

PROTOTYPING TO LEARN: CHARACTERIZING ENGINEERING STUDENTS' PROTOTYPING ACTIVITIES AND PROTOTYPES

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ABSTRACT

Prototyping is an activity core to designing and engineering, though an activity that has traditionally been under examined. Through observations of students' prototyping activities during a year-long design engineering project-based learning course, this paper hopes to better characterize the types of prototypes student engineers make in the course of their designing and to better understand how prototypes aid in their learning to be better designers. Common prototyping techniques are divided into categories of design thinking prototypes and engineering thinking prototypes. Student reflections are used to explore some emergent themes about their use of prototypes.

Keywords: Prototyping, Engineering Design, Design Learning, Design and Engineering Thinking

1 INTRODUCTION

Prototyping is an activity core to designing and engineering though an activity that has traditionally been under examined. Prototypes have been looked at as content [1] and conduct [2] but not through the lenses of students' learning practice in situ. Through observations of students' prototyping activities throughout a year-long design engineering project-based learning course, this paper hopes to better characterize the types of prototypes student engineers make in the course of their designing and to better understand how prototypes aid in their developing epistemic identities. Student reflections are also used to explore some emergent themes about their use of prototypes.

Developing a habit of prototyping early and often and continuously throughout the engineering design process is an approach used throughout mechanical engineering and design courses at Stanford University. An underlying part of a "prototyping culture" [2] includes both developing practices for using conceptual and experience prototyping to explore possible solution space as a means to communicate ideas and receive feedback, and relying on iterative physical prototyping as a means to learn and refine concepts further [3].

2 ROLE FOR PROTOTYPING

For a number of engineers in industry and academia a prototype is solely the culmination and resulting artifact of the engineering design process. Within the Express-Test-Cycle model to the engineering design process there is a community that relies on the production of a physical or tangible artifact as evidence of learning and iterations of prototypes are commonplace both in the early part of the design process to disambiguate among possible solution concepts and in the latter part of the design process to reduce uncertainties about the engineered implementations of a solution. Prototyping has been described as a communication tool [4] and a means to answer questions [2] between designers, but also between designers and others.

Houde [4] identified four types of prototypes, each with an associated use: role (purpose), look and feel (experience), implementation (physical), and integration (system), see Figure 1.

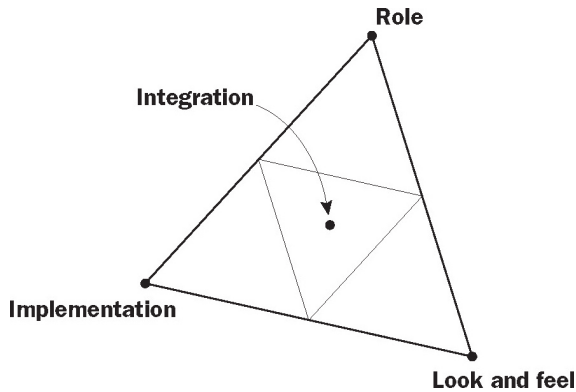


Figure 1. From Houde [4]: Four types of Prototypes: Role, Look and feel, Implementation, and Integration

Nielsen [6] described three different types of prototypes along a scale of features of services and functionality of features. Horizontal prototypes were those with shallow functionality but wide features of service. Vertical prototypes were of narrow features but deep in functionality. Scenarios overlapped the two with only a sliver of features and functionality. Nielsen’s model was applied to human-computer interaction applications.

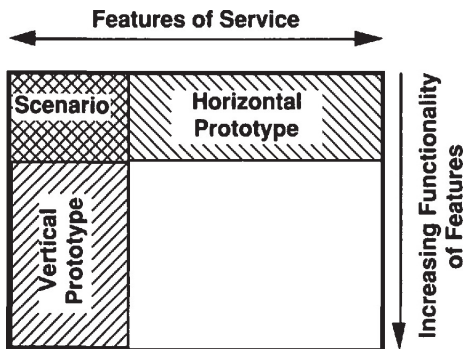


Figure 2. From Nielsen [6]: Three types of prototyping: Horizontal prototypes, Vertical Prototype and Scenario,

2 METHODOLOGY

Student graduate mechanical engineering students were observed in ME310 Design Project Experience with Corporative Partners, a year-long mechanical engineering core project-based learning [7] course at Stanford University. Students were divided into project teams and took design projects from prompt to concept to implementation. Their project steps, including prototyping activities, were characterized and categorized for general analysis of types reported here and for further analysis of student patterns of design steps [8].

