Increasing the Bandwidth of Social Navigation During the Prototyping Process

By Inna Koyrakh

Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning, and the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees of

Masters of Science in Media Arts and Sciences and
Master of Science in Mechanical Engineering

at the
Massachusetts Institute of Technology
February 2011

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Abstract

Social navigation is receiving information and insight from interacting with people or observing the results of their actions. This thesis explores methods for adding social navigation to situations where it would be useful but does not arise naturally. While many researchers have explored methods for incorporating individual components of social navigation, such as sharing buying preferences, existing systems do not provide a seamless experience between the various other aspects of social navigation. In addition, these systems do not address social navigation within the context of object ecologies. In exploring these issues, we focus on how we can increase the bandwidth of social navigation to help people during the design and prototyping process. Prototyping requires one to understand core product requirements, learn new skills quickly, and make choices about materials. We identify situations where we can use technology to increase social navigation and demonstrate InfroCrumbs – a novel way of gathering relevant crumbs of information during the design process to create object use history, and share it within a prototyping environment. We suggest that such a system can be useful during the design process and that capturing object use history is beneficial.

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1 Introduction

In the 1990's, researchers coined the term "social navigation" to describe how we navigate our world. They postulated that we interpret insignificant traces left by others to make inferences about objects. For example,

> "... imagine you are in a library, looking for a book about interface design. One of the books on the shelf is much more worn and dog-eared than the other, suggesting that lots of people have read it. You may decide it's a better place to start learning than the pristine books beside it on the shelf. In both cases, you didn't rely on maps or guides; instead, you used information from other people to help make your decision." (Dieberger, Dourish, Hook, Resnick, & Wexelblat, 2000)

An object, such as the library book, reveals information because each person leaves it a little different than how they found it. Examples where embedded object history helps us to navigate the world are easy to find: a worn path through a forest suggests worthy shortcuts, moguls along a ski slope suggest the best path of descent, and worn remote control buttons suggest the best channel. In each case, the object serves to aggregate the knowledge and experience of those who came before us, and presents us with the information in time and in place.

1.1 Motivation

The information we can get from storied objects is rich with meaning and provides a context for people to make decisions. We know from experience that interaction histories are indispensible. In the physical world, heavily trodden carpets help us find correct office locations, messy office bins offer starting points for finding commonly used objects, and worn control buttons at a museum kiosk suggest the most interesting exhibits. Though physical objects already aggregate wear, their physicality and lack of computing power limit both the type of available information and potential for social navigation. For instance:

- An object has no information about who has used it. Therefore, one does not know who to contact for further information related to the object.
-

- The object does not contain information about related items. Therefore, it is not possible to learn how the object is used more globally.
-
- The object does not aggregate information across multiple instances of the same item. Therefore, it is not possible to understand the full impact of the object.

Since these shortcomings are related to specific objects and their immediate ecologies, this information is not easily available. Such context would, however, provide us with intuition regarding the nature of objects, the situations that they create, and their associated individuals.

While not all types of interaction histories are reflected in the physical world, the ubiquity of sensor technologies and mobile computing platforms is making new types of interaction histories available. For example, RFID sensors can be paired with RFID tags to understand what we are holding and mobile devices can act as gateways for recording these interactions in a remote database. When these time-stamped touch points (i.e. object interactions) are aggregated across time, object classes, and people, machine learning techniques can be utilized to understand how often objects are used, who uses objects, and with which objects are associated. Interaction histories emerging from these techniques provide an added dimension of knowledge and context to items. The techniques allow us to put footprints on objects that would otherwise be bare, such as metals and electronics. They can even allow footprints to remain on obsolete objects. Capturing these new interactions opens us for convenience, provides additional context for decision making, and aids intuition.

One area where object context is very important is during the prototyping process. Specifically, prototyping requires one to understand core product requirements, learn new skills quickly, and make choices about materials. Most importantly, the type of knowledge required for preparing physical prototypes is highly experiential and highly contextual, requiring one to make connections between the task at hand and related experiences. In addition, relevant expertise is often available within the one's own company. Currently, people rely on Internet search, personal experience (study and experimentation), and friends or colleagues to achieve these design milestones in a timely manner. However, Internet search and experimentation are frequently inefficient and one's direct contacts may not have the required expertise. There is an unfilled need for obtaining contextually relevant, experiential information. We believe this need can be addressed by aggregating object interaction history across a group of colleagues.

In sum, wear on objects provides us with contextual information that helps us make decisions and aids our intuition. The wear on objects is amplified through social use - objects that are used by multiple people carry the most information. Our goal is to create a system for capturing and aggregating object use history in a non-intrusive manner, to make the information conveniently available during the prototyping process, and to adhere to the social structures of how people navigate contextual information in the workplace. We provide a brief overview of our system in Sections 1.2 and 1.3.

1.2 Prototype

We have built InfoCrumbs, a system for capturing, archiving and making sense of interactions with physical objects. The system comprises a wearable RFID reader, a smart phone, software running on a remote server, and assumes RFID tagged objects. Individuals sense objects via the wearable RFID reader and use the phone as a gateway to send and receive relevant information. We use microblogging and web based calendar applications to gain additional contextual information about the object interactions.

InfoCrumbs is specifically tailored for use during the prototyping process. When individuals encounter tagged tools, materials, or prototypes, they are able to view aggregate information about their use. For instance, users can determine who has expertise relevant to the tool or prototype within the organization. Users can also use the traces to understand the context of an object. For example, if the object is a prototype, users can see how it was made, if it is a tool, users can see what others tools and materials it can be combined with during fabrication. Information from project calendars and microblogging posts are used to assign object use history to projects and gather information about prototyping progress. Together with object use history, these technologies allow one to learn about prototyping in situ and find knowledgeable people within their own organization.

In sum, InfoCrumbs is a platform for understanding how objects are used in an organization or team and who uses them, and enabling conversations to coalesce around the goals and interests those objects represent. More broadly, the system is a step toward understanding how object use history may be utilized.

1.3 Illustrative Example

Consider the scenario where Jennifer is prototyping a game show buzzer with a button control (Figure 1a). She opens her browser and types "rubber prototyping material" into her Google search bar (Figure 1b). As expected, this search yields a large number of hits - about 9,110,000. She clicks on a few links but quickly realizes that it will take her a long time to sift through all the results, understand the material properties, and make a decision about which material to select. She remembers that McMaster-Carr is a popular supply company. She searches "rubber", but finds that McMaster Carr seems to have rubber material in premolded shapes – not very helpful.

Jennifer decides to take a walk around the lab for inspiration (Figure 1c). She passes some prototypes people have built and posters depicting past work. She picks up one of the controllers her company built several years ago and loves the feel of the buttons (Figure 1d). As Jennifer touches the prototype, her hand brushes the RFID tag affixed to the device. Her wearable RFID reader reads the tag and communicates its value to her smart phone (Figure 1e). She glances at her mobile phone and sees the various materials that went into building this device, including the #1 Rubber that was used to fabricate the rubber buttons. It also gives her a summary of the team members involved in the project. Knowing the material helps Jennifer to order the material quickly (Figure 1f). When the #1 Rubber arrives, Jennifer is able to reach out to prior team members to get tricks of the trade about working with this new material. She prototypes the buttons successfully and puts the remainder on the shelf of the common stock room (Figure 1g).

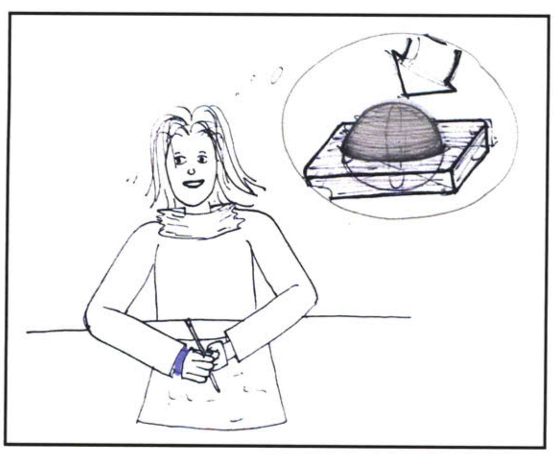
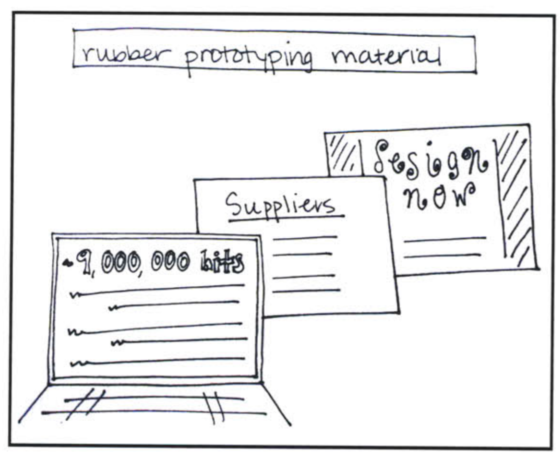


Figure 1(a)



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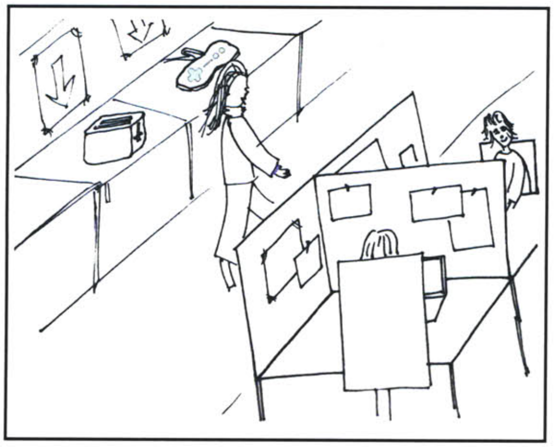

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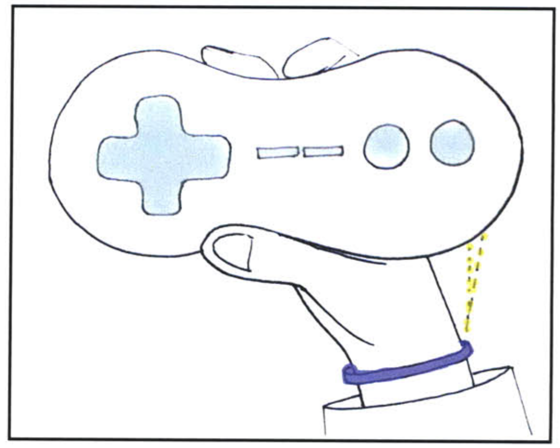

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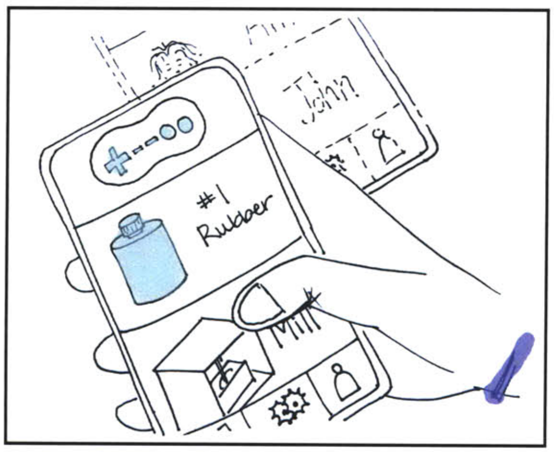

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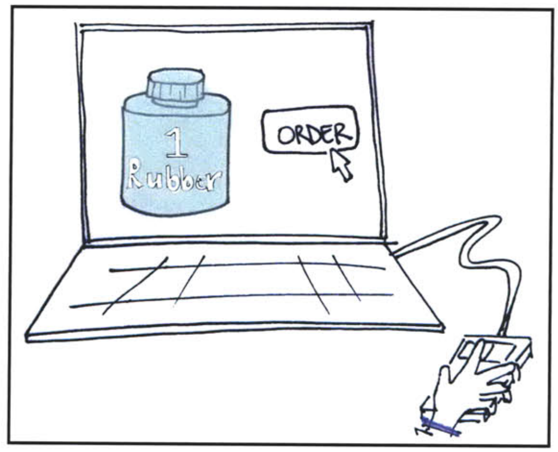
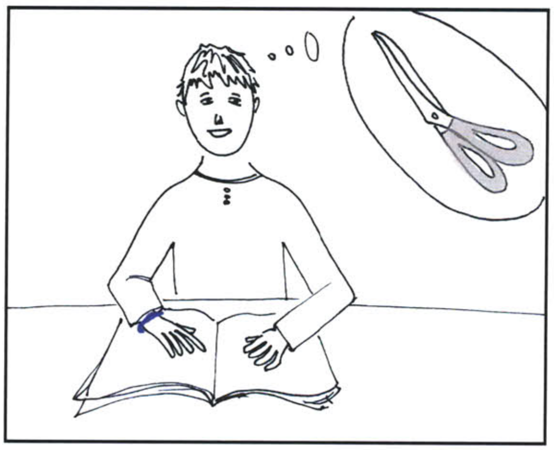


Figure 1(f)

Figure 1(g)

Mark, Jennifer's colleague, needs to create a quick prototype of handles for a pair of scissors (Figure 1h). He goes to the stock room to see what type of rubber the company has in stock (Figure 1i). Each time he picks up a new bottle he gets a list of projects the rubber was used for and a list of people that were involved. He picks up a bottle of #1 Rubber and sees that Jennifer used it recently for making a remote control (Figure 1j). He has seen Jennifer around the office, but has never talked to her before. This looks like a good opportunity to meet a new colleague and get up to speed on using a new material. Jennifer explains that the #1 Rubber will set over night, longer than the instructions state on the bottle, and that it will feel a little bit sticky when removed from the mold even when it's been set (Figure 1k). The tips help Mark prototype the scissors quickly (Figure 1l).



