The Anatomy of Prototypes: Prototypes as Filters, Prototypes as Manifestations of Design Ideas

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The role of prototypes is well established in the field of HCI and Design. A lack of knowledge, however, about the fundamental nature of prototypes still exists. Researchers have attempted to identify different types of prototypes, such as low- vs. high-fidelity prototypes, but these attempts have centered on evaluation rather than support of design exploration. There have also been efforts to provide new ways of thinking about the activity of using prototypes, such as experience prototyping and paper prototyping, but these efforts do not provide a discourse for understanding fundamental characteristics of prototypes. In this article, we propose an anatomy of prototypes as a framework for prototype conceptualization. We view prototypes not only in their role in evaluation but also in their generative role in enabling designers to reflect on their design activities in exploring a design space. We base this framework on the findings of two case studies that reveal two key dimensions: prototypes as filters and prototypes as manifestations. We explain why these two dimensions are important and how this conceptual framework can benefit our field by establishing more solid and systematic knowledge about prototypes and prototyping.

Categories and Subject Descriptors: H.5.2 [**Information Interfaces and Presentation**]: User Interfaces; H.1.2 [**Models and Principles**]: User/Machine Systems

General Terms: Design, Theory

Additional Key Words and Phrases: Prototype, prototyping, design, design space, human-computer interaction

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ACM Reference Format:
Lim, Y.-K., Stolterman, E., and Tenenberg, J. 2008. The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas. ACM Trans. Comput.-Hum. Interact. 15, 2, Article 7 (July 2008), 27 pages. DOI = 10.1145/1375761.1375762 http://doi.acm.org/10.1145/1375761.1375762

1. INTRODUCTION

The fields of human-computer interaction (HCI), software engineering, and design commonly use the term *prototype* to signify a specific kind of object used in the design process. The necessity of prototypes in these areas is obvious and unquestionable. Over the years, researchers and practitioners in HCI have proposed numerous prototyping techniques; these efforts primarily view prototypes as tools for evaluation of design failure or success, as evidenced in a recent panel session at one of the most prestigious HCI conferences, "'Get Real!' What's Wrong with HCI Prototyping And How Can We Fix It?" [Jones et al. 2007]. A close examination of actual design practices in which prototypes are pervasively used, however, shows that prototypes as a means for formal evaluation (such as usability testing) are a relatively small part of the entire design process. Prototypes are the means by which designers organically and evolutionarily learn, discover, generate, and refine designs. They are design-thinking enablers deeply embedded and immersed in design practice and not just tools for evaluating or proving successes or failures of design outcomes. Buxton [2007] advocates such a view, promoting the notion of sketching throughout the whole design process.

In this paper, we introduce a new way of thinking about prototypes and prototyping based on the need for exploring and establishing a fundamental definition of prototypes that extends current understanding and highlights critical roles. With this attempt, we conceptualize prototypes as tools for traversing a design space where all possible design alternatives and their rationales can be explored [Goel and Pirolli 1992; Moran and Caroll 1996]. Designers communicate the rationales of their design decisions through prototypes. Prototypes stimulate reflections, and designers use them to frame, refine, and discover possibilities in a design space. This view differs markedly from current approaches in software engineering contexts where engineers use prototypes to identify and satisfy requirements [Floyd 1984]. These requirement-oriented approaches have their limitations, especially since design activities are flexible rather than rigid, reflective rather than prescriptive, and problem-setting rather than problem-solving [Schön 1982]. A design idea that satisfies all the identified requirements does not guarantee that it is the best design since a number of ways can meet each requirement. If the focus of prototyping is framing and exploring a design space, what matters is not identifying or satisfying requirements using prototypes but finding the manifestation that in its simplest form, filters the qualities in which designers are interested, without distorting the understanding of the whole. We call this the *fundamental prototyping principle*.[1]

[1]The discussion of the benefits of applying this principle resonates with the new way of thinking about prototyping in HCI illustrated in Wong [1992].

In order to support this perspective and to provide a stable foundation for the study of prototypes in HCI, we propose a framework for conceptualizing prototypes; we see such a framework as an anatomy of prototypes. The framework is an attempt to create an understanding of the nature of prototypes in general and to provide a language for articulating the characteristics of a particular prototype. Such a framework will enable designers to specify more effectively the goals and questions to explore when planning and making their prototypes. It will also better guide designers in thinking critically about their approach to prototyping.

Two fundamental aspects of prototypes form the basis of our framework:

1) prototypes are for traversing a design space, leading to the creation of meaningful knowledge about the final design as envisioned in the process of design, and
2) prototypes are purposefully formed manifestations of design ideas.

When exploring a certain aspect of a design idea, designers can focus on demonstrating various ideas for interaction techniques without determining other qualities of the design, such as its appearance or its functionality. When exploring only the design's form aspect in evaluating portability-related ergonomics, they may develop various prototypes with different sizes, weights, and shapes without any interactivity or functionality in place.

As a part of our framework, we identify an initial set of design aspects that a prototype might exhibit. We call these aspects *filtering dimensions*. We use the term *filter*, since by selecting aspects of a design idea, the designer focuses on particular regions within an imagined or possible design space. The designer screens out unnecessary aspects of the design that a particular prototype does not need to explore. Designers may purposefully do this so that they can extract knowledge about specific aspects of the design more precisely and effectively. The decision of what to filter out is always based on the purpose of prototyping.

When creating a prototype that manifests a certain aspect of a design idea, designers need to make careful choices about the prototype's material, the resolution of its details (which corresponds to the concept of fidelity), and the *scope* of what the prototype covers (which can be understood as a level of inclusiveness—that is, whether the prototype covers only one aspect of the design idea or several aspects of the design idea). These three considerations of manifesting a design idea—namely, the material, resolution, and scope of a prototype—are also part of the prototype's anatomy. We call these considerations manifestation dimensions.

A designer can determine the manifestation dimensions of a prototype by considering the *economic principle of prototyping,* which we define as follows: the best prototype is one that, in the simplest and most efficient way, makes the possibilities and limitations of a design idea visible and measurable. If we keep the economic principle of prototyping in mind, determining the values of the manifestation dimensions—that is, the materials, resolution, and scope of the prototype—can be approached in a rational and systematic way. Based on this conception of an anatomy of prototypes, we view prototypes as filters intended

Table I. The Principles of Prototyping and the Anatomy of Prototypes

Fundamental prototyping principle:
Prototyping is an activity with the purpose of creating a manifestation that, in its simplest form, filters the qualities in which designers are interested, without distorting the understanding of the whole.
Economic principle of prototyping:
The best prototype is one that, in the simplest and the most efficient way, makes the possibilities and limitations of a design idea visible and measurable.
Anatomy of prototypes:
Prototypes are filters that traverse a design space and are manifestations of design ideas that concretize and externalize conceptual ideas.

to traverse and sift through a design space and as *manifestations* of design ideas that concretize and externalize conceptual ideas. Table I summarizes the core proposal of our definition of the anatomy of prototypes and its key principles.

