elements of design *processes* and characteristics of *designers*. This section places those themes in conversation with each other, with other perspectives on engineering design, and with best practices for design educators.

Comparison Across Disciplines

A key component of our research question is comparing and contrasting the conceptualizations of engineering design presented by faculty of different disciplines. We begin by discussing commonalities seen across many interviews and subsequently address areas of divergence. As a note, our data represent a small subset of engineering disciplines and perspectives that exist on design. Trends in our sample may or may not reflect differences between other engineers or other contexts.

Commonalities

Areas of some consensus among our participants cluster around design as an iterative process, around requirements definition, and around testing and validation. The subcodes 'systematic,' 'iteration,' and 'multiple steps' account for a large portion of the code occurrences in the Characteristics code of Theme 1. When taken together, these subcodes characterize design as a methodical process involving multiple, iterative steps. This result is expected, as most engineering design process models have steps and iteration but should not be taken for granted. Some participants in our study did not characterize design this way, and which could indicate a disciplinary or personal difference in design conceptualization.

Turning to commonalities in design phases, the importance of defining the problem in terms of requirements/criteria and/or constraints was a recurring theme. This notion aligns with the first phase of the VDI 2221, where the output of the first step is a series of specifications for the design [22]. The creation of design criteria may also be a natural starting point in an academic or industry setting where the problem is already scoped. On the other end of the design process, testing was an activity that featured prominently in the data. Whether the testing was physical or simulated, participants felt strongly that designs must be tested against the criteria. It makes sense that criteria definition and testing would work together because the criteria define what tests are necessary and test results let designers know if criteria are satisfied.

Across Theme 2: Characteristics of Designers, decision-making competencies and technical knowledge were recognized by 12 of 15 participants. The subcodes contained in both of these codes align well with one of the dimensions of Informed Design outlined by Crismond and Adams [19]. In their study of design literature, the researchers identified 'Making and explaining knowledge-driven decisions' as a key practice for informed designers. In their explanation of this dimension, they touch on many of the same competencies that were mentioned by our participants, namely creativity, dealing with ambiguity, and using technical knowledge to justify decisions [19]. The frequent mention of these competencies underscores their importance for all students, regardless of their intended major or career path.

Differences
As noted in the embodiment design code, different disciplines had different relationships with physical prototyping. This relates to differences we noticed with the final product of design. Disciplines that had large, difficult to build products, like Aerospace Engineering, relied on simulation instead of physical prototypes. Similarly, disciplines with processes or code as a final product placed more emphasis on modeling and simulation than prototyping. The connection between the type of design artifact a designer is creating and the tools used to embody it may seem obvious, but we were intrigued to find this in our data. At the level of undergraduate design courses, we had expected to find a heavier emphasis on low-fidelity prototyping and physical testing. Based on these findings, it is important for design models to represent many different kinds of embodiment design. For example, Ulrich and Eppinger's product design model [25] is intended for the design of physical products. The detail design stage focuses on physical elements like geometry, tolerances, and tooling for manufacturing [25, p. 14], but these design elements do not apply to the design of a process, software, or non-physical product. More general design process models, like the VDI 2221 [22] or Pahl et al. [9]refer to the design product as a 'layout,' which is agnostic to the form of the design.

Another area where participants tended to differ in their conceptualizations of design was the professional behaviors code. As referenced in the Findings section, the subcodes in this area covered diverse ideas from sustainability to teamwork. Four of the subcodes are related to working with others, including collaboration, respectful disagreement, and project management. Teamwork and management are recognized as essential skills for engineers, but they are often considered professional skills rather than core design skills. We only asked participants about design skills, so it is possible that some participants considered professional skills as outside the scope of the interview. The remaining two subcodes (ethics and sustainability) refer to the values and priorities a designer should have. Both ethics and sustainability were only mentioned twice, despite being included in ABET student outcomes [2] and recognized as important engineering priorities [26].

While many other individual differences exist between participants, our relatively small sample limits the trends that can emerge from the interview data. Our findings, however, do suggest that engineering faculty conceptualize engineering design and designers differently. Whether the differences are due to personal experience or disciplinary culture is difficult to discern. For many subcodes, the differences between participants from the same discipline are just as diverse as the differences between interviews of different disciplines. Further study is necessary to isolate the role of disciplinary culture and knowledge in faculty design conceptualizations.

