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Engineering Students' Performance of Prototyping: Process, Purpose, and Perception in the Design Classroom*

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Learning to design is important to engineering students. Learning to prototype and use prototyping as part of the design process is a critical part of learning to design. Prior research shows that students prototype in different ways and towards different goals than professionals during the engineering design process. In this study we explore students' use of prototyping from a lens of prototyping as performance of the design process, as opposed to looking at professional purposes for prototype creation. We use a mixed-methods approach consisting of survey data across an undergraduate biomedical engineering curriculum and interviews with juniors and seniors in the program. Our results suggest that students attach their prototyping to the context in which it occurs. Prototyping to our participants is a goal of the design process, seen as necessary to demonstration of course accomplishment, and involves purposeful but a-professional goals such as learning to build things as a relevant factor in their prototyping. We discuss the implications of different but purposeful student prototyping for researchers and instructors through links to information literacy and prototyping as a source of design information.

Keywords: perception; design process; prototyping; classroom

1. Introduction

There is nearly universal agreement that engineering students need to learn the engineering design process – and as a result, engineering educators need to understand how students design [1–3]. Within those efforts, a small but growing body of work has focused on how and why engineering students create prototypes and use prototyping [4–7]. That work is often based on studies of professionals in engineering and design, which have identified a variety of roles for prototyping – including thinking, demonstrating, testing functionality, and communicating [7]. Taxonomies of the roles that prototyping play for professionals then often become the lens for understanding students. The resulting studies have repeatedly shown that engineering students possess a narrower perception of prototyping, use prototypes in a limited set of roles, and test them in less complex ways [5, 6, 8].

Such studies typically rely on professional prototyping as their primary lens, which creates a gap in how students' prototyping decisions are understood. At a broad level, the purposeful creation of artifacts to serve concrete, specific, and articulable goals within the design process is critical to how engineering professionals prototype [7]. However, the goals of a design instructor, a design course, and the students learning design can mean that prototypes play a different role. That is, the primary purpose of a classroom is to learn design and achieve a grade while the creation of a design is an outcome of doing so. Such purposes might have fundamental differences from professional design work [9]. Failure of students' goals to align with expert goals does not inherently mean their action is purposeless. Research grounded in comparisons to professional purposes limit a researchers' ability to represent perceptive choices that students make in a classroom. As noted in Newstetter [9] and others' work [10], there are cases where students shift classroom designerly actions towards goals not extant in the professional world (e.g., employing a specific design tool because they are instructed to).

For our study, we adopt a different perspective of prototyping as performance of design [11]. The performative perspective integrates students' use of prototypes in a design project with the broader context of their undergraduate educational experience. It centers the student and their goals in the creation of a prototype. In doing so, it decenters the role that the prototype plays in progressing the design itself. Doing so encodes a purpose in the student's design process, rather than in the resulting artifact. By doing so, we aim to bridge the work by Lauff with the classroom realities of Newstetter.

In this study, we use a mixed-methods study to investigate student prototyping and attitudes across the design course sequence of a biomedical engineering undergraduate degree program. The quantitative work involves a survey to capture students' perception of purposeful vs. performative roles in different prototyping contexts. We integrate the survey with qualitative data from interviews about students' examples of prototyping from their own

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design experience. The purpose is to understand how engineering students perform, perceive, and explain prototyping when working on a design project within the context of engineering design courses. Towards that purpose we used two research questions to guide this study:

RQ 1: How does experience and context affect engineering students' perceptions of the role of prototyping?
RQ 2: How do engineering students describe and implement prototyping in their design work?

These research questions allow us to look at engineering students' performance of prototyping across a single engineering curriculum. Our exploration provides a novel understanding of complexity of students' perceptions of prototyping. Such a comparison of cultures of prototyping is to see what parts of student learning can and cannot be understood from the professional lens [12]. The results presented both support and dispute aspects of using professional prototyping as a framework to understand engineering students' prototypes during design education. They also show the influence that curriculum has on students' perceptions.

2. Relevant Literature on Prototyping

2.1 Students as Novice Prototypers

Across several disciplines, studies consistently show gaps in students' knowledge and use of prototyping compared to experts. In engineering, studies show that mechanical engineering students have narrower perceptions of why one prototypes than do professionals [6]. In that study, students identified prototypes primarily as a functionality testing tool, rather than the broader uses of prototypes identified by professionals. Carfagni and colleagues used a similar categorization of prototyping roles, and found that students saw prototyping during conceptual phases as distracting and unnecessary, and they rarely plan prototypes to communicate and/or make decisions [13]. They also highlight that students in an engineering design class found elaborating a prototyping strategy difficult. Petrakis, Wodehouse, and Hird [5] make a clear statement of the impact of such differences noting "students do not make full use of the benefits of prototyping and require more explicit guidelines and encouragement" [p. 5]. In their study, students viewed prototypes as tools for validation or feedback and were least likely to use prototypes as milestones, comparison, and requirements prioritization. Finally, in design classrooms, the framework through which students view their prototypes can have a significant impact on not only what they choose to build, but what they learn from the process [4].

Work by IDEO's founders suggests that students lack confidence in their ability to employ certain tools (e.g., drawing or physical prototyping) for prototyping unless they feel they have mastered the tools first [14]. Such a connection between the skills to build prototypes and the use of prototypes in design has been shown by others. Students who spend time learning and applying hands-on prototyping skills report that they are able to develop more creative solutions to problems [15]. As students' confidence in tools of creation evolve, they become less averse to the risk associated with radically different concepts in their concept generation activities. One possible interpretation is that students are overly focused on ensuring their prototypes are high quality or high fidelity, and area where work does exist on interventions to counter such concerns [4, 16, 17]. The implications of student's focus on fidelity can also manifest in other ways. For example, Deringer et al. [8] suggest a gulf between how novice designers describe their prototypes and how they actually use them to further their design. They find that initial explanations of prototypes are less sophisticated than their actual use may represent, which represents a jumping off point for our study.

2.2 Prototyping at the Intersection of Courses, Students, and Professionals

Much of the work used to inform the understanding of student prototyping also informs how students are taught to prototype. Such work typically draws on studies of professional prototyping, and shows that the culture – manifested through media, methods, and processes is discipline and organization specific [12]. Studies of professional prototyping and their influence on design courses are briefly addressed here.

Several studies of engineering student prototyping mentioned above build on Lauff's development of categories of prototypes. Through observation of professionals, Lauff [7] created a list of roles that prototypes play in different companies as both a validation and a tool for the field to aid common language when studying prototyping. In professional design work, an organization's patterns of prototyping can create cultural norms unique to that organization which encompass a common understanding of the use of prototypes. This organizational culture of prototyping can shape the way the designers employ prototyping and design development methods in that context [12].

There are numerous, and somewhat varying, descriptions of prototyping [8]. Professional prototyping skills and behaviors inevitably become projected into classrooms. Dym's gold-standard engineering design textbook models the design process in five stages [18]. Prototyping takes place in the first three stages of the that model. Professional models of prototyping have also guided the development of frameworks and interventions for students [4]. In literature, a prototype is often defined as:

> "a distinct product (hardware or software) that allows hands-on testing in a realistic environment. In scope and scale, it represents a concept, subsystem, or production article with potential utility. It is built to improve the quality of decisions, not merely to demonstrate satisfaction of contract specifications. It is fabricated in the expectation of change, and is oriented towards providing information affecting risk management decisions." [19]

Such a definition, however, naturally interacts with external structures (e.g., semester-long courses) and students new to engineering when it is operationalized in a design course. As a result, the process of deliberate prototyping can be replaced by students making seemingly arbitrary decisions [20, 21]. While deliberate application of prototyping methods can reduce risk and enhance effectiveness of the solutions a team produces, applying these methods in an effective way requires experience and understanding which are initially beyond the capabilities of undergraduate design students [20]. This is the learning outcome of engineering design courses in which this study is interested: to give students experience in the entire process of design, integrating a wide variety of skills they have acquired through science and math classes as well as design skills such as developing and communicating ideas, and applying them to solve a defined engineering problem [8].

