Design of Intelligent Interiors

By

Leonardo Amerigo Bonanni
B.A. Columbia University, 1999.
M.Arch. Massachusetts Institute of Technology, 2003.

Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning, in partial fulfillment of the requirements for the degree of Master of Science at the Massachusetts Institute of Technology, September 2005.

Author

Program in Media Arts and Sciences
May 31, 2005

Certified by

Dr. Edwin J. Selker
MIT Media Laboratory

Accepted by

Dr. Andrew B. Lippman
Departmental Chair
Committee on Graduate Studies
Program in Media Arts and Sciences

Design of Intelligent Interiors

By

Leonardo Amerigo Bonanni

Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of Master of Science in Media Arts and Sciences,
on August 6, 2005.

Abstract

Ubiquitous computing is transforming interior design by allowing utilities, goods and information to be delivered where and when we need them. How will new information technologies impact the design of interior spaces? Intelligent interiors can be more flexible and expressive than traditional spaces. Automation, personal fabrication and augmented reality can be applied to interior spaces with new interaction modes that operate at an architectural scale. Water, light, and other utilities can be automated in a way that empowers users by providing direct feedback, tangible benefit and being fail-soft. Appliances can make it possible to produce and recycle a large number of variable goods locally and on demand. Many of the objects and surfaces of interior spaces can serve as displays to provide information intuitively where and when it is needed. This thesis demonstrates how distributed intelligence can increase productivity and enrich the experience of interior spaces.

Experiments with augmentations to the utilities, goods and information of a working kitchen suggest guidelines for interaction with intelligent interior spaces. The perceptual load and quality of interaction needs to be balanced; for example in our experiments projected text was almost always distracting. This work demonstrated that: information should behave at the scale of architectural space; an intelligent interior space should provide as much fidelity at the lowest bandwidth possible to support activity without distracting from tasks; the association of information to the tasks and objects referred to should be concrete and obvious; and appropriate feedback should accompany new interaction to increase the control and confidence of users. This thesis shows that new interaction modes for interior spaces can be intuitively understood and valued. In addition to being more flexible and functional, intelligent interiors can enrich everyday activity with new sensory experiences.

Design of Intelligent Interiors

Thesis Committee

Thesis Advisor

Dr. Edwin J. Selker
Associate Professor
Media Laboratory

Thesis Reader

Dr. Michael J. Hawley
Director of Special Projects
University of Memphis

Thesis Reader

John Maeda
Associate Professor
Media Laboratory

Design of Intelligent Interiors

Acknowledgements

Anyone glancing at this thesis could see that the breadth and depth of work it describes could only be the fruit of collaboration. It is.

My greatest debt is to Chia-Hsun (Jackie) Lee, without whom it would have been impossible to design, build, evaluate, re-design, re-build and re-evaluate a dozen demonstrations over the course of two years. Sam Sarcia is responsible for much of the mechanical design and fabrication of the physical prototypes – none of which have broken since he built them. Subodh Paudel grew into a masterful electrical engineer and is responsible for most of the hardware and software that went into these projects. Michael Barrett single-handedly designed and built the intelligent interior on which this thesis is based. Jon Wetzel's image understanding work was elemental to several projects. Runye Zha inspired my research in materials. Nicholas Meyer amazed me with his programming aptitude. Mikko Solomon built like a pro. Robert Gens touched several projects in a fireball of productivity. Darragh Buckley became a proficient CAD/CAM fabricator. Manas Mittal was dedicated to the development of control systems. Oliver Venn brought crucial biological insight. Diana Sim had the good humor to take on weird material experiments. Scott Barth was a dedicated helper and mechanical engineer.

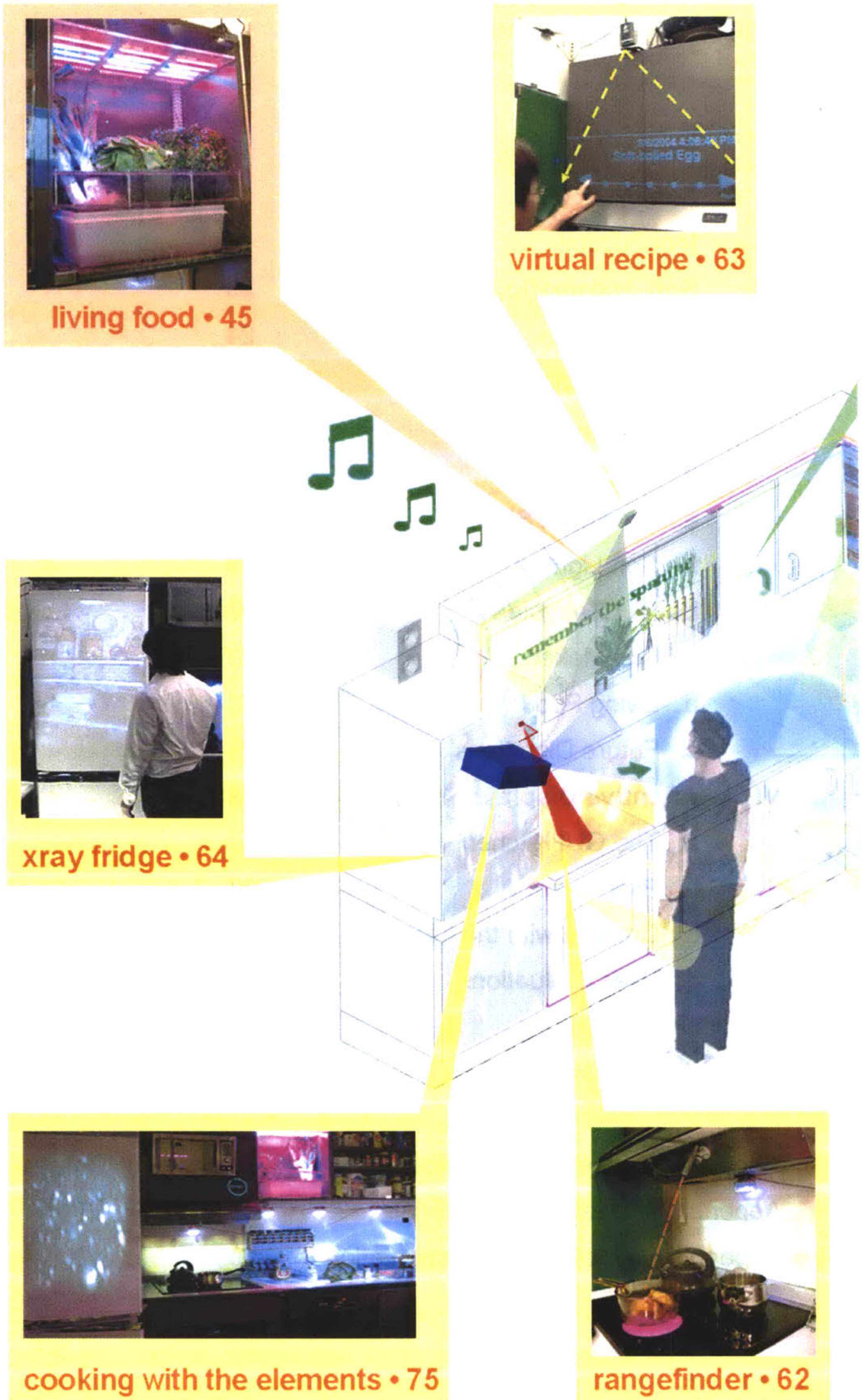
Without the professional advice and hands-on help of my friend Toshiyuki Takasaki, I would not have survived my first month at the Media Lab. I was also blessed to enjoy the consulting of another gifted engineer, Jerimy Arnold. Ernesto Arroyo calmly guided many of my decisions over the past two years. Matthew Hockenberry taught me anything I might know about human factors.

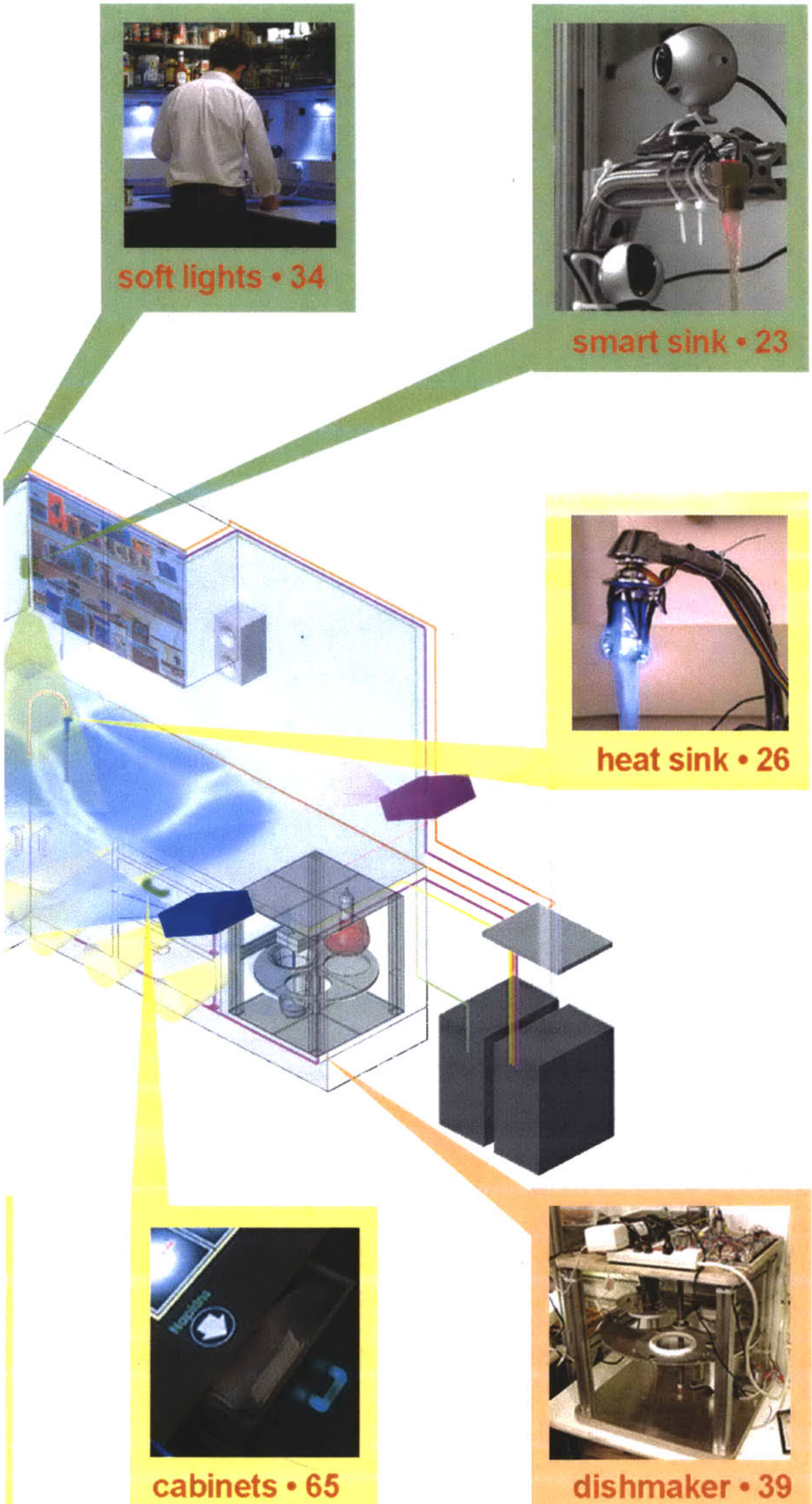
The adventure of these past two years was sponsored by Cleanup Corporation, and guided by close collaboration with Makoto Takashima, Saeko Tezuka, Muneharu Yoshida, and all the dedicated designers. They taught me a great deal about design, and our collaboration is the pride of my Master's degree.

None of this would have been possible without Yumiko Mori, Michael Hawley, and Ted Selker – they inspired me, guided me, and gave me incredible opportunities. I am forever grateful for their ideas, their support and the confidence they have in me.

Design of Intelligent Interiors
Table of Contents

Index of Prototypes: soft automation local lifecycles attentive displays




soft lights • 34
smart sink • 23
heat sink • 26
cabinets • 65
dishmaker • 39

Design of Intelligent Interiors

Summary

Since the invention of fire, the design of interior spaces has been defined by the technologies within. With the advent of modern plumbing, refrigeration and automation, more and more activities can be performed at the same time within cleaner and more compact environments. At the same time as new appliances can provide the heat of fire without the smoke; new sensory experiences are being created by multimedia displays. Ubiquitous intelligence is transforming interior spaces by allowing utilities, goods and information to appear dynamically where and when they are needed. Intelligent interiors can become immersive sensory environments that combine the advantages of automation and modern technology with sensory feedback and materiality.

The kitchen is the most technologically integrated part of our houses. The residential "hearth" is becoming a living-dining space where multiple users perform various tasks contemporaneously in the same space. This thesis considers three directions in which digital augmentation can enhance mundane tasks while enriching and broadening user experience: utilities, goods, and information. Three new directions for designing intelligent interior spaces are identified and expanded through working prototypes and evaluations: *Soft Automation* describes a means of actuating architectural utilities such as water and light to be intelligently responsive by providing direct feedback, tangible benefit and being fail-soft. *Local Lifecycles* proposes appliances that can extend product lifecycles within a single space through compact appliances that manufacture and recycle goods on demand and on-site. *Attentive Displays* proposes a means for ubiquitous information to be tailored to the perception, comprehension and performance of people in a space.

Soft Automation

Automatic faucets and lights are often relegated to institutional use because they do not provide enough control for individual users. For architectural services to be automated without leaving a user feeling restricted, the interfaces should provide tangible benefit over existing services, be fail-soft so as not to perform worse than conventional fixtures if they break, and provide direct feedback so that a user can understand and anticipate the decisions of the system. *Soft Automation* is explored through six prototypes:

1. A *Soft Sink* made from silicone rubber that provides the tangible benefit of being safer than traditional sinks.
2. *Heat Sink* communicates the temperature of tap water by direct feedback, projecting red or blue light into the stream of water itself. In user studies, 94% of users understand the functioning of *Heat Sink* at first use while 78% enjoy the direct feedback it provides.
3. *In Sink* uses a webcam to analyze the task being performed in the sink and provides the tangible benefit of automatically turning on the water at the appropriate temperature while communicating the temperature visually for direct feedback.
4. *Clean Sink* uses various direct feedback modes to encourage doctors to wash their hands before entering a patient's room.
5. *Up+Down Sink* uses a webcam to measure the posture of a user and provides the tangible benefit of moving to the most comfortable position for each person while returning to a universally accessible fail-soft default position. In user studies, 88% of users found the vertical adjustment provided a tangible benefit over fixed-height work surfaces.
6. *Soft Lights* are networked task lights that offer the tangible benefit of automatically turning on and off in zones that provide direct feedback on the position and movement of users while having fail-soft characteristics that keep them from turning off completely and allowing for direct override.

Local Lifecycles

Large parts of interior spaces are dedicated to the storage of seldom-used products like dishes in the kitchen. *Local Lifecycles* are compact appliances that allow variable production of goods within an interior space through on-demand manufacturing and localized recycling. Two prototypes and two designs demonstrate and explore the potential of *Local Lifecycles*:

1. *DishMaker* is a dishwasher-sized prototype that can variably produce cups, bowls and plates on demand and recycle them when you are finished eating so that they can be stored in their compact raw material form.
2. *Living Food* extends the useful life of store-bought vegetables and greens through a cabinet-sized appliance that provides the proper light, humidity, temperature and nutrients to grow a variety of greens for weeks longer than they can be stored in the refrigerator.

Attentive Displays

As projectors and multimedia displays become less expensive, it becomes possible for any of the surfaces of a space to display information. Over the past two years, Chia-Hsun Lee and I designed and built an augmented cooking and dining environment, evaluated it in pilot studies, re-designed and formally evaluated in a user evaluation. In the first iteration, *The GUI Kitchen*, augmentation of the space results from the aggregation of five interfaces:

1. *Heat Sink* turn the tap into a graphical user interface by projecting red or blue light in the stream of water based its temperature.
2. *Xray Fridge* takes a picture of the refrigerator's contents each time the door is opened and projects images of the refrigerator's contents onto the door.
3. *RangeFinder* measures the surface temperature of the cook-top and relays the information to a central computer for use in setting automatic timers and alarms.

4. *Virtual Recipe* uses multimedia projectors and camera-based sensing of projected "virtual buttons" to display interactive recipes and suggestions onto the cabinets and countertops of the space.
5. *Augmented Cabinetry* provides attention cues to orient and remind a user of where to go and what to do next.

Recipe-based and meal-based pilot studies of the space revealed that camera-based sensing of projected "virtual buttons" is counterintuitive; paper recipes perform better than the distributed projection of textual and graphical instructions; and current multimedia projectors have too low of a resolution to aid in retrieving items. On the other hand, ambient displays like the self-illuminated handles of *Augmented Cabinetry* and the colored illumination of *Heat Sink* were pleasing and effective, especially since no comparable displays exist.

The second iteration of the augmented kitchen, *Cooking with the Elements*, consists of a centrally-controlled *attentive display* covering the appliances, countertops and backsplashes of the kitchen with a room-sized seamless multimedia projection. *Attentive Displays* are a combination of ambient displays and augmented reality that were generated from the lessons of our pilot studies to produce intuitive information displays that operate at the scale of architectural space. To effectively display information for people in a space, sensors and models of users and tasks are necessary to tailor the information to the users' perception, comprehension and performance. An array of sensors measures the location of people and the status of appliances in the space while intuitive immersive interfaces provide direct feedback to users. The system projects low-resolution dynamic textures to indicate that the range is hot, the freezer is open or the water is running. The contents of refrigerator and cabinets are projected once a user approaches, while indicators grow larger if a user is distant or distracted. Soft Lights create "work zones" around the room and flicker in the periphery of the user's vision in case an interruption is necessary.

