NOVICE DESIGNERS' USE OF PROTOTYPES AS COMMUNICATION TOOLS

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ABSTRACT

Prototypes are critical design artifacts, and recent studies have established the ability of prototypes to facilitate communication. However, prior work suggests that novice designers often fail to perceive prototypes as effective communication tools, and struggle to rationalize design decisions made during prototyping tasks. To understand the interactions between communication and prototypes, design pitches from 40 undergraduate engineering design teams were collected and qualitatively analysed. Our findings suggest that students used prototypes to explain and persuade, aligning with prior studies of design practitioners. The results also suggest that students tend to use prototypes to justify design decisions and adverse outcomes. Future work will seek to understand novice designers' use of prototypes as communication tools in further depth. Ultimately, this work will inform the creation of pedagogical strategies to provide students with the skills needed to effectively communicate design solutions and intent.

Keywords: Prototypes, Design education, Communication, Design theory, Capstone design

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1 INTRODUCTION

1.1 Design as a Social Process

Design is inherently a highly heterogenous activity that is characterized by the involvement of a number of human and non-human actors (Law, 2012). The processes and decisions involved in design are often mediated by interactions and negotiations between designers, users, and stakeholders, hence making design as much of a social activity as it is a technical one (Bucciarelli, 1988, 1994). A central element of the social nature of design is the communication among multiple individuals engaged in a design process (Bucciarelli, 1988). Prior research has established that effective communication can create a shared understanding (Cash *et al.*, 2017; den Otter and Emmitt, 2008), aid in the synthesis of disparate individual knowledge (Deken *et al.*, 2012; Dong, 2005), and facilitate collaboration (Kleinsmann *et al.*, 2013; Shah *et al.*, 2019) in design teams. At the same time, it is equally important for designers to communicate with individuals *outside* of design teams. These individuals may have different backgrounds and knowledge, and to establish a shared meaning with these individuals, designers must effectively communicate. It is critical that designers navigate the technical nuances of design and establish shared meaning through communication, as designers are equally likely to engage with non-technical audiences as they are with technical audiences (Darling and Dannels, 2003). While prior work has investigated the communicative patterns of designers within design teams (Dong, 2005; Stumpf and McDonnell, 2002), relatively little work has explored the communicative patterns of designers when engaged with external audiences. Therefore, this work is motivated by the need to better understand how designers communicate with individuals outside of design teams.

1.2 Prototypes as Communication Tools

Designers leverage a variety of objects to communicate, including sketches, prototypes, and simulations. In this paper, we collectively refer to these objects as artifacts. These artifacts form a unique design language of their own (Dym *et al.*, 2005), and play a key role in mediating the interactions between the various individuals in the design process (Bucciarelli, 2002). Also known as 'boundary objects' (Star and Griesemer, 1989), these artifacts lie at the interface of distinct social worlds, and allow for negotiation and communication between individuals inhabiting these worlds.

Prototypes, as physical manifestations of design solutions, are one such example of boundary objects in engineering design (Lauff *et al.*, 2018a; Subrahmanian *et al.*, 2003). In professional design settings, prototypes are leveraged across distinct social environments to enable communication between different individuals of the design process, as highlighted by Lauff *et al.* (2020) in their ethnographic study of professional designers. Their findings revealed that prototypes were used to explain and obtain feedback about a design concept, and subsequently negotiate aspects of the design solution (Lauff *et al.*, 2020). This aligns with prior research highlighting the efficacy of prototypes in communicating design ideas and creating shared mental models within a design team (Gerber and Carroll, 2012; Lauff *et al.*, 2018). When interacting with end-users, Lauff *et al*. (2020) found that designers used prototypes to persuade users and build confidence in the design solution. Using a prototype to communicate can be particularly useful for promoting stakeholder buy-in (Greenberg *et al.*, 2013; Starkey *et al.*, 2019), and successful start-ups have been shown to actively use prototypes to gain financial capital (Nelson *et al.*, 2020). Prototypes are effective communication tools (Gill *et al.*, 2011), and their role as a communication tool constantly evolves based on context in which they are enacted (Lauff *et al.*, 2020).