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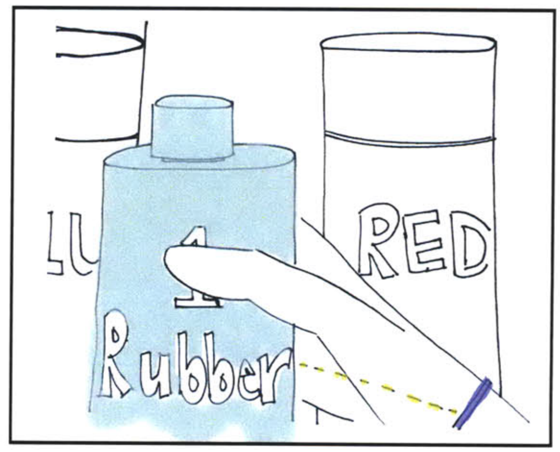


Figure 1(i)

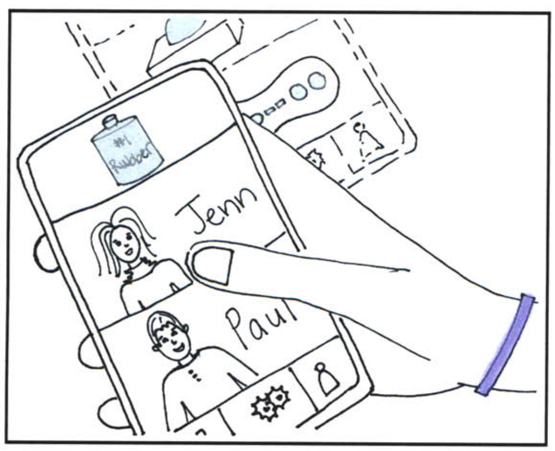


Figure 1(j)

Figure 1(k)

Figure 1 (l)

1.4 Thesis Overview

In this thesis we put forth the notion that (physical) object histories are a valuable asset that can enhance our ability to find information. We demonstrate a novel system for capturing and synthesizing object use history. In particular, we provide a system for synthesizing historical usage data in time and in place to help people make decisions during the prototyping process.

We first discuss the related work (**Chapter 2**) with respect to social navigation in HCI. We use the insights to formulate a definition for social navigation which we apply to the prototyping process. In **Chapter 3**, we discuss the how the prototyping process is carried out in the workplace. In particular, we play close attention to knowledge procurement and dissemination in order to understand the opportunities for social navigation. **Chapter 4** describes the opportunities for social navigation in more detail. We suggest how we might increase the bandwidth of social navigation in various circumstances, and explain how we arrived at our current prototype. Our lay out our system design and give a brief overview of our analytical methods in **Chapter 5**. A detailed description of the antenna design for our RFID system is given in **Chapter 6**. Finally we present the design of our selected interaction in **Chapter 7**, and provide our concluding remarks in **Chapter 8**.

2 Social Navigation

Social navigation is receiving information and insight from interacting with people or observing the results of their actions. In the analog world, social navigation aids our intuition. The power of social navigation to help us make decisions during uncertainty has led the research community to study its underlying mechanisms and to consider how to translate them to situations where they do not arise naturally. Social navigation was named as such by the HCI community, but was studied long before it was given a name. At its definition evolved over the years, it came to include passive scenarios such as aggregate traces as well as active situations such as recommendations. In this chapter we discuss several seminal projects in the HCI literature that have largely defined the notion of social navigation. We start with the HCI literature because, like us, the community has tried to understand how to add elements of social information to systems where it does not arise naturally. The literature serves to define the bounds of social navigation, which we later relate to the prototyping process.

2.1 Social Navigation in Digital Systems

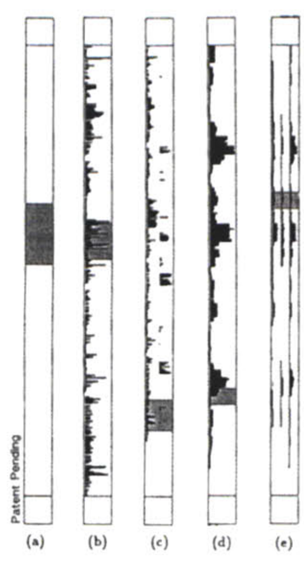


Figure 2. Scroll bars showing digital wear in word processing documents. Image reproduced from Hill, Hollan, Wroblewski, & McCandless, 1992.

Hill and Hollan (1992) were among the first to allude to social navigation in the HCI literature. Though they did not invent the term, they put forth the notion that the results of human activity are "a source of useful information". To demonstrate this concept, they developed Edit Wear and Read Wear, a scroll bar widget that graphically identifies portions of a document with accrued histories of use (**Figure 2**). Examining the scroll bar allowed users to understand what parts of the document changed frequently, which sections were most often read, and who was responsible for the changes. In explaining their design decisions, Hill and Hollan likened their digital wear to physical wear and established interaction history as an important source of information. They also began to suggest guidelines for developing similar systems. For example, they noted that like physical wear, digital wear should aim to be unobtrusive, informative, and be placed where it can make an informative difference.

The term "social navigation" was coined by Dourish and Chalmers in 1994 while investigating information systems. At the time, contemporary methods of navigating through information were largely based on semantic and spatial relationships. Dourish and Chalmers noticed that in the physical world, "movement from one item to another is *provoked as an artifact of the activity of another or group or others*". They suggested that attending to the notion of social navigation in information systems could lead to more navigable systems.

In the beginning, social navigation was defined as passive; a result of people's aggregate actions and behaviors. Andreas Dieberger noted that in the physical world, people engage in "voluntary sharing of information with friends and colleagues" (Dieberger, Supporting Social Navigation on the World Wide Web, 1997). Similar behavior was observed to occur online, and Dieberger therefore expanded the definition to include more active forms of social navigation, such as commenting and voting.

Wexelblat and Maes (Wexelblat & Maes, 1999) classified social navigation as something that arises from shared interaction history and presented the first major framework for building history-rich interfaces. Their six part framework, based largely on principles from urban planning and social anthropology, includes six dimensions:

> Proxemic vs. distemic - The degree to which the system relies on a user's past knowledge and experience.
>
> Active vs. passive - The level of effort a person has to exude in order to create a piece of history.
>
> Rate/form or change - The method with which time series data is treated.
>
> Kind of information - The type of information collected; can be broadly categorized into who, what, why and how.
>
> Personal vs. social - Whether the source of information is purely personal or originated from other people.
>
> Degree of permeation - The degree to which the interaction history is a part of the "history rich object".

The ideas were prototyped in the Footprints system, which showed how interaction history can be applied to helping people find information on the web. The system did two main things. First, it recorded how users navigate a website and presented them with an aggregate representation of how others had traversed the website (passive navigation). Second, it allowed users to leave annotations and comments on the webpage for others to see (active navigation). All interaction history was shared anonymously to create a social navigation system.

Svenson and Hook (2001) suggested that social navigation also involves "dynamism". They observed that social traces are not pre-planned aspects of the system, but are rather byproducts of what people do naturally. They note, "social navigation is a closer reflection of what people actually do than it is a result of what designers think people should be doing".

2.2 Social Navigation in Physical Systems

As technologies for creating media and digital information have matured, people have developed the ability to share information tied closely to the physical world. Initially, people shared information through URL pointers, citations, and word of mouth referrals. New technologies allowed people to associate digital information with physical objects and locations more directly. Moreover, the physically situated information could be retrieved in time and in place via mobile computing devices. Examples of such technologies include location sensors (e.g., GPS, WI-FI positioning, Bluetooth positioning, etc.), tags (e.g., RFID, IR, QR codes, barcodes, etc.), databases, and the Internet. Together, this class of technologies gave the physical world a patina of information much like the patina left on bronze doorknobs.

Initial applications for links between digital and physical systems grew out of a desire for conveniently situated information. George Fitzmaurice and his colleagues demonstrated a spatially aware mobile computer that could provide additional information about countries when brought near a map or additional information about books when brought near library stacks (Fitzmaurice, 1993). Soon after, Ishii and Ullmer presented phicons - physical objects that can be used to recall associated data (Ishii & Ullmer, 1997). Want and colleagues showed that objects can be given a web presence by assigning them URLs (Want, Fishkin, Gujar, & Harrison, Bridging Physical and Virtual Worlds with Electronic Tags, 1999). The URLs are anchored to the physical world by tagging various objects with RFID tags, IR emitters, barcodes, or other glyphs. Some example applications included business cards that are proxies for personal web pages and physical objects that act as keys to media content. Kindberg and colleagues built on the work by developing a system where people, places, and things can all exhibit a web presence (Kindberg, et al., 2000).

With the convergence of mobile phones (wireless data connectivity), GPS (location) and cameras (for reading QR codes and barcodes), a tighter coupling between data and the physical world was finally realized and a new dimension of social navigation was unleashed. One of the first examples of social navigation in this dimension was the "Yellow Arrow" project (Counts Media, Inc, 2004). Participants in the project place a unique Yellow Arrow sticker at different locations in a city. They also send an SMS with the code of their arrow and a caption to the Yellow Arrow project number. Individuals who discovered the arrow could SMS the code to find the note left by the previous project participant. In this way, people were able to leave notes on locations throughout the world. Examples of more formal/mature platforms for social navigation exist in the form of Yelp (Yelp, 2010) and foursquare (foursquare, 2010) mobile applications. Like many applications, these allow individuals to post reviews of restaurants and locations. Individuals searching for reviews can share their GPS location with the application to narrow their search. In this way, people can obtain information from their predecessors about their surroundings.

In sum, building links between digital and physical systems have resulted in an enhanced user experience for information exchange. These links liberated information and provided a method for individuals to both create and consume data in time and in place. These systems absorbed many of the social navigational principles developed by the web-based HCI community. They also added a new, large scale, physical dimension to social navigation.

2.3 Continuum of Social Navigation

While the literature describes social navigation as something that occurs between information creators and information consumers, the community focuses it's analysis on history creation – history consumption is viewed in terms of experimental results. Social navigation is, however, most relevant when the history is consumed. Here, we revisit the salient examples put forth by our predecessors to understand how the perceptions of the information creator and consumer differ.

Most of the literature starts with aggregate wear. This includes worn paths, patinas on doorknobs, and dog-eared books. In this case, the creator and the consumer don't know each other. The creator creates wear through normal, everyday activity with the object without realizing it. Their actions are asynchronous. Some tacit knowledge about the target object is passed on in time, but the knowledge is an aggregate that can only be understood because it is situated in context. The consumer of this aggregate knowledge does not realize their reliance.

Information obtained by observing others includes such things as inferring the quality of a restaurant or a nightclub by the size of the line and inferring the location of the subway by following the mob of people during rush hour. This is the type of navigation first identified by Dourish and Chalmers, 1994, as action that is "*provoked as an artifact of the activity of another or group or others*". We see this type of navigation as originating from awareness and observation of how others behave. Like aggregate wear, no information is created or transferred explicitly. In fact, the majority of the information would be lost if it's not consumed on the spot (only low bandwidth wear would remain). Information transfer exists only when there is an observer. Interestingly, the observer does not realize that information is being transferred; it simply diffuses as part of normal human socialization. (Note: The case where the observer does not realize they are learning is distinct from the case where the observer does realize they are learning. We do not include the later case in our analysis, as spying is generally considered to be anti-social behavior.) Because there is no contact between the information creator and consumer, information is based on inference and there is significant information degradation.

The literature identifies voluntary information sharing as social navigation. We see this category as two: the first category is indirect information where as the second is direct information. Indirect information is online reviews, annotations, reports, and other archived forms of information. The information is created for the purpose of sharing knowledge and expertise. The information creator goes out of their way to write the information down. Admittedly the information is sometimes written for the information creator himself or herself, for example to think through a situation, but this is not always the case. Most of the time it is written down to be shared with any number of others (many of them unknown). The producer creates it knowing it will be used at a later date. The information consumer realizes they are gaining knowledge. In many cases, they are seeking it. The knowledge exchange here is asynchronous, granular, and there is some expectation that it contains more details that are best gained via experience.

Direct communication is transmitted via e-mail, instant messenger, and conversation. Like indirect communication, information shared via direct communication is created with the purpose of being shared. Direct information is also purposefully consumed. However, the bandwidth of direct communication is much higher because both the information creator and consumer are able to clarify their questions and answers and are therefore more likely to achieve a common understanding. The information exchanged is targeted, specific, and contextual. Because both parties are likely to know each other personally, and they are more likely to know each others tastes and idiosyncrasies. Information transfer via direct communication has the greatest bandwidth of the types we discussed.

As we have seen from our discussion, the behavior of the information creator and behavior of the information consumer are symmetric across the passive-active dimensions. When information is created passively, it is consumer passively, and vice versa. Figure 3 shows the passive-active continuum of social navigation. We graph the history creation and consumption on separate axes. The x-axis represents the relative effort it takes to receive the information. The y-axis represents the relative effort it takes to convey the information. However, symmetry makes this distinction moot. Currently, links between the physical and digital world result in a better/more convenient interface. They allow indirect and direct recommendations to occur in a situated, contextualized environment.

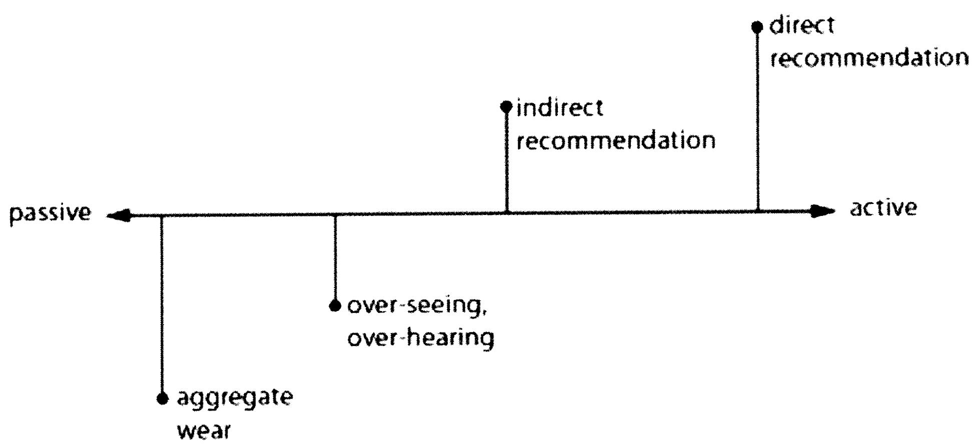


Figure 3. Social navigation continuum.