Formal evaluation of these interfaces revealed that the projection of dynamic textures and sound can elicit emotion in novice users. Projection of an animated fire as an indicator that the range is on communicates effectively to 94% of users, whereas only 14% understand the existing indicator. A high-resolution projection of a cabinet's contents works as well as a glass door in helping users locate items, with the advantage of being able to be turned off or annotated with digital information. Task lights can act as ambient information displays to interrupt visual tasks: 83% of users noticed the lights flickering in the periphery of their vision despite the novelty of this modality. These *Attentive Displays* proved far more successful in user studies than the *GUI Kitchen*.

Lessons Learned from User Studies

1. Text and graphics distributed throughout an interior space are not as easy to understand as when they can be hand-held as on paper.
2. Step-by-step instructions are not as effective as complete recipes.
3. Displaying information on the surfaces and objects it refers to is more effective and intuitive than abstract or remote indicators.
4. Self-illuminating objects can be pleasing, attract attention, and convey information intuitively.
5. Displays that are based on the proximity of users can provide useful information without taxing attention when not in use.
6. Work surfaces, lights and fixtures that automatically adjust to the different posture and activity of each individual can be easier to use and more comfortable.
7. Distributed sound and images has the potential of making interior spaces more expressive.

Future Directions

Once architectural utilities, goods and information are free to appear where and when they are needed, designers can add feedback to everyday activities and create new sensory experiences by taking advantage of immersive multimedia displays. This thesis showed through several demonstrations that ubiquitous computing can make it possible to re-gain some of the control and feedback of pre-industrial life at the same time as having the convenience and hygiene of modern appliances. Once we can have the fire without the smoke, we can create new kinds of feedback to inform and enrich everyday activities with a new sensuality. This thesis proposes a number of new interaction modes that could one day become commonplace in interior spaces:

- Products can better indicate their status if their entire surface can self-illuminate or be projected with information.
- Displays can be more useful if they respond to the proximity of users, and they can be less obtrusive if they disappear when not needed.
- Task lighting can be an effective medium for ambient information display.
- Appliances can adjust mechanically to the posture and action of different users without being disruptive.
- Many of the things we buy and use can be made and recycled locally.
- Sound, images and animations can create the illusion of sensory perception.
- Distributed sound and images can become a powerful part of the expressive palette of interior design.

Introduction

"The house is a machine for living"

In this famous quote, modernist architect Le Corbusier encapsulates the relationship between new technologies and the design of space. The buildings we inhabit are an answer to human desires and a product of the technologies available to satisfy them. The modernist movement showed that technology can liberate the way spaces are conceived and inhabited. Automated appliances were re-forming space and promising a cleaner, more efficient way of living. The crisp geometry of modernist architecture reflected the new possibility for pure living spaces made possible through modern appliances. Never before was it possible to have hot and cold water, smoke, fire, and ice near each other in such clean, open, well-lit spaces. At the same time as interior spaces were liberated from daily labor, an ever greater variety of goods and services was being made available to people through global industrialization.

Together with the newfound ability to distance our intimate interior spaces from the mechanisms of production and disposal, we have lost feedback and control over these systems. The widespread pollution and waste of natural resources evolved in part from the seeming ease with which our modern homes and offices are supplied with energy and goods, and the means by which these are disposed of. The 'invisibility' of these elaborate industrial systems was encouraged by the design of interior spaces that are 'out of touch' with nature. And modern appliances are becoming so automated and devoid of feedback that we often waste water and energy because we forget that we have left the oven on, or the sink running. We buy and dispose of countless objects and other objects to store those objects. When interior spaces were the site of production, sustenance and disposal people had total control over the fire being made, the water being drawn or the clothing sewn and pottery cast. Our ability today to provide services goods and information on demand can bring us back some of the feedback and control of pre-industrial life with the efficiency and variety of today.

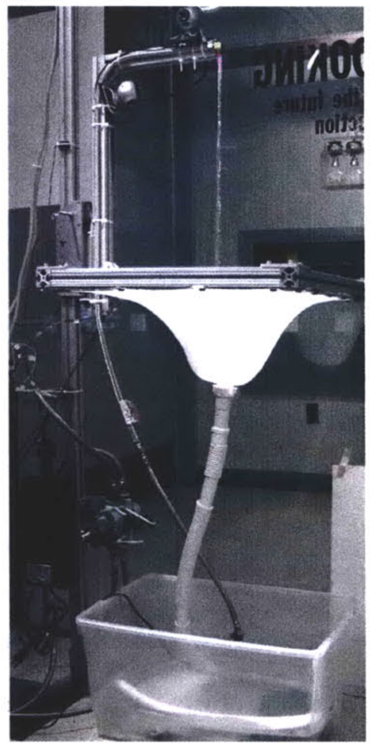
A more subtle shift in the design of interior spaces is being brought about as computers become distributed throughout interior spaces, first as home automation systems for security and entertainment. Until now each improvement in technology for interior spaces made itself more invisible, so that all the conveniences of modern life can fit just as well in a French chateau as in a space station. Information technology is shaping interior spaces in new directions: distributed displays and computers are making it possible to experience a breadth of sensory stimulus never before possible. While kitchens and bathrooms have become ever more compact, clean and quiet; entire rooms in our homes and offices are being dedicated to multimedia entertainment and work. Home theaters, family rooms, tele-conference centers and even bedrooms and offices are focused around large displays and immersive audio. These "information appliances" function in a manner opposite to traditional appliances: rather than being smaller, quieter and more efficient these machines are becoming larger, louder, more immersive. These two opposing trends – towards smaller less obtrusive labor-saving appliances and towards larger, more immersive information appliances – suggest that interior spaces will one day be almost free of physical constraints and full of experiential possibilities.

Design of Intelligent Interiors explores the trend towards the re-sensorization of interior space with a series of projects to reveal many possibilities once information, physical goods and services can appear where and when they are needed. *Soft Automation* describes some solutions to the problem of automating building services so that people have greater feedback and control. *Local Lifecycles* presents some new appliances that can subvert the processes of production and distribution by localizing production and recycling. Finally, *Attentive Displays* reveals some of the considerations when designing displays that operate at an architectural scale. Our ability to eliminate the labor of life is only being exceeded by our desire to invent new, more immersive experiences. This thesis suggests guidelines whereby designers can take advantage of both trends to enrich the experience and sensuality of the built environment.

Soft Automation

Soft Automation: appliances can be automated without taking control from a user if they have
1. Tangible Benefit
2. Fail-Soft
3. Direct Feedback

We have all felt the frustration of automatic faucets and lights – the lack of control and feedback and the frustration when they don't work. Such automation systems are only found in institutional settings where they serve to conserve water and energy and promote hygiene by taking control away from the users. More sophisticated modeling of users and tasks together with better sensing and actuation can improve the quality of these devices so that they can be used in a greater variety of settings. Interaction with basic services such as plumbing, ventilation and lighting can benefit from computer-aided interaction if these automated services offer tangible benefit, are fail-soft, and offer direct feedback. People are more likely to accept automation if the benefit is immediately evident (tangible benefit). Architectural services need to fail in a way that is not dangerous (fail-soft). If the computers give *direct feedback* on their decisions, people will feel more confident using the system.



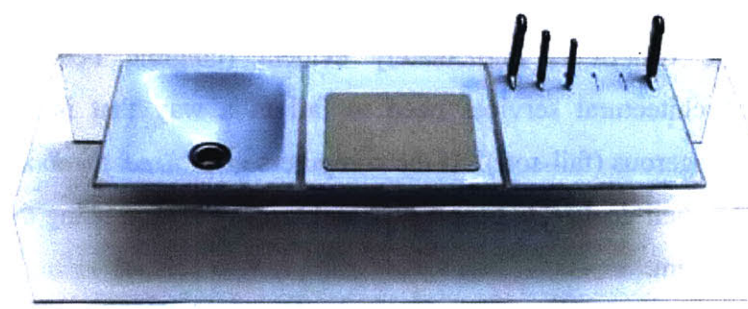
The smart sink development platform showing support column at left, heater and valves at lower left and water tank containing pump.

Smart Sinks

Kitchen and bathroom sinks are important sites for augmented interaction because of the high stakes these fixtures play in our personal and public lives. Aside from being hostile to computers, bathrooms and kitchens are the most dangerous rooms in a house[1]. Washing our hands is

[1] "Bathrooms and kitchens are the most dangerous rooms in the house." http://www.pdrhealth.com/content/lifelong_health/chapters/fgac36.shtml

the most effective means for preventing infection[2]. For years we have been using sinks in public places that automatically sense our hands and turn on for the purpose of hygiene and water conservation. Recently, some industries have been installing complex systems to monitor their employees' hand-washing [Hygenius]. Microprocessor-based water filtration systems with displays are starting to make their way into residential kitchen sinks [Moen]. Because of its importance in our health and safety, the sink can benefit in a number of ways from computer-mediated interaction. *Smart Sinks* are a series of prototypes on a common platform that seek to demonstrate a number of interaction modalities and design considerations for intelligent behavior at the sink.



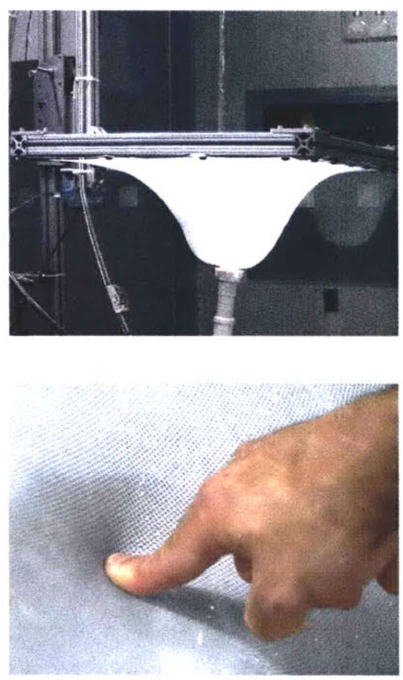
Soft Sink

Bathrooms and kitchens are noisy and dangerous places, in part because sinks, countertops and bathroom fixtures are made of hard materials like ceramic and stainless steel. What if the materiality of these spaces could be softened to make them not only quieter and safer but more comfortable

[2] "handwashing is the simplest and most effective, proven method to reduce the incidence of nosocomial infections" [Shojania]

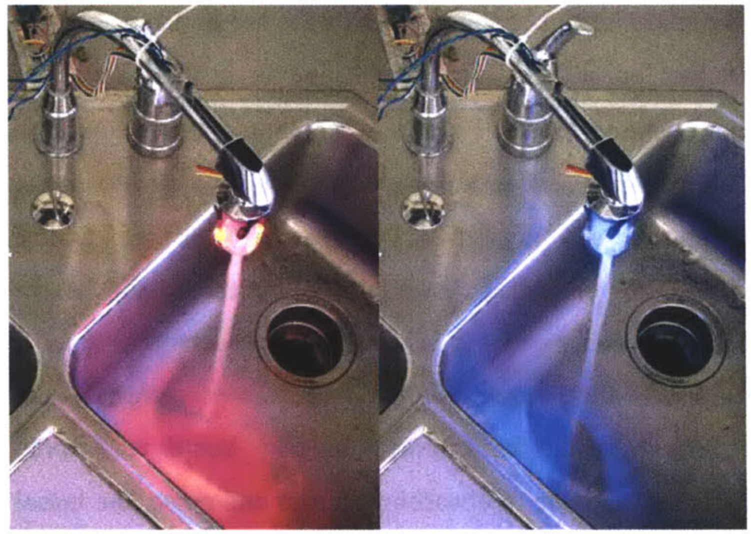
and welcoming? *Soft Sink* seeks to replace the contact surfaces of countertops and sinks with softer materials that absorb sound and impact. New high-performance rubbers like silicone are becoming suitable for use in places like the kitchen because of their resistance to a wide range of temperatures (0-700°F) and hygienic properties [Ashby]. The first *Soft Sink* prototype was made in 2002 by Joshua Barandon and myself as coursework for the course "MAS.742: Industrial Design Intelligence" at the Media Lab. It consists of a platinum-cure silicone layer over a rigid substrate providing a soft, temperature-resistant covering for a knife-block, cutting board and sink. Although capable of absorbing impact and noise, the initial prototype was scaled down and the silicone was prone to tearing. The second version of *Soft Sink* was fabricated at a much larger scale (2' x 2') of translucent platinum-cure silicone with an embedded elastic fabric for tear resistance. The ¼"-thick membrane was cast over a slumped piece of acrylic with catenary curves so that it would be able to be suspended from a rigid frame without deforming under the weight of water.

The first *Soft Sink* prototype showing the blue silicone shock-absorbing skin on a rigid substrate.



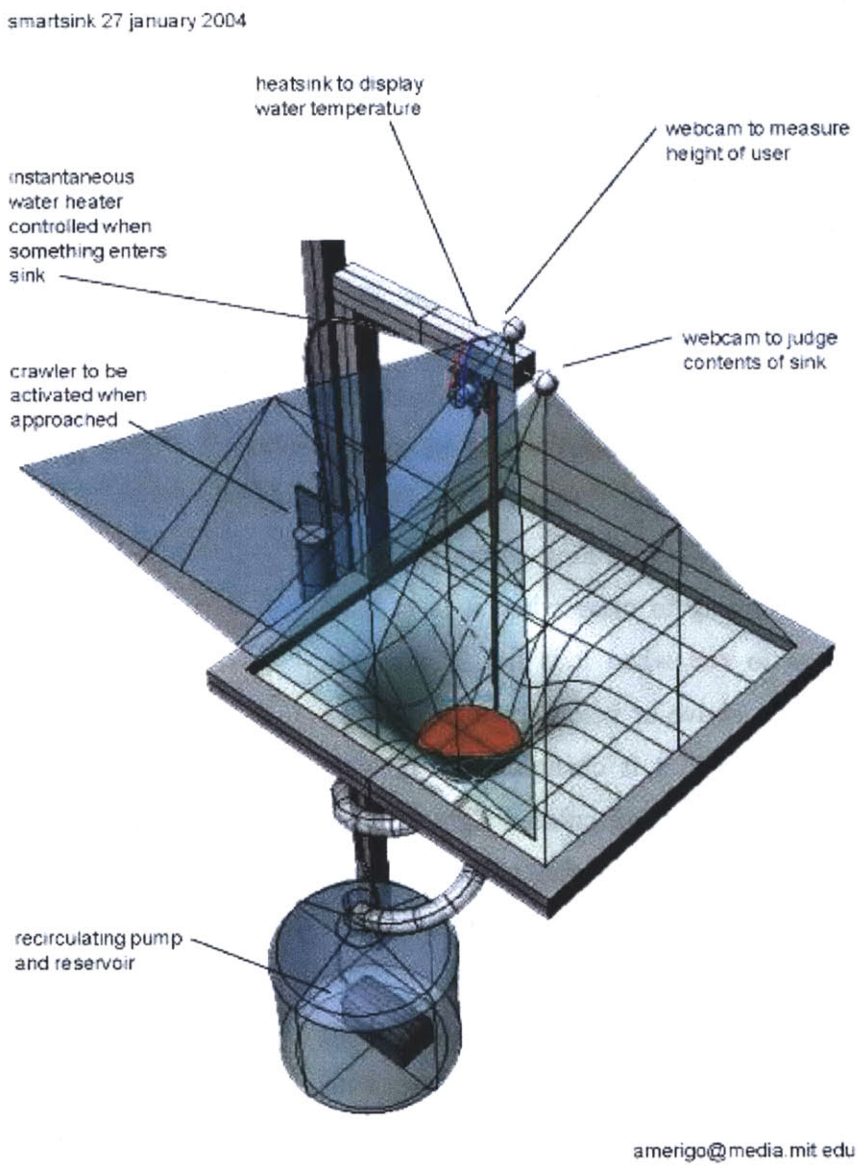
The second *Soft Sink* prototype showing the catenary form of the sink vessel (top) and mesh-embedded silicone membrane (bottom).

Although not computerized, this initial manipulation set the tone for further research in the domain of the sink by demonstrating the vast improvements possible and suggesting that a 'softening' of both the material itself and the interaction with sinks in general can greatly improve quality of interaction with this common fixture. Countless visitors to the lab noted with pleasure the tangible benefit of being able to toss a wine glass into the sink from across the room without breaking it.



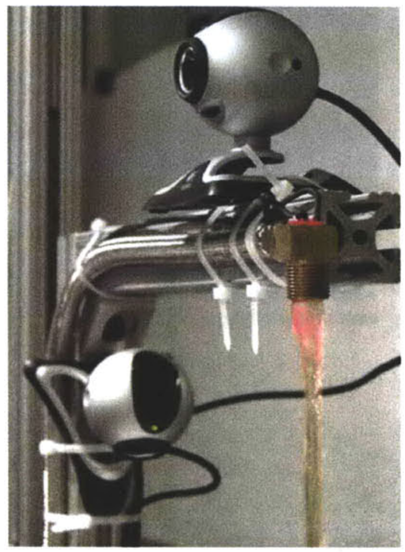
Heat Sink

The faucet does not afford much information about its status. How many times have we scalded ourselves by touching a stream of water that should have been comfortable? How often do we let the sink run for an arbitrary time in order to be sure of the water's temperature before using it? The controls either do not communicate the actual temperature of the water, or they provide a relative temperature that is mediated by the previous use. The water itself does not communicate its temperature except when it is so hot that is releases steam. The first example of direct feedback is a system to transform the sink into a graphical user interface with real-time feedback on the temperature of the water (called *Heat Sink*). Colored LEDs powered by a solid-state micro-circuit on the tap project colored light into the stream of water to communicate its temperature to users. Although early design iterations used full-spectrum color in addition to flashing to communicate multiple types of information about the water, red and blue were ultimately used because they unambiguously communicate the temperature at a scale that people understand. People perceive hot water as being warmer than their hands, while cold is colder. At the same time, nobody knows what numeric values these represent (hot = 32+, cold= 32-) or what their range is (the coldest water is usually much farther from threshold than the hottest). Although multiple colors would be able to communicate more information, people would not understand them intuitively. *Heat Sink* colors the water blue when it is cold, fading to clear when it is at hand temperature and then to **red** when it is hot. Users can understand whether it is above or below medium, and the fading allows them to see if it is changing and in what direction. By internally projecting colored light into the stream of water, *Heat Sink* takes advantage of the fact that a user is concentrating on the water, not a separate control or display. Demonstrations of the system to corporate sponsors and press reveal that people express satisfaction and delight over the illumination of the water with intuitively colored light. User studies of the *Heat Sink* with 16 novice users aged 18-35 reveal that 94% understand the system during the first use (See Appendix C). Because of its apparent simplicity and intuitiveness, the *Heat Sink* inspired the *Attentive Displays* discussed in part V.