In this article, we first examine current understandings of prototypes in the field of HCI. We discuss what we mean by prototypes as *filters* and *manifestations*. Then we introduce the details of our concept, the *anatomy of prototypes.* We explore two prototyping case studies that serve as our sources in identifying the nature of prototypes and demonstrate how the identified dimensions can help in generating, conceptualizing, and comparing prototypes. We end by discussing the benefits and potentials of our proposal for research and design practice in the fields of HCI and Design.

2. HOW PROTOTYPING IS UNDERSTOOD IN CURRENT RESEARCH IN HCI

In HCI, many researchers and practitioners have developed their own ways of prototyping for their various purposes. Discussions on prototyping have primarily focused on the issue of the prototype's *fidelity*, largely because fidelity is a matter of cost. Some have therefore emphasized the benefits of using low-fidelity prototyping techniques. These techniques include paper prototyping for all types of interactive products, including computer-based applications, mobile devices, and Web sites [Grady 2000; Rettig 1994; Snyder 2003]; Switcharoo for physical interactive products [Avrahami and Hudson 2002]; Calder for physical interfaces [Greenberg and Boyle 2002; Lee et al. 2004]; Buck prototyping for mobile devices [Pering 2002]; rapid prototyping for mobile devices using augmented reality technology [Nam and Lee 2003]; and DART for augmented reality systems [MacIntyre et al. 2004].

Nonetheless, low-fidelity prototyping has brought another round of discussion, focused on the validity of prototyping [Cockton and Woolrych 2002; Convertino et al. 2004]. There have been discussions on the validity of less exhaustive usability methods in terms of the number of users to test [Spool and Schroeder 2001], the length of observation, in situ versus lab tests, and user profiles. Particularly in the case of in situ tests, the fidelity of prototypes deeply matters because researchers cannot, in most cases, conduct the tests in the actual situation as the prototype is not fully functional or is not very similar to the final product [Reichl et al. 2007]. Most low-fidelity prototyping examples focus primarily on design exploration and communication and less on formal design evaluation.

Although the notion of a prototype's fidelity is helpful for orienting designers in the ways of building prototypes, some research results, including our own research, show that the simple distinction of low- versus high-fidelity prototypes can sometimes be problematic [Lim et al. 2006; McCurdy et al. 2006]. For example, McCurdy et al. [2006] suggest that such a binary distinction should be reexamined. They demonstrate the effectiveness of more sophisticated prototyping, namely a mixed-fidelity approach—that is, a prototype that combines low-fidelity and high-fidelity on different dimensions of design consideration. Lim et al. [2006] show that not only the fidelity but also other contextual factors involved in prototyping, such as the materials of prototypes and testing conditions, affect the results of prototyping.

Prototyping for externalizing and representing design ideas is another pervasive technique in designing interactive artifacts. Designers commonly use sketching as a means to externalize concepts [Buxton 2007]. Many researchers have explored developing tools for creating interactive prototypes that utilize a sketching technique. Examples of sketch-based prototyping have existed since the SILK tool by Landay and Myers [Landay 1996]. SILK uses a tablet based input device to essentially sketch an interface. The program allows for dynamic interaction corresponding to the rough button and form field shapes drawn by the designer. DENIM is another example of a sketch-based prototyping environment, following in the footsteps of SILK [Lin et al. 2000]. DENIM is used to prototype entire websites and allows for an intuitive sketching and linking scheme to lay out individual web pages. Sketch-based prototyping remains a popular topic for research, and a number of recent studies and tools have extended the sketch motif in prototyping—such as DEMAIS, a multimedia sketch-based editor [Bailey et al. 2001], and DART, a rapid prototyping environment for augmented reality environments [MacIntyre et al. 2004].

Participatory design is another popular approach in HCI, and this approach also utilizes various prototyping techniques. Many of the participatory approaches are used for understanding user needs and for exploring design ideas. (Some of the representative techniques include CARD [Muller 2001], game-based design [Brandt and Messeter 2004], and a role-playing approach [Svanaes and Seland 2004].) In participatory design, the use of prototypes focuses on actively engaging users in creating and exploring design ideas. Because the users are not expert designers, the results from participatory design approaches usually need to be reinterpreted to understand users' needs and values rather than directly adapting their design ideas into the final design.

The examples named here are only a few of the many uses and styles of prototyping in interaction design. In each technique, the prototype that is created filters different aspects of the design ideas, though none of these techniques solve every aspect of a design. We argue that these techniques are in some cases used without a reflective understanding of how they differ from each other in terms of their roles and characteristics. Some researchers have tried to compare the pros and cons of different techniques [Avrahami and Hudson 2002; Gutierrez 1989; Liu and Khooshabeh 2003; Pering 2002; Rudd et al. 1996;

Sefelin et al. 2003; Thompson and Wishbow 1992; Virzi et al. 1996; Walker et al. 2002], and this represents a first step in understanding how each style of prototype functions differently. Most of those comparisons, however, are based on anecdotal experiences rather than empirical studies.

Of course, some of the examples were more rigorously conducted, including Liu and Khooshabeh [2003]; Sefelin et al. [2003]; Virzi et al. [1996]; Walker et al. [2002]. Sefelin et al. [2003] examine if users' willingness to criticize or make suggestions about a design differs when using paper-based or computer-based low-fidelity prototyping. Virzi et al. [1996] claim that low- and high-fidelity prototypes are equally suitable for finding usability problems. The systems that they use for the evaluation, however, are standard GUI-based ones, which differ from mobile or ubiquitous computing systems; they also do not clarify what types of problems were identified by which type of prototyping technique. Liu and Khooshabeh [2003], who study prototyping techniques for ubiquitous computing environments, claim that it is critical to choose carefully the fidelity and automation level of the evaluated prototypes.

We are primarily concerned with the lack of a fundamental definition of prototypes in the different ways of using and defining prototypes that many researchers and practitioners propose. We appreciate some researchers' attempts to summarize taxonomies of prototypes based on their different uses in design or development processes. Lichter et al. [1993] identify four types of prototypes within the context of the software development process. The first type is the *presentation prototype,* which presents aspects of design ideas in order to facilitate communication between a client and a software manufacturer. The second type is the *prototype proper,* which describes certain aspects of design ideas in order to understand and discover problems within those ideas. The third type is the *breadboard,* which quickly evaluates "construction-related questions" within the development team. The fourth type is the *pilot system,* which closely resembles the actual application for final refinements. Gutierrez [1989] also suggests various forms of prototyping that derive from existing examples relevant to software development activities; they include game playing, exploratory prototyping, system simulation, scenario-based design, experimental prototyping, production prototyping, and pilot systems.

