PROTOTYPING IN THE WILD:

THE ROLE OF PROTOTYPES IN COMPANIES

by

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Abstract

Lauff, Carlye Anne (Ph.D., Mechanical Engineering)

Prototyping in the Wild: The Role of Prototypes in Companies

Thesis co-directed by Dr. Mark E. Rentschler and Dr. Daria Kotys-Schwartz

Prototypes are complex artifacts in the design process. They are an essential part of the product development process, and yet one of the least formally explored areas of design practice. This research is a qualitative, empirical, and industrial-based study using inductive ethnographic observations to further our understanding of the various roles prototypes play on design teams in organizations. This research observed the entire product development process within three companies in the fields of consumer electronics, footwear, and medical devices. The guiding research questions were: What is a prototype? What are the roles of prototypes on design teams? How do these roles change or manifest throughout the process?

Through analysis, I uncovered that prototypes are tools for enhanced communication, increased learning, and informed decision-making. I provide a newly modified definition of a prototype, which is used to expand designers' mental models. I proved that prototypes are dynamic artifacts that shape social situations during product development. Specifically, I uncovered that the primary purpose of prototypes changes based on the context of use. I explored five unique contexts, and I describe how the primary role of prototypes shifts between a tool for communication, learning, and decision-making based on the context of use within companies. These insights can help designers, project managers, and other stakeholders become aware of the many benefits and biases that prototypes create in common situations throughout the design process.

This research is significant because it provides empirical insights into the role of prototypes in professional environments. There is a need to better understand design practices in industry, such as prototyping, and translate these findings back into design education. I have already begun to translate this research to academia, by creating prototyping workshops, lessons, and tools to aid students in mechanical engineering. Ultimately, this research validates prior prototyping theories and claims, while adding new perspectives through further exploiting each role of a prototype and how it changes over time and with use. This research provides a new framework for viewing prototypes, specifically how prototypes have agency. Prototypes enable actions to occur, and they influence human behavior in social situations.

Dedication

To my Mom, you taught me the value of hard work.

To Ben, you brought the perfect balance into my life.

To my friends and family, for their unwavering support and encouragement.

To all of the fearless and trailblazing women in my life, you inspire me to keep reaching new heights.

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Chapter 1 – Introduction

1.1 Motivation

"Prototyping is one of the most critical activities in new product development" [1], and yet "prototyping may be simultaneously one of the most important and least formally explored areas of design practice" [2]. There is a need for an empirical understanding of how prototypes are used on design teams both in academia and industry. As the management science researcher Michael Schrage summarized, "the great ethnographies of prototyping have yet to be written" [3].

Research on the design process has mostly focused on early stages, such as concept generation and selection [4]–[8]. Topics like sketching [9], [10], design fixation [11]–[13], and product dissection [14] have also been studied extensively. More recently, researchers have begun exploring prototyping's role in product development [2], [15]–[19]. Most of these studies focus on developing strategies to prototype [2], [15], [18], [19] or on testing specific hypotheses, such as if fewer parts in prototypes correlate to better final designs [16], [17]. The majority of studies on prototyping come from software engineering or the field of human-computer interaction (HCI) [3], [20], [21], with limited studies on prototyping in comparison from mechanical engineering. Additionally, all of these contributions have primarily focused on student design teams in universities. There have been relatively few studies published regarding the role of prototypes in companies [22], [23]. There is a need to understand both students and professional design practices, and to translate best practices from industry back to academia.

For companies, it is becoming increasingly important to remain highly competitive in the current global economy. Being competitive requires the commercialization of innovative and desirable end-products. Prototyping is a key component of developing these products, and often one of the costliest. In a 2001 study, Cooper stated that up to 50% of resources are wasted during new product development in large companies [24]. Many of these wasted resources occur during inefficient prototyping and on cancelled products; this can be partially attributed to poorly developed prototypes. Therefore, there is a need to understand current prototyping practices employed by companies, and then develop strategies to prototype more effectively.

From an engineering education perspective, there is a need to further our understanding of professional design practices. Design is often called the "backbone of engineering" [25], and therefore, many universities have begun to implement engineering design courses throughout all four years of undergraduate programs. Both the National Academy of Engineers (NAE) and the American Society of Mechanical Engineers (ASME) recognize that there are many disconnects between undergraduate education and professional design practices [26]. Both organizations have calls for re-imagining engineering design education in the 21st century. Design education can take on many forms, but project-based learning (PBL) is one that prevails across most universities [27]. PBL has been shown to improve engineering students' communication and teamwork skills, while simultaneously providing opportunities for technical knowledge application. PBL often involves iterations of building and testing prototypes. This approach is described as being beneficial to students, without much understanding of how prototypes are being used on design teams.

This dissertation research is a contribution to the fields of design theory and methodology, management science, and engineering design education by adding new knowledge about the roles of prototypes on design teams in academia and industry. Prototypes can be described in terms of attributes or actions. More often, in engineering design they are described by their attributes: the mediums, materials, and components required to produce the artifact. In this research, I chose to explore the actions, or agency, of prototypes: how they enable or influence social interactions on design teams. From studying design in its natural environment, I am working towards developing a prototyping framework grounded in the emergent findings from practice and detailed inductive inquiry. An inductive research study allows insights and findings to emerge throughout the data collection and analysis process, rather than testing out hypotheses. As Ken Friedman, a prominent design researcher stated, "one of the deep problems in design research is the failure to develop grounded theory out of practice" [28]. I hope to combat this challenge through this dissertation, where I draw on principles from grounded theory analysis during data analysis to inductively uncover the roles and actions of prototypes on design teams in practice.

In summary, there are multiple motivations for this dissertation research. There is a lack of research studies around the topic of prototypes, specifically qualitative studies within company contexts. Additionally, prototyping is one of the costliest aspects of product development for companies, and companies are often unguided in their practices. There is a need to gain a deeper understanding of prototyping practices in industry, which could eventually reduce costs for organizations. There is also a need to expand theory and mental models around prototypes by studying the actions and agency of prototypes. In engineering design, there is a focus on the attributes of prototypes; their technical components through describing their appearance. Instead, there is a need to understand the influence or behaviors prototypes have on the design process. And lastly, there is a need to understand professional design practices as a means to translate best practices back to engineering education.

1.2 Background

Before discussing relevant literature around prototyping, I want to first situate prototyping within the context of design research and the field of design theory and methodology. The next two sub-sections will include a brief history and overview.

1.2.1 Design & Design Research

To understand the role prototyping plays on design teams and in companies, we must first step back to look at the overall design process. Design work has been described as the foundation of engineering [25], and prototyping is often described as one "stage" in that process. Thus, the study of prototyping is part of design research.

Design is a broad term that holds a lot of meaning. It can be used as a noun, verb, or adjective. Even as a noun, it can be further refined to refer to either the "designer" as the person doing the work or the "design" as the final product or output from the work. Some regard design as synonymous with creativity. Almost always, though, design is considered a process (i.e. the design process). Within this process, there have been guidelines established in every discipline to train new designers. Across most disciplines, there is a stage or phase known as prototyping.

The field of design research, also referred to as "design science", has grown and evolved in the last century. The word "design" entered the English language in the 1930s. It began as a verb describing the process of intention and action. To design based on the earliest Webster-Merriam dictionary is "to conceive and plan out in the mind…to have as a purpose: intend… to devise for a specific function or end", then later it was adjusted in definition stating, "to make a drawing, pattern or sketch of…to draw the plans for… to create, fashion, execute, or construct according to plan: device, contrive…" [29, p. 343]. It is clear from these definitions that the act of designing is to have a perceived plan and then act on it through creating the desired artifact. This translates very well into the design process, which is used by most of the design professions to create final desired artifacts.

The design profession has grown over the last century. In the twentieth century, the design profession took shape in fields such as graphic design, information design, product design, industrial design, and design management. As time progressed, architects and engineers also began to think of their work as design. Herbert Simon, who is considered one of the founding father of "design science", indicated that all professional practices, even physicians and lawyers, involve design in the broad human sense [30]. In the twenty-first century, the idea of a design profession expanded, involving a wide range of challenges, contexts, and goals. Design is now considered part of almost every discipline spanning engineering, education, art, architecture, urban planning, business, computer science, and more. As Simon stated, "[e]veryone designs who devises courses of action aimed at changing existing situations into preferred ones" [30]. This means that the term "design" is to improve the world around us, which can range from designing physical spaces, educational curricula, technological gadgets, or anything else that improves our human lives.

The field of design research is relatively new in comparison to most fields of study. The Design Research Society (DRS) was founded in 1966; they just celebrated the 52nd anniversary of existence. In comparison, the American Society for Mechanical Engineers (ASME) was formed in 1880, over 138 years ago. DRS emerged from the first conference on design methods, held in 1962 in London [31]. That conference is generally regarded as the event that marked the launch of design as a subject and field of enquiry [32]. This propelled the design methods and research movement. Academic journals in this field began around the 1980s: Design Studies in 1979, Design Issues in 1984, and Research in Engineering Design in 1989. Nigel Cross, the current President of DRS, outlines a brief history of the field of design research, from 1960s to the early 2000s, in his editorial in Design Issues [32]. Additionally, Otto and Wood have outlined a brief history of design theory development in their book on product design [33, pp. 43–46]. The design research society's mission is "to promote the study of and research into the process of designing in all its many fields" [34]. Researchers in DRS span the fields of industrial design, mechanical engineering, architecture, urban planning, design history, and more. Design is clearly accepted as a transdisciplinary field – meaning it transcends many established disciplines.

1.2.2 Design Theory & Methodology

Within design research, there is a specific focus area in design theory and methodology. This is one field to which this dissertation research contributes. The field of design theory and methodology explores the underlying ways that humans engage in design, while also providing methods, tools, or strategies for designers. The purpose is to better explain, through theory, how design is enacted and then to offer methods or tools to guide designers through the process.

Nigel Cross, a key researcher within the Design Research Society, explains this specific field of research eloquently in the introduction to his book on Design Methodology. "Design methodology…is the study of principles, practices and procedures of design in a rather broad and general sense. Its central concern is with how designing both is and might be conducted. This concern, therefore, includes the study of how designers work and think; the establishment of appropriate structures for the design process; the development and application of new design methods, techniques, and procedures; and reflection on the nature and extent of design knowledge and its application to design problems." [35, p. vii]. Clearly, the field of design theory and methodology is vast and can tackle challenges from understanding how designers work to creating structures to support design work.

Two prominent design researchers from the twentieth century fundamentally shifted mindsets around design research, and specifically design theory and methodology: Herbert Simon and Donald Schön. Simon, who was introduced earlier, self-identified across the fields of artificial intelligence, cognitive psychology, computer science, economics, and political science. Simon won the 1978 Nobel Memorial Prize in Economics for pioneering research into the decision-making process within economic organizations [36]. His theory on rational decision-making describes it as three stages, intelligence gathering, design, and choice. He coined the term "bounded rationality," the idea that individuals are limited by the information they have, their cognitive limitations of their minds, and the finite time to make decisions [37]. Simon is often credited with establishing the foundation of design science, which is the scientific study of design practices [30]. In his book, *The sciences of the artificial*, Simon explores the notion of "artificial" entities, those that are created rather than naturally existing. He notes that artificial objects must be created through design: "Engineering, medicine, business, architecture, and painting are concerned not with the necessary but with the contingent – not with how things are but with how they might be – in short, with design" [30, p. xi]. The science of the "artificial" is the science of design, which is now considered design research.

Donald Schön also self-identified across multiple disciplines including philosophy, urban planning, sociology, education, and music. Schön sought to establish "an epistemology of practice implicit in the artistic, intuitive processes which [design and other] practitioners bring to situations of uncertainty, instability, uniqueness and value conflict" [38]. Design as a discipline means that design should be studied on its own terms, within its own rigorous culture, based on a reflective practice of designing. This helped to legitimize the different research within the various "fields" of design. Research in engineering design should be conducted separately from other fields, like architectural or software, because it has innate differences in practices that cannot be described by studying other design fields. Both Simon and Schön helped to advance the broad understanding of design and to legitimize the study and research in the field of design, specifically building theories for how designers work in practice.

The nature of design activity has always been a fundamental interest to the design research community. Cross explained that, "the intention has always been to try and develop an objective understanding of how designers design, which might then in turn lead to the development of improved design procedures" [35, p. 167]. In my perspectives, there are three main factors interacting within the design theory and methodology: people, process, and products/prototypes. This field can study the intersection of any of these aspects. My research looks at the intersections of prototypes and people, and their influence on the design process through the actions they enable. Through studying designers in practice within academia and industry, I am working to develop a deeper understating of prototyping practices, which may influence design procedures.

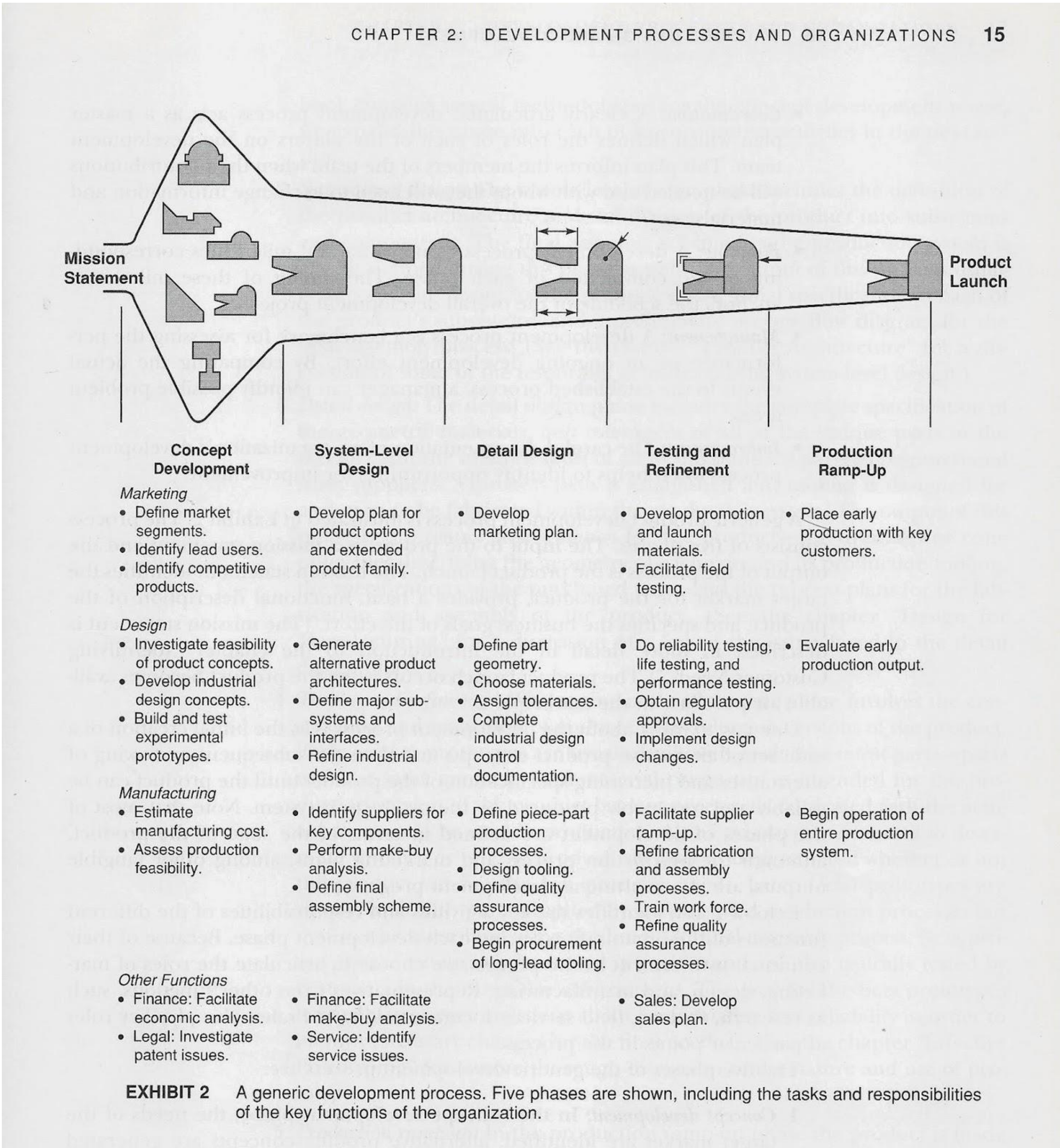
1.3 Review of Literature

This literature review is broken into three major categories around prototyping. The first section (1.3.1) situates prototyping within the engineering design process, specific to mechanical engineering. The second section (1.3.2) discusses the various prototyping taxonomies, models, frameworks, and strategies, along experimental studies around prototyping from both HCI and mechanical engineering. The final section of the literature review (1.3.3) explores research within companies, specifically studies of design professionals, ethnographies in companies, self-reported studies, and similar.

1.3.1 Prototyping in the Design Process

In all design processes, prototyping is often described as a stage or a tool in the process. In this section, I will focus on how prototyping is described in mechanical engineering. The product development process (the design process) is described as a “sequence of steps or activities that an enterprise employs to conceive, design, and commercialize a product” [39, p. 12]. In mechanical engineering, there are several quintessential product design and development textbooks that are used extensively across the United States to teach engineering design courses. Two of the most popular textbooks include “Product Design and Development” by Karl Ulrich and Steven Eppinger [39] and “Product Design: Techniques in Reverse Engineering and New Product Development” by Kevin Otto and Kristin Wood [33]. Both of these textbooks describe the engineering design process holistically, with specific chapters tailored to describing the difference design phases, as well as relevant design topics (i.e. design for manufacturing and managing projects). There are other textbooks, like David Ullman’s (1992) on the mechanical design process [40]. In this book, he describes the purpose of prototyping based on the function and stage in product development. These categories are: proof-of-concept prototype, proof-of-product prototype, proof-of process prototype, and proof-of production prototype.

Eppinger and Ulrich’s (2004) design process is broken into five major phases as seen in Figure 1: Concept Development, System-level Design, Detail Design, Testing and Refinement, and Production Ramp-Up. There is a sub-process within testing and refinement, where the series of engineering prototypes are explored. In this textbook, a prototype is defined as “an approximation of the product along one or more dimension of interest” and that prototyping is “the process of developing such an approximation of the product” (pg. 291). These dimensions include the degree to which prototypes are physical or analytical on one axis and then how focused or comprehensive they are on the other axis.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	Concept Development	System-Level Design	Detail Design	Testing and Refinement	Production Ramp-Up
Marketing	• Define market segments. • Identify lead users. • Identify competitive products.	• Develop plan for product options and extended product family.	• Develop marketing plan.	• Develop promotion and launch materials. • Facilitate field testing.	• Place early production with key customers.
Design	• Investigate feasibility of product concepts. • Develop industrial design concepts. • Build and test experimental prototypes.	• Generate alternative product architectures. • Define major sub-systems and interfaces. • Refine industrial design.	• Define part geometry. • Choose materials. • Assign tolerances. • Complete industrial design control documentation.	• Do reliability testing, life testing, and performance testing. • Obtain regulatory approvals. • Implement design changes.	• Evaluate early production output.
Manufacturing	• Estimate manufacturing cost. • Assess production feasibility.	• Identify suppliers for key components. • Perform make-buy analysis. • Define final assembly scheme.	• Define piece-part production processes. • Design tooling. • Define quality assurance processes. • Begin procurement of long-lead tooling.	• Facilitate supplier ramp-up. • Refine fabrication and assembly processes. • Train work force. • Refine quality assurance processes.	• Begin operation of entire production system.
Other Functions	• Finance: Facilitate economic analysis. • Legal: Investigate patent issues.	• Finance: Facilitate make-buy analysis. • Service: Identify service issues.		• Sales: Develop sales plan.	

EXHIBIT 2 A generic development process. Five phases are shown, including the tasks and responsibilities of the key functions of the organization.

Figure 1. Product Development Process (from Eppinger & Ulrich)

Eppinger and Ulrich (2004) believe that prototypes are used for four purposes in product development: learning, communication, integration, and milestones. Learning from prototypes is described as “will it work?” and “how well does it meet customer needs?”. Communication about or with prototypes (mostly in physical form) is described as allowing for better understanding between parties such as top management, vendors, partners, extended team members, customers, and investors. Prototypes for integration are described as means to ensure that components and subsystems of the product work together. Lastly, prototypes are used as milestones to demonstrate that the product has achieved some tangible goal. Eppinger and Ulrich also provide a brief four-step method for planning for prototypes. Step 1 is defining the purpose of the prototype; Step 2 is establishing the level of approximation of the prototype; Step 3 is outlining an experimental plan; and Step 4 is creating a schedule for procurement, construction, and testing.

Otto and Wood discuss product design, specifically for new product development (NPD), in their textbook [33]. They have an emphasis on techniques like reverse engineering for NPD, and include prototyping as a stage in the design process similar to Eppinger and Ulrich. Prototyping is mentioned many times throughout the book. In the chapter on modeling product metrics, they discuss the difference between analytical and physical prototypes (p. 611), focused versus comprehensive prototypes (p. 612), and even decision trade-offs between them (p. 613). In chapter 17, they discuss physical prototypes (pp. 833-890). They break down the uses of prototypes by discipline, namely industrial design, electrical engineering, and mechanical engineering. They indicate six categories of how prototypes might be used: (1) communication, (2) demonstration, (3) scheduling/milestone, (4) feasibility, (5) parametric modeling, and (6) architectural interfacing. Additionally, they go into detail about different materials that can be used to prototype (wood, plastic metal, adhesives) as well as various prototyping processes (CNC, cast metal, injection molding, bread boarding, etc.). They even have guidelines for prototype design (Table 17.12, p. 873) which include the purpose, medium, processes, material, cost, time, and testing. Finally, they walk through an example of creating a new children's toy, indicating all the prototypes along the way.

When observing the design process on teams in courses and industry, I started with Eppinger and Ulrich's model of the design process. Specifically, that there were stage-gates that each team must pass through from problem statement to concept development to system-design and detailed-design to testing and refinement before production ramp-up.

1.3.2 Prototyping Literature

The study of prototyping has evolved in the last two decades. There are more prototyping studies from fields like computer science and human-computer interaction (HCI), and there still remains limited studies from mechanical engineering. This section is sub-divided into three categories: (1) models, frameworks, and taxonomies of prototypes, (2) strategies for prototyping, and (3) experimental studies around aspects of prototyping.

1.3.2.1 Models, Frameworks, and Taxonomies of Prototypes

Researchers have created models, frameworks, and taxonomies of prototypes [20], [41]–[45]. A model is a representation or explanation of something else; a framework is a basic structure underlying a system or concept; and a taxonomy is a scheme of classification.

Houde and Hill (1997) describe their model of prototyping in their chapter "What do Prototypes Prototype?" found in the *Handbook of Human-Computer Interaction* [43]. They use four principle categories to describe a prototype: (1) role, (2) implementation, (3) look and feel, and (4) integration. These categories are expressed along an interactive triangle, as seen in Figure 2. They also initiated a challenge in the language of the term prototype. As stated in their chapter, "the ways that we talk, and even think, about prototypes can get in the ways of their effective use. Current terminology for describing prototypes centers on attributes of prototypes themselves…such terms can be distracting" [43, p. 367]. Their practical recommendations are to define the term prototype broadly, to build multiple prototypes, and to know your audience and prepare the prototype specifically for them. "By focusing on the purpose of the prototype – that is, on what it prototypes – we can make better decisions about the kinds of prototypes to build. With a clear purpose for each prototype, we can better use prototypes to think and communicate about design" (p. 380). This philosophical perspective can be translated to developing physical prototypes, as well.

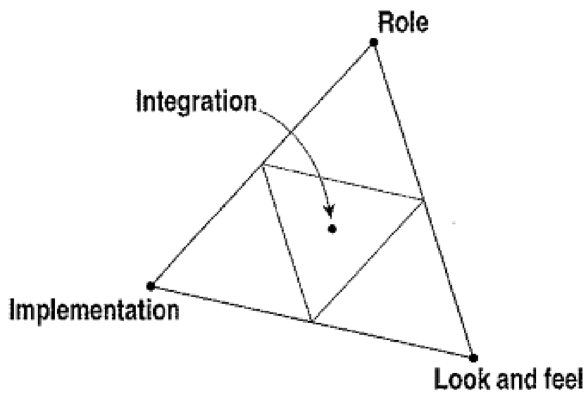

Figure 2. Model of prototypes (from Houde & Hill, 1997)

Lim et al. (2007) describe the anatomy of prototypes in the field of HCI [20]. In their model, prototypes are described as filters and manifestations of design ideas. They describe the two fundamental characteristics of prototypes: (1) traversing a design space that leads to creating meaningful knowledge about some aspects of the final design envisioned in the process of design, and (2) purposefully formed manifestations of design ideas. As filters, prototypes help the designer examine what is included and excluded in the design – as to better traverse this design space. As manifestations, prototypes are a means of iteratively representing the evolving design; they act as an extension of the designer's mind. The anatomy of prototypes represents a way of thinking about prototypes, rather than a prescriptive method for designing prototypes. They note in this paper that there "is still a lack of knowledge about the fundamental nature of prototypes due to their complex and dynamic nature" [20, p. 1]

Nielson (1989) describes three different types of prototypes along two scales as seen in Figure 3. In the horizontal direction, prototypes are described based on features of service and on the vertical direction they are described in terms of increasing functionality of features [46]. The horizontal prototypes are described as "shallow" in terms of functionality, but "wide" in their features of service. Vertical prototypes are "deep" in functionality, but "narrow" in features. This model was developed out of the HCI, and focused on describing the attributes and functionality of prototypes.

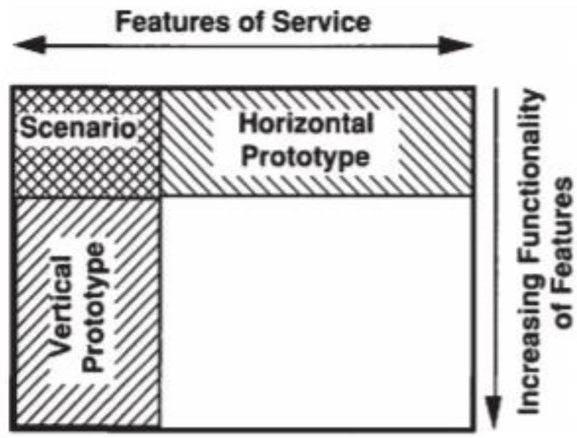

Figure 3. Framework of prototypes (from Nielson, 1989)

Beaudouin-Lafon and Mackay (2003) define a prototype as "a concrete representation of part or all of an interactive system" [41]. They analyze prototypes and prototyping techniques along four dimensions: (1) representation – the form of the prototype, (2) precision – the level of details at which the prototype is evaluated, (3) interactivity – the extent to which the user can actually interact with the prototype, and (4) evolution – the extended life cycle of the prototype**.** This framework was also developed in the field of HCI, and it focuses on the tangible attributes of prototypes.

Lichter et al. (1993) discuss bridging the gap between theory and practice in HCI [21]. They believe that prototyping is a technique used primarily to improve the calculation of risks and costs of new projects. They note that there has been a lack of documenting the use of prototyping in the field of industrial software. Their approach was to describe the different kinds of prototypes (i.e. presentation, proper, breadboard, and pilot system), goals of prototypes (i.e. exploratory, experimental, or evolutionary), and prototype construction techniques (i.e. horizontal and vertical). They, then, use several case studies to describe these different categories. For each of the five software prototypes, they indicated the tools that supported prototyping, the groups involved, the kinds of prototypes developed, the goals of prototyping, the main reason for prototyping, the success of the project, and the main problems.

McCurdy et al. (2006) also explore the prototyping process within the field of HCI. They developed a set of five dimensions of a prototype: (1) level of visual refinement, (2) breadth of functionality, (3) depth of functionality, (4) richness of interactivity, and (5) richness of data model. At each dimension, a prototype could vary in fidelity from low to high. Fidelity is a characteristic of a prototype that moves along a scale, usually from low fidelity to high fidelity. Low fidelity is often associated with paper prototypes, ones that take minimal time, money, and effort to create. On the contrary, higher fidelity prototypes are much more refined, usually taking much more time, money, and effort to create. In this article, they state that optimal prototypes would have mixed levels of fidelity. You move from lower fidelity prototypes in less critical dimensions and higher fidelity prototypes in more critical dimensions [47].

Lande and Leifer (2009) from mechanical engineering describe prototyping as an activity core to designing and engineering. Their paper describes a framework of prototyping based around design thinking and engineering thinking prototyping activities in an academic setting. They highlight the importance of cycles of converging and diverging thought resulting in an iterative nature of prototypes [44]. In particular, moving from design thinking to engineering thinking, which they consider different and equally critical. This is based on their “ways of thinking” framework [48]. They create a “T-shaped” prototyping model to describe the wide exploration of design prototypes that are core to “design thinking” and the deep dive into physical aspects of each solution that are part of “engineering thinking”. Design thinking prototypes (horizontal) should enable divergent thinking about various solutions, whereas engineering prototypes (vertical) should enable convergent thinking to a final technical solution. This model is based on observations and interviews with undergraduate students in product design and mechanical engineering [49].

In his mechanical engineering master’s thesis, Michaelraj (2009) describes a taxonomy for physical prototypes and validates this model by testing historical prototype data. He considers four factors in this taxonomy: (1) communication, (2) evaluation purpose, (3) cost, and (4) design stage. He, then, also considers four characteristics of the physical prototype itself: (1) size, (2) type, (3) material, and (4) fabrication [45, pp. 8–22]. This work is also published in a conference paper [42]. A summary of his taxonomy can be seen in Table 1. This taxonomy blends factors like attributes of prototypes, actions like "communication", intent through the "purpose", and design stages. It considers a number of important prototyping factors but organized them in a rather disorganized way.

Table 1. Physical Prototype Taxonomy from Michaelraj (2009)

Factors of a Physical Prototype		
Communication	Intent	Declarative *(Inform, Record)*
		Interrogative *(Request, Propose, Test)*
		Imperative *(Guide, Commit, Decide)*
	Mode of Communication *(Visual, Tactile, Auditory, Mixed)*	
Evaluation Purpose	Single Design	Form *(Is it acceptable, what is good/bad)*
		Function *(Does it function, how well does it perform)*
		Fit *(will it fit, how well does it fit)*
	Multiple Designs	Form *(which ones are acceptable, which one has better visual, tactile, and/or auditory appeal)*
		Function *(which ones work, which one performs better)*
		Fit *(which ones fit, which ones fit better)*
Cost	Time *(fabrication, procurement)*	
	Availability *(internal resources, external resources)*	
Design Stage *(Clarification of the task, conceptual, embodiment, detailed, production)*		
Characteristics of a Physical Prototype		
Size	Number of Parts relative to the final sub-system	
	Number of disciplines	
	Number of constraint questions that can be answered	
	Number of criteria questions that can be answered	
	Relative scale (dimensioned) to final	
Type *(Novel, Variant)*		
Material	Intrinsic Properties	
	Processed Form	
Fabrication	Joining methods	
	Part production processes	

I have included all of these models, frameworks, and taxonomies of prototypes to paint a holistic picture of the literature around prototypes. The majority of these studies come from HCI, with the exception of two from Lande and Leifer [48] and Michaelraj [45]. Prototyping literature in HCI seems to be "well defined", but there "is still a lack of knowledge about the fundamental nature of prototypes due to their complex and dynamic nature" [20, p. 1]. Additionally, all of these studies tend to focus on the attributes of prototypes: describing their functionalities, interactivity, precision of technical elements, materials/components, and similar. There is a need to further explore the "actions", or agency, of prototypes and how they influence social situations. In this research, I also used Houde and Hill's recommendations to define the term prototype broadly and to focus on the purpose of prototypes [43]. This broad perspective on prototypes helps to inductively derive the nature of prototypes in companies.

1.3.2.2 Strategies for Prototyping

In addition to the variety of models, frameworks, and taxonomies to describe prototypes, there are several researchers who have developed strategies to approach prototyping, especially for novice designers [1], [2], [15], [18], [19], [50]–[52]. In the following paragraphs, I describe each of these studies briefly.

Some of the first prototyping strategies developed were from Stefen Thomke (1998) and Matthew Wall (1991) out of management science, which is rooted in work with several high-tech companies. Both of these papers came from an engineering management perspective, focusing on time, money, and performance in the overall product development picture. Wall identified prototyping processes for development of an electromechanical design, including computer aided design (CAD), stereolithography (SLA), computer numerically controlled (CNC) machining, and rubber molding [52]. Similarly, Wall evaluated a variety of these prototyping technologies (CNC, CAD, STL, RM) against factors like cost, time, and accuracy for new product development [1]. Thomke (1998) emphasized switching between multiple prototyping modes throughout product development. A mode referred to either computer-based prototypes or physical (often rapidly designed) prototypes. He believed that switching between computer and physical modes would allow for overall reduction in time and costs on a project [51]. Ultimately, Thomke developed a process for prototyping, which can be seen in Figure 4. Thomke and Bell continued work in this area, and developed mathematical models to manage the optimal timing, frequency, and fidelity of sequential testing of prototypes [50].

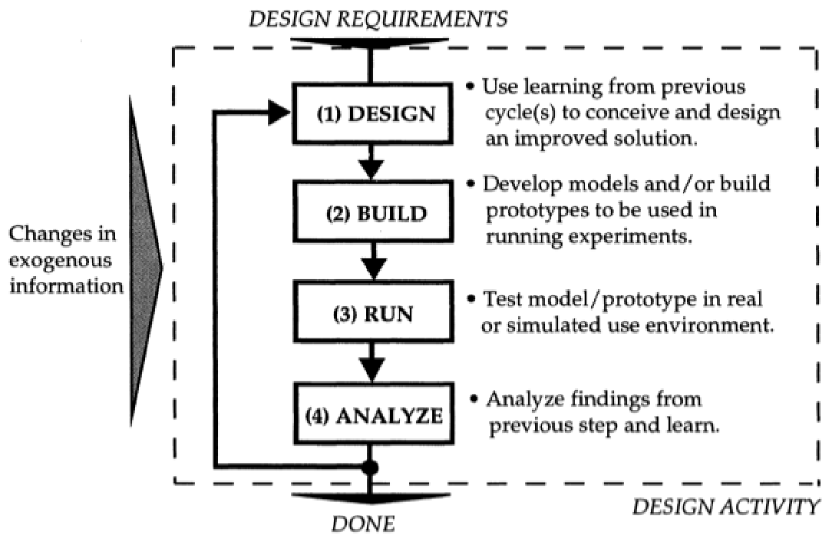

Figure 4. Process for Prototyping (from Thomke, 1998)

Additionally from the field of management science, there are a number of researchers who propose predictive models to enhance the product development cycle [1], [50], [53], [54]. The largest sunk cost is in the development of fully functional prototypes. Therefore, many of these authors evaluate methods to reduce cost and time in this stage. These predicative models help with critical decision making around optimization of prototypes as well as suggesting a budget and schedule for the team to follow.

In 2012, Christie et al. summarized literature from the business and engineering perspectives on prototyping, as well as introducing a detailed prototyping strategy [18]. They define a prototyping strategy "as the set of decisions that dictate what actions will be taken to accomplish the development of the prototype(s)." They indicated a breakdown in communication, often between engineering and management (the business-side); and they argue that developing a prototyping strategy could remedy these common issues. In the broadest sense, they consider prototypes to be either digital of physical. Each type of prototype can vary in level of fidelity and complexity. They identified nine different factors to consider when developing a prototype and thirteen questions to ask yourself to aid in the creation of your prototyping strategy.

Camburn et al. (2013) also published a developmental paper on prototyping strategies in conceptual phases around the same time as Christie et al. (2012). This study was expanded into a journal publication on the strategies for effective design prototyping [55]. They developed a hierarchical list of all decisions for a broad prototyping strategy, as seen in Table 2. They validated this strategy with an academic design problem. Students were required to design and develop a way to get a quarter as close as possible to a target. This work evolved over the following year, and the team published another conference paper about their heuristic-based tool that guides designers in planning a prototyping strategy based on questions to Likert-scale questions. Results from a controlled study showed that students' performance improved across a number of assessment metrics [15]. These strategies are great tools to help students learn how to prototype in a broad sense, as it allows individuals to think about the underlying purpose and plan for the prototype.

Table 2. Hierarchical Decisions for a Broad Prototyping Strategy (from Camburn et al., 2013)

Scale	Scaled or actual boundary conditions/parameters	
	Scaled or actual function	
	Scaled or actual geometry (dimensions, shape, tolerances)	
Integration	Physical integration or segmentation/subsystem isolation	
	Functional integration or segmentation	
Logistics	**Allocations**	Rigid or flexible scheduling
		Rigid or flexible budgeting
	Make	Number of design concepts (in parallel)
		Number of iterations of each concept
Embodiment	COTS (Commercial Off-the-Shelf) or custom parts	
	Material	Actual or easy to manufacture
	Method	*Ad hoc* or precise (formal or systematic)
	Virtual or physical	
	Outsourced or in-house	
Evaluation	Relaxed or stringent parametric design requirements	
	Exploration or verification	
	Testing	Dynamic or static
		Run conditions or failure conditions
		Multiple test conditions or single condition
		Continuous or discrete variation of parameters

More recently in 2017, Menold et al. published their "Prototype for X" (PFX) framework, which includes strategies for prototyping more effectively [19], [56], [57]. Specifically, they look at prototyping for feasibility, viability, and desirability. Their model for this can be seen in Figure 5. Each prototype needs to go through a frame, build, and test cycle. Here, the framing of the prototype is critical and is focused on the categories of feasibility, viability, or desirability. They tested this framework in their pilot study with junior-level mechanical engineering students developing vacuum-cleaners, but they plan to expand this work to a number of different industries.

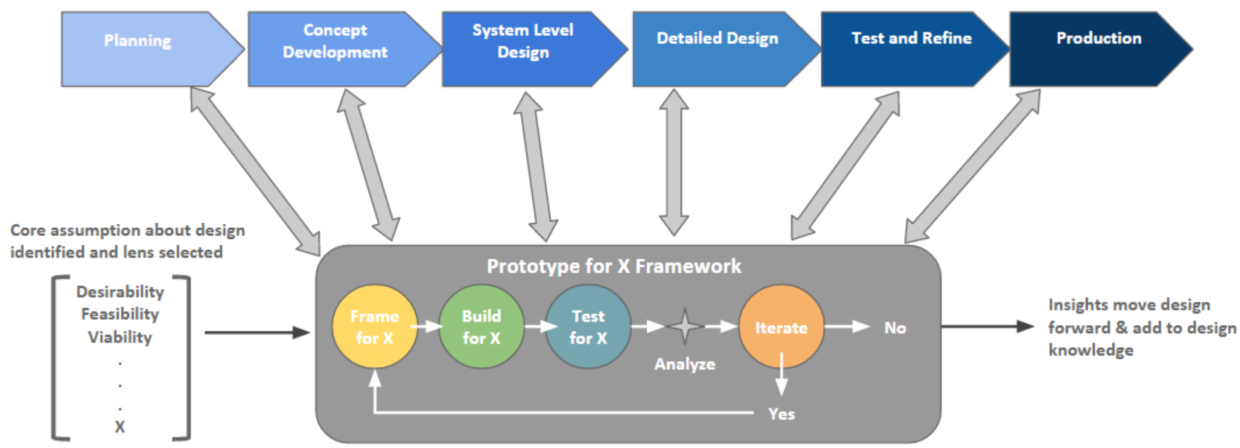

Figure 5. Prototype for X Strategy from Menold et al. (2016)

These strategies are helpful for new designers, especially since it has been shown that novice designers need guidance when prototyping [58], [59]. These studies have helped us understand how students approach prototyping, especially when guided by certain methods. However, there is still a need to better understand how design teams – both students and industry – engage in prototyping naturally. It can be argued that we must understand how professionals engage in prototyping, and then translate those practices or ideas back into design education to better prepare students for what they will face in industry.

1.3.2.3 Experimental Studies

In addition to the prototyping frameworks and strategies, there are several prototyping experimental studies. Each experimental study tests certain hypotheses, such as arguing for parallel prototyping over sequential prototyping [60] or how using less components in prototypes leads to better products [16]. Most of these studies use student design teams and simple design tasks in the experiments. They are excellent resources for better understanding specific variables while prototyping, and these studies can be used to validate portions of prototyping frameworks or strategies.

For digital prototypes, often from HCI, there have been variety of studies done measuring the effects of prototyping in parallel versus series [61], prototyping under time constraints [62], and the impact of user feedback on the design [63]. There are studies comparing paper and computer-based low fidelity prototypes [64], as well as testing how prototypes aid in knowledge acquisition [65]. These studies are valuable to growing our knowledge around prototyping. However, these studies cannot be directly translated to physical prototypes, so there are opportunities for future research in these topics.

Studies around physical prototyping have focused mostly around front-end design and cognition, such as how physical models impact idea generation [2], [11], [66]. Researchers have expanded from this topic to study how physical representations impact creativity in early stages like concept generation [7], [62]. Additionally, research has been done to study the impact of sketching during the creation of preliminary prototypes [9], [10]. Some researchers have even looked at product dissection, which can be considered a form of prototyping that aids in learning, to measure impacts on students mental models [14], [67]. Other studies have looked specifically at how physical representations can impact design fixation [13], [68], [69]. All of these studies are centered around low-fidelity prototyping in early stages of the design process (ideation/concept generation), mostly with students on simple design tasks. A few studies in mechanical engineering have looked at more complex prototypes. In particular, Yang looks at the complexity of the prototype and number of prototypes impact on the final design [16], [17]. In these studies, she used an advanced mechanical engineering mechatronics design course, where the students must create a robot.

All of these experimental studies are conducted in a controlled environment, and there is typically a focus on testing one variable while prototyping. Most of the design tasks are simple compare to more complex design problems in the workplace. Similarly, the physical prototype studies mostly focused on early stage low-fidelity models. There is still a need for understanding how prototyping physical products occurs in a workplace environment. Only through understanding how this occurs, can we then aim to properly improve the processes and strategies around prototyping and product development.

1.3.3 Research on Design Professions

This final section of the literature review is aimed at laying the foundation for research studying the design profession, including self-reported company studies, ethnographic work, and management/product development books. Each year, over $141 billion are invested by large companies in product research and design activities, and up to 50% of that money is spent on cancelled products or those which yield inadequate results [24]. Prototyping represents the largest sunk cost of the product development process; however, it remains the least researched or understood, especially from a company perspective. There have been several studies conducted within companies, which I will discuss.

1.3.3.1 Design Work in Companies

Simon defined design in the broadest sense of human action. To design is to “devise courses of action aimed at changing existing situations into preferred ones” [37, p. 129]. As mentioned earlier, Simon’s book *The Sciences of the Artificial* was a ground breaking work looking at professions from the perspective of design. He indicated that professional practice is centrally concerned with design. He proposed to fill the gap between the natural sciences and design practice with a science of design. The study of design can only be done through learning about actual designers in practice.

Architecture is considered a field of design practice, and this field has been studied in practice [70]–[73]. Darke studied the process of design as practiced by architect, and found that designers do not start with a full and explicit list of factors to be considered, but rather find a way to reduce the variety of potential solutions to the yet imperfectly understood problem [71]. Akin explores using a protocol analysis technique to show empirically how the state of the art design process (analysis-synthesis-evaluation cycle) does not hold true [70]. Lawson used interviews and experimental sessions to measure disagreement in design conversations among architects [72]. Thomas and Carroll indicate eight simplified insights about cognitive processes of designers, including aspects like structuring design problems in terms of sub-problems and to specify specific goals [73]. There is extensive work studying the field of architecture, along with other design disciplines like industrial design and visual design.

The study of the use of engineering drawing and visual representations as part of design work has been well documented from empirical studies [74]. In the book “Engineering and the Mind’s Eye”, Ferguson argues that drawings are the primary mode of communication between designers and manufacturers of products, thus making them critical objects [75]. He claims that the rise of the engineering design profession from the artisan design profession can be linked to introduction of sketches and drawing as part of the planning and intent that goes into designing an object. This is called the mediating visual representational language for design.

Bucciarelli’s book on *Designing Engineers* gives a critical perspective on the profession of engineering design [76]. In this book, he describes three vastly different design projects in the workplace including an x-ray inspection system for airports, a photoprint machine, and a residential photovoltaic energy system. He examines both how the designers engage in the process of creating the final artifact along with how the participants understand how things work. He provides an alternate view of engineering as a social construction process reconciling goals, objectives, tests and interpretations in the development of a product by participants with perspectives from different object worlds. He argues that design is just as much about agreeing on set definitions and negotiating as it is about producing the final technical artifacts or product.

The field of Science and Technology Studies (STS) has produced many articles and books describing professional scientific and engineering work. STS is the study of how social, political, and cultural values affect scientific researchers and technological innovation, and how these in turn, affect society, politics and culture. One STS researcher, Bruno Latour, specifically studied scientists and engineers. In his book, "Science in Action: How to Follow Scientists and Engineers through Society," Latour argues that social context and technical content are both essential to a proper understanding of scientific activity [77]. Later, Latour wrote "Aramis, or the Love of Technology," which discusses a large-scale transportation project [78]. Aramis is the code name given to this engineering project, and the book is a comprehensive story about the engineering process involved in Aramis. The goal of Aramis was to create a futuristic automated personal rapid transportation system. The project started in 1969, and moved forward to be conceptualized, prototyped, tested, scaled, funded, and then ultimately terminated in 1987 before actually being built. The book can be considered a quasi-mystery to uncover "who killed Aramis" (the transportation system). This book introduces the framework of actor-network theory (ANT), which is a social science theory to describe social phenomena [79]. Ultimately, it is determined that no one factor "killed" Aramis, but that all of the actors failed to sustain it through negotiation and adaptation to a changing social situation. This highlights again the value of social aspects on the overall development of a technical product or system.