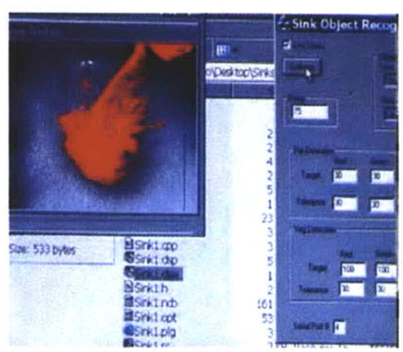

smartsink 27 january 2004
heatsink to display water temperature
webcam to measure height of user
instantaneous water heater controlled when something enters sink
webcam to judge contents of sink
crawler to be activated when approached
recirculating pump and reservoir
amerigo@media.mit.edu

In Sink

Today's automated faucets turn on and off automatically so that we don't touch the controls or leave the water running. These systems are useful for hand-washing because they only work with a fixed water temperature and pressure. What if an automatic faucet could account for the myriad activities that occur in a setting like the kitchen? *In Sink* is a prototype of a sink that can interpret a variety of tasks being performed by the user to provide useful hands-free control of water temperature and flow. A CCD camera mounted under the faucet continually observes the contents of the sink. Using image recognition [C++ program using Microsoft Vision SDK Library], a computer controls the water temperature and flow based on the type of object in the sink, its size and the length of time it stays. Colors and shapes are used to identify vegetables, hands and pots. When the camera detects hands, the sink dispenses warm water as long as the hands are in the sink. If the camera detects green vegetables, the sink supplies cold water. If the camera detects a black or shiny round thing it interprets it as a pot and fills it with cold water for boiling or hot water for washing if a sponge is present. While In Sink automates sink function in a new and unexpected way, it seeks to provide direct feedback by projecting colored light into the stream of water to communicate the system's decision to a user. This automation has the tangible benefit of allowing users to use the sink with dirty or full hands without being distracted from the task at hand. At the same time the system is fail-soft and defaults to

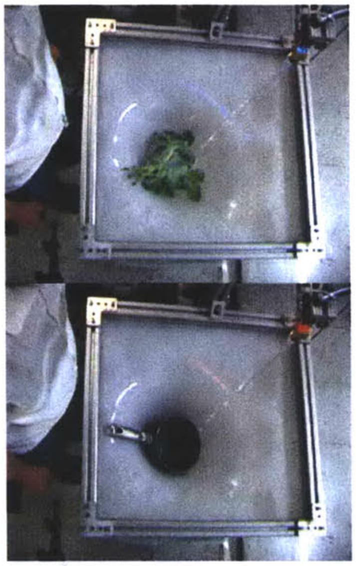


In Sink showing task-focused (below) and user-focused (above) cameras as well as Heat Sink indicating hot water.



In Sink image recognition software (red indicates objects introduced to the sink).

dispensing lukewarm water when conflicting objects are recognized. Because a setting such as a bathroom or kitchen has a constrained set of possible actions, it is possible to account for a variety of scenarios with the single task-focused webcam. New behaviors have to be hard-coded into the current system, although a simple learning interface would be included in a commercialized version of *In Sink*. The next application called *Clean Sink* confirms that a webcam-based faucet sensor is not only robust but capable of a wide range of applications.



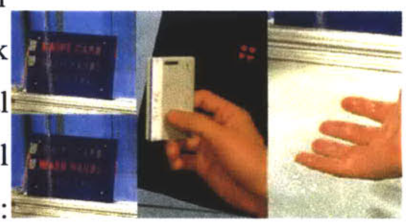
InSink showing cold water for washing vegetables (above) and hot water for washing a pot (below).

Clean Sink

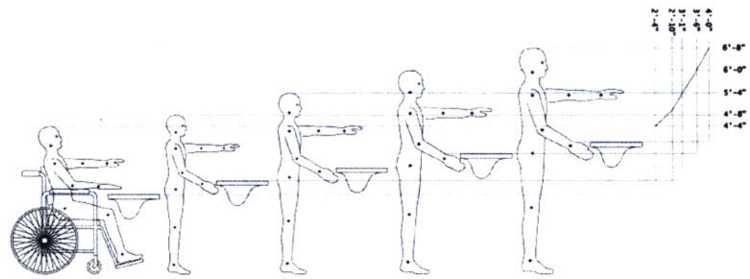
Hospital employees wash their hands only half as much as they should[3]. Since hand-washing remains the most effective means of preventing infection, being able to enforce hand-washing compliance can effectively save lives [CDC]. Some expensive systems on the market promise to enforce hand-washing by forcing employees to log in when using a sink and installing video cameras to record and observe compliance [Hygenius]. These systems are clumsy and while they may be effective for determining culpability after contamination has occurred, they do not directly prevent contamination. *Clean Sink* is a working prototype that expands on the vision recognition systems from *In Sink* to create a hand-washing compliance

[3] "Although handwashing has been proven to be the single most effective method to reduce nosocomial infections, compliance with recommended hand hygiene practices is unacceptably low ... a recent review of 11 studies noted that the level of compliance with basic handwashing ranged from 16% to 81% ... Of these 11 studies, only 2 noted compliance levels above 50%" From [Lautenbach]

enforcement. The same CCD camera used to control water flow and temperature records that hands are in the sink under a stream of warm water for a pre-determined interval of time before letting a user enter clean areas. Several means of enforcement have been prototyped in our lab: reward, logging, facilitation and lock-out. Depending on how critical the application is, any combination of these can be used. In the most benign, an illuminated sign says 'thank you for washing your hands' once hand-washing is confirmed. *Heat Sink* can also be used to make a pleasing show of colored light once hands are clean, especially if the system is used to motivate children in a school environment. For critical application such as food service or health care, we have prototyped an enforcement mechanism that uses a combination of Radio-Frequency Identification and control over the room doors and lights. An RFID reader can read standard-issue identification cards in the pockets of a user to maintain a log of hand-washing. Next, an electric door lock and relayed room lights make it impossible for a person to enter clean areas and operate in them until the sink confirms that hand-washing has been achieved. All of this is possible with systems already existing in most modern facilities. The only additional hardware needed is a camera with computer mounted on the faucet itself. This example demonstrates that computer-mediated interaction at the sink can have important new consequences over hygiene and, ultimately, life or death.



Clean Sink showing indicator (left) RFID reader (middle) and sink (right).



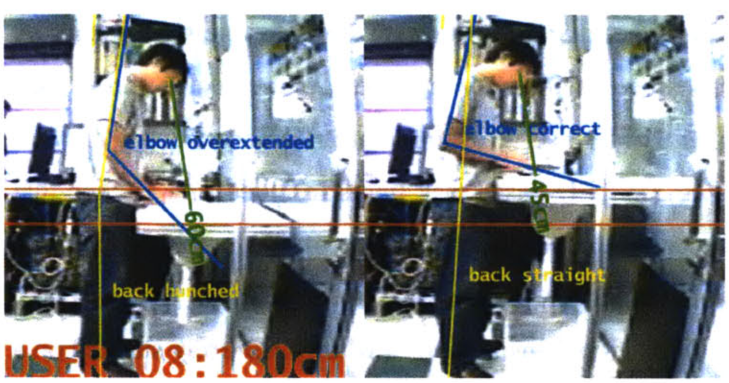
The ergonomic model used to determine the height of the Up+Down Sink based on a user's posture.

Up + Down Sink

Up+Down Sink height tracking program (above) and two different heights (below).

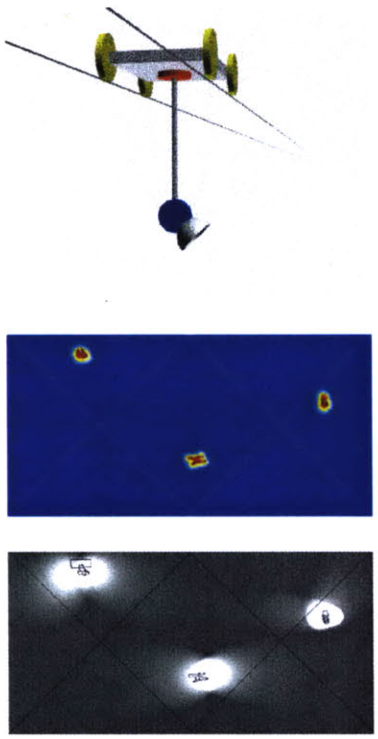
Bathrooms and Kitchens are shared by all the members of a household. For bathroom and kitchen fixtures to comply with the Americans with Disabilities Act [ADA] and OSHA [OSHA] *and* be comfortable for all people – seated or standing, they should be mobile. Several research projects have investigated direct-actuation height adjustment as a means of controlling context [Mori 2004] with the finding that people are unlikely to consistently adjust a work surface's height if they have to do it themselves. As you approach the *Up+Down Sink,* a webcam mounted on the faucet measures your posture and the entire sink raises to your ideal height. When you leave, the sink returns to its universally accessible height. In combination with an undercut in the basin, the *Up+Down Sink* is a handicap-accessible sink that can be comfortably used by tall persons, children and seated individuals.

A user study of the *Up+Down Sink* was conducted with 9 people aged 20-47 to determine how ergonomically and emotionally comfortable it is (See Appendix B). The sink was covered with a countertop-like surface and users were asked to approach it and chop a carrot. For the two questions "Was the counter at a comfortable height?" and "Do you feel that this counter would be useful?" eight out of nine users preferred the dynamic work surface to a standard countertop. I expected that subjects would be surprised and even startled by the immediate movement of the counter as they approach, but this effect was only noted in written comments of 2/9 users and did not deter from their overall opinion of the system (paired samples t-test with $p<0.01$). One hypothesis is that users immediately felt a tangible benefit as the work surface rose up towards them at the same time they would be bending down. Two users for whom the sink was intentionally raised above a comfortable height responded positively to the survey, probably because of the Hawthorne effect which suggests that people are perform better when they know they are being observed, regardless of whether or not it actually helps.



Graphic analysis of user studies showing typical posture (left) corrected posture (right).

Soft Lights

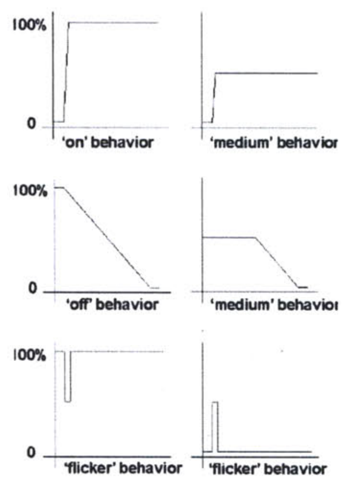


Drawings from an early proposal for lights that can track users and move on rails to provide the best quality of light for several users with very few fixtures in a large space.

Like automatic faucets, automatic lights are relegated to institutional use because of the lack of adaptability of their current incarnations. These lights are typically mounted together with long-range motion sensors, and turn on for a pre-set time when triggered. At the same time sophisticated radio switches and highly controllable LED-based lights are starting to enter the market [Color Kinetics]. What if the lights could be designed to work in typical interior spaces like offices and living rooms by having 'softer' transitions, better sensing and behaviors that can be useful? An early project of mine demonstrates that actuated illumination can save resources and provide a better quality of light. These *tracking lights* a simple spotlights that travel on rails. Based on the location of people in the space, the lights can not only turn on and follow people but also change their angle and brightness to provide the best type of glare-free lighting for applications in the space. *Soft Lights* takes the idea one step further by proposing intelligently actuated, perceptually tuned task lights that also serve as ambient information displays. *Soft Lights* are LED-based task lights installed in a kitchen that take on a number of behaviors to offer tangible benefit in a fail-soft manner. Michael Barrett designed the hardware for *Soft Lights* consisting of a white LED array stacked on a PWM control board with communication to a central multiplexer controlled by a PC. Proximity sensors distributed throughout the space can gauge the location of people in the room, and the appropriate lights are turned on. Like typical automatic lights, *SoftLights* offer the tangible benefit of not requiring users to find and touch a remote switch. The ways these networked task lights fade on in zones as a user approaches offer simple direct feedback. Beyond this, the lights are carefully tuned to perceptual thresholds so that their actuation does not startle users and never leaves anyone in the dark.

Soft Lights are LED-based task lights that respond to a user's performance by turning on in groups to create personal zones.

SoftLights have controllers designed and built by Michael Barrett to accept different commands from a central processor: on, off, medium, and flicker. The lights are at 5% brightness at all times in case of sensor failure. They turn 'on' gradually, so that they startle newcomers as little as possible. Lights directly in front of a user are turned on at 100% brightness, whereas lights at their periphery are turned on to only 50% brightness. This creates a 'work zone' that annotates the space with light so that other people can understand the bounds of one person's work space. If a user leaves, the lights turn 'off' even more gradually, so that there is never the surprise of lights suddenly turning off.



SoftLights have pre-programmed behaviors triggered by a central controller based on the presence and position of users. These graphs indicate the PWM intensities coded onto each light's controller whether they are being turned 'on', 'off', 'medium' or to interrupt a user with a 'flicker'.

Soft Lights also have a role as ambient information displays: if something occurs that they need to be alerted to, such as someone entering the room or the phone ringing, the lights have a 'flicker' behavior that rapidly fluctuates the brightness of lights in a user's peripheral vision. Arroyo demonstrated that light flicker can be an effective minimally disruptive interruption modality [Arroyo 2003]. In a user evaluation of *Soft Lights*, 18 users aged 18-35 were filling out a questionnaire at the countertop while lights at the periphery of their vision were flickered a number of times. 83% (15/18) users reported noticing the lights flicker, although they could not accurately determine how many times, even though they were not asked to look for this behavior and the question was a surprise at the end of an unrelated string of questions. This suggests that flickering behavior can be an effective means of distracting a user involved in a visual task, even if the lights flickered are not in the central field of vision. Such flickering behavior could be used as an additional mode to remind someone that the food is ready, that the phone is ringing, or that someone is passing behind them. In my first implementation, the lights flicker to alert you that someone is behind you while you are busy with a task. Soft Lights demonstrate how an intelligent interior space can select the best way to interrupt you depending on how important your task is and what modality is most effective.

Local Lifecycles

Local Lifecycles are possible if products can be produced:

- where they are used
- on demand
- variably
- and recycled locally.

The industrial revolution was able to produce a great number and variety of goods by centralizing manufacturing away from the point of use. In turn, this has led to pollution and waste as goods are produced and transported several times before their point of use, and then again after their useful life is over. New manufacturing and materials are making it possible to produce a wide variety of goods in a local setting. Rapid prototyping has led to a number of different products already affordable by research laboratories and educational institutions [Stratasys, Z Corp.]. These employ sophisticated modeling and fabrication to produce accurate, complex forms in small quantities over large periods of time. Neil Gershenfeld suggests that in the future, "personal fabrication" devices will allow people to produce many types of products locally by downloading the design information and 'printing' products at home [Gershenfeld]. While provocative, the idea of locally producing complex goods containing circuitry, optics, and mechanical actuation is far from possible. The objects we can currently produce are homogenous lumps of paper, plaster or plastic and require intensive training and post-processing. In a way, these systems have evolved little from the original rapid prototyping methods, in which highly skilled craftsmen used clay and other locally available materials to make everything from cars to pre-historic dishware. These objects cannot be recycled locally in the same way that they are produced, and are still limited in their variety. On the other hand, they prove that computer control allows for far more rapid and precise manipulation of materials in smaller environments.

"Cradle-to-cradle" manufacturing has been proposed to describe product design that consider the entire life-cycle of a product [McDonough]. One of the lessons of this theory is that "trash=food:" the end of a product's life should be designed to serve as the beginning of another. This is even more useful if it can be achieved locally, for example if a biodegradable soda bottle contains a flower seed and will actually beautify the landscape when thrown out of an automobile window. Bill Stumpf (designer of the famed Aeron chair) proposed a 'Metabolic House' that is capable of digesting its own waste through an architectural digestive system [Lupton]. This idea harkens back to an agrarian existence where the means to make food and goods was local, albeit limited.

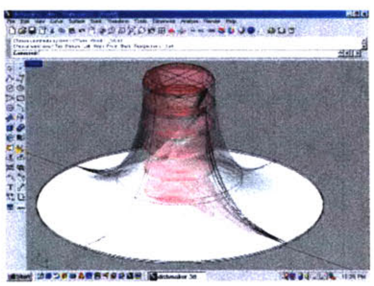
By combining the idea of personal fabrication with the "trash=food" philosophy, we can begin to design appliances that produce consumer goods locally while designed to re-cycle them into new, useful products. Rather than tackling the programmed obsolescence of electronic goods, we can make a much bigger dent in the way interior spaces are used by variably producing simple items we use in large quantities and devote considerable storage to.