All of these existing attempts to define a taxonomy of prototypes are primarily based on different ways of using prototypes in a development and design process. Developing generally applicable prototyping methods does not seem viable in face of the complex variety of interactive artifacts in HCI design. Current prototyping research can best be described as an ongoing attempt to come up with what to do with prototypes without understanding what they actually are. Although these attempts eventually enable us to understand indirectly what prototypes are, we will not be able to establish a fundamental definition of prototypes that is sophisticated enough to characterize their complex and dynamic nature if we continue to research only this direction. Although the different ways of using prototypes need to continue to be explored and practiced, we see a strong need for a fundamental knowledge about what prototypes are in order to be able to further advance knowledge and research about prototyping. We believe that the search for fundamental knowledge about prototypes will not only help researchers and practitioners become more creative and effective in determining what we can do with prototypes in design but will also establish a coherent understanding of the different techniques and approaches of existing and forthcoming examples of prototyping. In addition, this knowledge will support and inform designers and researchers in their development of new prototyping techniques.

The lack of a fundamental understanding of prototypes is what motivates our attempt to define an anatomy of prototypes. Instead of focusing on the wide variety of purposes and processes in which prototypes are used, we want to define prototypes of any type in a systematic and careful manner. Without conscious awareness of how prototypes influence the way users may interpret them during testing or how designers use them to identify problems, refine designs, and generate more ideas, the results of using prototypes can lead to undesirable effects. We propose the idea of an anatomy of prototypes accommodating two key aspects of prototypes, namely prototypes as filters and prototypes as manifestations of design ideas.

3. PROTOTYPES AS FILTERS

How, then, do prototypes help designers traverse design spaces? A primary strength of a prototype is in its incompleteness. It is the incompleteness that makes it possible to examine an idea's qualities without building a copy of the final design. Prototypes are helpful as much in what they do not include as in what they do. For example, a two-dimensional prototype of a three-dimensional building can help us to determine the spatial relationship of the rooms, without placing any constraints on the materials used for walls and floors. This incompleteness structures the designer's traversal of a design space by allowing decisions along certain dimensions (appearances of walls and floors) to be deferred until decisions along other dimensions (spatial relationship of rooms) have already been made.

This characteristic of a prototype—being an incomplete portrayal of a design idea—is the reason behind our metaphorical description of prototypes as filters. We view prototypes as a means for design, and in this sense our notion of filters is very different from the notion of filtering out nuisance variables in scientific experiments. In design and development processes, prototypes are used not for proving solutions but for discovering problems or for exploring new solution directions. Even though they can serve other purposes, prototypes in this context are a means of *generative and evaluative discovery*. When incomplete, a prototype reveals certain aspects of a design idea—that is, it filters certain qualities. For example, let us assume that a designer needs to evaluate her ideas about the ergonomics of one-thumb interactions with a mobile device. She may make various three-dimensional forms of the mobile device to figure out which ideas work better. When testing her ideas with three-dimensional form prototypes, she not only evaluates which ideas work better than the others, but also, more importantly, she discovers what factors of the forms make the ergonomics better, leading her to generate more or new design ideas. Those three-dimensional prototypes open up a new design space to explore—a space that may offer

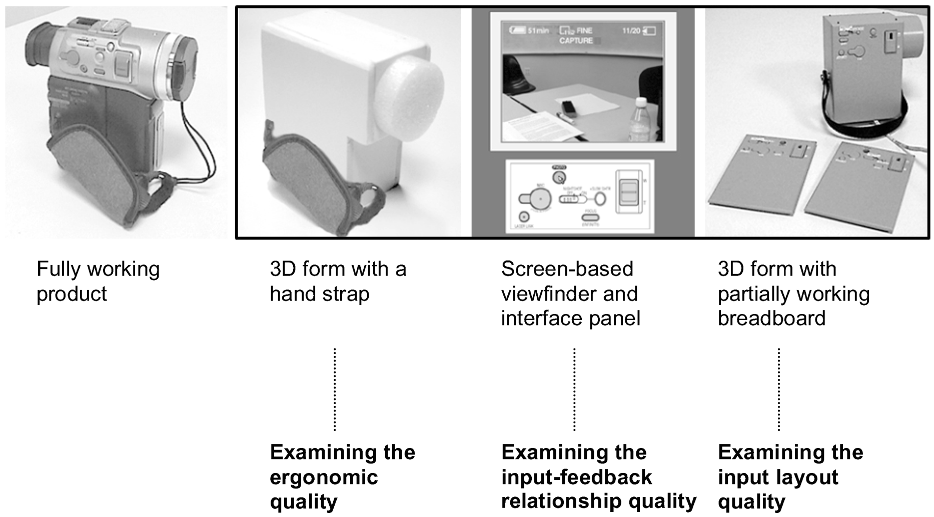

Fig. 1. A series of prototypes that represent different qualities of interest to a designer to filter out different aspects of a design [Lim 2003].

possibilities and better choices of the forms of the mobile device that are more effective ergonomically. The competence involved in prototyping is therefore the skill of designing a prototype so that it filters the qualities of interest to the designer. In other words, the most efficient prototype is the most incomplete one that still filters the qualities the designer wants to examine and explore. Figure 1 shows an example of showing different possible prototypes representing different qualities of interest that can be filtered out through each of them when exploring the design of a digital camcoder.

Normally, a design space is extremely large and complex; it is not feasible to explore the whole space at one time. One of the most difficult challenges of design is that we cannot control all possible effects of the design we produce. Prototypes are a tangible attempt to view a design's future impact so that we can predict and evaluate certain effects before we unleash it on the world. Knowing that prototypes filter certain aspects of a design, we can become more aware of the complexity and responsibility of a design, and hence be more thoughtful about our design decision making.

Prototypes are intricately intertwined with the evolution of design ideas throughout the design process. We constantly evaluate and reflect on the values of what we design—if those designs are socially responsible, economically viable, experientially pleasing, culturally sound, operationally usable, technologically compatible, and functionally error-free. These are some of the important values that designers try to satisfy. Throughout the design process, prototypes are what manifest the design thinking process to reach such design outcomes.

4. PROTOTYPES AS MANIFESTATIONS OF DESIGN IDEAS

It is widely accepted that design is a continuous coupling of internal mental activities and external realization activities. Recent research in education and cognition indicates that designs are constituted through iterated interaction with external design manifestations. Within the domain of engineering, Adams [2002] reports, "iteration is a significant component of design activity that occurs frequently throughout the design process; and measures of iterative activity were significant indicators of design success ... and greater engineering experience." Recent cognitive research informs this view by advancing the notion of the extended mind: a view of the mind that extends beyond the confines of the individual brain to include external artifacts. Andy Clark points out the commonsensical bias we have toward viewing the mind (and cognition) as a purely internal affair: "we are in the grip of a simple prejudice: the prejudice that whatever matters about MY mind must depend solely on what goes on inside my own biological skin-bag, inside the ancient fortress of skin and skull. But this fortress was meant to be breached" [Clark 2001].