While prior research has established the efficacy of prototypes being effective tools for communication (Lauff *et al.*, 2018, 2020), much of this research has been limited to professional design settings. Yet, novice and professional designers are known to have fundamentally different perceptions of prototypes (Deininger *et al.*, 2017; Lauff *et al.*, 2017). While professional designers often hold a multi-faceted perception of prototypes, novice designers have a much more limited mental model. Prior work has demonstrated that novices tend to see prototyping primarily as a method to evaluate the functionality of a design solution (Deininger *et al.*, 2017; Lauff *et al.*, 2017). Recent work by Krishnakumar *et al.* (2021) also suggests that novice designers struggle to rationalize their design decisions after a prototyping task, often attributing failure to external factors and employing a number of rhetorical strategies to justify their design solution.

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Communication, both within and outside of design teams, is an integral element of design. In the context of this work, we define a design team as a team of novice designers directly engaged in the design process. Prototypes, as physical manifestations of design solutions often facilitate this communication. Yet, novice designers often do not see the potential of prototypes as communication tools. Further, there is only a limited body of research investigating novice designers' use of prototypes to communicate design solutions to an external audience (Krishnakumar *et al.*, 2021). This gap in the literature creates an opportunity for us to study how novice designers employ prototypes during interactions with external audiences, which will be foundational for guiding future design education best practices. In this study, we seek to address this research gap and are guided by the research question *'How do novice designers use prototypes to communicate design solutions to an external audience?'*

2 METHODOLOGY

To answer the research question, an Institutional Review Board approved study was conducted at the Senior Design Showcase event at a large Mid-Atlantic University in the United States. The Senior Design Showcase is the culmination of the Capstone Design Program in the College of Engineering, where students present their solutions to the public and are judged by a panel of industry experts. Students work in multidisciplinary teams to solve real-world design problems strongly resembling those faced in design practice (Young, 1993). These teams carry out the entire design process and are often required to produce a functional prototype of their solution prior to the completion of the course. At the Senior Design Showcase, teams present their final design solutions to an external audience. As this event is conducted at the end of their projects, the prototypes are high-fidelity and comprehensive prototypes (Ulrich and Eppinger, 2012), ranging from digital CAD models and simulations to three-dimensional working physical models. Students are also asked to prepare a pitch of their project describing the design problem and solution while keeping in mind that attendees of the event come from both technical and non-technical backgrounds. While teams are given a general guideline of keeping pitches 3-5 minutes long, each team decides the appropriate duration of their pitch needed to convey the necessary information to the audience. As our research question pertained to the nexus between prototypes and communication, the Senior Design Showcase was the ideal event to understand the fundamental ways in which novice designers leverage prototypes to communicate with external audiences.

2.1 Participants

The participants for this study were senior level students enrolled in the College of Engineering. Students had experience in delivering technical presentations on design outcomes through other courses prior to starting their capstone projects. Further, most sections of the capstone course hold mock Showcase sessions for students to practice their pitches before the actual event. The Capstone Design Program consisted of 84 industry sponsored projects. However, not all projects required students to create either a digital or physical prototype of their design solution. Therefore, we first assessed the descriptions and deliverables of each project and selected those that indicated either a physical or digital prototype as being one of the deliverables. This filtering process resulted in 68 teams who were approached, and 56 teams (two to six students per team) consented to participate in the study.

2.2 Procedure

Leading up to the Senior Design Showcase, owing to the large amount of data that would need to be collected in a limited duration of time, a team of 18 data collectors were recruited for data collection. All data collectors were experienced in human-subjects' research and were trained by the first author in the specific data collection methods used in this study. On the day of the Senior Design Showcase, teams were approached and briefed about the study, and consent was obtained. Next, students were asked to present their project pitch, and all pitches were video recorded. As some teams may not have all team members presenting the pitch, the research team regularly probed students who had not spoken, asking if they had anything else to add. Finally, the study concluded with a brief survey leveraging a 4-point Likert scale (Strongly Disagree = 1 to Strongly Agree = 4) to collect self-assessments of performance. In this survey, students were asked to rate their perceived performance on various aspects of their pitches, such as their use of prototypes, and their communication of technical information.

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3 ANALYSIS

Prior to the analysis, the recorded pitches were transcribed. Eight teams' videos were removed from the analysis due to technical difficulties during the data collection process. Further, eight additional teams either did not have prototypes or were recorded at an angle that inhibited the use of their prototypes while presenting their pitches. As we did not want these pitches to affect our results, these videos were also removed. Hence, 40 teams' pitches were used for the analysis. The qualitative analysis was done using NVivo v12 software. Figure 1 shows the outline of the data analysis process.