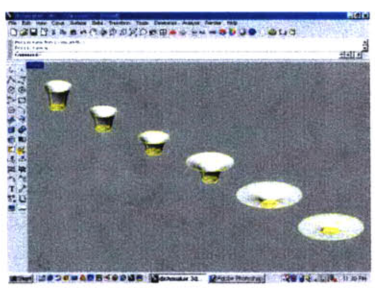
DishMaker

Our homes are cluttered with staples that we collect in case they one day serve their purpose. Dishes in the kitchen are one example of an object that actually wastes energy by having a long product life. Aside from the cost of production of infinitely durable plates and bowls, dishes require frequent washing for the duration of their lives – not to mention storage with its associated materials and space. By targeting this specific problem in the kitchen, the *DishMaker* project seeks to produce a personal fabrication interface capable reducing the amount of things we live with. The scope of the idea is to obtain new dishes on demand for eating and to be able to recycle them back into the system. The term "dishmaker" was chosen to reflect the potential to replace a large part of what a dishwasher does with a more fundamental recycling effort. The mechanism it produces plates, bowls and cups that can be used for eating. It recycles them so that they can be reproduced for the next meal. By storing the dishes in their raw material, the *DishMaker* seeks to eliminate clutter as well as to replace storage space with production space.

Dish Maker Implementation

When discussing dream kitchen projects in a meeting of the Counter Intelligence Special Interest Group of the Media Lab, Barbara Wheaton[4] expressed the desire to throw away dirty dishes after each meal and get new ones for the next. I interpreted her wish as a micro-factory capable of variable production and recycling within the envelope of a conventional kitchen appliance such as a dishwasher. Theoretically, such a device could replace part of the cabinets and dishwasher since the material would return to storage in its raw form. The question was whether we could make a variable molding machine capable of producing multiple objects rapidly and recycle them for re-production. Unlike a rapid prototyping machine, this micro-factory would have limited variability but unlimited speed and volume. In addition, it would have to recycle the products indefinitely.



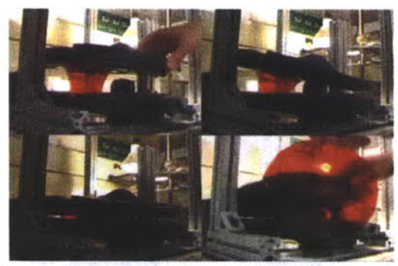


Early studies of the geometric family of dishes ranging from glasses to plates.

Fortunately, dishes are not as variable in form as typical rapid prototypes. The geometric family of concave, waterproof containers can be produced in a number of ways. Ted Selker suggested a pottery wheel-approach whereby a robotic arm could throw clay on a robotic pottery wheel. I formulated several polymer-clay

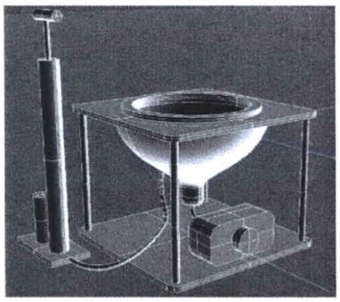
[4] Barbara Wheaton is a culinary historian and Honorary Curator of the Culinary Collection of the Schlesinger Library at Radcliffe College in Cambridge MA (USA). She advised the Counter Intelligence project from its inception in 1998 until 2003.

composites for this purpose, but the need to melt and mold molten plastic complicated the device into a small injection-molder with high energy consumption unsuitable to a non-industrial setting. If recycling requires that a solid material be melted and subsequently re-cooled, the energetic expenditure is only reasonable at an industrial scale. Acrylic and other amorphous polymers have "shape memory," meaning that under certain conditions the material returns to its original form [Choi]. This property eliminates the need to melt the plastic, reducing the energy consumption of forming and recycling dramatically (10X). Runye Zha and I showed that wafers formed to variable depths could be recycled many (30+) times in a sandwich press under slight heat and pressure. As proof of concept, I bought an electric sandwich press and placed formed acrylic dishes in it at low heat. The heat and weight of the press has a miraculous effect on the plastic: for the first minute nothing happens, and then the plastic starts to buckle. During this process, the material is actually behaving elastically: the walls of the dish thicken and return to their original form, a 6" diameter acrylic wafer 0.063" thick. What's more, the optically clear acrylic remains as clear as it originally was for multiple deformations. During a typical open house at the Media Lab, I would demonstrate the *DishMaker* by loading a single puck and repeatedly forming and recycling it for up to 4 hours. The material does not degrade unless the system malfunctions and it burns or is broken. This is the results of the glassy structure of the cast acrylic, which is



A proof of concept of recycling dishes: a conventional sandwich press was used to apply low heat (~300F) and slight pressure to return the 3" deep bowl to its original flat form in ~90 sec. Note the optical clarity of the recycled plastic puck (lower right).

inherently amorphous. Such amorphous polymers are often transparent, and the non-crystalline arrangement of the polymer chains leaves cross-linked areas. Elastic materials (rubbers) are cross-linked, and it is these links between polymer chains that return the material to its original form after repeated deformations. The acrylic used in the *DishMaker*, on the other hand, can only be deformed elastically under slight heat. Although it holds a new form when cool, the application of heat again returns in to its original form. This can happen repeatedly so long as the material is not broken or deformed beyond a certain amount. In our experiments, a 6" diameter puck could be formed as deep at 6" and return to being flat and optically clear. More complex or deeper forming might break cross-linked polymers chains to the point that the material does not recover.

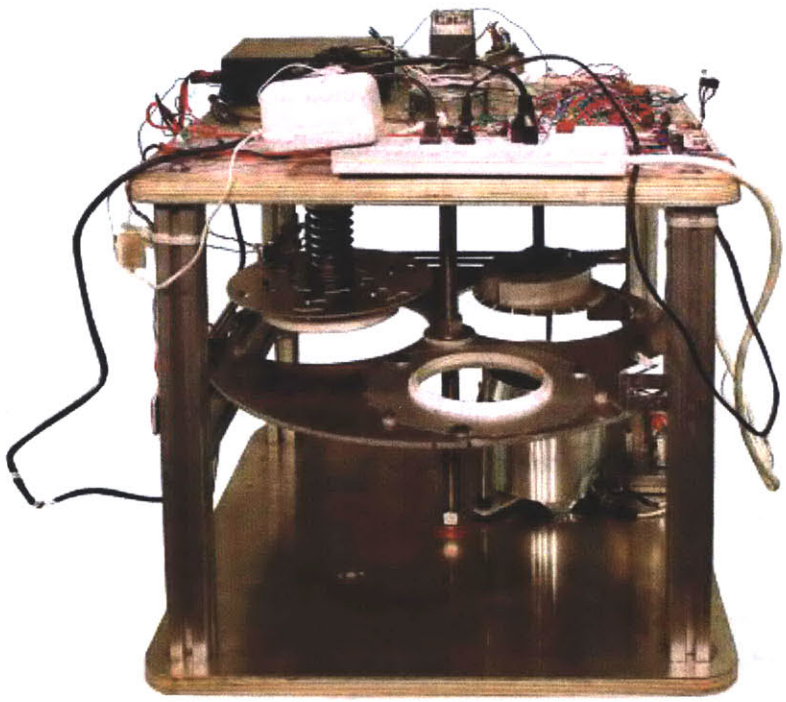


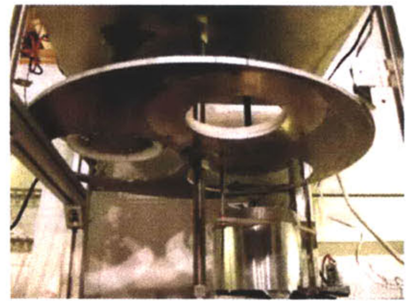
The original design for DishMaker 1.0 – a conventional reflector lamp with custom seal and a bicycle pump.

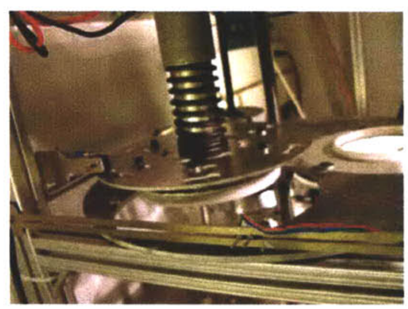
DishMaker 1.0 inflating a plastic puck.

The first dishes produced by DishMaker 1.0.

Next Sam Sarcia and I built a blow-molding *DishMaker 1.0* capable of using air pressure to blow vessels of various depths. The device consisted of a heat lamp and specially designed pressure housing. Although compact and simple, *DishMaker* 1.0 required a compressor and was thus unsuited to a typical kitchen. The problems of how to load material and take it through the various stages had yet to be considered. We then designed constructed a machine the size of a dishwasher that can stamp, dispense and recycle plastic pucks into dishes of various sizes with simple components already found in most kitchens: electric motors, heating coils, and micro-switches. *DishMaker 2.0* contains forming and recycling stations on a rotating platform in an enclosure the size of a dish washer. The appliance uses sensors to measure heat, the position of parts of the mechanism and the state of the dish. It is controlled by PIC microcontrollers and powered by electric motors and heaters. The machine can produce one dish every 90 seconds and recycle it into different dishes.

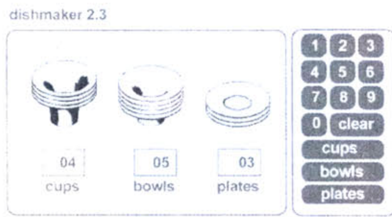






Dish Maker 2.1 personal manufacturing appliance showing three-stage circular platform with loading station (front) heating/recycling (right) and stamping (left) as well as control hardware (top).

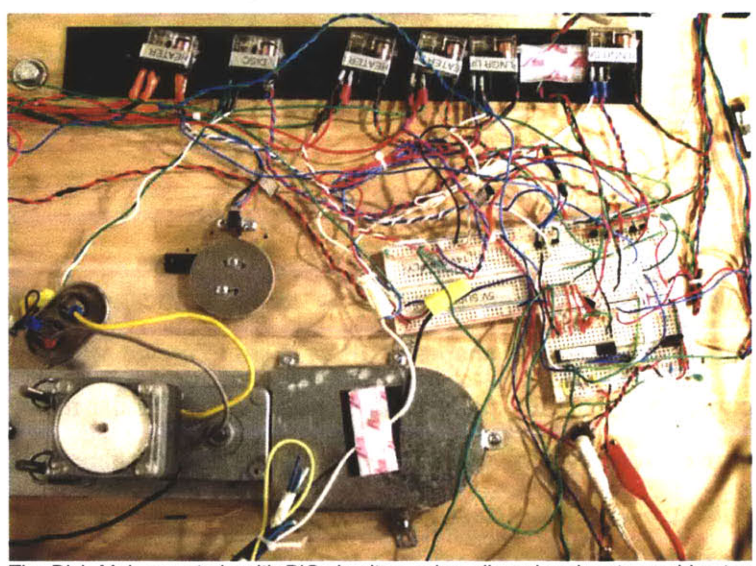
The interface design approach is to let a meal planner choose from several shapes to allow them to create as many cups, bowls, dishes, plates as the need for a particular meal. Our current system makes a variety of convex shapes all with a 6-inch diameter. Figure 6 shows the interface that replaces digging through cabinets for dishes. Subodh



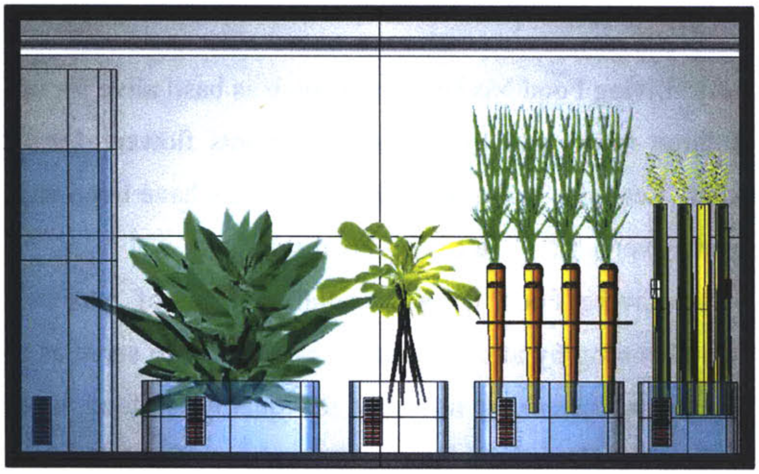
The touch-screen interface for the *DishMaker* .

Paudel built the control system for the *DishMaker*, which is based on a factory where the machine has to be careful not to destroy itself. The PIC microprocessors that control the actuation and heat are driven through a GUI on a PC. The interface is a touch screen with a microwave-style command panel that offers users the ability to choose an indefinite number of cups, bowls, and plates.

Several visitors to our lab have eaten from freshly stamped dishes and subsequently recycled them. Although the heating process helps to sterilize the dishes, food particles must still be removed by some other mechanism. In the short term, a *DishMaker* could vastly reduce packaging waste in a localized business like a supermarket, convention hall or ballpark. Future work will seek to increase the variability and quality of dishes while reducing the energy and time required to make them. Ideally, the *DishMaker* will become an all-in-one cabinet that contains anything you need, produced the moment you reach in.



The Dish Maker controls with PIC circuit on a breadboard and motor and heater relays (top).

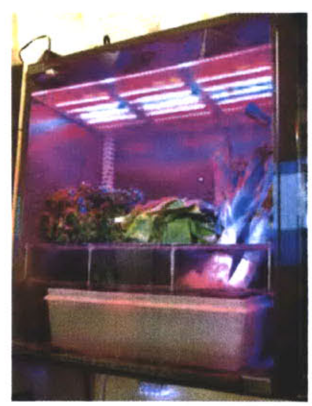


Living Food

Mr. Basil, the first prototype of Living Food, is a blender-sized acrylic tube with LED array (top) and plant gel reservoir (bottom).

While storing seldom-used dishes is a problem, at least the dishes do not degrade while in storage. Much of the food we buy, on the other hand, not only takes up space to be stored but eventually decomposes. Living Food is a project that seeks to replace a part of the refrigerator with a controlled micro-climate in a conventional cabinet that not only preserves but resuscitates and grows store-bought herbs and greens such as basil, scallions and lettuce.

Living Food contains nutrient solution that is misted on rootless greens while LED-based lighting showers the leaves with tropical-intensity light 12 hours a day. To efficiently produce such high-intensity illumination, I designed arrays of blue and red LEDs that provide the optimal absorption wavelengths (~475nm and ~650nm) for the green plants [Goins]. A cloth mesh secures the plant roots without promoting rot, as cyclic mistings keep the plant nutrified but not wet. For plants such as scallions that are purchased with roots, a plant gel polymer can be used to directly feed the roots and keep the plant growing [Plant



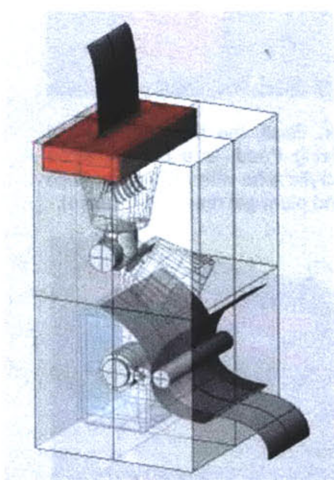
The second prototype of Living Food is a cabinet with LEDs (top) mesh plant holder and misting reservoir (bottom).

Gel]. Living Food has kept plants such as basil alive for up to three weeks and even made the plants flower after a point. Scallions and other plants with roots have lived and grown over a month in Living Food storage.

Ted Selker's baby-spraying alternative to diapers as appeared in the New York Times Magazine.

Living Food is as an agrarian form of personal manufacturing by allowing any interior space to serve as a mini-farm, increasing not only the quality of food in a kitchen but also of the interior atmosphere. One idea that has not been implemented is to create a duct so that CO_2 released by a stove can be vented to the plants to increase their growth. Such systems could also be included in modern HVAC to act as natural filters that not only clean pollutants but oxygenate interior atmospheres.

Future Directions



Design for a paper recycler showing shredder (red) and rollers (dark gray).

Personal Manufacturing promises to liberate interior spaces from the tyranny of storage by producing a variety of goods on demand and recycling them locally. Ted Selker has proposed an alternative to diapers for babies that consists of a low-temperature plastic fabric that can be sprayed onto babies and recycled at the end of the day. The idea could be extended to clothing, towels, utensils, even tools and personal electronic devices that could be produced as needed and disposed of by being recycled into a newer model. The DishMaker and Living Food suggest that local lifecycles are only possible with a limited variety of products or for a limited time. But products can remain useful even if they need to be down-cycled locally. One such idea is a local paper-recycling machine that could be used in offices and restaurants to locally recycle waste paper into useful cast pulp objects such as cups, coasters, and even furniture. Materials can have multiple life-cycles, even if they are "down-cycled" (reduced in quality by mixing), saving the expense of transporting them to and from central production and recycling facilities.

Attentive Displays

The decrease in price of projectors and large displays is making it possible to distribute information throughout an interior space. Once the surfaces and objects of a space can change appearance, what kind of information can be communicated at an architectural scale? Contemporary architects and designers have suggested that architectural-scale displays behave as larger versions of televisions and computer monitors. But the amount of information that can be displayed far exceeds the capacity of people in the space to perceive it. Important, task-based information should be shown in an intuitive way right where people are looking; whereas less pertinent information can be revealed in non-intrusive peripheral displays. When any surface can be covered with information, the information should shrink or grow depending on what is important. Attentive displays are room-sized displays designed for the attention of users and themselves attentive to the behavior of people. Head-worn displays and CAVEs can create immersive new environments, while active workspaces can augment everyday tasks. Intelligent interiors with ubiquitous attentive displays can respond to the behaviors of people in a space so that important information is prioritized based on an understanding of the user's performance. Chia-Hsun Lee and I designed an intelligent kitchen built and evaluated over two iterations by a multi-disciplinary team. Studies of this intelligent kitchen reveal that spatial annotation performs well for intuitive ambient displays such as immersive textures or one-to-one projection; but

Attentive Displays are spatial annotations based on users'

- perception
- comprehension
- performance

In Hariri and Hariri (above) and LOT/EK (below) architectural surfaces are used as immersive video screens.

treating the surfaces of a space as computer displays was not as effective as giving people a hand-held version of a recipe. It is becoming possible for these environments to easily enrich everyday activities with enhanced sensory feedback.