We have several remarks with regard to Figure 3. On the left are passive, aggregate forms of information that can be gleaned from the environment. This type of information is often situated and utilized without realization. This type of information is by nature tacit because it is created through use and experience. On the right are forms of information that were actively sought. The information is often physically removed from the object or circumstance. Much of the knowledge transferred this way is tacit, but can be well-known book knowledge as well. In all cases, the information transferred among people is a reflection of what people actually know and do, not what experts think they should know and do (Svensson, Höök, Laaksolahti, & Waern, 2001).

2.4 Opportunities for Social Navigation in Digi-Physical Systems

Current research on social navigation is heavily focused on information exchange such as recommendation. For example, Netflix (Netflix, inc., 2010) provides movie suggestions based on one's prior viewing history and the aggregate viewing history of other Netflix customers. Another example is the review capability of Amazon (Amazon.com, Inc., 2010), which allows people to share their experiences with products. Both Amazon and Netflix hover at the indirect recommendation segment of the social navigation continuum. They also include some aspects of aggregate wear and over-hearing/over-seeing. Other services that incorporate similar models of information sharing exist. However, there are several opportunities to increase the bandwidth of socially generated information exchange.

First, there is a gap between indirect recommendation and direct recommendation. This means that there is little opportunity for clarifying information, mutual learning, and building on each other's idea. Systems also tend to segregate each of the components of continuum, for example, providing either indirect recommendation or aggregate wear. While this may be appropriate for some systems, close knit communities, such as those found in the workplace, would benefit from the ability to move around the segments more fluidly, just as people do in more natural information foraging situations. Most notably, real-time, bi-directional communication is missing from the digital information mix. Real-time, bi-directional communication is particularly important for systems for sharing object-based information.

Another opportunity is for sharing information about objects in the immediate environment; objects which people share and use on a regular basis. Current object based systems are reliant on GPS or other positioning techniques and function at large distances. This restricts them to the navigation of very large objects, such as places and stores. Systems which handle smaller objects, such as QR codes, are not automated and require an excessive amount of user input (the user must take a photo of each item separately). RFID systems have the advantage of being automated and affording implicit object interaction. When combined with other technologies, RFID can provide us with information about another subset of our environment.

A third opportunity is learning about patterns that emerge in a community. A colleague recently lamented that mapping software does not reflect the paths that *native* people actually travel. Instead, it maps suggest an algorithmic travel path from point A to point B that often does not take into account things like road conditions and time of day (e.g., rush hour). Collecting object level information about how objects are used opens opportunities to learn about situations in the physical domain that were previously not available. The aggregate information can give the pulse of the community, for example, what types of activities are done together, what objects are important, and who are key players when it comes to various bodies of knowledge.

One of the areas where knowing what people actually do is absolutely crucial is in the context of prototyping communities. There, it is important to know what things are related, who can be asked for help, and which objects are important. Object based information has many potential applications. For example, it can be help people plan time on prototyping machines, self organize into more efficient working patterns, learn new techniques, troubleshoot projects by identifying missing pieces, and make connections with others over mutual interests or experiences.

3 Social Navigation in Prototyping

The HCI community has explored various methods for incorporating aspects of social navigation into online and digital systems. They have added wear, ratings, votes, comments, and most frequented paths to digital content. Most importantly, they have shown that people benefit from the experience of their predecessors. The success of social navigation techniques in other domains suggest that object use histories and annotations hold opportunities for enhancing the prototyping process. It is well established that engineers and designers find social aspects of information foraging important to learning and creating. Before we can understand how we may leverage the potential of social navigation during the prototyping process, we investigate the role that social navigation currently plays.

3.1 Design Process

Prototyping is an integral part of the design process. While there are many variants of the engineering design process, it is generally accepted as having six stages: task definition, task analysis, conceptualization, embodiment design, detailed design, and final implementation (Howard, Culley, & Dekoninck, 2008). Although often written as a linear process, it is known that the steps are iterative, especially with respect to task analysis, conceptualization, and embodiment design.

The design process begins with a need finding process or a market analysis to establish a design direction (task definition). Once selected, the design direction is analyzed, clarified, and narrowed to a more appropriate scope (task analysis). Conceptualization (e.g., brainstorming) leads to a plethora of ideas for how to address the problem. Several different concepts are selected for further exploration during the embodiment design phase – this is also known as the prototyping phase. Insights from prototyping are used to re-evaluate the initial task analyses and concepts until a satisfactory embodiment is reached. The preferred embodiment is selected for more detailed engineering and finally, implementation/commercialization. This process is summarized in Figure 4.

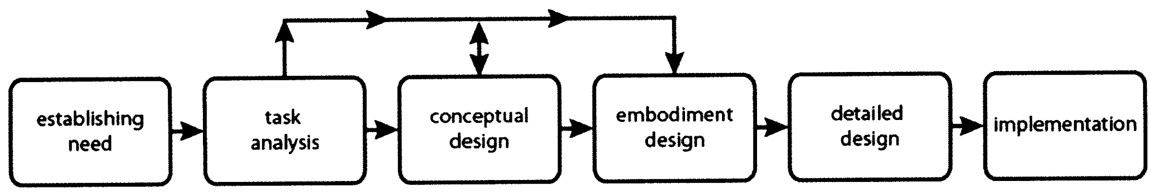


Figure 4. Generalized design process.

The diagram in Figure 4 must be read with the understanding that each of the phases has sub processes and an appropriate tool set to address them. For example, the conceptual design phase can be addressed with brainstorming, mind mapping, association, and other similar techniques. In addition, the boundaries between the phases are fluid. For example, some design processes combine task analysis and conceptual design (Urban & Hauser, 1980) while others combine embodiment design and detailed design (Ullman, 1997). Certainly other models of the design process exist, but on average fit within this characterization. A good summary of the literature is presented by Howard, Culley and Dekoninck (2008) and corresponding references.

While iterative, the design process is also a funnel. Initial stages require divergence to generate many ideas and design directions. Early prototypes are cheap to implement because they are low fidelity and do not require much detailed design work. As the process progresses, prototypes and ideas become enriched, become more expensive to produce, and require detailed engineering analysis. With time, the product becomes more concrete and convergences rather than divergences.

In this work, we are mostly interested in the embodiment design and detailed design phases of the process, which are often called the "prototyping" phases. In addition, while the framework we presented can be adapted to designing virtually anything, we restrict our attention to physical product development and the corresponding practitioners, namely mechanical engineers, industrial designers, and the like.

3.2 Prototyping Process

Ulrich and Eppinger define prototype as "an approximation of the product along one or more dimensions of interest" and prototyping as "the process of developing such an approximation"(Ulrich & Eppinger, 2008). Prototyping is the process by which engineers and designers test ideas and gain additional insights. They take the concepts generated on napkins, sketches, and 3D design software and instantiate them in the physical world where they can experience the objects first hand.

Ulrich and Eppinger classify prototypes along two axes, physical vs analytic and focused vs comprehensive (**Figure 5**) (Ulrich & Eppinger, 2008). It is worthwhile to understand this continuum. Analytic prototypes are mathematical models, simulations, and 3D CAD renderings. On the other hand, physical prototypes are physical instantiations of the product. Focused prototypes are ones that test a particular aspect of product, such as the independent circuit, while comprehensive prototypes look at the prototype as a whole. A comprehensive model can be a compilation of several focused models, such as the circuit board combined with its housing and graphical user interface.

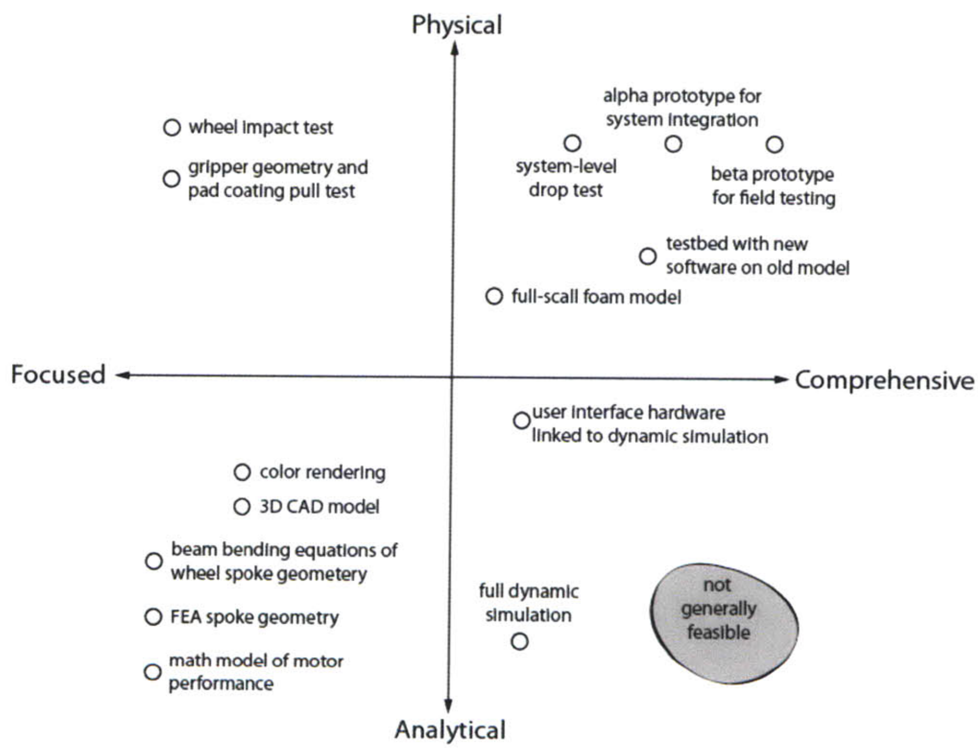


Figure 5. Types of prototypes. Reproduced from Ulrich and Eppinger, 2008.

Prototypes vary in fidelity depending on where they fit in the product development process. We would like to add a third, perpendicular axis, to the Ulrich and Eppinger graphical system: the axis of prototype fidelity. Early prototypes can be quick, low fidelity sketches (Buxton 2007). For example, Figure 8 shows a low fidelity prototype of a shaft coupler made of shaped cardboard. Figure 7 shows a much more advanced version where a similar shaft coupler was machined using a water jet cutter. Early prototypes,

Figure 6. Low fidelity prototype of shaft coupler using tape and cardboard.

Figure 7. High fidelity prototype of shaft coupler made from aluminum machined on the water jet cutter.

such as the one in Figure 8, are especially useful at the conceptualization stages of the design process and don't require much planning to execute; anything that designers and engineers have on hand can be useful to explore initial design directions. As the design process continues, prototyping becomes more structured and requires more planning. Late stage prototypes can be of very high fidelity and are eventually nearly indistinguishable from the final product (Yang M. C., 2005). The appropriate degree of fidelity depends largely on the needs of the designer. It is generally accepted that the cheapest effective prototype is the most appropriate prototype (Dijk, Vergeest, & Horvath, 1998). For a further discussion of the relevant literature on prototyping during the design process, see Yang 2005. Since the focus of our work is on the physical prototyping process, we show our prototype continuum without the physical axis in Figure 9.

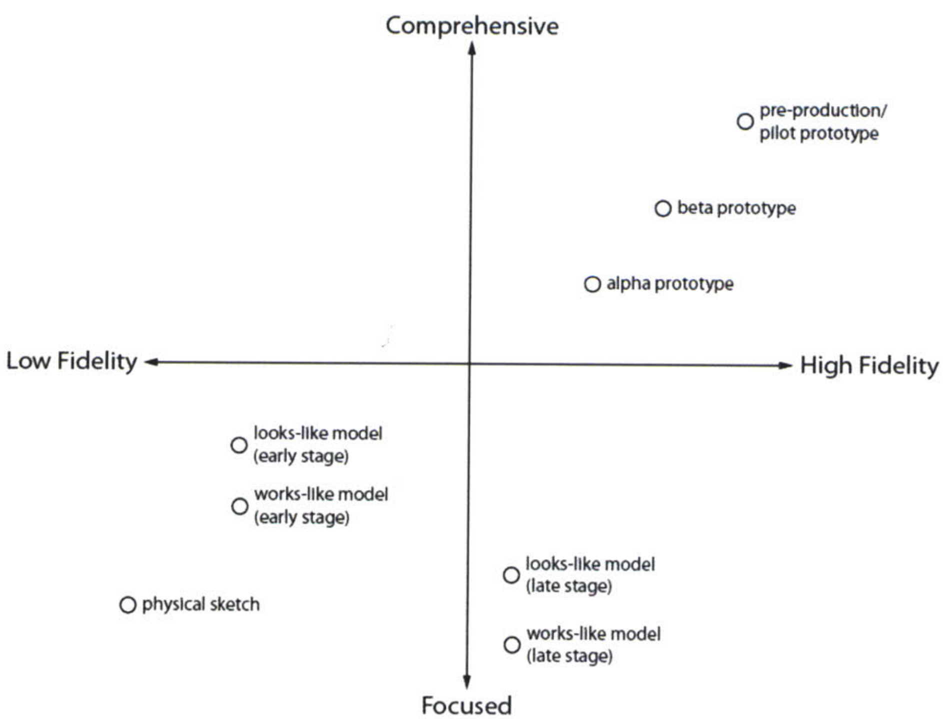


Figure 8. Types of physical prototypes, adapted from Ulrich and Eppinger, 2008. Low fidelity- high fidelity axis added.

The design process is an iteration on thinking, creating, analyzing, and implementing. Prototypes arise from concept exploration. They arise from the desire to fabricate, test, or instantiate an idea. Once an idea is hatched, a plan of action is required. Ulrich and Eppinger (2008) characterize this plan of action in four steps: (1) define the purpose of the prototype, (2) establish the level of approximation, (3) outline the plan of action, (4) create a schedule for securing materials, building and testing. Progression through each phase of the prototyping process, from physical sketch to pre-production, depends on solving technical and design issues. Giving form to the ideas and concepts requires the knowledge of how to build prototypes.

Prototypes at different resolution of fidelity require a varying degree of comfort and familiarity with materials and fabrication equipment. Modern fabrication processes are vast and multidisciplinary, In the best scenario, one knows everything about the endeavor: the process, tools, and materials. In the worst case scenario, one knows nothing about how to prototype their concept. In reality, people are somewhere on this spectrum. Where they are depends on their experience level and on the requirements of the particular project.