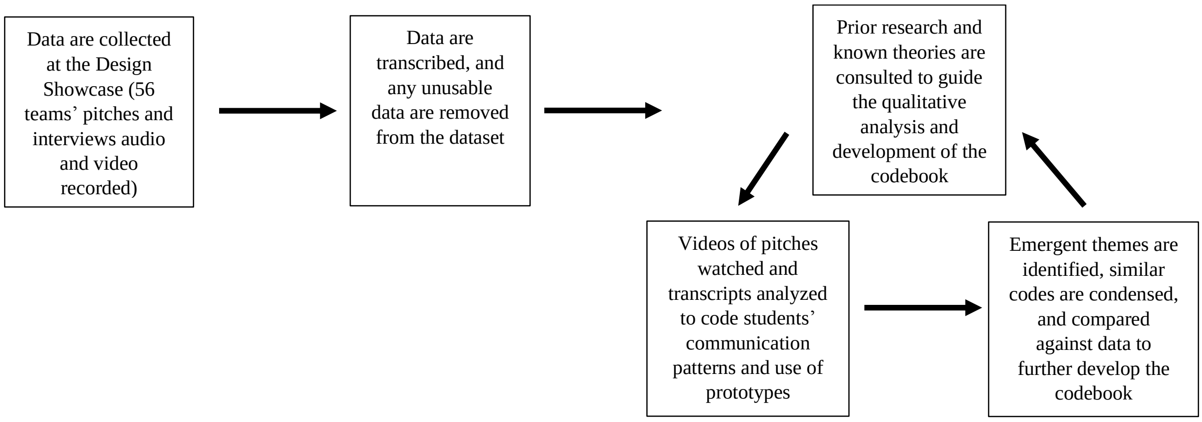

Figure 1. Outline of qualitative data analysis process

3.1 Codebook Development

Guided by our primary research question *'How do novice designers use prototypes to communicate design solutions to an external audience?'*, we used an abductive coding paradigm (Timmermans and Tavory, 2012) with the constant comparative method of qualitative analysis (Glaser, 1965) to analyse students' project pitches. Abductive coding is a method of qualitative analysis that allows for the incorporation of prior literature into the coding process while being responsive to themes that do not fit into prior research (Timmermans and Tavory, 2012). This approach was selected since prior research has explored how prototypes are leveraged as tools for communication, but this work was primarily conducted in professional design settings (Lauff *et al.*, 2018, 2020).

Specifically, we used work by Lauff *et al.* (2020), who studied the role of prototypes in enabling communication between stakeholders on a global design company, as the basis for our codebook. Lauff *et al.* (2020) found prototypes being used across a number of contexts to achieve four distinct outcomes during communication: explaining, negotiating, providing feedback, and persuading. It should be noted however, that their work differed from this study in two key aspects. First, the ethnographic study by Lauff *et al.* (2020) was conducted in a design firm, and the current study was conducted at a Senior Design Showcase event where undergraduate capstone students presented their final design solutions. Second, Lauff *et al.* (2020) studied how prototypes were leveraged for communication across different social contexts. These ranged from the early design stages where communication takes place within design teams to product pitches where communication takes place between external audiences, such as company executives and end-users. In comparison, this study was limited to a single context, where students presented their final design solutions to an external audience (judges and general members of the public). As a result, we expected some codes in Lauff *et al.* (2020) to either manifest differently or not appear in our analysis. For example, as the Senior Design Showcase takes place at the culmination of students' capstone projects, and as the research team did not provide any opinion on the design solutions while collecting data, we did not expect the code 'Provide Feedback' to appear in our analysis.

Table 1 shows the final developed codebook. The codebook is divided into three distinct sections: Communicative Outcome, Use of Prototypes, and Mode of Communication. The first section of the codebook, Communicative Outcome, contains codes that indicate the result of the communication achieved by students as they presented their project pitches. We observed three distinct communicative outcomes during students' pitches: explain, justify, and persuade. Further, it should be noted that at the Senior Design Showcase, students explained their design solutions to judges and individuals who were entirely unrelated to their capstone projects, and therefore, were most likely unaware about what their

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design problems were. Hence, most students did not use their prototypes to simply explain the details of their final design solution. Rather, we observed a number of teams walking through the entire design process during their pitches; by stating what the initial problem was, how they developed the design solution, how the final solution functioned, and what next steps for the project were. As a result, the code 'Explain' was divided into separate subcodes, as shown in Table 1.