Related Work

A CAVE (CAVE Automatic Virtual Environment) is a cubic room where the floor, ceiling and walls can be rear-projected so that a user can experience a wide variety of immersive scenarios [Cruz-Neira]. Used primarily for scientific simulations, CAVEs can dynamically generate believable views by tracking the head and eyes of someone inside. Virtual Reality such as is achieved in a CAVE can also be accomplished by head-mounted immersive displays. But CAVEs and Virtual Reality are not suitable for real spaces that contain other people or objects. Augmented Reality (AR) overlays digital information onto the real world through head-mounted displays. Although wearing computerized goggles is unnatural, AR can be used to help people understand and learn complex tasks such as industrial processes or medical procedures [Feiner]. The *Everywhere Display* is a multimedia projector with a computer-controlled mirror that can project information on many of the surfaces of a space, but it can only project in one location at a time [Pinhanez]. One kitchen of the future uniformly tiles the backsplash with high-resolution LCD displays [Mori]. But indiscriminately plastering the environment with video-quality information could overwhelm people and their attention. Vertegaal and Selker suggest *attentive interfaces* where the displays in a room decide what to show based on models of the user's attention [Vertegaal]. These systems are usually based on the displays knowing where people are looking through eye-tracking technology. *Attentive Displays* operate at an architectural scale where it is possible to infer sufficient information about where a user's attention is from their location in a room.

Once all the surfaces and objects of an interior space can become information displays, what kinds of information should be displayed? *DigitalDesk* and the *DigitalDesk Calculator* demonstrate that real work can be augmented by computers; for example when a camera detected that numbers were being written by hand a virtual calculator would be projected next to them on the desk [Wellner]. *CounterActive* teaches people how to cook by projecting an interactive recipe on a kitchen counter embedded with a capacitive touch-sensitive array [Ju 2001]. One advantage of these real-world task-based systems is that information can be projected directly where the task is being performed. For example, in Microsoft's version of *CounterActive*, users measure out flour by pouring it onto a projected circle until it is completely covered [Microsoft]. Mapping information onto tasks directly at a one-to-one scale can seamlessly augment physical work.

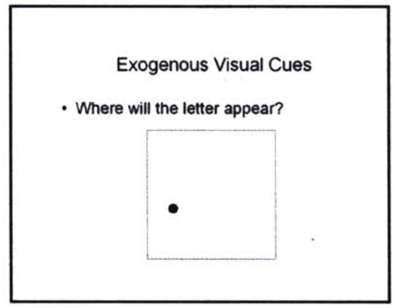
Wendy Ju's CounterActive demonstrates how digital projection can augment the cooking experience.

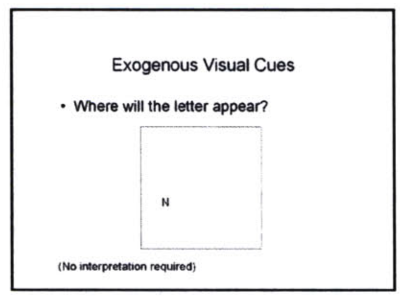
While task-specific information can be useful to project where the task is being performed, it can also be useful to project some kinds of information at the periphery of a user's attention. Ambient displays seek to display information throughout the built environment in a manner that does not tax the attention of users. *Windmills* and the *Stock Orb* are two systems that display a limited amount of information in the form of decorative objects [Ishii 2001, Ambient Devices]. The windmills are simple paper fans that turn fast or slow depending on the speed of traffic on a network. The Stock Orb is a ball that glows different colors to reflect market performance. The aim of ambient interfaces is to communicate simple information in a non-intrusive way. Ambient displays can also be counter-intuitive: for example, the Orb requires users to know that its color refers to stock market values and that red indicates decreasing market performance while yellow indicates no change. On the other hand, the real world is full of ambient displays that communicate information intuitively and non-intrusively: a window can let us know the weather and the time of day; the drip-drip of a faucet reminds us to turn it off, etc… *InStink* utilizes computer-dispensed perfumes as an ambient interface that maps information in a more direct way: the smell of food can remind someone to go home where dinner is being readied. Ambient displays that overlay intuitive sensory information on everyday tasks can act as cognitive prostheses, revealing more about the world without burdening a user with artificial modalities [Kaye].

Ambient Devices' Stock Orb is a beautiful self-illuminating blob that conveys information about the stock market if you can interpret it [ambientdevices.com]

Jofish Kaye demonstrating his olfactory display [jofish.com]

Attentive Displays seek to combine the usefulness of AR with the attention-based design of Ambient Displays. Chia-Hsun Lee and I designed and evaluated a number of *attentive displays* in a real-world kitchen. The *GUI Kitchen* can coordinate the multiple events that take place within, from people working and playing to the autonomous behavior of the stove, dishwasher and refrigerator. How can all of the users of a kitchen be made aware of the many visible and invisible operations under way in the kitchen? Various projection techniques are suited to different scenarios in a graphically annotated kitchen. For example, water temperature can be usefully inferred from the simple projection of colored light – red for hot and blue for cold. Full-color images can be a simple way to describe the contents of a refrigerator. We have proposed a series of interfaces that project attentive task-based interfaces onto the refrigerator, cabinets, countertop, even the water and food being prepared. Two iterations were designed and evaluated: The GUI Kitchen and Cooking with the Elements. These projects and the results of evaluations will be presented after an introduction of the concerns behind the design of attentive displays.

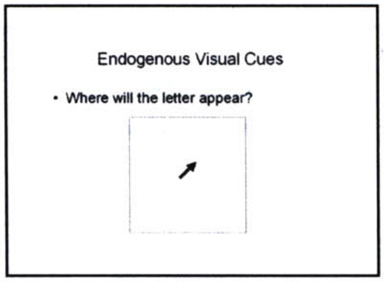


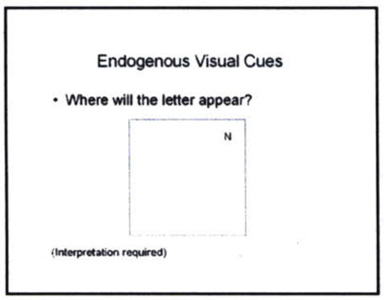


Example of Exogenous Attention Cues: these slides are shown in succession from top to bottom, with the attention cue (dot) appearing exactly where the information (letter) will appear, directing attention without requiring interpretation.

Perception

Attentive Displays are responsive to the attention of users in the space based on sensor feedback that reveals the position and activity of people. At the same time, to be effectively designed these displays need to operate at a cognitive level that matches the scale of architectural space. In large immersive environments, information that is far from a user or behind them needs to attract the attention of users or interrupt them from their task. Once a user has determined that a display merits their attention, he/she also needs to be able to comprehend the display intuitively. This section deals with perception, comprehension and performance as crucial design considerations for *Attentive Displays*.





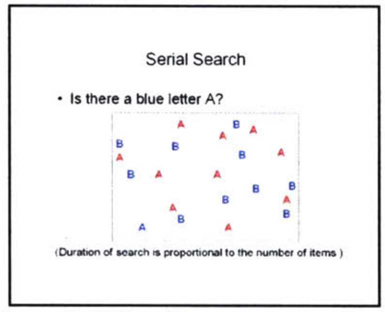
Example of Endogenous Attention Cues: these slides are shown in succession from top to bottom, with the attention cue (arrow) requiring interpretation to direct attention towards the target (letter).

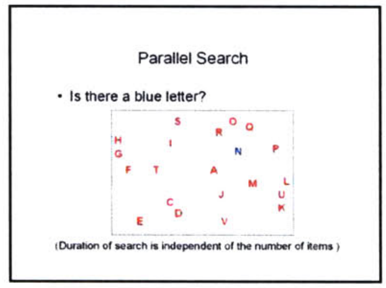
Attention Cues

While people may be familiar with a given interior space, they often leave things unattended or lose track of their activities through sheer absent-mindedness. Attention cues are an effective means of re-directing the attention of people in a visual space. Two types of cues exist: Exogenous and Endogenous. Exogenous cues require no additional mental processing to direct attention, for example a flashing red light on a bicycle which indicates where the cyclist is located. Endogenous Cues are less direct and require interpretation to direct attention, for example an arrow pointing to an object of interest. Throughout the design of *attentive displays*, exogenous cues are preferable because they provide direct feedback and require very little interpretation to direct attention. Endogenous cues are employed only when a user is not responsive to exogenous cues such as when the object of interest is obstructed or outside their visual field.

Visual Search

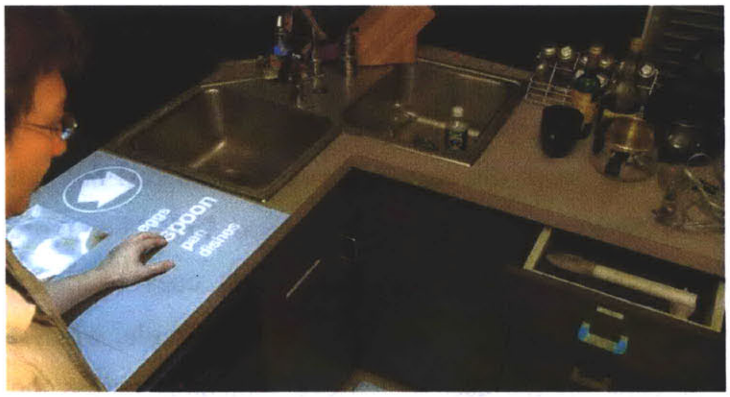
Visual Search refers to the ability for someone to discern one object among many. Two types of visual search exist: Serial and Parallel. Serial Visual Search refers to a typical search where the time required to find an item is proportional to the number of items being searched among (ie. a needle in a haystack). Typically a search of this type results from the items being hard to differentiate. A Parallel Visual Search refers to a search where the items being sought 'pop out' from the rest, and thus search times are fairly constant regardless of the number of items being searched. In the design of *attentive displays*, 'pop-out' is often employed to distinguish the item of interest through self-illumination, such as with the *Heat Sink*. For more complex tasks, we employ endogenous cues to direct attention as efficiently as possible. For example, when a recipe calls for the user to retrieve something across the room, we project the recipe in front of the user, an endogenous cue (like an arrow) mid-way between the user and their task, and finally an illuminated drawer handle where the user needs to place their hand to retrieve the object.





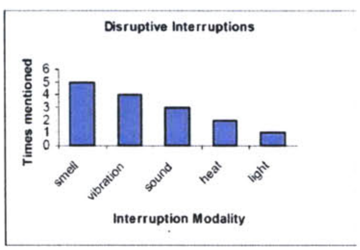
Examples of Serial Search (above) and Parallel Search (below) showing how "pop-out" can be used to shorten a search regardless of the number of items searched.

Augmented reality projection can show information and project interfaces directly on the task being performed. This type of exogenous attention cueing requires the least mental processing. In the case of the faucet, the temperature is projected as a simple color on the water itself, eliminating the need to look at the faucet handle. For more complex tasks, endogenous cues are used to direct attention. For example, when a recipe calls for the user to retrieve something across the room, we project the recipe in front of the user, an endogenous cue (like an arrow) mid-way between the user and their task, and finally illuminated drawer handle where the user needs to place their hand to retrieve the object. Even practiced users of the space might experience a reduced reaction time and more confidence when the objects to concentrate on are illuminated.



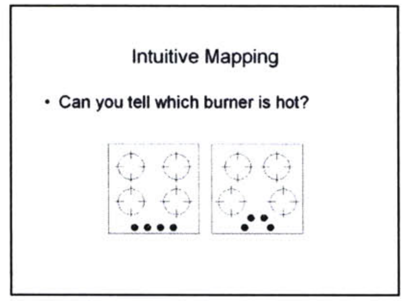
Where's the spoon? An example of endogenous cueing (left) and exogenous cueing (right) in the GUI kitchen.

Interruptions



Disruptiveness of various interruption modalities [from Arroyo 2002]

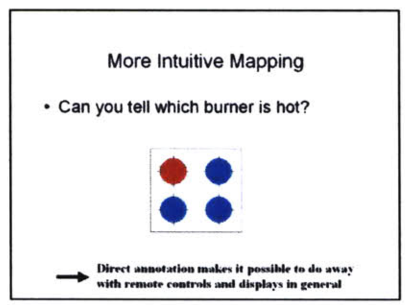
When someone has to be alerted to something, they have to be interrupted from their current focus of attention. In order to be effective across a wide range of applications such as found in a modern interior space, multi-modal interruptions are necessary. Modes are simply different sensory channels (sight, sound, touch, temperature, smell, etc...) each with its advantages and disadvantages [Arroyo 2002]. For example, a sonic alarm is very effective to wake people up from sleep but is probably overkill to communicate the weather. In a study of the effectiveness and disruption caused by multiple types of interruption, smell was determined to be the most disruptive while light was the least. When designing interruption and communication modes for interior spaces, ambient conditions are crucial: for example, a voice-activated kitchen may work very until unless there are multiple people cooking at the same time. Smell can be the most disruptive interruption, but only works in the absence of the ambient aromas that are part of the cooking process. *Attentive displays* seek to vary the modality user to interrupt users depending on their performance, so that a new modality can be used if a user does not notice the previous or if their performance degrades.



Slide adapted from Norman showing how remote controls can be designed to provide intuitive mapping, for example knobs on a range. While the design on the right makes it easier to understand which knob refers to which burner, it is still counterintuitive to find out which burner is hot.

Comprehension

Once a display can attract the attention of a user, it should communicate the information as simply and intuitively as possible. *Design of Everyday Things* demonstrates how the placement of knobs on a range should be intuitively designed [Norman]. On several occasions during the design of the interfaces for this thesis, people have asked why we need intuitive interfaces in our homes since we already know them intimately and we are accustomed to their idiosyncrasies. Norman makes the point that interfaces should be intuitive to prevent mistakes and make people feel a sense of control. We extend the list of reasons to include the fact that many times only one or two people in a space are actually responsible for spaces like the kitchen, and that the obscurity of many procedures can be socially exclusive. Many of these problems occur in the design of intelligent interiors because controls and indicators are often located remotely – how often do we fumble for light switches and thermostats or turn on the wrong burner? In our case, we encountered many problems



With *Attentive Displays*, information can be located where it refers to and intuitively interpreted.

because the Media Lab is peculiarly multi-cultural, and different people use kitchens very differently. Not only should interfaces be intuitively located, but whenever possible their content should be understandable regardless of someone's cultural or educational background. With our ability to directly annotate objects and spaces through projected information, we can extend this example so that the information is intuitively located *and* intuitively interpreted.

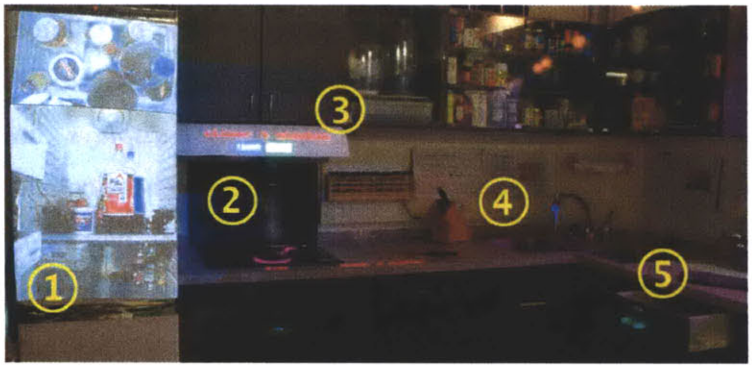
Performance

As Wendy Ju noted in her discussion of the *CounterActive* system, a truly intelligent recipe would also be able to follow up on the performance of its users[5]. The *Intelligent Office* demonstrated that a number of sensors distributed throughout interior spaces can accurately determine the number of people and their positions to offer several kinds of hands-free automation [Coen]. When he walks in to the room, the central computer recognizes him and – using voice as a primary medium – can open the shades, turn on music, display information on the wall. When he lies down motionless, lights dim and the shades draw while soothing music plays. In more task-based spaces, performance-based displays can respond to the attention of users within. *EyeAre* uses head-mounted infrared transmitters to activate displays where a user is looking while de-activating ones that are deemed less interesting [Selker 2001]. In a more

[5] "The user testing suggests, however, that to really teach cooking and provide adaptability, the CounterActive system needs to detect the user's actions." From Ju, W. "The Design of Active Workspaces" pp. 45.

subtle example, Orit Zuckerman's *Moving Portraits* reveal more about their subject if a user stands in front of them for a certain time. A simple proximity sensor can inform a display as to the presence, and therefore the likely attention of a viewer. This could easily be translated to the design of interior spaces: imagine that when the space notices you are standing in front of a machine for a certain amount of time, it can give you advice on how to use it. In *Attentive Displays*, multi-modal interruptions are triggered seek to remind you of tasks you have put off – for example, setting the water to boil or the oven to pre-heat before other tasks.

Distributed sensors in an intelligent interior space can measure your performance as well as inferring your attention. Depending on the space, proximity sensors can infer the task being performed and the number of people in the room. Imaging-based sensing using cameras and thermal imagers can be useful in distinguishing between tasks in a single place or measuring the performance of tools and people in places like the kitchen or bathroom. The sensors can even be distributed throughout the space to keep track of inventories and maintain appliances and services. In the design of intelligent interiors, distributed sensors serve to assist and orient people and make them aware of the status of tools and surfaces in the space.

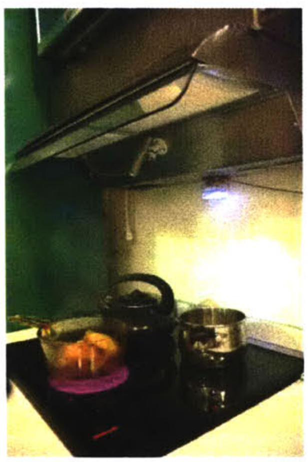


Augmented Reality Kitchen: information projection on the refrigerator (1), the range (2), the cabinet (3), the faucet(4) and drawers(5).