As industries mature and new materials, processes, and machines are developed, it is not reasonable to assume that people be expert with all materials and tools necessary to build and innovate new products. In fact, new materials, processes, and machines are enablers that change industries and require acquisition of new skills. Everyone is a novice when it comes to particular tasks. What this means, is that engineers and design professionals need to learn quickly and continuously throughout their professional lives. When asked how students stay abreast of materials after they graduate from school, Apple's Chief industrial designer, Jonathan Ive, agrees:

> The best place for it to happen, of course, is in the workplace itself. "For a designer to continually learn about materials is not extracurricular, it's absolutely essential."(Noe, 2010)

The "Testing" in Step 4 of the design and prototyping process suggests that uncertainty is accounted for during the design process – that the disconnect between think/conceptualize and build is recognized. However, one of the understated components of Step 3 and 4 is actually "gather appropriate information so that you can prototype". This omission is precisely the thing we would like to address.

3.4 Social Methods of Learning During the Prototyping Process

Here we analyze how individuals procure the knowledge they need in order to create successful prototypes. Although formal education, experimentation, and independent inquiry via print (or digital) materials are known to be sources of knowledge, we focus our attention on social aspects of information foraging and exchange during the prototyping process. In keeping with our discussion of social navigation in Section 2, we focus on prototyping analogs to aggregate wear, observation/overhearing, indirect recommendation, and direct recommendation, namely product observation, over-hearing/over-seeing, documentation, and direct personal inquiry (Figure 9).

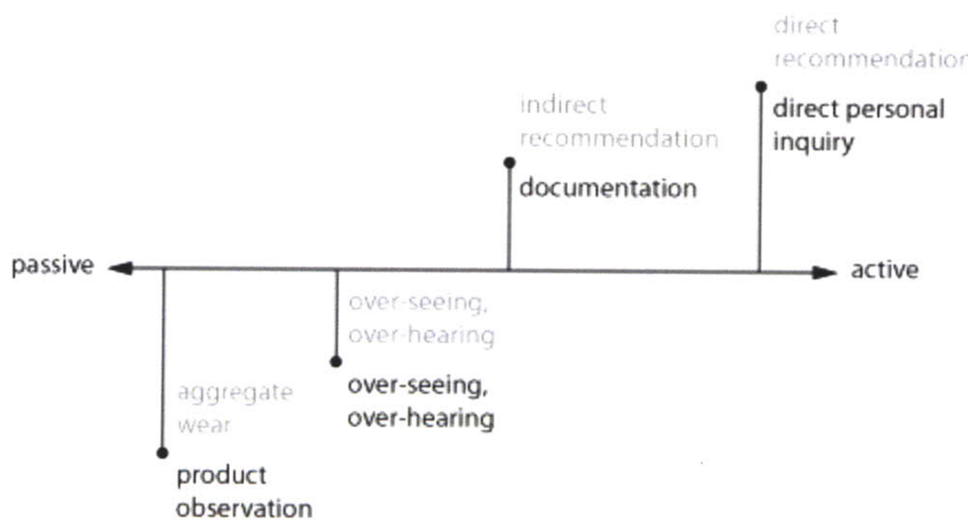


Figure 9. Social Navigation Continuum, updated for the prototyping process.

3.4.1 Product Observation

Observation is a known method of learning how to prototype and fabricate artifacts. As early as the 1500's, philosopher and tutor Juan Louis Vives advised students to examine the built world in order to expand their stock of nonverbal and tacit knowledge. The intention was so that engineering choices would grounded in reality rather than in "foolish dreams'". In fact, it used to be an expectation within the engineering curriculum that students would observe the work of experienced engineers (Ferguson, 1992).

Product observation is still used as a method of observing how experienced engineering and design teams have solved analogous problems. Take the modern electric toothbrush, many of which are charged via an inductive base, as an example (**Figure 10**). The author has personally witnessed several designers purchase a similar toothbrush in order to take it apart, observe how the inductive charging works, and re-appropriate the mechanism for other purposes. In one such instance, the designer transferred the knowledge from the toothbrush charging bay to building a charging station for an electric assist bicycle.

Figure 10. Oral-B Vitality Precision Clean Rechargeable Electric Toothbrush. Credit: Amazon.com

The designer was able to do so, because the finished toothbrush is a repository of tacit knowledge. Its design is a result of assumptions, judgments, and decisions by a team of designers. Materials were selected based on their ability to be worked into desired geometries and withstand stresses, mechanisms were selected because they could achieve the desired motions, and the charging dock was created to simplify the charging process. Since the toothbrush is on the market and available for a reasonable price, designers can infer that making comparable design choices will yield a viable product. Some of this tacit knowledge has been filtered through the design process and distilled into the final product – it can be gleaned through observation and is essential for successful design (Ferguson, 1992).

One interesting thing to note in this example, is that the charging unit from one device was reappropriated for a seemingly dissimilar device. The reason the engineer was able to borrow aspects of the toothbrush solution because is was in his repertoire of known solutions. Having a large repertoire is one of the keys for creative problem solving. As Ferguson notes in his book, "a creative technologist possesses a mental set of stock solutions from which he draws in addressing problems" (Ferguson, 1992). Therefore, object observation is a useful method of learning not only for the task at hand, but also to enhance the set of available stock solutions.

McMaster-Carr, a supplier of mechanical prototyping materials, recognizes the intuition people have from observing the world and has started to use it as a basis for helping people make material choices. In addition to datasheets and mechanical parameters, McMaster-Carr now publishes a chart which helps to relate technical parameters to human experience (Figure 11, Figure 12).

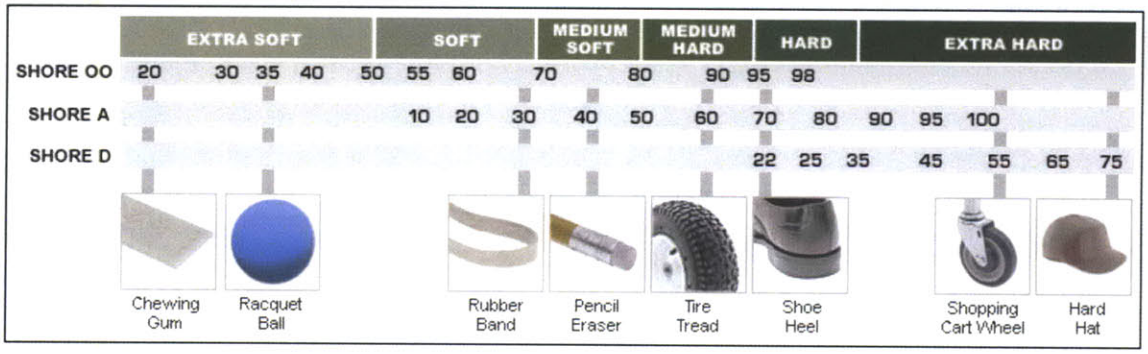


Figure 11. Duromater ratings from McMaster-Carr.

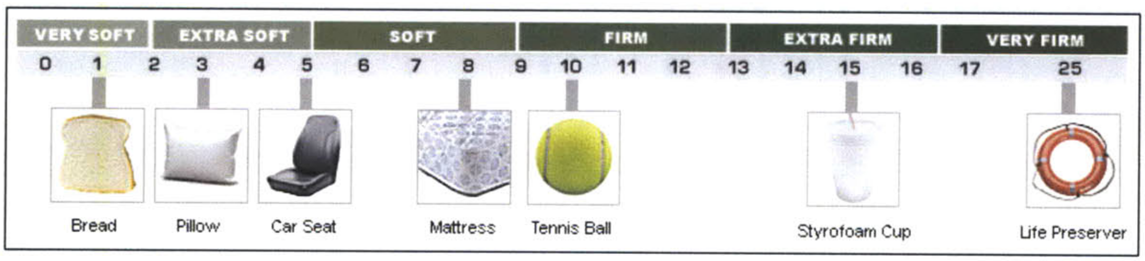


Figure 12. Foam firmness ratings from McMaster-Carr.

Observation is learning by social navigation. The information is created as a byproduct of a design process and consumed as part of everyday experience (the central point of our anecdote with the electric toothbrush was that the designer knew of the toothbrush and its charging mechanism long before he had to build an related product). As such, it is passive for both the create and the consumer, and is analogous to aggregate wear (Figure 9).

3.4.2 Over-hearing/Over-seeing

Over-hearing and over-seeing are import methods of understanding the subtleties of fabrication and of gaining non verbal tacit knowledge. We use our own spelling so that we may convey the subtleties of our intended meaning. Over-hearing and over-seeing is seeing and hearing without intent. It occurs by virtue of being collocated with others. The information creator, whether they are building something or talking loudly in the middle of a room, has no intention of creating information for individual who they perceive to be out of range. Similarly, the information consumer is not purposefully watching or hearing any information. In fact, they might be engrossed in a different project all together. Although the individuals are not aware of it, they are still processing the stimuli in their environment (this is the same phenomenon as hearing your name at a cocktail party). This processing is what gives rise to the information transfer.

While this may seem like an abstract process, it isn't. Take, for example, the Media Lab machine shop, where one of the rooms contains an adjacent laser cutter and a vacuum former. Mike and Julie have come downstairs to use the shop to complete their projects. Mike is an expert laser cutter user who regularly uses it to cut thin acrylic, wood, and cardboard materials for various prototyping projects. However Mike came to the shop for vacuum forming. Julie is the shop using the laser cutter to cut intricate shapes in fabric. Mike has never considered using the laser cutter to cut fabric, but after "over-seeing" Julie doing so, he will not hesitate to use if for a similar purpose in the future. Julie's friend Peter comes to the shop. Julie starts telling him how the zigzag pattern being burned into the material will impart a desired elasticity. In addition, she mentions how exciting it is that fabric can be manufactured to have electric properties. Mike did not know that fabric could be conductive or that cutting it in a zigzag pattern would increase it's elasticity. However, after "over-hearing" Julie's explanation, this knowledge is part of Mike's design repertoire.

Over-hearing and over-seeing is a form of social navigation because it involves the transfer of tacit knowledge available through experience. In reference to our social navigation continuum, over-hearing and over-seeing are analogous to observation and overhearing.

3.4.3 Documentation

Baya and colleagues define design information as "all data that is generated, used, referred to, consulted with during the design process from the early conceptual stage to the final detail design stage" (Baya, Gevins, Baudin, Mabogunje, Toye, & Leifer, 1992). We extend their definition to design documentation, so that design documentation is all documentation that is generated, used, referred to, consulted with during the design process from the early conceptual stage to the final detail design stage. This broad definition includes reports, design histories, e-mails, meetings notes, and anything else of a similar nature.

Our focus is how documentation fits in to the social navigation framework. Hertzum suggests six roles for documentation with an organization, two of which are to convey meaning and to mediate contacts among people (Hertzum M. , 1999). The first of these is well accepted: Formal project documents are generated toward the end of the design process and reflect final design specifications. Informal documents, on the other hand, reflect information about the design process (Yang, Wood, & Cutkosky, 2005). Moreover, when studying the information retrieval habits of a group of engineers, researchers Tao Liang and Larry Leifer found that as much as 85% of information retrieved from their design database was related to the design process (Liang & Leifer, 2000). Documents as a means for mediating contacts between individuals is less obvious. However, many researchers agree that engineers and designers find documents in order to determine their authors (Hertzum & Pejtersen, 2000). Since the authors are generally knowledgeable about the subject matter, the documents server as pointers to experts. The final knowledge transfer occurs when the engineers are able contact the authors directly.

Using documentation to find information or simply as pointers to experts is an example of social navigation. Documents either help to convey tacit knowledge gained during product development or help to broker contacts between individuals. In both cases, they help people to reuse organizational knowledge and intuit follow-on solutions.

3.4.4 Direct Personal Inquiry

Direct personal communication, communication with colleagues, is among the most import sources of information for engineers. Engineers spend as much as 40-60% of their time discussing their work with colleagues (King, Casto, & Jones, 1994) and agree that communication internal to an organization is more critical than external communications. In one study, internal sources (conversations with colleagues, consulting supervisors, and reading in-house technical reports) ranked among the most important sources of information by 82% of surveyed engineers (Shuchman, 1982).

The importance of direct personal inquiry is not surprising for many reasons. First, as tasks become more complicated, the number of people familiar and able to provide adequate answers decreases (Bystrom & Jarvelin, 1995). Second, little information exists for cutting edge and new information. In fact, if ones company is leading technology trends, colleagues may be the only ones familiar with the products and involved processes. At the very least they may be among the only ones who have synthesized all of the relevant knowledge. Third, discussions with colleagues are real time and clarification can be obtained immediately. Since no single designers know all the involved domains in sufficient detail, many "find it more reassuring to obtain information on unfamiliar issues from a competent colleague than attempt to figure it out themselves based on the available design documentation" (Hertzum & Pejtersen, 2000). Other practical reasons for looking internally include avoiding duplicating work and efficiency of information transfer (Hertzum & Pejtersen, 2000).

While all of these are good practical reasons for seeking information from colleagues, we are especially interested in the one proposed by Hertzum & Pejtersen: "documentation seems to be biased toward technical aspects of the chosen solution, while information about the context of the design process is typically not available" (Hertzum & Pejtersen, 2000). This suggests that designers and researchers rely on direct personal inquiry to understand the decisions and design rationale behind the documented project. In essence, they seek out colleagues as a source of tacit knowledge and wisdom. As a form of social navigation, this resonates with the definition put forth by Svenson and Hook (2001). The tacit knowledge learned through working on a project is a result of how people actually worked through the project, rather than the preplanned trajectory set out in the beginning.

3.5 Systemic View

Until now, we have explored four distinct aspects of social navigation during the product design and prototyping processes. In reality, professional behavior transcends these boundaries. Product observation, over-seeing/over-hearing are a part of circumstantial awareness. Circumstantial awareness allows individuals to learn and gain knowledge from being immersed in an environment. Information gained via circumstantial awareness is sought without having a preconceived goal. Circumstantial awareness creates the opportunity to learn passively, to learn by absorbing information from the environment, and is a direct result of being collocated with colleagues. Here, environmental stimuli are processed and then further information is sought.