Table 1. Codebook for analysing students' pitches

Section	Code	Subcode	Definition
Communicative Outcome	Explain	Design problem	Explaining the design problem given by the project sponsor
		Design process	Explaining the problem-solving process and methods used
		Features of design solution	Explaining the features of the final design solution
		Functioning of design solution	Explaining the working of the final design solution
		Future state of design solution	Explaining any further changes to the design solution
	Justify	-	Justifying design decisions made during the design process
	Persuade		Persuading the audience about the success or novelty of the design solution
Use of Prototypes	Standalone	-	Prototype is not gestured towards or engaged during the pitch
	Point		Making gestures in the direction of the prototype during the pitch
	Actively engage		Actively interacting with the prototype during the pitch
Mode of Communication	Verbal	-	Using only verbal communication
	Verbal + Visual	-	Using verbal communication with use of a visual, such as a 2D image of a prototype
	Verbal + Tactile	-	Using verbal communication with use of a physical prototype through tactile interactions

The second section of the codebook identifies the manner in which students engaged with their prototypes during their pitches. Three specific types of engagement were identified: standalone, point, and actively engage, the definitions of which are seen in Table 1. The last section of the codebook identifies the mode of communication used by students during their pitches. All the pitches were coded using this codebook, and the analysis was performed using the transcripts and the recorded videos of the pitches in conjunction. This allowed us to analyse both the content of students' pitches, while also making note of how students engaged with their prototypes. All qualitative coding was done by the first author, and the first and fifth author met on a weekly basis to discuss the development of the codebook.

4 RESULTS

Due to space limitations of this paper, we will be reviewing three pitches that we feel best represent the themes identified in our qualitative analysis, and show how these themes occur together during students' project pitches. However, it should be noted that the themes in our codebook above were observed throughout the data. These pitches were also selected because they represent the diversity in students' approaches to communicating their design solutions, the types of prototypes presented, and the variations in how these prototypes were used during students' pitches. We have also included screenshots from the students' pitches to indicate how students interacted with their prototypes, and we describe these gestural interactions in the non-italicized text within the square brackets in the excerpts.

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4.1 Team 1

Team 1, whose project involved the design of a device to detect respiratory viruses in the air, consisted of 5 team members. The team had their functioning, physical prototype at the Senior Design Showcase along with a poster, as seen in Figures 2 (a) and (b). While presenting their pitch, the team first established the objective of their project and then stated how it would be used around the university to detect viruses present in the air. Then, a team member explained the different features of their device:
"So our design consists of three primary filtering stages [student indicates filters on CAD model on poster]. *First stage is a 5 micron filter* [student takes filter out of prototype] *and it is used to filter any debris out of the air that is not of interest to our sponsor. And the second stage* [student indicates second stage on CAD model on poster] *is a one micron filter that is to filter bacteria and other pathogens that are not specifically viruses, and the third backup stage* [student indicates third stage on CAD model on poster] *is used to filter the actual virus particles out of the air."*

(a) *(b)*

Figure 2. Team 1 presenting their project pitch

As seen in the quote above and in Figure 2(a), the student actively engaged with both the physical prototype and the CAD model in the poster. Throughout the excerpt above, the student combined verbal, visual, and tactile modes of communication while actively engaging with the prototype to explain the different features of the design solution and how the design solution functions. Later during the pitch, another team member (Figure 2(b)) communicated how their solution met the objectives of their sponsor, and how it was the appropriate solution to the design problem:
"The customer wanted a device that is portable, and reliable, um, it satisfies both those, um, criteria [student points towards the prototype]. *This switch we've been able to turn on and off several times* [student turns device on and off]. *Works every time. The device is portable using this tripod* [student points towards tripod on the prototype], *you can move it several different sample locations. And risks involved in the project include that these filters* [student points towards filters on prototype] *may not capture the viruses needed and it was a big uncertainty when creating this project, but using this machined part* [student points towards metal component on the prototype], *we think this would be a, the best solution to um, combat this problem."*
As seen in the quote above and in Figure 2(b), the student combined verbal and tactile modes of communication, along with pointing at and actively engaging with the prototype to persuade the audience about the success of the design solution. The student cited two customer needs (portability and reliability), and the prototype was then used as a means to demonstrate how these two needs were met by the design solution. We hypothesize the student may have done this in an attempt to persuade the audience about the appropriateness of their design solution given the original design constraints.