The GUI Kitchen

Domestic kitchens are technologically integrated laboratories where multiple users carry out different, complex tasks with numerous tools, work surfaces and appliances. The tools of the kitchen are numerous and complex, often requiring instruction before they can be used. The appliances rarely provide feedback on their status or prompt users for interaction. The kitchen is a dangerous environment where lack of information about the status of tools and surfaces can result in burns or cuts. Kitchens are natural candidates for augmented reality interfaces because there is a high need for users to remain in contact with physical reality while using a number of sophisticated tools that benefit from digital information []. The augmented kitchen assists users in determining temperatures, finding things, following recipes and timing various steps of preparing a meal. Useful information can be overlaid on nearly every surface of the space without interfering with their functions. In each case, the quality and quantity of information projection needs to be tailored to the amount and type of attention directed at each task.

The first iteration of *attentive displays* in emphasizes the concern for perception, comprehension and performance-sensing. Projectors and other types of illumination are dispersed throughout a kitchen to uncover the range of interactions possible between the kitchen and its users. Various input devices coupled with the projectors inform the projected content. Textual annotations are projected on the entire working environment. The refrigerator is "painted" with text and images to describe its contents and the items that need to be purchased. The electric range informs users on the temperature of its burners. A single multimedia projector can position the information directly on all of these appliances, where users will be certain to notice it. The same system used to annotate the kitchen can be used to decorate the space. Games and other interaction can be projected on work surfaces when the work is finished, while decorative textures can be mapped to change the mood and function of the space depending on its function.



In the RangeFinder, an infrared thermometer mounted in the hood measures the surface temperature of food. In one demo, the temperature is projected directly onto the food being cooked.

RangeFinder

RangeFinder is a remote infrared thermometer that measures the surface temperature of food in pans on the range and projects the food temperature and cooking time directly onto the cabinet, counter, cookware and the food itself. *RangeFinder* can determine when food reaches a desired temperature (for example, when water boils or when meat is cooked) and time the duration of the state, eliminating the need for to set a separate timer or use a thermometer. In addition to cueing recipe steps, the temperature information is displayed numerically on the cabinet in front of the user as well as onto the range itself. *RangeFinder* is a modified commercial infrared thermometer mounted inside the range hood that communicates to a PC running Virtual Recipe through a PIC-based microprocessor.

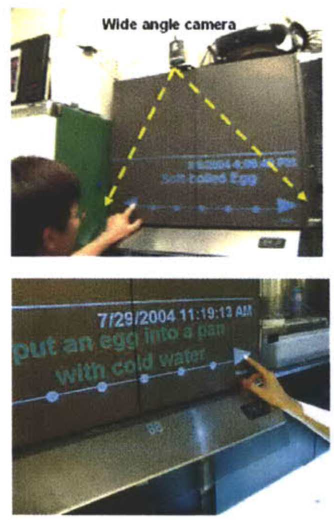
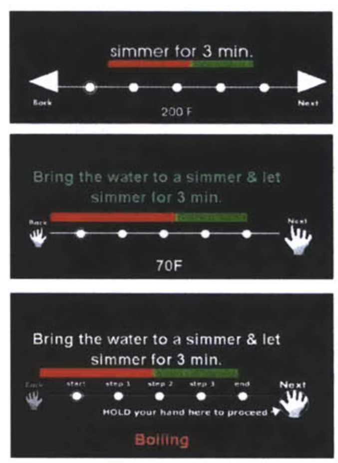


Figure 3. Virtual Recipe projected onto the cabinets and Rangefinder temperature on the hood.

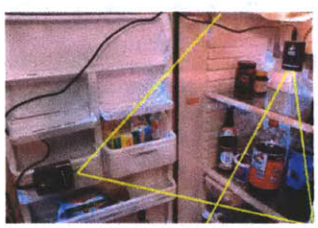
Virtual Recipe

For user evaluations of the Augmented Reality Kitchen, the system guides users through a step-by-step recipe inspired by the instructional methods employed in *CounterActive*. Instead of being projected on the countertop alone, two multimedia projectors display recipes on the cabinets in front of users as well as on the work surfaces of the range and counter. Users navigate the steps of the recipe by passing their hand in front of projected "virtual buttons" interpreted through a vision recognition algorithm (C++ program in Microsoft Vision SDK). Users with wet or dirty hands don't have to touch any surface as webcams detect the change in appearance of the buttons when the hand passes over them. Infrared proximity sensors along the edge of the countertop determine the location of users and help to project the *Virtual Recipe* directly in front of them. When a certain step calls for an item stored in the cabinets, the *Virtual Recipe* cues the appropriate drawer handle to illuminate.



Evolution of Virtual Recipe GUI design

Five initial users were shown the projected recipe instructions in the space to determine if they were capable of following them. Traditional elements of GUI design did not work in the augmented reality projection. For example, the arrows that typically indicate navigation did not make themselves understood immediately to pilot study users. Successive design iterations replaced the arrows with hands and finally added textual instruction to make the interface self-evident. Together with the virtual button interface, we played audio feedback to indicate that the button was successfully depressed. By the end of these pilot studies, the *GUI Kitchen* performed as well as a paper recipe in guiding users to a successful conclusion.



FridgeCam showing the tiled projection of front and top views on the door of the refrigerator (top) and camera placement (below).

Xray Fridge

Users of a kitchen often open the refrigerator too often and for too long because they are unsure of its contents or layout. *Xray Fridge* is an augmented reality interface that projects spatial information about the contents of the refrigerator directly onto the door for the purpose of reducing the duration and frequency of door opening. By capturing different views each time the refrigerator door is opened and projecting an image on the outside of the door, *Xray Fridge* helps users locate refrigerator contents in three dimensions. *Xray Fridge* consists of two wide-angle CCD cameras mounted to the inside of the refrigerator that capture images when the refrigerator light turns on and projects them with a multimedia projector. The current *Xray Fridge* is limited to the vertical resolution of the multimedia projector that is shared with *Virtual Recipe*. Pilot studies reveal that a low-resolution display hampers recognition of the refrigerator's contents because users often feel more confident when they can read text on labels too small to be projected. The advent of high-resolution displays and projectors in combination with multi-dimensional projection like *Xray Fridge* will allow highly insulating enclosures such as the refrigerator door to perform better at helping users find items than transparent doors.

Augmented Cabinetry

One of the most time-consuming tasks in a kitchen is finding items in cabinets, when multiple people share a kitchen. While transparent cabinet doors can help identify the objects near the door, they add to the visual complexity of the space and can actually increase search time by increasing the number of items in the visual search. Augmented Cabinetry is a spatial user interface that reduces the time required to locate items in the kitchen cabinets without adding visual complexity to the space. LEDs embedded in translucent cabinet handles illuminate on cue from the virtual recipe system. If the required items are located far from the user, the system cues the final location with an arrow projected midway between the user and the item in question. Information on the user's location is gathered by the proximity sensor array along the countertop edge. The cues are timed to provide as much information as required depending on the experience and

Augmented Cabinetry

performance of a user. In the beginning, the handles illuminate continuously. Next, they start to modulate in brightness. If the drawer is not yet opened, an intermediary endogenous cue is projected midway between the user and the drawer. Finally, a projection appears in front of the user indicating the direction of the item with text and an arrow. In this way an expert user does not encounter needless information. If the cue is urgent, an auditory warning sounds as the last cue. *Augmented Cabinetry* works by a hard-wired network of illuminating drawer handles controlled by a PIC-based microcontroller through the Virtual Recipe system on a PC.

First GUI Kitchen Pilot Study

The *GUI Kitchen* was evaluated in two pilot studies to determine how could actually help people cook better: recipe-based and meal-based. Chia-Hsun Lee and I asked people to carry out a simple recipe – soft-boiling an egg – and thereby interact with the refrigerator, cabinets, countertop, sink and range. The control group tried the same recipe using instructions printed on paper. Participants spent three minutes familiarizing themselves with the contents of the refrigerator and cabinets of the kitchen so that they were not strangers in the space. The experiment was designed to determine which interfaces were more useful than existing ones. Our hypothesis was that users would spend less time on steps of the recipe, and that they would feel more confident with the augmented kitchen because of the enhanced feedback of our interfaces.

In performing even the simplest recipe, there are countless steps involved. For example, the first step of soft-boiling an egg consists of many sub-steps: "put an egg in a pan and fill the pan with cold water" actually entails finding a pan, finding an egg, turning on the water, determining that the water is cold, filling the pan, and turning off the water. Each sub-step is actually subject to additional complication if, for example, the pan is hard to find. The GUI kitchen seeks to shorten these sub-steps by automatically providing feedback on the status of the kitchen. By visually communicating the temperature of the water, *Heat Sink* should eliminate the steps of touching the water and drying hands. By automatically measuring the temperature of the range, *RangeFinder* could eliminate the steps of observing boil, setting a timer and turning it off. *Augmented Cabinetry* should reduce search times, even for users familiar with the kitchen, by reminding people of the next step in the process. The *FridgeCam* could be used to look for items in the refrigerator without opening it.

An experimental group of 5 and a control group of 8 were asked to perform the same recipe in the same space with the same physical interfaces. The experimental group used the augmented reality kitchen with interactive recipe. The aims were to evaluate the system based on three criteria: the performance of the technology, the performance of the system, and the users' aesthetic perception of the system. Users responded to written to pre-test and post-test questionnaires and were videotaped to evaluate progress.

First GUI Kitchen Pilot Study Results

While not significantly faster than the control group for several metrics, the major results of the experimental group is that even with a small sample size a scenario laden with new and unusual tools performs as well as one that people are accustomed to. Both the timing of steps in the videotape and analysis of questionnaires showed no statistical difference between the augmented recipe and paper-based one, indicating that the novel system performs as well as the control. Only the Heat Sink and Augmented Cabinetry were shown to perform significantly better in questionnaires. The illuminated drawers showed a statistically significant improvement over control drawers (paired samples t-test $p<.05$). Users usually opened more drawers than we expected, because they were looking around the room and ignored drawers that were beckoning them with lighted handles below their waist. Future improvements we can make would be to draw people's attention with blinking illumination or sound. In the control group, users wasted more time on searching in vain until they found what they needed.

This pilot study revealed two major lessons: the advantage of exogenous cueing in locating items even in a familiar environment and the advantage of paper recipes over sequential, digital ones in allowing for a multi-tasking approach. New ambient displays like the *augmented cabinetry* and *heat sink* are intuitive and helped users feel confident in a strange new kitchen. The projection of text and images throughout the space, however, was confusing and inappropriate. Rather than behave as thinking beings, study subjects were reduced to a part of the machine forced to obey one step at a time. People given the printed recipe, on the other hand, were able to understand the scope of each step in relation to others and prepare themselves mentally with a goal in mind.

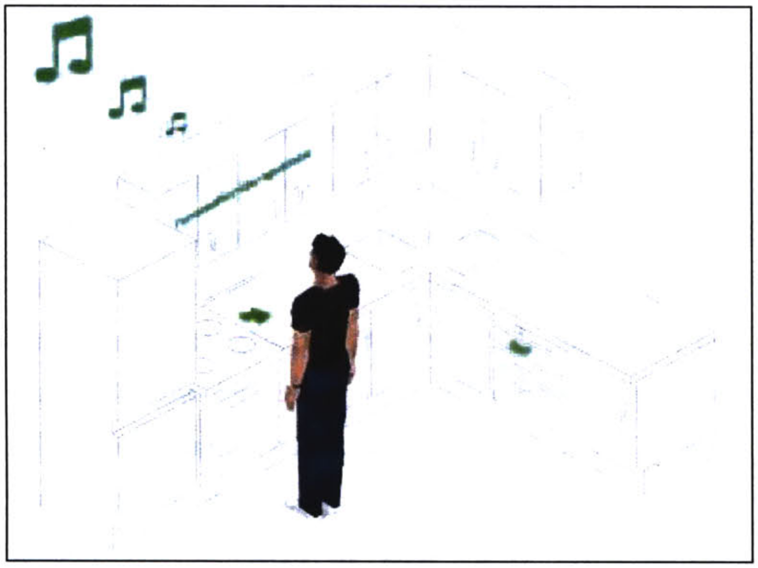
The design of this pilot study was largely to blame for its inconclusive results. The combination of multiple interfaces into a multi-step recipe made it was difficult to isolate the individual systems to find out which aspects were strongest. Each interface was discovered to have strengths and weaknesses from informal observation of the study:

- While the image of the refrigerator's contents projected onto the door in *FridgeCam* should perform as well as a glass door in helping people find items inside, it was significantly worse because of the resolution of the display. Users often identify ingredients by words on the label or other small features not discernable with the projector we were using.

-While the *virtual recipe* interface was self-explanatory, the use of step-by-step instructions (adopted from *CounterActive*) was limiting to users. Being able to read a conventional sheet of paper empowered them to plan ahead and multi-task in some cases, which inspired the design of the second pilot study. Furthermore, the large textual projections took some users considerable time to read versus paper instructions. This is because of resolution as well as field of view and the relative distance of the observer.

-Although the drawer handles illuminated to cue users' attention, often the user would still search in vain because the single modality was not sufficient to interrupt them. The next pilot study would use a multi-modal system to attract attention.

-The *Heat Sink* was the most successful interface because it was intuitive, could not distract, and was hard to compare to any existing display. The next iteration of the kitchen will be entirely based on the success of this simple ambient display.

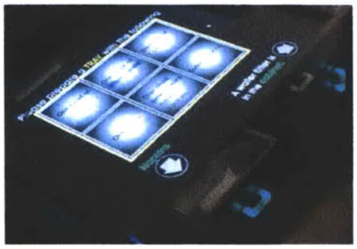


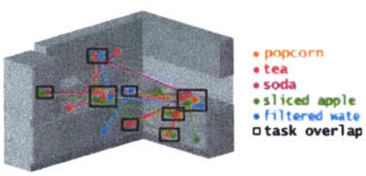
In the second users study, users were reminded with several types of attention cues: first, an exogenous cue like the drawer handle illuminating; then an endogenous cue like an arrow midway between the user and the task; often accompanied by text; finally a sonic alarm to interrupt them from the task at hand.

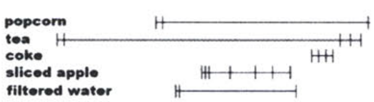
Second GUI Kitchen Pilot Study

To take advantage of the virtual recipe's ability to project information anywhere in the kitchen, Chia-Hsun Lee and I designed a study where computer-generated guidance would give a significant advantage over paper-based instruction. The second pilot study asked users to carry out multiple, discrete tasks akin to preparing a meal. They were asked to prepare multiple items for a snack tray, some of which required lengthy preparation and others which could be prepared instantaneously. The idea was to generate spatial instructions reminding users which item should be started first, and when multiple tasks could be accomplished at the same time. In addition, multiple modalities were used to attract the attention of users if they were lost or misdirected.

In the second study ten users were asked to prepare a snack tray, six with projected instructions and four with a paper list of items. Again, the study revealed more about its own design than the kitchen's. Although users with the projected instruction could achieve tasks more efficiently than with paper, the study's shortcoming was in assuming that people could achieve the same end with the same means. As it turned out, seemingly simple tasks like making microwave popcorn were new to some of our subjects; while others were so expert at orchestrating multiple tasks that they invented shortcuts we had not anticipated. The lesson of this study was that a truly augmented space should be able to suggest multiple ways of achieving a given task, based on the user's skill, location and performance. In the end, this study discouraged further attempts to improve efficiency and sent us back to the drawing board to develop interfaces that would be useful and understandable to anyone who uses the kitchen.





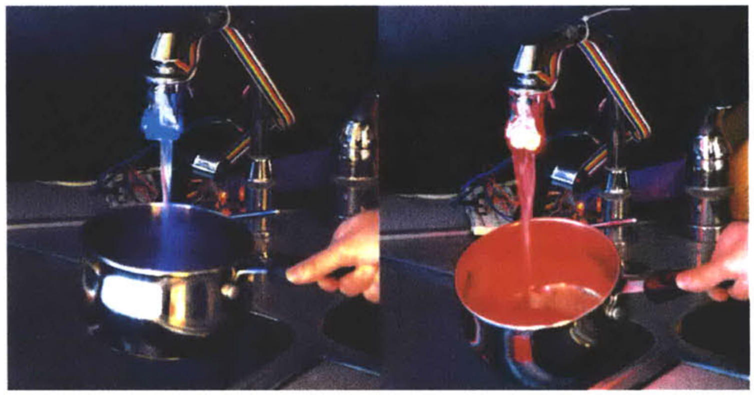


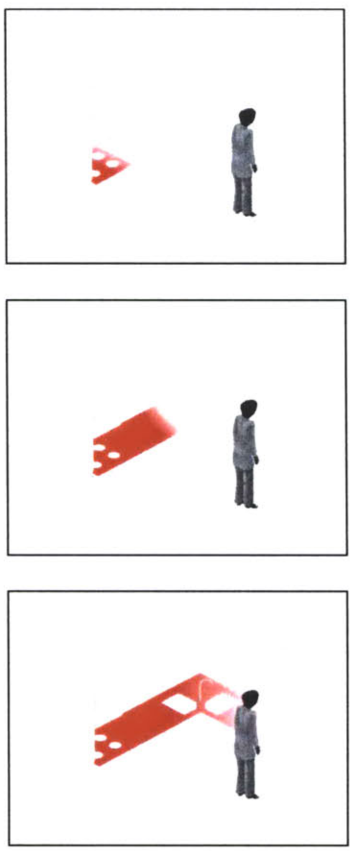
The second GUI Kitchen pilot study used distributed textual and graphical projections to direct subjects in the preparation of multiple items for a meal. Models of the preparation of each item (bottom) and its location in the space (second from bottom) were used to design spatial projections (top two images) to direct activity. The study revealed that large-scale text and graphics can be confusing and need to be combined more intuitive information and multi-modal interruption to work well for all users.

Cooking with the Elements: Multimedia projections enrich a conventional kitchen by projecting intuitive displays to reveal the status of tools and surfaces.