Clark describes an empirical study by Van Leeuwen, Vertijnen, and Hekkert [Van Leeuwen et al. 2001] on the interaction between artist and artifact in the act of creation. "The sketch pad is not just a convenience for the artist, not simply a kind of external memory or durable medium for the storage of particular ideas. Instead, the iterated process of externalizing and reperceiving is integral to the process of artistic cognition itself" [Clark 2001, p.19]. What Clark suggests is that *externalization* of thought gives rise to new perceptual and cognitive operations that allow for reflection, critique, and iteration. That is, the act of bringing thoughts into material form is not incidental to the act of creation but is itself constitutive of and essential to creation. Mind, then, is not simply the sum total of representations and processes within the brain but also includes external manifestations of thought. Donald Schön famously captures this perspective when he states that we have to externalize our ideas so that the "world can speak back to us." The realized idea becomes a discussant, a collaborator, helping us to understand and examine our own ideas [Schön 1987]. Therefore, when a designer creates and envisions an idea, she necessarily develops the idea by moving it out into the world. She performs this transformation and externalization by realizing the idea in some kind of "physical" manifestation [Lim 2003; Tyszberowicz and Yehudai 1992; Zucconi et al. 1990].

These manifestations can take almost any form, shape, and appearance, based on the choice of material. The simplest form, the rough sketch on a piece of paper, is as important to the designer as it is to the abstract artist. Even simple configurations of images and text can serve an important design purpose. Looking at our own or a colleague's sketch, we can get a sense of eventual possibilities or limitations inherent in the idea. As an idea evolves and is refined, the need for more complex prototypes or manifestations increases.

The characteristic of prototypes as manifestations of design ideas is the same in all design fields, but it is especially interesting and important within Human-Computer Interaction (HCI) design. One reason is that the material used in the field—digital material—is of a different kind, a "material without qualities" [Löwgren and Stolterman 2004]. As they can take almost any shape or form, digital materials have very few intrinsic "material" limitations. Physical materials—such as wood, concrete, or steel—all have limitations and distinct properties that limit us in the choice of the desired form and function of a design. Working with the design of a digital artifact means that the material qualities determine form and function to a lesser degree, and that the design space therefore is larger and less restricted. We argue that the choice of filters is almost infinite in interaction design since the design space is itself infinite and not limited in the same sense as in other design areas.

Due to the greater possibilities inherent in digital material, the choices in prototyping are even more open-ended. The designer may use very different materials in prototyping than those in the final target product, especially when she needs to select the most efficient and cost-effective choices to manifest design ideas. For example, designers can use paper prototypes to approximate screen-based web designs. The material chosen for a prototype has direct implications on users' perceptions when it is used for evaluating a design concept, (e.g., as in Lim et al. [2006]). All these material issues lead to an even greater problem in deciding what prototypes to build and use and for what purposes.

In the definition of the anatomy of prototypes, we incorporate several issues in the manifestation of ideas, including the implications of the disparity between prototype materials and the expected real materials of a final design outcome; the dissimilarities between the manifested details of design ideas with prototypes and the details of the actual final design—that is, issues related to the level of resolution; and the differences between what a prototype covers and what the final design actually contains—that is, issues of the level of scope.

5. ANATOMY OF PROTOTYPES

We argue that the purpose of designing a prototype is to find the manifestation that, in its simplest form, will filter the qualities in which the designer is interested without distorting the understanding of the whole. We call this the fundamental prototyping principle. This principle serves as the foundation of our attempt to develop an anatomy of prototypes. It embeds two notions about prototypes, namely prototypes as filters and prototypes as manifestations of design ideas. In this section, we propose a beginning definition and an outline of an anatomy of prototypes. But, before doing that, we need to identify the difference between the meaning of *prototype* and *prototyping*. *Prototypes* are representative and manifested forms of design ideas. *Prototyping* is the activity of making and utilizing prototypes in design. Current research has primarily focused on the different types of prototyping without any rigorous analysis of what prototypes are, except in the notion of a prototype's fidelity, as we discuss earlier. For the purpose of this paper, it is important to understand prototypes and prototyping as two separate objects of study.

Anatomy is commonly defined as the "the science of bodily structure" [anatomy 2006]. We use this notion both literally and metaphorically to sketch an anatomy of prototypes, to "dissect" or uncover the fundamental dimensions along which to understand any particular prototype. We use the notion of anatomy descriptively rather than prescriptively. An anatomy is a description of possible shapes and structures; it shows how things *can* be organized. The anatomy itself does *not* tell designers how to design prototypes, but it can

Table II. Example Variables of Each Filtering Dimension

Filtering Dimension	Example Variables
Appearance	size; color; shape; margin; form; weight; texture; proportion; hardness; transparency; gradation; haptic; sound
Data	data size; data type (e.g., number; string; media); data use; privacy type; hierarchy; organization
Functionality	system function; users' functionality need
Interactivity	input behavior; output behavior; feedback behavior; information behavior
Spatial structure	arrangement of interface or information elements; relationship among interface or information elements—which can be either two- or three-dimensional, intangible or tangible, or mixed

Table III. The Definition and Variables of Each Manifestation Dimension

Manifestation Dimension	Definition	Example Variables
Material	Medium (either visible or invisible) used to form a prototype	Physical media, e.g., paper, wood, and plastic; tools for manipulating physical matters, e.g., knife, scissors, pen, and sandpaper; computational prototyping tools, e.g., Macromedia Flash and Visual Basic; physical computing tools, e.g., Phidgets and Basic Stamps; available existing artifacts, e.g., a beeper to simulate an heart attack
Resolution	Level of detail or sophistication of what is manifested (corresponding to fidelity)	Accuracy of performance, e.g., feedback time responding to an input by a user—giving user feedback in a paper prototype is slower than in a computer-based one); appearance details; interactivity details; realistic versus faked data
Scope	Range of what is covered to be manifested	Level of contextualization, e.g., website color scheme testing with only color scheme charts or color schemes placed in a website layout structure; book search navigation usability testing with only the book search related interface or the whole navigation interface

inform them about the fundamental nature of prototypes and the possibilities in thinking about them.

Our proposed anatomy of prototypes includes (1) filtering dimensions and (2) manifestation dimensions. These two types of dimensions correspond to the two important characteristics of prototypes—prototypes as filters, and prototypes as manifestations of design ideas.

In defining the set of filtering dimensions, we include appearance, data, functionality, interactivity, and spatial structure (Table II). These dimensions correspond to the various aspects of a design idea that a designer tries to represent in a prototype. They also refer to the aspects of a design idea that the designer must consider in the exploration and refinement of the design. We define the three core aspects of the manifested forms of prototypes as materials, resolution, and scope (Table III).

Although they represent two different ways of looking at prototypes, both the prototype's filtering dimensions and the manifestation dimensions are tightly related to each other. For example, designers who explore possible ideas of using a one-handed mobile device interface—which is the interactivity dimension in terms of filtering—may consider how to manifest these ideas using prototypes. Here we can readily imagine unlimited possibilities to manifest an idea addressing the *same* filtering dimension. In terms of the prototypes' material, designers may use foam core as a material to mock up a prototype design that is the same size as the target design in order to simulate the holding postures for the mobile device, or they can use clay or wood to give more realistic three-dimensional forms for ideas related to thumb positions and gestures for interacting with the mobile device. The designers may continue to use three-dimensional forms since their purpose is to explore the effects of one-handed interactivity with the mobile device. This example shows us that, while affected by the filtering dimension, the choice of manifestation dimensions involves various issues such as resources, cost, and user perception in the use of a prototype.