In a study about team collaboration, researchers Bellotti and Bly found that "informal and subtle aspects of social interaction are critical to accomplishing work" and that "awareness of ongoing activity creates shared knowledge and provides a key context for the interactions that occur". They noticed that individuals would wander around the office, doing a "walkabout" merely to bump into others. Information was obtained passively as they overhead conversations and saw project prototypes. When some piece of information was interesting, or when they had something to contribute, individuals would stop and initiate conversation (Bellotti & Bly, 1996):

> "We sometimes saw people wandering around just to see what was going on, apparently with no other motive. Gus called this doing a "walkabout". In fact, useful information seemed to be obtainable passively, just by coming into close proximity to others. Conversations could be overheard and people seen working together at PCS or on design models or showing each other documents.
>
> QED employees often actively pursued things they became passively aware of, especially by initiating informal communication, showing interest in others' activity to find out more about its significance or to offer advice or help. A conversation, or a new theme in an ongoing discussion was often prompted by an observation on a current activity... or on some item in the local vicinity. Awareness of someone's current work focus provided an entry into a topic of mutual concern. It also allowed people to solicit or spontaneously offer feedback on designs which we were told repeatedly in interview was a key advantage of working in close proximity to one another."

Let us offer a personal anecdote of the role of over-hearing during social navigation. While working through a technical detail of a prototype, we went to consult a colleague. The colleague happened to be working in a public space. Though our colleague was unable to comment on our design, a nearby colleague heard our explanation offered the feedback we required. This anecdote clarifies the importance of overhearing and peripheral awareness in several ways. Unaware that our colleague had relevant expertise, we would not have elected to discuss our project with him. Therefore, overhearing catalyzed an interaction that would not otherwise have taken place and increased our access to knowledge within the organization. In addition, our challenge turned out to be different than we anticipated. Therefore, overhearing helped us to change the scope of our inquiry. Overhearing increased the diversity of ideas to which we were exposed (Bellotti & Bly, 1996), and access to diverse ideas is crucial for coming up with innovative methods of conceptualizing and prototyping innovative products (Ferguson, 1992).

In sum, awareness catalyzed knowledge and expertise exchange within the organization (Bellotti & Bly, 1996). This allows colleagues to capitalize on each other's strengths during time of need and opens opportunities for collaboration. It unlocks the tacit knowledge. With respect to prototyping, this means people are made aware of material idiosyncrasies and novel prototyping methods. Finally, this knowledge increases the individual technical repertoire, which is directly linked to creative problem solving.

4 Increasing the Bandwidth of Social Navigation in Prototyping

Researchers agree that designing and engineering rely heavily on tacit knowledge and that much of this tacit knowledge is transferred via social navigation. Work on increasing the bandwidth of social navigation in prototyping has been centered on knowledge management systems and physical computing systems. We discuss some of these contemporary approaches and identify several remaining shortcomings. Finally, we suggest object use histories as an approach to increasing the bandwidth of social navigation in during the prototyping process.

4.1 Computer Assisted Knowledge Transfer During Prototyping

Contemporary approaches to social navigation have been to create knowledge management system and physical computing systems to support people during the prototyping process. The first of these in concerned with capturing and retrieving information efficiently so that people are able to reuse institutional knowledge. The second has been concerned with integrating the intuitional knowledge into a natural workflow. It is worth noting that although we have named two distinct categories, the lines between these them are often blurred.

4.1.1 Knowledge Management of Informal Design Processes

The knowledge management systems have traditionally been a repository of design documents. Recently, researchers have broadened the traditional scope of documents to include informal documents, such as notes in an electronic sketchbook (Bellotti & Bly, 1996; Yang, Wood, & Cutkosky, 2005). The goal is similar - to provide better access to informal design knowledge. The idea being that reusing knowledge reduces redundant work. We suggest that reducing redundant work is very similar to having an intuition about how something is done. Intuition, after all, is gained from experience.

Up until now, design histories have not dealt with the knowledge available in the physical world. Design notebooks have been suggested as a method of capturing early design data (Bellotti & Bly, 1996). It has even been suggested that time stamped informal information can be gleaned from electronic design notebooks and integrated into larger knowledge management efforts (Liang, et al., 1999). However, researchers have not used granular information about how prototyping is actually done in order to instantiate a concept. In addition, informal design knowledge does not currently include object use data, which has the propensity to create new types of knowledge and answer new types of questions.

4.1.2 Physical Computing During Prototyping

There has been a big push from the HCI community to build stronger links between our physical and digital worlds. With respect to prototyping, the research community has recognized the importance of situated information and has produced several examples related to product design and prototyping. Here we briefly discuss two types of projects. One, where usage data is used to facilitate prototyping. Another type of project win which data about projects is linked to the product and make available.

Figure 13. TouchCounters for usage frequency visualization, and usage correlation visualization. Credit: Yarin and Ishii, TouchCounters: Designing Interactive Electronic Labels for Physical Containers 2000.

The most notable work in the area of social navigation and physical prototyping is TouchCounter (Yarin & Ishii, TouchCounters: Designing Interactive Electronic Labels for Physical Containers, 1999). Physical containers containing prototyping equipment were augmented with internet enabled LED arrays **Figure 13**. Each container recorded how many times it was open and lit the appropriate number of LED's to indicated use. When viewed as a whole, the containers described which containers are used the most. These hot spots indicated which boxes were more likely to contain their required supplies, and where thus good starting points for a search. Once a container was selected, the display on the remaining containers changed to indicate which other boxes where often selected at the same time as this one, thus giving individuals an indication of where to look for related boxes.

TouchCounters showed that augmentation in a prototyping system is welcome, and presented an interface for identifying shared objects. However, the system had several limitations. First, TouchCounters were associated with boxes rather than individual items. This did not account for objects that were misplaced between boxes and could not give item level information. Second, the data collected was not conductive to creating usage history for any prototypes and projects. Finally, the system was user agonistic and therefore did not support knowledge exchange between individuals.

The importance of object level has not been overlooked. Physical computing in the design process has benefited from research on establishing links between the physical and virtual worlds. These foundations were laid by Want and his colleagues, who showed that an object can be given a web presence by assigning it a URL (Want, Fishkin, Gujar, & Harrison, Bridging Physical and Virtual Worlds with Electronic Tags, 1999). The URL is anchored to the physical world by tagging the object with RFID tags, IR emitters, barcodes, or other glyphs. Some example applications include business cards that are proxies for personal web pages and physical objects that act as keys to media content. Kindberg and his colleagues built on the work by developing a system where people, places, and things can all exhibit a web presence (Kindberg, et al., 2000). These works laid the foundation for researchers and designers to explore the role of objects and object-based information systems.

Figure 14. IDEO Tech Box. Credit: CJArnold@AU 2007

Designers have long known the importance of getting inspiration and information from physically manipulating and exploring products and materials. The product design firm IDEO, for example, has a curated display of technical objects (**Figure 14**), packaging and on materials displayed for idea generation (Buxton, 2007). Each of the items in the "Tech Box" is tagged and additional information about the objects can be found in an internal database. The intention for the Tech Box is to be a spot of inspiration and discovery, and as such, it is often curated with new and unusual items.

Figure 15. CoWall. Credit: Ehn and Linde 2004

In an effort to create an environment for "informal collaboration and inspiration, for presenting and collecting material", Pelle Ehn and Per Linde developed CoWall (Ehn & Linde, 2004). CoWall is a "tangible project archive" in which RFID-tagged objected are displayed on individual shelves (**Figure 15**). When any of the tagged projects are placed on a surface embedded with an RFID reader, information about the project is projected onto a wall. CoWall suggests that there is an interest in connecting information about prototypes and prototyping materials with relevant information during the design process.

The wealth of these projects, and others like them, show that there is a desire to share information about the design process and to interact with others over common objects. The systems we've discussed consider how the physical and digital world of objects might be bridged within the design process. However, a major limitation of these systems is that they are disjoint from the actual design process. All of these projects exist in a separate space that is for "ideating". While it is true that a designer looking for inspiration can wonder over to these displays, these projects are not integrated into the design process. Rather, these artifacts and displays are out of the way. A further limitation is that any material presented via the interaction must be carefully scripted, meaning that only a few objects can be shared in this way.

4.2 Shortcomings

We have seen how technology is being applied to remedy some of the shortcomings of social navigation during the prototyping process. Researchers in the mechanical engineering, computer science, and management communities have been developing better knowledge management systems for the capture, retrieval and reuse of design information (including early design processes). Researchers in the human-computer interaction community have been developing better methods for situating information, connecting the digital and physical domains. They have made great strides toward allowing people to reuse institutional knowledge in a natural way. However, we believe opportunities for improvement remain.

Though we have seen that documents serve as pointers to people, current technologies do not bridge artifacts and relevant people within the organization. While it is true that people can infer the function of a tool or material by looking at it, the object contains little information about its use. A worn knob can act as a hint and a manual can be used as a supplement, but both are often insufficient for learning how to incorporate the tool or material into a personal design process. Observing a material or tool is often enough to get a sense for its utility, but it is not a replacement for watching someone use it.

When people over-see and over-hear, they often do so within a context. For example, when Robert over-sees Peter using a drill presses, he also sees him using wood and clamps. However, when Robert passes by the drill press in the shop, he sees non of the peripheral equipment or materials - the context of use is completely missing. Context about which tools and materials are used together allows a designer or engineer to intuit the process of fabricating a new project.

Observing products is a very powerful method of learning about material behaviors and inferring about fabrication methods. However, there is no natural way to bridge the knowledge we gain from the physical world with the equipment and materials in the workplace. Similarly, there is no bridge from tools/materials to projects. Manuals and datasheets omit or overstate information, and are not an ideal replacement for learning through experience (e.g., McMaster-Carr, Figure 11 and Figure 12) or through discussions with colleagues.

In current prototyping processes, much of the relevant documentation is removed in place and in time from where decisions are made and projects are fabricated. Obtaining information about an object requires determining its name and model and doing a search for documents or knowledgeable people. A more natural interaction would involve situated information, such as touching an object and receive additional information instantaneously.

Methods of creating documents lag current technological capability. Resources for capturing annotations and recommendations are removed from the natural activity of the user. Most notes are currently recorded in paper based notebooks rather into file repositories. Electronic notebooks will make capture of intermediate information, such as design rationale and prototyping insights, more accessible company wide (Hong, G., & Leifer, 1994). However, knowledge management systems, which require several intermediate steps to input data are inconvenient and therefore miss a lot of experiential insight.

4.3 Increasing the Bandwidth

We believe that a system based on object use history has the potential to add a new dimension of value to people during the prototyping process. Technologies, particularly communication and sensor technologies, have opened new opportunities to create paths, footprints, and patinas surrounding physical objects and to easily obtain certain process information. In addition, technologies for situating this digitally manifest wear are widely available and quickly becoming democratized. In this section we describe how our prototype, Infocrumbs, increases the bandwidth of social navigation during the prototyping process by leveraging sensor technologies to collect object use histories, micro-blogging habits to collect comments and rationale, and project management software to link it all to their respective projects.

In the previous section, we lamented the lack of contextual information during the prototyping process. We noted that while tools and materials are often used in the context of particular fabrication patterns, there is no mechanism to reveal these patterns. There is also no mechanism for providing an intuition for the results one should expect when using tools and materials. Finally, tools and materials do not include pointers to colleagues who can help to resolve challenges arising from their use. We suggest that these shortcomings can be overcome by capturing, archiving and making sense of interactions with physical objects, such as prototyping tools and materials. Usage time stamps can be used to ascertain patterns of use that reveal relevant information.

We also noted that information about the early design process is not easily accessible. Usage data forms a major aspect of increasing the amount of data available from the early stages of the design process, including the prototyping process. However, digital media is a natural method for collecting additional informal information. We suggest enabling micro-blogging as an in-place way for people to add information directly to objects. Similarly, calendar and project management information can be used to attribute the work to specific projects with minimal additional effort from the users.

Finally, we suggest increasing the bandwidth of social communication by situating the information close the where it is needed. Because information is tied directly to artifacts involved in the prototyping process, individuals are able to see the connection between their current process and what others have done before. This makes prior information more valuable and useful.

5 System Design

The InfoCrumbs system allows people to capture, archive and make sense of their interactions with physical objects. In passive mode, people merely record that an interaction with an object has occurred. In active mode, they can leave notes, comments and links. When multiple people use the same objects, the usage history pertaining to those items is synthesized and shared. The system level focus is on data collection and synthesis. Figure 16 provides and overview of the structure of the software and communication modules. The individual components are further described throughout this chapter.

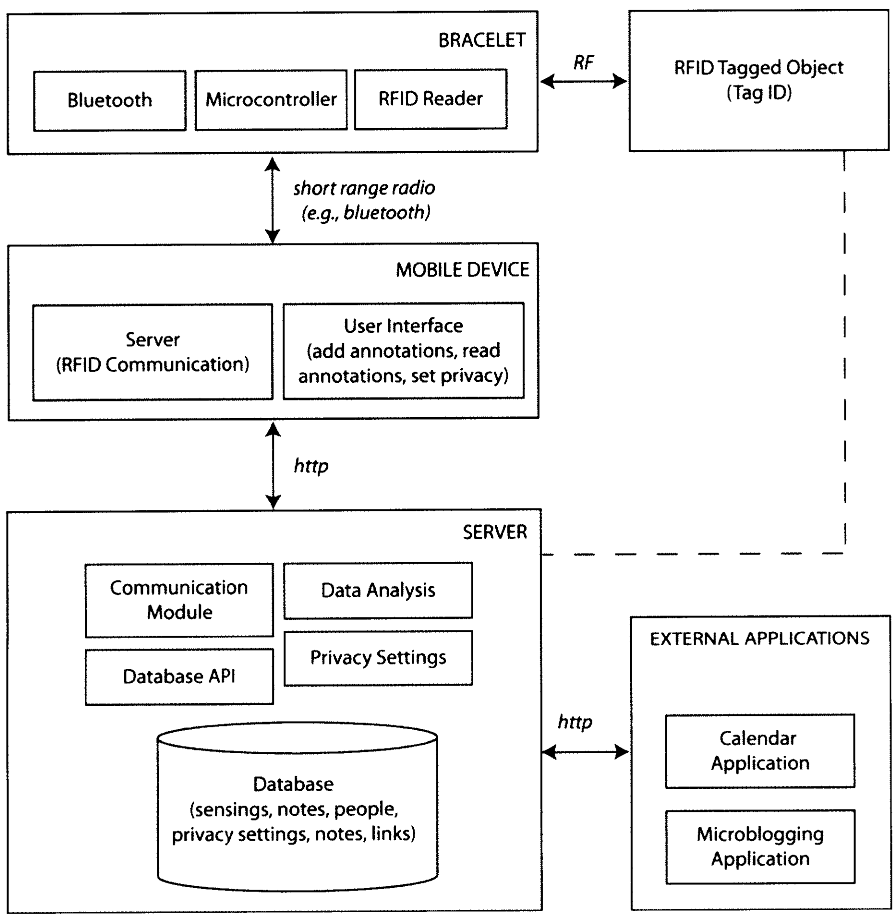


Figure 16. System diagram.