Cooking with the Elements

In the GUI kitchen, users had problems following complex multi-step instructions with the aid of augmented reality displays broadcast throughout the space. On the other hand, low-bandwidth colored illumination was useful in communicating information and directing attention. The successes and failures of the first two pilot studies encouraged us to build an intelligent interior space where displays were simple enough to be understood by anyone, and capable of adapting to the attention and performance of users so that they would be seen no matter where they are. Cooking with the Elements is an aggregation of *Attentive Displays* designed according to the perception, comprehension and performance of users in the space. These interfaces seek to combine the attentive design of ambient interfaces with the utility of one-to-one projected augmentation by overlaying an environment with intuitive, immersive information interfaces. Our test bed is a kitchen because it stands as the epitome of a feedback-less modern space. In Cooking with the Elements, a system of sensors and projectors was installed specifically for the purpose of overlaying the existing space with sensory feedback to assist and enrich the user's experience.

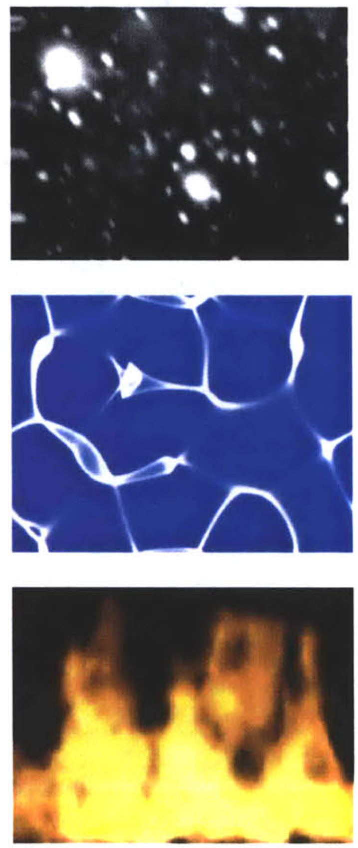




Attentive Displays follow a user who may be busy or unaware.

The original *Attentive Display* on which this study is based is the *Heat Sink*. Kitchen users have come to depend on remote controls and indicators to know the temperature of food and water or the status of the stove. *Heat Sink* is a simple solid-state circuit that projects colored light into the stream of tap water to indicate its temperature intuitively: red for hot fading to blue for cold. An early iteration of the *Heat Sink* mapped temperature to a full red-green-blue spectrum like the *Stock Orb*. The final choice of simple red and blue was based on the fact that people do not intuitively understand the temperature of 'green' water; their main concern is to determine whether the water is colder or hotter than their hands before touching it. By using various intensities of only two colors, *Heat Sink* displays only the minimum essential information and does not inconvenience the task at hand or require prior knowledge. Taking a cue from projected augmented reality interfaces, the projection of colored light directly into the stream proves more successful than remote indicators like the control knob because the information is overlaid directly on the user's focus of attention.

The modern kitchen is a technological marvel that combines the elements of fire, water, ice and earth in a compact hygienic space. Following from the *Heat Sink*, *Cooking with the Elements* maps intuitive multimedia textures to the countertops of a conventional kitchen to enrich and inform tasks in the space. Numerous researchers have demonstrated the ability of digital information to elicit physical emotions, such as icy images lessening the pain of burn patients. Common problems such as knowing if the oven is hot or keeping the refrigerator door open too long can be intuitively annotated with dynamic audiovisual textures projected onto the surfaces of the appliances themselves. Likewise, the countertop can serve as a control panel that communicates the status of tools and surfaces intuitively in response to where users are and what they are paying attention to.



Stills from the dynamic textures used to add sensory feedback to the kitchen in *Cooking with the Elements*.

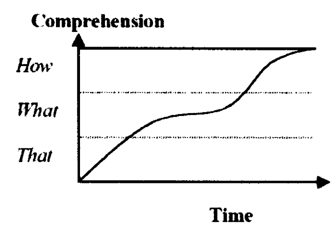
Cooking with the elements consists of inputs that measure the status of people and tools and outputs that turn the surfaces of the space into audiovisual displays. Three tiled multimedia projections seamlessly cover all the countertops and appliances of the kitchen. Proximity sensors situated along the countertop edge locate users while temperature and water sensors and micro-switches detect the status of the cabinets, countertops, sink, and appliances. A Macromedia Director movie is generated across the seamless projection to map the dynamic multimedia textures to the space. When someone opens the refrigerator, the sound of a cold wind plays and projected snow begins to accumulate as an indication of how long the door is open and the energy wasted. When the electric range is on or the stove reaches desired temperature, an animated fire is projected to the crackling sound of burning wood. If the sink is left running, a projected pool of water grows to cover the countertop while the sound of a creek fills the room. Depending on where users are located, these displays grow or shrink to remain in the periphery of their attention and never to detract from their current task. In case a user forgets the water running or the stove on, the displays grow so that anyone entering the space is immediately aware that something is wrong. Although the displayed textures only convey limited information (hot, cold, wet) they seek to do so in a completely intuitive manner that is always accessible and never annoying. Cooking with the Elements enriches the sensory nature of cooking and returns some of the feedback that was lost when kitchens became modern and hermetic.

The soul of *Cooking with the Elements* is a ring of proximity sensors (top and middle) that combines with the appliance sensors into a multiplexed data acquisition board communicating through a PIC and serial port with a PC (bottom).

Implementation

Networked homes are being developed by numerous companies to allow remote control of entertainment, security and convenience appliances. Typically these systems employ limited radio or power line communication to take advantage of the proximity and low bandwidth of transmission. *Cooking with the Elements* is a functional kitchen with networked sensors and appliances that can follow users with information and make cooking simpler.

Based on experience gained working with Cleanup Corp. (Japan) Ernesto Arroyo, Chia-Hsun Lee, Michael Barrett and I designed a sensor network to keep track of the tools and people in the space. Since kitchens are built as a single object, it is possible to hard-wire all of the sensors in the space: 12 proximity sensors to detect the position of people around the room, 10 micro-switches to determine which appliance or cabinet is being opened, three CCD cameras, temperature and flow sensors on the tap, and a remote thermometer above the cook-top. These sensors are mounted throughout the kitchen and connected to a multiplexed data and power board communicating through a PIC microcontroller to a PC running a Macromedia Director movie. In turn, the system can output video and audio seamlessly throughout the environment. While earlier demonstrations employed discrete projections onto the countertop, refrigerator, and cabinets, a seamless projection covering all visible areas can produce displays that smoothly follow the user.



Ambient displays are notoriously difficult to evaluate because users have to know *that* the display is there, *what* it refers to and *how* it communicates information. Attentive Displays seek to cut this learning curve short by placing information where people will notice it, mapping it directly to what it refers to and using intuitive language to convey the information. [from Holmquist]

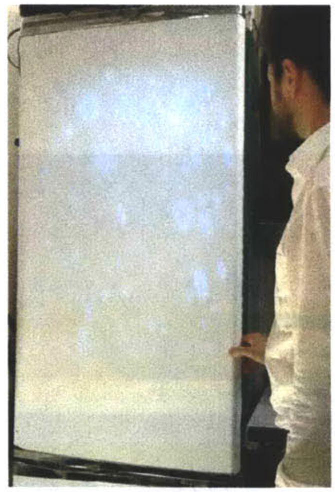
User Evaluations

Several attempts have been made to evaluate the effectiveness of ambient interfaces. A heuristic approach has been proposed; but direct evaluation is difficult because the interfaces are often obscure. One framework for evaluating ambient displays points out the three stages of understanding ambient displays: noticing *that* there is a display, understanding *what* the display refers to, and finally understanding *how* the display communicated the status of what it refers to [Holmquist]. Peripheral Displays Toolkit describes the importance of weighing attentional demands in designing peripheral displays [Matthews]. *Attentive Displays* seek to avoid the lengthy learning curve of ambient displays by putting intuitive displays where they will be noticed, often mapping information directly onto what it refers to, and using intuitive language to convey the information.

Cooking with the Elements is based on the premise that people intuitively understand synesthesia, or sensory information in one sense that operates synchronously with another sense. So, while projected digital information can be confusing and perform poorly with respect to printed information, projected images, colors and textures can perform better as indicators than their remote or nonexistent counterparts. To confirm the hypothesis that people generally understand projected sensory feedback despite its novelty, Chia-Hsun Lee, Michael Barrett and I conducted a formal evaluation of several of these systems. The evaluation considered five augmentations to kitchen interfaces: the freezer, range, faucet, cabinets and task lighting. Task performance, observation and questionnaires were tallied as part of the evaluation. The five systems were tested as follows:

Freezer

As described in *Cooking with the Elements*, opening the augmented freezer results in the projection of abstract snowfall and the accompanying sound of a cold wind. It is hypothesized that this system will lead to users feeling cold, and that over a long period of time the feedback will discourage people from leaving the freezer door open too long. 18 users aged 18-29 were asked to "find a tub of Haagen-Dazs ice cream in the freezer and place it on the countertop." Afterwards, they were asked to answer two written questions:



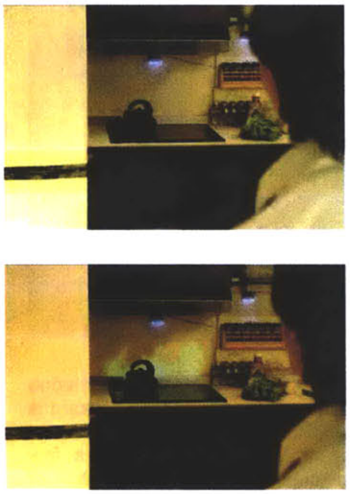
In the freezer test, when someone open s the refrigerator a blizzard is projected on the door and the sound of wind plays after a few seconds. Almost half of respondents reported feeling cold or rushed to close the door, suggesting that multimedia projection can elicit emotion during everyday activities.

> What happened when you opened the freezer?
> How did it make you feel?

The ambiguity of the task and feedback was designed to confuse the users' expectations about the subsequent, more concrete tasks. Nevertheless, 44% (8/18) of users reported feeling cold and/or rushed to close the freezer door.

Range

After the ice-breaker study, the far more direct range indicator was evaluated. This indicator works by sensing the temperature of the cook-top and projecting an animated fire on the wall behind the range when the temperature is high. It is intended to alert users who have forgotten that the range is on or who have not turned it on themselves. It is especially effective since the range in our test kitchen is electric and affords little indication of its temperature aside from remote red LEDs. Users were asked to stand outside the room (approximately 10' from the range) while the investigator entered and pressed some buttons on the electric range. This was repeated twice with a randomized projection of fire on the wall behind the range. In all cases, the range was on. 16 users aged 18-28 were asked to answer the following questions:



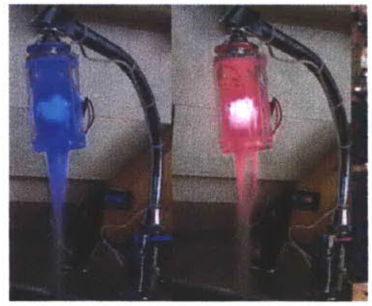
Can you tell if the range is hot? Users are asked if the range is on or off from a few feet away (like the photograph). Even though the range is on and hot in both pictures, only 19% think so in the top and 94% think so in the bottom.

> What do you think is the status of the stove? On/Off
>
> How did you determine the status of the range?

19% (3/16) of users reported the stove being on without the projection; whereas 94% (15/16) reported the stove being on with the projection (paired t-test $p<.001$). This is especially remarkable considering that the interface is completely novel to all of the users in the study. On the other hand, the projection of fire borders on 'virtual reality' and completely disambiguates the display. It should be noted that while the fire can be an effective indicator of the range being hot, it becomes far more difficult to indicate the relative temperature of the range. Considerations such as changing the volume of the fire and replicating glowing embers may be successful only once a user becomes accustomed to them.

Faucet

Although the *Heat Sink* has shown to be intuitive in hundreds of demonstrations to Media Lab sponsors over the past two years, a formal evaluation was conducted to determine its intuitiveness at first use to someone who is left alone. The hypothesis of this study was that users would realize that the red illumination indicates hot water and the blue illumination indicates cold water. 16 users aged 17-28 were asked to "fill one cup with VERY HOT water and fill another cup with VERY COLD water" and "describe how you determined the temperature of the water" "without touching the water or faucet itself." 94% (15/16) users reported understanding that the colored lights indicated water temperature within the first use.



Can you tell the temperature of the tap water? 94% of subjects in our user study could.

Cabinet

The fourth user study sought to determine the effectiveness of projecting the contents of a cabinet or refrigerator onto the door of the cabinet at full scale. Although this system was not proven useful in early pilot studies of Counter Intelligence, the study was re-designed and the resolution improved to make the projected image in many ways superior to the view of the cabinet's contents through a glass door. Conceivably, a projection of a cabinet's contents would be less intrusive than a glass door because the projection could be turned off or changed. Users were asked to retrieve an item from one of two cabinets with either opaque doors, glass doors or a projection of the contents onto opaque doors. As expected, 9/18 users aged 18-29 had a 50% of opening the right cabinet with opaque doors vs. a 100% chance of opening the right cabinet door when projected or made of glass. Users were asked to

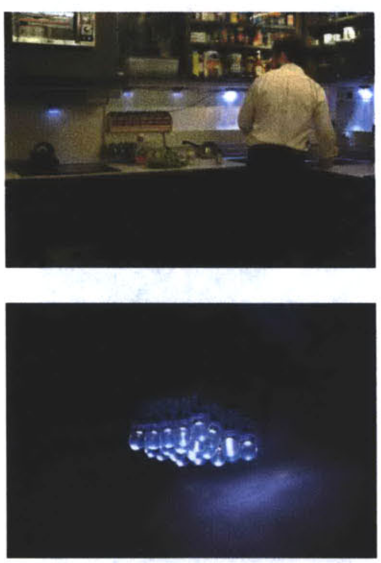
Can you find the ketchup, the mustard, the coca-cola? In the same exercise with these three conditions, people could find the items as fast in a projected cabinet as in a glass cabinet.

A two-dimensional projection of the cabinet's contents can reveal more than glass doors: at an oblique angle the bottle of Mrs. Dash next to the ketchup is invisible through the glass door (right), while in the projected view it is clearly visible (left).

approach the cabinets from across the room, and so they were able to visually search their 'target' (a bottle of ketchup, a bottle of mustard, or a can of coca-cola) from afar and had no significant search time difference between glass doors and projection. In fact, when viewed from an angle the projected image of cabinet contents is actually far easier to read than the glass doors within which shadows and obstruction can obscure items.

Task Lights

While automated lighting is relegated to security functions and garages, part of the test kitchen was outfitted with enhanced automated lighting that not only turned on and off in a much 'smoother' way than traditional automated lights; they also had the ability to interrupt a user's actions by flickering upon a signal from the central computer. The hypothesis of this study was that users would notice lights in the periphery of their vision flickering even though this is a completely novel means of task interruption. To test this, users were asked to fill out a length post-evaluation questionnaire at the kitchen countertop. Lights at the extremities of the counter were flickered briefly 3-6 times as they filled out the questionnaire. At the end, users were asked if they "noticed the lights flickering (turning on and off quickly) while filling out this questionnaire." 83% of users noticed the lights flickering, although none of them could remember how many times this happened precisely. This indicates that flickering of lights can act as an

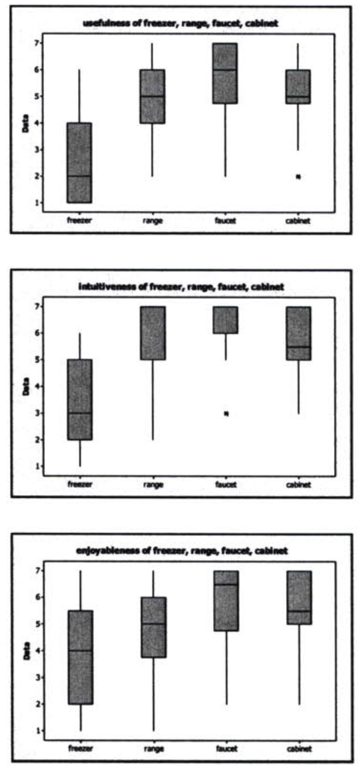


Soft Lights are LED-based task lights that respond to a user's performance by turning on in groups to create personal zones.

effective interruption, but that the act of flickering is far more powerful than the number of flickers themselves.

Subjective Evaluation

At the conclusion of the study, users were asked to rate four of the interfaces for utility, intuitiveness and enjoyableness. Users were asked to answer "How useful/intuitive/enjoyable did you find the following interfaces" on a scale of 1 (least) to 7 (most). The results indicate that the decoy study (freezer) generated widely varying, mostly negative responses while the faucet, cabinet and range were received positively overall. Although not statistically relevant, these results (which were obtained in part as a distraction for the *Soft Lights* study) reveal the next realm of exploration in the design of intelligent interiors: the creation of new sensory experiences from the combination of physical interfaces already in the space and the overlay of digitally mediated information.



Results of the subjective evaluation, showing that the heatsink, x-ray cabinet and range performed better than the freezer.

Conclusion

I embarked on this thesis to discover how digital augmentation could transform the way we design and interact with interior spaces. Early prototypes were encouraging: the glowing water in *Heat Sink* revealed that everyday tasks can be made more enjoyable through digital augmentation; and the *Up+Down Sink* showed that even futuristic automation could be acceptable if it offered enough tangible benefit. However, the first user studies of the *GUI Kitchen* revealed how hard it was to design new interfaces for home automation that could be understood by most of the people in a user evaluation. This led me to ask what parts of modern kitchens were actually intuitive to *anyone* upon first use. Ultimately the goal of my thesis became to design an intuitive space and apply those lessons to interior design in general.