Manifestation dimensions other than material are also related to the filtering dimension. In this mobile device design example, designers are particularly interested in the possibilities and effectiveness of one-handed interaction, such as different ways of operating inputs using one thumb or with one-handed gestures. For this purpose, designers may not need to implement sophisticated details of the interface's look-and-feel as long as the prototype provides key interface indicators that are clear enough for users to understand where they can place and move their thumbs. In this case, the purpose guides the designers to determine the right level of resolution of the prototype—another manifestation dimension. It also applies to the *scope* of the prototype in terms of what other parts of the design the designer needs to include in a prototype in order to be able to examine the filtered aspect(s) of the design. For example, a designer can decide whether or not to include corresponding outcome screens according to her selected aspect(s). Thus, a designer has to decide what aspects of a design idea should be filtered when forming a prototype. One prototype might only filter an appearance aspect, while another filters all aspects at once. The challenge for a designer is to design the prototype that supports her design intention most effectively.

5.1 Filtering Dimensions

As a part of the anatomy, we define five filtering dimensions that we believe, in a reasonable way, cover the core aspects of a design idea in interactive systems design. The *appearance dimension* is the physical properties of a design. It may include forms, colors, textures, sizes, weights, and shapes, as well as proportional relationships among these elements. It is not restricted to visual appearance, since characteristics such as weight, texture, size, and shape can be sensed by touch as well as by sight. The *data dimension* is the information architecture and the data model of a design. It may include the size of data, the number of letters to be shown in each label, the amount of visible and invisible data on screen, the semantic organization of the contents, the ways of labeling and naming, the levels of privacy of data, and the types of information. The *functionality dimension* is the functions that can be performed by the design. Focusing on this dimension, designers may determine preferred functionalities and scenarios associated with using different functions. The *interactivity dimension* is the ways in which people interact with each part of a system. It may include feedback, input behaviors, operation behaviors, and output behaviors. The *spatial structure dimension* is how each component of a system is combined with others. It may include considerations of laying out interface or information elements in an interactive space. If the design includes partially tangible and intangible interfaces, such as mixed-reality systems, this dimension may involve the relationships and interconnections between tangible and intangible interfaces.

This list of dimensions is not meant to be complete; it is, however, meant to be useful, in ways we elaborate later. Table II shows relevant variables to be discussed in relation to each filtering dimension.

The dimensions are tightly related to and influenced by each other; it is therefore impossible to treat them separately. For example, the interactivity aspect of the iPod's wheel interface drives its basic appearance. The data dimension is likewise tightly related to other dimensions. The size of music data that the iPod can contain—a decision about the *data dimension*—led the decision making on interface design issues related to *interactivity*. Since an iPod can hold more than 200 songs, the iPod's development team avoided the use of buttons to browse songs, instead inventing the wheel interface to browse naturally through a large number of songs with a thumb [Levy 2006]. This new way of browsing songs is tightly related to the interactivity dimension. The result of this new idea of interactivity led to novel decisions concerning its appearance.

In spite of the relationships among the dimensions, a necessity of crafting and working on each dimension separately also exists; the separation ensures that the selected dimension is itself carefully designed to fulfill important design values. For example, designers cannot determine the design details of the iPod's appearance—such as size of the interface wheel circle, font size of the wheel's label, color, shape of the symbols used as labels, and texture of the surface of the interface wheel—without separately exploring this appearance dimension of the design space using various prototypes. Prototypes can enable designers to explore a dimension space in order to reach a decision on the final appearance of the design outcome. Through the process of making prototypes, designers constantly evaluate their ideas (whether formally using user tests or informally and heuristically by using their own expertise), generating better ideas.

Prototypes allow designers to do this by filtering a dimension out from other ones but also enable them to see the relationships among different dimensions as well. The anatomy of prototypes we propose can guide designers to be aware of and think about these multiple dimensions even while working on a specific dimension.

It is obvious that the relationships between these dimensions are intricate and dynamic; no dimension is separate from any other. We see this recognition of intertwined relationships among the dimensions as an outcome of the prototype's anatomy. Attempting to clarify these dimensions reveals the complexity of prototypes. The anatomy we propose can serve an educational purpose as it enables the articulation of structures—for example, anatomies—of different prototypes as design knowledge that can be taught.

5.2 Manifestation Dimensions

Though it may provide an initial *direction* for prototype formation, knowing only what to filter based on the set of filtering dimensions cannot fully determine how to form a prototype nor provide strategies for forming it. We use the term “formation” instead of “construction” since a prototype may not need to be “constructed” out of physical matter but can be formed by invisible triggers or behaviors. For example, a case of experience prototyping proposed by Buchenau and Suri [2000] used a beeper to simulate a person having a heart attack in order to understand what kinds of possible situations surrounded the heart attack accident. They asked participants to journal the surrounding situation when they heard the randomly activated beeper ringing or vibrating. In this prototyping example, a prototype is not constructed with raw physical materials. A prototype is formed by a situation and an existing object behaving in a certain way—that is, the beeper beeping randomly to simulate a heart attack.

What determines the specifics of how to form prototypes are the issues of what prototypes should be composed or made out of, that is, the materials (whether visible or invisible) by which the prototype is made manifest; what level of fidelity the prototype should be, that is, the resolution of a prototype; and how complete the prototype should be, that is, the scope of a prototype. We call these three dimensions manifestation dimensions. The meaning of scope is completeness and differs from the notion of resolution. Scope is how completely a prototype covers the range of aspects of what we design even if those aspects are not related to what we want to filter through the prototype. Those additional aspects may help us understand the prototype more effectively. Table III shows the definition and corresponding variables of each manifestation dimension.

As we discuss earlier, the economic principle of prototyping should guide designers to determine the values of these dimensions when forming a prototype. Based on her purpose in prototyping, a designer may use paper as a material for prototyping instead of working computer screens. This is an example of a prototype material decision. The designer can also vary the details of what is shown in a prototype. Even if using paper, she can have a very detailed and sophisticated drawing or a rough sketch. This is an example of a prototype resolution decision. When figuring out which color scheme is best for her Web site design, a designer may use color schemes without the details of text, icons, and menus on the Web page. This is an example of a prototype scope decision. How to decide these values is based on the economic principle of prototyping.

What must be understood here is that a prototype is fundamentally different from the final product, whether or not it is identical to the final product. Prototypes are means and tools for design and are not the ultimate target for design. In this regard, the designer’s mindset in forming prototypes is different from that in forming the final design. When treating something as a prototype, the designer can start to put in different materials or take out certain materials based on the purpose of using that prototype for the design.

We argue that the manifestation dimensions influence how well a prototype performs as an informing tool in the design process. The manifestation dimensions affect the performance of the prototype—not in the sense of how much the prototype performs like a final product but how well the prototype performs as a tool for evaluating design ideas and generating better design ideas—without altering the filtering dimensions the designer has chosen to evaluate. The manifestation dimensions may modify or influence how well and to what degree the prototype filters the desired filtering dimensions.