3. Study Design

We used a concurrent mixed methods study design using an IRB approved survey and interview process. All data was collected in a single undergraduate engineering program at one institution. The study occurred during the 2021 spring semester, when courses and students were still impacted by the COVID pandemic and the institution operated in a hybrid educational modality.

3.1 Setting and Population

Data was collected in one undergraduate biomedical engineering program at a large public research university. The undergraduate curriculum heavily focuses on design, project, and team-based learning experiences. Required courses include four design- and project-based experiences, typically taken one per year. In each of those courses, prototyping, and the production of at least one prototype artifact are expected. A curricular flowchart and description of each of the design courses appears in the appendices to aid reference throughout the study.

Starting in 2021, department faculty have engaged in a conscious effort to align on a shared model of design across the curriculum. The lack of such alignment within an engineering design curriculum has been noted in other studies, and is a problem [22]. The effort to build a shared model of design includes aligning language used in courses (e.g., "user centered"), design process representations (e.g., iterative, non-linear), specific activities (e.g., user stories) and the use of a shared set of design tools (e.g., persona templates).

We included the entire population of undergraduate students in the department in the study. The population is majority female, and more ethnically and racially diverse than other departments at the university. At matriculation, approximately equal percentages of students plan to pursue industry careers, graduate school, and medical school upon graduation. The university, and department, are classified as highly selective with an ~20% acceptance rate, 25th percentile SAT score of 1300, and an average high school GPA of 4.08. In the department, approximately 70% of students participate in undergraduate research, and approximately 65% participate in an engineering internship during their degrees.

3.2 Data Sources and Collection

3.2.1 Survey

The first data source for this study is a survey of all undergraduates in the studied program using typical survey procedures. We performed survey distribution and recruitment via email. From 1076 undergraduates, we received 102 responses (response rate 9.4%). While the response rate is low, the demographics of the response sample are generally representative of the population (i.e., biomedical engineering students, not all engineering students). Further, the number of responses gives reasonable power for the analyses performed. Our hypothesis is that the low response rate is in part due to increased surveying during the pandemic, which has generated lower than expected response rates in related several projects.

The survey asked participants to answer questions about prototyping in three different contexts. The contexts were prototyping in general, prototyping in the context of a design course, and prototyping in the context of a personal projects. For each context, participants responded to 10 binary choice sentence completion questions drawn randomly from a pool of 18 and presented in a random order. They then had the opportunity to add general comments about how they approach prototyping in that context. The random pool approach sought to increase diversity of information and create variation in the questions that participants saw across the three contexts. The full survey appears in the appendix.

The 18 sentence-completion questions each provided participants with a stem and two choices. The first choice reflects a *purposeful* approach to prototyping, wherein prototyping involves an active role with the potential for input that adds value to the design process. The second choice reflects Danholt's [11] *performative* approach to design, wherein prototyping passively communicates ideas, completes deliverables, and demonstrates engagement.

We developed the questions using a repeated process of brainstorming and reflecting on experiences with student prototyping from our design courses. Using our experiences, we initially wrote each question as a single sentence the represented experiences with how students or experts utilize prototyping, and then drafted endings for the sentence to embody different perspectives on prototyping. From the single question, the sentence stem was adjusted for the other contexts. An example of the three contextual stems and the two choices appears in Fig. 1.

For this study, our quantitative analysis focuses on comparisons using inferential statistical tools and descriptive statistics. The results describe response patterns to individual questions, overall scores between contexts using chi squared tests, and the longitudinal influence of certain classes on prototyping behaviors across the curriculum using regression techniques [23]. Such longitudinal comparisons between early and later career students have proven hugely valuable in prior engineering design education work [e.g., 25]. We also performed a brief analysis of the comments left in the survey about prototyping in all three contexts. In the results we present a word cloud and quotes from the survey results as a bridge between the survey and the interviews.

3.2.2 Interviews

In parallel with the survey, we performed loosely structured interviews with 6 undergraduate students who had either completed or were currently enrolled in our third-year design course. We focused on that course because it involves the most extensive instruction in prototyping within the design courses in the curriculum. The interview protocol (see appendix) discussed specific prototyping experiences and prototypes that participants had created. The discussion of specific prototyping experiences focused on the participant's design notebooks from the third-year course. We tested the interview protocol between the researchers and via pilot interviews with TA's. All of the interviews were conducted by one author to protect students' anonymity when discussing experiences in a specific course that the second author is an instructor for most semesters. The interviews were audio recorded and then professionally transcribed.

The analytic process resulted in a representative summary of how each interview participant perceived prototyping from their own experiences. Our analysis is grounded in the tools of narrative analysis [25]. These techniques are particularly important because they contrast the interview data as holistic and resistant to fragmentation in analysis, which we view as particularly important to understand the complex and context specific ways that engineering students prototype [26]. In keeping with our performative lens, we focused on students doing prototyping, and the variation with how they enact and describe it. We treated each interview as an individual narrative of how prototyping happens from the worldview of that student. Critiques of narrative analysis have expressed concern that it reifies an interior self as a subjective truth [27]. However, in our study, such reification of students' subjective prototyping truths can then be compared with the normative frameworks from professional prototyping studies, which is what we seek to understand.

Initial sentence from brainstorming:
In a design class, prototyping is a stage in the design process.

Final sentence stems for all three contexts:

General:	Prototyping is...
Design course:	In a design class, prototyping is...
Personal projects:	When working on personal projects, I use prototyping as...

Response options:
Response options are the same for all stems
Choice 1: A part of all stages of the design process
Choice 2: A stage in the design process

Fig. 1. Example survey item showing Initial form, variation of stems for three contexts, and response options (In appendix version of survey as item 2.2, 3.2, and 4.2).

In the analytic process, we used a process of memoing, summarization, and discussion between the two researchers to generate narrative descriptions of how each student performs prototyping. Throughout, we reserved critique and treated each interview as a holistic and correct description of prototyping. Such memo'ing and discursive interaction are particularly appropriate for qualitative analysis situations where data exploration and theory building are the goal [28]. Both authors memo'ed each interview after its completion, beginning with the first pilot and continuing through all interviews (see appendix). In the memos, we highlighted observations for later analysis and to evolve the interview process. Later, we engaged in an iterative process of individually writing, sharing, and discussing a summary of each interview.

3.3 Positionality

Throughout the study and both forms of data collection, both authors see our perspectives as inseparable from our analysis and work. Those perspectives affect both our motivation for conducting the work and our positionality as we make sense of the data we chose to collect. Our work on this study was motivated by shared observations in teaching design courses in the BME program. Preliminary work suggested several student conceptions of prototyping that deviate from professional uses of prototyping and align with a course-centric performative use.

One author's background is in product development and human-centered design. For over ten years, he has been the primary instructor of a required introductory medical device design class which requires students to build empathy for human users of health care systems and devices, and then to redesign a solution with the intent of addressing a physiological need currently unmet or inaccessible to a group of people. This course is also the students' introduction to technical and practical design skills such as drawing, parametric design software, and prototyping.