There are two more contemporary studies of engineering in the workplace [80], [81]. Suchman reports on a case study involving a major bridge-building project. In this article, Suchman notes that the design and technical practices that engineers view as "the real work" of engineering did take place in this project; however, her analysis shows that the work of "sensemaking, persuasion and accountability" (p. 315) are as consequential for the realization of the bridge project. These practices are equally important parts of engineering work and should be considered in the practice of engineering. Similarly, Trevelyan studies engineering in diverse settings in Australia and South Asia [81]. The article argues that "the foundation of engineering practice is distributed expertise enacted through social interactions between people: engineering relies on harnessing the knowledge, expertise and skills carried by many people, much of it implicit and unwritten knowledge. Therefore, social interactions lie at the core of engineering practice" (p. 175). It is clear that across multiple authors studying engineering there is great importance to better understanding the social interactions that underlie the technical artifact creation.

Overall, there is a small empirical base on what professional engineering practice involves [76]–[78], [81]–[91]. Trevelyan and Tilli conducted an extensive review of several different literatures on engineering work, including, among others, the technical literature on engineering research and development, competency standards of professional organizations within engineering, engineering education literature, engineering management literature, and ethnographic studies of engineering [90]. These authors concluded that most of these literatures provide an inadequate picture of engineering work, especially what occurs during design or product development. Stevens et al. give a review of professional work in their chapter "Professional engineering work" in the *Handbook of Engineering Education Research* [88, pp. 119–138]. They argue for a better understanding of contemporary engineering practice as means to translate best practices back to academia. It is the goal of this research to study prototyping practices within industry as a means to better understand how professionals engage in design practice. This will then be translated back to design education, and compared to insights on how students engage in design practices, too.

1.3.3.2 Prototyping in Companies

In this literature review, I identified one article that conducted both an ethnographic study and focused on prototyping within a company [22]. Gerber and Carroll conducted an 18-month ethnographic study of a high tech firm using the theoretical framework of "design as a learning process" [92]. They focused on the psychological experience of engaging in low-fidelity prototyping. This allowed the employees at the company to reframe failure as a learning opportunity, support a sense of forward progress, and strengthen beliefs about creative ability. This study focused on the psychological experience of prototyping rather than a general grounded understanding of the role and impact of the whole process [22], [93].

Recently, Jensen et al. published their work on prototypes "eliciting unknown unknowns" in the design process within companies [23]. Unknown unknowns are aspects of the design not considered prior to building and testing the prototype. They conducted a mixed-methods study, using a collection of observations, interviews, and artifacts. They analyzed nineteen prototypes across eight companies in terms of functionality, timing, stakeholder involvement, and requirement elicitation. Their main take-away was that prototypes help with uncovering known unknowns and unknown unknowns about the design process. This can be related to the learning and decision-making that is occurring in the design process.

To my knowledge, only two self-reported studies from companies around prototyping practices have been reported. RAND Corporation and Toyota have white papers on their believed best practices around prototyping within their companies [94], [95]. These are key insights into how a company prototypes from a personal perspective. Other companies, like Dyson, promote their culture of prototyping on their company website, Dyson Foundation, and James Dyson Award. They note that James Dyson took five years and 5,127 prototypes before he developed the world's first bag-less vacuum cleaner [96]. They have even developed free online lessons for teaching prototyping aimed at middle and high school students.

Likewise, there are a number of prototyping books that are written from the business perspective, such as how to create a culture of prototyping to enhance corporate innovation. Many of these books use anecdotal stories from companies to support their viewpoints [97]–[103]. One of the famous quotes from David Kelly, founder of product design consultancy IDEO, is to "never go to a meeting without a prototype" [104]. It is often that prototypes and prototyping is considered important, or even critical, to the success of a company. Yet, there is not a fundamental understanding of the role of prototypes and how they aid in the success of corporations.

There have been more mainstream prototyping tools developed over the years from professionals who saw a need to improve and explain the prototyping process. Tom Chi, a prior project manager at Google, developed his own version of "rapid prototyping." This notion became popular after his TED talk on the subject [105]. In this talk he explains the concept of rapid prototyping through Google Glass, a project he led. In Figure 6, you can see fourteen prototypes of Google Glass. The main lessons he teaches are to find the quickest path to experience, that doing is the best kind of thinking, and to use materials that move at the speed of thought to maximize the rate of learning. Since then, Chi has developed a course of "prototype thinking" that he teaches [106].

Figure 6. Prototypes of Google Glass from Tom Chi

Likewise, other product design consultancies have tried to distill their creative process for prototyping and develop courses on the subject. Lynda, an online learning platform, just launched a short course on prototyping named "Design Thinking: Prototyping" [107]. They partnered with Frog Design Consultancy to launch the course. In the course, Randall Elliott of frog teaches the audience how to use prototyping to make better decisions, use those design decisions for the next steps, and make sure those steps lead to great experiences. Similarly, IDEO, a global product design consultancy, has launched a prototyping toolkit on ideo.org [108]. They have also partnered with +Acumen to launch a free online course to guide new designers through building rough prototypes, gaining feedback on them, and iterating early and often to get to desired solutions. It appears that prototyping at companies is a self-taught with company specific processes. It can even be argued that prototyping methods and tools are companies secret recipe for successful product development and innovation, meaning that it can be difficult to learn how prototyping occurs within organizations.

1.4 Summary of Gaps in Literature and Need for Research

This literature review has discussed three major topics: prototypes as described in the engineering design process, academic literature around prototyping including models, frameworks, and strategies, and empirical studies conducted within companies and the design profession. I will summarize the main gaps in the literature, and how this research aims to contribute to filling these voids.

In the first section describing prototyping in the engineering design process, it is clear that prototyping is a valuable part of the process. It is indicated that prototyping is a critical stage of the design process, and yet there is not much guidance given as how to prototype effectively. The mindset is to "just do it," which can be difficult for new designers or students to grasp the importance and ability to prototype effectively. The gap here is that prototyping is not described holistically. If there existed literature from companies' demonstrating the importance and role of prototyping in the workplace, then it would be easy to implement that knowledge into design textbooks. This, paired with prototyping strategies and best practices, could help new designers understand how and why to use prototypes in their design projects.

In the second section on frameworks, models, taxonomies, and strategies for prototyping, there are multiple viewpoints on describing prototypes, mostly from the field of human-computer interaction. These models are extremely helpful as a starting place to identifying a new framework for physical prototypes. There is clearly a gap in the literature and a need to develop a holistic framework for both digital and physical prototypes. There are many valuable lessons to be learned from HCI, but there will be inevitably be many differences when looking at the development of physical products. A majority of these models look at the attributes of prototypes, without always considering the actions that prototypes enable. This is where we will have a major contribution; this dissertation looks at the actions, or agency, that prototypes create instead of the attributes of the prototypes. Additionally, many of these studies, especially the strategies for prototyping, use students, an academic setting, and simple design tasks to develop and validate these strategies. Often the complexity of design tasks in prototyping research does not mimic real-world problems, making it difficult to generalize findings. There is an additional need to develop a framework out of the empirical studies of professionals. I aim to bridge all of these gaps by solely focusing on the prototyping for physical products, and by studying how companies engage in prototyping practices.

In the section on experimental studies, there are many valuable studies on different aspects of prototyping. All of the studies are conducted in a controlled academic environment. Each experiment is set up for students to engage in a simple design task, like an egg balloon drop or launching a quarter. Similarly, these studies tend to focus on testing one variable while prototyping. These experimental tests are valuable for testing certain hypotheses and validating claims about prototypes. However, using simple design tasks and student teams does not reflect the complex design challenges that happen in the workplace. There is clearly a need for understanding how prototyping occurs in the environment outside of academia, specifically in companies who design products. There are also many limitations to studying simple design tasks, since design problems in the workplace are vastly more complicated. Only through understanding how prototyping in companies occurs, can I then aim to properly improve the processes and strategies around prototyping and product development. I aim to fill this gap by conducting a study of how professionals engage in prototyping in the workplace.

In the third section on professionals and designers, there was only one ethnographic study of prototyping in companies. This study focused on one company and looked at low-fidelity prototyping and its impact on the psychological experience for designers. There are studies on engineering design as a profession, along with studies of other design fields like architecture. However, each of these has focused on different aspects such as ethics or professionalism. There are limited studies on prototyping in companies, and I aim to fill that gap with our research. Likewise, many innovative companies and consultancies, such as Dyson, Google, and IDEO, extol the importance of prototypes, yet research in engineering design offers little guidance or insight in the prototyping process itself. As a result, engineers and designers are often left to “blindly” prototype; prototyping without a clear focus can lead to wasted time and resources and potentially increase the frequency of failed projects, products, and businesses. Clearly, there is an important need to understand the prototyping process in companies both from a research and productivity standpoint.

In conclusion, there are many gaps in the literature and a need to conduct research around prototypes within companies. A framework and deeper understanding of prototypes, emerging from empirical data in companies, currently does not exist. Similarly, there is no fundamental understanding of physical prototypes, specifically from the fields of engineering design and mechanical engineering. I aim to contribute to filling many of these voids see in the literature and contribute to the fields of design theory and methodology, management science, and engineering design education with this work.

1.5 Dissertation Outline

This research was motivated by the need to study the role of prototypes on design teams both in industry and academia. This dissertation intends to further our understanding of prototypes as critical objects in the design process. Using qualitative methods for data collection and analysis, I inductively analyze the role of prototypes and compare to existing theories and frameworks. This research furthers our understanding of prototypes on design teams, specifically how they can influence the design process through their actions, or agency.

This dissertation is a compilation of various journal and conference papers. At the start of each chapter, there is an introduction to set up the chapter. At the end of each chapter, there is a summary section that highlights the main takeaways from that chapter, while also transitioning to the following chapter.

In Chapter 2, I report on the pilot study comparing the perceptions of prototypes between mechanical engineering students and professional engineers. The findings from this pilot study indicate that the interpretation of the term “prototype” varies between students and professionals. Specifically, the students have a narrower perception and identify prototypes as only having a few key elements, namely for building and testing functionality and feasibility of physical elements in a product. Comparatively, professionals have a broad perception of prototypes. They identify a wider range of attributes and actions, including prototypes as a communication tool, an aid in making decisions, and a way to learn about unknowns throughout the design process. This chapter further motivates the need to understand how professionals use prototypes.

In Chapter 3, I explore the use of prototypes on student design teams through the conceptual framework of intermediary objects. This study focuses on two first-year engineering design courses, one that used multiple prototypes (frame-build-test iterations) and the other that used minimal prototypes and instead emphasized design theory. Through comparing the courses, I am able to expand our understanding of what prototypes can do on design teams, specifically how they create "design coordination". Design coordination builds on the theory of intermediary objects, and highlights how prototypes are critical objects that influence the development of social networks and technical skills for designers. This chapter furthers our theoretical understanding of prototypes. The literature review, methodology, and discussion become a foundation for the research conducted within companies in the following chapters.

In Chapter 4, I first introduce the three companies in this research from the fields of consumer electronics, footwear and medical devices. These companies all create evolutionary physical products, meaning that they constantly develop the next version of a prior product. This chapter explores how design methods are used in the early stages of the design process during the planning, concept generation, and concept selection phases. I find that all three companies engage in both internal and external benchmarking and reverse engineering as design methods during the early stages of their process. I refer to benchmarking and reverse engineering as prototyping design methods, since they serve as tools to solidify the design intent for each company's products. I map out the process that the design teams use as a mean for others to understand the broad nature of prototypes and how aspects like benchmarking and reverse engineering are critical steps taken by design teams in industry when creating evolutionary products.

In Chapter 5, I describe the emergent roles of prototypes across these three companies: prototypes as tools for communication, learning, and decision-making. These insights validate prior literature, while adding new perspectives through exploiting each of these roles further. I also introduce a new definition for a prototype and provide some insights into becoming aware of the intentional and unintentional actions that prototypes enable. This chapter emphasizes how prototypes are actors on design teams, influencing actions that are taken through the design process.

In Chapter 6, I build off of the work presented in Chapter 5 and describe how the primary roles of prototypes shift based on the context of use. In this chapter, I provide an in-depth case study of one company, mapping out how the prototypes travel between contexts serving different primary purposes. I explore five unique contexts and describe how these contexts are constructed. This chapter furthers our understanding of how objects, like prototypes, have power and influence in the design process.

In Chapter 7, I reflect on the chapters in this dissertation research, giving a summary of what was discussed. I provide details about the research contributions, as well as details on the limitations and validity of this work. I provide recommendations for future researchers, specifically around collecting qualitative data and working within companies. Finally, I conclude with some areas for future research, such as further exploring the influence of prototypes on decision-making and testing how low-fidelity prototyping materials can enable convergent verse divergent thinking during early-stage design.

1.6 Statement on Authorship

The research presented in this dissertation is the culmination of work from multiple researchers. Just as design is not an independent activity, neither is design research. In writing up the ideas presented in this dissertation, such as in Chapters 1, 7, and the introductions and conclusions for Chapters 2-6, I use "I, me, and my" to describe the work since I am communicating my ideas. However, in the conference papers and journal papers presented in Chapter 2-6, I use "we, us, and our", since that is how each research article has been published.

While I initiated and led all of the projects described here, the contributions from a talented group of collaborators must be acknowledged. Without their efforts, the research could not have been realized in its current scope. My co-advisors, Dr. Mark Rentschler and Dr. Daria Kotys-Schwartz, aided in all aspects of the research. Dr. Daniel Knight helped with the research methods, especially data analysis. He is a co-author on the manuscript that has been submitted for review to Design Studies in Chapter 6. Dr. Joanna Wielder-Lewis was a graduate research assistant for data collection and analysis during our work with student design teams, and she is a co-author on the accepted IJEE article in Chapter 3. This dissertation is the culmination of multiple peer-reviewed conference proceedings and archival journal research papers: some published, accepted, in-press, and in-review.

Chapter 2 – What is a prototype? Perceptions of Prototypes

2.1 Introduction

In this chapter, I discuss a pilot study that explores the differences in perceptions between students and professionals around the term "prototype". Section 2.2 is the text from the conference paper and original peer-reviewed research article from the 2017 ASME International Design Engineering Technical Conference (IDETC) in the Design Education Conference (DEC). This paper (DETC2017-68117) is entitled "Perceptions of Prototypes: Pilot Study Comparing Students and Professionals" and is co-authored with Daria Kotys-Schwartz and Mark Rentschler [59].

This pilot study sets the foundation and motivation for remaining chapters in this dissertation. It provides validation that there is no uniform understanding of the term "prototype", and that there are differences in perceptions of the term between students and professionals. This study also shows that there are disconnects between design professionals and design education, which motivates some of the outcomes and contributions of this work to translate findings back from industry to education. I have worked to translate insights from professionals back to students through workshops, activities, and tools. Some of these are presented in the final sub-section within Section 2.2.

2.2 Perceptions of Prototypes: Pilot Study Comparing Students and Professionals

Just as design is a fundamental part of engineering work, prototyping is an essential part of the design process. For many engineering design courses, students must develop a final prototype as part of the course requirements. And in industry, engineers build multiple prototypes when creating a product for market. Although prototyping is core to design education, there is a lack of research on understanding the perceptions and usage of prototypes from both students and professionals. Without understanding students' perceptions of prototypes, we cannot adequately train them. Likewise, without knowing how professionals use prototypes, we cannot translate these practices back to design education.

This paper reports on the pilot study comparing the perceptions of prototypes between mechanical engineering students and professional engineers. The findings indicate that the interpretation of the term "prototype" varies between students and professionals. Specifically, these mechanical engineering students have a narrower *perception* and identify prototypes as only having a few key elements, namely for building and testing functionality and feasibility of physical elements in a product. Comparatively, professionals have a *broad perception* of prototypes. They identify a wider range of attributes, including prototypes as a communication tool, an aid in making decisions, and a way to learn about unknowns throughout the design process.

Many instructors in design education are cognizant of the importance of prototyping. However, we believe that students require explicit instruction about key concepts. It is not enough to just tell students to "prototype." As design educators, we must be aware of the various roles of prototypes, and teach these concepts to students. We provide some immediate recommendations for practice, including a list of ten principles of prototypes to create similar mental models between students.

2.2.1 Introduction

Design is often considered to be the a central activity of engineering, and yet many researchers have pointed to a misalignment between design education and design in the workplace [25], [76], [109]. Even with the expansion of hands-on design experiences in the engineering curriculum over the last 30 years [27], the National Academy of Engineering has stated that there is still a “disconnect between engineers in practice and engineers in academe” [26]. As a way to strengthen this translation from student to professional, researchers can identify the disparate perceptions and practices between engineering students and engineering professionals.

It is the goal of this pilot study to begin to understand how students perceive and use prototypes, and then compare this to engineering professionals. We specifically use two mechanical engineering design courses, as we are interested in how students trained in this discipline approach prototypes. We acknowledge that most prototypes are physical in nature. We choose to compare this to a wide range of design professionals, as it is typical for engineers to work in diverse teams across many fields in the workplace. We hypothesize that there are differences in the ways that students and professionals perceive prototypes. This hypothesis comes from studying design teams on a prior research project, CEED: Cognitive Ethnographies of Engineering Design, where we worked with six undergraduate teams and two companies for two years understanding design practices [110], [111]. We aim to translate industry findings about design practices and prototypes back to engineering design curriculum through lectures, activities, and course development.

The remainder of this paper is organized as follows. First, we discuss background information related to the complex terminology of prototypes, along with how prototyping is situated in the design process. Second, relevant literature to prototyping and perceptions research is discussed. Next, we outline the research design of this pilot study, which includes elements of data collection and analysis, along with limitations of the study. Following, we discuss the emergent preliminary findings. Finally, the paper ends with some initial recommendations for practice and opportunities future research.

2.2.2 Background

In this section, we discuss the terminology around “design” and “prototypes” and then examine prototyping definitions from design textbooks used in mechanical engineering. This background information is necessary to frame our pilot study, and to understand how prototyping is often presented to students in design courses.

2.2.2.1 The Multiple Meanings of Design & Prototype

Design is a powerful word that can be interpreted in different ways from people of diverse disciplines, backgrounds and experiences [112]. Similarly, the term “prototype” is very broad term that can hold multiple meanings for people [43]. This breadth of the terms “design” and “prototype” can cause many misunderstandings and miscommunications.

Design as a discipline has evolved since it entered the English language in the 1930s [29]. It has moved from being artisan-focused, to more artistic and creative in nature, to more logical and planned [113]. Similarly, the role of the “designer” has evolved. The renowned researcher, Herbert Simon, indicates that all professional practices, even physicians and lawyers involve design in the broadest human sense. Design here is defined as “to devise courses of action aimed at changing existing situations into preferred ones” [30]. Design in this sense is considered part of almost every discipline spanning engineering, education, art, architecture, urban planning, business, and more.

Houde and Hill perfectly summarize the inevitable complexity of a prototype in their chapter “What do prototypes prototype?” Here, they state that “the term prototype has a different expectation of what a prototype is. Industrial designers call a molded foam model a prototype. Interaction designers refer to a simulation of onscreen appearance and behavior as a prototype. Programmers call a test program a prototype. A user studies expert may call a storyboard, which shows a scenario of something being used, a prototype” [43]. This summarizes the breadth of expectations and mental-models created with the term prototype.

Prototypes can range in physical appearance and purpose across disciplines. They can be either digital or physical representations, and span from 2D, 3D, to 4D. Prototypes also can be described along a spectrum of fidelity from low-resolution "pretotypes" [114] to high-resolution pre-production models. The term "pretotype," coined by Alberto Savoia in 2009, came from the need to describe lower-fidelity prototypes compared to ones where more time, money, and materials were invested.

This range in definitions, purposes, and uses of the term prototype can be difficult for students to grasp. Our pilot study aims to identify how both mechanical engineering students and professionals describe prototypes, and then use the learnings to better inform design instruction.

2.2.2.2 Teaching of Prototyping in Design Courses

In an academic setting, prototypes are typically a required deliverable in design courses. Curriculum relative to prototyping is dependent on the instructor, and many use engineering textbooks to guide their instruction. In mechanical engineering, there are several quintessential product design and development textbooks that are used extensively across the United States to teach engineering design courses [33], [39], [40]. Students' beliefs about prototypes are likely underpinned by the textbooks used in their design courses.

Eppinger and Ulrich define a prototype in their textbook as "an approximation of the product along one or more dimension of interest" and prototyping as "the process of developing such an approximation of the product" [39, p. 189]. These dimensions include the degree to which prototypes are physical or analytical, and focused to comprehensive. Eppinger and Ulrich believe that prototypes are used for four purposes in product development: learning, communication, integration, and milestones.

Otto and Wood discuss physical prototypes as fitting into several categories: industrial design, electrical engineering, and mechanical engineering focused prototypes [33]. They indicate six categories of how prototypes might be used: communication, demonstration, scheduling/milestone, feasibility, parametric modeling, and architectural interfacing. Additionally, they describe different applicable prototype materials and various prototyping processes.

Similar to Eppinger and Ulrich [39] and Otto and Wood [33], David Ullman (1992) discusses the entirety of the design process with a focus on mechanical products [40]. In this book on the mechanical design process, he describes the purpose of prototyping based on the function and stage in product development. These categories are: proof-of-concept prototype, proof-of-product prototype, proof-of process prototype, and proof-of production prototype [40]. These three textbooks all highlight the importance of prototypes in the design process. They also are a basis for how many students learn about prototypes.

2.2.3 Related Literature

In this section, we first discuss academic research studies related to prototyping followed by studies on students' perceptions of concepts in engineering education. We highlight the gaps in knowledge, namely the need for research on the perceptions of prototypes and more translation from industry to academia.

2.2.3.1 Prototyping Research Studies

Research studies around prototyping have evolved in the last two decades. There is an abundance of prototyping studies from fields like computer science and human-computer interaction, and there remains gaps of knowledge from the field of mechanical engineering around physical products.

Most prototyping research falls into three major categories. The first is developing taxonomies, models, and frameworks to describe prototyping [20], [45], [46], [49]; the second is developing strategies for prototyping more effectively [2], [15], [18], [19]; and the third is experimental studies around specific aspects of prototyping [16], [60]. We will highlight a study for each of these categories.

Lande and Leifer created a framework of prototyping based on a research study involving mechanical engineering students. Their framework cycles between converging and diverging thinking, moving from "design thinking" prototypes to "engineering thinking" prototypes [44], [49]. This framework is visualized in a T-shaped model, where there is a wide exploration of design prototypes (horizontal portion of the T-model) and a deep dive into physical aspects of each solution (vertical portion of the T-model). This T-shaped framework is based on empirical studies of students, which reflects how they conceptualize prototyping and the design process.

Menold et al. developed a "Prototype for X" (PFX) framework, which includes strategies for prototyping [19], [57]. Namely, prototyping for feasibility, viability, and/or desirability. Each prototype needs to go through a "frame, build, test" cycle with respect to these different X's. This framework and strategy was tested with junior-level mechanical engineering students, who were developing drill-powered vacuum-cleaners. This study found that students' using PFX methods had superior final prototypes compared to the control group.

Yang's experimental study tested if simpler prototypes translate to a more successful design [16]. This research involved mechanical engineering students developing an electro-mechanical design. Two findings from this study are that prototypes with fewer parts correlate with better design outcome and that prototypes with fewer parts added to them over the course of development also correlate with better outcomes.

Overall, there is still a need to understand how students perceive a prototype—since their perceptions influence their approach to prototyping during a design project. Without knowing how students conceptualize a prototype, we cannot teach them frameworks and strategies effectively. More importantly, there is a need to determine whether students' perceptions about prototypes are in-line with professional engineers in the workplace. If there are disconnects, as we hypothesize, then there should be efforts from engineering educators to enhance this knowledge.

2.2.3.2 Perceptions of Concepts Engineering Design

Lastly, we highlight research that explores students, instructors, and professionals' perceptions of certain engineering design concepts. A perception is how a person identifies and interprets information, which then becomes their way to understand, represent, and explain that same information. Perceptions can shape the way people learn about elements of design, approach aspects of the design process, communicate with one another, and make decisions.

Atman et al. compared engineering students' and expert practitioners' behaviors when engaging in the design process [115]. This study uses verbal protocol analysis to compare what the designers say to what they do. This work helps identify whether there are differences between the perceptions of designers and their actual words and actions. Findings support the argument that problem scoping and information gathering are major differences between advanced engineers and students, and important competencies for engineering students to develop.

Atman et al. also compared freshman and senior engineering students' approaches to designing, as a means to measure how students perceptions, behaviors and approaches to design change over the course of their education [116], [117]. Results show that seniors produced higher quality solutions, spent more time solving the problem, considered more alternative solutions and made more transitions between design steps than the freshmen.

Kazerounian and Foley studied students and instructors perceptions of creativity in engineering design [118]. This study shows that these engineering students experience almost none of the "Ten Maxims of Creativity," a list of ten factors that constitute and foster a creative educational paradigm. These maxims were developed by the researchers based on a large body of literature on creativity, their own experiences, and interviews with successful innovators, industrial designers, and practicing engineers. In their recommendations for practice, the researchers encourage engineering instructors to be greater "cheerleaders" for innovation, specifically by encouraging students to take risks, inspiring them with stories of successful innovators, teaching them to embrace inevitable learning opportunities from "failure" in design, and by explicitly requiring and rewarding creativity.

Within engineering design, there are studies that explore students' perceptions of sketching, along with how designers perceive their own design fixation. Storer explored sketching in the design process, specifically how undergraduate students interpret and use sketching based on the instructor's bias towards teaching sketching [119]. The findings indicate that the instructor's ability to be reflective of their own experiences sketching and their personal sketching skills, can transform and improve the teaching and learning of these skills for students. Linsey et al. explored how designers perceive their own design fixation [120]. For this study, clear evidence exists that even expert designers do not know when they are being influenced or fixated in the design process.

These studies show the importance of understanding students, instructors, and professionals' perceptions of engineering designs elements. Although these studies measured and discussed perceptions of designers' approaches to the design process, creativity, and design fixation, there is still a need to understand how designers' perceive prototypes in the design process and if this differs between students and professionals.

2.2.4 Research Design for Pilot Study

This research is a pilot study; pilot studies are valuable for gaining insights into a new research area before conducting a larger, primary study. As Maxell states, "one important use that pilot studies have in qualitative research is to develop an understanding of the concepts and theories held by the people you are studying" [121, p. 67]. As such, we conducted this six-month long pilot study, from July 2015 to January 2016, to better understand how students and professionals discuss and engage in prototyping. The purpose of this work is to inform our new definition of a prototype. This preluded our primary research study understanding the role of prototypes in companies. Additionally, this research follows the guidelines from the Institutional Review Board under IRBs #13-0410 and #15-0659.

The two guiding research questions are: (1) what is the perceived purpose of prototypes from both mechanical engineering students and design professionals? (2) Are there any significant differences between these two populations' perceptions?

To answer these open-ended questions, we used a qualitative approach to our research design. The data collected was in the form of surveys and semi-structured interviews. The surveys were given to every participant in the study, and then interviews were conducted with a handful of students and professionals to gain greater insight into their experiences with prototypes.

After collecting the surveys and conducting the interviews, we then analyzed the data and compared the responses. The goal being to identify if any differences exist between the two populations and to what extent. Specifically, if students' mental-models of prototypes differ drastically from professionals as hypothesized.

2.2.4.1 Participants

There are two populations of participants in this research study. The first are students from junior-level and senior-level mechanical design courses at a large public university. The second are working professionals with backgrounds in engineering and design across the United States. A summary of the participants is listed in Table 3.

The students were recruited from two courses during the fall of 2015. There are 252 students total, 88 from the junior-level course and 164 from the senior-level course. The junior-level course is one semester (16 weeks), three credits, and a project-based learning (PBL) course with a design project focused on building a drill-powered vehicle. Teams have between three and four students on them. The senior-level course is year-long (32 weeks), six credits, and an industry sponsored course. The teams have between five and eight students on them. Projects are all different, but each requiring a final working physical prototype.

All of the mechanical engineering student participants were required to take a first-year engineering design projects course, where they learned about the design process through a 10-week design project. In this first-year design course, they do not learn in-depth knowledge about prototyping. Most of them were required to build a final "works-like" prototype for this course. We surveyed how many prior design projects each student had completed. On average, students from the junior-level had only participated in between one and two prior design projects, and students from the senior level had between three and four prior projects. We asked for clarification of the projects, and students indicated that design projects came from first-year engineering design, junior-level design (for seniors only), other design course electives, personal projects, and internships. In general, we would consider these students to be novices in product design. Additionally, in these courses, there were approximately 84% male students and 16% female students.

Table 3. Demographics of Participants

	Junior Level	Senior Level	Professionals
Number of participants	88	164	47
Percentage of male participants	85%	83%	62%
Average prior design projects	1.4	3.3	-
Average years working	-	-	5.5

We recruited professional engineers starting in August 2015. To recruit them, we used our personal networks and the university's engineering alumni database. There were 47 individual professionals that participated in the survey, and then 14 who participated in the follow-up interviews from those surveyed. There is great diversity in the companies where these professionals work. The companies ranged in size from small (<100 employees) to extremely large global corporations. The industry range includes aerospace, biomedical devices, energy, consumer products, apparel, and electronics and embedded systems. We felt like this wide range of industries and sizes of companies allowed us to gain a wider view of the perceptions and uses of prototypes. Of the professionals, approximately 62% were male and 38% were female. Their background included approximately 62% mechanical engineering, 12% electrical and computer engineering, 9% other engineering background, and 17% design or technology-based degrees. The professionals ranged in years of expertise from 2 years to 27 years. The average was 5.5 years of experience.

2.2.4.2 Data Collection: Surveys

Data collected in this pilot study includes surveys and interviews. The surveys had between 8 and 12 open-ended questions. For students, there were 8 questions and for professionals there were 12, since we included extra questions related to their background (education, degree, years working) and company demographics. The purpose of the survey was to understand students' and professionals' beliefs and experiences around prototypes. Listed here are some of the core questions asked in both surveys.

- *What is your definition of a prototype?*
- *What is the purpose of prototyping?*
- *What are some examples of prototypes that you've created in recent design project(s)?*
- *What are the benefits and drawback to prototyping?*

These surveys were distributed at the beginning of the semester before the students had fully engaged in the design process (weeks 5-8). They had not yet built any prototypes in their current design course. These surveys were distributed to each class at the beginning of the class period, and filled out by hand for about ten minutes. These surveys were then collected by the research team and entered into a digital format. Each student was logged using their Mechanical Engineering ID number rather than their name to protect their identity. Similarly, each professional was given an ID number so that their identity remained protected.

2.2.4.3 Data Analysis: Survey Responses

Before conducting interviews, we preliminarily analyzed the surveys. The first step was reading through all the survey responses to get a sense of the emerging themes. Since there were multiple questions, we decided to compare one question at a time. We started with the first two questions, since they helped answer our first research question about the differences in perceptions of prototypes. The survey questions that we analyzed were "*what is your definition of a prototype?*" and *"what is the purpose of prototyping?"* These were two individual questions on the survey, which allowed the participants the chance to elaborate on their idea of a prototype. We felt that by having two questions that are similarly related, yet slightly different we could evoke more information in the responses.

Table 4. Initial Categories of Prototypes

Eppinger and Ulrich [39]	**Otto and Wood** [33]	**Ullman** [40]
Learning	Communication	Proof of concept
Communication	Demonstration	Proof of product
Integration	Scheduling / Milestone	Proof of process
Milestones	Feasibility	Proof of production
Spectrum of fidelity	Modeling	
Spectrum from physical to analytical	Integration	

After reading the responses, we created categories to code the responses. These initial categories were informed by the prototyping literature. A summary of these categories is listed in Table 4. We also concurrently conducted open-coding of the responses to see if there were any additional themes not considered [121], [122]. This process of qualitative open-coding combined with the literature gave the team our final categories, which will be discussed in the preliminary findings section. We used these final categories to code the responses in the surveys.

The next step in our analysis was to run a frequency count through VBA program in Excel to identify which words were used the most often by students and professionals that correlated to each of the categories listed. We accounted for all derivations of words. For example, the words "build, built, building" were all counted as one unit together. This allowed the research team to quantify the perceptions of prototypes based on the two populations. Graphs of the frequency of responses is shown in the preliminary findings section.

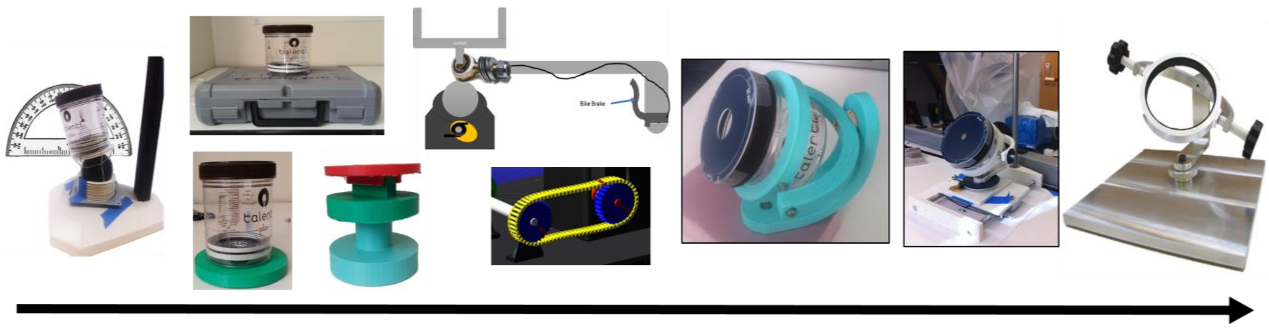

Figure 7. Example of Collection of Prototypes from Students During Demi-Structured Interviews

2.2.4.4 Data Collection: Interviews

After we collected and preliminarily analyzed the surveys, we conducted semi-structured interviews with a handful of participants to gain an in-depth look at their perception of prototypes [123]. These interviews lasted between one and two hours and were held either in-person or over video-conference. All of the interviews were audio recorded so that they could be extensively analyzed in the future. Some of the open-ended questions in these semi-structured interviews included:

- *Can you walk us through an example of a recent design project you've worked on, highlighting each time you created a prototype?*
- *How did you go about creating that prototype? (Asking follow-up questions related to materials, lead-times, cost, programs, processes, and technologies.)*

- *Can you elaborate on what "prototyping for proof of concept" means? (Or other statements from surveys.)*
- *Why did you create the prototype with these specific features? (Or similar follow-up questions.)*

For the academic setting, we interviewed nine students towards the end of the semester. In addition to these interview questions, we had the students describe chronologically the prototypes and representations of the design created. This included having the students show us pictures, documents, presentations, or physical models that were critical to the project. In doing this, we aimed to identify all the prototypes created in the project, even if they were not always considered a prototype by the student. We collected pictures of these prototypes and stored them for future analysis. An example of a collection of prototype images from one design project is seen in Figure 7, which shows the prototype evolution chronologically from left to right. This collection of pictures highlights the multitude of physical and digital representations of the evolving design over the duration of the project. This project was developing a micro-surgery training tool for brain surgeons.

For the professionals, we conducted 14 in-person or online video interviews. These professionals were chosen because of their interest in a follow-up interview and because they represented a diverse range of industries. Similar questions were asked during these interviews as with the students. We were unable to collect any images or physical prototypes, but the individuals spoke extensively about the prototypes developed during recent design projects.

2.2.5 Findings from Pilot Study

As discussed in the Research Design section, we used both literature and open-coding to develop a list of themes to consider when analyzing the definitions of prototypes. We developed five major themes, with between two and four sub-themes. These themes, sub-themes, and key words are listed in Table 5. For each theme, we indicate an example partial response from the surveys that is representative of this theme.

From these themes listed in Table 5, we coded the survey responses. We measured the frequency of each prototype code (build/test, functionality, decision making, communication, and learning) across each population and then plotted them in Figure 8. This plot shows the comparison frequency percentage of the coded responses for prototypes between the students, indicated by black bars, and professionals, indicated by gray bars. On the x-axis, there are the five different prototype categories from Table 5. On the y-axis, the frequency percentage of the students and professionals' responses to the prototype survey are plotted. For example, Figure 8 shows that 8% of students responded to the survey indicating that prototypes serves the role of communication, while 51% of professionals responded that prototypes serve the role of communication. Since there are drastically different numbers of participants for the two populations, we chose to display the data in this comparative graph using frequency percentage responses for each prototype code, as a way to visualize the differences.

Table 5. Prototype Themes for Analysis

Theme	Sub-Theme	Partial Example Responses
Build/Test	Materials	*"to ensure the correct materials"*
	Components	*"to build and test aspects of the design"*
	Users	*"to understand if this meets user needs"*
Functionality	Technical aspects	*"to test functionality"*
	Integration	*"to ensure the whole system works"*
Decision Making	Concepts, ideas	*"to refine a concept"*
	Business-related	*"to determine viability of the design"*
	Product	*"to decide on aspects of the design"*
	Process	*"to finalize production processes"*
Communication	Explain, Demonstrate	*"to show the team"*
	Persuade, Negotiate	*"to have the project manager agree"*
	Visualize	*"to better understand the design in 3D"*
Learning	Prior knowledge	*"to see if the concept works"*
	New knowledge	*"to learn about new materials"*

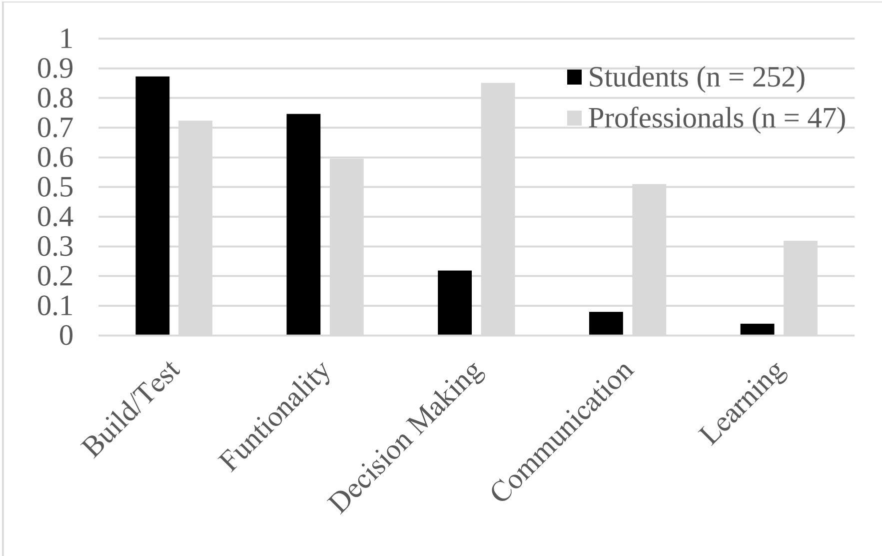

Figure 8. Frequency Percentage of Coded Student and Professional Prototyping Responses

For the "Build/Test" code, 87% of students and 72% of professionals indicated that prototypes are used for this purpose. For "Functionality", 74% of students and 59% of professionals indicated that prototypes are used for this purpose. Only 22% of the students indicated that prototypes are used for decision-making, while 8% indicated that they are used for communication, and only 4% believe they are used for learning. Contrasting this, 85% of professionals indicated prototypes are used for decision-making, 51% said they are used for communication, and 32% said they are used for learning.

From Figure 8, it is clear that both students and professionals seem to agree that prototypes are used to build and test concepts around functionality. Students' responses, overall, heavily favored the idea that prototypes are meant to be built and then tested for elements of functionality. Conversely, the students rarely mentioned that prototypes were meant for decision making, communication or learning. Professionals, on the other hand, indicated that prototypes are used for decision making, communication, and learning more often than students.

To further display this data, we have several representative quotes from students and professionals. After each set of three quotes, we will explain how these quotes link back to the prototype codes listed in Table 5 and displayed in Figure 8.

Example Student Responses:

S1: "[Prototyping is] making a replica of the full design in order to better see how well it will function."

S2: "Prototyping means creating a first draft of a product to test feasibility of the concept."

S3: "It means to construct a similar device that tests the desired capabilities of the final product. The purpose is to reexamine the desired function of the product and decide major design considerations based on the results."

These three quotes are representative of the general responses from the students. In the S1 response, this shows how they see prototypes as a means test functionality. They also mention that prototypes need to be a "full-system," which is something that was more commonly stated amongst students. This response was coded as "build/test" and "functionality". In the S2 response, prototypes are also described as a means to test feasibility. This response was also coded as "build/test" and "functionality". It was common for student responses to be one sentence long and concise like this answer shows. Finally, in the S3 response, they indicate that prototypes need to test capabilities similar to the desired final product. They also hint here at decision making as an underlying purpose of prototypes. This response was coded as "build/test", "functionality", and "decision making".

In these responses, the students indicate that prototypes are meant for the full-system (or final product), and that they must test functionality and feasibility of the design. It is important to note this idea of the full-design, as that plays a role in the students' mental models of prototypes, too.

Example Professional Responses

P1: "For me, my definition [of prototyping] is pretty loose. If you can get enough to give you the read, you need to make the next decision. That's all it is. So to me the thing is you come to a problem, you prototype, so that you can quickly get to the next decision."

P2: "You can prototype almost anything…from technical components like PCBs, the layout of a system and how it all works together, the software, any aspects of user-interfacing, look and feel of a product, and more. It helps you learn about what to do next."

P3: "Prototypes are stepping stones to a final desired product. They help you get across your idea to others and learn about things you never would have thought of without building and testing it first."

These three quotes are meant to be representative of all of the professional responses to the survey. The professionals' responses were typically more detailed than the students. The quote from P1 explains how prototyping is a "loose" term, meaning that it can hold multiple meanings. They mention that prototypes are able to help with decision making through rapidly building and testing concepts. This response was coded as "build/test" and "decision making". The quote from P2 shows how prototypes can be almost anything from testing technical elements (both digital and physical) to understandings user needs. They also highlight the importance of learning from prototypes to inform future direction. This response was coded as "decision making" and "learning". Lastly, the quote from P3 shows that prototypes are incremental stepping stones, meaning there are multiple prototypes needed throughout the design process. They indicate how prototypes are a means of communication by "getting your idea across to others" and learning about things you never would have considered before in the design. This response was coded as "build/test", "communicate", and "learning."

The professionals' responses often included several of the major categories, build/test, functionality, decision-making, communication, and learning in their responses. It is important to note that prototypes were often described across different mediums (digital, physical) and levels of fidelity. Also, that examples of prototypes, like in P2's response, were often shared in responses, which enable more interpretation of the statements.

2.2.6 Discussion

As a reminder, the guiding research question was to understand differences in the perceptions of prototypes between students and professionals. This pilot study indicates some variances in perceptions between the two populations. This agrees with our initial hypothesis.

Overall, students show a narrower *perception* of a prototype compared to professionals. Here, *narrow perception* refers to being "limited in prototype scope attributes." Often, the students indicated that prototypes are just a means to test functionality, and that the medium of a prototype must be the full-system of the physical design.

Comparatively, professionals showed a *broad perception* of a prototype, linking this term to multiple meanings from learning to decision-making. Here, *broad perception* refers to being "widened in prototype scope attributes." These professionals often indicated that prototypes can vary in levels of fidelity and complexity. These professionals considered prototypes to be useful in different categories; testing aspects of aesthetics, usability, desirability, viability, and functionality.

Professionals indicated that prototypes are used for building and testing, along with verifying functional elements, which agrees with the students' perceptions. However, many professionals also indicate that prototypes aid in decision making, communication, and learning throughout the design process. Not many students were able to articulate prototypes as being used for decision making, communication or learning in their responses, which is one of the biggest takeaways from this study. Professionals also mentioned prototypes as being both digital and physical, while varying in levels of fidelity. Students' comments often were that the prototype was physical and of the full-design.

We believe that one of the main reasons for this disconnect between the definitions of students and professionals is due to the broad nature of the term prototype. As described in the background section, different design disciplines refer to prototypes in their own ways. Most professionals have worked on interdisciplinary teams, and thus are exposed to different meanings and uses for prototypes. Contrasting this, the mechanical engineering students have only worked on design teams with other mechanical engineering students. This restricts their perception of prototypes since they are surrounded by like-minded individuals. Mechanical engineering often associates prototypes as being mechanical systems, which likely restricts the students' viewpoints.

Another reason for this disconnect in perceptions can be likely linked to the total number of design projects. Students have completed fewer projects than the professionals. We believe you learn new skills with each new project, such as how to prototype more effectively. The students have completed on average less than three design projects; this limits the number of times that they have built and tested prototypes. Comparatively, professionals completed design projects during their undergraduate degree, and then have participated in multiple projects at their companies. There may be other reasons for this disconnect between narrow and broad perceptions, such as the beliefs of the design instructors, nature of the design course, and industry of the professionals.