In ME310, student teams created project documentation reports detailing their design development process including prototyping, design solution requirements, and specifications. Example prototypes shared in Figures 4-9 are taken from a seminar in distributed collaboration that is paired with the ME310 course. These example prototypes are similar to those produced in ME310 but don’t carry intellectual property issues associated with the corporate sponsored projects of ME310. The project prompt though was to redesign the coffee cup transportation system, a more broad design brief than redesign the coffee cup.

Team and individual reflections within their documentations reports were also captured and categorized. Selected student reflections appear in Section 4 as evidence of some emergent themes about students’ relationships with learning and prototyping.

3 DESIGN THINKING VS. ENGINEERING THINKING

Design thinking [9] and engineering thinking [10, 11] are separate yet complimentary parts of a design process [8], Figure 3.

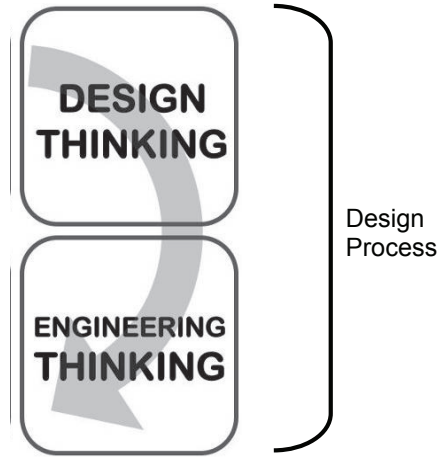


Figure 3. Design process divided into design thinking and engineering thinking

The priorities and guiding principles of design and engineering are, as well, distinct and yet complimentary. Design thinking is keen on functionality, engineering thinking high on physicality. Design thinking is for preserving ambiguity, engineering thinking reducing uncertainty.

Examples of design prototyping and engineering prototyping are listed in Table 1, aligned with the types of prototyping described by Houde [5] and Nielsen [6]. This paper attempts to further classify and describe these examples.

Table 1. Categories of Prototyping

Category:	<i>Design Thinking Prototyping</i>	<i>Engineering Thinking Prototyping</i>
Examples:	<ul style="list-style-type: none"> - Sketches - Benchmarking Existing - Conceptual Prototyping - Experience Prototyping 	<ul style="list-style-type: none"> - CAD - Critical Function Prototype - Funky System Prototype - Functional System Prototype
Houde’s Taxonomy:	<ul style="list-style-type: none"> - Role - Look and Feel 	<ul style="list-style-type: none"> - Implementation - Integration
Nielsen’s Taxonomy:	<ul style="list-style-type: none"> - Horizontal 	<ul style="list-style-type: none"> - Vertical

3.1 Design Thinking Prototyping

The design thinking aspect of the engineering design process focuses on problem definition, generating ideas, and modeling [12]. At this stage ideas are being generated, discussed, shared and assessed. For these purposes mockups can be helpful and vary from conceptual prototypes that quickly convey an idea to experience prototypes that explore the imagined scenario of use. These can be effective means to both convey an idea and to improve upon an idea by modifying or using as a jumping off point to yet another idea.

3.1.1 Sketching and Benchmarking Existing Solutions

Often the first substantiation of an idea is a sketch or brainstormed list with descriptive sketches, captured in 2 dimensions in a design notebook or dry erase board. Benchmarking existing technologies and solutions is also common practice. Often students have purchased or printed out specifications sheets from these existing examples to learn more about how they work.

3.1.2 Conceptual Prototyping

Taking an idea from concept to enabling its reality in the form of a non-functioning mockup allows interaction and discourse not as easily achieved with ideas presented verbally or written recorded as a brainstorm or expressed visually as sketches. Using examples from a short form design activity to redesign the coffee transportation experience, Figure 4 depicts some conceptual prototypes generated initially. These prototypes were made quickly with common materials available in the student lab. In this case, cardboard, string and fasteners were used. These mockups are non-functioning (in that they don't support the weight of the cup).