Implications for Design Education Research
While exploratory in nature, the findings of this study provide implications for other researchers interested in how educators and engineers conceptualize design. Much work has been done on

engineering design models and processes, but it is less clear, however, how do design educators form their conceptualizations of design? This study investigated a small part of this larger question, but we hope that the findings will help others develop and interpret future research. It is with this aim that we present the following implications:

- **Discerning the influence of personal and disciplinary experience:** We collected limited amounts of background information from our participants by asking them how they had developed their conceptualization of engineering design. Our approach was exploratory and emergent, but researchers hoping to take a more phenomenological approach should consider what background information is necessary to isolate the impacts of disciplinary culture.
- **Design is done by designers:** The themes of our findings highlight the importance and interconnection of both the design process and the designers. There is a plethora of research about design processes [27] and an equally large corpus about design expertise [28], but we believe that more discussion bridging these two research areas is necessary to understand how they impact one another.
- **Delineating disciplines:** Because our study only considered one institution with more than a dozen engineering departments, it made sense to organize our participants by their home department. A more intentional definition of discipline is recommended for future studies with multiple institutions or industries.

Implications for Design Educators

As engineering educators focused on first-year curricula, we identified several implications from this study that could prove useful for engineering design educators. Our focus is on interdisciplinary design for students who have not yet selected a discipline, but the following implications could apply to any undergraduate design context.

- **Qualities and Characteristics of the designer matter:** Our participants clearly thought the designers' characteristics were important elements of engineering design, but they often discussed how students fell short in developing these competencies. If we want students to develop design expertise, providing explicit discussion of how a designer impacts the design process is necessary.
- **Product determines (some) process:** Design educators across the curriculum may interface with many types of final products from design projects. With the ever-increasing diversity of analysis tools available to engineers, it is important for educators to incorporate some autonomy for teams to select the best verification mechanisms for their type of design product.

Conclusions

This study interviewed 15 engineering faculty in 11 different disciplines at a large, public US university to understand their conceptualization of engineering design. We sought to answer the research question, how do different disciplines represent unique and common elements of engineering design in undergraduate courses? Through qualitative analysis of interview notes and examination of code occurrences in each interview, we identified two primary themes in how participants discussed engineering design: elements of the design process and characteristics of designers. Participants had the greatest agreement on the importance of requirements definition, testing, application of technical knowledge, and effective decision-making in design. Disagreement was more common when discussing embodiment design, detail design, and necessary professional skills for engineers. Based on our findings, there are differences in faculty conceptualizations of engineering design, but the impact of discipline is difficult to isolate. Future work in this area would likely need a larger sample size and more background information about participants' disciplinary identities.

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Appendix

Table A1: Interview Questions and Example Follow Up Questions

Question Focus "Level"	Question	Possible Follow Up Question(s)
Discipline-Level	What does "engineering design" look like or mean in [discipline name here] engineering?	Where / How have you learned this?
Course-Level	What do you think are the most important parts (concepts / lessons / experiences) of design in your [discipline name here] engineering course?	Why?
Course-Level	What do you most hope students take away from your design course?	
Course-Level	What is a challenge of teaching design you face in your course?	
Open-Ended	What else should we know as we explore teaching engineering design?	

Table A2. Interview Participants

Participant Code	Engineering Discipline	Industry Experience	Course Level
A	Aerospace	Yes	Capstone
B	Aerospace	Yes	Capstone
C	Biological Systems	None Mentioned	Capstone
D	Construction Eng. Management	Yes	Middle Year
E	Computer Science	None Mentioned	Middle Year
F	Electrical and Computer	None Mentioned	Middle Year
G	Electrical and Computer	None Mentioned	Capstone
H	Engineering Education	None Mentioned	First Year
I	Engineering Education	Yes	Capstone
J	Engineering Education	None Mentioned	Capstone
K	Industrial and Systems	Yes	Capstone
L	Mechanical	Yes	Capstone
M	Mining	None Mentioned	Middle Year
N	Materials Science	Yes	Middle Year
O	Ocean	Yes	Capstone