2.2.7 Limitations of Pilot Study

There are several limitations in this study. The most important being that this is a pilot study meant to gain a sense of perceptions, and is in no way representative of all perceptions in either population. This study only includes junior and senior mechanical engineering students from one semester at one university, and a limited population of professionals. We can only make preliminary claims about differences in perceptions of prototypes between students and professionals; we can merely point to some emerging trends from the small sample size.

Other limitations include the population and numbers of participants being skewed between students and professionals due to the ease of collecting student responses in a classroom compared to motivating professionals to take the time to fill out a survey or conduct an interview. Another limitation of this study is that we did not survey the instructors of the design courses, as these instructors could have an impact of the students' final perceptions of prototypes. Finally, the surveys and interviews are only preliminarily analyzed, since the purpose of this work is to gain a baseline understanding of perceptions of prototypes. We have exit-surveys with these same students that could indicate a change in perception over the course, which are not yet analyzed.

Additionally, with all qualitative research, there is a risk that some perspectives or insights can be accidently excluded during data collection and analysis. However, qualitative research provides the opportunity to draw new insights to social situations, like perceptions of prototypes through surveys and interviews.

2.2.8 Recommendations for Practice

Although this is a pilot study, we have some immediate recommendations for practice. We believe it is necessary for instructors to be explicit about the importance of prototypes. Many instructors in design education are cognizant of the importance of prototyping. However, we believe that students require explicit instruction about key concepts. It is not enough to just tell students to "prototype." As design educators, we must be aware of the various roles of prototypes, and teach these concepts. Part of being explicit about prototypes is describing the broad nature of them. If the purpose of design education is to prepare students for industry, then we must teach students about prototypes as they are described by professionals in companies.

We have some suggestions for *broadening* the term prototype to ensure that students' mental models of prototypes are expanded from the traditional mechanical engineering sense. These ten principles about prototypes have emerged from our research. The first three (1-3) describe the appearance of a prototype. The next four (4-7) explore the notion of a prototype as an iterative tool. The last three principles (8-10) describe the underlying nature of prototypes. Together, these ten beliefs help create a similar mental model about prototypes for students.

1) You can prototype anything. This includes products, processes, services, and experiences.
2) Prototypes can be various levels of fidelity. This ranges from rough paper sketches to fully functioning pre-production models.

3) Prototypes can be represented in many mediums. This includes digital to physical and from 2D, to 3D, to 4D.
4) Prototypes are iterative. The testing and feedback from a prototype should inform the next iteration.
5) Prototypes need feedback through specific use case exploration (purposefully testing) or user testing.
6) Prototypes need an underlying purpose. The questions and assumptions should guide the plan to create, test, reflect, and then iterate again.
7) Prototypes answer questions related to desirability, viability, and feasibility.
8) Prototype failure can always be reframed as a learning opportunity. The failure should give insights into the next decision and iteration of the design.
9) Prototypes are a tool, not just merely a stage in the design process. They should be used many times to improve the overall design, rather than a stage that you pass through just once.
10) The role of a prototype is to enable communication, inform decision making, and aid in learning. Prototypes can transcend all three roles at once.

Our research team has also developed and implemented a 50-minute lecture on prototypes in both junior and senior design courses, where we show several case studies of prototypes usage in design projects during the first half of the class. We then have the students complete an activity during the second half of the class. This lecture occurs within the two weeks after design teams and projects have been chosen. In this prototyping activity, the students work in their assigned teams on their design project. The students must outline all their assumptions about the design problem; indicate all the unanswered questions; and create a plan to prototype, test, and gain feedback for these assumptions and questions. After the lecture and in-class activity, we require an out-of-class assignment where each team must create three low-fidelity prototypes in a week and document the process to create them. This process includes listing the questions and assumptions they need answered, followed by a plan to build and test the prototypes. The assignment must show images of the prototypes they create, along with the feedback, outcomes, or decisions made from these prototypes. The purpose of the out-of-class assignment is to show students the breadth of possibility in creating prototypes early in the design process. We are happy to share these lectures and activities with any design instructor or engineering educator.

2.2.9 Summary

In summary, this is an explorative pilot study with the purpose of gaining a baseline understanding of the perceptions of prototypes from students and professionals. The two guiding research questions are: What is the perceived purpose of prototypes from both mechanical engineering students and design professionals? And are there any significant differences between these two populations' perceptions?

Our preliminary findings indicate that there are differences in perceptions and uses of prototypes between students and professionals. Mechanical engineering students are more likely to think of a prototype in a narrower sense; such as requiring that the prototype is the full design, or entire system, and only testing functionality. Conversely, many professionals with years of experience on diverse design teams, have a broad view on the purpose of prototyping. They consider sub-systems, individual components, system integration, and user experience all aspects of prototyping. These are valuable key insights into the prototype perception discrepancies between students and professionals that inform future research.

2.2.10 Future Research

In building off of this initial pilot study, there are immediate next steps in our research. We are analyzing the remainder of the survey responses and the materials collected about prototypes from the interviews. For each prototype mentioned, we note the mediums of creation, modes for testing, and underlying purposes. The goal here is to further understand how students and professionals perceive and use prototypes.

The research team also collected pre- and post- surveys on students' perceptions of prototypes after giving the prototyping lecture, activity, and assignment. We will measure the change in perceptions, which will indicate whether the lecture and activities changed the prototype perceptions of the students.

Additionally, this pilot study is part of a larger research project with the goal of understanding the role of prototypes in companies. We used the definitions of prototypes from literature and this pilot study to develop our own holistic definition. Developing this definition is critical to ensuring that we identify all the various prototypes on the design projects in the companies. From this in-depth primary research study, we aim to create a holistic framework to describe prototypes in the design process and identify some best practices of prototyping from the companies. Then, we will translate this work back to academia so that students can be better prepared for their transition to industry, thus narrowing the "disconnect between engineers in practice and engineers in academe" indicated by the NAE [26].

There is an opportunity for additional extensive research around this topic. One avenue is measuring the change in perceptions of prototypes longitudinally for students in design courses over four years. We hypothesize that perceptions of prototypes evolve during those four years, especially with an increase in design courses taken. If this hypothesis held true, then it would support the increase in design courses added to undergraduate engineering curriculum to better align students with professional practices. Another research opportunity is comparing the perceptions of prototypes between different engineering disciplines. We hypothesize that there would be differences, especially between majors that are more digital-focused, like computer engineering, compared to more physical-focused majors, like mechanical engineering. Likewise, there is the possibility of comparing perceptions of students between a range of universities across the United States and world.

2.3 Chapter 2 Summary

This chapter discussed the pilot study on perceptions of prototypes. The purpose was to gain a baseline understanding of the perceived understanding of the term from students and professionals, and to compare between them. The findings indicate that there are differences in perceptions and uses of prototypes between students and professionals. Mechanical engineering students are more likely to think of a prototype in a narrower sense; such as requiring that the prototype is the full design, or entire system, and only testing functionality. Conversely, many professionals with years of experience on diverse design teams, have a broad view on prototyping. They consider sub-systems, individual components, system integration, and user experience all aspects of prototyping. These are valuable key insights into the prototype perception discrepancies between students and professionals, which motivates the need to further understand how both populations engage in prototyping in the design process.

From this pilot study, I introduce some immediate recommendations for design education. I believe it is necessary for design instructors to be explicit about the importance of prototypes. It is not enough to just tell students to "prototype." As design educators, we must be aware of the various roles of prototypes, and teach these concepts. Part of being explicit about prototypes is describing their broad nature. I include some suggestions for broadening the term prototype to ensure that students' mental models of prototypes are expanded from the traditional mechanical engineering sense observed in this pilot study. I created ten principles about prototypes, and these ten beliefs help create similar mental models between students.

This pilot study sets the foundation for remaining chapters in this dissertation. It provides validation that there is no uniform understanding of the term "prototype". This motivates us to further understand how students and professionals engage in design, specifically with prototypes. The next chapter explores student design teams, specifically their engagement with prototypes through the entire semester and design projects. This next chapter furthers our theoretical understanding of prototypes, by building off social science theories on objects and artifacts. It introduces a new concept of prototypes as objects that coordinate design activity – through building social networks and connections and also enhancing technical skill development.

Chapter 3 – Prototypes as Design Coordination Objects

3.1 Introduction

Chapter 3 focuses on furthering our theoretical understanding of prototypes through the framework of Vinck's intermediary objects. This chapter solely uses data collected from student design teams within a university. In this study, I compare two first-year design courses as a way to uncover the importance of prototypes on design teams. In one course, prototypes were emphasized; students were required to cycle through rapid plan-build-test cycles. In the other course, prototypes were de-emphasized and rather the theoretical understanding of design was emphasized. This side-by-side comparison is important to seeing the value that prototypes add on design teams outside of just the technical skills. It is through the absence of prototypes in one class, that the importance of prototypes in the other class can be identified.

Through analyzing the use of prototypes through the framing of intermediary objects, I uncovered how critical prototypes are to social and technical skill development. I refer to this as "design coordination". Prototypes have the ability to frame students' experiences: connect them with experts, negotiate aspects of the design, communicate with the client, persuade outside stakeholders, gain feedback from judges, and more. The first study becomes the foundation for the research conducted within companies, as it furthers the understanding of prototypes as organizing objects.

Section 3.2 is the in-press journal article entitled "Prototypes as Intermediary Objects for Design Coordination" to the International Journal of Engineering Education (IJEE) [124]. This paper is co-authored with Joanna Weilder-Lewis, Daria Kotys-Schwartz, and Mark Rentschler. Section 3.2 includes all of the original sections and sub-sections from the accepted IJEE research paper. Section 3.3 offers a summary of the paper and transitions into Chapter 4, which begins to look at the data from companies.

3.2 Prototypes as Intermediary Objects for Design Coordination in First-Year Design

Design has been called one of the defining characteristic of engineering, and it has been long-argued that design is equally social and technical in practice. The field of Science and Technology Studies (STS) has a research tradition of exploring the interwoven social aspects of technical fields like engineering design. We borrow a concept from STS – the notion of *intermediary objects* – to better understand first-year engineering design teams and explain how prototypes mediate technical skill development and social relationships. An intermediary object is both a conceptual framework and an analytic tool that enables researchers and educators to identify critical aspects of design coordination. In this paper, we compare two differently organized sections of a first-year engineering design course as a way to highlight the importance of prototypes in mediating these technical and social relations. It is not until these two courses are compared side-by-side that we uncover the critical importance of prototypes as intermediary objects. Based on this comparative case analysis, we argue that prototypes are pivotal intermediary objects, which aid in students' development of their engineering skills and pathways toward becoming an engineer. This paper contributes to the field of engineering education by connecting traditions from STS and exploring how the creation of prototypes impacts design education. In doing so, we provide some immediate recommendations for organizing engineering design courses, and we indicate future research on understanding the role of prototypes in design education and practice.

3.2.1 Introduction

Engineering design is a socio-technical activity that has been studied by many social scientists [30], [77], [80], [91], [125]. Design is taken to be the defining characteristic of engineering [25], and it has been long-argued that it is equally social and technical [76], [109]. From this heterogeneous engineering perspective, design is not merely composed of social and technical elements, but the social and technical are mutually constitutive of design and must always be considered in parallel when studying and participating in design work. In this research, we seek to understand the relationships between these two facets through looking at the physical and technical artifacts created during the design process and their connection and coordination to the social networks supporting them. The framework of *intermediary objects* [126]–[128] provides us the ability to describe these social and technical connections, while also being evaluative in comparing the two design courses; we use it as both a conceptual framework and an analytic tool in this qualitative study.

The goal of this paper is to use Vinck's framework of intermediary objects to further our understanding of design coordination, particularly in design education [9-11]. Design coordination is the integration of all social and technical elements into a final artifact for a project. First-year design courses were chosen as the space for this study because they are often students' first experience participating in a project-based design course, which we believe would further emphasize key elements in design. We compare two different sections of a first-year engineering design course because the importance of prototypes as intermediary objects is emphasized when comparing them. It is through the absence of higher fidelity final prototypes in one section that the importance of prototypes is realized in the other section. The research team observed these two independent sections during the same semester in the spring of 2014, where we used ethnographically informed methods for data collection, such as participant observation.

Intermediary objects represent the intersection of social and technical worlds, and often provide a basis for common language between different people. As Vinck et al. stated, "Physical objects are also units of language and communication between humans. Things are language units. They are sometimes regarded as the only common language between people… We have to understand their capacity for coordinating humans and creating understanding between them" [128]. In our qualitative analysis, we explore how the creation of physical artifacts, specifically prototypes, manifests the connection of networks between various actors. Actors is a term from Actor-Network Theory (ANT) that includes both humans, such as the students and instructors, and the non-humans, such as the final reports and prototypes created during the design project [129]. Vinck used principles from ANT to develop his intermediary objects theory. In this paper, we examine how prototypes serve as intermediary objects between actors, specifically for students as they learn engineering design. This helps to answer our guiding research question: How do physical prototypes, as intermediary objects, further our understanding of social and technical skill development during first-year engineering design courses?

The rest of the paper will be organized as follow. First, we discuss the evolution of first-year design courses and the use of prototypes in design education. We note the need for conceptualizing prototypes' role in design education through a heterogeneous engineering perspective, and how intermediary objects are an ideal framework because of their explanatory and normative nature. Second, we describe intermediary objects, both as a conceptual framework and analytic tool. Third, we discuss the qualitative research methods, including our comparative case study approach, descriptions of the two design courses, and data collection and analysis methods. Fourth, we discuss the two case studies. In doing so, we show how prototypes are intermediary objects, and how these prototypes connect students to social and technical aspects of engineering design. Finally, we conclude with a discussion of the two cases and initial recommendations for organizing design education.

3.2.2 Background Literature

3.2.2.1 Approaches to First-Year Engineering Design Courses

First-year engineering design courses have varied over time in the United States. Sheppard and Jennison documented how engineering curriculum has changed over the last sixty years ebbing and flowing between hands-on, practical courses to scientific, theory-driven courses, as well as how instruction has differed [27], [130]. The changes in engineering curriculum are attributable to several external factors including national concerns, industry demands, and educational theory [131]. There are internal factors that have impacted the upsurge in first-year design education, such as the connection between lower attrition rates and first-year design courses [132], [133]. Additionally, there has been a push for making design the “backbone” of the engineering curriculum by integrating design courses throughout students’ entire four years [134]. This push to incorporate design courses created an upsurge of freshman design courses added to engineering curricula worldwide in the twenty-first century [130], [135], [136].

Instruction of first-year design courses has varied with common methods such as the use of full-scale projects, small-scale projects, case-study analysis and reverse engineering, as well as integrating projects with community service. The typical first-year design course includes lecture-style presentation of the stepwise refinement of design methodology. Alongside the design process theory, there is usually a project-aspect to reaffirm the lessons. Engineering educators use a variety of learning theories to inform pedagogical practice, including active and cooperative learning, learning communities and service learning [137]. Currently, the most popular approach to design courses is project-based learning, often referred to as PBL [25]. In PBL, learning is student-centered and self-directed as students work in small groups with teachers as guides, while a given problem organizes and provides the stimulus for learning [138]. In this research, PBL was the recommended practice for teaching the first-year engineering design courses we observed.

Often, engineering design education overemphasizes the technical elements of a design project, while minimizing the social processes of design [81], [109]. This is referred by social scientists as a ‘technicist’ view of engineering, where the focus of engineering is on the tangible tools and representations of projects often referred to as the “nuts and bolts” or the technical aspects [86], [139]. Contrasting this technicist view, engineering can also be viewed as ‘heterogeneous’, which believes that engineering is socio-technical. Suchman, a sociologist who studied engineering teams, describes this notion of heterogeneous engineering when she examined a quintessential engineering project – building a bridge [80]. During this project, she found that social processes are not merely an important aspect of the design separable from the technical; rather, the design of the bridge represents the mutual constitution of material and social relations through the production of a stable artifact – the documents and technical drawings that represent the bridge itself. We use this latter mindset during our research; a heterogeneous engineering perspective on first-year design courses shows how the social and physical elements of design are inextricable, a perspective not yet heavily applied in engineering education. We use a conceptual tool closely tied to heterogeneous engineering – *intermediary objects* – to operationalize the use of prototypes in the first-year design courses.

3.2.2.2 Prototypes in Design Education

Prototyping is an integral part of the design process; prototypes are recognized as important milestones on projects within design education [39]. They are usually required as the final output of a design project, even in first-year design courses. As Diegel and Potgieter stated, "engineering students are often expected, as part of their course, to produce physical artifacts that demonstrate their ability to apply the knowledge that they have learned" [140, p. 357]. Prototypes are more than just a final artifact; they are the embodiment of the knowledge of the student and the learning from the course project. We define a prototype as any physical or digital representation of the intended final design that serves as an object for communication, learning, and/or decision-making.

Several researchers developed prototyping strategies and frameworks to aid students [2], [15], [18], [19], [55], [57]. It has been shown that students have varied understandings of the term prototype [57], [59]. Lauff et al. compared students' perceptions to professional engineers and found that there are discrepancies between the two groups; students in mechanical engineering tend to have a narrower view of the term prototype, and often believe that a prototype must include testing a full system or product [59]. This contrasts professionals, who view prototypes as varying between components, sub-systems, and the full product. Researchers like Menold et al. have developed prototype frameworks to aid students in developing similar mental models about prototypes, while providing details to build and test multiple prototypes [19], [57]. In their model, "Prototype for X" or PFX, each prototype goes through a frame, build, and test cycle. They tested this framework with junior-level mechanical engineering students developing drill-powered vacuum-cleaners, and findings from this work suggest that a framework with supporting strategies aids novice designers in creating prototypes.

Design instructors have the freedom to teach prototyping their own way. Many instructors use guidelines from engineering design textbooks [39], [141], while also integrating their personal experiences. Most instructors know the importance of prototyping, and often encourage students to rapidly build and test their ideas. Since prototypes are an essential part of the design process and of design education, we believe that further research around the topic is necessary. It is the goal of this paper to explore the role of prototypes on first-year design teams, and uncover how they aid in design coordination.

3.2.3 Intermediary Objects: Conceptual Framework and Analytic Tool

In this research, intermediary objects are used as both a conceptual framework and an analytic tool. As a conceptual framework, it highlights the intertwined and mutually constitutive social and technical aspects of the design process. As a data analysis tool, it operationalizes prototypes, exploring their ability to mediate technical skill development and coordinate the building and strengthening of social networks critical to the design project.

Intermediary objects are artifacts that are produced during the design process and either mark a transition from one stage of the project to another or else coordinate meaning between groups of actors [128]. The object is intermediary in the sense that it "represents the network, by being both visible and standing for it, and translat(ing) it in time and space" [142, p. 335]. In engineering design, these objects often take the form of textual documents, technical drawings, and physical artifacts. Being intermediary means that the object acts as a link between people in order to try and bring about an agreement; it acts as a mediator. For example, a technical drawing of a product acts as a mediator between different groups of people, like the engineers and manufacturers. The technical drawing also marks a distinct point in time, such as the transition between different stages of the design process from two-dimensional concept development to manufacturing the three-dimensional artifact.

Vinck et al. further describe the term intermediary objects in this excerpt: "Intermediary objects are representations of a final, absent object. They are supposed to be objects that can be communicated and exchanged between design partners. Their goal is to improve exchanges, enable viewpoints from various trades to be expressed and compromises to be achieved. When design is shared out between different designers, the circulation of these objects becomes the place for constructing (dividing and integrating) collective action" [128, p. 299]. This expands further on the idea of intermediary objects in that they are a glimpse of what the final object/product will be, which is "absent" at this point in time. The intermediary object lets you peer into the future and imagine what the final design might encompass. These objects also serve an important role in understanding the collective actions of multiple people during a design project: all of the viewpoints and compromises that must be made.

The framework of intermediary objects draws on Actor-Network Theory, which views material objects as equal and important actors. They are like the "social glue" that helps set or prescribe the order of social relations [143]. In Suchman's article examining a bridge building project in California, she found that the design of the bridge represents the mutual constitution of material and social relations through the production of a stable artifact [80]. All of the technical drawings and architectural models were this "social glue" that facilitated the vast social networks between engineers, government, building contractors, and more. In one of Latour's articles, a primary developer of ANT, he explored the design and development of a futuristic personal transportation device, named Aramis, and found that the project failed due to the inability of the actors to negotiate and adapt to changing social situations [144]. In this work, it could be argued that the lack of physical representations of this "futuristic device" caused a lack of the strong "social glue" needed between the various people required to make the project succeed – the engineers, designers, builders, government agencies, and more. In both of these examples, the social elements of design are critical to the success of the project. These objects – textual, digital, or physical – mediate these interactions between people and act as the "glue" that can help accomplish the design task. They are the critical intermediary objects.

There are many ways in which intermediary objects can coordinate, mediate, and facilitate social interactions. Vinck et al. describe six coordination attributes of intermediary objects, which are helpful in further understanding their innate attributes and behaviors [127]. These attributes are embodied in all intermediary objects. However, some attributes can be stronger in their representation than others.

1. Representation in retrospect: The object can look back in time at the decisions made to the current state; it is a reflective embodiment of all activity to this point.
2. Perspective representation: The object represents what is desired in the final object.
3. Commissioning: The object carries the intentions of the authors.
4. Mediation: The object transforms the intentions of the authors.
5. Prescription: The object imposes choices and decisions on their users.
6. Facilitating interactions, confrontations, and interpretations: The objects facilitates multiple forms of communication, including compromises.

As mentioned, intermediary objects can range from textual documents, technical drawings, and physical artifacts. Although each of these objects are important, we focused on just one – the physical artifacts, which are one type of prototype. By analyzing these physical prototypes as intermediary objects, we sought to answer our research question: *How do physical prototypes, as intermediary objects, further our understanding of social and technical skill development during first-year engineering design courses?* Next, we discuss the qualitative research methods for how we collected data and analyzed data from the two courses using this framework.

3.2.4 Research Design

Qualitative and interpretivist research is increasingly prevalent in engineering education research [145], [146]. Qualitative methods are used in engineering education research to further understand design practices [147], particularly in the study of how students engage in the study of design [148], [149], as well as how instructors enact curriculum to support the learning of design [150]. Interpretive research investigates the local meaning of action in order to draw a comparison to broader phenomena [151]. Examining the particularities of two first-year design courses increases our understanding of undergraduate engineering design not by generalizing from each but, rather, by articulating how each is unique. In comparing the two courses' development of physical prototypes through the framework of intermediary objects, we are able to see how the lack of prototypes in one case enhances our understanding of the importance of prototypes in the other case.

3.2.4.1 Case Study Method

A case study is an empirical inquiry into a phenomenon that underscores the importance of contextual conditions in understanding the case [46]. Each case presented here attempts to further our understanding of students' social and technical skill development in first-year design courses; the description of a case becomes a measure from which we can gauge our understanding of undergraduate design practices. Each course has particular features such as its facilitation and structure, that when compared to the other course gives meaning to the larger phenomenon of first-year design education. Case studies provide a way of both "seeing" and "not-seeing" design, and the absence of design elements are acknowledged through comparison. The courses we chose to study were selected because they differed with respect to by whom and how they were taught, the student make-up of the course, and the emphasis of particular design elements. This approach to research is instrumental in both examining and expanding our theoretical understanding of design. Case studies are also helpful in engineering education because they can help to translate empirical findings to other similar cases, while building a deeper understanding of design practices [152].

To establish credibility in this study, we provide detailed descriptions of our research setting below, used multiple sources of data, triangulated our data, and performed member checks across the research team [153]. We observed both design courses throughout the entirety of the semester, and we used multiple forms of evidence including video observations and audio recordings of students' work and class lectures, interviews with the students, teaching assistants, and instructors, and collection of the course artifacts, including materials created by the instructors (e.g. syllabi, grading-rubrics) and materials created by the students (e.g. sketches, presentations, reports, prototypes). All of this data further supports the trustworthiness of the study, as we aimed to gain a well-rounded description of design practices [154], [155].

3.2.4.2 Research Setting: First-Year Design Courses

This study examines two sections of the same first-year engineering design project course, which we refer to as Course 100 and Course 101. This university enrolls approximately 900 engineering freshmen each academic year; it has a program and physical space dedicated to the teaching and learning of engineering, named the Center for Engineering and Teaching Excellence (CETE). CETE organizes and oversees all sections of the traditional first-year engineering design courses. CETE is both a center that conducts research, outreach, trainings, and support of first-year design courses, and is also a physical space on campus that includes classrooms, experimental labs, machine shop, offices, study spaces, equipment checkout room, and rapid prototyping tools. An experimental section of first-year design was introduced during spring 2014, and it was labeled Course 101 to differentiate it from the traditional Course 100. This experimental course, on paper, is considered equal to the traditional first-year design course: they both are 3-credit-hours and fulfilled the freshmen project College of Engineering requirement for most majors.

The experimental Course 101 was organized to serve students participating in a newly formed living and learning program, focusing on international engineering challenges called the International Living and Learning Program (ILLP). In this program, students lived in the same dormitory with a faculty mentor and attended several shared classes. Living and learning programs attempt to integrate students' experiences both in and out of class by providing a community that allows for faculty and peer interactions, with the hope that it creates an academically and socially supportive living environment [156], [157].

CETE has synthesized engineering education best practices, as defined by its directors and current research team, and created an introductory textbook for Course 100 instructors to use. This textbook reflects many of the ideals of the National Academy of Engineering [26]. CETE also hosts weekly meetings for

Course 100 instructors to share best practices. Instructors for Course 100 vary across the College of Engineering; they include Assistant and Associate Professors, Lecturers, Postdoctoral Researches, and Graduate students. Although CETE recommends best practices for the course, instructors are free to organize their specific sections around their preferences. The Course 100 observed integrated all the best practices, from team formation to skills-based workshops. The instructor of Course 101 did not attend these weekly meetings, and as such did not implement most of the recommended practices into their section. A table summarizing the two first-year design courses is seen in Table 6.

The participants in this study include the instructors, teaching assistants, and students of both sections of Course 100/101, as well as support staff, guest lecturers, and all the human and non-human resources. Human resources include people like the machine shop manager, electronics shop manager, local hardware store employees, and guest speakers on topics like Arduinos and technical writing. Non-human resources include software programs like SolidWorks and physical tools like breadboard circuits and rapid prototyping equipment (i.e. 3D printers, laser cutters). The traditional Course 100 had one instructor, two teaching assistants, and thirty students, which is standard across all Course 100 sections, while the experimental Course 101 had one instructor, one teaching assistant, and forty-five students.

At this university, both Course 100 and 101 are 16-weeks long and a first-year introduction course to engineering design using a project-based learning approach. Instructors provide the students with open-ended challenges, and the students then work in small teams to solve the problems. Both courses provided an introductory project first, followed by the main project second. However, these projects were structured differently between these two sections in terms of duration, scope, and final deliverables. Here, we examine and compare the two syllabi.

- Course 100 syllabus: *"The Introductory Project is meant to get newly-formed groups working together in a small project aimed at improving the packaging of a children's toy… The Main Design Project will enable you and your team to explore basic engineering concepts to design and build a fun-filled playhouse for a child with a physical disability and his little brother... Groups will develop prototypes and a final product aimed at meeting the customer's needs."*

- Course 101 syllabus: "This *Engineering Projects [course] will provide students with an overview of the concerns and opportunities facing designers in the engineering industry... In this course, students will get an overview of the broad set of issues that influence engineering projects. Through the use of both* <u>*traditional problems and case studies*</u>*, students will be introduced to decisions related to infrastructure, built environment and global factors and the uncertainty related to such projects*."

Table 6. Descriptions of the two First-Year Engineering Design Courses

	Course 100: Traditional Section	**Course 101: Experimental Section**
Course Name and Number of Credits	Engineering Design First-Year Projects Course, 3-credits	Engineering Design First-Year Projects Course, 3-credits
Instructor	1 Senior Instructor in Civil Engineering (female)	1 Associate Professor in Civil Engineering (male)
Teaching Assistants	2 masters' students in Mechanical Engineering (male)	1 PhD student in Engineering Education (female)
Course Days and Time	Mondays and Wednesdays for 50-min., Fridays for 75-min.	Tuesdays and Thursdays for 75-min.
Course Location	Course 100 classroom in the Center for Engineering Teaching Excellence (CETE)	Dormitory all-purpose room, part of the Integrated Living and Learning Program (ILLP)
Number of Students	30 students	45 students
Course Textbook	*Introductory Engineering Design:* *A Projects-Based Approach* by CETE researchers	*Design thinking: process and methods manual* by Robert Curedale
Design Projects and Duration	1) Intro Project (3-weeks) - create a spill-proof bubble container 2) Main Design project (10-weeks) - create an interactive light display (LED-matrix) for a child's playhouse	1) First Project (9-weeks) - create a physical model of a sustainable health community 2) Second Project (6-weeks) - create a representation of the sustainable health community (water bottle to track H2O consumption through LEDs)
Required to Attend Final Engineering Exposition	Yes	No

From Course 100's syllabus, it is evident that designing and building prototypes is critical to the course. The creation of physical artifacts is a core requirement and final deliverable. The syllabus also mentions utilizing the students' developing engineering skills, which is reinforcing the technical elements necessary in design work. This is contrasted with experimental Course 101's syllabus, which emphasized decision-making at a broader scale. The Course 101 syllabus does not describe any objects, like prototypes, that were to be engineered, nor does it mention the two projects that are required in the course. The syllabus does mention the importance of considering multiple issues while designing, including economic, technical, and social factors.

We compare these two sections of first-year engineering design because of the different number and quality of prototypes developed between the two cases. It is clear from the descriptions of the syllabi that the courses are inherently different, especially in their approach to teaching the design process. This comparative case study helps us answer our guiding research – *how can physical prototypes, as intermediary objects, further our understanding of social and technical skill development during first-year engineering design courses?* – by identifying the role prototypes play on both design teams in the two courses. Through our analysis using the intermediary objects framework, we saw the importance of prototypes in mediating skill development and relationships, or design coordination.

3.2.4.3 Data Collection: Participant Observation

As a research team, we engaged in participant observation in both Course 100 and 101 for the duration of the spring semester, which was three hours a week for 16-weeks totaling over 96 hours. Two members of the research team attended every class, workshop, and review session with the classes. The researchers drew from qualitative research techniques for doing fieldwork [158]. These techniques include both direct and indirect observational methods to capture elements of participants' activities surrounding their design project. During observations, we video-recorded the classroom and wrote field notes both during and after the class. When students travelled outside of the classroom, for example to the machine shop, we followed them and would audio record conversations. We also audio recorded and wrote field notes for five weekly CETE instructor meetings, informally interviewed the instructors during class time, as well as interviewed both the teaching assistants and the co-directors of the CETE. Additionally, we collected course documents such as syllabi and handouts, grading and scoring rubrics, as well as student end of the semester course evaluations.

Since the courses were held in different buildings, our observations took place in two locations. We observed Course 100 in the CETE building, which is a purposefully designed teaching and learning space. In this building, there are classrooms designed specifically for the first-year engineering courses. They are designed with both the lecture and hands-on activities in mind. The CETE building connects directly to the College of Engineering Center, and houses a machine shop, rapid prototyping lab, experimental testing facilities, woodworking space, and electronics lab, among other resources. Conversely, we observed Course 101 in a multipurpose room in a residential academic program building. This building is where the students from ILLP lived and took this first-year engineering design course. The building is a half-mile walk to the engineering center, and the students in Course 101 were allowed to use all of the facilities there.

The actual structure of the two different classrooms impacted how students worked on teams and how the researchers were able to engage in their participant observer roles. For example, in Course 100 the students would travel within the same building to attend workshops or receive help from engineering experts. There was also workshop space to build prototypes in the classroom. In Course 101, the students had to travel approximately 15-minutes across campus to receive engineering help from experts, and they had to work on the floor of the conference-style room when building their prototypes. This required more planning by the students to venture across campus during a working-class session. As participant observers, the researchers become integrated into the lives of the students on the design teams. They attended each of the classes, sat with the student teams, and traveled with them as they attended workshops or sought advice from experts. This provided the researcher the chance to observe general aspects of the two completely separate buildings, and how the resources both within the building and externally impacted the design teams.

3.2.4.4 Data Analysis: Comparative Analysis through Intermediary Objects

Our analysis was guided by the theory of heterogeneous engineering, explicated prior, in that we attended to moments in our data where the interconnection of technical and social elements of design were evident [3]. For example, we analyzed segments of data when there were heavy social interactions (i.e. team discussions, expert workshops, trainings) alongside technical creations (i.e. applied workshop activities, building prototypes). We engaged in constant comparative analysis, using the two distinct cases to compare to each other [159]. Data collection and analysis were simultaneously performed during the semester when the data was collected, and then analysis continued over the following two years. The data analysis for this project has been on-going for three years as this project is part of a larger research project exploring the similarities and differences between student design courses and professional workplaces [110], [111].

During analysis meetings, the researchers used theoretical sampling, which is the process of selecting relevant pieces of data to discuss as a group to build understanding. The primary researchers chose the segments of video to present to the whole research team. For example, the primary researchers would pick a 15-minute segment from the past week where students were attending a workshop on Arduinos and then applying these skills to their design projects or building their prototypes. During the semester of data collection, analysis occurred by re-watching these recorded video segments from the two courses as a research team, and then discussing the innate similarities and differences through the heterogeneous engineering framework. We kept a log-book of the data we discussed at each meeting, the important actors, both human and non-human, and their interactions with timestamps from the video.

Following the semester of data collection, we transcribed portions of the classes and interviews with students, instructors, and teaching assistants. The researchers, then, used a combination of re-playing audio and video files, along with reading through transcriptions during the continued data analysis meetings. We noticed that the experimental design course, Course 101, had significantly less physical artifacts created by the students, and as such we turned our analysis to focus on the importance of this. To further explore the importance of physical artifacts, we employed the framework of intermediary objects in our analysis. We divide intermediary objects into three major categories: textual documents, technical drawings, and physical artifacts. In Table 7, we list examples of the various types of intermediary objects that were identified in the two engineering design courses. However, as indicated, we focused on the creation of prototypes, which is considered a type of physical artifact. We believe that isolating one type of object can more clearly discuss how these objects mediated social connections between the students and other important human actors.

For this research, a prototype is considered a physical or digital embodiment of critical elements in the final design [160]. As such, prototypes can range in levels of fidelity and complexity as well as through diverse mediums. In Table 7, we list several physical artifacts, which range from low-fidelity prototypes to higher-fidelity prototypes. For simplicity, low-fidelity prototypes require less time, materials, or resources to create compared to higher-fidelity prototypes. Since design is an iterative process, prototypes often evolve from this lower-fidelity state to a more refined higher-fidelity state as the timeline for the project advances. Students are often expected to deliver a higher-fidelity prototype, or final product, at the end of their design courses. We decided to focus solely on the prototypes created in these courses, with specific attention to the final prototypes.

After deciding to focus on the prototypes as an intermediary object, we then looked for moments in the data where prototypes were present. We coded these moments deductively according to the six attributes of intermediary objects detailed by Vinck including: representation in retrospect, perspective representation, commissioning, mediation, prescription, and facilitating interaction, confrontation, and interpretation [10]. We then looked for patterns across the codes and were able to identify three central phenomena where prototypes were significant for students' intertwined social connection and technical knowledge and skill development in design. These included the connection with experts, the social networks within the class, and the participation – or lack thereof – in the final design exposition.

Table 7. Intermediary objects in the first-year design courses

	Course 100: Traditional	Course 101: Experimental
Textual Documents	Syllabus, project brief, reflective journal entries, table of costs (BOM), final poster, final report	Syllabus, project 1 brief, project 2 brief, homework writing assignments, writing segments for professional writer, final report
Technical drawings	Hand sketches, PCB schematic, LED-matrix layout, CAD 3D model	Hand sketches
Physical Artifacts	Spill-proof bubble container, breadboard of electronics, PCB, LED-matrix cube, finished playhouse	Model of city, plastic water bottle

3.2.5 Two Case Studies of Prototyping in First-year Design

In this section, we describe the two first-year design courses under study and emphasize how the prototypes, as intermediary objects, coordinate the connection to different social networks along with their enhancement of technical knowledge. Both of these cases are described fairly in-depth, which is a guiding principle for reporting ethnographic work [161]. We present each case fully before taking up points of comparison in the Discussion.

These cases appear mostly in chronological order from the beginning of the semester when the projects start to the final College of Engineering Design Exposition to create a more coherent story. We describe one team's development of the final prototype for Course 100 and one team's development of two prototypes in Course 101, as this latter course put equal value on each prototype. In doing so, we highlight the importance of the various workshops and lectures along with the social networks within the classroom and how all of these people helped in the creation of the final prototypes. We also mention the materials used in the prototype, the different experts utilized in creating the final prototype, and the culmination of all the work into the final College of Engineering Design Exposition.

3.2.5.1 Course 100: Traditional First-Year Engineering Design Course

The instructor stated at the beginning of the semester, *"the most important learning objective [in this course] is to understand and apply the design process. That is, design, build, evaluate, and repeat until the desired results are obtained."* As such, the instructor emphasizes creating and iterating on prototypes. The first three-weeks of the course were spent teaching the students the design process; they participated in a short introductory project where they were challenged to create a bubble container that would not spill. This is the first prototype that students were required to create, and it was low-fidelity due to the short timeline for the project. This project introduced students to the design process and increased their comfort when working in teams. After this introductory project, the students began the main ten-week long project, which was the design of a children's playhouse. In this project, the teams were expected to define, budget, iterate, and construct a final product to present at the College of Engineering Design Exposition. The final project counted for 50% of each student's grade.

3.2.5.1.1 Prototype for Main Project

We observed one team in this section of Course 100 that was responsible for developing two sensory devices for a playhouse. This playhouse was to be designed for both disabled and able-bodied children, and the final product – the playhouse – would be implemented into the client's (a local family) basement. The team we observed consisted of five members. After brainstorming ideas, the team decided to develop two different LED light displays as their sensory devices. The first sensory device was a motion activated light strip that would light up an area within the playhouse. The second sensory device was referred to as the LED-matrix, which was created to add a level of aesthetics to the playhouse and be an interactive toy for the children in the playhouse. The LED-matrix was a three-foot by three-foot plastic-encased LED display that showed different patterns and colors when activated by a large button easily pushed by a child. The team divided into sub-groups to work on each sensory device. We followed the sub-group working on the LED-matrix more in-depth and continue to report on that team.

3.2.5.1.2 Expert Connections through Workshops & Guest Lectures

Throughout the entire semester, students were expected to attend multiple skill-building workshops, including laser cutting, manufacturing, power tools, SolidWorks (3D computer-aided design program), electronic circuits, and using Arduinos (microcontroller) among others. In addition to workshops, the professor arranged for multiple guest speakers to attend class. They included the main project's client, a machine shop supervisor who provided feedback during a design review, the electronics shop manager, engineering education specialists who discussed team dynamics and social styles, and various experts on building construction including a structural engineer, an expert in lighting, and a lecturer on aesthetics. Each of these workshops and guest lectures was a chance for students to learn new technical knowledge, and also a way for them to be introduced to experts in the College of Engineering and local community resources.

During our analysis, it became evident that each of these "introductions" to subject-experts through personalized workshops and lectures were pivotal to the students' final design projects and the creation of the final prototypes. These workshops gave the students an opportunity to learn new technical skills, like how to program an Arduino, and then connect them to a local person (often from CETE) to associate with that skill. For example, during the fourth week of the course, the electronics manager gave an in-class workshop on circuits. He began his lecture by stating, "*I am not here to make you an expert. I am here to tell you about circuits and actuators."* Later, he tells the students, "*I am a mentor to help you make use of electronics and get you over any hurdle [in this course or others]."* Similarly, the instructor told the students that these workshops were "*to prepare*" the students to work on the playhouse, and that she was not expecting the students to immediately become experts. However, she knew that students would require certain skills to move forward on the design of the playhouse. By introducing the "expert" (i.e. CETE electronics manager) along with "tool(s)" (i.e. Arduino, circuits, LEDs), the social relationship was made explicit alongside the technical importance of the object; but neither was possible without the other. In this course, we observed how the LED-matrix team was introduced to circuits, electronics, and Arduinos in workshops with the electronics manager, and then how they were later able to identify the in-house CETE experts by name and use them as a resource and connection in developing their final prototype.

The LED-matrix team leveraged resources in the CETE to assemble materials and construct elements of the final prototype. Within the CETE, the team made a wooden base and acrylic box cut to specific dimensions for the LED-matrix. None of the team members were initially confident with their machining skills. One member mentioned their lack of confidence in machining in an interview, saying, *"I'm an idiot when it comes to machining. I don't know what's going on. He [the machine shop manager] helped us a lot with just basic stuff, like how to use the table saw."* Another team member spent many hours in the electronics shop soldering the LED strip. This person told us in an interview that, *"when it finally came down to programming the Arduino that we used, I just basically went to Tom [the CETE electronic center manager] and was like, 'I have no idea what I'm doing. Help me out.' He helped me out through it all, and he was pretty excited to do it, so that was nice."* These are just two example of how the students on the LED-matrix design team used the creation of the final prototype to mediate and leverage the different social interactions and technical skills necessary to complete the project.

The materials for the LED-matrix were acquired both on and off-campus. The prototype, and the materials required to create it, mediate connections between the students and these suppliers, distributions, or similar. This team went to a local hardware store to purchase acrylic, as well as to an electronics store to purchase an Arduino. They ordered an LED strip online from an electronics website, and then also purchased wire from the CETE electronics shop. They found scraps of wood for the base from surplus in the basement of the CETE. In an interview with one of the LED-matrix team members, they remarked that *"it was important for me to know whom to contact for help"* and that they *"routinely asked the CETE equipment manager for advice."* In building the prototypes, the students were connected to new experts and resources on-campus, in the local community, and to online communities. These connections to resources, like the equipment manager, became critical to the creation of their final design.

3.2.5.1.3 Social networks within the class

The relationships developed amongst the team, entire class, instructor, and TAs influenced each of the design projects and the prototypes created. We saw how the LED-matrix team leveraged different skills between their team members. For example, one team member found a set of blueprints for the LED-matrix design online: a 10-by-10 array of LEDs programmed by an Arduino to display different colors and patterns. The rest of the team used this person's initial research and benchmarking of a product to inform the direction of the design. In order to design the final LED-matrix, the three sub-teammates had to leverage expertise from each other and other human actors. One of the team members was an emerging expert in beginner electronics, and the rest of the team leaned on him for guidance throughout the project.

Additionally, the LED-matrix idea and prototypes had to be vetted by the class and the instructor during in-class design reviews. In these reviews, the instructor and teaching assistants provided feedback to the team to improve their design. The team was required to present multiple times on their design throughout the semester including their initial design idea, a request for materials, and two design reviews. The prototype acted as the object that connected each design team to the instructor, teaching assistants, and class in each of these reviews. The conversations and feedback circled around the physical object for each team.

These interactions amongst the entire class occurred due to the size of the section. The CETE co-director described the class size in an interview, *"each section [of Course 100] is around 30 students. It is very intentionally kept small. That size is about right for the sort of interaction that we want."* This is a powerful statement by one of the CETE co-directors because it shows the intentional nature of the design course to truly mediate these social relationships or types of interactions. In Course 100, we witnessed the power of students being able to use their teammates, classmates, instructor, teaching assistant, and workshop and guest lecture speakers in meaningful ways for their design projects. They leveraged these social connections to gain knowledge about key elements, like circuits from the electronics manager, and integrate this technical information back into their prototype.

3.2.5.1.4 Design Exposition

After the LED-matrix was constructed, the team had to coordinate with the entire class to mount the interactive display in the playhouse, which was the final product from the class to the client. This is a unique challenge for a design course, the added element of organizing all the design projects together into one final playhouse. It required the individual teams within the class to develop relationships with one another, and inform, negotiate, and persuade each another throughout the project timeline. Additionally, the playhouse needed coordination to be displayed at the final Design Exposition and then transported to the family's home.

The semester culminates with the College of Engineering Design Exposition in the CETE. This is a mandatory part of the class, and factors into a significant portion of the students' grades. On the day of exposition, the teams are expected to have a formal poster that is professionally printed, a short pitch prepared for the judges, and a working final prototype. At the Exposition, a panel of judges coordinated by the CETE evaluates each team across all sections of Course 100 with an identical rubric. The experience of attending the Design Exposition, connects the student teams to the larger engineering community. There are professors, students, engineering professionals, and community members there. The event takes place over three-hours, which gives the teams an abundant amount of time to pitch their project and network with those who stop by their booth.

3.2.5.1.5 Course 100 Summary

It is evident that the creation of prototypes in Course 100 led to the connection of many human actors, each who played a critical role in the creation of the team's LED-matrix prototype that was then integrated into the final playhouse. In particular, the design of the LED-matrix involved the coordination of people, materials, resources and tools: all of which extended beyond the classroom walls and, yet were informed by the intent and structure of the design course itself. At every turn of the project, a different set of socio-technical resources were leveraged. Understanding the design of the LED-matrix required an appreciation of much more than the materials and steps taken by individuals on the team. Any description of the design of the LED-matrix without an account of this coordination inside and outside of the classroom would be an impoverished account. This is significant not only for the description of the design, but more importantly for an appreciation of how student design projects occurs and how design instruction can be organized to facilitate, or not, networks of opportunities for students. The CETE is a network of opportunity for engineering design courses, the extent to which is appreciated when compared to a section taught outside its confines and without the same rigor and expectation of prototypes.