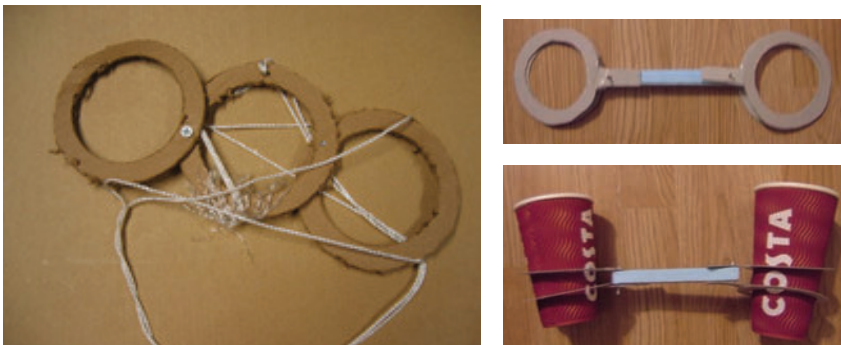


Figure 4. Conceptual Prototypes of coffee cup transportation exercise

3.1.3 Experience Prototyping

Experience prototyping can consist of putting oneself in the place of the targeted user. In the example of the coffee cup exercise, attempts to mimic the experience of a person carrying more than one cup of coffee were made, see Figure 5. Experience prototyping can also include using conceptual prototypes in scenarios to illustrate a prototype of the experience, either within the design team or engaging prototypical users to assess the experience.

The ensuing necessity for a willing suspense of disbelief with limited or non-existence of functionality is important. At this point in the engineering design process the ambiguity of the presented idea embodied in the prototype and the opening up of the problem space can be helpful in fostering more and better ideas to iterate upon.



Figure 5 Experience Prototyping carrying more than one cup of coffee

3.2 Engineering Thinking Prototyping

After ideas are evaluated a narrowing of possible solutions happens and the characterizations of prototyping activities does change. While iteration may take the design team back to the earlier stages of the design process to clarify or troubleshoot, much of the continued efforts in the engineering design process refine and specify the final design.

3.2.1 CAD Prototyping

The language of engineering prototyping is much more precise than that of its design prototyping corollaries. For example, informal sketches are replaced by specific CAD drawings and rendering, Figure 6.



Figure 6. Supporting 2D and 3D CAD of a coffee cup transportation solution

3.2.2 Critical Function Prototyping

Focused functional sub-systems that examine the physicality or mechanisms of only a part of the engineered system, vital to the viability of the solution can be called critical function prototypes. It can be as simple as the interface of the handle connections, as seen in Figure 7.



Figure 7. Exploring a critical function, the handle, for the coffee cup exercise

3.2.3 Funky and Functional System Prototyping

Houde's [5] integration is substantiated by student funky and functional system prototypes. They are attempts to pull together the parts of the system, first in an efficient and possibly unrefined way (funky) and then something suitable for display to others in more of a pre-production prototype (functional). Figure 8 shows the almost finished coffee cup solutions, first by using USPS Tyvek bags (funky) and then fashioning a custom made bag just for this purpose, Figure 9.



Figure 8 Funky system prototype solution



Figure 9 Functional System Prototype Solution

3.3 T-Shaped Prototyping

Student design and engineering work practice and design learning is aided greatly by continued and iterative design and engineering prototyping activities, or “T-shaped” prototyping activities. By “T-shaped” we mean both wide in exploring design prototyping or functional areas and engineering prototyping diving deep into physical aspects of the solution (see Figure 10).

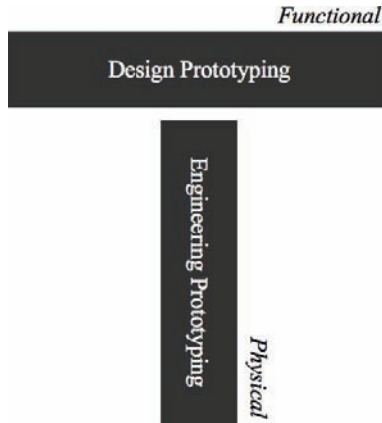


Figure 10 T-Shaped Prototyping Model

4 EMERGENT THEMES FROM STUDENT REFLECTIONS

Students reflections on their prototyping experiences in the ME310 course yielded some additional emergent themes beyond those discussed from the literature or design/engineering split above.

4.1 A Place to Start

Students found prototyping activities, of any sort, to be helpful to ground their projects and help with the project direction. Table 2 lists some of the student impressions.

Table 2 Student Reflections as Prototyping as a Place to Start

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| <ol style="list-style-type: none">a. “The team felt that prototyping was the best way to bring a sense of direction for the [quarter], and that it was a necessary activity before developing a plan.”b. “I think having a prototyping session helped everyone really focus on what they wanted out of the project. Building prototypes independently helped all of us understand what we enjoyed doing, what we wanted out of the project, and what we are good at doing.” |
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4.2 Getting Smarter

Students also commented on the scaffolded learnings gathered from their prototyping activities that helped them build on the work that they had done and get smarter along the course of the project. Table 3 lists some of their reflections in this regard.