5.1 Mobile Device

Each user has a mobile device that serves as a user interface and an RFID server for receiving sensings from the RFID bracelet (Figure 17). A python engine receives RFID data from the wearable RFID device 20 times a second, filters the data to reduce false positives, and transmits the filtered data to a larger repository of data on a community the server.

A Flash-based user interface receives the RFID sensing from the local RFID server, shows the user information about the object in their hand and presents some information about its use. For example, if the use picks up a prototype, the interface shows an aggregate view of how much information is available about the item. The user can then use the phone to find additional information about tools and materials that were used in its fabrication and presents options for reaching out to other people who have previously used the object. The mobile phone is also a micro-blogging platform for making quick notes and comments about the objects or noting any changes with regard to design rationale.

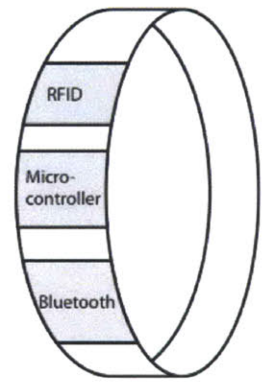


Figure 17. RFID bracelet sends discovered RFID tags to a mobile device.

5.2 Server

The server hosts a database, a data analysis module, and a communication module for communicating with the mobile device. The database contains notes, comments, as well as a history of all interactions with objects. An analysis module synthesizes and presents the user with relevant information about items they are holding.

All server communication is conducted via the JSON data-interchange format and the http protocol. Since the primary function of the server is data storage and analysis, this structure is extensible and supports many types of interactions.

5.3 Data Acquisition

Data for creating the design histories is acquired from three sources, the RFID bracelet, a project management or calendar application, and micro-blogging. Each of the data sources is assumed to be independent and is later aggregated based on time stamps and user id. There several major advantages to the decoupling. One advantage of decoupling the data sources is that failure to micro-blog or record project time does not interfere with many aspects of final data analysis. The RFID data alone is enough to establish correlation between various tools and materials being used within the organization. Another advantage is that the burden of actively creating data is lessened because information can be pulled from sources people already use. For instance, planning project work time via Google calendar is sufficient for linking projects with their component tools and materials. Similarly, micro-blogging about a change in project direction would be sufficient for capturing fleeting design rationale.

5.3.1. Usage Data

Users wearing an RFID bracelet sense the objects with which they interact and send time stamp data points to the central server. The RFID takes multiple samples a second. To compress the data, the client side application aggregates sequential time stamps into a usage interval. Each data packet sent to the server contains the object RFID value, the usage time interval, and the user id.

5.3.2. Project Data

We assume that individuals in the workplace keep track of the time they allocate to various projects via a project management application. In our prototype, we use Google Calendar as an approximation of such a system. Recording the project name and their user id on a public Google Calendar is sufficient information for us to correlate projects with their component tools, materials, and design rationale micro-blogs.

5.3.3 Microblogging Data

Microblogging is our chosen platform technology for recording fleeting information during the prototyping process. The blog entry is associated with a project or object via one of two methods. The first method is time stamp correlation, while the second method also uses the "#" symbol.

We follow contemporary convention inspired by the Twitter microblogging service. Typing the "@" symbol in front of a user id will associate the comment will forward the message to the respective user. Including the "#" symbol in front of a word or RFID tag will associate the comment with that word or object.

5.3.4 Correlating Data Sources, Illustrative Example

The following is a simple example the various streams of data are correlated (**Figure 18**). Abby worked on the "talking head" project from 1-2 pm today. She happened to use the vacuum former, tagged with RFID_123, and posted a micro blog message about her experience during that time frame. Our system would realize that all of these are associated to one project by correlating the time stamps.

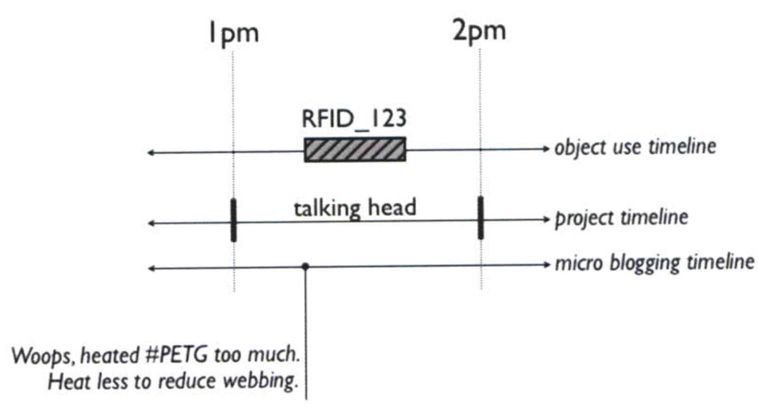


Figure 18. Example, correlating multiple data sources.

5.4 Making Sense of Data

Historical use data is analyzed to extract who uses particular items and which items are frequently used together. Who uses objects is be evident because data contributed to the shared data set is tagged with a personal ID. Items frequently used together are extracted by analyzing interaction time stamps. We assume that each person uses objects in order and the order of item use is always preserved in the historical data (e.g., relative time stamps are accurate), so that streams of object use are known. Objects used close in time are attributed to a project by user input and by correlation with a project calendar (e.g., Google calendar). The result of the analysis is linked data between people, objects and projects. Objects and projects are revealed on the mobile phone UI in response to objects detected via RFID. The information provides individuals with a list of people they can reach out to for more information about the object and an overview of which projects utilize the same tools/materials.

5.4.1 Object vs. Class

Each artifact or tool in the system has an individual identity and is also part of an object class. For example, a book called "Sketching User Experiences" has an individual identity, but is also part of other books with the same title. We accomplish this by assigning each item a unique RFID tag and a global ID (e.g., UPC, manufacturer ID). The global ID is used to identify objects in an object class. In future work, additional object hierarchies may be based on semantic tagging. We present the user with class level information as we find it more relevant for understanding how something is used in an organization.

6 Object Sensing

We developed an RFID sensing bracelet to sense object interactions throughout the prototyping process. We selected a bracelet form factor because it is already socially acceptable to wear watches and bracelets. Watches with extended functionality are readily found and we would expect that with appropriate utility and design people would embrace wristbands that provide additional efficiencies.

The bracelet form factor is appropriate because the sense of touch is associated with the hand. Additionally, it is crucial that wearing such a device would not interfere with the activities of a person. Within a short period of time, we would expect that one might forget they are wearing the device at all. In this sense, it would be a calm computing device that would embody the spirit of Mark Weiser's disappearing technologies (Weiser, The Computer for the 21st Century, 1991). Finally, this means that the device must work at a distance that provides a comfortable interaction with the object.

6.1 RFID Wearables for Implicit Computer Interaction

The earliest wearable RFID systems for enabling implicit computer interaction were proposed by Schmidt and his colleagues in 2000 (Schmidt, Gellersen, & Merz, 2000). Their system embedded an RFID sensing module in a glove and showed that RFID tagged objects can be used for context aware computing (e.g., using a spoon to invoke a recipe). They also showed that such a system could be integrated into an enterprise inventory system.

Philipose and his colleagues at Intel expanded the scope of wearable RFID to include activity recognition. Their prototypes, the iGlove and iBracelet (**Figure 19**), included an accelerometer, and allowed the researchers to infer daily household tasks. The ReachMedia project also combined wearable RFID with accelerometers. In a departure from previous projects, a user outfitted with a ReachMedia bracelet gained the ability to use gesture input to select auditory menu items (Feldman, Tapia, Sadi, Maes, & Schmandt, 2005).

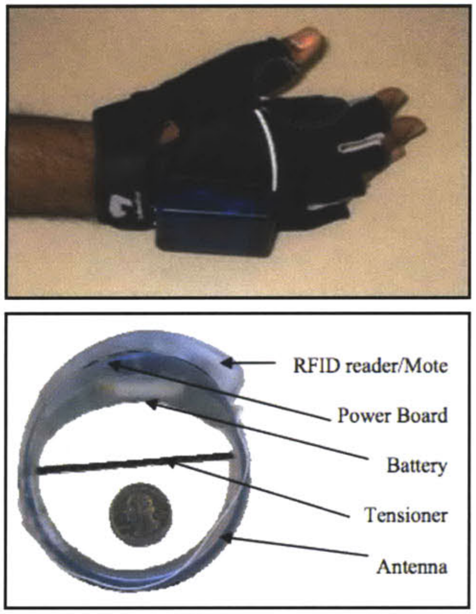


Figure 19. Intel's iGlove (top) and iBracelet(bottom).

The Schmidt glove, the iGlove/iBracelet, and ReachMedia are all based on HF RFID technologies and have a relatively short range distance. RFID modules based on UHF technology, which can handle much longer distances. Recently, researchers developed UHF RFID tags that can transmit adjacent sensor readings in addition to their individual IDs. The InfoField project demonstrated that wearable UHF reader combined with such tags can be used to infer activity from RFID integrated sensors in the environment (Lee, 2009). Such scenarios include opening sensor augmented books and holding sensor augmented teddy bears.

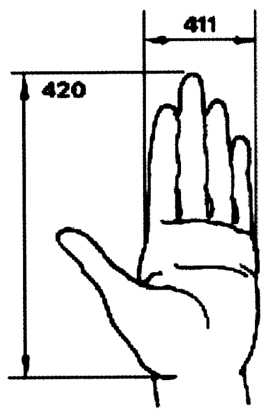
6.2 Required Sensing Range

The required sensing range depends on what types of interactions we hope to capture. We identified two hand positions which represent the extremes of object interaction: (1) button press/finger pointing, and (2) holding or cradling an object. Capturing a button press/finger pointing interaction requires a sensing range that is at least as long as the distance between the wrist and the tip of the longest finger Table 1 For the average American male, that is approximately 18 cm (NASA, 2008). Sensing a holding or cradling interaction requires a sensing range that is at least as long as the distance between the wrist and the center of the palm. We approximate this length by hand breadth, as depicted in Table 1. For the average American male, that is approximately 9 cm(NASA, 2008). The two cases we just described are at the extremes. Most other hand positions should fall somewhere in between. It is important to acknowledge that in future prototypes we would also need a margin of error to account for movement of the bracelet during normal use and for RFID tag placement.

For the current prototype we focused our attention on holding and cradling interactions. Our goal was therefore to attain at least a 10 cm sensing range (on the order of hand breadth) with our antenna design. We were successful in reaching this goal. We expect that we can extend this range in the future with RF amplification.

Table 1. Typical Hand Dimensions for American Men and Women.

Anthropometric Dimensional Data for an American Male and Female				
No.	**Dimension**	**5th percentile cm (in)**	**50th percentile cm (in)**	**95th percentile cm (in)**
American Female				
420	Hand length	15.8 (6.2)	17.2 (6.8)	18.7 (7.3)
411	Hand breadth	6.9 (2.7)	7.8 (3.1)	8.6 (3.4)
American Male				
420	Hand length	17.9 (7.0)	19.3 (7.6)	20.6 (8.1)
411	Hand breadth	8.2 (3.2)	8.9 (3.5)	9.6 (3.8)



6.3 Hardware Overview

The bracelet hardware is comprised of a Skyetek M1-Mini RFID Reader, an antenna with a tuning circuit, a microcontroller, a Bluetooth module, and a rechargeable lithium ion battery (Figure 20). The RFID module senses RFID tags and reports them to the microcontroller. The microcontroller then communicates the tag identity to the mobile device. We selected the Roving Networks RN-41 SMD Bluetooth module for serial communication between the bracelet and the mobile device. This module is low powered, operates at 3.3V, and has a completely encapsulated Bluetooth stack (Roving Networks, 2009). The Arduino Mini Pro microcontroller was selected for this prototype because of its small size, low power, and ease of use for prototyping. The Arduino currently runs on Atmel's 328P AVR Microcontroller. In future iterations we would consider combining this microcontroller, Bluetooth, and antenna tuning circuit into a custom breakout board. The RFID module, antenna, and antenna tuning circuit are discussed extensively in Sections 6.3, 6.4, and 6.5, respectively.

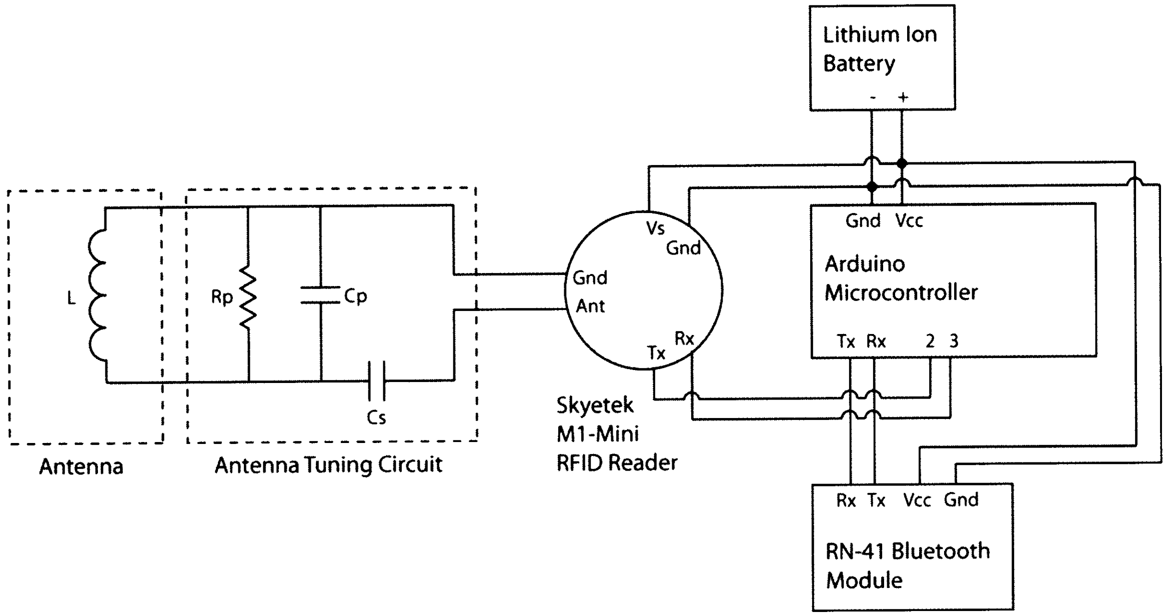


Figure 20. RFID bracelet hardware diagram.