The second author is trained as a mechanical engineer and engineering education researcher. His research interests include faculty and students' perceptions of education and engineering. Within design literature, he has published on students' processes of innovation and students' non-integrated designerly ontologies. Currently, he is the primary instructor and developer of the first-year design course within the studied undergraduate program. There, as students develop an identity as an engineering designer, he has worked over the past two years to modify activities and projects to motivate more 'authentic' design experiences. This work includes changing projects, deliverables, assignments, and grading methodologies to increasingly center process over outcome and student reflection over summative assessment.

4. Results

The results are organized into two sections based on research question. The first section address RQ1 using the survey results. The second section addresses RQ2 using both the survey comments and the interviews.

4.1 RQ 1: Survey Results

Overall, participants selected the *performative* option in 28% of their responses and the *purposeful* option in 72%. The percent of performative responses ranged from 71% to 2% across the 18 questions (Fig. 2). We expect the range is reflective of the first deployment of the items and focus on items and patterns of interest rather than a latent belief for these results. The three questions that received the most performative responses are detailed in Table 1. The question most likely to receive a performative response was one that situates a prototype as the goal of the design process – a choice endorsed 71% of the time overall, and 82% of the time when the question was contextualized in a design course.

A higher likelihood of performative responses in the course context transcended individual questions and was statistically significant across the instrument (Fig. 3). A chi squared test shows that context and responses are significantly linked across all three contexts ($\chi^2(2, N = 2866) = 19.58$, $p < 0.001$, $V = 0.08$) and when the course and general context of prototyping are compared ($\chi^2(1, N = 1947) = 18.02$, $p < 0.001$, $V = 0.10$). The effect size reflects a 10% (small) but significant increase in performative responses when answered in the context of design courses.

We also analyzed the influence of course experiences and gender. This analysis used binomial regression ($n_{observations} = 5508$) to predict all items' responses with completion of each course as the predictor of interest. The model added design context as a second predictor to correct for the differences reported above. Results (Table 2) show that the first-year design course does not significantly impact students' answers. However, the second year, third year, and capstone design courses all significantly decrease the likelihood of a performative responses. Such an increase is in line with increasing prototyping confidence across the program. No other variables, including gender ($p = 0.93$) and high school graduation year ($p = 0.23$) predicted changes in responses. A limitation is that because of the distribution of students responding, we were not able to assess interactional effects

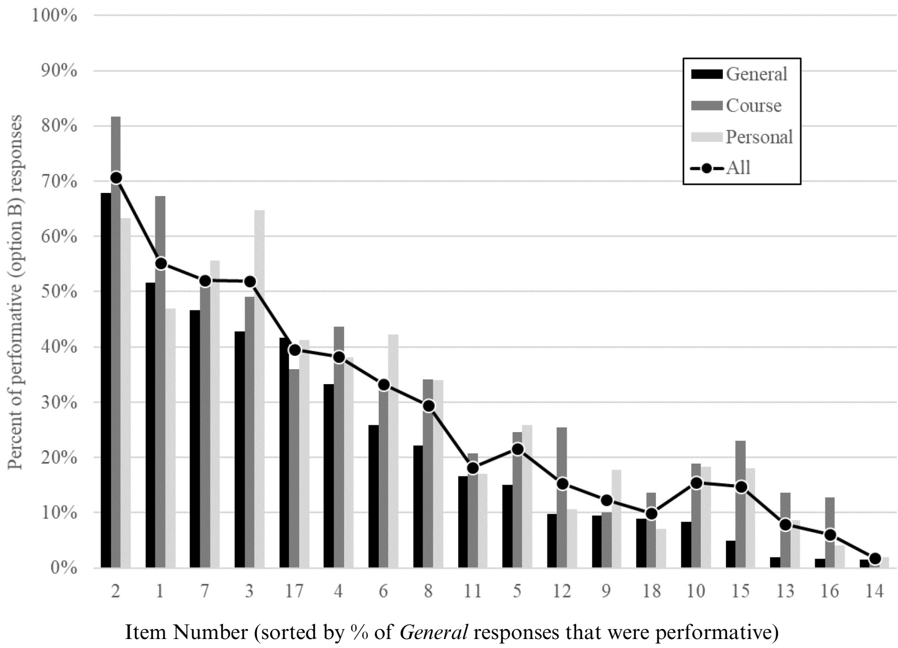

Fig. 2. Sorted plot of responses to items overall and by context.

Table 1. Three questions receiving the most performative prototyping responses (expanded version of this table appears in the appendices)

	% performative responses by context			
Performative response option	**All**	**General**	**Course**	**Personal**
Creating a prototype is the goal of the design process	71%	68%	82%	63%
Prototyping is a stage in the design process	55%	52%	67%	47%
If time is limited, I would create one higher quality prototype	52%	47%	53%	56%

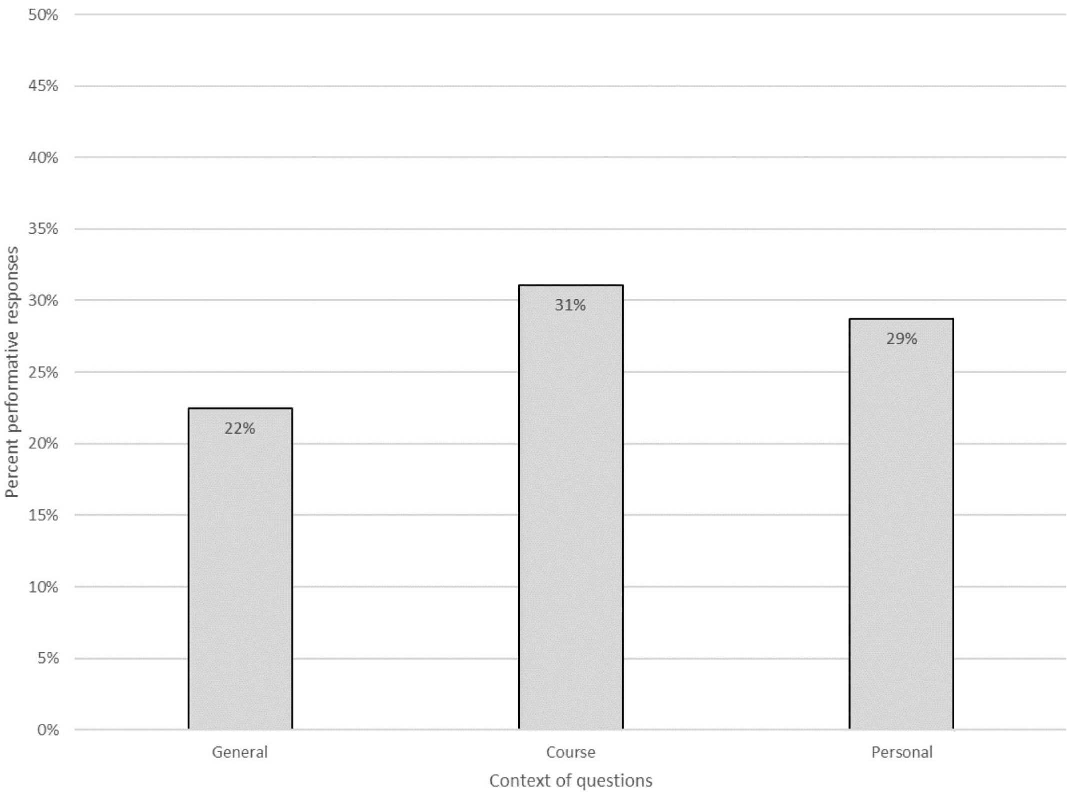

Fig. 3. Comparison of the percentage of performative responses by context.