3.2.5.2 Course 101: Experimental First-Year Engineering Design Course

The instructor of Course 101 stated that, *"the objective of this course is to introduce topics related to decision making in engineering design"* and to allow students *"an overview of the broad set of issues that influence engineering projects"* as well as adopt the theme of *"learning from the past."* Students were expected to complete two projects, each worth 30% of their grade. The projects were meant to reinforce theories of design and incorporate design thinking skills in favor of instantiating the iterative design cycle of plan, build, evaluate, and repeat; the focus was on the design and build components, not the evaluate and repeat ones. Each project was to take about six weeks in the syllabus, although the projects ended up lasting nine-weeks for the first and five-weeks for the second. The overall theme for both projects was "design of a sustainable community." We discuss the prototypes for both projects because they were given equal-weight in this course compared to Course 100.

3.2.5.2.1 Social networks in the class

Since Course 101 was part of a living and learning community, this enhanced the personal relationships between the students, instructor and teaching assistant in the course. The first project was based on a hypothetical design of a sustainable community. At the beginning of the project, the instructor and teaching assistant listed on the whiteboard all of the elements they believed were necessary to build a successful community including: healthcare, education, food supply, and others. Each team then chose one of the different areas to be their focus for the semester. One team argued that security and defense were important elements of a successful community; the instructor agreed and let them add this to the list and select this as their focus. The purpose of this exercise, and many like it, was to engage the students in debate and conversation with one another to learn how to come to reasonable decisions in design. These activities enhanced the communication between the human actors within the course.

We followed the healthcare team, and report here on their two prototypes. The team consisted of four students, two of which were roommates, and all four were friends. Simply by being roommates, the team had a deeper level of connectivity than other design teams in Course 100. Additionally, in a follow-up interview with the teaching assistant, we learned that several students from the course were hired as undergraduate researchers in the instructor's research lab after the semester ended. This demonstrates the strong social connection between the students, instructor and teaching assistant, which results in additional benefits and a certain trajectory for the engineering undergraduate students [162].

3.2.5.2.2 Expert Connections through Workshops & Guest Lectures

Each week the instructor planned lectures that presented an overview of a topic such as "ancient world design and engineering" and "modern engineering design." There was one planned guest lecture, which was for a professional writer who spoke about the importance of writing in engineering. This professional writer gave the students feedback on their writing three times during the semester. There was one last-minute workshop added on circuits/electronics during Week 6, when the instructor realized that the students needed to learn more electronics to aid in their first design project. The instructor decided to add a last-minute requirement to the project, which required each "townlet" to light up one LED. In adding this requirement, he needed the CETE electronics manager to come teach a workshop to the class on circuits, electronics, and Arduinos.

This one workshop given by the electronics lab manager highlights the significance of introducing subject-area experts to student design teams. After this workshop, the students were more confident in their ability to light up the LED required in the first project. This electronics expert came back again when the students develop the prototype for the second project. Additionally, the students were connected to the professional writer. This was a valuable relationship, since it improved the students writing and connected them to an expert in the field. This relationship helped the students in compiling their final report for the project, which is a textual document and also a type of intermediary object.

3.2.5.2.3 Prototype for First Project

The healthcare team decided to build a model of a hospital, their "townlet", as part of their contribution to the sustainable community. In doing so, they were to focus on the conceptual features needed for the community rather than the specific details. For example, he said they needed to account for lighting but not necessarily an exact number of lights. At the end for the fourth week, the instructor told the students he was giving them the *"last piece of the puzzle [for the project,"* the location for their community. He brought in a topographical map of a nearby town to use as a model for the students' hypothetical community. The original intention was to make a replica of the town on an eight-foot by four-foot board, in which each team would design a one-foot by one-foot section and then collaborate together. Each team had to ask for a particular part of topography (i.e. flatland, access to water, in the mountain or valley), and they would build their portion of the sustainable community there. After a few weeks, the instructor decided that it would be too difficult to scale all of the different projects, so each team was to make a model on a separate one-foot by one-foot board. This model of the team's healthcare community serves the role of the final prototype in the first design project.

The teaching assistant was tasked with getting supplies and materials for the creation of each team's model. Instead of requesting materials, the TA bought generic arts and crafts supplies and distributed them to the teams. She brought the healthcare team foam core, exacto-knives, tempera paint and a drop cloth;

she also bought them a miniature toy helicopter and ambulance to represent the "healthcare" elements. For the next five weeks, students alternated between in-class lectures and working on the model. The students working on the healthcare portion of town claimed the space in the hallway in front of the classroom to work on their project. They would spread out the drop cloth to cover the hallway carpet they were working on, cut pieces of foam core, and paint them while conversing with one another. While the team painted their hospital, students from other teams would often come to ask to borrow supplies such as a hot glue gun or scissors. When the team finished class each day, they took the project to the two roommates' shared dorm room.

3.2.5.2.4 Prototype for Second Project

After the initial project was presented, students were told that they would need to develop a technological solution to a problem in their chosen field. This served as the second project, which was labeled the "innovation" project. The teams were allowed to reorganize themselves, but the healthcare team decided to remain the same. After a week of deliberating, the healthcare team decided to develop a water bottle that digitally displayed how much water you have consumed, citing that 75% of Americans are chronically dehydrated. The final prototype and presentation was to be submitted three weeks after they presented their initial idea.

The team's initial idea was to use a magnetic or light sensor with a flow meter in the mouthpiece of water bottle. Upon realizing they had limited time and understanding of electronics, the team decided to create a water bottle that lights up LEDs based on the electronic lab managers' presentation. Their final design lit up one LED each time the water bottle was filled. When the water bottle is filled four times, the person has reached the recommended consumption of 64-ounces. The team presented a water bottle attached to an Arduino with three LEDs that light up during their final presentation to the class. One of the team members called the project a *"success"* even though the water bottle was subject to malfunctions, stating, *"in spite of all of these shortcomings, I believe that we achieved quite a bit considering our* *limitations and constraints"* and *"I gained some insight into the world of electrical engineering and Arduinos."*

The integration of an Arduino, LED, and sensors in the final prototype of the water bottle for the healthcare team is an important moment in the culmination of the prototype embodying social and technical elements of design. The team leveraged the electronic manager, their only technical workshop and resource introduced to them. The team then felt comfortable enough to leave the ILLP building, venture to the CETE, and learn more from the electronics manager more details required to develop the electronic components of this final prototype. This prototype mediated the social networks of the students to allow them to complete the technical elements of the prototype.

3.2.5.2.5 Design Exposition

Towards the end of the term, the instructor had students vote on whether they wished to participate in the College of Engineering Design Exposition. The majority of students elected not to participate, thus none of the class participated. Since the class did not participate in the exposition, they did not need to create a final higher-fidelity prototype to bring to that exposition nor create a final poster or pitch presentation. Their final prototype was the water bottle connected to the Arduino. Because this course did not attend the final exposition, they were unable to network with fellow engineering student students, instructors, subject area experts, CETE employees, and community members. This limited them in broadening their social network in engineering, which impacts their trajectories in becoming an engineer [60].

3.2.5.2.6 Course 101 Summary

Just like in Course 100, the two prototypes that the healthcare team designed represented the coordination of people, tools, and resources. The resources needed to construct the hospital were provided by the teaching assistant with a few being obtained from the CETE (i.e. Arduino, sensor, LEDs). When the electronics manager presented a workshop on circuits to the class, the instructor was providing another resource to his students. The healthcare team could not have presented their water bottle prototype without the assistance of him. All of the students had to work together to discuss the creation of the model town, and therefore had to work together in a symbiotic nature. The prototypes in this course, although both were lower fidelity, still connected the students to different social networks and the technical knowledge associated with these networks.

3.2.6 Discussion

For both courses, we illustrate in narrative-form the two case studies and how the design of prototypes are products of socio-technical coordination. There are many facets of Course 100 that can be compared and critiqued with that of Course 101; we knew that there would be differences prior to beginning our observations, but we wanted to use these courses in comparison to highlight aspects about design that we may not have considered just observing one section. By using a heterogeneous perspective and intermediary object framework, we can begin to articulate the importance of objects, like prototypes, in mediating the social and technical elements of design work.

The creation of the prototypes in both first-year design courses mediated the relationships between the students and other critical actors. The act of planning, building, and testing the prototypes reinforced technical knowledge for the students. However, the technical components of design were not possible without the social interactions that co-constitute the objects. We argue that recognizing prototypes as intermediary objects reveals the ways in which students' experiences are organized on their design team and the coordination of the design projects. We describe these interactions in the model depicted in Figure 9. This diagram displays how prototypes are objects that embody both the technical knowledge and the social relationships that enable the enhancement of that technical knowledge. The design team enacts these relationships and develops the technical competencies that are then used in creating the prototypes.

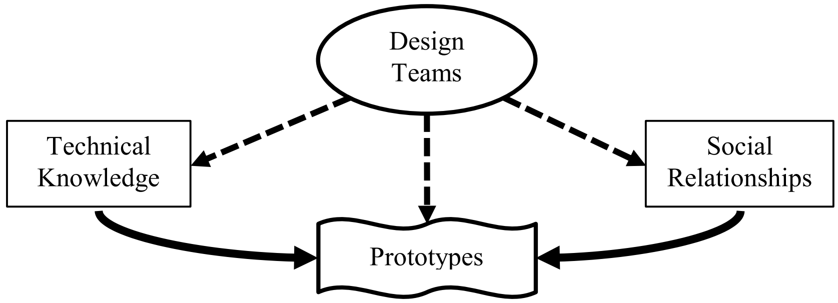

Figure 9. Model of prototypes, as intermediary objects, facilitating technical knowledge development and social relationships for the design teams

Comparing two different sections of first-year projects through an intermediary object lens articulates how and why course design and structure, classroom community, and instructor facilitation are consequential for learning design and becoming and engineer. These social arrangements impact the ways in which the design coordination occurs. As Table 8 illustrates, Vinck's six attributes of intermediary objects are present in the prototypes for both courses [10]. By calling attention to these attributes, we can evaluate the organization of each course and make recommendations for future practice.

The prototypes serve the role of *retrospective representation*, in that they are a reflective embodiment of all the factors that came together over time into the final artifacts. The water bottle, for example, represents the culmination of many conversations and decisions that ultimately take form in the final prototype. The LED-matrix also embodies the knowledge distributed from the various teammates, instructor, TAs, CETE workshop manager, and CETE electronics lab manager. The prototypes represent greater sophistication of the design process with each cycle of design and increased fidelity. The prototypes also serve the role of *perspective representation*, which reflects what is desired in the final product. All of these prototypes, regardless of their level of fidelity, can be improved and iterated on further, which is the underlying intention in creating that prototype. The final prototypes presented in each course, the LED-matrix and water bottle, are representations in their current state of what the final design is expected to be. The LED-matrix was expected to be a working toy for a children's playhouse, while both the hospital and water bottle were never intended to be fully functioning; rather, they were representations of students' thinking. In this way, the course design impacts the final representation of the prototypes.

Table 8. The attributes of intermediary objects in the prototypes [10] compared between the courses

	Course 100 – LED-Matrix for the Playhouse	**Course 101 – Model Hospital & Water bottle**
Representation in retrospect: *the object can look back in time at the decisions made to the current state; it is a reflective embodiment of all activity to this point.*	high fidelity prototype with multiple cycles of design iteration	low fidelity prototypes with only one cycle of design iteration
Perspective representation: *the object represents what is desired in the final object.*	working toy for family playhouse	representation of student thinking
Commissioning: *the object carries the intentions of the authors.*	toy that demonstrates knowledge of circuits, design processes, and materials	physical manifestation of healthcare idea
Mediation: *the object transforms the intentions of the authors*.	the intention shifts from a toy with particular features to a representation of good design as judged at design expo	the intention shifts from a functioning design to a representation of possible future design
Prescription: *the object imposes choices and decisions on their users.*	e.g., how the LED-matrix integrates into the overall playhouse design	e.g., the decision to present or not at the final design expo
Facilitating interactions, confrontations, and interpretations: *the objects facilitates multiple forms of communication, including compromises.*	e.g., LED-matrix facilitated interactions with electronics shop manager, machinist, instructor, and TAs	e.g., the water bottle facilitate interaction with the electronics shop manager

The intentions of the authors or designers of the prototypes are both incorporated and transformed by the objects. An intermediary object is *commissioning*, insofar as it carries the intensions of the designers; it is *mediating* insofar as the object transforms those same intentions. The final LED-matrix embodies the different team members' ideas for the project and then manifests those into reality through the prototype itself. One student found a similar LED-matrix project online, which carries his intention for the project.

These same intentions are then made real through the prototype; it transforms the intentions of that student from commissioning to mediating. The object also shifts the intentions of the design team in relation to the rest of the class. One initial intention of the LED-matrix was to have a physical object that represented the students' knowledge of circuits, design processes, and materials from which to be graded. As the prototype increased in fidelity, it stood out among the other projects, and the student team hoped it would be awarded for its design at the public design expo. The water bottle, on the other hand, stagnated as the student team shifted their intention from a final, working prototype to a final representation of their idea for increasing water consumption of Americans. The intention of displaying the object to the public was present in the LED-matrix but absent from the water-bottle and hospital. In this way, the different types of classroom community mattered. Course 100 always had the expectation their work would be viewed by a larger public, whereas Course 101 kept their work insulated to their classroom.

Students in Course 101 were allowed to choose not to participate in the final design exposition, and this choice was evident in the final prototype being a low-fidelity model. Intermediary objects are *prescriptive* in that they impose choices and decisions on the actors involved. In the LED-matrix, the design of this object imposed certain decisions of how the entire playhouse would integrate together, how the student team worked with the rest of the class, and ultimately how the children would play with the interactive piece. Because the LED-matrix was one part of a larger whole, more choices and decisions were negotiated, than were needed for either the water bottle, or the hospital. Recall the instructor for Course 101 decided that students did not have to integrate their individual model into a single town. Therefore, the choices stayed mostly among the student team.

Lastly, the prototypes *facilitate interactions*, mainly through communication with multiple human actors. These interactions enabled by the prototypes in the courses is shown in Table 9. In the creation of the water bottle, the team had to interact with one another, the instructor, and the electronics manager. The prototype was the common medium of communication between all of these actors in developing the final design. Because the LED-matrix was both more complex and iterated on, the network of actors was much larger. This notion that prototypes enable communication between different groups of actors, as mentioned in the sixth attribute of intermediary objects, is also a key feature of boundary objects [163]. However, we believe that these prototypes on the design teams push the concept of communication between actors another step further. Prototypes coordinate all of the work on design teams; they mediate the socio-technical activities in which students engage and represent both materiality of an object and the "invisible work" by which the object becomes tailored to local use. Part of this invisible work is the instructor expectations and facilitation for design. The instructor for the CETE course expected the design process to allow for increased fidelity of the prototype, intentionally connected students to multiple experts, and expected students to publicly share their work. The instructor for Course 101 did not share these same expectations.

Table 9. Course 100/101 prototypes' connections to social networks

Course	Prototypes	Connections to Human Actors and Social Networks
100	Spill-proof bubble container	CETE machine shop manager, employees in the CETE proto-shack
	Breadboard of electronics	CETE electronics manager, guest expert in lighting
	Printed circuit board (PCB)	CETE electronics manager, guest expert in lighting
	LED-matrix cube	CETE electronics manager, CETE machine shop manager, CETE proto-shack employees, guest expert in lighting, aesthetics specialist, students in course, instructor, teaching assistants
	Entire playhouse	Guest speakers: structural engineer, expert in lighting, aesthetics specialist, students in course, instructor, teaching assistants
101	Model of hospital	CETE electronics manager, students in course, instructor, teaching assistant
	Water bottle	CETE electronics manager

In Course 100, the prototypes increased in levels of fidelity from the initial electronics schematic and breadboard design to the final LED-matrix and then the entire playhouse. These iterations require students to reflect on what worked and did not work for each prototype. This reinforces their learning through synthesizing information. In the planning of creating a next version of the prototype, students must consider who they must contact to further their technical understanding. This cycle of "built-test-reflect-repeat" connects students to social networks that enhance their technical skill development. All of these relationships and technical knowledge is embodied in the creation of each prototype. While in Course 101, the prototypes never increased in fidelity or complexity. Instead, the initial prototypes of the model hospital and the water bottle also served as the two final prototypes required for the course; neither were required to be iterated or improved upon. This lack of iteration and refinement decreases the possibility that students reflect on the prototype and critically think and plan for the next version. In creating a single prototype, they only need to interact with human actors, like the electronics manager, only once. This lessens their connection to him as a resource, and minimizes their ability to develop technical skills related to electronics.

The prototypes for the Course 100 served as a more robust conduit for ideas, materials, and relationships beginning with the idea phase and culminating at the Design Exposition. For example, in the creation of the LED-matrix, the students interacted with the Internet, each other, an electronics retailer, a hardware store, the electronics lab facility and manager, the machine shop, the laser cutter facility and manager, the instructors and TAs, as well as coordinating with the entire class and the family for whom the playhouse was being built. They then presented the LED-matrix at the Design Exposition, which made the team visible to an audience of engineering educators, professionals, and the public creating further potential connections for the students. At the Design Exposition, the final prototype also acted as a communication tool between various networks: the engineering teams and various networks of people present.

The sustainable community model and the water bottle for the Course 101 also served the role of prototypes, and therefore, as objects of coordination in the design process. The model of the hospital represented the coordination between the team members, the instructor, and the teaching assistant. The teaching assistant procured all of the design supplies and delivered them to the team. The students then had to negotiate with one another to determine who would receive which supplies. However, neither final product, the hospital model nor the water bottle, were showcased in Design Exposition, thus limiting both visibility and further coordinating activity with people who attended this event.

The prototypes represent not only the theory and practice of design; they are heterogeneous organization of people, tools, and resources and the result of a socio-technical process. In engineering education, the objects created during design – often the various prototypes – are a tool of instruction that connects students to socio-technical systems to which they may not have otherwise been a part. How an instructor organizes for the implementation of these objects of design is consequential for how students learn design and, thus, learn to become engineers [60].

The prototypes in a first-year projects design class serve the same purpose as the bridge in Suchman's theory of organizing alignment [80]. The representation of a bridge, or its prototype in multiple forms, was the object that coordinated all of the activity; in the end the building of the bridge itself was outsourced. Therefore, since the bridge was outsourced, the prototypes then acted as the objects of coordination for the team. The prototypes, then, facilitate the organizing work connecting people, resources, and tools. In this way, engineering educators should consider how they plan for prototype development in first-year design classes, as they are critical in organizing the students' design activity.

3.2.7 Recommendations for Practice

There are several recommendations for engineering educators, specifically instructors of engineering design courses. Overall, we hope that instructors are mindful of the organization of their design courses, so that they provide students with the chance to build both their technical skills and social networks. Design is an equally social and technical process [76], [109], and there is importance in educators planning for this – one way being through the mindful creation of higher fidelity prototypes. We propose three broad questions that design instructors should ask themselves before organizing a design course, based on our findings and theoretical framing of design:

1) Who and what type of actors, both people and tools, do you want students to engage with in this course?

2) How can material resources and technical requirements connect students to these human and non-human actors?

3) What course features (e.g., presentations, public showcases) will enhance students' design processes?

For project-based design courses, instructors should appropriately scope projects to accomplish them within the course time limits. Scoping of suitable design projects is one of the most difficult tasks, as it sets the stage for the entire course [164]. In scoping these projects, we recommend that instructors require one of the final deliverables to be a higher fidelity prototype. This requirement allows the team to work towards a tangible outcome, while also requiring them to iterate on the initial lower-fidelity prototype several times. Other researchers have explored some of the psychological benefits of prototyping, such as increasing designers' self-efficacy [60] and confidence in their abilities through "small wins" [22]. With each iteration of the prototype, the students will increase the number of social interactions with subject experts. Ideally, having multiple prototypes would also force multiple check-in that would strengthen the relationships between the teams, instructor, and teaching assistants. Other researchers have shown the strength in these design critique sessions, whether among peers or subject experts [165], [166]. This is what we observed occurring in Course 100 compared to Course 101. One argument could be made is that Course 101 had a project scope that was too broad, and thus the students could not deliver these higher resolution prototypes, which limited their connections to other critical engineering social networks and technical skills development.

We also recommend that instructors require a final design exposition and host multiple workshops and guest lectures throughout the semester. By having a final design exposition, whether within the course or across the department or college, it can give students the added motivation to build higher resolution final prototypes and synthesize their work into a poster, presentation, and/or paper. Students are then often required to participate in several design reviews leading up to the finale exposition, like in Course 100, which can further develop the students' social and technical skills [167]. We hypothesize that there are additional benefits from this final culmination of the students' work; they may have a greater sense of pride in their design work, and build their self-efficacy related to many factors like teamwork, technical communication, and solving ambiguous problems. The act of presenting at the design exposition, also connects the students to an even wider community including professionals and community members. A final recommendation is that the instructor organize guest lectures or external workshops to teach technical skills by experts in those fields. It is critical that the instructor leverage other experts in the engineering center or affiliated with the university, as students need to be introduced to other people in those technical areas. We saw in both courses the importance of knowing who to go ask for help and where they were located. The act of hosting these workshops and guest lectures is critical to expanding the students' social network that can be critical in design within the course or even later in their career as an engineer.

Finally, universities should consider when multiple design classes count for the same degree requirements, particularly when two courses are drastically different in their approach and learning outcomes as that will give students different experiences of design. This could under-prepare one section of students, which may lead to students changing majors, leaving the university, repeating courses, or simply feeling frustrated while taking the next engineering design course. We have also heard that it is a fear of instructors for junior and senior level engineering design courses; they worry that the students in their courses have never experienced an appropriate project-based learning course, where they were required to deliver a final high resolution prototype. In summary, engineering design instructors should be cognizant of the structure of their design course and how their organization can impact the students' experiences and development in becoming an engineer.

3.2.8 Conclusion

The design of any object, like prototypes, is an intentional activity that can only be fully explained by attending to the heterogeneous organization of socio-technical systems. With this in mind, engineering educators can and should be purposeful in the intentional organization of first-year design courses, while recognizing that people, materials, and ideas all matter and are inextricably combined through intermediary objects. The prototype can serve a normative role in describing the social and technical interworking, and it also serves and explanatory and mediating role between a diversity of people, including experts in certain subject areas that are necessary for the final design.

Becoming an engineer is a socio-technical process in which some students are actively pulled in while others are pushed out [162]. We argue that students get connected, or not, to particular socio-technical systems that support their learning of design through their design courses. The introduction of actors, like the various engineering subject experts and resources, creates trajectories into networks that will be differentially taken up or disregarded as students' progress through their undergraduate years. Our research demonstrates that the organizing features of design courses, including the coordination of people and resources through workshops and guest lectures, strengthens certain social connections and thus heightens technical skill development. Therefore, engineering educators should be mindful of the decisions they make regarding how they organize for classroom projects, as this can have a sizeable impact on how the students learn design skills. Through our research, we see that students get tied to larger networks through the act of creating multiple prototypes in their design courses. These prototypes coordinate students' activities on design teams; they mediate the socio-technical activities in which students engage.

3.3 Chapter 3 Summary

This chapter explored the use of prototypes on student design teams through Vinck's framework of intermediary objects. Prototypes, as intermediary objects, facilitate technical knowledge development and social relationships for students on the design teams. This study focuses on two first-year engineering design courses, one that uses multiple prototypes and the other that uses minimal prototypes. This side-by-side comparison is important to seeing the value that prototypes add on design teams outside of just the technical skills. It is through the absence of prototypes in one class, that the importance of prototypes in the other class can be identified. Through comparing the courses, I expand our understanding of what prototypes can do on design teams, specifically how they create "design coordination". Design coordination builds on the theory of intermediary objects, and highlights how prototypes are critical objects that influence social networks and technical skills development. It shows how prototypes have the ability to frame students' experiences: connect them with experts, negotiate aspects of the design, communicate with the client, persuade outside stakeholders, gain feedback from judges, and more.

The study becomes the foundation for the research conducted within companies, as it furthers the theoretical understanding of prototypes as organizing objects. This concept of design coordination is taken up when collecting and analyzing data at the three companies. The following three chapters (4, 5, and 6) explore the role of prototypes on design teams in industry. Chapter 4 looks at the early stages of the design process, and how benchmarking and reverse engineering are essential to evolutionary product development in each company. This chapter maps out the early stages of the design process, and expands our mental model of how prototyping through these two methods can solidify the design intent, specifications, materials/components, market, and customer/user experience. Chapters 5 and 6 then explore the primary roles of prototypes, and how they change based on the context of use.

Chapter 4 – Early Prototyping Techniques in Evolutionary Product Development

4.1 Introduction

Chapter 4 is the first introduction to the three companies in this dissertation research. These companies will be the focus of Chapters 4, 5, and 6 as I further discuss the use and role of prototypes. Each of these companies develops physical end products in the fields of consumer electronic devices, surgical medical devices, and footwear. This chapter explores the early stages of the product development process for each company in the development of one final product. Each company end up creating “evolutionary” products, meaning that they constantly develop the next version of a prior product without any major changes. This contrasts “revolutionary” products, which have the potential to change the field in one or more ways. Prototyping techniques like benchmarking and reverse engineering are used in the early stages of the design process, when the details of the product are still being determined. Although topics like benchmarking and reverse engineering have been discussed in prior literature, they have not conceptualized as methods for prototyping during early stage design.

This chapter explores how prototypes are used in the early stages of the design process, specifically as tools for reverse engineering and benchmarking to solidify the design intent. This chapter is based off the conference paper currently in review for the 2018 ASME IDETC Design Theory and Methodology Conference. The conference will occur over August 26-29, 2018 in Quebec City, Canada. This paper is entitled “Design Methods used during Early Stages of Product Development: Three Company Cases”, and it is paper number DETC-2018-85406. This paper is co-authored with my advisors, Daria Kotys-Schwartz and Mark Rentschler. The following section 4.2 includes the paper in its current state.

4.2 Design Methods used during Early Stages of Product Development: Three Company Cases

Companies need to employ new design methods and tools to remain competitive in today's global economy. Design methods are used to help teams move through the different stages of the design process, such as during project scoping, concept generation, and concept selection. Concept generation design methods are meant to help teams generate diverse, novel, and creative potential solutions. Most methods are developed and refined based on studies with student teams. This limits our understanding of how professionals engage with design methods in practice. This is a case study exploring the design methods used by three companies during the early stages of new product development, primarily during concept generation. These companies are from the consumer electronics, footwear, and medical devices industries, and they were each tasked with developing a new physical end product. We identified that all three teams heavily relied on internal and external benchmarking and reverse engineering design methods as part of concept generation. Ultimately, the products developed were all considered *evolutionary*, meaning that the final product was a slightly improved version of similar products already on the market. This contrasts *revolutionary* products, which can change or disrupt the current field in one or more ways. This research contributes to design theory and methodology through empirically studying how companies engage in the design process, identifying the methods employed by professionals, and raising new questions about design methods, especially translation to industry. This research also contributes to design education by identifying methods that professionals use in practice, which can translate to direct recommendations for improving project-based engineering design courses.

4.2.1 Introduction

Currently, there is a small empirical base on what contemporary professional engineering practice involves [74], [76], [80], [81], [83], [90], [91], [162]. Actual observations of professional engineering work are critical resources for both understanding aspects of the design process and also rethinking engineering design education. It has been urged to make design pedagogy the highest priority in new engineering education curriculum decisions; "design is what engineers do, and the intelligent and thoughtful decision of the engineering curriculum should be the community's first allegiance" [25]. In order to improve design pedagogy, we must first better understand how professionals engage in design practices, and then use those insights to refine design processes and methods for education.

Design research can be broadly divided into design processes and design methods. These topics are distinctly different, and, yet related and dependent on each other. Design processes are described as the systematic and desired sequence of steps or actions taken, such as Ulrich and Eppinger's six-stage process for product development [39]. This is an idealistic theory to describe the stages that all designers must go through. Contrasting this, design methods are the tools or techniques created to help designers through one or more of the design process stages. For example, design heuristics [4], [168], [169], design-by-analogy [170], [171], and humor-driven practices [172], [173] are all design methods to help with the concept development stage within the design process. Design methods, or tools, are concerned with *how* to approach specific design phases. The execution of design methods can vary between design teams, even within the same company or design course.

Otto and Wood stated that "new products drive business…to remain competitive, industry is continually searching for new methods to evolve their products" [174]. Since new product development is important to industry, we engaged in an empirical study of three companies in the fields of consumer electronics, footwear, and medical devices. Our goal was to identify what design methods were used by the teams during the early stages of the design process. In each company, we observed the entire design and development process for one new product. In the analysis, we mapped out the early stages of each of the companies' design processes indicating the methods and tools that they used.

This is a qualitative research study, drawing on ethnographic methods for data collection. We report the findings as a collective and comparative case study across the three companies. The findings show that companies have adapted their own benchmarking and reverse engineering techniques in early product development as a means to stay competitive in the market and to provide incrementally and evolutionary better final products. Benchmarking is a technique used to measure or compare similar products, features, and services. Reverse engineering is a product redesign technique used to fully understand the current instantiation of a product. This research helps fill the gap in understanding how professional engineers engage in engineering design, specifically the methods used during the early stages of design practice.

4.2.2 Background

4.2.2.1 Design Processes & Methods

The product development process is described as a "sequence of steps or activities that an enterprise employs to conceive, design, and commercialize a product" [39, p. 12]. There are many frameworks and theories to describe the design process. For example, there is a six-stage waterfall design process [39, p. 14], the five flexible stages of the human-centered design process (also known as design thinking) [175, p. 106], and the spiral design process first introduced in software industry to be more agile [176, p. 491]. Within mechanical engineering, there are four popular design processes for product development: Otto and Wood [33], Pahl and Beitz [177], Ullman [40], and Ulrich and Eppinger [39].

For the framing of this study, we chose to initially treat each company as using Ulrich and Eppinger's six-stage framework, which includes 1) planning, 2) concept development, 3) system-level design, 4) detail design, 5) testing and refinement, and 6) production ramp-up [39]. They indicate that there are approximately six variations of this process depending on variants within each company, but that generally each will follow this general framework. For early stage design, we include the first two phases: planning and concept development. Figure 10 displays the concept development process as described by Ulrich and Eppinger [39, p. 118]. This concept development stages includes seven sub-stages, from identifying customer needs to planning for downstream development. There are three factors that influence each sub-stage: economic analysis, benchmarking competitive products, and building and testing models and prototypes.

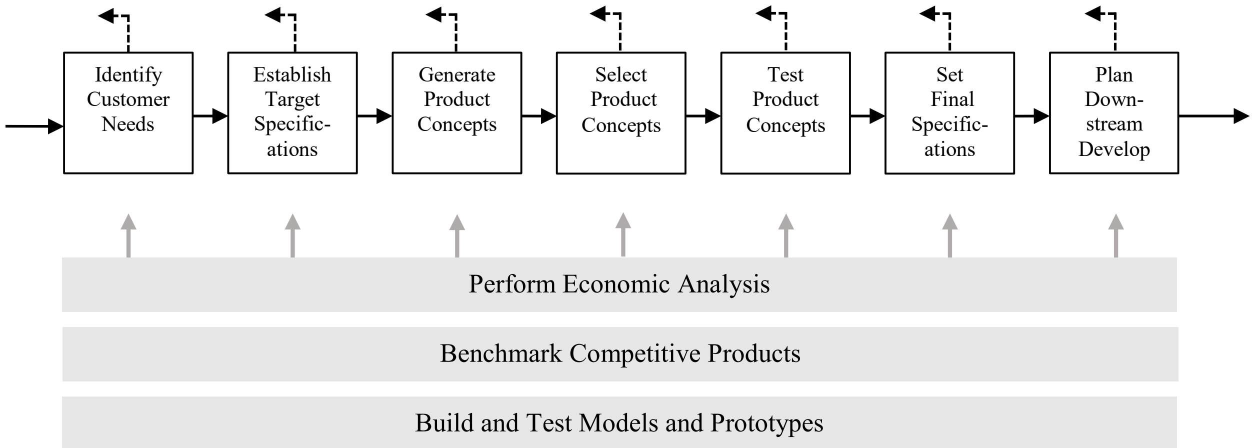

Figure 10. Concept development process (reproduced from Ulrich & Eppinger, Exhibit 7-2, page 118)

Betz, and other researches, have described product development in companies as naturally falling into an S-curve over time, as shown in Figure 11 [178]. This diagram exemplifies the evolution of lamps, a type of physical product similar to the products created by the companies in this study. With the launch of a new product, like the incandescent lamp, it appears to be innovative and new to the market. In the beginning years, there are minor changes made to the design, resulting in evolutionary growth. Then, at some point there will be a "jump" in product development – possibly in terms of materials or technology. At this time, the product becomes more revolutionary than evolutionary. This process tends to repeats the same pattern, with the newest technology staying stagnate for some years creating the upper "flatness" of the S-curve. This is one way to describe the repeated pattern of product development in companies.

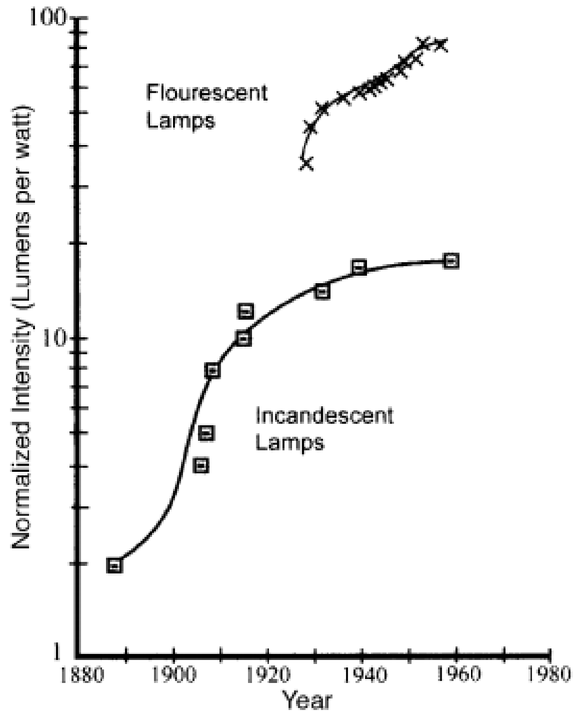

Figure 11. Product evolution S-curves (from Betz, 1993)

Companies are free to choose a design process to frame their projects. Each of the companies in this study used their own specific design process and approach to product development. Within the design process, there are many design tools and methods developed to help with each step. Design methodologies have emerged out of design research; they are used to guide companies with their product development efforts and also as the foundation for teaching design courses within universities. There are design methods created to be tools for design team during every stage of the design process. In this paper, we specifically explore concept generation methods.

4.2.2.2 Concept Generation Methods

"Innovation in design depends on successful concept generation" [4]. Concept generation, often referred to as ideation, is part of the early stages of the design process, when designers can explore multiple potential solutions to solve their design problem. There are many concept generation methods developed by researchers, including: design heuristics [4], [169], design by analogy [170], TRIZ [179], SCAMPER [180], brainstorming [181], and sketching [182], [183] amongst others. Design heuristics are a popular design tool in design education. They were developed to be cognitive short-cuts for designers to develop more varied concepts in the early stages of the design process [168]. This work emerged from studying how professional industrial designers and engineering designers engaged in concept generation during a set design challenge.

Most of the commonly discussed concept generation tools occur in two-dimensions, through writing, sketching, cards, and/or through a series of prescribed steps. For three-dimensional concept generation tools, designers can build low-fidelity physical models (prototypes) [12], engage in product dissection, and/or fully reverse engineering a product. Reverse engineering is a product redesign technique used to fully understand the current instantiation of a product; it was developed and popularized by researchers like Ingle, Wood, and Otto [33], [184]. It is used as a tool to help students gain confidence and technical skills through hands-on activities [185], and it is also used by companies as a tool during product development [174]. Using more refined models and prototypes can lead to design fixation, which can limit designers' minds to exploring other concepts [120].

The researchers who created the 77 design heuristics method for concept generation stated that current ideation methods "lack systematic evidence…for their usefulness in engineering design" [4]. They mean that these concept generation tools were developed to help designers, and yet they have not been tested for their appropriateness on varying types of design problems/processes or with diverse groups of people, like design professionals. There is a need to further study how concept generations techniques, both in 2D and 3D, are used in professional design practice on a variety of design projects.

4.2.2.3 Empirical Studies of Engineering Design Practice

There is strong evidence that supports how an inadequate picture of engineering work, including design, is conveyed to the general public [90]. Currently, "real engineering," or that of professional engineering companies, is portrayed based on personal experience or anecdotal evidence that usually highlights only the technical aspects of the work [86]. Engineering design work is equally social and technical [80]; technical products are developed on diverse teams of people who make decisions. Engineering as a profession is changing rapidly, largely because the field is closely tied to new technological developments [186], which continues to advance at an alarming pace. The rapid changes in the engineering profession argue for research documenting the contemporary practices of professionals [187]. However, we currently have little to no insight into how engineers at companies engage in design projects, nor what design tools and methods they use.

From an engineering education perspective, there is a need to further our understanding of professional design practices. Design is often called the "backbone of engineering" [25]. As a response to this, many universities have begun to implement engineering design courses throughout all four years of undergraduate programs. However, both the National Academy of Engineers and the American Society of Mechanical Engineers recognize that there are many disconnects between undergraduate education and professional design practices [26]. Both organizations have calls for re-imagining engineering design education in the 21st century. A portion of this re-imagining education includes updates to design processes and methods used within the engineering design courses.

4.2.3 Research Objectives

This work is part of a larger research project studying the roles of prototypes on design teams in companies [188], where we followed these three companies through the duration of their product development process. This qualitative study used ethnographically informed methods for data collection and a grounded theory approach to data analysis. Over the three years of data collection and analysis, we noticed similar design methods used between each of companies in the early stages of the design process. This led us to asking and answering another research question related to design methods: *how do company design teams engage in the early stages of the design process for new product development, specifically* *what design methods do they use?* This paper is focused on answering this one research question. We display the findings through a comparative case study across the three companies.

4.2.4 Methodology

This research used qualitative methods for data collection and analysis. For data collection, we used ethnographically informed methods to capture participants' activities within the companies. For data analysis in this paper, we engaged in a comparative case study across these three companies.

4.2.4.1 Cases: Three Companies

This research observed the entire product design and development process for three companies headquartered in the United States. These companies come from the fields of consumer electronics, footwear, and medical devices. The researchers worked with executives at these companies to gain access and determine the appropriate design projects to follow [189]. Within each company, we followed a specific design project tasked with developing a new physical end product within the field. The product would replace a prior product or series of products in the market. The teams were each given creative freedom to explore unique solutions, as long as they fit within a few design requirements and specifications.

4.2.4.1.1 Consumer Electronics Company

The first company in this research study is a medium-sized consumer electronics company. They have one main headquarter building where all of the in-house design, manufacturing, and distribution occurs. The majority of their products are sold online through their e-commerce website. Other consumer electronics websites and stores sell their products, too. Currently, their catalogue of products totals over 3,000. Each year, they launch about 150 products, which are either new or revised from their catalogue.

This consumer electronics company maintains a strong open-source philosophy. All of the files for products they create are available to the public online. From a design perspective, this includes any 3D files, printed circuit board files, code files, or similar. They use common open-source platforms in the electronics industry including GitHub, EAGLE, Sketchup, Blender and Arduino to share many of these files. Additionally, each product they launch includes a "hook-up guide" written by the lead engineer, along with any necessary product specification sheets, and finally a tutorial for how to create a simple project from the product.

The design process employed by this company is unique compared to the other companies in this research study. The engineering manager created a product development process flowchart (Figure 12) that attempts to accurately represent all of the steps in the process. There are seven main groups of people involved, indicated by the different colors. For example, engineering is in green, quality control/assurance is in blue, and tasks that span multiple groups are in white.

There is one main engineer assigned to each new design project. This engineer is required to conduct all of the design work for that project. Engineers typically work on between 3-6 projects at a time and individually launch up to 30 products per year. Each engineer can choose which projects to work on, and they typically pick projects that fit into their specific expertise area or an area that they hope to become more familiar with through the project.

The engineer must go through several stage-gates to launch the project. First, the engineer completes a specification ("spec") report. Then, there is an open call for comments on the spec from the engineering department. Once this feedback is collected, the lead engineer then takes the information and makes necessary changes. Once the spec is locked, the lead engineer officially starts the design process: creating GitHub pages, schematics and layouts, and bill of materials (BOMs) all are part of creating the full system prototypes.

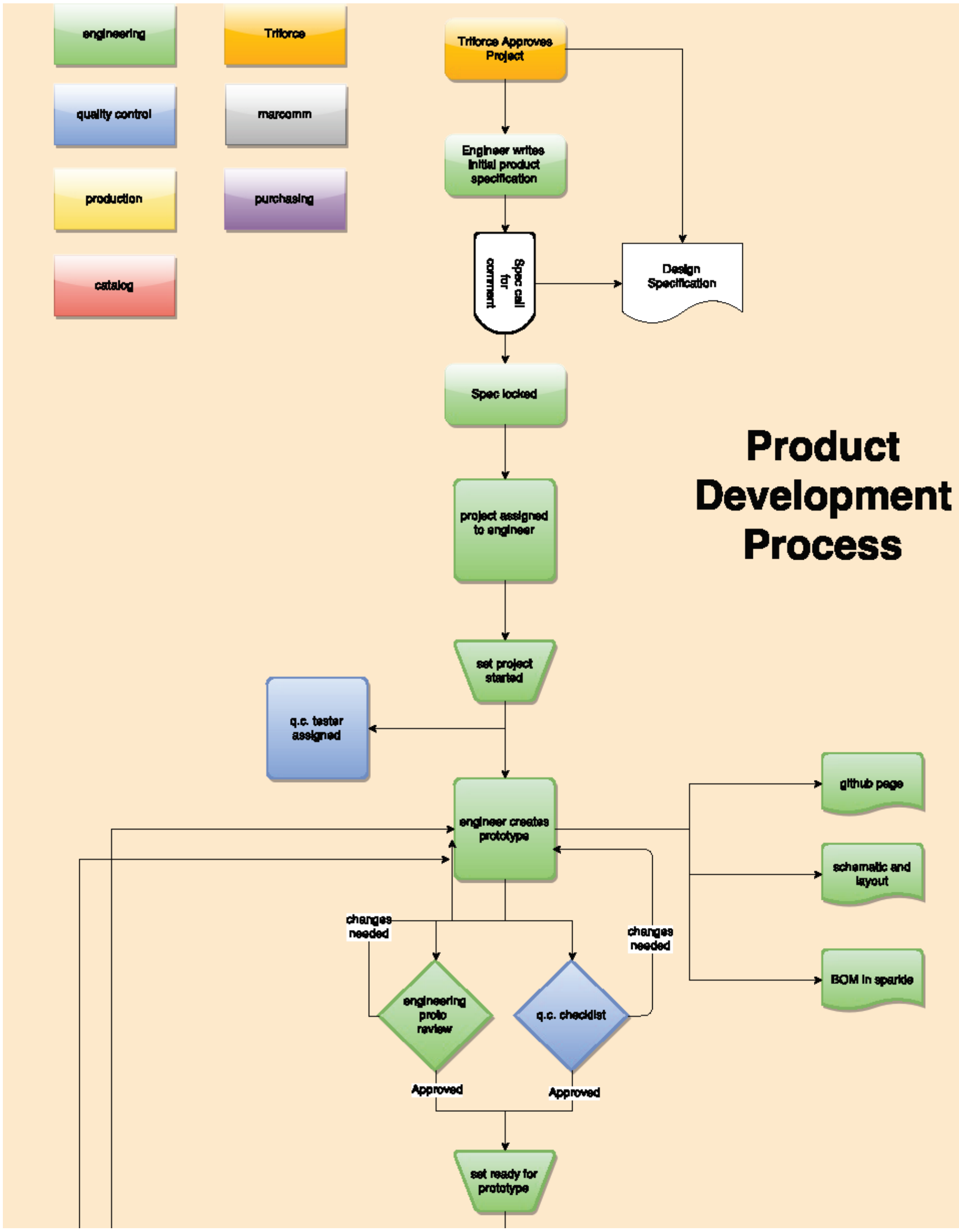

Figure 12. Consumer electronics company product development process (early portions only)

Once the digital design work is complete, the product must have a formal design review. This design review process has changed over the course of our research. The current structure for a design review is that the lead engineer schedules a meeting with three people: one member of production, one member of quality assurance, and the engineering manager. Together these four employees must vet the design and confirm moving towards production. Key aspects like design for manufacturability are addressed in this review. After the design review is successfully completed, the lead engineer then works with the parts-vetter and production staff to create the first full system physical prototype (known as "protos"). Once the protos are received, the lead engineer confirms the functionality. If everything works fine, then the final production boards are ordered. While waiting for the production board, the lead engineer finalizes all the documentation to prepare for launching on their website.

The project followed during this research was an audio board. The project lasted for about 10 months, beginning in March 2016 and ending/launching in December 2016. It was a lower-priority project, meaning that occasionally the launch date was pushed back to allow for more high-priority projects to be launched. This project had one lead engineer developing it, who was fairly new to the company. She was hired earlier in the year and had completed four projects prior to this audio project. The project was launched with all of the open-source files and included one introductory project tutorial.

