Making Prototypes Work: Reflections from a Course in Tangible User Interfaces

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ABSTRACT
This paper discusses the role of electronic or other prototypes in the interaction design process, based on the experience of a class in tangible user interfaces. It shows how four kinds of prototypes (spatial vs. temporal and tangible vs. intangible) can be used to improve various aspects of a design concept. The difficulties of electronic prototyping discussed include time, fragility, inflexibility, and distraction. Advantages such as immediacy and the possibility for the exploration of complex interactions are also explained. The paper illustrates the relationship of design students to working prototypes and their importance in a design education. A distinction is made between electronic prototypes as an element of the design process and as a tool for public communication and exhibition. Suggestions are offered for tools that would make it easier to build working prototypes.

Author Keywords
Prototyping, electronic prototypes, interaction design, education, design process.

ACM Classification Keywords
H.5.2. [Information interfaces and presentation (e.g., HCI)]: User Interfaces---Prototyping.

INTRODUCTION
Prototypes are an essential part of any design process. They have been the subject of much research, e.g. [1, 5, 7]. Many other projects propose new toolkits for electronic prototyping [3, 4]. Few papers, however, discuss the specific characteristics of building working prototypes in the design process.

This paper reflects on this through the experience of a course in tangible user interfaces. The class was part of a year-long program in interaction design. Twenty-one students worked in groups of two or three on a four-week project (their only course at the time). Emphasis was placed on building working electronic prototypes for presentation in a public exhibition. Students were forbidden from using screens in their projects, but the brief was left otherwise quite open. During the first half of the course, students defined their own design directions and developed concepts, mostly with non-working prototypes. The second half of the course was spent implementing the chosen concepts. Arduino was the primary prototyping platform, but students also used pre-existing modules, breadboarded circuits, custom-designed PCBs, consumer devices, etc.

PROTOTYPE CATEGORIES
The prototypes created during the course can be divided into four rough categories, along two poles: spatial vs. temporal and intangible vs. tangible. Spatial prototypes focus on form and appearance; temporal prototypes on behavior or interaction. Intangible refers to the content of the prototype (e.g. sketching, performance, or video), although such prototypes may be embodied in a tangible medium (e.g. paper). Tangible prototypes are three-dimensional objects - electronic or not - created as part of the design process. Because screens were not allowed in the final projects, students tended to avoid them when prototyping.

Spatial, Intangible Prototypes
All of the students used sketches, photos, and other two-dimensional images in the course of their early concept development. These are invaluable for capturing early ideas and for thinking through options. They also facilitate easy reference of other projects or desired aesthetics. Because, however, this category of prototypes is so ubiquitous throughout design, it is not discussed further here.

Spatial, Tangible Prototypes
Models are a staple of industrial design practice, but they can serve new purposes within interaction design. In addition to previewing the appearance, construction, and ergonomics of an object, they allow for an exploration of its affordances. That is, by creating a physical mockup of an object, it becomes possible to understand the ways people will attempt to interact with it, and the ways it can be manipulated. This process is crucial for testing which elements to include in an interface and how to organize them. Following are two examples of models built during

Figure 1. Foam core and tape prototype of a scale for measuring the environmental impact of food.

the course and a discussion of the affordances explored by each (see [6] for an in-depth discussion of this kind of prototype).

e.g. Scale for Weighing the Environmental Impact of Food

One group of students decided to make a scale that would allow consumers to "weigh" the environmental impact of their purchases (particularly food). They built an initial prototype consisting of a piece of foam core stuck atop a roll of tape, along with physical tokens representing different foods and various measures of environmental impact (figure 1). This allowed students and faculty to try the permutations of food and environmental variable allowed by a balance. It quickly became apparent that although it felt natural to place food items on either side of the balance, using blocks to represent different standards of measurement was unclear. What, for example, would it mean for "food miles" and a banana to be placed on one side of the scale, with "C02 emissions" and apples on the other? In the end, students settled on a system in which a food item was placed on one side of the scale, with trees (representing the carbon impact from transportation of the item) on the other.

e.g. Calendar for Autistic Children

Another group of students decided to create a three-dimensional calendar for autistic children and their parents or caregivers. Such children have widely varying cognitive abilities and, therefore, need diverse tools to help them prepare for upcoming activities. Existing solutions tend to be flat and wall-mounted, limiting their possible uses.

The students created a quick prototype using a set of drawers for storing electronic components. These were labelled with photos or icons representing various activities, and organized by day of the week and time of day. The students imagined that each drawer would be tagged with a sound that could be played by the child (or recorded by the parent) using an accompanying radio-like device. In discussing the prototype with caregivers and parents, the students gained a better understanding of the flexibility needed in the calender: to show photos, icons, drawing, or to contain objects (an accidental discovery resulting from the drawers used for the prototype). They also realized the importance of integrating the sound recording and playback into the drawers themselves. Their final prototype consisted of a set of wooden boxes with transparent fronts, slots for images, room for objects, and integrated sound module.