Table 2. Influence of completing certain courses on performative vs. purposeful prototyping responses

Course	% Performative responses		Predictor impact	
	Not completed	**Completed**	p[3]	**Effect**[4]
BMED1000[1]	27.0%	27.6%	0.38	
BMED2250[1]	31.8%	26.2%	0.002	7.9%
BMED2310[1]	30.3%	25.2%	0.001	6.9%
BMED4602[1]	27.8%	19.4%	0.013	11.8%
BMED3110	27.6%	26.7%	0.48	
Entrepreneurship[2]	27.0%	29.3%	0.41	

[1] Indicates that the course is part of the required undergraduate design sequence.
[2] Includes any entrepreneurial course experience available at the university.
[3] Null hypothesis: completion of the course does not predict students' change the likelihood of selecting a purposeful response after correcting for item context.
[4] Effect refers the percentage change in likelihood of a performative response. Values were calculated by converting logit scale parameter estimates to a percent probability.

among the courses. We also reiterate the low response rate as a potential limitation and suggest that further work on developing and using this survey would be useful to the field.

4.2 RQ2: Qualitative Results

The qualitative results are reported in two parts. The survey comments are used as a bridge between the survey and the interviews, giving context by using students' own words when completing the items analyzed above. Then, the results of the interviews build on the comments to provide extensive and structured examples of students' beliefs and implementations of prototyping in their design courses.

4.2.1 Survey Comments

At the end of each contextualized set of items, students could describe the purpose they saw in creating a prototype in that context. The questions were context specific (e.g., *When I build a prototype for a design class, my goal is to. . .*). Of 102 participants, 84 meaningfully responded to the general prompt, 80 to the design course prompt, and 70 to the personal project prompt. Sixty-eight participants responded to all three prompts. We used the survey software to generate a word cloud of each set of comments with text size scaled to frequency. The word cloud program automatically removed trivial words (e.g., *to*, *and*, *a*, *that*, *I*) and we further removed a further three words (*prototype*, *design*, & *idea*) that were not useful in understanding the similarities and differences across the three prompts. Fig. 4, Fig. 5, and Fig. 6 show the 15 most frequently used non-trivial words for the general, design course, and personal project prompts respectively.

Fig. 4. General prompt word cloud (The purpose of creating a prototype is . . .).

For the general prompt, the three most frequently used words were *test*, *product*, and *demonstrate* in that order. The design course prompt had markedly different most common words, *create*, *build*, and *model*. The personal project was more similar to the general context – *test*, *make*, and

Fig. 5. Design Course prompt word cloud (When I'm working on a personal project, I build prototypes to. . .).

Fig. 6. Personal project prompt word cloud (When I'm working on a personal project, I build prototypes to. . .).

Table 3. Complete responses from three randomly selected participants

#	Context		
	General prompt	**Design course prompt**	**Personal project prompt**
1	To explore some aspect of a solution to a problem.	Create something that shows the most important functions of the device.	Validate my ideas, test certain aspects, and move forward towards a final goal.
2	To visually demonstrate the functions or ideas surrounding a problem or idea.	Visually demonstrate the features and functions of what I am prototyping.	Visually show the idea.
3	To test varying features of a design before moving forward with an idea. You can also use prototypes to test form and function of a design.	Build a prototype to test a certain aspect of the design, and then iterate on that design based on the results of the testing.	Test an idea and use those tests to inform final design ideas.

product. We were particular interested in the word *test* being the most common word in both the personal project and general prompts but only the fourth most common word in the design course prompt.

We also randomly selected three participants from the 68 who responded to all three prompts. We found those responses (Table 3) interesting in the similarities and diversity across the three participants as well across the different contexts. One participant (#2) focused on visual representation in all three contexts. Another (#1) sees contextual shifts from exploratory, to demonstrative, to productive validation. The last (#3) states testing as a consistent theme, but what is tested changes across contexts from testing features, function, and form to a single aspect, to just the idea for informational purposes. All three participants scope design course prototyping narrowly and in ways which could imply an outside evaluator of their prototype.

4.2.2 Interviews

We report the results of the interviews in a series of steps. Table 4 reports a summary of each participants' perception of prototypes and prototyping. Fig. 7 then visualizes the summaries on two axes useful to understand similarities and differences between the perspectives we observed. In the text of this section, we identify and explain key takeaways from the interviews.

All six interviews represented unique and complex perceptions of the role(s) that prototypes and prototyping play in design. The roles that participants perceive for prototypes and prototyping ranged broadly – noting that several (e.g., Charlie) differentiated prototypes and prototyping. Roles included ones familiar from existing literature on professional prototyping (e.g., gathering user input, proving a concept, and testing functionality). However, participants also articulated roles for prototypes not represented in professional frameworks – such as Adrian who saw insight as gained by building rather than testing the prototype or Joe who saw prototypes as a thing you use to define basic specifications and elements of function for the next prototype. Similarly, Blake saw prototyping as a trial and error process wherein you build your idea and then analyze it for other things you want to include. Blake particularly differentiated ''analysis with a calculator'' from ''testing'' of a prototype and noted that testing was more important. Even within roles identifiable in expert prototypes, like communication, the details of participants' exact implementations varied. For example, participants' descriptions of testing universally focused on validating that the prototype performed the intended function of the design – divorcing testing from validating algorithmic models, or analytically derived hypotheses. Such categorically similar but practically varied from expert-like use of prototypes extended to communication. To Charlie, communication could include showing off the idea to potential customers or communicating an idea that you couldn't through words or other media – but also included proving that their team could actually build the idea proposed by showing they could build a prototype. To that final goal, Charlie posited ''spite'' as one of the reasons for building a prototype in their capstone course.

> ''But it was kind of out of like spite because we were told – we had gotten the comment of, 'You're just going to tape a Raspberry Pi to someone's shoe?' And we wanted to prove to them like, 'No, that's not what we're doing, like we're actually like making our own proto board and like having like a miniaturized device work properly. . . .' So it was really frustrating when they were like, 'Oh, you're just going to tape a Raspberry pi to a shoe.' We were like, 'No; like people – it's not new hardware. Like why are we not – why are we focused on like – why are we obsessed with this when we like are proving to you that we've talked to all these physical therapists and like they want this type of data and we know that we can give it to them?' ''

Those subtle shifts parallel a common thread among most participant's (e.g., Adrian, Blake, Dakota, Joe, Natalia) descriptions where prototypes are articulated as a 'draft' of a final device.