4.2.4.1.2 Footwear Company

The second company in this research study is a large, global footwear company. There have design and development offices in three countries. Products are sold both online and in retail stores. Online sales come from both their own e-commerce site and from third-party companies. In-store sales come from both their stores (direct-to-consumer) and from third-party companies (wholesale). They launch two seasons of footwear every year. They have four major footwear divisions: women, men, kids, and classics. Each division has their own design and development team that consists of 6-10 core team members.

The Director of Product Development describes their general design process as "ask, build, ship, and receive." Ideally, this process is completed in "one loop," but he indicates that never happens. In this process, the "ask" comes from their marketing team who works directly with the different distribution sites. In fashion, trends typically "trickle down" from high fashion to more general fashion companies for mass consumers every few years. Each season, marketing determines the quantity and types of products to develop for each division of footwear. These “asks” are then translated to the product design and development teams to “build” and “ship” the products off to these locations where they “receive” them. Within the “build” stage, there are four more specific product development phases: 1) Design, 2) Early Development, 3) Late Development, and 4) Commercialization (Figure 13). The Director describes these four phases of “build” as each corresponding with different milestones in their product development timeline.

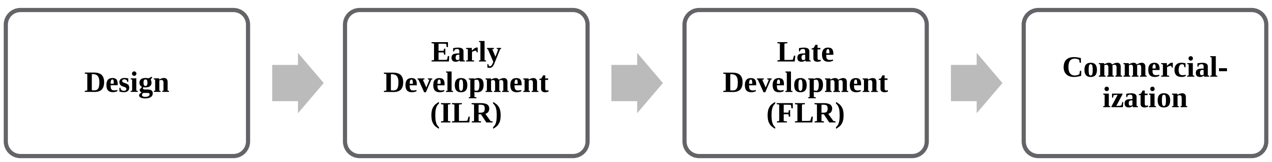

Figure 13. Footwear company product development process

This company starts the product development process for each season of footwear 18 months before the products launch to market. At each phase, there are several major milestones or design-gates. During the design phase, there are internal design reviews where each design team presents the potential designs for the season to various other employees, including details on style/silhouette, new upper-designs (i.e. above the base of the shoe), new lower-designs (i.e. base of the shoe), types of materials, colors, graphics, licensed artwork, and any embellishments added to a shoe. There are typically two design reviews in this phase that are only held internally between the design team and upper management representatives. After early development, there is an “Initial Line Review” (ILR) where all the designs are vetted both internally and externally from upper management and potential buyers/supplies. Feedback from ILR is taken by each core design team to move into the later development phase. At the end of this late development phase there is a “Final Line Review” (FLR), which is similar to ILR in structure. After FLR all changes and decisions are finalized by the design team and the chosen footwear for the whole product line move into the final commercialization phase. The design team then works directly with the manufacturing sites to ensure quality products and on-time delivery.

In this research, we worked with the kids' footwear team on the product line development for the fall/winter 2017 line (FW17). This design process started in March 2016 and the late stage development was finished in December 2016, commercialization occurred during January-April 2017, with the launch of the product occurring in August 2017. On the kids' core design and development team, there are two project line managers, three designers, and three developers. They receive additional support from other employees when needed, such as a specialist on supply chain for materials or an engineer for 3D modeling shoes. There were 100 shoes launched during FW17, but we focused on the design and development of a new product: the kids' waterproof winter boot. This product was adapted for boys and girls, varying in colors, graphics, and embellishments.

4.2.4.1.3 Medical Device Company

The third company is a large medical device company that specializes in surgical and monitoring products. They have eight manufacturing, distribution, and/or design facilities in the United States. This research took place at one of these locations where manufacturing, distribution, and design all occurred on-site. Their catalogue of products spans thousands of devices. Typically, one surgical device can have up to ten different versions on the same product platform, where factors like the size, strength, material, cables and power source will be altered.

The design process is heavily influenced by the regulations enforced by medical device development in the United States. There are strict verification and validation stages, where immense testing and documentation must occur to ensure that the product passes all of the FDA regulations (Figure 14). Additionally, a FDA 510K submission for the proposed medical product must be approved in the process. Because of these strict guidelines, medical devices often take many years to complete.

This medical device company implement a new “lean product development process” during our observations. Lean product development was considered more of a mindset, where the company changed aspects of their daily and weekly schedules to mitigate potential problems and block time to complete design tasks. Part of this lean process included 15-minute “stand-up” morning meetings three days a week. These meetings were not supposed to be an update necessarily, but rather a time to identify potential threats and connect resources to one another to reduce future problems. The company also began using a new project management software, which allowed the team members to mark daily tasks, deadlines, and any hurdles they faced. Additionally, morning time was meant to be “blocked” for individual or team work time. Originally, there were no other meetings allowed between 8am-12pm. However, over time, this rule relaxed and people began to schedule meetings in the mornings.

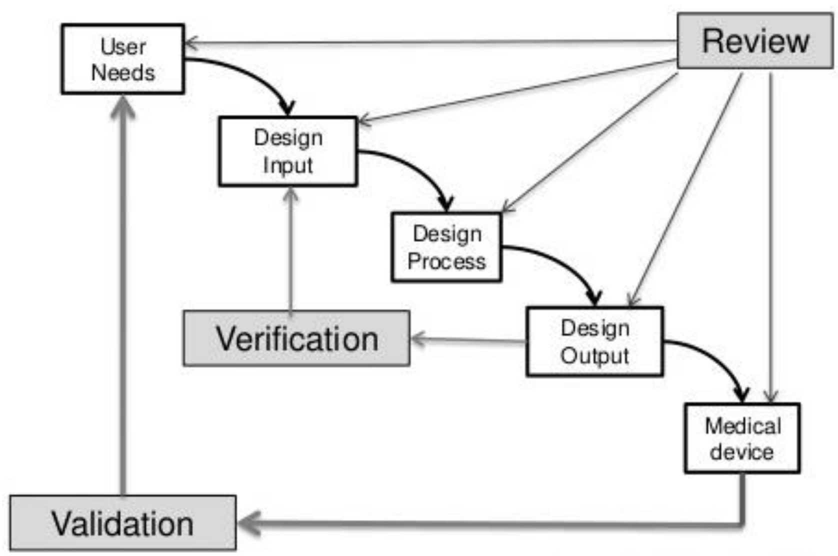

Figure 14. Medical device company product development process, based on FDA [190]

The project followed at this company was the design of a new surgical device. The company had a related prior product in their catalogue. Currently, this company only holds about 1% of the market for this particular device, and they would like to increase this holding. This project was brought to the company by the marketing team after surveying and interviewing surgeons about their preferences with these types of devices. This was considered a high-priority project, and engineers were taken from other projects at the company in order to focus their time and efforts to create this new and improve surgical device. The project timeline was sped-up, with the goal to launch the device within one year. This aggressive timeline provided an excellent opportunity to observe the design process for a medical device amplified. Additionally, this project was a collaboration with three locations from the same company participating. This created many teleconferences and site visits to ensure that everyone was on the same page throughout the process.

We followed this project from initial inception during the summer of 2014. We attended the week long project kick-off that was held at the site we observed in late July 2014. Then, this project was followed into February 2015, when ultimately the project was dropped due to company problems. The location where we observed was being shut-down. The project was put on hold until the reorganization of the company was complete. To this day, this product has not been launched, although the majority of the design and development work is complete.

4.2.4.2 Data Collection

The goal of data collection was to capture all of the details surrounding product development in each company, including design methods used and prototyping practices. The data collection strategies were influenced by the traditions of ethnography, understanding both the cultures of the companies and design teams as well as the practices of design and prototyping [158]. We conducted lengthy observations at each of the three companies to ensure that we became fully indoctrinated into the company culture and design team, and as a means to gather copious amounts of data about the design process, methods/tools, and team dynamics. We spent approximately 10 months at each company following a specific design team and project at length. There were over 200 hours of observations across the companies. These observations occurred between one and three days each week, for two to six hours each day.

We used a variety of fieldwork methods to capture aspects of participants' activities throughout the product development cycle. These include both direct and indirect methods, all which are heavily informed by Czarniawsha's methods for conducting fieldwork in modern societies [158]. During the observations, field notes were taken directly on the computer. While taking notes, there was also audio or video recording of the activities taking place. The researcher time-stamped all of the field notes with each new activity, so that later during analysis the research team could align the notes with video/audio recordings. After the observations, the researcher extended the field notes with more thorough details and reflections from the day. During the observations, the researcher also documented the artifacts/objects used, spaces, documents, and temporary surfaces. These were photographed and saved to our secure server that housed all of the data collected.

The researcher engaged in a participant-observer role at the companies [190]. The role was chosen because the research team felt that developing a relationship with the people at the company was key to the success of the observations. Therefore, the researcher chose to engage with the team at non-critical times, such as before and after meetings or while in the hallways. When the employees were in the middle of a meeting or doing work in their office, the researcher would be in more of the observer role because they wanted to respect the employees' time and work at the company and capture the actions without interrupting. More details about the data collection methods can be seen in another article from this same research project [188].

4.2.4.3 Data Analysis

There were several methods of data analysis used on this research project. These include analytic memos, descriptive representations, reconstructive analysis, inductive five-stage coding from grounded theory, comparative case studies and mapping of activities [121], [191], [192]. For this paper, a comparative case study and mapping of activities were done as the two primary methods of data analysis to answer the research question: *how do company design teams engage in the early stages of the design process for new product development, specifically what design methods do they use?*

A case study is an exploration of one or more "bounded systems" through in-depth data collection involving multiple sources of information in a rich context. A bounded system can be bounded by place and time, and it can be compared and contrasted to other bounded systems in a multi-site study [190, pp. 61–64]. Each system, or company, contains multiple sources of information including field notes, observations, interviews, audio-visual material, documents, and reports. Analysis occurred both within-case and across-cases [153]. Each company and design project can be considered its own individual bounded system. We chose to use three very different industries (consumer electronics, footwear, and medical device) for the cases to allow for both in-case and across-case analysis. Therefore, this becomes as comparative case study across them.

For this comparative case study, we reconstructed the early stages of the design process for each company through re-visiting the data collected and mapping out the steps for each organization. This intensive mapping of activities and interactions allowed us retrospectively analyze the steps that each design teams took in the creation of their final product. It also allowed us to identify the design methods and tools employed by the team during the initial project scoping, concept generation, and concept selections stages.

4.2.5 Findings

In this section, we present three cases of early product development within the companies. We map the early design processes across these companies, and highlight the design methods used by each company. We consider the early design process to include three major stages: 1) planning and project scoping, 2) concept generation, and 3) concept selection. These are all steps in the concept development process, displayed in Figure 10. Across these three phases, there are aspects of systems-level design, detailed-design, and testing and refinement that occur. Comparative insights across the companies are discussed following these three cases in the Discussion section.

4.2.5.1 Case 1: Consumer Electronics Company

Within the consumer electronics company, the project observed was the development of a new version of an audio breakout board. The company had an older and different version of this product, and they were looking to update the technology and features. This company operates in a field that is very supportive of open source technology and products, meaning that their products, supporting files, and documentation are shared openly as a means to collectively innovate. This company has their own unique product development process; the beginning stages of this process are outlined in Figure 12, which was created by the engineering manager.

In reconstructing the early stages of the design process, this consumer electronics company's process is displayed in Figure 15. This breaks the process into three main categories displayed on the left: planning and project scope, concept generation, and concept selection. On the right of Figure 15, there are details about the stages, specifically highlighting any design methods used.

During the first phase of project planning and project scope, the lead engineer used one design tool: the specification ("spec") sheet. This spec document was developed by the engineering manager and is used as a tool to help engineers consider many important factors before starting the design project. The specifications for this project included five major factors: 1) updating all technology and components to the latest versions, 2) must be under $30 for the consumer, 3) needed to have an enhanced user interface and experience, 4) needed to include "fun" project examples to use with the audio board, and 5) needed to be better than their lead competitor. Most of these specifications are vague, and can be interpreted differently. For example, an "enhanced user interface" could be associated to some user experience (UX) testing like A/B testing, usability timed tests, or other design tools. However, there were no target specifications identified, so the engineer could interpret as desired.

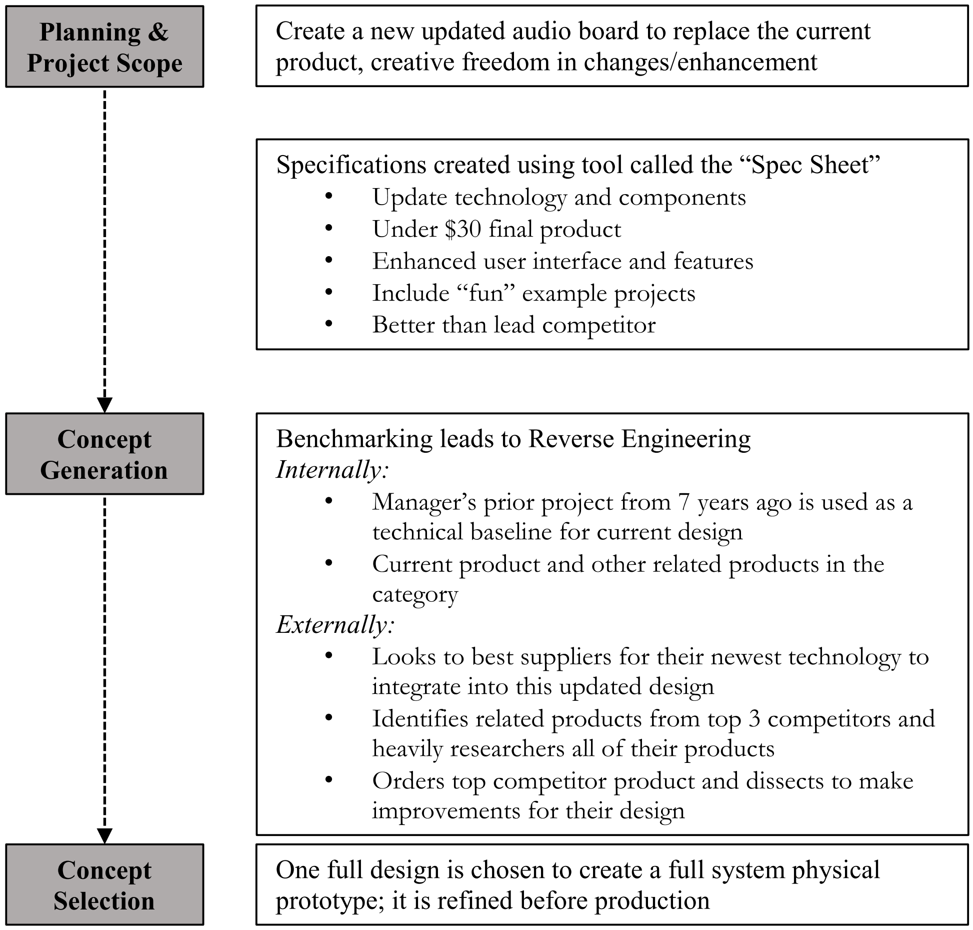

Figure 15. Consumer Electronics Company reconstruction of design methods during early stage design process

After the spec sheet was reviewed and approved by the engineering department, the lead engineer began to design the new audio board. There were no systematic guidelines for how she must go through this process; she had creative freedom to design the board. The only requirements were to create a schematic and layout, GitHub page, and bill of materials before the design review. For this project, she began designing the board by benchmarking products, both internally and externally. Internally, she learns that there is one similar product on the market that was about five years old. Some of the components on the product needed to be upgraded to the newest technology. Since they outsource certain components, they needed to update the product in order to not become obsolete. She also learns through a conversation with her manager that he developed a similar, yet different, technology about seven years prior. She was able to use that project as a starting place for this project. In this following excerpt, the lead engineer on this project elaborates on how she gained inspiration for the current direction of the project based on these internal products and ideal manufacturers.

> Lead Engineer: *The manufactures of the chips actually have several example designs that are just available for anyone to use. And when I found out that I wanted to use this chip because of all the support that they had online for it. I emailed [the engineering director] and was like I am going to use that chip and he said that was funny because he designed an mp3 player based on this board like 6 or 7 years ago. So he sent me the design file for that and I just dumped it down. I took off all of the extra buttons. So this is what his looks like and then mine is much, much simpler (clicking on the computer between the two screens). 'Cause all I want to do...he is using 256 nan-flash and I am only using 16. And I am using spy-serial. The purpose of this board is just a sound effects. You want to load a couple different sound bites and then have it triggered serially when, say like a PIR sensor gets activated or something like that.*

In that excerpt, the lead engineer discusses two main reasons for why she chooses the current 'chip' for this project. First, she wants to order a component that has lots of technical support in case she runs into issues. Second, she learned from the engineering manager that he created a similar, yet different, project several years ago, and that she can use that as a starting point for this project. This benchmarking of the prior products within the company is a valuable tool for this design project, as it clearly sets the intent for what the final product includes.

In addition to internally benchmarking and reverse engineering her manager's prior mp3 project, the lead engineer also looked at their lead competitor for inspiration. She ordered one of their similar products, downloaded all of the supporting documentation, and analyzed how they went about creating the product. She elaborates on this approach in this excerpt.

> Lead Engineer: *So [our competitor] actually copied the same exact schematic from the VLS website. So they actually didn't do any [new] design work themselves, either. So I just wanted to make sure that I've added a little more [to our product] ... some pull-up resistors to the data lines*

so that when they are high they are actually high and when they are low they are actually low. Things like that. So it will be slightly improved, but really we are all doing the same thing.

In this excerpt, the lead engineer identifies a few problems with the competitor product. Namely, in the connections between certain components. She makes changes to her design based on these insights, such as moving *"some pull-up resistors to the data line".* She even acknowledges that this product is only an incremental improvement to the overall field by stating that *"it will be slightly improved, but really we are all doing the same thing"*. In addition to reverse engineering the competitor product, she also reads reviews for the product online and in forums. This gives her insights from the users' perspectives about what is challenging with the current technology and what they desire in a newer product.

In leading up to the final concept selection and design review, the lead engineer heavily relies on two design methods: benchmarking and reverse engineering of both internal and external products. In terms of software design tools, she used Google Documents to create the spec sheet and bill of materials, EAGLE to create the schematic and layout for the printed circuit boards, and GitHub to store the code developed.

4.2.5.2 Case 2: Footwear Company

Within the footwear company, the project observed was the development of a kid's waterproof winter boot. The company had many winter boots from prior seasons, but this product was entitled "new" within their product development process. This means the team had full creative freedom over the design and development of the product. In the early stages of the project, the project scope was set by upper management and the marketing team. The kids' footwear team was told to create or update 30 products; these changes ranged from complete new products to just changing the colors and graphics on other products.

For the new kids' boot, there were several guidelines established before the design of the boot could begin, as shown at the top of Figure 16. The first guideline was that the boot needed to be sold at a price point of approximately $70, making it a very high quality winter boot. In lines with this price point, the team needed to ensure that all of the materials on the boot were waterproof and that the boot itself was warm to wear. The team also needed to ensure that this boot could be put on comfortably by a child on their own and that it looked "fun" enough that children wanted these boots and parents purchased them. Many of these specifications could also be interpreted in various ways.

After the team understood the requirements, they were free to develop concepts. There were three product designers on the team and three product developers. The product designers primarily used sketching and line art to explore concepts. Line art is considered a more refined version of sketching and it is done digitally using Adobe Illustrator software. Sketching and line art were only done after the team benchmarked products.

The design team first benchmarked products, both internally and externally, in order to better define the design intent for this new boot project. The looked at historical data within the company on what colors and shapes of boots did well. They also surveyed their key competitors to see the trends in their recent boots over the last five years. These methods are described in the middle of Figure 16.

In benchmarking competitor products, the team learned about certain features that they wanted in their design. For example, one designer on the team introduces multiple feature ideas for the boot, such as of using cinching cords or lace ties on the front of the boot. Both of these ideas were based on what competitors had done in prior years, and this designer draws on this competitor inspiration in the discussion with the team. She shows pictures of the competitor boots with these same features and says to the team, *"…another option is we can do a 'tongue' like this and then you can cinch the tongue down."* She also offers the idea, "*…that [competitor] boot, that kids boot that ties [and] has the lace on the front. It's like a cotton lace and it's really cute… I think we should explore that as an option, too."* There were dozens of conversations that centered on these competitor features and how to incorporate them into their new boot design. Even the project manager draws on competitors' products, she identifies a trend in using non-functional bungee cords on the boots from researching their competitors and offers that as a suggestion to the team. These examples show how the team heavily considers competitor products in their own concept development process.

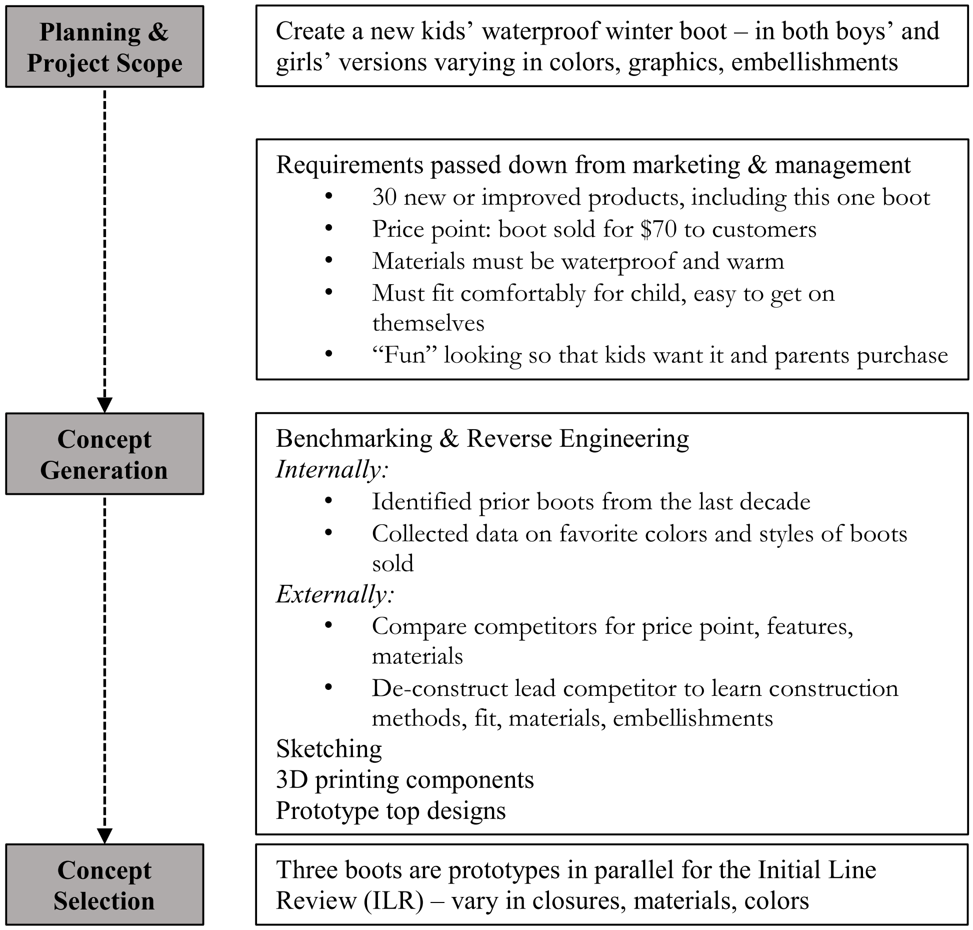

Figure 16. Footwear Company reconstruction of design methods during early stage design process

The team also reverse engineered their top competitor boot to understand the materials, construction, fit, and embellishments. In reverse engineering the product, they cut apart the product to deconstruct each material and attachment method. They used this information in making final decisions about their product. The lead product developer de-constructed the competitor boot and showed it to the rest of the team. He stated, "*if anyone wants to look at the cut-away from the bootie [come look at this sample]. It's their own [proprietary] process. But I think we can replicate this process for our own creation."* One of the other team members inquired with a material specialist within their company if they can replicate the waterproof material and construction process. The team used what they learned from reverse engineering the competitor boot to solidify important material and construction aspects of their new boot product.

In addition to benchmarking and reverse engineering related products, the team also 3D printed potential embellishments. They considered adding a flower feature to the boot, so they had a 3D print of it created in-house and used that as a way to further generate ideas and improve the over design.

Once the team decided on a general direction for the new boot, they decided to prototype three options in parallel. They wanted to explore three different closure systems, materials, and colors. The project manager proposes this parallel prototyping idea to the team before the Initial Line Review (ILR) stating: *"Do we have time to sample this [boot] in three options? ...on how it closes, just sample the different closure options? And we can even vary the materials across them so that we can narrow in on a decision. Get more bang for our buck with these samples."* It this short quote, the manager brought up the idea that the team can create three prototypes for ILR, with each prototype sample varying in material and closure. These prototypes are sketched, turned into line art, and then prototypes are hand-crafted from the European office and shipped back to the United Stated before ILR.

The footwear company uses a variety of design methods: benchmarking, reverse engineering, sketching, 3D printing, and parallel prototyping to aid in their concept generation. They use several design tool software, including Adobe Illustrator and SolidWorks, for creating digital mock-ups of the possible concepts. They also use their in-house 3D printer and cobbler/sewing materials to create the physical prototypes.

4.2.5.3 Case 3: Medical Devices Company

Within the medical device company, the project observed was the development of a new laparoscopic medical device. The company tasked the team with creating a "new" device that would win them more of the market. This enabled the team to creatively explore options for this device, as long as it met the needs of the surgeons, medical staff, and hospitals. The project scope was set by the marketing team. They had surveyed surgeons and discovered that there was an opportunity to develop a device that heavily considered ergonomics and human factors into the design.

For this device, there were several guidelines identified, as shown in Figure 17. These guidelines emerged from a team activity using the fishbone diagram method. A fishbone diagram can also be referred to as a "cause and effect diagram" or "Ishikawa diagram", and it is a visualization tool for categorizing the potential causes of a problem. The project leader led the session and helped the team think about future potential problems with the device so that they could scope a better project. It was decided that the primary purpose of the new product, as stated in the design brief, was to *"improve the ergonomics, especially the ability for surgeons to use the cutting and sealing features in an easy and intuitive manner"*.

After setting the project scope and specifications, the design team began their process by benchmarking the competition. They identified their primary competitor in this product space, ordered several of their products, and began to reverse engineer their design. During a team meeting, one of the engineers stated, *"We really like the ergonomics of this [competitor] handle. The button placement is perfect; it requires the 'right' amount of pressure to engage. It's also a good weight and size. I think we can just copy this for our design…"* In this quote, it becomes very clear that the team learned valuable lessons about the competitor product during reverse engineering and that it led to them directly copying certain factors for their new product, including the handle design.

Additionally, the team also tested and reverse engineered their own similar products. In a meeting during the first month of the design project, the project manager started the meeting by passing around a display of one of their related products that was dissected. This product was labeled, with each of the components displayed individually in relation to where it would be assembled. It was like a real-life version of an exploded assembly drawing. Then, there was a live demo where the team could use a few of the current products and test them. Many of the engineers had never held these products. One of the engineers mentioned right after the demo that *"I feel like I really understand how this feels now. It's great, but I also get the awkward handle-button placement while cutting and sealing."* This engineer was able to gain a deeper understanding of the problem with the ergonomics of the current medical device handle through testing the current products. This learning will help him when improving the ergonomics of the new product.

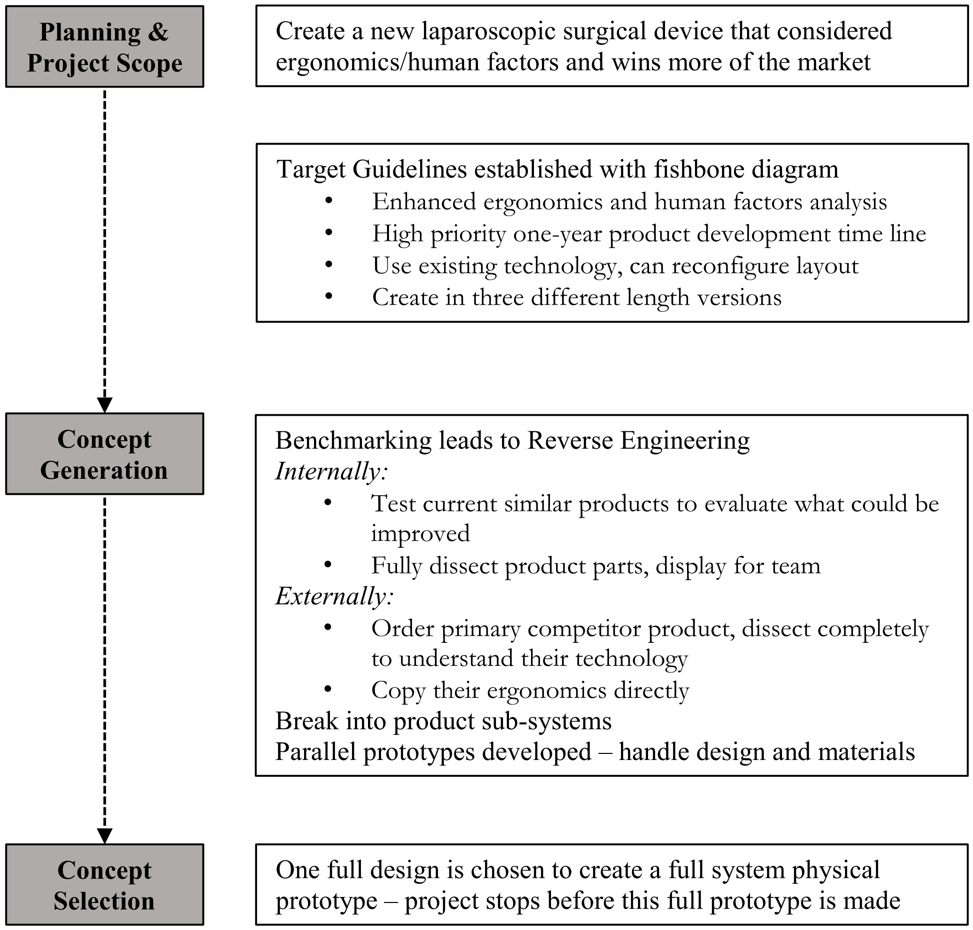

Figure 17. Medical Device Company reconstruction of design methods during early stage design process

The design team also chose to break this complex product into sub-systems. These included: mechanical design, mechanism design, electrical components design, system integration/software, and human factors. One of the engineers on the mechanical design and human factors teams was tasked with selecting the handle materials and understanding the human factors that would heavily influence the ergonomics. In a meeting he stated, *"we ordered two [prototypes] in parallel. We are trying to flush that [the materials] out in the design process."* In this short quote, he indicated that the team parallel prototyped different handle materials and angles as a way to further refine their concepts and make a final decision.

This medical device company engaged in several different design methods during the early stages of the design process. First, they used the fishbone diagram method to further scope the project. Then, they used benchmarking and reverse engineering of both internal and external products during concept generation. Finally, they broke the problem into sub-sections, which can be considered a form of functional decomposition. Through this method, they began to parallel prototype different materials and angles of the handle. They used SolidWorks software to model the different handles for 3D printing them.

4.2.6 Discussion

This comparative case study of three companies mapped out the early stages of the design process, specifically indicating the design methods used. Each company was tasked with creating a new product: 1) the consumer electronics company created a new audio board, 2) the footwear company developed a new kids' waterproof winter boot, 3) and the medical device company created a new surgical device. The early stages of the design process include the elements of concept development, including planning and project scoping, concept generation, and concept selection as shown in the top of Figure 18 (gray boxes). Below these three stages, we summarize the design methods used by the companies (blue and yellow boxes). Design methods and tools are used by design teams to help them move through stages of product development.

It becomes clear when comparing across these three very different companies that there are two design methods employed by them all during concept generation: *benchmarking and reverse engineering* (yellow boxes in Figure 18). These techniques were used by each company for products within the same field (i.e. footwear only compares to other footwear products). Each company used benchmarking and reverse engineering both internally and externally. Internally, they identified similar prior products in their company to understand where improvements could be made and what technology or designs could be leveraged. Externally, they identified key competitors' products to learn about aspects like product construction, materials, features, embellishments, ergonomics, price point, and overall value to customers.

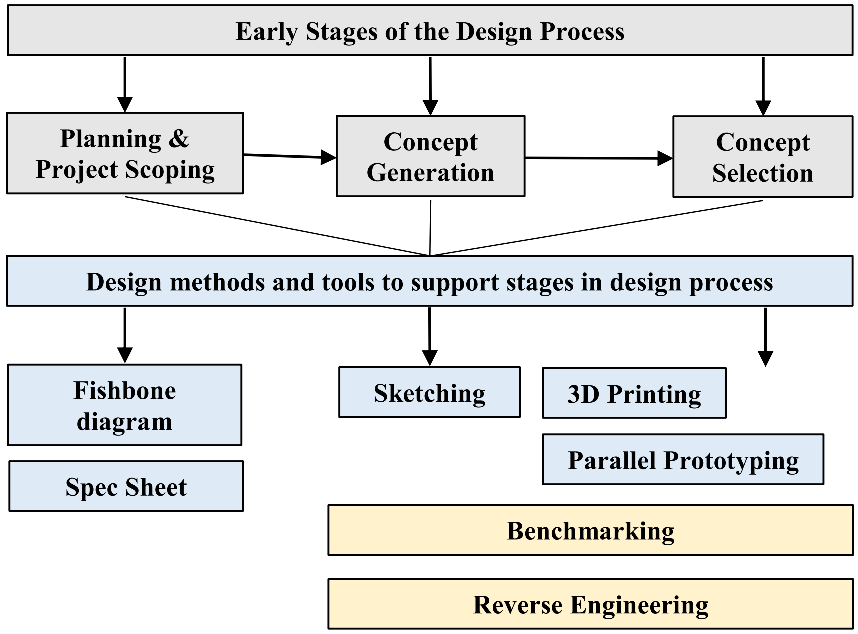

Figure 18. Design methods used during early stages of design

These companies engaged in reverse engineering techniques to further uncover the best and worst aspects of their competitor products. The consumer electronics company purchased their competitor's audio board, and de-constructed the technical components. The footwear company purchased their key competitor's winter boot, and they de-constructed it to learn more about the materials and construction process to inform their own material selection and manufacturing processes. The medical device company purchased their competitor's medical device, and analyzed it for ergonomics, human factors like grip and button placement. Each company used the learnings from reverse engineering to inform the direction of their current product development and to incrementally improve their design to ideally outperform their competition.

We believe that product development can be divided broadly into two categories: evolutionary or revolutionary products [178], [193]. Evolutionary products are developed in incremental steps, building on the similar products that come before them. Whereas, revolutionary products can make huge leaps in development in terms of aspects like materials, manufacturing process, or technology features. Revolutionary products disrupt the traditions of a field. Another interesting similarity across these companies was that they all ended up creating "evolutionary" products. The companies considered all of these projects "new" products. This begs the question of whether the design process or design methods employed by the companies caused them to create more "evolutionary" versus "revolutionary" products. The methods of benchmarking and reverse engineering could cause the design teams to become fixated on the current design space, limiting them being able to see other novel, creative, and unique solutions to the problem.

The companies also all seemed to compress the design process phases together, constantly moving between systems-level and detailed-design elements based on the design methods that they employed. It appeared that concept generation naturally led each team directly to concept selection, partially due to the lack of choices/concepts developed. This compression of concept generation and selection could be in part due to the design methods used, as benchmarking and reverse engineering tend to move the team into a final solution space. None of the companies consulted design research literature or best practices to identify other design methods to employ during their product development processes. This makes us wonder whether the teams would embrace new methods, like design heuristics or design by analogy during concept generation, if these methods were introduced to them. This also begs the questions of how to best translate design methods and tools developed in academia to industry? There are so many methods being developed by researchers that could help companies during product development, yet these companies are unaware of their existence.

This research identifies how three companies used design methods in the early stages of product development. This comparative case study is not generalizable to all industries, but it provides some interesting insights into how professional designers engage in the early stages of the design process. This study created many more questions for the design research community. How do these empirical insights about professional design practices inform design theory and future design methods? Does benchmarking and reverse engineering during concept generation cause design fixation and ultimately only incremental improvements to the product ("evolutionary" product development)? Should companies engage in different design methods based on their desire to create more "revolutionary" new products? Would benchmarking or reverse engineering across disciplines lead to more revolutionary products (compared to these methods employed only within their own field)? How can we better translate design methods and tools to industry? And how can these observations and insights from industry best translate back into design education?

We do not have answers to these questions yet, but we believe that each question brings up valuable ideas to consider in the future. We hope that this study creates a platform for an interesting discussion amongst the design research community, especially in terms of translation of design methods to companies. In future research efforts, we aim to begin to address some of these issues and research questions identified.

4.2.7 Conclusion

In conclusion, this research explored how three companies engaged in the early stages of the design process. Specifically, we uncovered the design methods used by professionals during concept generation. All three of the companies employed two design methods: *benchmarking and reverse engineering*. This is an interesting insight, since these companies were diverse: ranging from consumer electronics, to footwear, to medical devices. Each of the companies believed that they were engaging in "new product development", and yet they all developed "evolutionary" products that only slightly improved that status-quo of products in the market.

This research study is valuable for the field of design theory and methodology because it empirically uncovers how three different companies engaged in concept generation methods. There are dozens of concept generation methods and tools developed in academia, and yet these companies are unaware of their existence. This creates a lot more questions for the design research community, such as: How do we better translate design methods into industry? And do methods like benchmarking and reverse engineering cause design fixation, resulting in only incrementally better final products?

This research also has direct implications for design education. Through studying the design processes in three companies, we uncovered how professionals engage in benchmarking and reverse engineering as key techniques for evolutionary product development. These are helpful insights because it validates that these two methods are prevalent in industry, which means that they should be taught during project-based courses for students. Additionally, this research shows that many companies engage in evolutionary product development. This mindset is helpful for students so that they are not always trying to re-invent something that has already been created. This shows the value in doing extensive research about similar products, as a way to learn how to improve on the existing technology. It is also valuable to teach students the differences between evolutionary and revolutionary product development. The design process approach and methods used for these two types of products are likely different. This can help design educators' better frame the methods taught and used in their design courses to ensure that students are well-prepared for their specific projects, whether for new product development or otherwise.

4.3 Chapter 4 Summary

In this chapter, I introduce the three companies in this research from the fields of consumer electronics, footwear and medical devices. These companies all create evolutionary physical products, meaning that they constantly develop the next version of a prior product. This chapter explores how prototyping methods, like reverse engineering and benchmarking, are used in early stages to solidify the design intent. I map out the process that the design teams use as a mean for others to understand the broad nature of prototypes and how aspects like benchmarking and reverse engineering are critical steps taken by design teams in industry when creating evolutionary products. These insights can be translated back to design education; techniques like benchmarking and reverse engineering should be taught as methods for early prototyping in design courses since they are critical in professional settings.

I also propose the notion that reverse engineering is considered a form of prototyping, especially during evolutionary product development. My definition of prototype is that it is a physical or digital embodiment of critical elements of the intended design, and an iterative tool to enhance communication, enable learning, and inform decision making at any point in the design process. In these companies, the teams reverse engineer competitors' products as a way to physically identify aspects to include in their intended final product. Also, it is used as a tool to enhance communication amongst the team, enable learning about product elements, and also make decisions related to their final product. Reverse engineering is used as a tool to actively refine the concepts and push the team towards a final product.

Chapter 4 introduces the three companies in this research. These companies are the central focus of Chapters 5 and 6. Chapter 5 describes the emergent roles of prototypes: as tools for communication, learning, and decision making. Chapter 6 then describes how the primary purpose of prototypes shifts based on the context of use. These following two chapters build our understanding of prototypes use in companies. These insights can translate back to design education, while also gaining a deeper theoretical understanding of prototypes various roles throughout the design process.

Chapter 5 – The emergent roles of prototypes in companies

5.1 Introduction

In this chapter, I describe the three overarching emergent roles of prototypes across the three companies. Prototypes are tools for communication, learning, and decision-making. These insights validate prior literature, while adding new perspectives through exploiting each of these roles further. I also introduce a new definition for a prototype and provide some insights into becoming aware of the intentional and unintentional actions of prototypes. This chapter emphasizes how prototypes are actors on design teams, influencing actions and behaviors throughout the design process.

Section 5.2 is the current journal article in press entitled “What is a prototype? What are the roles of prototypes in companies?” to the ASME Journal of Mechanical Design (JMD) [188]. This paper is co-authored with my co-advisors, Daria Kotys-Schwartz and Mark Rentschler. Following the paper, Section 5.3 offers a summary of the paper and transitions into Chapter 6, which describes how these roles of prototypes change based on the context of use.

5.2 What is a prototype? What are the roles of prototypes in companies?

Prototyping is an essential part of product development in companies, and yet it is one of the least explored areas of design practice. There are limited ethnographic studies conducted within companies, specifically around the topic of prototyping. This is an empirical and industrial-based study using inductive ethnographic observations to further our understanding of the various roles prototypes play in organizations. This research observed the entire product development cycle within three companies in the fields of consumer electronics, footwear, and medical devices. Our guiding research questions are: What is a prototype? What are the roles of prototypes across these three companies? Through our analysis, we uncovered that prototypes are tools for enhanced communication, increased learning, and informed decision-making. Specifically, we further refine these categories to display the types of communication, learning, and decision-making that occur. These insights are significant because they validate many prior prototyping theories and claims, while also adding new perspectives through further exploiting each role. Finally, we provide newly modified definitions of a prototype and prototyping based on this empirical work, which we hope expands designers' mental models for the terms.

5.2.1 Introduction

"Prototyping is one of the most critical activities in new product development" [1], and yet "prototyping may be simultaneously one of the most important and least formally explored areas of design" [2], [57]. Research on the product development process has often focused on early stages of design, such as concept generation and selection [4]–[8], [194], [195]. Topics like sketching [9], [10], [182], [196], design fixation [11]–[13], [197], and product dissection [14], [198], [199] have been studied extensively. More recently, studies have begun exploring the phase of prototyping within mechanical engineering [2], [15]–[19], [55], [56]. Most of these studies focus on developing strategies to prototype [2], [15], [18], [19] or on testing specific hypotheses, such as if fewer parts in prototypes correlate to better final designs [16], [17]. These contributions have largely studied student design teams in universities, which has significantly contributed to our understanding of prototypes [2], [10], [12], [15]–[17], [19], [56], [57]. However, there are relatively few studies regarding the role of prototypes within company contexts [22], [23], [93]. We contribute to this area by exploring the nature of prototypes across three diverse industries, which allows us to compare our findings to the existing literature on prototypes. Our research inductively derives three roles and a new definition for prototypes using a grounded theory approach [200]; the insights emerge from empirical observations over ten-months in companies in the fields of consumer electronics, footwear, and medical devices.

5.2.2 Relevant Literature

5.2.2.1 Prototyping in the Design Process

Research around prototyping has increased in the last two decades. There is an abundance of prototyping studies from fields like computer science and human-computer interaction (HCI), while limited-in-comparison studies from mechanical engineering. Within the field of mechanical engineering, researchers have developed several prototyping strategies for novice designers [2], [15], [18], [55]–[57]. Students, as a type of novice designer, often have a narrow perception of prototypes, and thus need guidance while prototyping [58], [59]. In these frameworks, novice designers are prompted with questions prior to prototyping ranging from topics about the technical elements of the intended design to resource allocation and management.

While there are numerous prototyping taxonomies, models, and frameworks [20], [41]–[43], [45], [49], there is "still a lack of knowledge about the fundamental nature of prototypes due to their complex and dynamic nature" [20]. Houde and Hill's seminal work on prototyping from HCI describes prototypes as existing on an interactive triangle with four main features: role, implementation, look and feel, and integration [43]. Recommendations from their work include defining prototypes broadly, building multiple prototypes throughout the design process, and preparing prototypes based on the audiences. As such, we have taken a broad approach to defining prototypes as any manifestation of the design, to ensure that we capture all prototypes and prototyping practices in our research. Our focus is to add value to the field by validating some of these prior findings, while adding new insights around the roles of prototypes from industry.

5.2.2.2 Empirical Studies of Design Practice

Empirical studies of companies further our understanding of 'design in the wild', which is critical to developing grounded theory out of practice [28]. Early design researchers used empirical data from companies, like Kodak [1], Apple [201], and other high tech firms [22], [23], [51], [94] to understand design practices before developing theories or strategies to implement in organizations.

Several prominent researchers have studied design practices, and subsequently shifted mindsets about the field and 'science of design' including Simon [30], Schön [38], and Latour [77], [144]. More recently, scholars from the field of engineering, such as Bucciarelli [76], [84], [85] and Treveylan [81], [109], specifically studied engineering design in practice. Design work is often considered fundamental to engineering, and thus observing engineering in practice gives insights to the entire design process [25]. Bucciarelli's *Designing Engineers* presents a critical perspective on the profession of engineering design [76]. He argues for a view of engineering as a social construction process reconciling goals, objectives, tests, and interpretations in the development of a product by participants with perspectives from different 'object worlds'. Similarly, Trevelyan studied professional engineers in locations across Australia and Asia. He states that "the foundation of engineering practice is distributed expertise enacted through social interactions between people: engineering relies on harnessing the knowledge, expertise and skills carried by many people, much of it implicit and unwritten knowledge. Therefore social interactions lie at the core of engineering practice" [81, p. 175]. This is referred to as technical coordination, where the social is always intertwined in the technical [109]. We believe that this concept of technical coordination is essential to the creation of prototypes; it helps explain how designers coordinate various technical knowledge and embody it within a prototype.