4.2 Team 2

Team 2, whose project involved the design of an application to track defects on a production line, consisted of 6 team members. The team had a poster present at the Senior Design Showcase, which contained a single image of the user interface of the designed application (located at the lower right corner of the poster), as seen in Figures 3 (a) and (b). The team first began their pitch by stating the problem statement and the specific customer needs they needed to satisfy. Following this, another student introduced the interface of the application, and explained how a user would interact with it:
"Uh, so like the [user interface] that we created, we use like HTML and CSS and imported some bootstrap libraries and made use of it to give a really user friendly interface. So we will have a home

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page and once you can navigate to the specific production line and which will be connected to the specific database. And we pretty much used a lot of, uh, uh, combo boxes and text boxes and also we were able to auto populate some of the fields, which would be more easy for [the sponsors] to access."
As seen in in the quote above, the student attempted to explain the features of the application and how a user would interact with it, while predominantly relying on verbal communication to describe this interaction. Further, by stating how the interface is *"really user friendly"* and how it would be *"more easy"* for production line workers to access, the student also appeared to persuade the audience about the success of their design solution. However, as the student explained the features and functioning of the application, and its suitability in solving the design problem, the visual of the application on the poster was never pointed at or actively engaged with, and was used as a standalone artifact.

(a) *(b)*

Figure 3. Team 2 presenting their project pitch

Following this, another student continued to describe how a user would interact with the application:
"So for the chart and statistics, we chose to use Power BI, so, so when we send that data to the database, the Power BI will pull the data from the database, like, like every hour or so, and it will display on the dashboard. For each chart if you click on the chart it will show us the, it will show like, if you click on the chart like 111, it will only show the data for 111. So it can help you do like analysis much easier and much faster. Yeah so the Power BI consists of like bar graphs, pie charts, and some tables."
As evidenced by the quote above, the student attempted to explain how a user would interact with the application to obtain data of interest to the user. The student then used this explanation as their basis for persuading the audience about the effectiveness of the solution, as seen in the quote *"So it can help you do like analysis much easier and much faster*". However, rather than leveraging visuals, like a prototype, to communicate this information, the student relied on verbal communication to create a mental image of how the application outputs data. As with the previous student on the team, at no point was the visual information on the poster gestured towards or interacted with. This was also observed with the remaining students on the team who presented the other parts of the project pitch. Interestingly, when examining students' levels of agreement to the statement "Our team leveraged our prototype, simulations, or other artifacts to better explain our project" on the survey, 4 team members indicated that they strongly agreed with the statement. This observation will be contextualized in section 5.

4.3 Team 3

Team 3, whose project involved the design of a self-stabilizing inverted pendulum, consisted of 5 team members. Along with their poster, the team also had their physical prototype and a video demonstration of their prototype, as seen in Figure 4.
A student from the team began the pitch by introducing the problem and explaining how their design solution functions. The student accompanied this explanation with a demonstration of the prototype. The student noted however, that their prototype was not fully functional, and stated that the device *"doesn't stand up on its own, but the [inertial measurement unit] reacts to what the direction [the device] is facing and how fast it's going"*. For the remainder of the pitch, the prototype was not actively engaged with again, and was either used as a standalone artifact or was gestured at. Later, another member of the team attempted to justify why the prototype was not fully functional. The student primarily used verbal communication, while either gesturing towards the prototype or using it as a standalone artifact:
"Kinda like how [the prototype not fully functioning] ended up happening was that really depends on the type of motors that we ended up getting [...] so the motors that we ended up getting, um, although

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it fits all the other specs that are needed, uh, cannot accelerate fast enough to create a larger angle. Then mechanically, uh, the issues that we kind of ran into is, uh, kind of like also time and financial issues. So the flywheels [student gestures towards prototype] *should technically be, uh, cut out and kind of made a little more like finely and more even. But we do not really have experience in terms of machining, so we did the best that we could, um, with the budget that we had..."*

Figure 4. Team 3 presenting their project pitch

As seen in the excerpt above, the student began by making a reference to the earlier demonstration of the prototype *("Kinda like how [the prototype not fully functioning] ended up happening")*. They then attempted the justify the lack of complete functionality of the prototype by citing issues with the motors that were purchased the team. The same student also used the prototype to justify other features of the design solution, such as the finish of the flywheels. Hence, the prototype was used not only as a means to explain the features of the design solution, but also as a means to rationalize design outcomes. This theme was observed in two different contexts: either when teams provided rationale behind a specific design decision, or when teams justified sub-par performance and adverse design outcomes.