6.4 RFID Module

Our main criteria in selecting the RFID module were reader size and read distance. The SkyeTek SkyeModule™ M1-mini HF reader(Skyetek, 2006) was selected for it's small size. With a 25.4 mm diameter and a 2.8 mm height, the entire module is smaller than a quarter. This reader is low power and runs at a frequency of 13.56 MHz. Although its internal antenna reads tags from approximately 3.5 cm, this reader is widely used in HCI sensing applications (Feldman, Tapia, Sadi, Maes, & Schmandt, 2005)(Berlin, Liu, van Laerhoven, & Schiele, 2010).We were able to extend this range to at least 10 cm with an external antenna. Like the Reach Media reader (Feldman, Tapia, Sadi, Maes, & Schmandt, 2005), we expect that our range could be further improved with an RF amplifier.

6.4.1 M1-Mini Modifications

The internal antenna of the M1-Mini RFID reader must be turned off prior to utilizing an external antenna. De-soldering the C_{series} capacitor turns off the internal antenna (SkyeTek, LLC, 2004). The C_{series} capacitor is outlined in red in **Figure 21**.

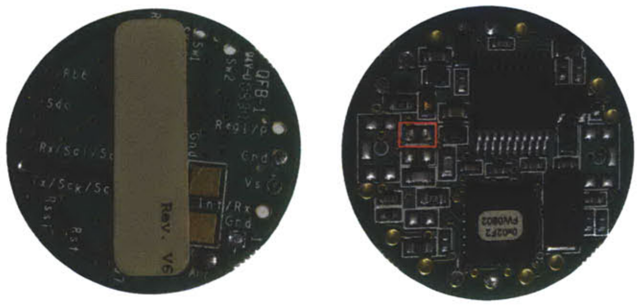


Figure 21. SkyeTek SkyeModule™ M1-mini HF reader, front and back. The Cseries capacitor is outlined in red. This capacitor is to be removed when using an external antenna.

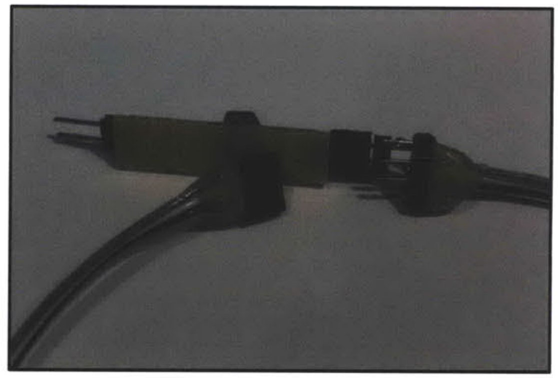
6.5 Antenna Design

The required read range for sensing objects is on the order of 10 cm (see Section 6.1 Required Sensing Range). Unfortunately, the M1-Mini RFID module has an internal antenna whose read range is approximately 3.5 cm. We were successful in modifying the M1-Mini RFID module to accept an external antenna and designing an antenna with an appropriate read range.

We designed a loop antenna to extend the range of the M1-mini RFID module. A loop antenna was selected for two main reasons. First, its effective diameter is on the order of the diameter of human wrist. Second, such an antenna would naturally be oriented with its field lines in the direction of any RFID tagged objects.

Our antenna is approximately 8 cm in diameter and has 3 or 4 loops. The diameter values is approximate because the final read distance is a function of the tuning circuit. The antenna was tuned to resonate at 13.56 MHz (+/- 0.5 MHz) via capacitance matching. Our eventual read distance was just over 10 cm, using a tuning circuit and no amplifier components. We discuss antenna turning in detail in Section 6.5.

One common problem in wearable antenna design is how to get the antenna/bracelet around the arm. We used standard 0.1" male and female connectors to preferentially join the ends of ribbon wire. Our basic loop antenna design is depicted in **Figure 22**(a) and **Figure 22**(b) Although this antenna is connected to a tuning circuit, this antenna can also be safely connected directly to the M1-Mini. A read distance of several centimeters was measured without the tuning circuit.



(a) (b)

Figure 22 (a) and (b). Early antenna prototype. Standard 0.1" male and female connectors are used to join the ends of ribbon wire into a solenoid. A tuning circuit causes the antenna to resonate at 13.56 MHz (+/- 0.5 MHz).

6.6 Antenna Tuning via Capacitance Matching

We tuned our antenna to resonate at 13.56 MHz using capacitance matching. Although there are multiple ways to implement capacitance matching, we arrived at the best results following the impedance matching method suggested by Berlin and colleagues (Berlin, Liu, van Laerhoven, & Schiele, 2010) and Soffke (Soffke, 2007). Impedance matching requires one to equate the impedance of the antenna and tuning circuit with the output impedance of the M1-mini. Desired bandwidth, Q, output impedance of the M1-Mini, Z_o, and antenna inductance, L, serve as additional constraints to solve the equation. We walk through the calculations for completion here, but refer the reader to Berlin and colleagues as well Soffke for a more detailed explanation.

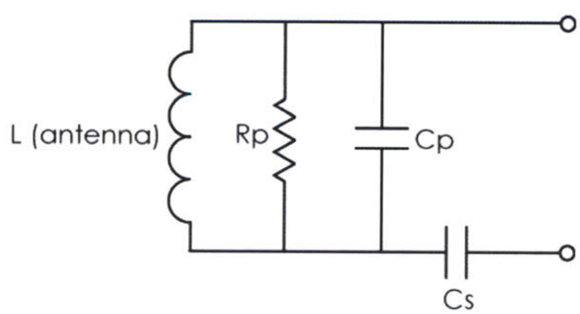


Figure 23. Antenna turning circuit.

This technique requires three steps: (1) determining the antenna inductance, L (2) selecting appropriate resistor, R_p, and capacitors, C_s and C_p, values (3) tuning the circuit experimentally. The basic circuit is shown in Figure 23. We note that while capacitance matching is a popular method for tuning antennas, it is not recommended for antennas with inductance less than 5 μH because the required capacitor values are very small (Texas Instruments, 2003).

6.6.1 Determining Antenna Inductance, L

Capacitance matching requires having an approximate knowledge of the antenna inductance. There are multiple ways to calculate the inductance, L, of an antenna. We first used theoretical calculations to make sure that our antenna inductance was approximately less than 5 μH (Texas Instruments, 2003), and then determined the inductance using a function generator and an oscilloscope.

Theoretical calculation:

We approximated our loop antenna as a short air-core cylindrical coil, and calculated the inductance according to Equation 1. Since our inductance was greater than 5 μH we moved on to calculate the antenna inductance experimentally.

$$L = \frac{r^2 \cdot N^2}{9 \cdot r + 10 \cdot l} \qquad (1)$$

where L = inductance (μH)

r = outer radius of coil (in)

l = length of coil (in)

N = number of turns

Experimental Calculation:

We built an LC circuit using our antenna and a capacitor **Figure 24** to determine the inductance, L, of our antenna. An LC circuit resonates at $\omega = 1/\sqrt{LC}$ *with* $\omega = 2\pi f$. We applied a variable AC current through the circuit with a function generator and observed the resulting amplitude with an oscilloscope. We varied the frequency of the current until we observed a peak in the voltage. Identifying the frequency that induced the peak voltage allowed us to calculate the inductance (Agarwal & Lang, 2005).

(2) $\omega = \frac{1}{\sqrt{LC}}$ with $\omega = 2\pi f$

(3) $L = \frac{1}{\omega^2 C} = \frac{1}{4\pi^2 f^2 C}$

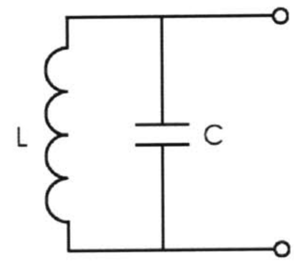


Figure 24. LC circuit used to determine the antenna inductance, L.

6.6.2 Selecting the Parallel Resistance, R_p

The parallel resistance can be specified by the quality factor, Q, the frequency, w, and the inductance, L, of the antenna. Q is a dimensionless value which stipulates the bandwidth relative to the center frequency. It also describes how damped the system is, and is therefore a measure of how much energy is in the circuit. A high Q denotes increased energy. While increased energy is desirable for increasing the read distance of the reader, a very high Q can interfere with the band-pass characteristics of the reader. We therefore selected Q=30 as suggested by Berlin et al.

For parallel and series RLC circuits, Equation (4) describes the relationship between the quality value, Q, frequency, w, and bandwidth, a. For a parallel RLC circuit, the bandwidth, a, is given by Equation (5). See Chapter 14 of Agarwal and Lang for a deeper treatment of the topic (Agarwal & Lang, 2005).

(4) $Q = \frac{\omega_0}{2\alpha}$

(5) $\alpha = \frac{1}{2RC}$

Substituting Equations (2) and (5) into Equation (4) yields resistance in terms of our known values, Q, w, and L, as shown in Equation (6). Note that this is an approximation, because our circuit has a series capacitor and is therefore not exactly parallel.

(6) $$R_p = Q\omega_0 L \text{ with } \omega_0 = 2\pi f$$

6.6.3 Selecting the Capacitors, C_p and C_s

After determining the antenna inductance, L, and parallel resistance, R_p, we were able to calculate approximate values for the parallel and series capacitors, C_p and C_s. The strategy for doing so involves finding the overall impedance of the circuit and matching it with the impedance of the RFID reader, Z_{RFID}. We should also note that we assume that the RFID reader impedance is completely real, namely that the real part, Z_{RFID}, is 50 ohms, as in Equation (7) and the imaginary part is zero ohms, as in Equation (8). This is a key assumption that will give us the final constraint for determining C_p and C_s.

As a matter of practice, the C_p calculated via this method will be a close approximation of the requisite capacitor value. Therefore, we used a variable capacitor and tuned our circuit experimentally once we understood the approximate capacitor values. A further discussion appears in Section 6.5.4.

(7) $$\Re(Z_{RFID}) = Z_0 = 50$$

(8) $$\Im(Z_{RFID}) = 0$$

The total impedance, Z_i, of the antenna tuning circuit in Figure 23 is given adding the impedance of each circuit element. The sum of impedances is given by Equation (7). Equations (8)-(11) specify the impedance of each circuit element. We note that the impedance of the resistor, R_p, is completely real, while the impedances of the antenna, L, and capacitors, C_s and C_p, is imaginary.

(7) $$\frac{1}{\frac{1}{Z_L}+\frac{1}{Z_{Rp}}+\frac{1}{Z_{Cp}}}+Z_{Cs}=Z_i$$

(8) $$Z_R=R_p$$

(9) $$Z_L=j\omega L$$

(10) $$Z_{C_p}=1/j\omega C_p$$

(11) $$Z_{C_s}=1/j\omega C_s$$

We use Equations (8)-(11) to write Equation (7) in terms of our known (R_p and L) and unknown (C_p, and C_s) circuit parameters. The resulting equation, Equation (12), is the impedance in terms of our circuit parameters.

(12) $$\frac{1}{\frac{1}{j\omega L}+\frac{1}{R}+\frac{1}{\frac{1}{j\omega C_p}}}+\frac{1}{j\omega C_s}=Z_i$$

To simplify our notation going forward, we introduced the variables G and B, in Equations (14) and (15), respectively. After substituting Equations (13) and (14) into Equation (12), we separate Equations (12) into its real and imaginary parts. Equation (15) is the impedance of the circuit in Figure 23.

(13) $$G=\frac{1}{R}$$

(14) $$B=\frac{-1}{\omega L}$$

(15) $$\frac{G}{G^2+(B+\omega C_p)^2}+j\left(\frac{1}{\omega C_s}-\frac{B+\omega C_p}{G^2+(B+\omega C_p)^2}\right)=Z_i$$

The impedance of the circuit, Z_i, is composed of real and imaginary components. The real and imaginary parts can be separated, as in Equation (16) and (17), respectively.

(16) $$\frac{G}{G^2+\left(B+\omega C_p\right)^2}=\Re\{Z_i\}$$

(17) $$\frac{1}{\omega C_s}-\frac{B+\omega C_p}{G^2+\left(B+\omega C_p\right)^2}=\Im(Z_i)$$

The impedance of the RFID reader, Z_{RFID}, is 50 ohm [cite]. If we assume that the impedance of RFID reader is completely real, as in Equations (7) and (8), we can equate the real part of the antenna circuit impedance, Re(Z_{RFID}) to Re(Z_i), as in Equation (18) and the imaginary part of the antenna circuit impedance to zero, as in Equation (19). We denote the real portion of Z_{RFID}, Re(Z_{RFID}), as Z_0.

(18) $$\Re(Z_i)=\Re(Z_{RFID})=Z_0=50$$

(19) $$\Im(Z_i)=\Im(Z_{RFID})=0$$

<u>Calculate the parallel capacitance, C_p:</u>

Equating the real part of the circuit impedance and the real part of the RFID reader impedance gives as Equation (20). The assumption that the entire impedance of the RFID is real results in an equation with just one unknown, C_p. C_p can be found easily through a series of algebraic manipulations. We refer the reader to Appendix A for a more detailed step though of the math. We note that one of the intermediary steps, reproduced in Equation (21), requires selecting between a positive and negative root. We chose the negative root as suggested by Soffke and refer the reader to (Soffke, 2007) for a more detailed explanation.