Temporal, Intangible Prototypes

Techniques like story-telling, role-play, and performance can quickly and flexibly explore possibilities for interaction. They allow for experimentation with the temporal nature of a design - how it responds to people and they to it. Although they involve the people and their bodies, the prototype as such consists of intangible actions rather than requiring the creation of a physical object. Such prototypes allow the demonstration of behavior and interaction without the necessity (and time) of building a working prototype. As such, they are particularly useful in the beginning of the design process, when the design space is being explored. Below are two examples from the course (see [1] for an overview of this kind of prototype).

e.g. Collaborative Physical Games

Two of the students wanted to make physical games that would be played by people working in pairs: each with certain limitations on their perception or actions (e.g. not being able to look at the playing surface). To test the experience of such an interaction, they attempted to trace a maze while blindfolded - with one student moving the pen forward and backward, another moving it left and right, and a third (who could see) directing. In the end, they created a robot that was collaboratively controlled by two players: one set the speed by tilting a controller forward and backward, the other steered it by tilting their controller left and right.

e.g. Soft Interfaces for Mobile Phones

Another pair of students wanted to design soft sleeves for a mobile device that would provide it with a custom interface for particular situations. They had two initial ideas: one that would turn the mobile into an alarm clock, another to customize it for running. In order to understand which had the greater potential, they made quick videos demonstrating the functionality of each sleeve. The first showed how the mobile could serve as a clock when masked by the sleeve, how the alarm would be silenced, and how an incoming call would be activated, and so on. The second demonstrated the way a jogger would control music playback on their mobile. It featured one of the students running in place with the mobile (in its sleeve) strapped to one arm, with the other hand slapping his arm to control the playback and volume. The second video was instantly appealing, as the logic of using large areas for basic control fit the context perfectly. As a result the students were quickly able to decide on that sleeve for further prototyping.

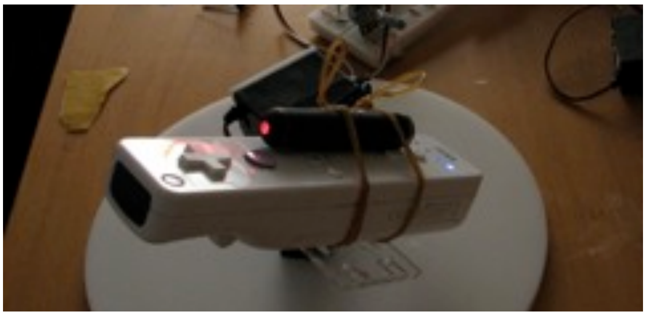

Figure 2. Prototype of an IR-tracking light.

Temporal, Tangible Prototypes

While all of the students built working electronic prototypes as some point during the class, for two groups they proved particularly important to understanding the design itself. A description of these groups' prototypes follows; the unique advantages and drawbacks of electronic prototypes are discussed in subsequent sections.

e.g. Beacon-Tracking Light

One group wanted to create lights that could follow a person or provide illumination in a desired location. They created a quick video that demonstrated the potential appeal of such a product, and proceeded quickly to an exploration of how to make such a system function. The students selected the IR camera in a Wii remote as the tracking system, and proceeded to build multiple versions of the actuation system for moving the lights. These included standard and continuous-rotation servo motors and stepper motors, with various mounting and bracketing systems. In this case, the building of working prototypes was crucial to understanding the speed, smoothness, and accuracy with which each actuation system could follow an IR beacon. It also allowed the students to attempt different techniques for the construction of the supports and enclosures for the motors and lights, and to test the performance of the motors under varying loads. Although some of these explorations strayed into the area of engineering, they were vital to understanding the quality of the movement of the light - a key aspect of the design.

e.g. Simultaneous Photography

Another group of students wanted to create a system which would allow for the taking of multiple simultaneous photographs of an event or scene. They created a quick software prototype in which multiple computers were networked together such that pressing a key on one would cause all of them to capture an image from an attached webcam. This provided the functionality they were interested in, but lacked the tangible qualities that would allow the cameras to be easily positioned in varying locations and perspectives. They also created a small set of wooden blocks with a circular indentation on one side - suggestive of the shape they desired. This model allowed them to test the affordances of the desired objects, but not to see the images that would result. To understand the photographic potential of their idea, they needed to build a working prototype.

What followed was a long and frustration excursion into the realm of operating systems, webcam drivers, graphical programming frameworks, and USB hubs. In the end, the students were able to create a system in which three computers were each connected to two webcams (of different models) - allowing for the taking of six simultaneous photographs. The prototype was ready only just before the final presentation of the class, so it did not permit refinement of the concept. It did, however, provide strong proof of the myriad possibilities presented by such a system: for multi-faceted portraits, panoramic photos, multiple snapshots of the same scene, etc. This appreciation of the potential of the concept would not have been possible without a working prototype.