5 DISCUSSION AND CONCLUSION

The goal of this study was to characterize novice designers' use of prototypes to communicate design outcomes to an external audience. Prior work by Lauff *et al.* (2020), who studied the role of prototypes in facilitating communication between stakeholders, was used as the basis for our qualitative analysis. Table 2 summarizes the results obtained through our qualitative analysis for the three teams.

Table 2. Summarized qualitative results from the three teams

Category	Team 1	Team 2	Team 3
Communicative Outcome	Explain, Persuade, Justify	Explain, Persuade	Explain, Justify
Use of Prototypes	Point, Actively engage, Standalone	Standalone	Point, Actively engage, Standalone
Mode of Communication	Verbal, Verbal + Visual, Verbal + Tactile	Verbal	Verbal, Verbal + Tactile

Similar to the findings by Lauff *et al.* (2020), our results show that prototypes were used by novice designers to explain design outcomes and persuade an audience about the outcomes' effectiveness. Using prototypes when communicating design outcomes is particularly useful in establishing a shared understanding of a design solution (Boujut and Blanco, 2003). Further, the visual representation of design information combined with a verbal explanation of the design artifact may reduce the cognitive burden in the audience (Lauff *et al*., 2018). Throughout their pitch, Team 1 actively engaged in tactile interactions with and gestured towards their prototype as they described their solution. By mapping each feature on the prototype to the customer need it satisfies, they also used their prototype to persuade the audience about the success of their solution in solving the design problem.
What is interesting to note, however, is the variation in students' use of prototypes as they presented their project pitches. Team 2 used their prototype solely as a standalone artifact, and at no point during the pitch did the design team incorporate visuals of their solution. The team predominantly used verbal communication when explaining how a user would interact with the digital application. When discussing the effectiveness of the digital interface, Team 2 predominately used verbal communicative strategies,

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stating it was *"really user-friendly"*, and how it can help users perform tasks *"much easier and much faster"*. We also note that Team 2's prototype consisted of a single visual of the interface of their application. Brandt (2007) argues that physical prototypes, due to their ability to evoke tactile senses, may promote more reflection and communication in designers as compared to two-dimensional visuals. It is possible that the modality of the prototype may have contributed to students' use of prototypes as communication tools. In future work, we intend to study what factors affect novice designers' use and perceptions of prototypes as communications tools. Interestingly, members of Team 2 generally agreed that they leveraged their prototype and other artifacts effectively during their pitch, as indicated by their survey responses. While this may indicate a potential dissonance between students' perceived and actual use of prototypes as communication tools, we intend on studying this in detail in future work to identify if, and how, students' perceived use of prototypes for communication differ from their actual use.

The abductive coding schema allowed us to uncover new themes in how students used prototypes to communicate design outcomes. Specifically, in addition to using prototypes to explain and persuade, we also observed prototypes being used as a means to justify design outcomes. Team 3 first explained the functioning of their design through a working demonstration of their prototype. This demonstration was then used to contextualize the problems faced during the project and justify why their prototype did not meet some of their sponsor's needs. Therefore, within the pitch, the role of the prototype evolved and the design team leveraged the prototype to both explain and justify their solution. In future work, we aim to uncover the manner in which students justify, or rationalize, their design outcomes, as prior work suggests novice designers tend to distance themselves from failures in prototyping tasks, and attribute these failures to external factors, such as a scarcity of time or resources (Krishnakumar *et al*., 2021).

Through our preliminary results, we note some similarities in how novices and experts use prototypes to explain design outcomes and persuade audiences about the success and effectiveness of the design outcome. We also observe that novice designers tended to use prototypes to rationalize design outcomes, either by justifying a specific design decision or rationalizing failure to meet an objective. The results also show variations in the manner in which prototypes were used to achieve these communicative outcomes, and a possible disconnect that may exist between novices' actual and perceived use of prototypes as communication tools. Future work will explore this phenomenon more thoroughly.

As with any study, this work has its associated limitations. While most teams had multiple team members presenting their pitches, and the research team ensured that all students were asked if they had anything else to add to the pitch, it is possible that individual traits of students may have affected proportion of speaking time per student. Further, the instructions students received about their pitches may have varied between course sections by instructor. We acknowledge this as a confounding variable.

We believe this preliminary work offers interesting insights into novice designers' use of prototypes as communication tools and opens gateways for other studies. In future work, we seek to develop a deep understanding of the fundamental ways in which novices perceive and use prototypes as communication tools, and then propose strategies for engineering design education that may better equip students with the skills needed to effectively communicate as professional designers.

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