(20) $$\frac{G}{G^2 + \left(B + \omega C_p\right)^2} = \Re\{Z_i\} = \Re\{Z_{RIFD}\} = Z_0$$

(21) $$C_p = -\frac{B}{\omega} \pm \frac{1}{\omega} \cdot \sqrt{\frac{G}{Z_0} - G^2}$$

(22) $$C_p = -\frac{B}{\omega} - \frac{1}{\omega} \cdot \sqrt{\frac{G}{Z_0} - G^2}$$

<u>Calculate the series capacitance, C_S:</u>

We take the imaginary part of Equation (15) to find Cs. We rely on our assumption that the imaginary part of the RFID module's impedance is zero to arrive at Equation (23).

(23) $$\frac{1}{\omega C_s} - \frac{B + \omega C_p}{G^2 + \left(B + \omega C_p\right)^2} = \Im(Z_i) = \Im(Z_{RFID}) = 0$$

Finally, since C_p is now known, we can solve for C_s.

(24) $$C_s = \frac{1}{\omega \cdot Z_0 \cdot \sqrt{\frac{1}{Z_0 \cdot G} - 1}}$$

6.6.4 Tuning the Circuit Experimentally

After arriving at approximate capacitor values in Section 6.5.3, we tuned our circuit experimentally. To tune the circuit we replaced C_p with a variable capacitor. We applied a 13.55 MHz AC current through the circuit with a function generator and observed the resulting amplitude with an oscilloscope. We then varied the capacitor value until we observed a peak in the voltage. We were able to tune this design easily to achieve at least 10 cm range without using RF amplifiers or other similar components.

7 Interaction Design

Our primary concern throughout the interaction design was to provide for a natural and pleasant interaction. First and foremost, we took our direction from the natural methods people use to navigate the prototyping process. Second, we aimed to minimize new forms of interaction and instead relied on techniques to which individuals were already accustomed. Finally, we sought to minimize information overload by synthesizing information into a compact, easily digestible form while providing avenues for deeper exploration. We explore these high level concepts further in this chapter.

7.1 Input Methods

Data logging can be a tedious and time consuming endeavor. For this reason, we made it a priority to minimize explicit data logging and annotation. We focused our efforts on identifying digital technologies to which individuals contribute information as part of their regular activity.

7.1.1 RFID Interaction

We selected RFID for implicit interaction with the computing for many important reasons. First, RFID based interactions are implicit. Other than wearing a wearable device, no additional requirements are placed on the user (Figure 25). The user does not have to log usage history or change any of their normal interactions with the device. The size of a small RFID reader is appropriate for a wearable. For example, the M1-Mini reader we used for this project is the size of a quarter and was easily incorporated into a socially acceptable wearable. RFID also allowed us to track objects individually. RFID tags are easily available in many sizes and we could easily outfit any number of devices with the tags.

From an organizational standpoint, RFID could easily become a standard aspect of inventory management. Organizations, such as the one at which we work, already tag significant objects with inventory information. Though the current tags don't carry RFID technology, RFID tags could be easily incorporated. In the long term, the price for RFID tags will continue to drop. Once the price per tag drops below a threshold amount, it is conceivable that RFID tags would be incorporated into purchased objects. In the second case adding RFID will no longer be an organizational responsibility.

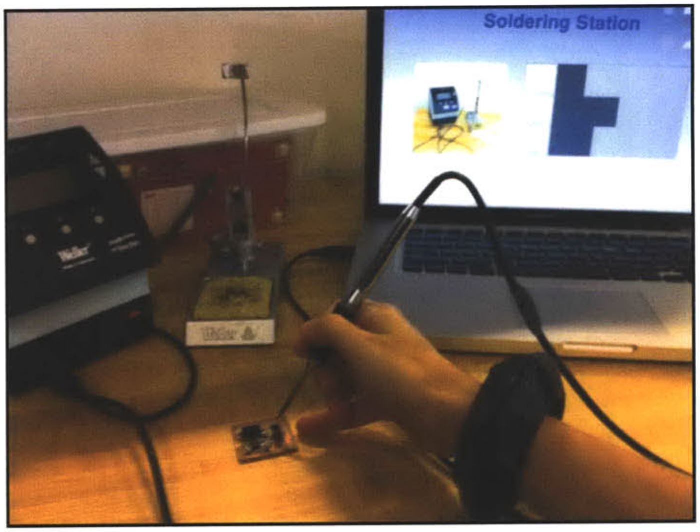


Figure 25. Implicit interaction with the computer. Retrieving aggregate information about the soldering iron via an RFID bracelet.

7.1.2 Microblogging

We selected microblogging as a method of gathering contextual information and commentary during the prototyping process. Our priority for adding information to the system was to use existing input methods. The rise of the Twitter microblogging platform, Facebook status updates, and away messages on instant messenger have proven to be a valuable source of information. Most importantly is that this information is completely voluntary, time stamped, often shared publically, and can be provided in time and in place via mobile phones. In fact, sharing information via these methods does not even require a smart phone and can be contributed via text message.

Microblogging was particularly interesting because it allows for multi-person conversation/collaboration and carries with it a database language that is creeping into everyday web lexicon. Posts can be easily attributed to objects via the hash sign (#) and can be addressed to others via the at symbol (@) (we have not implemented the "@" functionality). When combined with timestamps, these capabilities make microblogging an excellent choice for sharing prototyping tips with colleagues.

Although the central aspect of commenting within our prototype is conducted via a mircoblogging platform, we fully expect that other types of digitally created information can be included as part of the prototyping history(Liang, et al., 1999). The main tenant of using microblogging is to reduce the commitment on individuals to contribute or maintain data. Other web services, such as time-stamped flickr (flickr, 2010) photos, tumblr entry, or vimeo (vimeo, 2010) upload can be used to associate photos or videos with the object.

7.1.3 Calendar

In keeping with our goal to minimize additional modes of user interaction, we use the personal calendar as a method of ascribing usage history to projects. Calendars are convenient because companies often require individuals to account for their time so that hours can be attributed to projects. In addition, individuals often keep calendars as a way to plan their day. Using this readily available data frees users from the tedious task of remembering when they worked on projects or going back to tag data points. For our prototype, we use Google's Gmail to record project time. We then correlate the projects via object use timestamps.

7.2 Output Methods

Our initial methods for retrieving information were completely centered on the mobile platform. However, as our research evolved, we realized that the mobile platform is not sufficient for supplementing a process that is as spatial as prototyping. Here, we discuss our design decisions and how our prototype reflects this realization.

7.2.1 Mobile Device

First and foremost, we selected a mobile device (Nokia N810) as our mobile platform because it is carried everywhere and serves as a gateway to web-based services. As an ever present device, we could rely on its ability to convey information in-time and in-place. We could also take advantage of text input capability to enable commenting and annotations.

Our goal was to allow individuals to browse the data in three ways. Given a tool or material, we wanted to display associate projects and people. Given a project, we wanted to display associate tools, materials, and people. Given a person, we wanted to display associated projects, tools, and materials. We also wanted to provide methods for annotating and receiving comments, as well as methods for reaching out to other people in the company.

After building our first prototype and sizing it to fit the Nokia N810 screen, we quickly realized that displaying all of this information, or even a subset of it, would quickly overwhelm the user. To get any information from this type of interface would require a great deal of attention, which was contrary to our goal. In fact, social navigation, particularly product observation and over-hearing/over-seeing, is based on light interactions and awareness that gradually lead to deeper involvement with colleagues. We were much more interested in creating an interface that provided aggregate information, but could be used to gain deeper insight because it is a more natural reflection of the social navigation we presented in Chapter 3.

Rather than continue developing an information crowded display, we determined our most important parameters to be people, projects, and technical context. As such, we chose to present a single, large, normalized bar graph of each parameter to the user (Figure 26). The bar graph was just enough to show how much information exists about each category. A quick glace allows the user to understand whether there is a lot or a little information about the tool or material in the organization. Closer inspection allows the user to discern whether the object is used a lot or a little, how many people use it, and whether it is involved in many company projects. Such coarse information allows them to understand what information is readily available within the company. For example, if Sally notes that a lot of people know how to use the laser cutter, she can start to learn about the laser cutter by asking a friend. If not, she might have to inquire from many individuals.

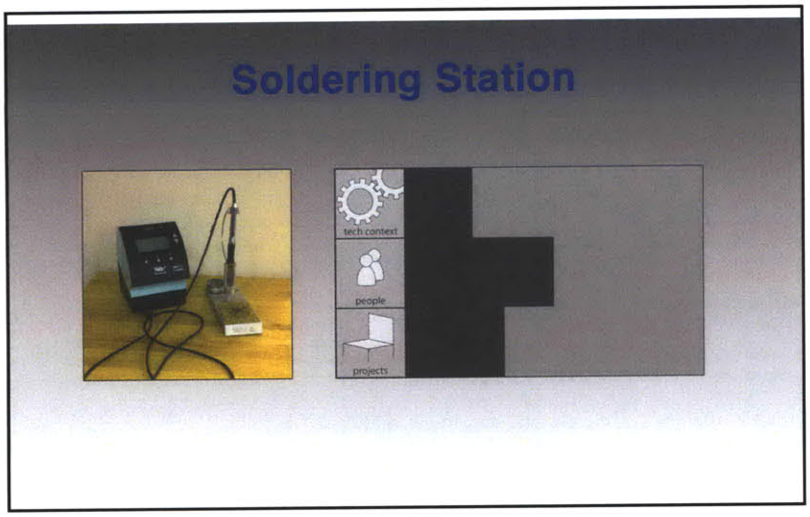


Figure 26. Screen shot depicting aggregate object usage.

Granular information can be viewed by clicking on any of these columns. The people column provides a list of people who use the tool or material frequently or recently. As a matter of convenience, the system notifies the user whether the individual is online and allows them to send an e-mail message from within the system. The projects column provides a list of projects that have made use of the tool or material. This is especially useful when trying to understand whether a particular tool is suitable for a given task. Finally, the technical context column shows which other tools and materials are often used in conjunction with the present one. Not only is this is a powerful way of learning one's way around the shop, but it can expand the repertoire of used tools by suggesting new ones to try or consider. It also acts as a hint for overcoming prototyping challenges.

One of the major components of the present system is its attention to connecting people. Our research on social navigation in the workplace revealed that people often treat documents as pointers to experts. We incorporated the strong social aspect of collegial information sharing by identifying people knowledgeable about current fabrication practices and providing direct access through our mobile platform.

7.2.2 Peripheral Screens

While prototyping, we realized that information would only be available to people if they took their phones out of their pockets to explore the information. However, individuals are more likely to use the system if they know it contains some relevant information (Liang

& Leifer, 2000). Rather than require people to remove their mobile device from their pocket, we chose to display high level aggregate information about the objects in use in the periphery, namely, on a screen. Should the person notice information of interested, they can then continue the rest of the interaction on their mobile device.

8 Reflections for Future Work

As part of this work, we have developed a working prototyping of the InfoCrumbs systems. In this section we summarize our thoughts for future iterations of the system.

We have achieved a sensing range of 10 cm for our RFID system without using any additional amplification. This is sufficient for capturing touch interactions for many objects, especially where the objects come close to the wrist or palm. However, the read distance restricts the type and size of objects the system can currently handle. We expect that increasing the read distance can increase the fidelity of many interactions.

Very small and very large objects pose a problem for HF RFID detection systems. For example, objects smaller than the size of an RFID tag cannot be captured due to difficultly tagging. Interactions with very large objects are sometimes missed when the RFID tag is outside the read distance. One way to address the issue of large size may be to include multiple RFID tags to insure that at least one tag is captured. Small objects will have to be addressed with other sensor systems. Consumable materials are somewhat difficult for the current system. While we can expect that materials such as wood initially have an RFID identifier, once the materials is cut the tag would be missing and the material would no longer be tagged. One way to circumvent this problem is to tag the material container, in this example, the wood shed. We expect that similar proxies could be developed for many other materials and objects. In fact smart use of proxies could remedy difficulties with sensing objects at extreme sizes.

One feature that has often been suggested in use tests is a way to link photos and documents to the projects and equipment. Since the idea here is to pull information from other sources, rather than to create another place for document generation, future versions of InfoCrumbs should include links to other types of databases. Internal company photo archives or external photo sharing services, such as flickr, should be incorporated with success. In general, the InfoCrumbs platform is built to be a method for aggregating existing information, enabling real time communications with others in the community (real time not yet implemented), and anchoring the existing information around real objects so that people can have a better understanding/easier time learning about their immediate environment. The prototyping context is an example environment where something like this appears to be very valuable.

Finally, it is highly desirable to create avenues for people to tag objects themselves. This would increase the information available about intermediate prototypes and objects. Not only would it relieve the administrative burden from adding tags to all objects flowing into and out of a firm, but also it would act as a filter for people to collaboratively decide what is important. Giving people the ability to tag objects themselves is also important so that the information is reflective of what people actually do in their communities.

9 Conclusion

Much of our knowledge is based on our interaction with the world. We know which roads to take because we've experienced the ones with potholes, know where traffic slows us down, and like to drive by the scenery. We buy books, sometimes with ulterior motives to look smarter or display our sense of humor, but the books we take off the shelf to read are distinct from these. The real interactions we have with the world are locked up in real object interactions. The more we are able to glean from those interactions, the more we will know about ourselves. The more we share those interactions, the more knowledge we can unlock within our communities.

Until now, knowledge about object use has not been accessible. In this thesis, we explored just one scenario where objects interactions can provide meaningful feedback and create knowledge in a community based around a specific set of objects. However, there are many other scenarios where insights into object use can be helpful, both personally and on a community level: Accounting for our revealed activity preferences can enhance vacation planning. Our health can improve when we account for what we actually eat and how much we actually exercise. Energy usage can decrease when we realize we wear shorts while increasing the temperature on the thermostat during winter. Recommendations systems can become more meaningful when they account for actual tastes and behaviors. Distinguishing between objects we buy and objects we actually use can help us to save money and reduce waste.

The fact is that people rely on each other to navigate through the world. We rely on each other to get our questions answered and want to be overheard when we're facing challenges. Sometime we want to be the ones to lay the path, other times the most efficient (or safest) way to go is to follow the footprints of a path well traveled.

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