There are two qualitative research studies that were conducted within company contexts and focused specifically on understanding prototyping [22], [23]. Gerber and Carroll conducted an 18-month ethnographic study of a high-tech firm using the theoretical framework of design as a learning process. This study focused on the psychological experience of engaging in low-fidelity prototyping, and their outcomes showed that low-fidelity prototyping allowed employees to reframe failure as a learning opportunity, support a sense of forward progress, and strengthen beliefs about creative ability [22]. The second empirical study described how prototypes are used to elicit 'unknown unknowns' on company projects [23]. Unknown unknowns are aspects of the design not considered prior to building and testing the prototype. They conducted a mixed-methods study, using a collection of observations, interviews, and artifacts. They analyzed nineteen prototypes across eight companies in terms of functionality, timing, stakeholder involvement, and requirement elicitation. Both of these research studies further our understanding of prototypes in companies. Our research builds on these empirical studies, by using ethnographically informed methods and a grounded theory approach to understand the various roles prototypes serve across three different industries.

5.2.2.3 Theorizing Objects in the Design Process

Since prototypes are at the core of this research, we surveyed relevant theories describing objects during the design process. Two of the most well-established theories include Vinck's intermediary objects [126]–[128] and Star's boundary objects [163], [202]. Intermediary objects mark a transition from one stage of the design process to another, or else coordinate meaning between different groups of people. They act as communication and coordination tools, while also mediating and exploring the roles between people. Boundary objects have a broader interpretation; they can be concrete or abstract objects or ideas, which are also a form of communication between people. Within engineering design, an example of a boundary object is a CAD drawing. This drawing is used to communicate design intent between engineers and machinists;

the object is robust enough to maintain a common identity between parties, and yet plastic enough to adapt to local needs and constraints of the various people employing them.

Within engineering design, Henderson studied visual representations in the design process, ranging from sketches to computer models to prototypes [203]. She argues that material objects are critical in the design process; and she reported that design cultures are intrinsically tied to how product representations are constructed in companies, and that these visual representations create tacit knowledge [143]. People gain tacit knowledge when creating prototypes, often about materials, manufacturing processes, and other technical aspects. This knowledge is embodied in the time taken to plan, build, test, and iterate on the prototypes, which can be difficult to replicate through more traditional learning methods like reading or lectures. Henderson used guiding principles from Actor-Network Theory, which acknowledges that both humans and objects are equal 'actors' when analyzing social situations. This shift in thinking about objects as equal in importance to humans opens new opportunities for seeing the value that objects, like prototypes, add during design projects.

5.2.3 Research Design

This is a qualitative research study, which allows us to observe design practices and ask open-ended questions about *how* prototypes are used and *why* they are used in those instances [190]. There is not one straightforward research design for a qualitative study. As Maxwell summarizes, "qualitative research design…is a 'do-it-yourself' rather than an 'off-the-shelf' process, one that involves 'tacking' back and forth between different components of the [research] design, assessing their implications for one another" [121, p. 3]. In this research, we borrow techniques from various traditions, such as ethnography, case studies, and grounded theory. We combine these approaches to answer our guiding research questions: What is a prototype? What are the roles of prototypes across these three companies? These guiding questions are open-ended and broad so that we do not limit the scope of our inductive analysis and emergent findings. These research questions emerged from our prior work in companies [110], [111] where we observed the importance of objects in the design process, and from our pilot studies that uncovered the differences in definitions and understandings of prototypes between students and professionals [59].

5.2.3.1 Conceptual Framework

The conceptual framework for this research is informed by the theory of heterogeneous engineering from the field of Science and Technology Studies, which has roots in Actor-Network Theory. Heterogeneous engineering was a concept first introduced by Law [204] and then used by Suchman [80] to describe the process of building a bridge. Heterogeneous engineering is the view that engineering design is a complex system of mutually constitutive social and technical relations. When Suchman examined a quintessential engineering project, building a bridge, she found that social processes are not merely an aspect of the design that is separable from technical processes; rather, the design of the bridge represents the mutual constitution of material and social relations through the joint production of a stable artifact [80]. This informed our study in the way that we analyzed the data, as we searched for instances that combined interactions between people and objects, namely the development of prototypes. Additionally, we used the social science theories on objects (i.e. Vinck's intermediary objects [126]–[128], Star's boundary objects [163], [202], and Henderson's visual representations and tacit knowledge [143], [203]) described in the Relevant Literature to aid in our data analysis, especially during theoretical coding as described in Figure 19.

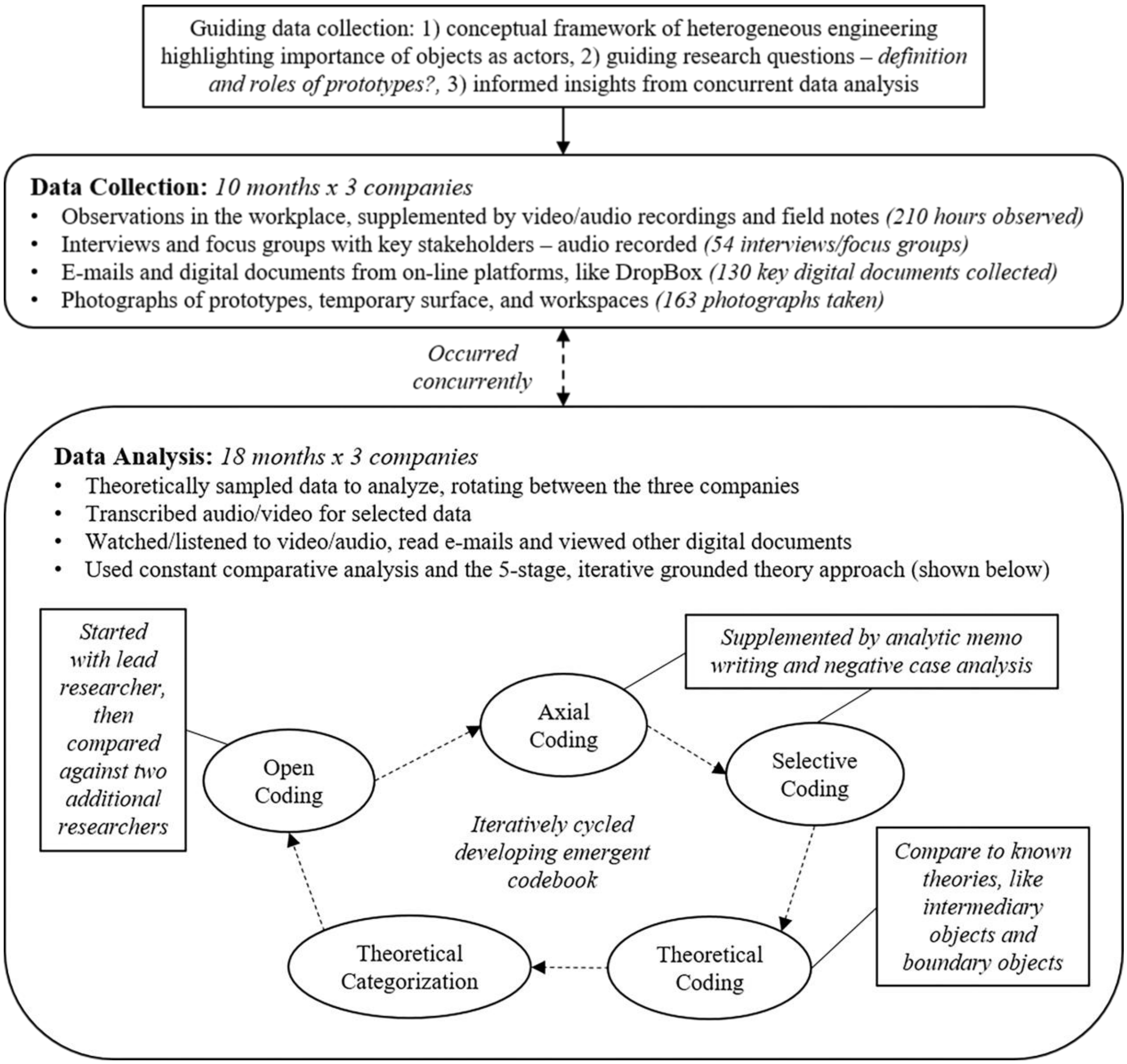

Figure 19. Research methods process

5.2.3.2 Companies

We studied three companies from the United States, each for the duration of one product's design and development. An overview of the companies is in Table 10. These companies mass produce physical products in the fields of consumer electronics, footwear, and medical devices. The diversity in companies allows us to compare the role of prototypes across them during data analysis.

Table 10. Summary of companies in research study

	Company 1	Company 2	Company 3
Industry	Consumer Electronics	Footwear	Medical Devices
Project Followed	Audio Board	Kid's Winter Boots	Surgical Device
Dates of Observations	March to December 2016	March to December 2016	June 2014 to March 2015
Duration of Observations	10 months	10 months	10 months
Size of Core Design Team	4 people	8 people	15 people
Status of Product	Launched	Launched	Project on hold

5.2.3.2.1 Company 1: Consumer Electronics Company

The first organization is a medium-sized, privately held consumer electronics (CE) company. There are approximately 200 employees at their headquarters, where all of the design, manufacturing, and distribution occurs. At CE, there is a primary engineer assigned to each design project, and they are required to conduct the majority of the design work for that project. The engineers typically work on three to six projects at a time, and they are each responsible for launching up to thirty new or revised products a year. The engineer must complete three internal design reviews that serve as major milestones in their product development process: one for the specification and requirements product report, one for the conceptual design and schematics of the product, and one to review the first round of full system prototypes. The lead engineer collaborates with two representatives from production and quality assurance and the engineering manager for these reviews. The project we observed was the design of an electronic audio board. The product development occurred over ten months, beginning in March 2016 and ending in December 2016; the audio board launched in early 2017.

5.2.3.2.2 Company 2: Footwear Company

The second organization is a large, publicly held footwear (FW) company with their headquarters in the United States and offices worldwide. There are approximately 2,000 employees involved in the design and development processes. FW starts the design process for a season of footwear 18-months before the products launch. Their process is broken into four major phases: design, early development, late development, and commercialization. Within each phase, there are several major milestones. In this research, we observed the kids' footwear team and the creation of a new snow boot for the fall/winter 2017 line. The design process began in March 2016 and the boot development was finished in December 2016. Between January and April 2017, the team worked to finalize commercialization details and mass production, and then the product line launched in August 2017.

5.2.3.2.3 Company 3: Medical Device Company

The third organization is a large, publicly held medical device (MD) company specializing in surgical products. The headquarters is in the United States, and they have eight additional manufacturing, distribution, and design facilities globally. There are approximately 3,500 employees worldwide. Their design process is influenced by the medical device regulations in the US. There are strict verification and validation stages, where immense testing and documentation occur to ensure the product passes all requirements. We observed the development of a surgical device. The project began in June 2014, and it was observed until March 2015 when the project paused due to company re-structuring. This project is still on-hold, although majority of the design and development work is complete.

5.2.3.3 Data Collection and Analysis

In this qualitative study, we borrow techniques from ethnography, grounded theory, and case study research to aid in data collection and analysis. Data analysis began concurrently with data collection, and continued for eight months following. Figure 19 displays the iterative process used during this research study and highlights the various techniques for data collection and analysis.

5.2.3.3.1 Data Collection – Ethnographically Informed Methods

We use a variety of fieldwork methods to capture participants' activities throughout the product development cycle. Our approach to data collection is ethnographically informed, and includes both direct and indirect methods for conducting fieldwork in modern societies [158]. The guiding research questions and conceptual framework influenced data collection, as shown in Figure 19. As such, we paid attention to social situations when people interacted or referenced different objects, such as prototypes.

These methods for data collection include: 1) observations in the workplace; 2) written field notes during observations that are subsequently summarized and logged daily; 3) audio-recordings of informal interviews, inspired by the traditions of ethnographic interviews [123], which occurred at the beginning of the research to build rapport and understanding and then towards the end to validate emergent findings; 4) audio or video-recordings of individual and collaborative activities including team meetings and design-stage gates; 5) collection of materials and artifacts that are produced by participants during their work, which includes 6) photographs of physical paper documents, 7) shared copies of electronic documents (i.e. e-mails and online collaborative platforms like DropBox), and 8) photographs of temporary surfaces like whiteboards, spaces and rooms where design activities took place, and 9) any physical artifacts like prototypes. These types and amounts of data collected are displayed in Figure 19.

Data collection occurred at the companies for the entire duration of each product's development. The time spent at each company varied by week, depending on the access and the number of meetings or events occurring. The primary researcher was given security badge access and office space to work at each location, further embedding them as participant observers at the companies. During the first few months at each company, the primary researcher spent between five and ten hours at each company per week, spread out over two to three days. As the research progressed, they visited the companies once a week for two to four hours. The hours of observations were reduced once the research team reached saturation in understanding the role of prototypes. Saturation in qualitative data occurs once there are no additional emerging themes from the concurrent data analysis.

5.2.3.3.2 Data Analysis – Grounded Theory Approach

Data analysis was influenced by the techniques used in grounded theory development [191]. It takes an inductive, comparative, and interactive approach to inquiry and offers several open-ended strategies [200]. Three tenants of grounded theory are: 1) creating the conditions for emergent inquiry through the systematic and active scrutiny of data; 2) the successive development and checking of emergent categories; and 3) the use of constant comparative analysis [205]. It intertwines data collection and analysis. The emergent themes from early analysis inform future data collection.

In conducting our analysis, we used the five-level coding procedure for constant comparative analysis as shown in Figure 19 [190], [200], [205]. These phases are conducted iteratively until theoretical saturation is reached and no new themes emerge. These five-levels are: 1) Open Coding, segmenting initial data into preliminary categories; 2) Axial Coding, organizing preliminary categories into broader themes; 3) Selective Coding, refining categories and themes towards an overarching theory or framework; 4) Theoretical Coding, comparing themes to known theories and concepts, and; 5) Theoretical Categorization, developing a sound theory or framework to describe the phenomena in the study.

The lead researcher transcribed and initially coded the theoretically sampled data. Theoretical sampling is selecting subsequent data to collect and analyze along criteria that will allow us to test and expand the scope of our grounded theory. As such, we often select potential negative cases of data to validate or expand our coding scheme. Then, two additional researchers analyzed the data independently using the evolving codebook. Each researcher would highlight or select portions of text that supported any of the primary, secondary, or tertiary codes. As a team, we used a combination of Microsoft Word/Excel digital data documents, physical printed copies of data, and the NVivo platform to code our data and evolve our codebook. This codebook evolved into its final state, displayed in Table 11, after achieving unanimous agreement amongst the three researchers. Unanimous agreement is reached when there are no discrepancies between the data coded by the three independent reviewers.

An example of coding data is shown here: as one researcher reads through a transcription of a design meeting after watching the video clip, they highlighted the segment of text *"we were wondering if we should move these lights [on the prototype] …or something?"* and link this language and actions to the primary code of "communication", the secondary code of "gathering feedback", and the tertiary code of an "active medium". In this example, the product developer is speaking while holding and interacting with the prototype. This person is talking to the rest of the design team, trying to gather their feedback on what changes should be made to the lights in the current design. It is critical to triangulate multiple types of data during analysis – video data, verbatim transcriptions, and the field notes – to gain a holistic picture. The field notes aided in selecting the data initially, then it was transcribed by the primary researcher, followed by the research team watching the video clip during a data analysis meeting, and then finally each researcher coded the transcriptions, and these were compared to one another to populate the evolving codebook.

We used constant comparative analysis to compare codes and categories from previously collected data to those of recently collected data, as supported by analytic memo writing [154]. We also considered each company to be their own case and subsequently used a comparative case study approach to aggregate the different categories for the roles of prototypes between the three organizations. The research team gathered once a week for 60-90 minutes over 18-months to review the theoretically sampled data and iterate and evolve the codebook, as displayed in Table 11.

Table 11. Data analysis codebook

Main Codes	Sub-Codes	Tertiary-Codes	Definitions
Communication	Explain	1) Standalone representation (passive) 2) Active medium	Using prototypes to explain the idea, concept, or design. This can include better defining the intent or trying to create a similar mental model between multiple people.
	Feedback		Using prototypes as a medium to facilitate feedback from others on how to improve the design.
	Negotiate		Using prototypes to negotiate aspects of the design.
	Persuade		Using prototypes to persuade others to choose the design or aspects of the design. This could be considered "priming" others to sell the idea, too.
Learning	Product space	1) Reinforcing knowledge 2) Gaining new knowledge	Using prototypes to learn about the product design space. This includes understanding related designs, companies, similar products (benchmarking), new technologies, reverse engineering, and more.
	Technical elements		Using prototypes to learn more about technical aspects of the design related to feasibility, functionality, and the processes required to create it. This can occur through building and testing, reverse engineering, trouble-shooting, experimenting, and similar.
	User interest		Using prototypes to learn more about users' interests both internally in the organization and externally with consumers and other key stakeholders.
	Business related		Using prototypes to learn about business related elements. This can include topics like costing, BOMs, supply chain aspects, processes to create the artifacts, and similar.
Decision-making	Desirability	1) Incremental 2) Milestones 3) Reference points	Using prototypes to make decisions about desirability of the design from multiple users' perspectives.
	Viability		Using prototypes to make decisions about viability of the design related to the business aspects.
	Feasibility		Using prototypes to make decisions about technical elements of the design related to feasibility, functionality, and processes to create it.

5.2.3.4 Ensuring Validity

There are various strategies for ensuring validity in qualitative projects [121], [153], [206], and suggestions from these articles have informed the validity of this study. Maxwell outlines eight methods to ensure validity [121, pp. 125–129], and we use seven of these methods to strengthen our qualitative study: 1) intensive long-term involvement with the companies (10 months at each company); 2) rich data collection in multiple forms (i.e. video, audio, transcriptions, digital documents); 3) respondent validation of the emergent themes; 4) searching for discrepant evidence and negative cases; 5) analysis conducted on a diverse research team; 6) triangulation of multiple sources of data (i.e. comparisons between observations, field notes, interviews, e-mails); and 7) comparisons between the emergent roles of prototypes across the three companies as different cases.

5.2.4 Emergent Findings

5.2.4.1 Emergent Roles of a Prototype

First, we describe the three salient roles of a prototype that emerged inductively. Our findings suggest that prototypes 1) enable communication, 2) aid in learning, and 3) inform decision-making. A prototype can encompass multiple roles at once. Each role can be further refined by sub-codes and tertiary-codes, allowing for richer descriptions of the roles. For example, "persuade" is a sub-code under "communication", which allows us to discuss how prototypes can act as a tool to persuade others about the design as a specific type of communication. In the following sections, we explore these three overarching roles of a prototype in each of the three companies, while emphasizing the sub-codes and tertiary-codes for each of these roles. In the Discussion section, we compare how the emergent themes validate existing literature and also provide new perspectives.

5.2.4.1.1 Role 1: Prototypes Enable Communication

The first emergent theme is that prototypes enable communication. We identify four types of communication enabled by prototypes, which include:

(1) explaining a concept,

(2) enabling feedback,

(3) facilitating negotiations, and

(4) persuading others.

For each of these, prototypes are a communication tool either as a passive standalone representation or an active medium for discussion. Prototypes are passive when they are referenced or discussed without direct interaction and active when they are being physically or digitally interacted with by individuals.

Prototypes enable communication by creating a similar mental model between people, thus reducing the cognitive burden that can occur during an abstract, verbal conversation. Thus, they create a common design language. As part of persuasion, prototypes can be used to induce a priming effect on people. This can result in making decisions on a project based on being primed by a prototype at a meeting, which could alter the decision compared to if those people were never shown that prototype. Often, multiple types of communication are enabled in the same situation around the same prototype. For example, a prototype can first create a common language between two or more people. Then, once that common ground is established, it can be used to gather feedback or negotiate aspects of the design.

To exemplify this theme of communication, we first show an excerpt from a weekly team meeting at the Footwear Company. In this meeting, one product developer updates the rest of the team on the changes to the prototype of the kids' snow boot. In discussing these changes, the product developer uses the prototype as an *active medium* (Figure 20, top) to further *explain* the detail of the alterations. Every time the words "here", "it" or "this" are used, it refers to the prototype on the table.

> <u>Product Developer:</u> *So as the boot grew [in height], our angle has changed here in the boot. So as you grow taller, it is going to kind-of come up a bit. So I'm going to work to correct the sharpness of the turn and then kind of clean all this up. And this will be vertical.*
>
> <u>Project Manager:</u> *Is that the right height? Are we good? We feel good about that height [on the boot]?*
>
> <u>Product Developer:</u> *As far as our instructions go, yeah we are. Um, so, everything will be sharpened and angled instead of just these squiggly free lines. Though, seeing this, you do have*

this gentle movement here in the heel-collar, um, is there anything you guys are seeing? Should it be swoopy? Should it be hard-edge?

<u>Project Manager:</u> *I think it's too swoopy.*

Figure 20. Prototypes of the kid's winter boots from the Footwear Company: early iterations of different materials, boot heights, and closure systems

In this instance, the prototype assists the team in multiple forms of communication. First, it is used by the product developer to *explain* the changes with the boot, thus making everyone aware of the current design. Then, it is used to *facilitate discussion and feedback* from the team members. In this excerpt, the project manager responds to the product developer and asks for clarification on the height of the boot, while also trying to facilitate discussion amongst the team so that they can make a decision regarding the boot height. The product developer responds to the height concern and poses two vague questions to the team: *"Should it be swoopy? Should it be hard-edged?"* These statements can be made because the prototype is used as a reference point in the conversation, with little concern for misunderstandings. This mixture of verbal conversation and physical interaction with the prototype aids the team in developing a shared understanding how the next iteration of the boot will change. In this example, the prototype of the boot is a tool that creates enhanced communication between the members on the team, which reduces the chance of any miscommunication and different interpretations.

The ability for prototypes to create clear communication is further demonstrated when compared to an example when no prototype is used during a team meeting. In this segment, there are three engineers from the Medical Device Company discussing a button feature on the surgical device being designed. The engineers are confused by the terminology, as some call this button feature a rocker switch. Some people use the terms interchangeably, while others feel that they are distinctly different.

<u>Engineer 1:</u> *By button, do you mean the rocker switch?*

<u>Engineer 2:</u> *Yeah. Obviously, well—that doesn't mean that—the rocker button it's called... The switch is different.*

<u>Engineer 3:</u> *Well I was kind of curious about the nomenclature with that, too. Because there's two buttons on the rocker switch, and so you see what I'm saying?*

<u>Project Manager:</u> *Don't call it a switch. It's not a switch, it's a button.*

This challenge in nomenclature about a feature on the prototype causes delays to the team meeting. In this example, the "button" versus "rocker switch" discussion occurred for ten minutes and derailed the primary purpose of the team meeting. One remedy to this challenge is showing the part of the prototype that is being discussed, either digitally or physically, as a way to create a common language (or similar mental model) between parties. This combination of verbal conversation and visual representation, through a prototype, could reduce the chance of confusion when explaining something technical to the team. This miscommunication on the surgical device is similar to what could have occurred with the boot when they used terms like “swoopy” and “hard-edge”. The terms can be interpreted differently, causing mental burden and confusion, without the aid of visual representations like prototypes during the discussion.

We provide one final example from the Consumer Electronics Company that shows how prototypes are used to *persuade* others. In this example, a cross-disciplinary team from engineering, manufacturing, quality-assurance, and marketing meet to discuss where the company should invest in new products. They have an open platform where any employee can submit product ideas. In this meeting, the team discusses four new ideas submitted by employees. Out of these ideas, two receive a “yes” to move forward towards product development, while the other two ideas receive a “no”.

The two ideas that received a “yes” were both further developed concepts; one idea had a simple prototype built to prove the concept. The marketing manager stated in regards to one of these “yes” projects that, *“I really like effort here – the direction this seems to be going.”* The engineering manager further comments on the concept with the prototype, stating that *“he has already proven the concept here, even roughly. I think it is worth pursuing further now.”* The other two ideas that were given a “no” were less specified in their submission, and that ambiguity in the design seemed to drive the decision to reject the proposals. The engineering manager stated, *“I just wish that this person would have taken the time to fill out the spec. It just shows no effort at all.”* The manufacturing manager added, *“I don’t even know what it is that they want to make or what problem they are trying to solve.”*

There were likely several factors that contributed to these decisions; one factor being that the simple prototypes were a *priming tool* to influence decision-making. These prototypes, one as a written detailed description/specification list and the other as a photographed representation of the physical object, were able to communicate clearly the intended products. In this instance, the simple prototypes served as a standalone representation for the managers to interpret. It is important to be cognizant about this psychological priming effect of prototypes throughout the design process, as it can influence decision-making based on perceived effort, rather than the merit of the concept.

In summary, prototypes provide value to companies, especially in enabling clear and concise communication between multiple stakeholders. These examples support our claims that prototypes are communication tools for explaining a concept, gathering feedback, aiding in negotiations, and persuading others.

5.2.4.1.2 Role 2: Prototypes Aid in Learning

The second emergent theme is that prototypes aid in learning. We have uncovered several categories where learning occurs through developing, interacting, or referencing prototypes. These include using prototype to learn about:

(1) the design space, including comparable products and related technologies;

(2) technical elements required in the design;

(3) users' preferences, interests, and behaviors; and

(4) business-related topics, such as costing for materials and manufacturing.

For each category, those involved can learn new information or reinforce already learnt knowledge through the prototypes. Our approach to identifying these types of knowledge gathering techniques is similar to how others have described the design process as working towards understanding and discovering values for all of the *known unknowns*, *unknown knowns*, and *unknown unknowns* about the product [23], [207]. Known unknowns are questions the designer knows need to be answered through testing prototypes. Unknown knowns deal with the unknown knowledge of the involved stakeholders. Unknown unknowns include details whose existence and relevance is unknown to the engineering designer.

One way that companies often learn about the product space early in the design process is by benchmarking related designs. Benchmarking can be as simple as browsing competitors' products and reading online reviews, or it can be a more complicated process using techniques like reverse engineering. We consider reverse engineering a product to be a form of prototyping, especially if the intent is to borrow techniques for materials and construction or to solidify the design of their new product.

We first show an example of benchmarking and reverse engineering a competitor product, as a form of prototyping for learning, from the Footwear Company. This example comes from a weekly team meeting, where team members discuss the design of the kids' snow boot. The present team members are the product developer, project manager, and product designer. The product developer is responsible for bringing this product to mass production; part of their job is material sourcing and establishing the procedure for boot construction. The project manager oversees the entire team and focuses on meeting milestones and staying within their allocated budget. The product designer works on front-end product ideation, and is responsible for creating the 2D product representations that are then given to the product developer to build. In this excerpt, these three people are discussing the changes to the boot prototype through comparing it to a competitor product. The team purchased a competitors' boot, which they deconstruct to evaluate the materials and construction. They compare the competitor boot next to their current boot prototype to evaluate the aesthetics and functional closures.

<u>Product Developer:</u> *Right now we have solved [the] waterproof [problem] up to this point. And the only thing left is…*

<u>Project Manager:</u> *Now I just don't feel like it's a $70 boot…*

<u>Product Designer:</u> *How much is that [competitor] one?*

<u>Project Manager:</u> *$70*

<u>Product Designer:</u> *Well, we'd have to put some trims on it and stuff.*

<u>Product Manager:</u> *I'm also wondering if we should copy them [the competitors] and have double tabs?*

<u>Product Designer:</u> *Yeah, yeah. That's a good idea.*

<u>Product Developer:</u> *Put tabs on either side [of the boot] instead of just the back?*

<u>Product Manager:</u> *Yes.*

In this segment, the project manager uses the competitors' boot to spur possible changes to their design. Both the current prototype boot and the competitors' boot sit side-by-side on the table and are being physically interacted with at this meeting. Prior to this meeting, the product developer deconstructed one competitor boot to evaluate the waterproof materials (reverse engineering), which aided in solving *"the* *waterproof problem"*. At the end of the discussion, the team ultimately agrees with the project manager and they change the boot to include two side tabs on the next iteration of the prototype.

As shown in this example, the competitor boot allows the team to learn more about the *product space*, including design features and costing, through interacting with the competitor product. They are *reinforcing their knowledge* about costing when they indicate that the competitor boot with its number of features is *"worth $70"*. This knowledge then challenges how many features, like the side tabs, must be included on their product so that it can be worth the same value as their competitor (*business aspects*).

In addition to learning more about the product space, prototypes also help the team understand *technical aspects* of the design. Building and testing prototypes aid the designers in building tacit knowledge around the product [208], including uncovering known unknowns and unexpected technical areas (which can be considered the unknown unknowns). If the prototypes do not work as intended, then they can be deconstructed, or "debugged", to aid in learning about technical aspects. This process can solidify technical knowledge for the designers.

In the next example from the Consumer Electronics Company, we show how prototypes can enhance learning. Their new product development process requires building and testing several full-system prototypes to ensure that all questions about the product's feasibility, desirability, and viability are answered. In this interview segment, the lead engineer ordered several integrated circuits (IC), referred to as *"chips"*, to prototype and test for use in the audio board product. The strategy was to prototype several options on breadboards to learn about what was desired in the final design. Through building multiple prototypes of the potential system, the engineer learned about related products and technologies, while enhancing her own *technical understanding* of audio boards. In this interview, the engineer reflects on how interacting with these prototypes gave her *new perspectives* on the form, usability, and desirability of the product. She printed the IC schematics and data sheets to aid in these breadboard prototypes and made notes on the physical sheets of paper as part of her own learning process (Figure 21, top). These notes are valuable for creating future schematics for the project, and are also a *reflection of her technical learnings*.

<u>Lead Engineer:</u> So the features I wanted came from using this [chip]…

<u>Researcher:</u> You learned what you wanted in the final design? And also what didn't work with it?

<u>Lead Engineer:</u> Yeah, so I was like I don't want to deal with any crazy software. I don't want to do too much file conversion to get it on there, like if I can't just plug it in, load it, and then use it then I don't want it. And I think that's the way that a lot of customers are, too. [The customers] who are starting out.

<u>Researcher:</u> So you are trying to be in the shoes of the customer when designing the product?

<u>Lead Engineer:</u> Right, exactly.

In this example, the lead engineer is learning more about the *product space* and *technical elements* that are required in the design. These learnings are embodied in the multiple chips tested and notes written on the printed schematic (Figure 21, top). Her learnings then help to inform decision-making, which is the third role of a prototype.

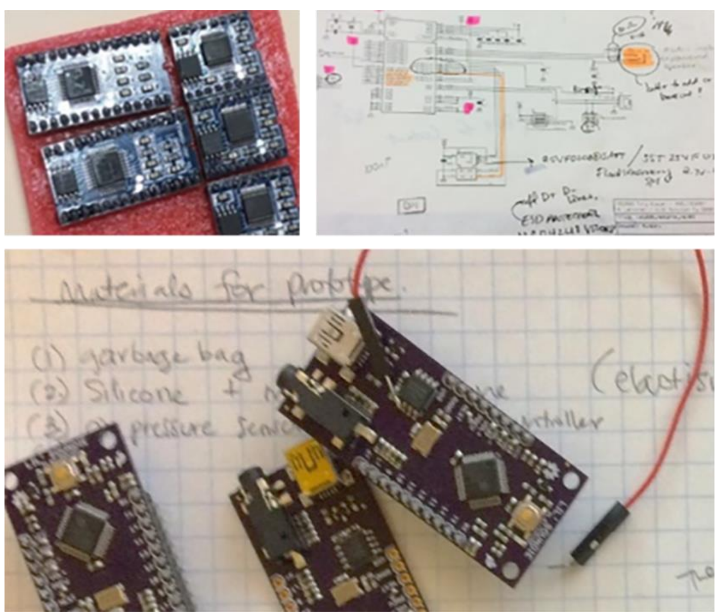

Figure 21. Prototypes from the audio board project at the Consumer Electronics Company: sample integrated circuits (IC) for breadboard prototypes (top left), notes for improvement on IC schematic from prototyping (top right), and full-system prototypes (bottom)

We provide one final example of how prototypes aid in learning from the Medical Device Company. At the project kick-off meeting, the team spent the first day understanding the current version of the surgical device on the market, and then the remainder of that week scoping the design project for the improved device. It was decided that the primary purpose of the new product, as stated in the design brief, was to *"improve the ergonomics, especially the ability for surgeons to use the cutting and sealing features in an easy and intuitive manner"*. There was harsh feedback from surgeons on the current version, indicating that the design of the surgical device did not accurately take into consideration the process the surgeon goes through when using the device in the operating room. This feedback was part of the motivation for this project, along with optimizing the temperature distribution.

The team facilitator took the current device apart and labeled all of the components (Figure 22, top). Prior products, like this first version of the surgical device, are considered prototypes since they are used as a baseline product that provides critical feedback when designing the improved the next version; these prior products help solidify the intent of the project. All of the prior products/prototypes were passed around the meeting room so that each team member could physically interact with the devices. The team also watched a live demonstration of the surgical device using meat as the pseudo-tissue. Afterwards, the woman leading the demo allowed others on the team to try the device on their own; five employees chose to use the device. One employee, who was a new engineer to the company, said right afterwards, *"I feel like I really understand how this feels now. It's great, but I also get the awkward handle-button placement while cutting and sealing."* It is clear from the statement that by interacting with the prototype this engineer was able to *gain a new level of learning* about the surgical device. The engineer experienced first-hand the ergonomics of the device, and this learning about the *functionalities* will help him when improving the ergonomics of it.

A statement we heard multiple times in various forms across all the companies is that "prototypes help you learn what you know and learn what you don't know." It is easy to imagine that a design will work perfectly in your mind, and by creating prototypes you can validate if these ideas work in reality. Prototypes can help employees learn more about the product space, technical elements, user preference, and business aspects. These learning from the prototypes can then inform decision-making, which is the third theme.

Figure 22. Prototypes of the benchmarked surgical device components (top) and two different material handle halves created in parallel (bottom) from the Medical Device Company

5.2.4.1.3 Role 3: Prototypes Inform Decision-making

The third and final emergent theme is that prototypes help inform decision-making during the design process. We explore how interacting with or referencing a prototype leads to decisions that are better informed. We have seen prototypes help make decisions in three broad categories, including the:

(1) desirability of the product,

(2) viability of the product, and

(3) feasibility of the product.

Decision-making is at the core of the design process; it is what allows you to move between stage-gates and meet deadlines [209]. Decisions around *desirability* deal with personal preferences from the design team, end-users, and all stakeholders. Decisions around *viability* include all business-related aspects, such as things like material costs, supply chain, and production rates. Lastly, decisions around *feasibility* deal with all technical aspects of the design from core components to system integration. Often, a single prototype can answer questions related to all three of these topics. This can speed up time in the design process, and move the product towards completion.

Prototypes help inform both small and large decisions. On design teams, prototypes can aid in incremental decisions on a daily basis. These small decisions culminate into a more refined prototype that is presented at major milestone meetings. As such, prototypes act as critical milestones for design projects, and, at these points in time, larger decisions can be made to continue forward with the product, pivot directions, or cancel the project altogether. These milestones, such as internal or external design reviews, add accountability to the project and keep the team on a schedule. By requiring prototypes and testing to occur, the team can ensure that members are held accountable. We see earlier iterations of prototypes referenced later in the design process; in these instances, the prototypes act as a reference points to anchor the decision-making about the product.

To exemplify this theme of decision-making, we share examples from the three companies. At the Footwear Company, prototypes often help answer critical questions tied to all three sub-codes at once: desirability, viability, and feasibility. In the following excerpt, the design team meets to discuss changes to the kids' boot prototype after the first large milestone review with external stakeholders. After the external review, the design team synthesized the stakeholders' feedback, using the current prototype to spur additional insights. Two of the major concerns were the materials used and the functional closures.

> <u>*Project Manager:*</u> *So we just want to talk to you [the Material Specialist] about this guy [boot prototype]. We sampled it in two materials: one was a coated PU and one was a nylon. I don't know if you can see the difference – this is the nylon and this is the PU. We like the nylon; it seems*

to be a little richer [in quality] than the PU. I don't think we got costing on it so we aren't sure if you know what the material is and [how much it costs]?

<u>Material Specialist:</u> *Wasn't that [PU] the keystone material, [Product Developer]?*

<u>Product Developer:</u> *So in the upper [material of the boot] in the BOM we've got the upper material as the PU. And then [the other prototype] is the keystone [nylon material], so yes.*

<u>Project Manager:</u> *You fit this [prototype] right? Kids didn't have a hard time getting this [boot] on and off?*

<u>Product Developer:</u> *Yeah it's a good C10 [size]. For a snow boot, it's more of a rain boot fit. It is a little tighter in terms of the shaft and the diameter. We know this type of a boot functions fine for us.*

<u>Project Manager:</u> *Do we have time to sample two options? On how it closes? Just sample two different closures.*

<u>Product Developer:</u> *Absolutely. It may not be in all color or… but if the components are very similar [and we are] just using them in a different way, [then] yes.*

In this example, the prototypes are used to aid in decision-making about materials, end-user fit, and functional closures, which relate to all three topics: *viability, feasibility, and desirability*. The prototypes presented at the design reviews acted as milestones in decision making, while the iterations on materials for prototypes are considered as tools for incremental decisions. In the excerpt, the team compares the current prototypes for the material costing (viability), and they determine that two more prototypes need to be created to test the closures (feasibility). The team confirms that the current prototypes have been tested with potential end-users to see if the kids like them (desirability) and if the kids can easily put the boots on their feet and close them (feasibility).

We show another example of how prototypes aid in decision-making from the Consumer Electronics Company. Their new product development process includes ordering a production ready prototype to test the technical elements of the board before they commit to mass production. In this example, the lead engineer on the audio board project describes how this project required two rounds of full-system prototypes, which is more than normally expected under ideal conditions. The second round was needed because the device would not work properly; the lead engineer "debugged" the system over several days with many incremental decisions based on the prototypes. These prototypes are shown in the bottom of Figure 21; the one with the red-wire is the initial full-system prototype, and the other two are the newly updated pre-production prototypes. These prototypes informed decisions around technical functionality for the final design and served as both milestones and incremental decision-making platforms.

> *Lead Engineer:* *So I ended up going through two rounds of prototypes.*
>
> *Researcher:* *Did that help you decide on what features to include?*
>
> *Lead Engineer:* *Yeah, and some things just didn't work [on the first prototype] … What I ended up doing was I made this huge map and printed out where each connection was being made and I actually applied a voltage directly to each one to see what was happening.*

In this example, the first full-system prototype was used to check the technical elements of the design. This prototype was needed to validate the functionality, which included checking if it worked as intended compared to the paper schematic prototypes. The full-system prototype also confirms whether the product can be made cost effectively in terms of materials, components, manufacturing processes, and time so that the business can remain profitable (viability).

We describe one final example of how prototypes aid in decision-making from the Medical Device Company. The team is on a tight one-year schedule for creating this new surgical device. To meet deadlines, they create prototypes in parallel to inform their decision-making. At this weekly team meeting, the different material options for the surgical device handle are discussed. By prototyping two material options in parallel (Figure 22, bottom), the team can make decisions about the aesthetics and location of the buttons (desirability), functional elements like the space needed to house the printed circuit board within the handle (feasibility), and the cost of a mold for mass production (viability) quicker than if they prototyped them in sequence. In this example, the project manager and one mechanical engineer discuss the status of the prototypes and the materials tested.

Project Manager: *Then my second question is, you mentioned bosses [in the material]. Has the material strength of glass-filled versus virgin material been completed?*

Mechanical Engineer: *It hasn't. In this prototyping process, we went ahead and ordered two different materials. We ordered two just to see if they're—if we can get away with using an ABS [plastic]. We're trying to flush that out in the design process, but we haven't by any means selected a material [yet].*

Project Manager: *Okay. Yeah, please include [another engineer] on that. He's a good resource for suggestions [on the material] and whatnot.*

In this example, the prototypes of the handle halves allow the team to discuss aspects related to feasibility, desirability, and viability all at once. Prototyping multiple handle materials in parallel helped the team to make a decision on final materials for the device, which relates to viability from a costing and material standpoint and then feasibility from a technical perspective. These prototypes serve as milestones for decision-making in the process for materials.

Decision-making is at the core of the design process, and it is the critical underlying role of prototypes. Prototypes often transcend all three roles at once; they aid in communication between people, facilitate deeper learning, and ultimately aid in more informed decision-making.

5.2.4.2 New Modified Definition and View on Prototypes

Finally, we present a new viewpoint on prototypes in the design process, which includes our own modified definitions for a prototype and prototyping. Bucciarelli argued that "design is just as much about agreeing on set definitions and negotiating as it is about producing the final technical artifacts or product" [76]. In our research, we recognize that the term prototype is complex, and thus sought to understand the meaning of prototypes from practice [59]. We propose a new definition based on these three roles of a prototype, which we hope will be further discussed, negotiated, and re-defined by the design research community.

Prototypes are complex and dynamic artifacts that shape many social situations during product development. We conceptualize prototypes as both active *tools* used in the design process and as influential *actors* impacting social situations. As tools, prototypes are devices used to *actively* carry out *intentional* functions. Prototypes are tools used to for specific tasks throughout the entire design process, such as gathering performance data during testing to make informed decisions. As actors, prototypes shape social situations and networks, either *intentionally* or *unintentionally*. Prototypes are actors that can either *actively* or *passively* shape social situations during the design process. As a passive and unintentional actor, prototypes might be left on display in the office and cause impromptu conversations and discussions about the product that ultimately influence the direction the team takes. As both *tools* and *actors,* designers and other stakeholders can see the value prototypes add as a platform for communication, facilitator in learning, and aid in decision-making in social situations. It is important to recognize that prototypes influence situations both intentionally and unintentionally, through both active and passive usage. These insights may appear as subtle distinctions in language and terminology, but we believe that this fundamental shift in mindset of *prototypes as tools and actors* throughout the entire design process can influence designers' approaches to prototyping.

An engineering prototype is often described as a means to "verify or improve functionality, performance and operation of a novel device or system" [2] or "an approximation of a product along one of more dimensions of interest" [39]. These definitions emphasize prototypes' purpose as aiding in technical elements of the design. Early in our research, we chose to broaden the scope of the term prototype based on prior literature, mainly from the field of HCI [20], [43]. The definitions provided here are broader than these traditional engineering definitions, and grounded in our emergent findings.

> *A **prototype** is a physical or digital embodiment of critical elements in the design, and an iterative tool to enhance communication, enable learning, and inform decision-making at any point in the design process.*
>
> ***Prototyping** is the process of creating the physical or digital embodiment of critical elements of the design.*

In this modified definition, we use *design* as a broad term to include anything from an initial idea to final product, service, or process. We use the phrase *physical or digital embodiment* to acknowledge the various mediums and levels of fidelity that a prototype can embody. Prototype mediums can range from 2D, including hand sketches, story boards, paper digital interfaces, and lines of code, to 3D, including foam models, CAD renderings, 3D printed parts, and breadboards, to even 4D, including role playing, virtual reality, interactive processes, and service design. These mediums are physical, digital, and immersive in the fourth dimension. Prototypes can also range in levels of fidelity from low-fidelity models created with simple materials like cardboard to high-fidelity models that include some of the same materials and components as will likely be in the final product.

We acknowledge that this definition of a prototype is very broad. Just as others have noted [23], a broad definition can lead to misunderstandings of what the term prototype encompasses. Although it is argued that this can hinder exploitation of its full potential, we believe that we must first acknowledge this breadth of the term prototype, and then subsequently be more purposeful in describing prototypes and their various functions in the future.

5.2.5 Discussion

"Current terminology for describing prototypes centers on attributes of prototypes" [20], and as such, we focus less on the attributes of prototypes and more on the *actions* that the prototypes enable. Our conceptual framework of heterogeneous engineering views prototypes as equal and important actors in the design process. Their manifestation influences social interactions, and therefore, enables new types of communication, learning, and decision-making. Our findings add to the body of literature from many social scientists on the importance of artifacts in the design process. Communication, learning, and decision-making as broad categories are not novel topics for prototypes; rather, we add new perspectives in the emergent sub-themes and tertiary-codes for each of these roles as seen in Table 11 and described in the following three paragraphs.

Prototypes, as objects in the design process, are well-established as a mode for communication [84], [85], [126]–[128], [163], [202]. They are a significant form of design language [16]. They mediate many social and technical situations [77], [80], [144], acting as a sort of 'social-glue' [203]. Envisioning the design process as an 'object world' [84], it expands our interpretation of how prototypes shape social situations. We build on these theories and claims by exploiting how prototypes can be active or passive standalone mediums for communication (tertiary-codes under communication in Table 11). As a tool for communication, prototypes enable a shared understanding amongst people, which often reduces misunderstandings between stakeholders. Further, we divide the types of communication into four categories: explaining a concept, enabling feedback, facilitating negotiations, and persuading others (sub-codes under communication in Table 11). The latter two sub-roles highlight the 'power' that prototypes embody. They serve as an actor on the design teams influencing the future course of action for decisions to be made.