Table A3. Theme 1: Elements of the Design Process Codebook

Code	Subcode	Definition
Problem Definition	define constraints	describing the limits and restrictions on the design and design process
	define design criteria/requirements	describing the objectives of the design in terms of design criteria, requirements, or specifications
	define scope	establishing boundaries of the problem that the designers will address and explaining the problem in engineering terms
	quantify measurements for criteria/constraints	defining quantitative measures for design criteria/specifications so they can be evaluated
	understand client needs	obtaining, interpreting, and clarifying the needs and desires of the client who will buy or use the design
Conceptual Design	adapting existing solutions	using what already exists and adapting other solutions from similar contexts to the design problem
	downselection/refinement	making decisions to reduce or refine design concepts; continuous process of converging on one design
	ideation/diverging	generating a broad range of ideas to address the design problem
Embodiment Design	modeling/calculation	using scientific/mathematical knowledge to estimate or predict the function of the design
	physical prototyping	constructing physical artifacts that represent elements of different design concepts and can be used for testing concepts
	simulation	using computer simulation to model the design
	systems integration	combining many different systems that each satisfy different design criteria into one cohesive design solution
	testing	conducting experiments or trials to assess how a design concept meets desired outcomes/criteria
Detail Design	business/economic consideration	considering how business factors could affect the design, including defining the economic value of the design and understanding costs associated with manufacturing and selling the design
	disciplinary standards	creating designs that are in accordance with the standards of the discipline and problem context
	legal regulations	creating designs that follow applicable laws and regulations
	validation/verification	ensuring that design criteria/constraints are appropriate and that the final design meets all criteria

Communication	documentation	documenting the process of design by recording the results and justification for the final design; creating supplementary materials like user manuals or maintenance schedules
	external communication	Communicating and explaining the design to people outside of the design team and stakeholders, including both verbal and written communication
	stakeholder interactions	communicating regularly with people/groups impacted by the problem to gather information, test concepts, or communicate results
	work with other engineers	passing off concepts/plans to other engineers or supporting others who are working on different parts of the problem
Final Product	code/software plan	the product of design is a plan/outline of software or specific software code
	component selection	the product of design is the selection of component(s) to fulfill the system's needs
	integrated systems	the product of a design process is an overarching system that integrates many smaller systems to achieve the criteria
	material selection	the product of design is a type of material used to build a product
	process	the product of design is a process or procedure
Characteristics	difficult	design activities require extensive time, thought, effort, and energy
	interdisciplinary	design activities utilize expertise from multiple disciplines and fields
	iteration	engaging in a recursive cycle of ideation, testing, and revision
	multiple steps	design is a process that involves several discrete, ordered steps
	open-ended/divergent	design addresses open-ended problems that do not have one right answer; the problems are often complex and multi-faceted
	positive improvement/progress	design is intended to produce improvement or progress over the current state of a problem
	sociotechnical	design is an activity that inherently requires consideration of and impacts both technical and social context
	solution to a problem	the purpose of design is to alleviate the negative effects of an undesirable situation
	systematic	design is a methodical process that involves specific methods in a specific order

Table A4. Theme 2: Characteristics of Designers Codebook

Code	Subcode	Definition
Professional Behavior	are ethical	learn about and apply ethical principles related to the problem
	are professional	act within professional expectations and maintain a mature disposition in all interactions
	are sustainable	value and consider environmental sustainability and green engineering in their design work
	can productively disagree	engage in civil debate and disagreement to evaluate design decisions
	collaborate with others	work effectively with others in technical and nontechnical teams
	effectively manage their project	plan and organize activities of the design team to efficiently and systematically complete the design
Utilize Technical Knowledge	apply disciplinary technical knowledge to the design problem	connect abstract technical knowledge to the specific needs of the design problem
	collect and analyze data	source and evaluate data about the problem or the proposed design features
	source new information to fill knowledge gaps	seek, find, and process new information (both technical and nontechnical) to understand the problem, generate concepts, and test/evaluate potential concepts
Make Difficult Decisions	are creative	generate and use of novel or unconventional thinking
	deal with ambiguity	recognize missing information and make assumptions to account for unknowns in the problem
	evaluate trade-offs	weigh competing interests, evaluate the most important criteria, and measure the benefit/cost of certain design choices
	use evidence to make and justify decisions	make series of decisions to refine the design and justifying those decisions with evidence