DIFFICULTIES OF ELECTRONIC PROTOTYPING

Working prototypes have many disadvantages and difficulties. Foremost among these is the *time* they take to build. In the course, most of the student groups spent fully two weeks (half of the time) constructing their final prototype. Compared to the hours or days taken on most of their earlier prototypes, this was a large commitment. It can also be difficult to estimate the time required to complete an electronic prototype, particularly because they tend to be non-functional until they are almost finished. Almost none of the students in the class slept the night before the final presentations as they struggled to get the prototypes into a demonstrable state.

Electronic prototypes can be particularly *inflexible*, difficult to adjust or craft as one's conception of the design changes. Component choices and circuit designs constrain the flexibility of the prototype, even as its functioning begins to reveal new possibilities. Tweaking prototypes is particularly difficult for non-technical students who may only know the specific component or piece of code they're working with. The components they’ve already used or purchased often shape the behavior or interface of a prototype.

Another obstacle to adjusting the design of a prototype is that any change risks breaking it completely. This points to one of the other weaknesses of electronic prototypes: their *fragility*. They are difficult to transport, hard to maintain, and often poorly documented. This greatly limits their lifespan and scope. Although four of the prototype built for the class were later exhibited at a conference, they required significant effort and rebuilding for the occasion. In particular, the more custom electronic circuitry involved (as opposed to standard modules or computer peripherals), the greater the difficulties.

One surprising drawback of electronic prototypes is their tendency to *engross and distract* students. It's easy to become so intent on getting something to work that you forget its purpose, or fail to consider other ways of achieving the same end. Often the prototype detracts from the design by moving focus from the interface and interactions to the implementation. Although many of the students do not intend to to use electronics later in their careers, in this class, they showed a strong desire to prove that they could make their prototypes work.

Finally, working prototypes (at least in an exhibition) tend to *discourage contemplation* of the role that the object would play in one's life. Visitors tend to be absorbed by the behavior and functionality of the prototype - playing with it rather than thinking about it. A combination of a model and video can better suggest the relationship one might have with an object outside of the exhibition (see [2] for an in-depth discussion).

ADVANTAGES OF ELECTRONIC PROTOTYPING

Despite their difficulties, electronic prototypes have some unique advantages over other formats. As a tool in the design process, they are key for *understanding a complex interaction* between person and object. Situations in which a device responds in rich or subtle ways to user input are difficult to evaluate without experiencing them directly. Electronic prototypes also allow for emergent behavior through the combination of multiple objects or their interaction with the real world.

As opposed to sketches, models, or even videos, which may require training in design to translate into a real interaction, electronic prototypes make *immediately accessible* the behavior or interaction being designed. The use of sensors and actuators to create autonomous activity may lend the prototype a sense of *magic*. These characteristics make electronic prototype excellent at attracting attention and engagement in an exhibition or other public setting.

PROCESS VERSUS OUTCOME

It is important to distinguish between a prototype as part of the design process and a prototype as its outcome. In the former case, it serves as a tool for the designer to reflect upon and refine the interface and object in question. In the latter, it becomes a way for the designer to communicate a concept with a broader audience. Many of the prototypes built in the second half of the course would not have been appropriate if intended only for the purposes of advancing the students' thinking about the design. As exhibition pieces, however, they required the additional time and effort that went into making them robust and autonomous.

OPPORTUNITIES FOR BETTER TOOLS

In the course, we experienced a large gap between non-working and working prototypes. The former tended to be quick, flexible, and built on students' existing skills. The latter were slow to make, constrained, and required lots of faculty assistance. Many systems and much research have addressed this gap (see [3, 4]) but there are still opportunities for better tools in the context of interaction design practice and education. There seems to be a need for products which provide high-level behaviors that can be combined in a flexible way. Key to such tools is a good balance between functionality and cost, particularly in educational settings. There's also a need for visual or other easy-to-use programming environments that do not require a computer for the functioning of final prototypes. Lego Mindstorms and Pico Crickets have such an environment, but both are limited in their ability to work with standard electronic components.

CONCLUSION

Electronic prototype have unique advantages and difficulties, especially in the context of a design education. Building one can be invaluable in helping students to understand their strengths and weaknesses in relation to other types of prototypes, even if it can sometimes distract from the process of actually designing a tangible interface. Additionally, working prototypes are a great way to engage a broader audience with new concepts, even if they don't always fully appreciate the design process or the meaning of the object. Better tools could narrow the gap between electronic objects and other forms of prototypes for tangible interfaces, making them a more integrated part of the interaction design process.

ACKNOWLEDGMENTS

The course discussed here was taught by Heather Martin, Christopher Scales, Durrell Bishop, David Cuartielles, Vinay Venkatraman, Alexander Wiethoff, and the author, who would also like to thank Simona Maschi and all the students and staff of CIID.

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