Table 4. Summary and key quotes regarding interview participants' perspectives on prototyping, sorted alphabetically by pseudonym

Participant	Summary	Key Quotes
Adrian	Prototyping is how you find out what you don't know, or how you show that you have solved the problem. Prototyping must progress your vision towards reality. Something is not a prototype unless it innovates on existing situations, testing off the shelf parts is a proof of concept, which is not a prototype. You gain insight about function by building, not testing, the prototype. Prototyping is where you identify problems with a concept and iteratively improve it. It is important that the fidelity of the prototype progresses, or your project isn't progressing.	*"[describing why something was not a prototype] there's one way to do that. And so like yes, we had the idea to use an accelerometer and a gyroscope . . . we had to find the math and the equations . . . [but] We didn't come up with the equations to do that math. It was like we were finding the research and then applying it to this specific problem."* *"So it's like the sort of thing where I find problems that I hadn't considered while just thinking about it conceptually when I'm physically prototyping."*
Blake	A prototype is a draft of the final product, it is a thing you edit through a process of trial and error. Prototyping can be a means to identifying features you might need to include, to think about and analyze your design, and/or a process of finalizing the product. You come up with an idea and then build it, and then you analyze it and think about it to see where what you envisioned needs to go and whether you can build it. You should be able to test it quantifiably, which is important so you aren't just analyzing something using a calculator. Part of the prototyping process is discovering the inputs and outputs of your device. Broadly, prototyping is separate from the design process (which occurs before) and both are a separate thing from the research or planning processes – which may co-occur but are independent.	*"I consider it a prototype because this is not exactly what I wanted, but I had to edit it a few times to make it the best version that it can be for the moment or given the situation. So the original plan was to make it look like it had honeycomb holes in it, but that didn't happen, so that makes this a prototype."* *"it was a rough sketch. It wasn't even like what we're doing now in 2310. It was just like lines and triangles. So we drew sketches of what we wanted to do. And then we like tried to reason our way through whether it would work or not, then we built the actual model using dried spaghetti pieces."* *"I would say you have like a rough draft version of the final product would be one, and then, two, to be able to see the important features of the final product, and . . . the last one would be like having any potential failures like right there, so we know what to fix before we actually do the final product."*
Charlie	Prototyping has two potential goals. Each prototype must show progression in terms of increasing function and fidelity or you aren't prototyping. One goal is communication, but the diversity of communication is enormous. It can include user feedback, proving the team can build their idea, or even to explain an idea to teammates. The other goal of prototyping is to solve a problem or figure out what you want to build through the prototyping process. This goal is intentionally separate. It involves testing functionality, and learning about the idea, most often how it should work or features you need to include in the design.	*"A prototype is for – I guess thinking back on everything that I've said, a prototype for me has really been communication; like a communication piece in terms of what I want this to do, what I want it to look like, and how I can showcase my idea to my teammates, or potential customers, or users, or buyer – or investors."* *"like we test all of these – like all of our prototypes. And even if it – even with like the – like I guess more – I guess the term is like 'low-fidelity', they still like proved a point or didn't prove a point, and then we were like, "Yes, this kind of sucks. Maybe we don't want to move forward with this idea." But it was – it took our ideas and made them into more of a reality, I guess. Even if it wasn't complete reality, it was still a way for us to be like, "Okay, if we did go in this direction, then what?"*
Dakota	Prototyping leads towards a goal of creating a device. The process, which varies depending on the project, is about being open to change and knowing that all knowledge is good knowledge. Personal projects are stream-of-consciousness, professional projects require a rigorous process where it's "important to be careful." Each step in the design process is prototyping if you build something concrete that represents your device and you learn from it. A prototype isn't a final device, it doesn't have to be physical, it can even be a math model. What makes it a prototype is working towards the final design, the intention, the testing, the progress. But prototyping must involve guided and structured thinking and is different from tinkering which is not a conscious, planned, and documented process.	*"And there's still a lot of learning, but it's going in with a general idea of what we would like the final product to look like. But an openness to pivot and adapt and change to what we find works and what doesn't. Because we come in and we say we're going to make this joint. And then it just doesn't work. Like OK. What else do we have? You know, it doesn't have to look just like this. And so how I go about it really is just being open to the change."* *"And then I just pick it up and make some stuff, and just make some changes, and just – it's not really a super involved conscious process. I don't take notes. I don't document anything. I just you know, work on it, change something, see how that goes. So I'm not as conscious about each individual step along the way."*
Joe	Prototyping and design thinking are generally one and the same – because the prototype is the outcome of the process. A prototype is an idea that you use to determine specifications – or what the next prototype should be. Something becomes a prototype when it includes the minimal elements for function. It can be something where you learn how to build it or if you can build it, but it has to function. User feedback isn't a fundamental part of the prototyping process, but it is one outcome of the process of figuring out how to build the right thing. Contexts for prototyping might include 'formal', 'informal', or 'personal'. During 'formal' projects you need use an explicit process, such as the FDA waterfall process. During informal projects, a generally similar process applies but you can be flexible on the steps and you don't need to document as much.	*"So the first prototype was to see I guess, yeah can we prototype like this? And then further prototypes were, okay well we have the sensor, we know the locations that we need to be able to accurately sense heart rate, now we need to design a prototype based off of those two criteria as well as try to fit you know standards of like comfortability for people when they wear this kind of thing."* *"I think, to me, a prototype is when it achieves I think what they say like the minimal requirements that it needs to be able to function. So, if I was to go out and make a prototype today, maybe like a you know some weird like speaker diaphragm thing that maybe will break if I put that much water in there; maybe [inaudible] work since there's no minerals there, but get a couple of like expands to see like if the flow actually measure, get some thermometers solder them up and turn it on."*
Natalie	A prototype is a 'draft' of how a device is built. Similar to drafting a paper, there is an ongoing and holistic progression of the device that ends with a final prototype. Something built to just be confirmatory is not a prototype, because it had not achieved the basic needs and function. A prototype leads towards more discovery in the sense of discovering inputs and outputs and increases the tangibility of the design. Sketching vs. making are different stages of the design process, which can be but not necessarily are prototypes. Something can be a prototype if it just looks like the final thing but that is out of order.	*"You're ready to build a prototype when you understand the purpose of the device that you're building, the functionality of it and its inputs and outputs. Like, you can build a prototype once you've done all the research necessary to, like, what it's supposed to do, why it's doing it, how you think it can be done. Like, that – I think that how you think it can be done is a major part of prototyping because this is where your ideation is coming to life, because you're proposing, like, different variations of how something can be done, how something can be produced."* *"Like, it's the first draft of a larger device. And so we never – because we never actually developed a device, I was thinking that this was, like, the prerequisite to the first draft. You know, this is the outline. Yeah."*