The reason that we name these manifestation dimensions is that these dimensions influence people's perception of and reaction to a particular prototype. For example, if we compare the two cases of evaluating how people perceive the colors of a room's walls—one with a three-dimensional virtual model through a computer and the other with a three-dimensional life-sized foam-board model in a physical space, we recognize that the two situations will affect the way in which people react to the colors due to the different materials used to represent the variable of a specific filtering dimension, that is, appearance, and more specifically colors, of the room's wall. In this regard, the selection of material—a virtual model or a physical model—modifies the appearance dimension of the design of the room.

When compared to other prototyping research approaches, one of the most significant contributions of our approach is that we strive to establish an understanding of the nature and anatomy of prototypes that can be utilized and extended for both research and practice. We claim that the anatomy of prototypes can be used to examine and analyze existing prototypes as well as inform designers in their design of new prototypes. In the next section, we describe two cases in which we have used the anatomy of prototypes in our analysis. After these cases, we return to the question of how to use the proposed anatomy of prototypes and what it can mean for future research, practice, and education.

6. TWO CASES EXPLAINED WITH THE ANATOMY OF PROTOTYPES

In this section, we describe two case studies based on our previous research. These two cases led us to identify the key dimensions of our proposed anatomy of prototypes. We present the two cases in order to describe the anatomy of prototypes by applying it to the real contexts of prototyping.

In the first case, we investigate how different prototypes filter different aspects of a design and how the prototypes influence the ways in which the users who interacted with the prototypes interpreted the design concept. In this regard, the first case is for understanding the effects of the filtering dimensions of prototypes. In the second case, we investigate how the choice of materials, resolutions, and scopes of prototypes influence users' reactions toward prototypes and affect their interpretations of the design. In this regard, the second case is for examining the effects of the manifestation dimensions of prototypes.

When we describe the prototypes used in each case, we use the structure of the anatomy of prototypes. The overall description of each prototype based on the anatomy of prototypes can be seen as a prototype profile that specifies what was considered in forming the prototypes. Since each case enables us to examine different parts of the anatomy dimensions—that is, the first case for the filtering dimensions and the second case for the manifestation dimensions, we present the prototype profiles based on those relevant dimensions. The two studies were carried out separately from each other and by different groups of researchers. The two studies have both been described in earlier writings [Skog and Söderlund 1999; Lim et al. 2006] but are reinterpreted for the purpose of this study.

6.1 Case 1: Prototyping a House Design

The analysis of the first case study led us to understand that a prototype can filter different aspects of a design. In this case study, two prototypes were formed, both representing the same design idea. The target design was a typical family house with a few bedrooms, a living room, a kitchen, a stairway to the second floor, and a couple of bathrooms. One prototype was a two-dimensional floor plan of the house, and the other prototype was a three-dimensional virtual model of the same house design. The original study of this case [Skog and Söderlund 1999] examines how users would convey their interpretations of the proposed design differently if the same design were represented in two prototypes focusing on two very different filtering dimensions.

6.1.1 *The Prototype Profiles.* The first prototype consisted of a two-dimensional paper-based blueprint of the house. It was a very simple representation that showed the floor plan of the house—the spatial layout. The blueprint showed precise sizes of spaces, proportions among spaces, and the structure of the rooms, along with the spatial relationships. Created with simple three-dimensional modeling software, the second prototype enabled people to interact with a three-dimensional virtual model of the house by virtually "walking" into the home, through rooms, turning around, and experiencing the home as if they were walking around a real home. The home was sparsely furnished.

Even though the two prototypes represented the same house, the very nature of how the aspects of the house were manifested was very different between the two. For instance, in a three-dimensional model, you are "forced" to have colors on the walls in the rooms, which is not the case on a blueprint. On a blueprint, you get a bird's-eye view of the house—a perspective not possible in the physical world or in the three-dimensional virtual space. In a three-dimensional virtual model, the space is something you can feel, while, in the blueprint, the space can only be experienced as layout and relationships. A two-dimensional blueprint, in this regard, may better filter the spatial structure dimension of the interior of the house, while a three-dimensional model may better filter the appearance dimension of the interior of the house. Table IV shows prototype profiles for the two prototypes according to the filtering dimensions of the anatomy of prototypes; these profiles enable us to see the significance of the filtering characteristics of prototypes.

6.1.2 *Prototyping and Results.* The researchers tested the two prototypes with two groups of users. The study consisted of eight subjects, four men and four women. They were divided into two groups of four. Each individual in each

Table IV. Prototype Profiles for the Prototypes Used in the First Case

Dimensions	2-Dimensional Blueprint	3-Dimensional Virtual Model
Filtering dimensions	**Addressed filtering dimensions:** *Spatial structure*—precise manifestation of relationships and proportions among spaces **Not addressed filtering dimensions:** appearance, data, functionality, interactivity	**Addressed filtering dimensions:** *Appearance*—colors and textures of walls; heights and widths of spaces *Interactivity*—the possibility to move around and interact with the 3-dimensional space *Spatial structure*—precise manifestation of relationships and proportions among spaces **Not addressed filtering dimensions:** data, functionality

group was asked to explore and interact with either (and only) the blueprint or the three-dimensional model. The experiment was performed individually.

Each person was told to examine the house as if she was considering buying the house. They were asked to form a reasoned judgment on how they liked the house and if they could imagine living there. They were allowed to use the time they thought they needed to get a fair understanding of the house. They used approximately 10–15 minutes. After each session, they were asked to describe the house, to express specific qualities and characteristics that they had noted. They were told to describe their experience of the house in their own words and try to express their judgments. They were not asked specific questions about the house. At the end of each interview, they were also asked to draw a blueprint of the house from memory. This was done to determine how the two different prototypes communicate the spatial structure of the house.

The results from the study show that the individuals interacting with the different prototypes established clearly different understandings of the house. The individuals that dealt with the blueprint of the house used a language that, not surprisingly, consisted of words that referred to the layout and spatial relationships between rooms. They commented on the overall use of the space, such as “the kitchen seems small compared to the living room.” The group that dealt with the three-dimensional virtual model commented on the appearance of the house interior, using aesthetic concepts rather than structural concepts. They also commented on how they felt about the house; they mentioned that the house felt large or small, airy or tight. The language they used also expressed their experience as if they had “been” in the house.

It is obvious that the overall judgment of the house differs markedly between the two groups. The individuals in the two groups also had different opinions on the functionality of the house. The blueprint group had many ideas about how to redesign and remodel the house, how to take down walls, etc. They also commented on the functionality of the kitchen. The people who interacted with the three-dimensional virtual model, however, had only minor comments on functionality. A possible explanation for this difference is that the three-dimensional virtual model is experienced more as a finished product, while the blueprint is experienced only as a proposal—provisional and open to change. Overall, the three-dimensional virtual model group commented that the house was small, which was something that no one in the other group mentioned. The final difference was that when the two groups were asked to draw the house's layout. The blueprint group created accurate drawings, while the three-dimensional virtual model group created completely inaccurate layouts. Individuals in the three-dimensional virtual model group were unable to put the rooms in the right places and grossly misjudged the sizes and shapes of rooms.