Table 3 Student Reflections as Prototyping as Getting Smarter

- a. “Developed from the combination of extensive benchmarking, conceptual prototyping, and user testing, this prototype presented the essential features in an integrated package. By verifying previous design concepts, the team has determined the advantageous features and areas for further refinement.”
- b. “The design requirements of the project were constantly refined based on the new knowledge gained from the prototypes. This prototype was very significant as it involved testing of a new idea that was critical to the implementation of [technology] in the intended device”
- c. “Based on extensive prototyping and testing done in the winter quarter, the team demonstrated the practical feasibility of the [technology].”

4.3 Working Better

Students found their prototyping habits to be beneficial to their work practice efficiency. It also helped them be strategic about their steps and establish assessments and benchmarks to guide their work. Table 4 lists some example student reflections about working better.

Table 4 Student Reflections as Prototyping as Working Better

- a. “[Team] generated numerous functional prototypes, each building upon what was learned during construction and testing of previous prototypes and through benchmarking. The change of focus early [winter quarter] and the series of prototypes made regarding [device] control, helped [team] have a clear vision of how the final product was going to look like and how it was going to be made. Some basic functions were approached with the functional prototypes, and user testing had refined the final prototype and has stemmed ideas for future improvements. [The team’s]’s progress and narrowing focus were [helped by] two central questions asked of every prototype: ‘What can we build on from this prototype?’ and ‘What can we discard?’”
- b. “The [spring quarter] series of prototypes fall into one category, the best way to place all components of the final product together. Prior to this date, the team’s prototypes sought to answer various questions, such as ‘How are the... [components going to] look like?’ Attempting to answer this question, the team made a series of prototypes, at first very rough and conceptual, then increasingly refined. The process of working from rough to refined prototypes saved the team a lot of time by not forcing them to worry about unimportant details along the way. Duct tape and hot glue proved to be especially helpful!”

5 CONCLUSIONS

Prototyping is at the core of how designers and engineers practice. This paper reviews and summarizes established frameworks into the role of prototyping and synthesizes them into a new way of characterizing prototyping: design thinking and engineering thinking prototyping activities. Projects that explore both the design thinking and engineering thinking prototyping spaces benefit from cycles of converging and diverging thought, learning at each step of the process, nominally making for a better outcome.

Student reflections on their prototyping experiences show emerging themes of prototypes as “a place to start,” a way towards “getting smarter,” and a means towards “working better.” Written reflections from students is used as supporting evidence.

It is encouraging to see students and coaches of students being strategic and meta-aware of their design steps as to best approach and guide design and engineering projects with prototyping activities

and types of prototypes. Perhaps the definitions and examples of types of prototypes can aid student engineers in better finding their way through the design process. It can also help prototype to learn and learn to prototype.

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REFERENCES

- [1] Lloyd P, Snelders D, "What was Philippe Starck thinking of?" (2003) *Design Studies*, 24 (3), pp. 237-253.
- [2] Schrage, M., "Cultures of Prototyping," in *Bringing Design to Software*, T Winograd, Editor. ACM Press: New York. pp. 191-205, 1996.
- [3] Buxton, B, *Sketching User Experiences*, Morgan Kaufmann, 2007.
- [4] Brandt, E, *How Tangible Mock-Ups Support Design Collaboration*, (2007) Knowledge, Technology, and Policy.
- [5] Houde, S, and Hill, C, "What Do Prototypes Prototype?," in *Handbook of Human-Computer Interaction* (2nd Ed.), M. Helander, T. Landauer, and P. Prabhu (eds.): Elsevier Science B. V: Amsterdam, 1997.
- [6] Nielsen, J, "Usability Engineering at a Discount," in *Proceedings of the Third International Conference on Human-computer Interaction on Designing and Using Human-Computer Interfaces and Knowledge Based Systems*, 1989.
- [7] Prince, M J , Felder, R M, "Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases," *Journal of Engineering Education*, April 2006, pp. 1-16.
- [8] Lande, M and L Leifer, "Introducing a 'Ways of Thinking' Framework for Student Engineers Learning to Do Design," in *Proceedings, American Society for Engineering Education Annual Conference*, 2009.
- [9] Dym, C, Sheppard, S, Agogino, A, Leifer, L, Frey, D, Eris, O, "Engineering Design Thinking, Teaching, and Learning," *Journal of Engineering Education*, 2005.
- [10] Robinson, JA, "Engineering Thinking and Rhetoric," *Journal of Engineering Education*, 1998.
- [11] Cardella, ME, *Engineering Mathematics: an Investigation of Students' Mathematical Thinking from a Cognitive Engineering Perspective*, Thesis (Ph. D.) University of Washington, 2006.
- [12] Atman, CJ, Bursic, KM, "Verbal Protocol Analysis as a Method to Document Engineering Student Design Processes," *Journal of Engineering Education*, 1998.

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