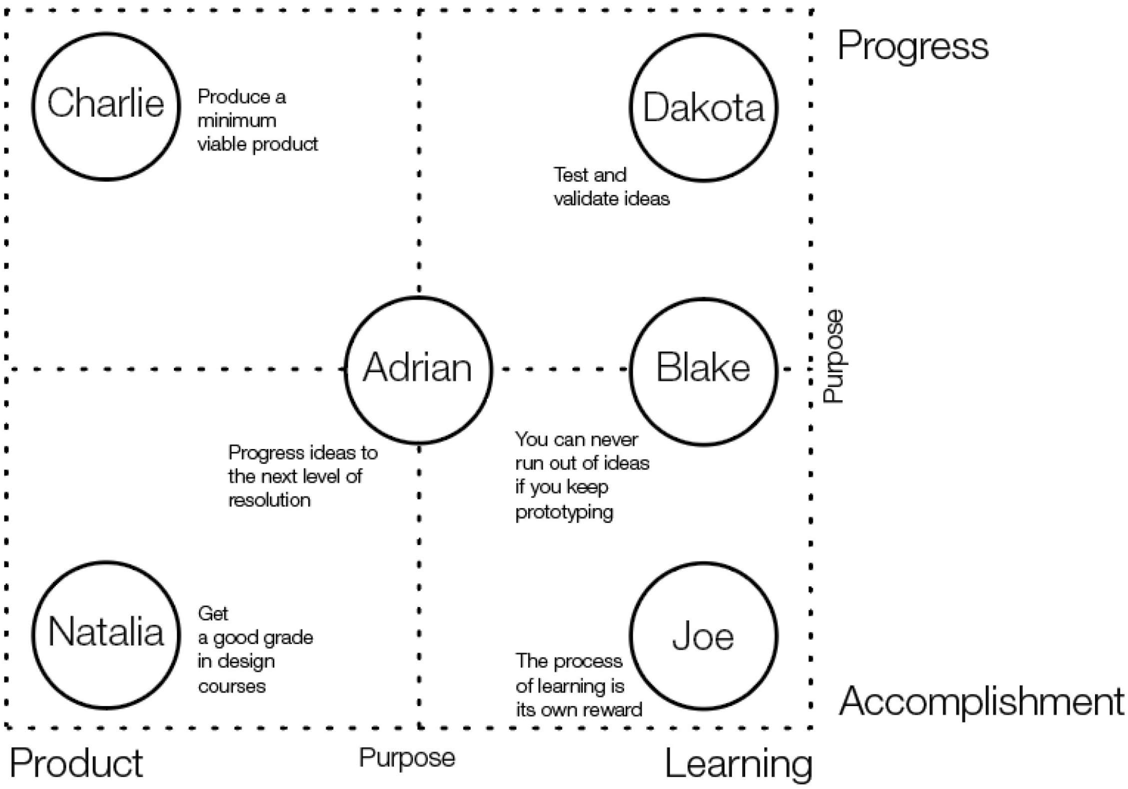

Fig. 7. Relations between the participants' perceptions of the role of prototypes and prototyping.

Natalia explicitly analogized prototyping to drafting a paper *"it's the first draft of a larger device. And so we never – because we never actually developed a device, I was thinking that this was, like, the prerequisite to the first draft. You know, this is the outline."* There was some variability in the idea of a prototype as a draft of the device. To Adrian, the prototypes must progress in form and function towards the final goal, but that progression is part of the design process and is separate from the prototype itself, which is where you identify problems with your current idea. Joe included other factors in the progression of prototype noting *"So the first prototype was to see I guess, yeah can we prototype like this?"*

Participants also linked the draft perspective of prototyping to their broader goals of the design process. To Joe, the goal of the design process *is* a prototype. Others explicitly situated prototypes made in courses as performance of course content – another goal. Adrian, for example, said "*at the end of the day, like, we did have a – like, we did have things that needed to be turned in. We did have things that needed to be submitted. And so, like, this was one of those things that needed to be submitted, but it also, like, helped us."* Prototypes as drafts was also suggested in the course-centric prototyping perspectives Blake and Natalia articulated. The only two participants currently enrolled in the third-year design course, they both described prototypes in ways reflective of linear representations of the design process – where the prototype is the outcome of the entire design process. As Natalia put it *You're ready to build a prototype when you understand the purpose of the device that you're building, the functionality of it and its inputs and outputs."* Others (e.g., Joe and Dakota) sought to clearly differentiate different design processes. Joe described "personal", "informal", and "formal" processes with an increasing focus on documentation and process and a decreasing focus on learning in each step.

Fig. 7. visualizes each participants' overall perception of prototyping on two dimensions – both intentionally labeled *Purpose*. Throughout the analysis process, we found ourselves consistently using comparisons between participants to uncover the explicit and implicit perceptions about prototyping that participants described. The two axes refer to two different dimensions of the use of prototyping in the interview. The horizontal purpose dimension ranges from learning to product and reflects a difference in the what is developed through prototyping. At one end, some like Joe and Blake see the purpose of prototyping as developing their own understanding or knowledge – and the creation of a prototype as part of that process. For Joe, that development was about personal knowledge, especially hands-on techniques for creating prototypes

or learning about new technologies. For Blake, the learning was more about how they design a product – prototypes helped learn about the design itself and what they missed at earlier steps. That is quite different from Charlie and Natalia who saw the purpose of prototyping as developing the product itself and the creation of prototypes as something that occurs through that process.

The vertical purpose dimension ranges from Accomplishment to Progress and reflects an outcome-derived purpose for prototyping. Natalia and Joe are focused on the accomplishment of individual goals that arise through the prototype creation process – goals delinked from the design process. For Natalia, accomplishment is the purpose of their design work: A project that can get a good grade results from having a prototype that shows she followed the design process as expected in the course. For Joe, that accomplishment is his own learning. Natalia and Joe's goals of accomplishment are quite different from Charlie and Dakota. Charlie and Dakota focus on making progress on some aspect of the project. Charlie sees the product as inherently evolving in each step, and consistently focused on getting stakeholder buy-in on the solution as a prototyping focus (e.g., language related to communicating, proving, demonstrating). Dakota similarly focuses on progress, but focuses on prototyping as learning about and testing the design itself.

Throughout the interviews, aspects of purposeful and performative prototyping were intermingled in each interview. From Charlie's prototypes, which were for the purpose of proving they could build their idea, to Adrian's comment that the courses required submissions, to implicit commentary in others the nature of showing something to an outside evaluator was consistently present. Aspects of prototyping as performative consistently became more salient when students described prototypes created for coursework. However, all participants also defined clear purposeful approaches as well. Such purposes spoke to varied but focused ways of creating value through the creation of prototypes that went beyond the goal of performing prototyping. When not limited to the binary choice provide in the survey, the intermix of purposeful and performative conceptions of prototyping appear more complex. We return to this in the discussion section.

5. Discussion

We have divided our discussion of the results into two sections. First, we address how the results fit within and advance existing knowledge about student prototypes and design. Second, we reflect on what the findings indicate to us as design instructors, and discuss modifications we are planning in our own courses that others may find useful.

5.1 Our Results and Literature on Student Prototyping

Generally, our results align with other studies of student prototyping. Students' conception and use of prototyping is different than that of professionals in multiple ways. Our results illuminate both similarities and differences with prior work that contextualize existing findings. We end the section by proposing a new lens that may help bridge our findings and prior work in the future. To frame the discussion, it is important to note that the students in this study all come from a single program, from biomedical engineering, and that the demographics of responses are typical of that program but not of engineering more broadly. Future work, that we plan to undertake, should include comparisons to students in other disciplines of engineering and design.

The primary similarity with prior work is that students do not use prototyping in the same ways as professionals. Our results suggest students interpret a fully functional prototype as the fundamental goal of the design process, and they see the goal of prototyping as creating a successful prototype. The survey question most likely to receive a performative response situated a prototype as *the goal* of the design process – a choice endorsed 71% of the time overall, and 82% of the time when the questions was contextualized in a design course. That response pattern is further supported by the qualitative results, where students explicitly state the goal of design as being the production of a prototype. Conflating the design and the prototype is fundamentally different from how experts would be expected to approach design – where developing the design is the goal and prototypes must serve that goal [7]. Our findings extend findings that students are less likely to use prototypes in the early stage of design – and suggest explanations from fundamental conceptions of design for those findings [6, 13].

Another similarity is that students do not universally link prototyping to validation of hypotheses, analytical work, or external feedback. Rather, for at least some participants, prototyping is first for personal learning and understand their own design. Using prototyping to learn or understand their design parallels earlier results that suggest students may not feel prepared to build the things they envision or scope the functional needs of a design in the abstract [14]. Our results do show that some students view the prototyping process as a way of developing their skills at building things, which prior results have shown help increase comfort with prototyping and generating creative solutions [14, 15]. Developing one's own skills is unlikely to be a goal professionals link to prototyping because it does not add value to a design [7]. However, such learning seems important to the growth of students' ability to design and should not be discounted. In fact, this finding is something that we plan to make a more explicit part of the learning goals of our design courses.