From this case study, we can observe how the choice of representational forms—that is, blueprint versus three-dimensional virtual model—is critical to how a prototype filters the properties of a target design. If we look at the two prototype profiles in Table IV, we can remark on how prototypes lead to different results when each prototype addresses different filtering dimensions. In this case, it is clear that the prototype profile strongly impacts the way in which users experience the final design. The prototype *cannot* give relevant information about certain aspects of the final design if those aspects are not manifested since they cannot be experienced. The blueprint prototype, for instance, cannot filter appearance since it does not manifest any such qualities. The three-dimensional virtual model manifests the interaction a person can have with a house, such as moving around, turning, etc., and it gave users the feeling of having been there, an experience that strongly influenced their judgment of the house. The blueprint group experienced nothing similar to this sense of being there. Even though both prototypes are manifestations of the same design, the two participant groups experienced and valued the spatial structure in distinctly different ways.

This case shows that a prototype filters only those dimensions manifested in the prototype. The blueprint prototype works well if the designer wants to find out more about (or filter) the spatial structure dimension, but it does not inform the designer about any other filtering dimension. Adding more filtering dimensions creates a more complex prototype that is more difficult to interpret. This added complexity means that the designer has to decide *what* to filter and carefully craft the prototype in relation to her chosen filtering dimensions. These findings resonate with our economic principle of prototyping.

6.2 Case 2: Prototyping a Mobile Phone Application

In the first case, the focus is on filtering dimensions and the importance of choosing *what* to filter. Deciding the filtering dimensions, however, does not provide fixed options for the choices in the manifestation dimensions. For example, the two-dimensional blueprint prototype used in the first case can be either represented on a sheet of paper or shown on a computer screen. Both manifestations address the same filtering dimension—that is, spatial structure—but the materials are different from each other. In the second case study, we found that differences in the manifestation dimensions, even if the filtering dimensions remain constant, lead to different outcomes. When choosing paper or computer-screen for the blueprint prototype, designers should carefully consider not only which way is more effective in terms of the economic value of prototyping but also how

Fig. 2. The paper prototyping setup and its use situation [Lim et al. 2006].

the chosen values of the manifestation dimension—in this case, material—may affect users' perceptions of the prototype.

For the second case, we analyzed one of our previous research projects [Lim et al. 2006]; in this project, we compare three different prototypes of the same design idea (a mobile phone) to determine how changes in manifestation influence user experience. The results of this study led us to realize the importance of the consideration of the manifestation dimensions in forming prototypes.

We formed three different prototypes in this study: a paper-based prototype, a partially working computer screen-based prototype, and a fully functional mobile phone. With this case, we describe the effects of the use of different values for the manifestation dimensions as applied in these different prototypes, as well as how these choices relate to the economic principle of prototyping. Despite being inexpensive material for visualizing design ideas, paper may cost more than computer-based prototyping tool when it needs to communicate a complex and detailed level of interactivity. We also discuss this issue in terms of selecting the right values for a prototype's manifestation dimensions.

6.2.1 *The Prototype Profiles.* The three prototypes constructed in this case study target the evaluation of usability of a text-messaging feature of a mobile phone—in this case, the Samsung VI660. The approaches behind the three prototypes are all commonly used in HCI. First, our first prototype was a paper prototype (Figure 2). Promoted as an example of an effective low-fidelity prototyping technique, paper prototyping is claimed to be beneficial for early concept evaluation and user involvement for idea generation [Rudd et al. 1996; Snyder 2003]. In this case study, we focused only on evaluating the usability of the design, considered an appropriate use of paper prototyping [Snyder 2003]. Second, the computer screen-based prototype (Figure 3) was used to represent both the keypad and the screen of the mobile phone. This is another popular approach for testing mobile phone usability as it is cheaper than making the hardware for these parts and connecting them together, for example, using augmented reality technology [Nam and Lee 2003; Pering 2002]. Third, a fully functional prototype, that is, an actual Samsung VI660, was used (Figure 4). Our use of the fully functional artifact was similar to how clinical trials use

Fig. 3. The computer-based prototype and its test setup [Lim et al. 2006].

Fig. 4. The fully functional prototype (Samsung VI660) [Lim et al. 2006].

a control group in comparison with one or more treatment groups. We wanted to determine how users would experience different manifestations of the same design aspects in comparison with the fully functional artifact.

Unlike the first case study, these three prototypes all focus on evaluating the same thing—the usability of the text-messaging feature of a mobile phone. In this case, the target filtering dimension is the same—that is, interactivity. The values of the manifestation dimensions, however, differ across the three prototypes. We describe the details and differences in those values for the *manifestation* dimensions as prototype profiles for the three prototypes in Table V.

When forming each prototype (except the fully working one that is the same as the actual phone) in the original study, the key constraint was following how each type of prototype is conventionally defined. For example, a paper prototype should be cheap to make and easily to sketch; a computer screen-based prototype created by using a toolkit can easily demonstrate and evaluate real-time interactions without constructing the actual physical parts of the product. With these examples and their use in test sessions, we discuss how

Table V. Prototype Profiles for the Prototypes used in the Second Case

Dimensions	Paper Prototype	Computer Screen-Based Prototype	Final Product
Manifestation dimensions	*Materials*—paper; foam core board; knife; pen; wooden sticks; glue; yellow cellophane paper; two-dimensional phone appearance color-printout *Resolution*—rough and simplified sketches of screens;  (picture from [Lim et al. 2006]) large time lags by human's simulating the product behaviors; buttons on the keypad are not push-enabled *Scope*— Limited to the text-messaging feature and making other parts as "not available" screens	*Materials*—mobile phone simulation toolkit; laptop computer; mouse *Resolution*— simplified screens using given interface formats from the simulation toolkit;  (picture from [Lim et al. 2006]) partially working in a simulated way; keying with a mouse (not a touch screen) *Scope*— Limited to the text-messaging feature and making other parts as "not available" screens	*Materials*—same as the final product *Resolution*—the same as the final product  (picture from [Lim et al. 2006]) *Scope*—exactly same as the final product

the different prototypes, which used different values of the manifestation dimensions, affected the users' perceptions of the same filtering dimension and the same design idea.

6.2.2 *Prototyping and Results.* In this study, the test sessions followed the conventional formal usability testing method, including a testing session with a think-aloud protocol while users carried out specified tasks, followed by a debriefing session where users answered questions in terms of their evaluation on the key aspects of design's usability. We recruited a total of fifteen participants—five per prototype. Each participant was given only one prototype of the three. The testing setup across the three prototypes was identical in terms of the list of the given tasks, the debriefing questions, and the script used by the facilitator to lead the testing. This study setup worked well in allowing us to focus solely the effects of the manifestation dimension variables on the results of the evaluation sessions.