Professional designers are often considered reflective in practice [38]. By interacting with prototypes, these designers can reinforce knowledge and/or gain new knowledge about the design space, such as 'unknown unknowns' [23]. Further, interactions with prototypes can enhance designers' tacit knowledge of a design space [203]. We divide learning through prototypes, whether new knowledge or reinforcing knowledge (tertiary-codes under learning in Table 11), into four topic areas: design space, technical elements, user-interest, and business-related topics (sub-codes under learning in Table 11). We exploit the broad nature of prototypes, indicating that benchmarking and reverse engineering products can be considered a form of prototyping, too. Viewing prototypes as vessels of knowledge can emphasize their importance to design teams and companies hoping to retain knowledge of best practices and lessons learned.

Prototypes have been described as milestones in the design process [39], or objects that mark transitions between stages [128]. Prototypes help to answer questions related to desirability, viability, and feasibility [57], [201]. We discuss prototypes further through breaking them into three categories: tools for incremental decisions, milestone decisions, and reference points to inform current decisions (tertiary-codes under decision-making in Table 11); and by also describing how prototypes enable decisions to be made in parallel or sequentially about topics related to desirability, viability, and feasibility (sub-codes under decision-making in Table 11). Prototypes evolve over time, and as such, each incremental decision culminates into more refined milestone prototypes, eventually leading to the launch of the product. There is value for companies in recognizing how the decisions made with each incremental prototype influences later decisions during milestones, and how prototypes as reference points from the past also can influence present-day decisions.

Further, we recognize that prototypes are "complex and dynamic in nature" [20]. Our data suggests that prototypes first create clear communication between all stakeholders and support learning, as means to then *enhance* and *inform* decision-making. For example, referencing the data from the Footwear Company, we see how the prototypes for the new children's winter boot are used for communication and learning before making informed decisions. Referring to the data in Role 1: Communication, we see the initial physical full-boot prototypes as a platform to explain the concept, gain feedback, and negotiate requirements first. Then, these conversations lead to new learnings for the product developer about the angle for the boot entry point and overall height. Here, the prototype boot is a tool for communication and learning first, which then aids in making a unanimous decision to change the boot height and angle. Referring to the data in Role 2: Learning, we see that the competitor boot spurs ideas about how to make their product more desirable, while still achieving a low-cost and functional solution. These learnings emerge from interacting and reverse-engineering the competitor boot, and then these insights are discussed. The prototype is used as a tool to ensure that communication is clear amongst the team members. Finally, the team reaches decisions about changing the closure, side-tabs, water-proof material, and price-point based on the learnings and communication that happened first.

Our data suggests that there is a typical process to how the roles of a prototype manifest: prototypes must first be tools for communication and learning, sometimes sequentially or in parallel, before they can *better inform* decision-making. The key is that these decisions are being informed by the prototype itself, with support from the clear communication and enhanced learnings that come prior. We created a simple model to exemplify this process and the interactions in Figure 23. This is not meant to be a prescriptive model, but rather a descriptive way to visualize how the roles of prototypes manifest in practice.

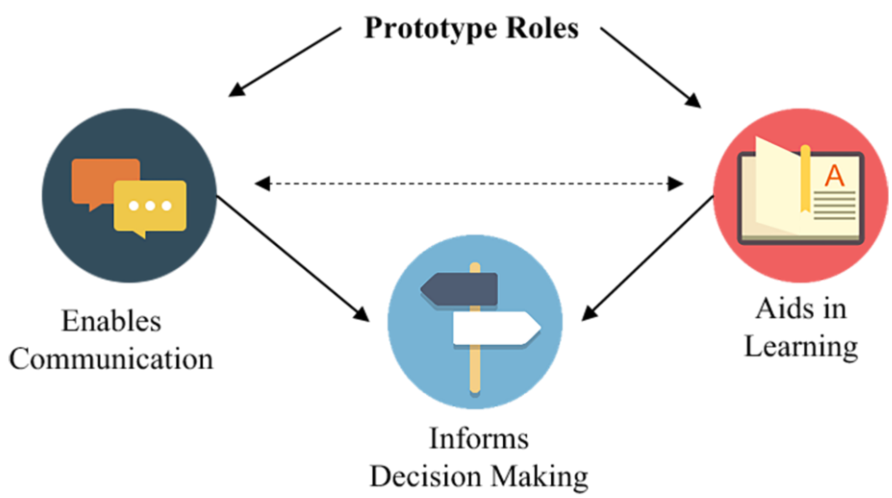

Figure 23. Three emergent roles of prototypes: communication and learning to support decision-making

5.2.6 Conclusion

In conclusion, this research answered our two guiding questions: What is a prototype? What are the roles of prototypes across these three companies? The findings come from our empirical and industrial-based study using ethnographic observations and inductive analysis across three companies in the fields of consumer electronics, footwear, and medical devices. We provide a modified definition of a prototype, based on empirical evidence that includes the three emergent roles. "*A prototype is a physical or digital* *embodiment of critical elements in the design, and an iterative tool to enhance communication, enable learning, and inform decision-making at any point in the design process."* In this definition, we recognize the importance of conceptualizing prototypes as both intentional tools and often unintentional actors in the design process.

Decision-making is at the heart of the design process [209], and likewise, decision-making is at the heart of prototyping. We posit that there is a typical process that the roles of a prototype manifest, and our data suggests that prototypes are tools for communication and learning first to then better inform decision-making (Figure 23). Prototypes are physical or digital manifestations of the design, which allow people to interact with the artifact and use it as a tool during conversations, to gather feedback, negotiate, or persuade others, while also learning more about the requirements for the final design. Ultimately, the end pursuit for a prototype is informing, and enhancing, decision-making in the design process to launch a product to market.

Finally, we acknowledge that as a design research community we need to negotiate and further debate the definition of a *prototype* since it is a broad and ambiguous term. Instead of focusing just on the attributes of prototypes, let us also focus on the actions and outcomes from using prototypes. We provide our new, modified definition of a prototype as a platform to increase conversations about prototypes between different industries and academic spaces, and to challenge preconceived notions and traditional engineering mindsets about what are considered prototypes.

5.3 Chapter 5 Summary

In this chapter, I describe the roles of prototypes across these three companies: as tools for communication, learning, and decision-making. Current terminology for describing prototypes centers on attributes of prototypes, and as such, I focus less on the attributes of prototypes and more on the *actions* that the prototypes enable. Communication, learning, and decision-making as broad categories are not novel topics for prototypes; rather, I add new perspectives in the emergent sub-themes and tertiary-codes for each of these roles. This chapter builds on prior chapters in this dissertation; it uses the conceptual framework of prototypes as objects of design coordination from Chapter 3 and it presents a new definition of prototypes based on the misconceptions for the term in Chapter 2.

Prototypes are complex and dynamic artifacts that shape many social situations during product development. I conceptualize prototypes as both active *tools* used in the design process and as influential *actors* impacting social situations. As tools, prototypes are devices used to *actively* carry out *intentional* functions. Prototypes are tools used to for specific tasks throughout the entire design process, such as gathering performance data during testing to make informed decisions. As actors, prototypes shape social situations and networks, either *intentionally* or *unintentionally*. As both *tools* and *actors*, designers and other stakeholders can see the value prototypes add as a platform for communication, facilitator in learning, and aid in decision-making in social situations. These insights may appear as subtle distinctions in language and terminology, but I believe that this fundamental shift in mindset of *prototypes as tools and actors* throughout the entire design process can influence designers' approaches to prototyping.

In the following chapter, I build off of the work presented in Chapter 5 and describe how the primary role of prototypes shifts based on the context of use. In the next chapter, I provide an in-depth case study at the footwear company, mapping out how the prototypes travel between contexts serving different primary purposes. I explore five unique contexts and describe how these contexts are defined. This chapter furthers our understanding of how objects, like prototypes, have power and influence in the design process.

Chapter 6 – The changing roles of prototypes based on the context

6.1 Introduction

In this chapter, I discuss how the primary purpose of prototypes changes based on the immediate context of use. This is an in-depth case study at the footwear company and it explores five unique contexts within this company's design project for a new kid's waterproof boot. This chapter builds on the work presented in previous chapters in this dissertation. It further shows how benchmarking and reverse engineering are critical early prototyping tools in evolutionary product development from Chapter 4. It builds on Chapter 3, describing how prototypes are coordinating objects influencing the design process. And lastly, this chapter builds on Chapter 5, which describes the three primary emergent roles of prototypes on design teams in industry.

Section 6.2 presents the journal paper entitled "Shifting Purpose: Contextual Influence on Prototypes Roles," which is currently in review for publication in the Design Studies journal. This manuscript is co-authored with Daniel Knight, Daria Kotys-Schwartz, and Mark Rentschler.

6.2 Shifting Purpose: Contextual Influence on Prototype Roles

Prototypes are complex and dynamic artifacts that shape social situations during product development. They are representations of critical design elements, and iterative tools to enhance communication, enable learning, and inform decision-making. A ten-month ethnographic study of a footwear company uncovered how the primary purposes of prototypes changed based on the context of use. This case study explores five unique contexts, and uncovers that the primary role of the prototypes shifts between a tool for communication, learning, and decision-making. Results also suggest that prototypes both influence the context and are simultaneously impacted by the context. These insights can help designers, project managers, and other stakeholders become aware of the benefits and biases prototypes create in common situations throughout the design process.

6.2.1. Introduction

"So you have a prototype – and it is a pretty robust medium, right? And then if you don't use that prototype for its intended purpose. Well, then you actually go backwards in the [product development] process." In this interview excerpt, the Director of Product Development at the footwear company GlobalWear reflects on the importance of prototypes during the design process. In hindsight towards the end of product development, this executive realizes that prototypes are critical objects that must be used for their intended purposes to ensure forward progress. The act of a project manager or executives' reflection-in-action [38] can be used as an opportunity for organizational learning that then translates to changes in organizational structure, procedure, or strategy. The goal of this paper is to bring awareness to how prototypes can influence different social situations, whether through their ability to persuade stakeholders, uncover unknowns about the product, or inform decision-making prior to market launch. Other companies have reflected on their product development processes as a means to better run their organizations [94], [210], and it is the hope that this research can help company stakeholders become aware of how prototypes are intentionally, or unintentionally, impacting their product development processes.

This case study retrospectively explores the use of multiple prototypes on one project tasked with designing a new children's waterproof winter boot at a footwear company, referred to by the pseudonym GlobalWear. *What do we consider a prototype in this research?* The term prototype can be interpreted differently, especially on diverse design teams with members from various backgrounds and experiences [59]. We define a prototype as "a physical or digital embodiment of critical elements in the design, and an iterative tool to enhance communication, enable learning, and inform decision-making at any point in the design process" based on our inductive analysis of prototypes within three companies [160]. When describing prototypes' attributes, they often are defined in terms of fidelity and mediums. Prototypes exist along a spectrum of fidelity between the physical and digital space: ranging from low-fidelity paper prototypes or digital sketches to high-fidelity pre-production models or renderings [20]. In terms of actions, prototypes enable enhanced communication, learning, and decision-making. Prototypes are "*robust mediums",* as stated by the executive at GlobalWear, and we interpret this to mean that prototypes are objects that can embody multiple meanings and enable various actions, such as a single prototype both serving as a vessel of knowledge and an active form of communication between stakeholders.

This research engaged in qualitative methods to collect and analyze data on the prototypes at GlobalWear [121], [158], [211]. Through our analysis, we uncover that the primary purposes of various winter boot prototypes changed based on the context of use. We provide a new framing for these "prototype contexts", by holding the company, project, and design process constant, and instead highlighting variations in context due to the people, period of time, place, underlying purpose of the context, prototype medium, and prototype usage. These insights can help designers, project managers, and other stakeholders become aware of how the role of prototypes changes throughout common situations during product development. If we understand how prototypes are currently being used, consciously or unconsciously, then it can help to enhance our communication, learning, and decision-making around prototypes moving forward. This reflection on prototypes throughout the product development process can then be used as a vehicle for organizational change if needed [101], [201], [212].

6.2.2 Theoretical Framework

Design is an equally social and technical process [84], where the social dynamics always underpin the technical elements to manifest a product or solution. Design involves the coordination of knowledge, resources, goals and requirements that come from multiple stakeholders, like management, clients, and users [213]. Prototypes are critical objects that embody technical knowledge and mediate many social situations between stakeholders, including communication [91], [202], power dynamics [143] and decision-making [74]. They are objects that traverse the concept to knowledge (C-K) space [214]. Social scientists have long studied the use of objects during engineering and design projects [85], [126], [143], [144]. Objects, like prototypes, are considered static until they are given meaning through socially-constructed environments where they are being created, tested, explained or negotiated [215]. Objects' realities are constantly being enacted through interactions with humans, thus their reality can change based on the immediate situation or context [216]. In this study, we consider one type of object – *prototypes* – and how they are used, interpreted, negotiated – or *enacted* – through different contexts during a design project.

In this case study, we use Mol's *the body multiple* theory [217] to analyze prototypes during product development. Mol developed a new ontological perspective on abstract or concrete objects through uncovering their multiple enactments in practice. Specifically, her work investigated a vascular disease, known as atherosclerosis, and how it is practiced, studied, researched, remedied and treated in a Dutch hospital. Each of these practices is a type of enactment of the disease; each enactment is different, such as the disease being studied by pathology researchers in a medical laboratory and then also being treated with exercises during patient rehabilitation. In Mol's account, the ontology of an object is decentralized to a multitude of practices. She shows the different enactments of disease in the human body, coming to the notion that objects have *"more than one [enactment] but less than many [or infinite]."*

Building off this theory, we explore how prototypes are enacted on a company design project in multiple ways during product development. We refer to the enactment of prototypes through their uses or actions they enable during social situations. We use a framework that views prototypes as tools for communication, learning, and decision-making to analyze the enactment of prototypes on one company design project [160]. We refer to communication as the imparting or exchanging of information; learning as both the gathering of new knowledge and the reinforcement of already learnt knowledge; and decision-making as the action or process of determining something or of resolving a question. As a tool for communication, prototypes can explain a concept, gather feedback, negotiate requirements, or act as a form of persuasion. As a tool for learning, prototypes enable knowledge acquisition of the product space, including technical, business, or human-related aspects for the intended design. As a tool for decision-making, prototypes can aid in making incremental or milestone decisions around topics related to functional, viable, or desirable qualities in the design.

These enactments of the multiple prototypes on a design project vary based on the context of use, as uncovered through our data analysis process. We refer to these contexts as the “prototype contexts” rather than “design contexts”. Design contexts are often defined by the overall design project and internal and external environmental factors [218]. Maffin describes engineering design contexts in terms of an organizations’ unique internal and external attributes (i.e. company, culture, markets, products, production process, suppliers), its strategic policies, and the key features of specific projects like their design strategy and design tools and methods [219]. In these descriptions of design contexts, prototypes are viewed as a consistent modelling, analysis, or design tools used within them. In this case study, we consider the design context – specifically the company, project, and design process – as consistent across each prototype context. Each prototype context then varies based on the people involved, surrounding space and environment, time in the design process, purpose of the context, and the prototype’s medium and level of fidelity. In a recent article by Jensen et al., they define contexts for prototypes in terms of stakeholder interactions dividing the types of communication around the prototype into three groups: internal/internal, internal/external, and external/external [23]. We build on their work and further define the contexts where prototypes are used, including aspects like the period of time in the design process, the physical space, and the prototype’s medium/fidelity.

6.2.3 Research Approach

6.2.3.1 Methodology

The findings presented in this paper come from a ten-month ethnographic study of one footwear company, referred to as GlobalWear. Within this organization, the research team observed one product design team that developed a new children's waterproof winter boot. The design and development process for this winter boot was followed longitudinally, from initial idea until the product launch. We gained access from the executive level, which gave us unrestricted access to all of their products, processes, software, tools and people. We were introduced to the design team employees before the observations began. We began the research by conducting individual interviews to become acquainted with each team member before observing their daily design practices.

The research question guiding this study is: *How does the primary role of the prototypes on a company design project shift based on their context of use?* Or put in terms of Mol's theory: *How are prototypes enacted throughout the design process?* We use a prototyping framework during our analysis to code for how prototypes are used in each context, which views prototypes as artifacts serving three main roles: as tools for communication, learning, and decision-making [160]. In reporting our findings, we use a case study approach to coherently tell the story of how prototypes are used in each context. This research is conducted in accordance with the human subjects review by the university Institutional Review Board, and we use pseudonyms for the company, employees, and products.

6.2.3.2 Site, Design Process, Project, Stakeholders

This case study occurs within a large global footwear company with headquarters in the United States. At GlobalWear, there are approximately 2,000 employees involved in the design and development processes for footwear. Each year, GlobalWear launches two seasonal lines of footwear. Their product development process for a season of footwear begins 18-months before the product line launches to market, and it is broken into four major phases: design phase, early development phase, late development phase, and commercialization. Within each phase, there are several major milestones that the design team must achieve. These milestones include two internal design reviews with executives at GlobalWear, and then two external product line reviews with external stakeholders, such as global wholesale buyers.

Within GlobalWear, we observed the design and development of the fall seasonal line for the children's footwear team. Within this line of products, we specifically focused on the creation of one new product: a children's waterproof winter boot. This new product had many challenging requirements: it needed to use advanced materials to ensure warmth and water protection and resistance; it had to be created with the least costly materials possible and assembled as efficiently as possible; it needed to pass safety tests for factors such as slippage; and it had to be desirable in terms of aesthetics, price point, and functionality for both consumers (adults/parents) to purchase and end-users (children) to wear.

This children's footwear team consists of eight core design team members: one project manager, one assistant project manager, one lead product designer, two junior product designers, one lead product developer, and two junior product developers. We consider this the core design team because they worked on the children's footwear line on a daily basis, and they met as a group once a week to review progress and challenges for the seasonal footwear line. In addition to the core design team, there are internal and external stakeholders involved in the product development process, including senior management and executives at GlobalWear, international buyers, and consumers and end-users. These various stakeholders are described in Table 12; they are one element in defining the prototype contexts at GlobalWear.

Table 12. GlobalWear Stakeholders and Responsibilities

GlobalWear Stakeholders	Internal vs. External	Primary Responsibilities
Project Manager (PM) and Assistant Project Manager (APM)	Internal on design team	• Manage the entire kids' footwear line of products • Focus on deadlines in the overall timeline, preparing for major meetings/milestones, and staying within the allocated budget
Product Developers (PDev)	Internal on design team	• Move 2D designs (line art) into 3D models and physical shoes • Create physical samples of shoes in different materials, develop the optimal construction of the shoe, and finalize design packs • Responsible for tooling and finalizing shoes before mass production at the factories
Product Designers (PDes)	Internal on design team	• Responsible for concept generation for all products in the seasonal line • Sketch and digitally mock-up different colors, graphics, embellishments on early 2D footwear ideas (line art). • Establish uniform colors (pantones/colorways) for the company, and develop aspects of the technical design packs
Senior management, directors and executives (SDE)	Internal within GlobalWear	• Involved with the high-level budget allocation for the children's footwear group and planning the entire footwear line across women/men/children • Attend internal design reviews, guide marketing approach and campaigns, distribution, among many other management responsibilities
Global Buyers (GB)	External	• Attend two external shoe line reviews for each season (ILR/FLR) to review the product line • Responsible for purchasing total quantities of seasonal shoes for their regions/stores
Consumers, end-users (CEU)	External	• Consumers: typically parents or adults who purchase the shoes and aid in dictating the success of the product in market • End-users: children who then wear the purchased shoes – based on fit and desire for the product this can influence purchasing behavior

6.2.3.3 Data collection

The data collection techniques were informed by contemporary approaches to ethnographic research [158]. We collected qualitative data in the form of audio and video recordings, field notes, interviews, focus groups, E-mails, software and project management programs, and digital and physical artifacts for ten months during our participant-observer role in the company. We observed critical aspects throughout the entire product development process for the new winter boot, including every weekly kids' team meeting (40 total), two internal design reviews lasting one full day each, two external design reviews lasting one week each, and three major debriefs after these reviews for one day each.

The primary researcher acted as a participant-observer during their time at GlobalWear [121], which totalled over 100 hours. As the project progressed, the researcher became integrated into the kids' footwear team and was introduced to other employees in the company as a team member. The researcher received a security badge, which enabled legitimate entry to the company for all of these observations. The researcher took field notes during the observations, paying specific attention to any interactions and discussions around prototypes. The researcher would time-stamp notes in approximately ten-minute intervals, and transcribe partial quotes in real-time to revisit afterwards. After each observation, the researcher would spend up to three hours filling in their field notes to ensure that they captured the design practices subjectively and holistically, as to the best of their ability. Audio-recorded interviews or focus groups with design team members occurred three times throughout the project, once at the beginning, then mid-way throughout the project, and finally at the end. Interviews were also conducted with company stakeholders, including senior management and executives. This totalled 27 interviews and focus groups over the course of the project. All of the data were saved to a secure server, which could only be accessed by the research team.

6.2.3.4 Data analysis

Data analysis began concurrently with data collection, and continued for one year after data collection was complete. Prior work on this research project used principles from grounded theory development to uncover three primary roles of a prototype across three industries who develop physical products [191], [220]. These findings indicate that prototypes are tools for communication, learning, and decision-making. We use these three roles as guiding constructs when answering our research question: *how does the primary role of the prototypes for a company design project shift based on their context of use?*

First, we identified the different contexts where prototypes are used. Prototype contexts are a subset of the overarching design context, meaning there can be multiple prototypes contexts within one company project design context. To define these contexts, we built off prior literature on design contexts: considering the company, project, and design process as consistent across all prototype contexts [219], the types of communication between internal and external stakeholders [23], and the underlying purpose of a context [221]. We added the elements of place, period of time, and prototype medium to help us uncover the primary purpose/use of the prototype in each context. In summary, this framing for the prototype contexts in this research study includes the people involved, underlying purpose of the context, place, period of time, prototype medium, and primary purpose/use of the prototype as seen in the descriptive model in Figure 24.

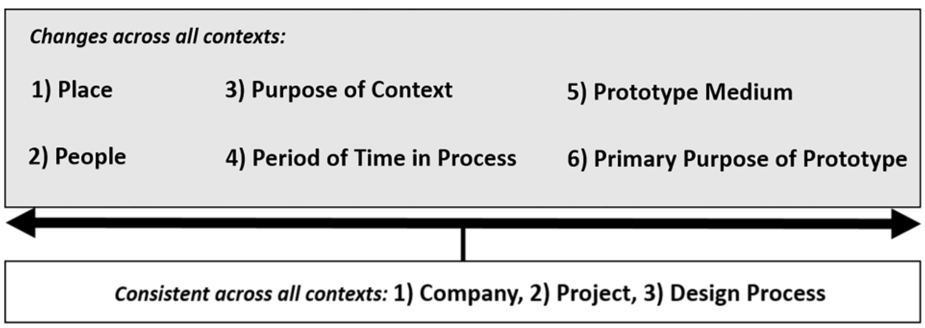

Figure 24. Model for the framing of prototype design contexts

After outlining these factors that define a prototyping context within GlobalWear, we then segmented the data based on how these contextual factors varied. In this case study, five contexts emerged through applying this framing of prototype contexts during the analysis process, as shown in Table 13. These contexts are titled by either the primary stakeholders involved or the primary event/purpose occurring in that context, for ease of describing and discussing them. These contexts are referred to as: Context 1 – the lone designer or developer; Context 2 – the core design team; Context 3 – internal design reviews; Context 4 – external design reviews; Context 5 – consumer and end-users.

The final goal of our data analysis process was to determine the primary purpose of the prototypes in each context. To uncover how the purpose of prototypes changes, we applied Mol's theory of objects having *"more than one [enactment] but less than many [or infinite]"* to our data analysis [217]. We did this by first organizing all of the data that contained prototypes for the five contexts, which included video/audio recordings, field notes from observations, E-mails, pictures of prototypes and surfaces like whiteboard, and interviews with members of the design team and internal stakeholders from GlobalWear. Once the data was sorted by context, then we analyzed the data in each context applying the framework that prototypes are tools for communication, learning, and decision-making [160]. All of the segments of data were analyzed using this coding scheme. It was coded initially by the primary researcher, and then the data were analyzed amongst the research team at weekly meetings over a seven-month period. Throughout the data analysis process, there were three analytic memos written to synthesize the emergent findings [121]. Those memos became the basis for this case study.

Table 13. Five contexts within GlobalWear case study defined by our prototype context framing

	Context 1: *Lone Designer or Developer*	**Context 2:** *Core Design Team*	**Context 3:** *Internal Design Reviews*	**Context 4:** *External Design Reviews*	**Context 5:** *Consumers and End-Users*
People	PDev and PDes – alone or together	Kid's footwear design team (DT)	DT, Senior management, directors & executives (SME)	DT, SME, and Global Buyers (GB)	DT, Consumers and end-users (CEU)
Period of Time	Daily over 10 months for entire product development process	Daily over 10 months for entire process (40 times), three debriefs after design reviews	2 internal design reviews	2 external design reviews	Varies – 2 times near the end of the process in Nov. & Dec. for approx. 1 hour each
Place	Office, design studio, in-house rapid prototyping space, external manufacturing centers	At GlobalWear in a conference room or design studio	At GlobalWear in the design studio living product line room	Within the company headquarters in the product showroom conference center	Varies outside the company, even outside the US
Underlying purpose of Context	Fulfill job responsibilities	Ensure progress, meet deadlines	Design review to update and gain approval from senior management	Product line review to update and gain approval from external stakeholders	Test product with consumers and/or end-users
Prototype Mediums	Highest variability: line art, color/graphic samples, 3D printed shoes, competitor products	Some variability, usually more refined prototypes from Context 1	Refined line art, samples of new colors/graphics /materials, product samples, more refined from Context 2	Line art along with mostly samples from factory, more refined from Context 3	Variability, typically samples from factory but also can be 3D printed
Primary Purpose/ Use of Prototypes	*Learning*: product space, technical aspects, business aspects	*Decision-making*: consensus building	*Communicate* explain, feedback, negotiate, and persuade	*Communicate*: explain, feedback, negotiate, and persuade	*Learning*: feasibility and desirability

6.2.4 Findings

In this section, we present our data and findings as a case study at GlobalWear. We discuss each of the five contexts, and use in-text quotations and images to describe the primary underlying purpose of the prototypes in each context. An overview of the primary roles of prototypes in each context is shown in Table 14. It should be noted that in the findings we discuss the emergent *primary purpose* of prototypes in each context; however, the prototypes still embody aspects of the other two roles. As Mol indicates, objects can serve "more than one" role. It was the goal of data analysis to uncover the *primary purpose/role* of the prototypes in each context. For example, as shown in Table 14, the primary purpose of prototypes is for decision-making in Context 2. However, prototypes in Context 2 also embody the roles of communication and learning in support of the primary function of the prototype in this specific context (decision-making).

Table 14. Comparing the Primary Purpose of Prototypes Based on Context

	Context 1: *Lone Designer or Developer*	**Context 2:** *Core Design Team*	**Context 3:** *Internal Design Reviews*	**Context 4:** *External Design Reviews*	**Context 5:** *Consumers and End-Users*
Communication			**X**	**X**	
Learning	**X**				**X**
Decision-making		**X**			

6.2.4.1 Context 1: The Lone Designer or Developer

The first context involves the individual product designers and developers on the team. These positions have overlap in their responsibilities, especially during the many iterations of the products. During an interview with the lead product developer, he stated that his position is *"involved even from when picking last of shoe, which is pretty initial, and we are involved all the way through [the design and development process]."* The last of shoe, is a technical term in the footwear industry that refers to the molded shape of a human foot for the intended shoe; every shoe has their own unique last.

In this context, the primary purpose of the prototype is to aid in learning about the product space, as seen in Table 14, specifically around the technical requirements and business aspects, like sourcing materials and creating the tooling molds. The designers and developers cycle through *"trial and error"* situations over multiple prototype iterations, which is in-line with existing prototyping literature on how early prototyping is a form of hypothesis testing and learning about a product [222], a way to uncover unknowns about the product [23], and can create *"small wins"* through the navigating uncertainty in developing a new product [22]. The GlobalWear shoe prototypes are only created in this context within this case study. By creating multiple prototypes, the designers and developers learn about what works and does not work. These rapid iterations of prototypes are not always shown or shared with other stakeholders, especially in the early stages of a project. One product designer stated during an interview, *"you know, it is like, too many cooks in the kitchen…now that can be disastrous."* This metaphor to cooking describes what can happen on design teams when too many people are involved and give their input on a design; there are too many opinions shared, which can be overwhelming especially in the early stages of a product. This reflects what we often saw at GlobalWear, where designers and developers would create and evaluate prototypes in rapid succession until they felt confident in the direction or if they needed input from others on the team.

The lead product developer reflected on their prototyping process during an interview near the end of the project stating, *"If you get the sample [back from the factory] and then try to figure it out later, that's not working. You need building blocks."* In this interview, the product developer indicates that you need to create multiple iterations of prototypes increasing in fidelity before you put more time, money, and effort into creating pre-production prototype samples from their manufacturing facility. Later, this product developer expands on the statement saying, *"You need to use your resources in-house first…we have 3D printers and model-makers to give a sense of the product first."* Building and learning from prototypes in-house is the method the product developers use to ensure that they are considering all elements of the product before committing to higher costs and invested time for pre-production samples from the factory.

One of the product designers described how prototypes are a learning mechanism for building confidence in the overall design. *"[Prototyping] is kind of like bowling with bumpers. It's kind of like are we within the bumpers? Or are we way off in another lane or something? And then once we build that confidence that this is the direction that we're taking and we feel good that everyone is on board… [then we go into production]."* The designers and developers learn important lessons between each prototype iteration, which is emphasized in this "bowling with bumpers" metaphor. The designers and developers bring the refined prototypes to the team meetings in Context 2, which are used to make decisions about what needs to change in the next iteration to achieve a design that everyone is "on board" with for production. This requires many iterations of learning and decision-making with prototypes, moving between Context 1 and the core design team in Context 2. With each iteration, the design team builds confidence in the direction of project through these prototypes.

6.2.4.2 Context 2: Core Design Team

The second context contains the eight members of the kid's footwear design team; they worked on aspects of the new winter boot project daily and met weekly to discuss progress and issues. The product designers and developers often bring selected prototypes to the meetings to aid in the discussion and decision-making process. It emerged that the primary purpose of prototypes in this context is to aid in decision-making, usually by consensus amongst the team with input from experts in different areas (i.e. graphic design, material sourcing, footwear construction).

To exemplify this theme, we include a short segment from a weekly team meeting on September 7, 2016. In the timeline, this meeting occurs between the two major external design reviews (Context 4). In this excerpt, the product developers (PDev1/PDev2) discuss the new kids' winter boot with the project managers (PM/APM) to come to a consensus on the appropriate height for the boot so that it can close appropriately with Velcro and also fit the necessary light patch. We only include a few lines of conversation from this discussion, which lasted approximately ten-minutes during a one-hour meeting.

<u>PDev1:</u> *So all three [boots] are tall (see Figure 25). Here is ours from last season. This is where our competitor is. And this is where we are in our current sample.*

<u>PM:</u> *Is this the height that we want? What does everyone think?*

<u>PDev1:</u> *Yeah, I think it looks good. But as we get closer to the original height, I've got some issues…*

<u>PDev2:</u> *So we only really need about this much area (using light up boot patch as reference) to do a nice light patch [on the boot], right? And that's a pretty good size light patch.*

<u>APM:</u> *(Takes prototype boot from PDev2, and open/closes the Velcro boot – putting hand inside and trying to pull out the gusset in there). So, if we move… well, this tack is a little high, is it not?*

<u>PDev1:</u> *I think we can work on it. What I would do is, I would keep the gusset as high as it is, but I would lower where the binding stiches into the pattern at the bottom of the "V".*

<u>APM:</u> *Do you feel like this opens enough?*

<u>PM:</u> *So when the kids are putting it [the boot] on, and they are smashing their foot in, just as long as this isn't up too high, so that they can't get the in-step down in there. Because then if this tack line moves to the bottom of the arch, or somewhere here, that might be better.*

<u>PDev1:</u> *Yeah, yeah. If we lower [the tack] a little bit, then I'll widen that triangle of the gusset accordingly.*

<u>PM:</u> *Yeah let's do that. And I think we have enough closure travel here (snaps Velcro back and forth on prototype) in the hook-and-loop for a constant contact. The boot is really coming together.*

<u>PDev1, PDev2, APM:</u> *Agreed.*

Figure 25. Prototype boot from last season (left); Competitor boot to benchmark their design against (middle); Current sample prototype of the boot (right)

This excerpt from a team meeting shows the discussion between the project managers and product developers, where they use the prototypes to come to final decisions on aspects like the height, tack point for the gusset, space for the light up patch, and fit for the kids' feet. This example is representative of how the core team uses prototypes to aid in decision-making during team meetings. These decisions are enhanced due to the ability for all members to have similar mental models of the intended design; they can each physically interact with the prototypes as a means of communication to ultimately influence decision making. The project manager wants the team to make a decision by consensus, as indicated when she asks *"what does everyone think?".* The product developers are experts in boot construction, so they influence the final decisions based on their opinions such as when the product developer says *"what I would do is…"*. These interactions with the boot allowed for decisions to be made, and ultimately the decision was made to alter the boot to allow more room for children's feet to enter it.

This context is unique because all of the feedback and learnings from the other contexts are brought back into Context 2; the core design team is given a chance to debrief on the insights and come to a decision about what needs to occur next for the prototype. Insights gained about aspects of the prototypes later in Contexts 3, 4, and 5, will also be filtered back to Context 2. For example, at the external line review in Context 4, feedback was given by external stakeholders to *"consider dropping the star and moon pattern"* and *"placing an indent on the middle of the boot base for European snow pants."* Both of these suggestions were part of the kids' team debrief meeting. At the meeting, they decided to remove the "moon" feature but keep the "star" pattern, and then also add a slight curved indentation to the boot to ensure the boot is appropriate for European culture.

6.2.4.3 Context 3: Internal Design Reviews

The third context involves the kids' design team and executives at the footwear company. There are two internal design reviews, which occurred in April and May 2016 for this fall seasonal footwear line before the external reviews. These milestones are a chance for the design team to pitch their concepts to the executives at GlobalWear. These executives are familiar with the kids' team on a high-level, since they are involved in the early stages of scoping the themes for the season and number of shoes required. The primary purpose of prototypes in this context is to clearly communicate (Table 14) the intended designs, by explaining the concepts to the executives, priming them with the prototypes, and then facilitating their feedback. These executives are able to ask questions and provide feedback on the product line, which is then taken back to the design team in Context 2 to come to final decisions moving forward. Figure 26 displays one product designer pitching the kids' fall seasonal line to the senior executives at GlobalWear.

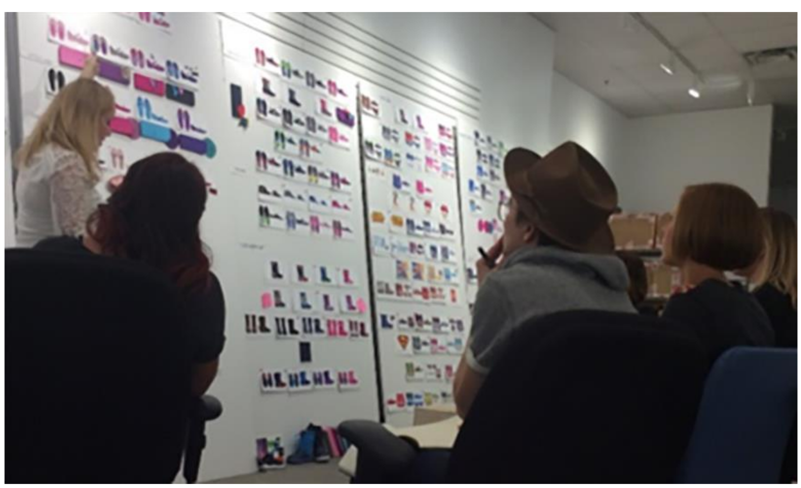

Figure 26. Product designer pitching the kid's footwear line to senior executives at GlobalWear

During an interview with a senior executive at GlobalWear in December 2016, we discussed the purpose and outcomes from the internal design reviews. The senior executive reflected on the reviews, stating that they are an opportunity to *"socialize"* around the product line because it is the first or second time that these concepts and designs are shared publicly within the company. *"These [internal] design reviews are the first time people see it. Right? And so they all socialize around it and those types of things. The design team is pitching their concepts, trying to convince us all that these are the best options. And then us executives, only talk about what we think we need in the line."* The prototypes represent an important part of the design process; they are objects that allow ideas to take form visually as a means to better communicate amongst stakeholders. They are a way for the design team to tell a coherent story around the product line and persuade the executives that this is the best direction forward.

We also include an excerpt from the second internal design review on May 13, 2016 with the core design team and five GlobalWear executives. The excerpt includes the product designer (PDes) describing the kids' boots in terms of colors, and then two executives (Ex1/Ex2) responding with their thoughts on the colors. This feedback is brought back to the kids' team in Context 2 to make final decisions. The kids' team has also prepared their back-up option to changing one color, which they show in this excerpt. The executives are very happy to see the effort the team put into the presentation, and as a result it further helps to persuade the executives that this is a good direction for the product line.

PDes: Moving into the kids' winter boot concepts (pointing to the line art boards, Figures 25 and 26). We have pepper-navy-tangerine combo, volt/slate gray combo. This one is smoke with yellow, and for the girls' SKUs: amethyst, candy, and tangerine.

Ex1: Thank you. This is a really great way to visualize the assortment. But are we scared of orange/red combo?

Ex2: I think it makes the red look more interesting. Do you need the green in that one?

Ex1: No, I'm also wondering if we should flip the navy and the red.

Ex2: Yeah, we could do that. Make it a navy shoe.

PDes: Yeah, that was our [the kids' team] top choice, too. We thought it might be stronger to have a red toe here, and so we did a back-up colorway (takes tacks out and replaces the shoe line art with another option below it).

Ex1: Wow, this is so easy, thank you for preparing. This is great.

In this segment, the concept boards of the product line with all of the 2D line art prototypes are the organizing objects for the design review. These prototypes are the artifacts that facilitate most of the conversation; they act as a platform for persuasion, discussion, and feedback. The kids' core design team takes all of the insights back to their team meeting in Context 2 to decide the best direction moving forward. There are no final decisions make about the footwear line at this internal design review. Instead, it is an opportunity for these internal stakeholders to voice their opinions on the footwear line, and for the 2D prototypes to facilitate a majority of the conversation.

6.2.4.4 Context 4: External Design Reviews

The fourth context includes the design team, executives, and external global buyers. There are two external line reviews per season. The first one occurs in July 2016, five months after the start of the project and two months after the last internal design review. The second external review occurs three months later in October 2016. The emergent primary role of prototypes in this context is also as a tool for communication (explain, persuade, negotiate, feedback) similar to Context 3, as shown in Table 14.

At the first external line review, the design team presents the complete product line for the upcoming season. They have line art and some early physical prototypes of new products, as shown in Figure 27. The walls are covered with updated product line art on white foam boards, and there are physical samples of key new products on wooden shelves. This external design review allows the buyers to voice their opinions and concerns. The feedback given from the buyers then informs how the team makes changes before the final external review meeting. After the final review, the kids' team finalizes the designs for mass manufacturing.

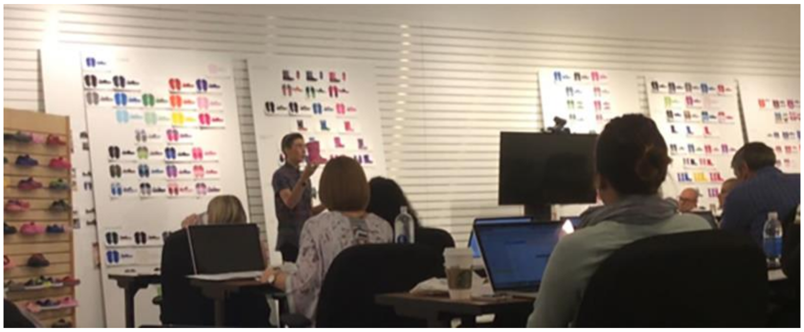

Figure 27. Kids' Team Assistant Project Manager using a boot sample prototype to persuade the external stakeholders during the opening remarks of the external design review

During the external line review, the design team presents the full line to the buyers and then waits to hear their comments, questions, or concerns. The design team is trying to sell their product line to these buyers. In an attempt to create buy-in, the team must have a compelling story with great visuals (line art prototypes) to support this story and the claims they are making. Next, we show an excerpt from this external design review, where the assistant project manager (AMA) is pitching the kids' winter boot product line to the external stakeholders during her opening remarks, as shown in Figure 27.

> *AMA: We have our first [new] product for the season: the water-proof winter boot. I am very excited on how this is looking for first round samples. Just a few things we are still working through. The cinch cord and materials are not quite yet final. We are probably going to raise this up about an inch, and make sure that this actually functions and cinches down. So that this is a great added feature benefit for 'mom'…[This] is very iconicly [us] now...with the base. And it is still at the $70 price point. It will have the functionality of the full-water proof boot. We are going to be able to tag and mark it with the technology that we are using.*

In this segment, the assistant project manager is pitching the new kid's winter boot. As shown in Figure 27, she uses the sample prototype along with words to sell this boot to them. She has multiple statements within her monologue that indicate this is a pitch and she is trying to sell this new product to these buyers. In particular, she states that she is *"very excited on how this is looking for first round* *samples"*, that it will have features which are *"great added benefit for mom"*, that it is *"very iconicly [us]"*, has a *"$70 price point"*, and has *"functionality of the full-water proof boot"* which they can "*tag and mark it with the technology we are using"*. Each of these statements is to excite the buyers and also anticipate any concerns they might have before they have a chance to state them.

The prototypes in Context 4 are used to persuade the buyers that this product line will be ready for market launch. The audience contains global buyers who are less involved in the design process for the footwear on a daily or weekly basis, meaning the core design team needs to be explicit in describing the products, while also creating a cohesive and detailed story about the product line. The stakes are fairly high in this context because the core design team needs these external stakeholders support to ensure the success of the company's product line launch to market for the season. The global buyers will "purchase" a certain quantity of the products to distribute to their regional stores. Therefore, the design team attempts to make the buyers excited about their new products, such as the waterproof boot, to ensure that they purchase large quantities of it.

6.2.4.5 Context 5: Consumers and End-Users

The fifth and final context includes all of the interactions between the company employees, like the core design team and sales team, with the consumers and/or end-users. For this design project, the consumers can include a variety of people, but are likely the parents, guardians, or extended family of the children. The end-users are children who wear the boots. In this case study, the design team does not plan in advance for testing the prototypes with the end-users or consumers on their seasonal timeline. Instead, testing occurs ad-hoc, as an after-thought, late in the project. Testing occurs with core team members' children and then with the sales team as they travel through Europe and Asia to different stores. Testing their products with children is mentioned regularly at team meetings, even though this is not a priority on their project timeline. For example, the project manager stated, "*how are they [the kids] possibly going to get their foot in here?"* and *"we should totally put that [boot] on somebody"* when discussing the new kids' winter boot in a team meeting in June 2016. Over the course of the design process, three impromptu end-users testing sessions occurred to check fit and function: one with the product developer's children and then two times with sales team members in Europe and Asia. The primary purpose of prototypes in this context is to learn more about the design space, specifically more about the functional requirements and desirability of the boot as shown in Table 14. Ultimately, these learnings through user testing and feedback filter back to the design team in Context 2, where these events inform the future direction of product.

Since this context was never observed first-hand, we report on the context as described by the team members during group meetings and interviews. In this excerpt from an interview, the lead product developer (PDev) discusses testing the prototype boot with end-users. The developer indicates the main learnings after trying the boots on with "actual kids".

PDev: I am almost at the end of the project and I actually had to make a change based on fitting…It affects how your foot steps into the boot. So we've been learning that the material in and behind the heel here, well above the heel behind the leg. When you step in the boot it becomes all bunched up, and the kids are getting stuck a little bit. And it is because we are staying too tight into what we know is on our last. So, I am just saying relax this.

The same product developer expands on the testing of prototypes with end-users during a team meeting. In this excerpt, the developer describes the challenges associated with end-user testing and how they do not perform testing in a uniform way, which makes interpreting the learnings difficult. Ultimately, they learn that the internal lining is too thick and can affect the fit for a kid's foot.

<u>PDev:</u> My kids here tried on the boots [here in the US] and initially I passed the fitting. In China, they passed the fitting…So we had samples go to our sales team in Europe and they had one of their little boys put on the boot [and it didn't fit] …And so I said, well since this is happening I should at least take a look at it…I circle back to all the historical products...cut apart a few boots and said okay so it is [a problem with] the lining material. This material inside [the boot] is like a quilted blanket…I pointed this out last week and we were able to catch it. It's a lesson learned.

In both of these instances, the product developer describes how the prototypes were able to aid in decision-making about functional aspects of the design *"based on fitting"* of the boots on children globally. This consumer and end-user context is considered an after-thought during the design process, since the changes to the design come with just enough time to make changes before production. The *"lessons learned*" are reported back to the kids' design team in Context 2, where decisions are made to change the boot design and passed back to the developer in Context 1 to follow-through with making the changes.