The differences between our results and prior work can be largely centered on how one views a comment in prior work that "students do not make full use of the benefits of prototyping" [5]. Our results consistently validated that statement, *if* one defines the full benefits of prototyping through how professionals use prototypes. However, students also seek other benefits from prototyping that are specific to their context and likely absent from professional work. For example, both our quantitative and qualitative results show that students skew prototyping in courses towards demonstrating that they have performed design. Within a students' experience, such a use can be highly beneficial (e.g., resulting in a better grade), but only if creation of a prototype exists in the intersubjective space between instructors and students wherein the goals of design work and of the class overlap. If a prototype is (or is perceived as) the goal, such behaviors are contextually beneficial despite being misaligned with how professionals would likely use prototypes.

As far as we are aware, no prior work has addressed whether being in a course changes how students create prototypes – although other studies of student design behavior clearly show a pattern of course demands influencing design processes and behaviors [9]. The survey comments illustrate a contextual shift from decontextualized prototypes for testing towards more demonstrative or performative actions (e.g., build, model, create) when contextualized in a classroom. While not formally tested here, we theorize the comments align with the inherent structures of education and benefits of achieving students perceive in a high grade or attitudes towards compliance. Highlighted explicitly by Adrian in the interviews, the need to turn something in is an important consideration for students when they prototype in a course. In this way, student prototyping can be highly purposeful (e.g., get an A) even if it does not purposefully advance the design itself. Here, we suggest more precise language by researchers may benefit educators as they adjust seek to improve students' prototyping skills.

Beyond surface level differences, professionals and students can even describe similar roles in highly disparate ways. Lauff [7] identified communication as a prototyping role and lists four types of communication – explaining a concept, generating user input, facilitating negotiations, and persuading others [p. 5]. Several of these forms are identifiable in how students described communication via prototype (c.f., Charlie's persuasive use of a prototype to sell an idea). However, students' prototypes did not always meet Lauff's key function of communication: advancing the design by facilitating feedback. Charlie described multiple types of communication using prototypes, but noted that gathering feedback is possible but not required when using prototypes to communicate. Communication within student prototyping included demonstrating skills or proving an idea or representing their effort. These are forms of communication using a prototype, but ones which Lauff's professionals may not recognize. Instead, students' communicative roles expand to include types of communication focused on demonstrating accomplishment (e.g., of a prototype) rather than progress on a design.

The similarities and differences with prior work suggest a need for a role-agnostic understanding of student prototyping and the trajectory of learning to prototype. We theorize that an information-centric, instead of a role-centric approach, would better illuminate and guide a trajectory of student prototyping expertise. Such an approach could benefit from other existing work on information literacy in engineering education (e.g., Gross and Latham, 2011). While exact definitions vary [30], the general stages include identifying a need for information, gathering that information, evaluating that information, and integrating that information into a project [31]. Information requests have already been shown to be a potential metric for tracking design progression [24]. Such information gathering is embedded in Lauff's work and noted as something students' struggle to articulate [8]. Decentering roles for information may also be helpful to identifying unexpected threshold skills that are required to use prototypes effectively but may not be covered sufficiently to enable good prototyping (e.g., Joe's comments about learning how to build certain types of objects and others' comments about gaining or proving skill with specific engineering tools such as CAD intermingled). What is gleaned from Lauff and other's studies of professional prototyping is that such actions by professionals are holistic and intentional from creation to integration of information into the design itself. Our results suggest the roles themselves are less useful as an interpretive tool, and instead, how one operationalizes those roles in search of (or not) specific information may better explain differences.

5.2 Implications for our Classroom Practice

As design educators, we are also left with a clear set of changes that we seek to take away from this study and implement in our classrooms. Primarily, they involve increasing structure in ways that force students to take an information-centric approach to prototyping where they plan for, engage in, and reflect on a process of prototyping rather than the creation of a prototype. During her interview Dakota, said:

> ". . . you can document different things, try different things, explore different angles. And you're not pressured to 'this has to work in this context for all these different aspects' of what we're doing. . . . Because you can kind of isolate variables in tests, and say how does this work with this? How does it work with that? Without the pressure of making the whole thing work. And so if you can break apart things and learn, and then be moving towards some final process without trying to rush there, and you can take your time and see what works, what doesn't. . .You know, it doesn't have to look just like this. And so how I go about it really is just being open to the change."

We see elements of what we want to elicit as well as clear things we want to train out in their statement. Their statement generally aligns with that described in literature such as *Engineering Design, a Project-Based Introduction* [18]. Specifically, that prototyping should not be performed with the "pressure" to achieve a presumed result. However, missing from their description is a clear process of planning – hypothesizing, data collection processes, targeted prototyping, and integration of information into the design. In its place is learning about how things work, which we suspect simply comes from a gap between their technical toolbox and the design tools that are supposed to enable them to put their tools into practice. Towards bridging that gap, we plan to try the following things in our classes in the near future.

First, for students to prototype earlier in class. Having students prototype earlier, and explain the goals of their prototypes earlier has the potential to reveal perspectives that may need nudging and multiple cycles of feedback when time exists to do so. While growth over the curriculum is an area we plan to explore in future research, we presume that the more cycles of action, guided reflection, and feedback on prototyping that students receive, the more likely there is to be a change in perspective. Second, acknowledge and design to counter the "student as actor" misconception by discussing the motivation of performative prototyping and its flaws. That includes foregrounding it early in the process, incentivizing honest reflection about the goals of a prototype, and structuring assignments to nudge students towards purposeful prototyping consistently. Third, provide a framework which rewards authentic prototyping. That framework will include a series of information-centric structured scenarios for prototyping to scaffold understanding and demonstrate the value of curiosity and a discovery-focused authentic prototyping process. An existing example is the *The Prototyping for X* framework, which allows instructors to clearly communicate to students what the goal of a series of prototypes should be while allowing students the freedom to leverage the creative benefits of a playful approach within that well-defined prototyping context [4].

Overall, in implementing these changes, we need to start by engaging students about what prototyping is in their own words, not beginning with a professional vocabulary. We plan to work to develop those definitions by embedding prototyping in each assignment, activity, or learning objective, and explaining the value prototypes can play at the current stage of a project. Currently, we use flow charts which represent an entire course, communicating how the output of each assignment becomes an input for a subsequent assignment. Going forward, we plan to develop similar structures to hold students accountable – such as explicitly planning goals and tests for each prototype prior to creation, execution of that prototype plan, and then reflecting on whether the prototype accomplished their goals in addition to unexpected learning. We expect there to be power in guided reflection and feedback to shift the perspectives.

However, this growth also likely takes time because it involves unlearning a mode of operation in schoolwork that is quite effective. Rather than eliminating the performative perspective in one intervention, we see it as a change best experienced. One interview participant, months after their interview, had lunch with one of the authors about a startup they were working on. The participant commented that "*thinking back on that interview I realized that I didn't use the design tools in a way that let me realize their value, and now with the startup I'm really focused on why we are making each prototype we make*."

6. Conclusions and Future Work

In this study, we have shown that engineering students have specific purposes that they individually attribute to the creation of prototypes and the prototyping process. Interviews suggest that those roles are highly varied in ways that include significant similarities to and differences from the way engineering professionals use prototypes.

Our survey results show that students are significantly more likely to select performative roles for prototyping in the context of a design course than in a general context. Further, students see creating a prototype as a goal of the design process rather than a means to an end within it – and prototyping as a stage in design rather than a part of all stages. Both findings align with prior literature.

From our interviews, we see layered and complex student conceptions of prototyping. When probed, students articulate those conceptions as often explicitly dependent on context and influenced by the structural confines of design courses. The broad set of roles of prototypes and the prototyping process reflect aspects of alignment and misalignment with professional uses of prototyping. One key area that may look like overlap, but likely is not, is in how the design process progresses through prototyping. There, multiple participants viewed the progress as coming from the construction of a prototype rather as much or more than any explicit attempts to test specific features.