One of the striking results from this study is that only twenty percent of the total usability findings are common to all three prototypes although the parts of the design tested were all same. A detailed analysis of these findings tells us that the manifestation dimensions—the materials used, the level of resolution, and the covered scope—significantly matter. Those findings identified by only one or two of the prototypes but not all three included both false findings—that is, things that were not problems in the design itself but were caused by the characteristics of the prototype itself—and missing findings—that is, things that were not found by a particular prototype due to its limited characteristics compared to the fully functional prototype.

With the paper prototype, the material used could not enable users to push the buttons on the keypad area. This made it difficult for the computer-person—whose task was to display corresponding feedback and output in response to the user's input—to know whether a user had pushed button or even which button was pushed, thus delaying responses. Furthermore, the abstractness and roughness of the screen images sometimes made users confused about an image's precise meaning, a confusion which we did not observe in the other prototypes. This instance tells us that the resolution dimension also significantly matters since the level of detail and sophistication of the images affected users' interpretations of the interface elements. With the computer screen-based prototype, the conventional graphical user interfaces (GUI) influenced the users' interpretations of the labels on the screen images. Since all the parts of the mobile phone design were shown on the computer screen, many users first tried to click directly on the screen images instead of using the buttons on the keypad image; some users also tried to use the keyboard attached to the laptop computer to type the text message even though we covered the keyboard with white paper (Figure 3). This instance tells us that the type of materials significantly affects users' ways of responding to prototypes. Without careful consideration of these effects, there is a high probability of obtaining unintended user interpretations of the design. However, as this prototype has similar feedback behavior to the fully working product in terms of the response times to users' inputs, many findings overlapped those of the fully functional one, despite the material difference. This finding informs us that a careful plan for forming a prototype—one that considers the dynamics among the material, resolution, and scope dimensions—enables precise projections of how the design may affect users. Using this result, we can see that it is possible to explore certain aspects of a design without making it fully working, as long as we carefully form the prototype while being aware of the effects of the manifestation dimensions. For the full details of findings in this case study, see Lim et al. [2006].

7. DISCUSSION: USING THE ANATOMY FRAMEWORK FOR PROTOTYPING IN INTERACTION DESIGN

The two case studies support and illustrate our initial idea about two fundamental characteristics of a prototype—one as a medium for exploring a design space by filtering certain aspects of design ideas, and the other as a medium that purposefully manifests those filtered aspects of the design ideas through different means of externalization. The results we gathered from the two case studies led us to see how significant those two characteristics of prototypes are in terms of knowledge that can be gained from prototyping. Based on our notion of an anatomy of prototypes and our case studies, we see three possible contributions to interaction design.

First, the anatomy framework provides a language that can be used to articulate any prototype. This capability can contribute to cumulative knowledge production in the study of prototypes within the field of interaction design and research. As it also creates a language, this framework can provide support for critique, examination, and analysis of prototypes used for manifesting design ideas. It can lead to building inventories of prototype ideas for different filtering dimensions. In addition, the accumulation of such inventories will reveal patterns of important aspects of designs for different types of interactive artifacts. Those patterns can also be categorized according to different design values or criteria, such as usability, ergonomics, aesthetics, performance, sustainability, and ethics. The idea of capturing emerging design patterns is analogous to what has been done with the use of the pattern language [Alexander et al. 1977] for design in HCI [Tidwell 2005; van Duyne et al. 2002].

Second, the anatomy framework of prototypes provides a critical thinking guide when designing and constructing prototypes. Since designers and researchers using it can better understand what characteristics of prototypes matter, this framework will help them to make careful and intentional choices of materials, resolutions, and scopes of prototypes—that is, the manifestation dimensions—in relation to the aspects of a design idea—that is, the filter dimensions,—that they plan to explore in their prototypes. This will be supportive not only for design and research practice in HCI but also for HCI and design education in relation to prototyping activities. The process of designing and constructing prototypes is a time- and resource-consuming process, making it difficult for students to gain adequate experience with the pros and cons of prototypes. If presented with carefully chosen prototypes that they can analyze with the help of the anatomy framework, students might be able to build an enhanced sensitivity to prototype quality and how they can serve design.

Third, this framework can be used for constructing prototype profiles in real design practice that can help designers in producing quick-and-dirty prototyping plans before they construct prototypes. These plans allow them to discuss and share their prototyping ideas with others in design teams in advance; such sharing will provide a communication point. It will also help in comparing and integrating different prototypes that partially represent a final design outcome. The deep understanding of fundamental characteristics of prototypes that this framework enables will also allow them to make salient and economic decisions about their prototyping.

8. CONCLUSION

The results from these studies have convinced us that it is possible to clearly identify and plan for prototype characteristics and that we must base those considerations on why and how we intend a particular prototype to support the design process. The studies also convinced us that it is possible to understand qualities of prototypes in a more conceptually structured and pragmatically useful way. This understanding means that, by being aware of an anatomy of prototypes, designers can approach the tasks of forming and using prototypes in a more deliberate, intentional, and reflective way, and, we hope, with a higher degree of precision.

We base our definition of the anatomy of prototypes on the fact that prototypes are not the same as the final design. To create a prototype is to find the manifestation that, in its most economic form, will filter the qualities in which the designer is interested, without distorting the understanding of the whole. A designer must be aware of the fact that the manifested forms of prototypes are different from the final form of the design and that prototypes can significantly affect the ways of perceiving the manifested ideas in various situations of using the prototypes.

We do not propose this framework as a prescriptive approach for the design of prototypes in interaction design. But, designers can learn from the framework and can let the framework and earlier experiences inform their decisions in a specific design situation. The anatomy of prototypes represents a way of thinking about prototypes, rather than a method that may lead to "good" prototypes. The framework can be seen as both an analytic and a reflective tool. It can provide designers with conceptual and reflective guidance not only on how to design prototypes but also on how to interpret prototyping results.

We believe that the notion of a "good" prototype can only be understood in relation to the specific purpose of the design process and to the specific issue that a designer is trying to explore, evaluate, or understand. The purposes for which prototypes are used can be broadly categorized into the following areas: (1) evaluation and testing; (2) the understanding of user experience, needs, and values; (3) idea generation; and (4) *communication among designers.* These categories are not meant to be mutually exclusive, and any one prototype can be used for multiple purposes. The notion of prototype profiles that we have introduced can be used for planning and specifying prototypes in design practice according to these different purposes.

This fundamental conception of prototypes is critical in our field as it provides a systematic way of understanding, describing, and forming the knowledge of prototypes, which is not established in prior research. It is, however, true that the framework we propose here is not an absolute one. We expect that our framework for prototyping will lead to more research comparing different roles and effects of prototypes in design, perhaps by adapting new and unconventional ways of constructing prototypes not yet commonly used.

ACKNOWLEDGMENTS

We would like to thank our Ph.D. candidate, Justin Donaldson, for his valuable input on this research. We also thank Melissa Beaver for her great help in proofreading our article.

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Received July 2007; revised April 2008; accepted May 2008