6.2.4.6 Summary

The primary roles of the prototypes for the kids' winter boot project change based on their context of use as summarized in Table 14 and displayed in Figure 28. The goal of this research is to uncover the primary role for the prototypes in each context to gain deeper insights into the use of prototypes during the product development process. For Context 1 with the lone designers or developers, prototypes are various levels of fidelity and mediums and serve the primary role of *learning* more about the design space. For Context 2 with the core design team, typically more refined prototypes are brought to the design team meetings by the designers and developers. These prototypes aid in *decision-making* amongst the design team. For Context 3, the design team brings the most refined versions of the prototypes to the internal design reviews with the senior management and executives at GlobalWear. The prototypes are used primarily as a form of *communication*; the intent is to persuade the stakeholders that this is the right direction for the project, while also gathering feedback on how to improve the products. For Context 4 during the external design reviews, the prototypes are the highest resolution, refined line art and physical samples of the shoes from the factory. Here, the prototypes are also used primarily as a form of *communication*, especially as a form of persuasion and storytelling. For Context 5, prototypes are used to gain new insights and *learnings* about the product from the consumers and end-users. All of the feedback and learnings from Contexts 3, 4, and 5 are filtered back to the design team in Context 2. The team holds additional de-brief meetings after the internal and external reviews where they make final decisions on the prototypes. Once decisions are made, then specific jobs are assigned to the product designers and developers to move forward with the next prototype iteration in Context 1. This process is shown in Figure 28.

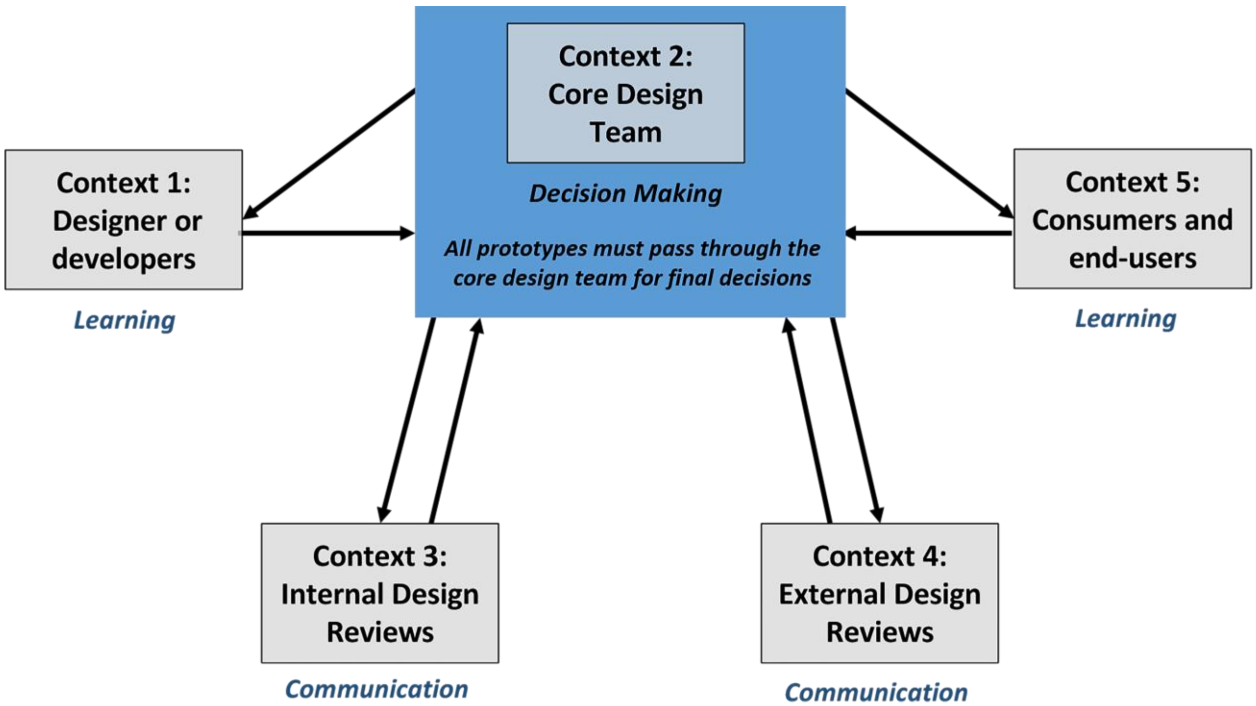

Figure 28. Visual process for how the five contexts interact: all prototypes and decisions must pass through Context 2 with the core design team

6.2.4.7 Limitations and Validity

While qualitative research may be well-suited for building theory, it potentially suffers from research bias and sampling errors [223]. Participant observations in companies often occurred during opportune times, thus causing some bias of the types of events observed. Even though the researcher made sure to take copious notes while observing, it was impossible to capture all instances and interaction. Thus, field notes are often supplemented by audio and video recordings and interviews to better round-out the data collected.

Similarly, there is risk that the researcher is overly biased in how events are recorded. The researcher attempts to write down objective notes when collecting data [224]. An objective description entails describing what is happening rather than trying to draw inferences initially about why things are occurring. With all interpretive research, there is a risk that some perspectives or insights can be accidently excluded. Despite following systematic guidelines for collecting and analyzing data, qualitative research is not well suited for generalizability of the insights it generates [155]. However, qualitative research provides the opportunity to draw new insights into social situations, like prototyping in companies, and thus develop theory to better describe the situation, which could eventually be applied more generally.

Researchers have developed strategies for ensuring validity in qualitative projects [121], [153], [206]. Suggestions from these articles has informed the validity of this study, such as conducting intensive long-term research (10-months), collecting various types of data and then triangulating those multiple data sources, using a diverse research team during analysis, conducting negative case analysis, and validating our analysis with some key stakeholders from the company. In this research, we attempt to address threats to validity, but we also recognize that understanding the shifting roles of prototypes is the primary goal of this work [225].

6.2.5 Discussion and implications for product development

We wish to discuss two topics as a result of this work, each which has implications for product development. First, our framing of the prototype contexts within the larger design context (company, design project, design process) enables stakeholders to become aware of the interactions and outcomes between prototypes and their immediate contexts. Second, we explore the notion that prototypes are objects that are shared and refined – *enacted* – across multiple contexts during product development as a means to learn more about the product space, communicate the design intent, and make decisions about the product. These various purposes of the prototypes allow the design team and company to build confidence around the product and create a cohesive story before market launch.

A prototype is nothing more than a physical or digital object until it is given meaning through the socially-constructed contexts and environments in which it is being used. This is why the purpose of the prototypes for the waterproof winter boot project can shift based on the immediate context of use. Moreover, because relations between objects are not given and instead created in each specific context, prototypes are inevitably used differently in contexts that include certain people, various physical spaces, and a specific period of time in the design process. As a result, no object's purpose is ever singular; the objects' realities are always multiple, and as shown through our analysis. The objects' reality is constantly being enacted through practice, and it can change based on the situation. As a result, both the medium/fidelity of the prototype and the level of interaction with the prototypes influences the context. And conversely, the specific context – defined by the people, place, period of time, and underlying purpose – influence the role of the prototype in each instance.

This insight about the ever-changing roles of prototypes based on the context can help designers, product managers, and other stakeholders become aware of how prototypes are used throughout the design process and what biases and benefits they can bring in each situation. We define the prototype context based on the people involved, physical place, period of time, underlying purpose, prototype medium, and primary purpose of the prototype (Figure 24). This provides a new framing for viewing contexts during a design project at a company, and allows us to see how these aspects are interrelated and can influence the trajectory for a project/product. Project managers can use this information to capitalize on the strengths of the prototype for each context.

The environment influences the use of prototypes. The various people – design team members and internal/external stakeholders – influence the direction of the project. Each of these people is brought into the design process at a specific period of time, and the space/place used for events reflects the underlying purpose for that context. These elements impact how prototypes are used. For example, fully constructed prototypes are brought to Context 5 with end-users near the end of the project. This context influences the underlying use of prototypes as tools for learning. Additionally, the prototype medium in each context influences the purpose of the prototype in that instance. For example, more refined pre-production samples are used in Context 4 to create a story around the prototypes and persuade external stakeholders. The medium of the prototypes is critical here to gaining buy-in. By understanding how prototypes can influence or shape the situation at hand, and conversely how people and the environment might influence the use of prototypes, you can become aware of how critical prototypes are during the entire product development process.

Prototypes are objects that embody knowledge, communication, and decisions across the five contexts. The process of going through each context enhances the overall confidence in the product before launching to market. First, the digital and physical prototypes are created and iterated on in Context 1 by the designers and developers. Then, the more refined prototypes are shared, communicated, interpreted repeatedly in Context 2 through Context 5. Each of these contexts are needed because they enhance the overall confidence in the product. All five contexts together are necessary to make sure that all of GlobalWear's stakeholders "feel good" before launching the product to market. As a senior executive at GlobalWear shared in an interview, *"[Prototypes] they build confidence in the direction we are going. The ultimate goal is gaining that confidence to launch to market."* It is important to become aware that going through these motions of presenting prototypes to each context builds confidence in a product. Building confidence is good as long as it is rooted in data or emotions, and not just the motion of going through each context which can provide false confidence.

6.2.6 Conclusion

This research views product development as an equally social and technically process, where objects – *like prototypes* – are critical to social interactions and embodying technical knowledge. We adopt a social science theory as a framework to view objects as having multiple enactments, or uses, based on their context of use [217]. This theory allows us to conduct an in-depth case study at one footwear company where we uncover how the primary role of one design project's prototypes shifts based on the context of use.

We identify prototypes as physical or digital embodiments of critical elements in the design, and iterative tools to enhance communication, enable learning, and inform decision-making at any point during the design process. We defined prototype contexts as including the people, place, period of time, purpose of the context, prototype medium, and primary purpose/use of the prototype. These prototype contexts keep the company, project, and design process constant across them. We uncover that prototypes are primarily a tool for learning when used in the contexts involving the *"trial and error"* of individual designers and developers (Context 1) and the testing with consumers and end-users (Context 5). Prototypes in these contexts are used to gain insights into the many unknowns around a product during a design project. Prototypes are primarily a tool for communication when used during internal and external design reviews with various stakeholders (Contexts 3 and 4). As tools for communication, the prototypes are used initially for persuading these stakeholders and then for facilitating feedback and discussion around the product. Finally, prototypes are primarily a tool for decision-making on the core design team, during the weekly team meetings and de-brief events after the design reviews (Context 2). In uncovering these leading roles, we saw that prototypes influence the context and are simultaneously influenced by the context where they are being used. This framing can allow designers, project managers, and other stakeholders to become aware of how prototypes are being used both *intentionally* and *unintentionally* in their own companies and design projects. Becoming aware of the biases and benefits that prototypes enable based on their context of use is essential to achieving better product development practices.

6.3 Chapter 6 Summary

In this chapter, I describe product development as an equally social and technically process, where objects – *like prototypes* – are critical to social interactions and embodying technical knowledge. I adopt a social science theory from Annemarie Mol as a framework to view objects as having multiple enactments, or uses, based on their context of use. This theory allows me to conduct an in-depth case study at one footwear company where I uncover how the primary role of the boot project's prototypes shifts based on the context of use.

Prototypes are simply static physical or digital objects until they are given meaning through the socially-constructed contexts and environments in which they are being used. This is why the purpose of the prototypes for the waterproof winter boot project in the footwear company can shift based on the immediate context of use. I defined prototype contexts as including the people, place, period of time, purpose of the context, prototype medium, and primary purpose/use of the prototype. These prototype contexts keep the company, project, and design process constant across them.

I uncover that prototypes are primarily a tool for learning when used in the contexts involving the *"trial and error"* of individual designers and developers (Context 1) and the testing with consumers and end-users (Context 5). Prototypes in these contexts are used to gain insights into the many unknowns around a product during a design project. Prototypes are primarily a tool for communication when used during internal and external design reviews with various stakeholders (Contexts 3 and 4). As tools for communication, the prototypes are used initially for persuading these stakeholders and then for facilitating feedback and discussion around the product. Finally, prototypes are primarily a tool for decision-making on the core design team, during the weekly team meetings and de-brief events after the design reviews (Context 2).

In uncovering these leading roles, it becomes apparent that prototypes influence the context and are simultaneously influenced by the context where they are being used. This framing can allow designers, project managers, and other stakeholders to become aware of how prototypes are being used both *intentionally* and *unintentionally* in their own companies and design projects. Becoming aware of the biases and benefits that prototypes enable based on their context of use is essential to achieving better product development practices.

This chapter is the culmination of all the chapters before it. It builds on the three roles of prototypes in Chapter 5; it highlights prototypes used for benchmarking and reverse engineering from Chapter 4; it expands on the notion of design coordination from Chapter 3; and it furthers our understanding of how professionals use prototypes in practice, which is needed from Chapter 2.

Chapter 7 – Conclusions & Future Work

In this final chapter, I discuss the main conclusions and contributions from this dissertation. I indicate how this work benefited the students and companies in this study, and how it has furthered our theoretical understanding of the role of prototypes on design teams through uncovering the actions that they enable. I also discuss the limitations and validity of this work, followed by recommendations for future researchers. Finally, I conclude with some areas for future research, such as exploring prototypes' influence on decision-making, their ability to enable convergent vs. divergent thinking, as well as the development of prototyping methods and tools.

7.1 Research Contributions

There are numerous contributions and implications for industry and design education from this research. This research contributes broadly to design theory and methodology, management science, and engineering design education. The primary contribution is a new framework for conceptualizing the role of prototypes in the design process through exploiting the actions that prototypes enable. This research engaged in a detailed ethnographic study of three companies in order to gain insights into professional design practices. I have already translated some of these insights into recommendations for companies and lesson plans and design tools for students. I summarize the key contributions of this dissertation research in this list:

- Deeper theoretical understanding of prototypes, specifically the actions and agency that prototypes create on design teams
- Introduction of the concept that prototypes are "design coordination" objects, critical to both the social and technical development of designers

- Empirical insights into product development process for three companies in the fields of consumer electronics, footwear, and medical devices, through detailed ethnographic methods for data collection and analysis
- New framing of prototypes through three roles: communication, learning, and decision making, and evidence that prototypes primary role changes based on the context of use
- New definition for a prototype and prototyping
- Validation that mental models around prototypes differ between students and professionals
- Bringing social science theories and research to the engineering design community
- Direct contributions to the three companies through feedback on their processes and prototyping behaviors, and also to design education through new workshops, activities, and tools for students from the insights from industry and this research

This research has directly contributed to the three companies within the study. I visited each company at the end of the project, and presented my emergent findings on prototypes to representatives from upper management. I gave each company a list of the ten prototyping principles, the framework on prototypes, and a diagram of how prototypes seem to move through their organization. I also gave each company a list of things that I believe they do really well, along with a list of areas to improve. These companies have taken some of my recommendations and translated them into procedural changes. For example, at the consumer electronics company, they have revised their design review process based on some of the feedback that I gave them. They originally had the entire engineering department review all products, and now they have a small team of three representatives from engineering, production, and quality review all new products with the lead engineer. Also, this company created an internal division for research and development of experimental prototypes after recognizing that their review process was favoring more refined evolutionary products rather than less refined yet possibly revolutionary products. Additionally, the footwear company created a short workshop to introduce the design teams to my framing of prototypes, and they are working towards moving their physical design room into a digital and virtual design space to enhance global collaborations.

This research has also directly contributed to design education. In the last two years, I have developed and refined a workshop series for mechanical engineering students on prototyping. I have taught this workshop to junior-level component design courses, senior design mechanical engineer capstone courses, advanced product design courses, and graduate design capstone courses. I introduce the broad nature of prototypes, and show how prototypes aid in multiple factors throughout the design process from exploring the design space, gaining feedback and refining requirements from clients, to testing functional components and aspects of users' interaction with the final solution. As part of the activities in class, I have students engage in functional decomposition, mind mapping, and black-box analysis of their projects. I have also developed a prototyping canvas, which maps out some of the key concepts students must think about before building and testing low-fidelity prototypes. After the in-class workshop, student teams are required to submit documentation of three 'preto-types' they created for their design project, showing the purpose, testing, and outcomes from the prototyping process.

It is the goal of this research to change the mindset around prototyping and to challenge what has been traditionally considered a prototype in mechanical engineering. This research is rooted in empirical data from students and companies, which created an argument for re-thinking the role of prototypes on design teams both in how it is taught in design education and used by companies.

7.2 Summary of Dissertation

The dissertation research was guided by several questions: What are prototypes? What are the role of prototypes in companies? How do these roles manifest or change throughout the process?

In answering the first question, I discovered that the term prototype is very broad and interpreted differently in various fields. Specifically, there are major difference in the interpretation between students and professionals. I have developed a new definition as an outcome of this research, which is rooted in the inductive analysis within the three companies. The current definition is*: a prototype is a physical or digital embodiment of critical elements of the intended design, and an iterative tool to enhance communication, enable learning, and inform decision-making at any point in the design process.* This definition includes aspects that answer the second research question, including the actions that prototypes enable.

In answering the second question, I uncovered three main categories: prototypes as tools that enable communication, enhance learning, and inform decision making. Although there are three salient roles, a prototype can transcend all three roles at once or can fall into just one or two categories at a time. The data supports that communication and learning are supporting pillars to decision making, and that a prototypes' ultimate purpose is to enhance and inform decision making.

The analysis on the role of prototypes led to another related research question: how do these roles manifest or change throughout the process? This question emerged from the analysis, as I saw these roles shifting over time based on the people involved and stage in the design process. In answering the third question, I used a Mol's social science theory on objects having 'more than one but less than many' enactments. To answer this question, I use an in-depth case study from the footwear company to show five unique contexts and how prototypes are enacted through each of them. The primary purpose of the prototype shifts based on the context of when the prototype is being used. Each prototype still embodies these three core roles – communication, learning, and decision making – just in slightly different ways.

Additionally, I have summarized the main takeaways from each chapter of the dissertation:

1. **Chapter 1:** There is a lack of ethnographic studies in companies around product development and prototyping; there is a need to understand and compare students and professionals design practices; there is a need to understand the action, not just the attributes, of prototypes.
2. **Chapter 2:** The term "prototype" is complex and interpreted differently between people, namely students and professionals in this study. There is a need to understand how professionals prototype, and to develop materials for design education to teach prototyping.

3. **Chapter 3:** In building on the theory of intermediary objects, I discuss how prototypes are objects of "design coordination" that are essential to social network development and technical knowledge development for design teams.
4. **Chapter 4:** Companies use prototyping methods in the early stages of the design process to aid in evolutionary product development. These methods and techniques include benchmarking and reverse engineering, and each of them are used to solidify the future product's design intent. These insights further validate the need to teach multiple prototyping tools, methods, and techniques in design education, and it also proposes the notion of using these techniques across disciplines to develop more revolutionary products.
5. **Chapter 5:** There are three primary roles of prototypes that emerged from observing companies: prototypes are tools for communication, learning, and decision-making. These describe the actions that prototypes enable. This chapter also presents the new definition of a prototype and prototyping.
6. **Chapter 6:** This chapter describes how the primary purpose, or use, of a prototype changes based on the context of use. This exemplifies that design contexts are extremely influential in how prototypes are used, specifically how factors like people, space, and time can impact the usage of prototypes.

7.3 Limitations & Validity

This section discusses the limitations of the research and potential threats to validity, including researcher bias. It is important to highlight each of these aspects, as it shows I was aware of the different limitations and validity throughout the research, and how I approached the research in a way to mitigate the impacts for them.

7.3.1 Limitations of Research

With all interpretive research, there is a risk that some perspectives or insights can be accidently excluded. While qualitative research may be well-suited for building theory, it suffers from research bias and potential sampling errors [223]. Participant observations in companies often occurred during opportune times, thus causing some bias of the types of events observed. Even I made sure to take copious notes while observing, it was impossible to capture all instances and interaction. Thus, field notes are often supplemented by audio and video recordings to better round-out the data collected.

Similarly, there is risk that I am overly biased in how events are recorded. I always attempt to write down objective notes when collecting and analyzing data [122]. An objective description entails describing what is happening rather than trying to draw inferences initially about why this is occurring in such a way. I also can unconsciously influence the data collected by choosing to record some events and not others. Additionally, as discrete as I was during data collection, my presence likely influenced the behaviors of the participants, especially early on in the research. These risks were minimized by, first, having a multi-disciplinary team of researchers including both engineering and education specialists; and second, sharing any interpretations of events with multiple other researchers to solicit their more unbiased feedback.

Despite following systematic guidelines for collecting and analyzing data, qualitative research is not well suited for testing the reliability, validity, and generalizability of the very insights it generates [155]. Thus, this research is not generalizable to all companies and design projects. However, qualitative research provides the opportunity to draw new insights to social situations, like prototyping in companies, and thus develop theory to better describe the situation. This is one of the main contributions of this research – furthering our theoretical understanding of prototypes on design teams.

7.3.2 Threats to Validity

Validity has long been a key issue in debates over the legitimacy of qualitative research. Several researchers have developed strategies for ensuring validity in qualitative projects [121], [153], [206], and suggestions from these articles has informed the validity of this study. However, there are some other qualitative researchers that argue that *understanding* of specific phenomena is more a fundamental concept to qualitative research than the validity of the study itself [225, p. 281], [226, p. 146]. Similarly, the rigor and validity of qualitative research is distinctly different than that of quantitative research and thus cannot be compared directly to tradition or methods in that field. In this research, I attempt to ensure against threats to validity, but I also recognize the underlying importance that *understanding* the role of prototyping is the primary goal.

Two of the largest threats to validity in qualitative research are the researchers' bias and reactivity of participants in the setting being studied [121, pp. 124–125]. The first argument is that the researchers' bias (values, experiences, beliefs, theories) influences the data collected and subsequently data analyzed. Although you can never fully eliminate a researchers' bias, you can combat how this could negatively affect the study. Early on, I wrote a memo outlining my beliefs about design process, prototyping, team work, and similar, and how these beliefs could impact data collection and analysis. Throughout this memo writing process, I was able to take a step back to ensure that my own biases were not impacting the research. It has been argued that by identifying your own researcher biases, that you can better inform the data collection and analysis process. By taking a particular view on the world, such as viewing design as an equally social and technical process, you are likely able to uncover nuances often missed by others.

The second argument is that a researcher influences the setting or individuals studied, which is known as "reactivity." Similar to researcher bias, it is impossible to eliminate the actual influence. It is noted that this is less of an issue for prolonged studies and ones that result in participant observation because the participants eventually become accustomed to the research and tend to "adopt" the researcher into the company and team culture, thus reducing this burden of reactivity.

With qualitative data, there are clear threats to validity. However, I have attempted to combat all of these threats to validity through a number of respectable and rigorous methods. Maxwell (2013) outlines a "checklist" to promote validity in qualitative research studies. This checklist includes eight topics (pp. 125-129): 1) Intensive, long term involvement, 2) Rich data collection, 3) Respondent validation, 4) Intervention, 5) Searching for discrepant evidence and negative cases, 6) Triangulation, 7) Numbers, and 8) Comparisons.

In this research study, I used seven of the eight methods to strengthen the validity of the study. In particular, I conducted intensive, long term research at each company (approximately a year at each location) (indicative of #1) that allowed for rich data collection from multiple means (indicative of #2). I compared the data collected from the three companies between one another (indicative of #8), while searching for discrepant evidence and negative cases (indicative of #5) to disprove any emergent findings. Additionally, I triangulated the data (indicative of #6), which is a means to collect and analyze a diverse range of data to compare findings. I brought the emergent themes and findings back to the participants to ensure validation of any results (indicative of #3). In the research with students, I created a prototyping intervention (indicative of #4), where I taught new lessons and materials about prototyping to them.

7.4 Recommendations for Future Researchers

In this section, I will summarize my recommendations for engaging in qualitative research methods within companies. It is my goal that I can share some best practices and lessons learned from my experiences. There are five main areas that I will discuss: 1) creating an IRB, 2) recruiting companies for research, 3) gaining trust and access at companies, 4) collecting meaningful data at companies, and 5) managing your relationship with the companies throughout the research project.

Before starting any research project with human subjects, you first must begin by creating an Institutional Review Board (IRB) research protocol. This IRB document clearly outlines the goals of the study, types of data collection and storage methods, length of the study, potential future risks and benefits for participants. This IRB must be reviewed by your university or institution. Once approved, you will then use the IRB to gain consent from any companies and participants who choose to be part of your study. The IRB clearly outlines ways in which the participants can remove themselves from the study if they ever feel uncomfortable and how they can report anything to the IRB if needed. This gives them the comfort to know that they can't be taken advantage of during the research project. Every participant needs to sign a consent form to be part of the research. As part of my IRB, I made sure that all companies and participants would remain anonymous. This helped the companies and participants feel more okay with signing up for the research.

After our IRB was approved, I was able to start the recruitment process of companies. I created a list of companies in different industries: aerospace, medical devices, consumer products, apparel, and so forth. I started listing any companies that were conveniently located because I wanted to reach out to them first. In parallel, I also used the research teams' professional and personal network to identify companies where we knew employees, had done prior research, or had a relationship with in some capacity. This narrowed down our initial list of companies to contact. I strategically e-mailed the companies that we had relationships with first, and I attempted to get as many in-person meetings as possible. It became critical to get an in-person meeting with someone at the management or executive level, since these people often could make the almost final decision. At these meetings, I would have a sale pitch prepared. I had to sell myself and my research to the representatives from these companies, while also showing how this research would benefit the company and not be disruptive to their normal working days. In terms of benefiting the companies, I told them that I would share any best practices, research, or tools/methods developed with them first. I also told them that I could give them an "outsiders" point of view on how effective their process was for product development. In a sense, I was a "free" consultant to them, and all of the companies took advantage of this. In terms of not disrupting normal work practices, I told the companies that we could have a trial period for my research. We could re-visit the research in a few weeks and make sure that we still had a good relationship. I also ensured that my practices for data collection would not disrupt meetings, and that I would hold interviews before/after work or during lunch. Most companies were also afraid of me ‘stealing’ their intellectual property. I signed non-disclosure agreements with the companies to put this issue at ease.

In any relationship, even in research, it is important to gain trust amongst all parties. To gain trust with the employees at each company, I initially set up one-on-one informal interview with the employees, typically over lunch. This allowed me to get to know them, and them to get to know me better. It was important for me to start off the research with a positive relationship with each team member, and for them to realize that I am just a normal person who is doing my PhD. I ensured each person that I was focused on understanding how prototypes mediated communication and decision making, and that I was not critiquing any of them individually. I also let them know that their identity would always remain anonymous, even to the upper management and executives within the companies. Moving the focus of my research to the ‘objects’ instead of the ‘people’ made it much easier to start collecting data from the companies. After the interviews, I began attending all team meetings. In an attempt to not disrupt any normal working meetings, I would save my questions until after the meeting, when most employees would talk about non-work related topics anyways. After a few weeks, I started to feel very integrated into the teams. This made collecting data much easier, since I developed a good working relationship with the teams in the companies.

After I successfully gained access to four companies and developed trust amongst the teams, it was time to start collecting data about the prototypes throughout the design process. I made sure to work with the executives at each company to determine an appropriate project to follow, specifically one that was starting in the near future. Collecting qualitative data in companies can be a scary as a young researcher. You have to embed yourself into the daily working lives of the employees and companies, and collect unbiased and meaningful data. Prior to collecting data, I think it is important to write a researcher memo, where you list many of your beliefs and biases that could come into play during data collection and analysis. I have some general pieces of advice from being in companies for over two years. First, it will get easier! After the first week(s), you will start to feel integrated into the teams and comfortable collecting unbiased and meaningful data. To prepare for each day at the company, it is important to summarize any insights from your prior visits, list your research questions, and anything you want to pay specific attention to during this next visit. It was very helpful for me to list my research questions at the top of my field notes. This allowed me to get into the appropriate mindset before each visit. It is also good to re-remind yourself to be unbiased and record things that are happening without putting any meaning into the events. Being in the field can be extremely draining. It is important to ensure that you collect audio or video data (if allowed) so that you can reference it in the future. In writing field notes, make note of times, places, people, and interactions. You should fill in these field notes after each visit when it is all fresh in your mind. It is important to summarize insights from the visit. This will help you prepare for the next visit. I also kept a log-book where I listed each visit at the companies. This was a nice snap-shot of all my interactions at the companies.

The last piece of advice that I have is about managing relationships with the companies. It is important to keep everyone updated throughout the process. I made sure to set up meetings with the executives at the mid-point of the project, at the end of data collection, and again towards the end of data analysis. In these meetings, I shared insights from the specific companies: what they were doing well and what they could improve on in the future. I also shared emergent findings and insights from my PhD research in terms of the roles of prototypes in the companies. I thought that these meetings were important because it ensured that the companies were knowledgeable throughout the whole research journey. This also leads to transparency in what is emerging from the data collected. The companies were generally interested in my insights, and also in how other industries were approaching prototyping and product development.

7.5 Areas for Future Research

Design theory and methodology is an exhilarating research field with lots of opportunities for future research. There are continuously advancements in rapid prototyping techniques, a surge in product design engineering education, and a push for more interdisciplinary research. As a design researcher, I plan to continue my research between the people, design processes, and prototypes / products as shown in Figure

29. My dissertation research studied how people interact with prototypes, and its influence on the design process. Future work with continue to study at these intersections, such as how introducing a new strategy in the design process can impact people's approach to prototyping and the final outcomes.

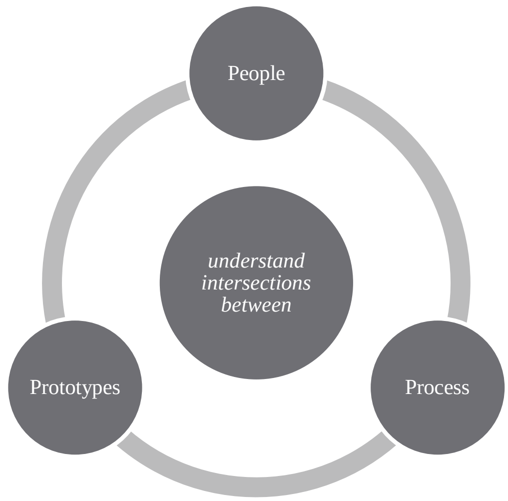

Figure 29. Future research at intersections of people, process, and products/prototypes

I have several immediate ideas for future research at the intersection of people, process, and prototypes. These include: 1) Exploring prototypes influence decision making (Section 7.5.1); 2) Expanding theory of prototypes: prototypes at the intersection of the cognitive, social, and physical worlds (Section 7.5.2); 3) Prototyping methods to plan for more purposeful prototypes (Section 7.5.3); 4) Prototypes enabling convergent and divergent thinking (Section 7.5.4).

7.5.1 Prototypes influence on decision making

Decision making is at the heart of the design process; likewise, decision making is at the heart of prototyping. Prototypes are physical manifestations of the design, which allow people to interact with the artifact and use it as a tool during conversations, to gather feedback, negotiate, or persuade others, while also learning more about the requirements for the final design. Ultimately, the end goal for a prototype is informing and enhancing decision making in the design process. Prototypes are tied to decision making, and thus are objects of influence and power on design teams. They can disrupt organizational structure by giving power to lower-level employees through the embodiment of the prototype. It is the goal of my future research to further study how prototypes influence decision making and how they embody power on design teams.

During this dissertation research, I have observed that prototypes can be both integrators and disruptors during the design process. As integrators, they bring the team together to make decisions, usually by consensus. This consensus-building can include some cognitive biases, such as being 'anchored' by the prototype or the 'bandwagon effect' of large groups. As disruptors, prototypes can disrupt the formal 'flow of power' in organization, by giving power to the owner of the prototype. I have observed that prototypes mediate many of the social interactions and decisions about a product, most of which are not documented. By viewing design teams in companies through the lens of *prototypes mediating decisions*, I will gain another representation of how decisions are made on projects and how power dynamics can rapidly change within organizations. Through this, I aim to identify the different decision making biases that occur when prototypes are used. This can then be used to aid designers in recognizing these common pitfalls while designing.

The last topic that I plan to explore is how prototypes are tied to power through their ability to aid in decision making. As shown in this dissertation research, prototypes help designers make decisions related to a number of topics. I observed how prototypes mediate many incremental decisions at the individual or team-level, which then culminate into major milestone prototypes shown to senior management, clients, or end-users. Product design is a decision making process, and yet, there are many taken-for-granted (and often not documented) incremental decisions from rapid prototypes occurring between all of the major design milestones. Power can be tied back to decision making; those who make the final decisions often have the power in a situation. Within companies, organizational charts can be viewed as a symbol of the internal power dynamics; it hierarchically maps the flow of power from the top of the chart to the bottom. I observed how prototypes are tools to mediate decisions, often at the "lower levels" of the organizational chart, and many times during these incremental decisions. Thus, prototypes can act as their own form of the organizational chart, in that they organize people around them to facilitate more lateral decision making for the product. Prototypes, in a sense, disrupt the formal "flow of power" in organizational charts and decision making on projects in companies. Prototypes mediate many of the social interactions and decisions made about a product, which has not been holistically documented. By viewing design teams in companies through the lens of "prototypes mediating decisions," I will gain another representation of how decisions are made on projects and how power dynamics can change.

7.5.2 Expanding theory on prototypes

This dissertation research has expanded our understanding of prototypes on design teams. It is my desire to take these principles learned, and to work towards a prototyping theory. Currently, I think this theory can build on a theory from existential philosophy describes three "worlds" that we operate in as humans. These worlds (or contexts) are: the cognitive world inside our own mind (eigenwelt = own world); the physical world made of material objects (umwelt = physical environment world); and the interpersonal or social world based on the interactions with others (mitwelt = with others / social world). I plan to use this theoretical framing to explore new way to conceptualize prototypes.

I believe that prototypes have the ability to merge all three worlds/contexts – cognitive, physical, and social – in a meaningful way that enhances decision making. In a simplified summary of this, a prototype first brings an idea from the designers' mind (eigenwelt) into the physical world (umwelt). Then, the prototype acts as a metaphorical bridge between different people to allow them to communicate more effectively (mitwelt). The prototype has the ability to create similar mental models between all of the people, which enables better communication and decision making. Finally, coming full-circle, the lessons learned from the prototyping experience are reinforced into the designers' mind (eigenwelt).

Contrasting this brief example, isolated decision making in any of these individual worlds (i.e. only interacting in the cognitive world leading to decision), likely results in less informed decisions about the intended final design. Similarly, moving purely from the cognitive world (eigenwelt) to the social world (mitwelt) through moving from thoughts to verbal conversations only, likely also results in less informed decisions.

These three worlds seem to already map back to three roles of the prototype that I identified. The cognitive world maps back to learning; the social world maps to the communication; and the physical world maps to the physical representation or artifacts that are the embodiment of the prototype itself. All of these together then lead to enhanced and informed decision making. In summary, prototypes are a tool to enhance and inform decision making, by blending social and technical elements of design and by bringing together the cognitive, physical, and social worlds.

7.5.3 Prototyping method/tool

It is a goal of mine to develop a robust prototyping tool to help design teams plan for more purposeful prototypes. As a first step toward this goal, I have created a list of 10 prototyping beliefs, a lecture and workshop on prototyping, and a "Prototyping Canvas" as shown in Figure 30. The prototyping canvas blend together aspects from the business model canvas, the lean start-up methods, and findings from this dissertation research. It has design teams map out all of the assumptions and questions related to the projects, related products and services, all of the stakeholder. It then has the team sketch possible prototype, create a testing plan, and document all lessons learned. The goal would be to develop this tool, and to first test with student design teams and then build it for specific industries. I desire to create a tool that both helps design education and professional design practices.

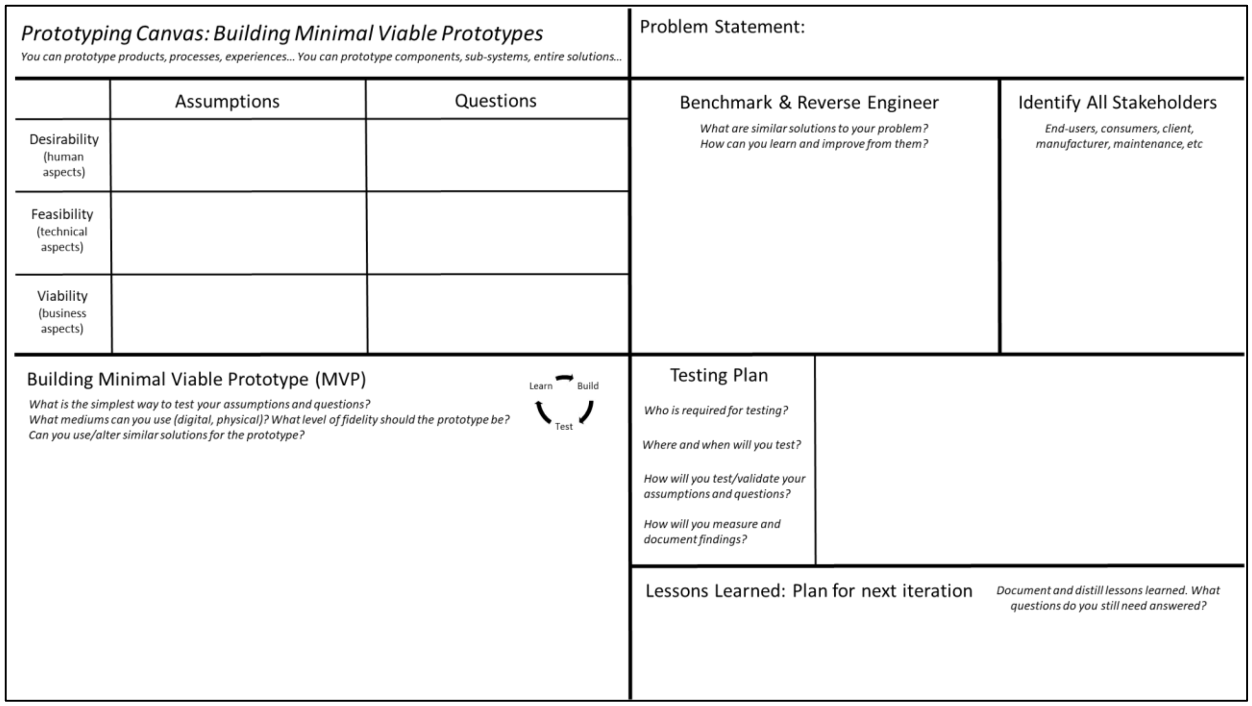

Figure 30. Prototyping Canvas

Building off the new theoretical understanding of prototypes, I have proposed two simple processes for building purposeful prototypes. In my future research, I plan to expand on these two frameworks and test their support in aiding teams to build prototypes. The first process is shown in Figure 31. It starts with identifying assumptions. These are all the assumptions that you have about the project, problem, product, and people. After you have identified all of the assumptions, it then has you determine the “actions” of the prototypes. These actions refer to how prototypes can act as tools for communication, learning, and decision making. Lastly, the process then focuses on building that prototypes as simply as possible to test the assumptions identified and aid in the actions required. A second proposed framework for building more purposeful prototypes is based on the “black box” model in engineering, as shown in Figure 32. It treats each prototype as a “black box” with input and outputs. The inputs refer to the design problem, stakeholders, context, question and many assumptions being made about the problem and solution. The outputs include the actions that are enabled by the prototype, along with the testing environment, context, and measured outcomes. This input-output thought process can help to create the prototype, in terms of deciding what materials, mediums, and level of fidelity required of the prototype to gain the desired outputs.

Figure 31. Proposed Prototype Process

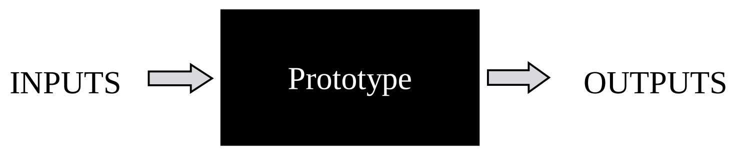

Figure 32. Black Box Method for Prototypes

Both of these framings are how I conceptualize prototypes. I plan to build on these ideas in future research, and create a simple tool that helps designers plan for more purposeful prototypes and have the guidance to create prototypes with the simplest materials and least amount of time possible to answer the questions and assumptions about the problem.

7.5.4 Prototypes influence on convergent and divergent thinking

Prototypes are unique in that they can enable both convergent and divergent thinking depending on the context of use and level of fidelity [101], [201]. As tools for divergent thinking, low-fidelity (lo-fi) prototypes can increase the diversity of creative ideas proposed during the early stages of a design project [227], [228]. However, prototypes also enable convergent thinking by allowing teams or clients to narrow in on a seemingly final concept and focus on detailed design. In this manner, prototypes may induce a level of design fixation, which often occurs when designers interact with physical models [67], [120], [229]. This can hinder the teams' ability to see alternative options, even ones that may better solve the problem. Creative ideas are necessary to solve complex design challenges. Creativity in the design process, often during concept generation, has been explored from a number of areas including using analogies [170], [230], design heuristics [4], [150], and humor [172], [173]. However, there is an opportunity to explore how prototyping, specifically lo-fi prototyping, can be used during concept generation to increase the diversity and quality of ideas proposed through divergent thinking idea generation.

I intend to answer the following research questions in this future research project: What are the effects of using lo-fi prototyping materials during team-based concept generation? How does using lo-fi prototyping materials impact divergent versus convergent thinking and the number, variety, quality, and creativity of the ideas? Does lo-fi prototyping during concept generation impact the perception of ideas from stakeholders and team members? Based on my prior research on prototyping, I hypothesize that prototyping materials used during concept generation will impact the amount of divergent versus convergent thinking based on the level of fidelity. There will be design fixation if the prototypes are too refined, while there may be increased creativity through tactile interactions with lower fidelity models. I also hypothesize that teams with more refined prototypes in these earlier stages will have enhanced communication and buy-in between team members and from stakeholders at the sacrifice of more creative solutions. As an outcome of this work, I aim to determine the appropriate level of fidelity of materials for low-fidelity prototypes as to enhance creativity and reduce design fixation on design teams. I will also use methods to evaluate the feedback and buy-in of external stakeholders based on the various ideation mediums.

To answer these research questions, I propose a mixed-methods experimental study of student designers during a semester long product design course. In this design course, the student teams will have the same design challenge. I will use the Design Problem Framework [231] as a guide for framing the challenges, which is grounded in research on cognitive styles and problem framing. I will also give all students pre-surveys to evaluate their cognitive style, creative self-efficacy, prototyping self-efficacy, and design self-efficacy to see if any of these have effects on concept generation and prototyping on the teams [19], [53], [232]. There will be three groups of design teams in the study, each framed with different materials provided during concept generation as shown in Table 15. I will use a think-aloud protocol for teams as they go through concept generation [233], and also video record the concept generation session to inductively analyze their approaches [200].

Table 15. Experimental Protocol

	Team 1	**Team 2**	**Team 3**
Fidelity of materials provided during early stage idea generation	Control group: paper and markers	Paper and markers, lo-fi prototyping materials (*i.e. foam, cardboard*)	Only lo-fi prototyping materials (*i.e. foam, cardboard*)

My first aim is to understand and quantify the effects lo-fi prototyping as part of a concept generation session. After the teams finish their concept generation during the session, I will collect all of the ideas. I will count the number of ideas based on the think-aloud protocol and ideas provided to us at the end of the session. Then, I will measure the quality of these ideas with two reviewers based on novelty, value, and relevance, aiming for an inter-rater reliability greater than 85%. I will compare the results between the teams to see how the use of lo-fi prototyping during idea generation impacts team concept generation and divergent thinking.

My second aim is to evaluate the feedback and buy-in of external stakeholders based on the ideation medium. After the concept generation stage of the project, I will have a trained industrial designer re-sketch all of these concepts to ensure that skill-level of the sketch/model does not influence the stakeholders' perception [234]. Then, I will show these re-sketched concepts to the external stakeholders, removing the biases caused from enhanced presentations influencing their opinions. These stakeholders will evaluate the ideas based on their understanding of the concept and perceived value. Capturing these metrics will allow me to go back and measure the idea quality without the bias of the medium. I can see which idea generation method led to better ideas as determined by the stakeholders.

7.6 Closing Remarks

This research has shown the complex and dynamic nature of prototypes. Prototypes are more than artifacts created during product development; they shape and influence many social situations throughout the entire process. Prototypes are tools to enhance communication between stakeholders, ranging from explaining a concept to persuading buy-in. Prototypes are essential to learning about a multitude of critical aspects in the design space, including many ‘unknown unknowns’. Ultimately, prototypes inform and enhance decision making about topics related to desirability, viability, and feasibility. Just as decision making is at the heart of the design process, decision making is also at the heart of prototyping.

Prototypes are objects that coordinate design work. They ensure forward progress is being made on design teams, while also building technical skills and social networks for the team members. Prototypes are important actors during design work. They have equal weight to human actors, like the designers or other stakeholders. As actors, prototypes shape social situations and networks, either intentionally or unintentionally. Just as humans can change their purpose or approach in different situations, so can prototypes. The primary purpose or use of a prototype often changes based on the context where it is being used. It can shift from being primarily used to facilitate feedback with executives to then being used to make decisions about users’ interactions and experiences. It is important to recognize how prototypes change their primary purpose in different contexts, since they can influence the trajectory of a project.

This dissertation provides a new conceptualization of prototypes through the framing of prototypes as both active tools and influential actors impacting the design process. This is a fundamental shift in mindset about prototypes, anchoring on the actions that prototypes enable, which can then influence social situations throughout the project. Prototypes have agency and power; they can influence actions that are taken through the design process.

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