We conclude that there is still a need to understand students' prototyping actions further. Specifically, researchers and educators should look beyond the roles identified in expert prototypes to demonstrate specific examples of students' use of prototyping in the context, because such contexts are fundamentally different from professionalized product development uses. Such an increase in the breadth and nuance of roles students embody can help educators refine course experiences as well as help researchers continue to better understand why and how students prototype in different contexts.

Future work that we plan and suggest for the field includes longitudinal studies as well continued development of the survey we used. We would find assessing how the perceptions participants express in interviews change over time to be quite illustrative, especially if they included engineering interviews and early career development. As for the survey, while it serves the purpose for this study, seeking to reduce items to those which are most effective at identifying a progressive development of students' prototyping attitudes would be useful. As would looking at how specific items or groups change across institutions and programs.

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Appendices

Expanded version of Table 1

		Response options		% Performative Responses			
Item	**Stem**	**Purposeful**	**Performative**	**All**	**General**	**Course**	**Personal**
2	Creating a prototype is . . .	A means to an end	A goal of the design process	71%	68%	82%	63%
1	Prototyping is . . .	A part of all stages of the design process	A stage in the design process	55%	52%	67%	47%
7	If time is limited, I would create . . .	More lower quality prototypes	one higher quality prototype	52%	47%	53%	56%

Survey

Items

Stems (Shown with General stem)	**Response option A**	**Response option B**
Prototyping is... *(Course) In a design class, prototyping is...* *(Personal) When working on personal projects, I see prototyping as . . .*	A part of all stages of the design process	A stage in the design process
Creating a prototype is...	A means to an end	A goal of the design process
The primary role of prototyping is...	To get feedback on ideas	To demonstrate ideas
Prototyping is . . .	A way to test your ideas	A way to show your ideas
The best prototypes are . . .	just detailed enough to do their job	As close as possible to final appearance
The appearance of a prototype is . . .	Less important than its usefulness	An important consideration when creating it
If time is limited, I would focus on creating . . .	More lower quality prototypes	One higher quality prototype
It is more valuable to create...	Many prototypes that each represent a part of the design	One prototype that represents the complete design
A prototype is anything...	Usually a productive activity to spend time on	Usually a drain on time, unless your idea is ready
Prototyping is . . .	A productive and valuable activity for to spend time on	A drain on time and resources that you should only do when your idea is ready

Stems (Shown with General stem)	Response option A	Response option B
An engineer is ready to build a prototype when . . .	They have defined questions in engineering terms relevant to their project	They have prior skills or experience relevant to the materials or processes needed for their project
The best materials for prototyping are . . .	Those you have available to you	Specifically intended for making prototypes
Simulations software like SolidWorks or Fusion360 are . . .	A useful companion to physical prototypes	A better alternative to physical prototypes
It is important that testing of prototypes . . .	Have both objective and subjective measurements depending on where you are in the process	Only have objective measurements so the results are accurate
It is important that testing of prototypes . . .	Have both objective and subjective measurements depending on where you are in the process	Only have subjective measurements so you know your idea is good.
Prototypes are best used when . . .	They are part of a plan that includes testing.	When you need to demonstrate something
Prototypes are best used . . .	To explore ideas as they emerge, without presuming a final solution	To present ideas that are final, without anticipating further work
The purpose of creating a prototype is . . .	*Open comments*	

Instructions for each context

General

On this page, you will be asked to answer 10 questions about prototyping. In each question, you will be presented with a partial sentence stem. You will then be shown two options to complete the sentence. Please pick whichever answer is more accurate in your experience. There are no right or wrong answers, we are interested in the opinions that you have developed about prototyping through your personal experiences.

Design Course

Now that we have your general opinions on how prototypes are used, we would like to get your opinions on how prototypes are used in design classes that you have taken. On this page, you will (again) be asked to answer 10 questions about prototyping. Some of those questions may be the same or similar to the ones on the previous page, some will be new. That is intentional. As in the first group of questions, you will be presented with a partial sentence stem. You will then be shown two options to complete the sentence. Please pick whichever answer is more accurate in your experience. There are no right or wrong answers, we are interested in the opinions that you have developed about prototyping through your personal experiences.

Personal Project

Lastly, we would like to get your opinions on how you use prototypes in personal projects that you have worked on. On this page, you will (again) be asked to answer 10 questions about prototyping. Some of those questions may be similar to the ones on the previous page, some will be new. That is intentional. As in the first group of questions, you will be presented with a partial sentence stem. You will then be shown two options to complete the sentence. Please pick whichever answer is more accurate in your experience. There are no right or wrong answers, we are interested in the opinions that you have developed about prototyping through your personal experiences.

Demographics

Please select any BMED courses that you have previously completed or are currently enrolled in

What year did you graduate from high school?

- 2020
- 2019
- 2018
- 2017
- 2016
- 2015 or before

What descriptor most closely represents your identity?

- Cis-
- Trans-
- Female
- Male
- Non-Binary
- Another identity not listed

Interview protocol

Warmup questions:

- Tell me about yourself
- What courses in the BME department have you taken?
- Of the courses you which ones did you like the most and why? / least and why?
- How have you found the different design courses in the program?
  - What did you like those classes?
  - What do
  - What projects have you worked on in those classes?
- Can you tell me about some of the different prototypes you have built in your life
  - *Ask for in class examples*
  - *Ask for personal examples*
  - *Ask for work examples*

Prototypes questions:

- *Ask student to pick 2 or 3 prototypes they have created and discuss*
  - Can you describe the prototype?
  - What was this purpose of this prototype?
  - Who was the audience of it?
  - What did you gain from its creation?
  - Was it useful?
  - Would you create a similar type of prototype in another design project? Why/not?

Belief questions (do not need to ask all):

- When you are working on a design project how do you go about prototyping?
- Does that process change depending on the type of project you are working on?
  - For example, do you prototype differently when working on personal projects vs. course projects?
- What is a prototype for?
- What other roles can a prototype take on?
- Where does prototyping fit into your personal process of designing something?
- When are you ready to build a prototype in the design process?
- How does prototyping add value to design?
- If you are asked in a class to work on a prototype, what do you think about?
  - What do you focus on in creating the prototype?
  - What is important for that prototype?
  - Would it change with the type of course or the instructor?
- If you working on a prototype of your own project how do you use prototyping?
  - What would you think about while creating that type of prototype?
  - What do you focus on in creating the prototype?
  - What is important for that prototype?
- What makes something a prototype?

Qualitative memo template

Five questions used for each interview memo:

What did you notice about how the interview went?
What was the most interesting thing to you that the participant said about prototyping?
In your own words, what roles and process did the participant describe for prototyping?
What didn't I (the interviewer) follow up on in the interview that I should?
Are there any changes to the process or protocol that we should make?

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Martin Jacobson received his BS in Industrial Design from Georgia Tech in 2006. His early work included the design of many successful consumer products and architectural spaces for clients such as The Home Depot, Tempur-Pedic, Schwinn, Disney, and Safety 1st. He began teaching medical device design in the Biomedical Engineering department at Georgia Tech in May 2010. Mr. Jacobson's expertise lies in finding elegant solutions to complex mechanical and human

factors problems, as well as in a number of manufacturing disciplines. Mr. Jacobson's educational activities include the design of innovative methods for teaching 3D CAD software while maintaining relevance of the ideas as engineering visualization skills with broader application, as well as teaching undergrad students and researchers high-precision CNC micromachining techniques which enable cutting-edge microfluidic research.