Surprisingly, it was easy to make new interfaces with computers, actuators, projectors and LEDs that people could understand upon first sight. Designing Intelligent Interiors is not similar to designing computer interfaces because people expect far greater simplicity and stability from the built environment. First, text and abstract information had to be eliminated because of how rarely people understand it and how slow it is to read. Next, information had to be able to follow people around the room, and interrupt them with different modes if necessary. Finally, the content and fidelity of each interface had to be tweaked to match the expectations of users. Full-color pictures could only be understood if they were sufficiently high-resolution. Often, it was necessary to reduce the amount of information or assistance to make it intuitive. The *Heat Sink* can only communicate relative temperature intuitively; to communicate absolute temperature users would need training. The range, refrigerator and sink are intuitive because the synesthetic imagery used matches one sense with feedback from another – heat with fire, water with the sound of a stream, refrigeration with snowfall. This led to the discovery with greatest potential: that digital augmentation in interior space can make people feel new sensations. The pursuit of intuitiveness in design of intelligent interiors led to interfaces that operate at the perceptual level of emotions. Half of the people that opened the refrigerator felt cold and rushed because of a windy sound and the flicker of a snowfall. How many more new sensations could be produced by immersive displays in intelligent interiors? Interacting with ubiquitous computing in architectural space has the potential to do far more than make life easier – it can make boring tasks entertaining, make people feel 'at home' immediately, and create new emotional experiences with more flexibility than anything possible with bricks and mortar. Intelligent interiors can make life easier *and* more enjoyable. The following are lessons I will take home from this work:

1. **Architectural surfaces are not computer screens.** Our attempts to distribute text and graphics throughout the *GUI Kitchen* were met with

confusion and disorientation. While it is becoming possible to cover every inch of our world with high-resolution images, we do not perceive as much from distributed displays as from a magazine. Instead, we can interact with architectural spaces at the scale of the surfaces and the objects within – both in perception and comprehension. Distributed displays are in the 'background' of attention and serve better for ambient information and to offer feedback on everyday tasks. Simple changes in lighting, color, images and animations convey information effectively at the scale of the architectural space.

2. **Anything can be a display**. We are accustomed to designing products with little screens and buttons, LEDs and knobs. Users can better understand the status of tools or surfaces if they act as displays themselves. *Heat Sink* shows that it is much better to infer the temperature of water from looking at the water than from looking at the control knob. *Cooking with the Elements* shows that a projection of fire communicates the temperature of a cook-top much better than LEDs. *Xray Fridge* demonstrates that one-to-one projection works just as well as seeing the inside of the fridge. Both products and interior spaces can benefit from acting displaying information at full scale and directly mapped to its source.

3. **Information should find you.** The potential of ubiquitous computing is to provide information anywhere in the space. Cooking with the Elements demonstrates that a simple network of proximity sensors – all of which should one day be built into appliances – can effectively track people and only show information where and when it is needed. Imagine displays that can tell when you need them, and know to show you more information when you are confused or distracted. In our early pilot studies, users would spend time oblivious of a certain graphic or blinking light. Intelligent interiors need to be capable of switching to another mode – light, sound, maybe even smell or heat – when you need to be interrupted.
4. **Interior design is ephemeral**. Walls, floors, furniture, materials, are only the infrastructure of interior space. What we do in the space is insubstantial: we listen, we watch, we eat, we bathe. Light, sound, smell, taste are the senses that interior spaces touch. *Cooking with the Elements* demonstrates that we can make people feel cold by playing the sound of wind; that red tap water is understood to be hot. Windows may be important, but much of the light that hits our eyes is put out by backlit screens or reflected off printed text and images. The essence of interior space can become even more ephemeral, and the design of intelligent interiors can provide sensory experiences as we

once knew and as we never before experienced. Imagine waking up to a real sunrise, any time you want.

5. **The built environment is universal**. A space like a kitchen is inhabited by many different people over many years. We can make interacting with the space more intuitive and comfortable for anyone, old or young, standing or seated. *Smart Sinks* show how many types of assistance are possible when one considers all of the different tasks (cooking, washing hands, dishwashing, washing food) performed by different people (tall, short, standing, seated) in just one place: the kitchen sink. Automating work surfaces and architectural services can be an effective means of including everyone and making it easier when we face difficulty. The same is true for information design: people can be made to immediately feel 'at home' in a space if they can intuitively understand it. Text and abstract symbols should be replaced with universal imagery whenever possible, and feedback should be provided even with the simplest actions to keep people focused and confident.
6. **In the future, everything will be soft and glow**. At the same time as this thesis presents futuristic visions of total home automation, the success of these new interaction modes depends on how well they are designed so as to be intuitive and comfortable. Many new products demonstrate that

attention to detail can make or break a new interface. *Soft Automation* seeks to define the care that needs to be taken so that new systems are easily understood and valued by users. Visitors to our lab have been pleased by self-illuminating objects like the *Heat Sink* and *Augmented Cabinetry*, and by modulated automation like *Soft Lights* and the *Up+Down Sink.* The excess of feedback and accommodation provided by these devices and others like the Stock Orb, or Apple's pulsing power light, reveal the care that was taken to please the user. By finely tuning new interaction according to the expectations and capacity of people, we can make new experiences more easy to understand and appreciate.

Bibliography

1. Abowd, G.D. "Classroom 2000: An Experiment with the Instrumentation of a Living Educational Environment." IBM Systems Journal, 1999.
2. Ambient Devices: www.ambientdevices.com
3. Americans with Disabilities Act: http://www.usdoj.gov/crt/ada/adahom1.htm
4. Arroyo, Ernesto. Multimodal Interfaces: Arbitrating Interruption Modalities Masters Thesis, Massachusetts Institute of Technology, 2002.
5. Arroyo, E., Bonanni, L., and Selker, T. "WaterBot: Exploring Feedback and Persuasive Techniques at the Sink." In Proc. CHI '05, pp. 631-9
6. Ashby, Mike and Kara Johnson. 2003. Materials and Design: the Art and Science of Material Selection in Product Design. Oxford: Butterworth-Heinemann.
7. Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., MacIntyre, B. "Recent Advances in Augmented Reality" in IEEE ComputerGraphics and Applications Vol. 21, Issue 6 (November 2001).
8. Bradbury, J. S., Shell, J.S., Knowles, C.B., "Hands On Cooking: Towards an Attentive Kitchen," in Proc. CHI 2003, pp. 996-7.
9. Bonanni, L., Lee, C.H., Selker, T. "Cooking with the Elements: Intuitive Immersive Interfaces for Augmented Reality Environments" forthcoming in Proc. INTERACT '05, Rome, Italy.
10. Bonanni, L., "Re-Machining Domesticity: A Technological Inversion of Standards" in Thresholds Journal of Visual Culture #19, 2005, pp. 53-56 .
11. Bonanni, L., Arroyo, E., Lee, C-H., Selker, T. "Smart Sinks: Real-World Opportunities for Context-Aware Interaction," in Proc. CHI 2005 pp. 1232-5.
12. Bonanni, L., Lee, C.H., "The Kitchen as a Graphical User Interface." in SIGGRAPH 2004 Electronic Art and Animation Catalog, pp.109-111. Forthcoming in Digital Creativity Journal.
13. Bonanni, L., Lee, C.H., Gens, R., Selker, T., "Augmented Reality Kitchen: Task-Specific Projection in a Multi-User Work Environment." In Proc. UIST'04
14. Bonanni, L., Lee, C.H., Selker, T., "Attention-Based Design of Augmented Reality Interfaces." In Proc. CHI '05, pp. 1228-31.
15. Bonanni, L., Lee, C.H., Selker, T., "CounterIntelligence: Augmented Reality Kitchen," in Proc. CHI '05 pp. 2239-45
16. Bonanni, L., Lee, C.H., Selker, T., "A Framework for Designing Intelligent Task-Oriented Augmented Reality User Interfaces." In Proc. IUI '05. Pp.317-9.
17. Bonanni, L., Sarcia, S., Paudel, S., Selker, T., "Dishmaker: Personal Fabrication Interface," in Proc. CHI '05 pp.2231-3.
18. Bonanni, Leonardo. "Autonomous Pedestrian Interfaces for Community Networking," M. Arch thesis, Massachusetts Institute of Technology, 2003.
19. Centers for Disease Control: http://www.cdc.com
20. Choi, Nok-Young. 2002. Amorphous, Multi-phase Polymer Network Systems with Shape-Memory Properties by Photopolymerization. Doctoral Dissertation, Reinisch-Westfalischen Technischen Hochschule, Aachen.

21. Coen, M. H., "The Future of Human-Computer Interaction, or How I learned to Stop Worrying and Love my Intelligent Room" in IEEE Intelligent Systems March/April 1999 pp. 8-19.
22. Color Kinetics http://colorkinetics.com/
23. Cruz-Neira, C., Sansin, D.J., DeFanti, T.A. "Surround-Screen Projection-Based Virtual Reality: The Design and Implementation of the CAVE" in Proc. SIGGRAPH '93 pp.136-42.
24. Feiner, S. "Augmented Reality – a New Way of Seeing," in Scientific American April 2002.
25. Gershenfeld, Neil. "When Things Start to Think." New York: Henry Holt and Company, 1999.
26. Goins, G. 2001. Performance of salad-type plants grown under narrow-spectrum light-emitting diodes in a controlled environment. *In*: Proceedings of Bioastronautics Investigators' Workshop, Jan. 17-19, 2001, Galveston, TX.
27. Holmquist, L. E. "Evaluating the Comprehension of Ambient Displays," in Proc. CHI 2004 pp. 1545.
28. HyGenius. Access Date:January 10th, 2004. http://www.hygenius.com
29. Ishii, H., Ren, S. and Frei, P., Pinwheels: Visualizing Information Flow in an Architectural Space (short paper), in Proc. CHI '01, 111-12.
30. Ishii, H. and Ullmer, B., "Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms," in Proc. CHI '97, ACM Press, pp. 234-241, 1997
31. Ju, W., Bonanni, L., Fletcher, R., Hurwitz, R., Judd, T., Post, R., Reynolds, M., Yoon, J. "Origami Desk: Integrating Technological Innovation and Human-Centric Design," June 2002, In Proc. DIS '02
32. Ju, W., R. Hurwiz, T. Judd, B. Lee. "CounterActive: An Interactive Cookbook for the Kitchen Counter." In Extended Abstracts CHI '01, pp. 269-270.
33. Ju, Wendy. "The Design of Active Workspaces." Master's thesis, MIT, Cambridge, MA. September 2001
34. Kaplan, L.M., McGuckin, M. "Increasing handwashing compliance with more accessible sinks" in PubMed Infect. Control 1986 Aug;7(8): pp. 408-10.
35. Kaye, J. N. (2001) Symbolic Olfactory Display. Master's Thesis, MIT Media Lab, 2001.
36. Kellogg, W. A., Carroll, J.M., Richards, J.T (1991). "Making Reality a Cyberspace," in Benedikt, M., ed., Cyberspace: First Steps. Cambridge, MA.: The MIT Press, 1991.
37. Koved, Larry and Selker, Ted. "Room With A View (RWAV): A Metaphor for Interactive Computing." 1990.
38. LOT/EK, "Urban Scan," Princeton, NJ: Princeton Architectural Press, 2001.
39. Mankoff, J., Dey, A.K., Hsieh, G., Kientz, J., Lederer, S., Ames, M. "Heuristic Evaluation of Ambient Displays," in CHI Letters Vol.5, No. 1. Pp. 169-76
40. Lupton, E., Miller, J.A. "The Bathroom, The Kitchen and the Aesthetics of Waste: a Process of Elimination." Cambridge, MA (USA): MIT List Visual Arts Center, 1992.

41. Matthews, T., Dey, A.K., Mankoff, J., Carter, S., Rattenbury, T. “A Toolkit for Managing User Attention in Peripheral Displays” in Proc. UIST ’04.
42. McDonough, William and Michael Braungart. “Cradle to Cradle: Remaking the Way we Make Things.” New York: North Point Press, 2002.
43. Microsoft Kitchen of the Future as seen in the Food Network’s documentary ‘Kitchens of the Future,’ 2003.
44. Moen PureTouch. Access Date: January10th, 2004. www.moen.com.
45. Mori, T. Kuroiwa, T. Morishita, H. Sato, T. “Assistance with Human Actions and Individuality Adaptation by Robotic Kitchen Counter.” In Proc. ASER ’04.
46. Norman, Donald. “The Design of Everyday Things,” Doubleday 1990.
47. Occupational Safety & Health Administration (OSHA): www.osha.gov
48. Patten, J., Ishii, H., Hines, J., Pangaro, G., “Sensetable: A Wireless Object Tracking Platform for Tangible User Interfaces.” In Proc. CHI ’01.
49. Pinhanez, C., Augmenting Reality with Projected Interactive Displays, in Proc. VAA ’01.
50. Plant Gel: www.plantgel.com
51. Podlaseck, M., Pinhanez, C., Alvarado, N., Chan, M., Dejesus, E., “On Interfaces Projected onto Real-World Objects,” in Proc. CHI 2003.
52. Raskar, R., Welch, G., Cutts, M., Lake, A., Stesin, L., Fuchs, H. “The Office of the Future: A unified Approach to Image-Based Modeling and Spatially Immersive Displays.” In Proc. SIGGRAPH ’98.
53. Riley, Terence. “The Un-Private House,” The Museum of Modern Art, New York: 1999.
54. Sekuler, Robert and Blake, Randolph. “Perception,” Boston: McGraw Hill, 2002
55. Selker, T., Arroyo E., Burleson, W. “Chameleon Tables: Using Context Information in Everyday Objects.” In Proc. CHI ’02.
56. Selker, T. “Visual Attentive Interfaces” BT Technology Journal Col 22 No 4 October 2004.
57. Selker, T., Lockerd, A., Martinez, J., Burleson, W. “Eye-aRe, a Glasses-Mounted Eye Motion Detection Interface,” in Proc. CHI ’01.
58. Shojania, et. al. eds. “Making Health Care Safer: A Critical Analysis of Patient Safety Practices.” Prepared for the Agency for Healthcare Research and Quality, Contract No. 290-97-0013 by the University of California at San Francisco (UCSF)-Stanford University Evidence-based Practice Center.
59. Siio, I., Mima, N., Frank, I., Ono, T., Weintraub, H., “Making Recipes in the Kitchen of the Future,” in Proc. CHI ’04.
60. Stratasys fuse-deposition modelers: http://www.padtinc.com/sales/stratasys/default.htm
61. Ullmer, B. and Ishii, H., “The metaDESK: Models and Prototypes for Tangible User Interfaces.” In Proc. UIST ’97.
62. Vertegaal, R. “Designing Attentive Interfaces” in Proc. ETRA ’02, New Orleans, Louisiana.
63. Wellner, P. “The DigitalDesk calculator: Tangible Manipulation on a desk top display,” in Proc. UIST ’91, 27-34.

64. Wickens, C.D., Gordon, S. E. and Liu, Y. "An Introduction to Human Factors Engineering," New York: Addison Wedley Longman, 1998.
65. Z Corporation: http://www.zcorp.com/

Appendix A

Index of Illustrations

All images are the author's own, except:

On pp. 45, from Riley 1999.

On pp. 45, from http://www.lot-ek.com.

On pp. 47, from Ju 2001.

On pp. 48, from http://alice-waters.jofish.com.

On pp. 52, from http://ambientdevices.com.

On pp. 54, from Arroyo 2002.

On pp. 77, from Holmquist.

Appendix B: User Studies

Up+Down Sink

Pilot Study Questionnaire

SmartSink Study
Pre-Test Questionnaire

1. How tall are you? ______________

2. Are you comfortable with the height of normal kitchen countertops?

very uncomfortable 1---2---3---4---5---6---7 very comfortable

3. Do you think that a countertop can benefit from electronics?

strongly agree 1---2---3---4---5---6---7 strongly disagree

Thank you for participating in the SmartSink Study.

SmartSink Study
Post-Test Questionnaire - standard

1. Was the counter difficult to work with?

very easy 1---2---3---4---5---6---7 very difficult

2. Was it easy to use the counter?

very easy 1---2---3---4---5---6---7 very difficult

3. Was the counter at a comfortable height?

very comfortable 1---2---3---4---5---6---7 very uncomfortable

4. Do you feel that this counter would be useful?

very useful 1---2---3---4---5---6---7 not useful

5. Do you have any comments or suggestions?

Thank you for participating in the SmartSink Study.

SmartSink Study
Post-Test Questionnaire - augmented

1. Was the counter difficult to work with?

very easy 1---2---3---4---5---6---7 very difficult

2. Was it easy to use the counter?

very easy 1---2---3---4---5---6---7 very difficult

3. Was the counter at a comfortable height?

very comfortable 1---2---3---4---5---6---7 very uncomfortable

4. Do you feel that this counter would be useful?

very useful 1---2---3---4---5---6---7 not useful

5. Do you have any comments or suggestions?

Thank you for participating in the SmartSink Study.

Appendix B: User Studies

Up+Down Sink

Results

9 users aged 18-48 measuring 160-188cm tall

Questions 1 & 2 had no significant results.

Question 3: Was the counter at a comfortable height?

Answers on a scale of 1 to 7, 1 being least comfortable and 7 most comfortable.

user	control	study	difference			*Variable 1*	*Variable 2*
9	3	3	0		Mean	4.44	2.56
8	5	2	3		Variance	1.03	2.03
7	6	1	5		Observations	9	9
4	5	6	-1		Pearson Correlation	-0.02	
23	5	2	3		Hypothesized Mean Difference	0	
22	4	2	2		df	8	
21	4	2	2		t Stat	3.21	
20	5	3	2		P(T<=t) one-tail	0.006	
19	3	2	1		t Critical one-tail	1.860	
average	4.44	2.56	1.89		P(T<=t) two-tail	0.012	
					t Critical two-tail	2.306	

Question 4: Do you feel that this counter would be useful?

Answers on a scale of 1 to 7, 1 being least useful and 7 being most useful.

user	control	study	difference			*Variable 1*	*Variable 2*
9	3	3	0		Mean	4.33	3
8	4	2	2		Variance	2.25	2.5
7	5	2	3		Observations	9	9
4	6	6	0		Pearson Correlation	0.69	
23	2	2	0		Hypothesized Mean Difference	0	
22	3	1	2		df	8	
21	6	5	-1		t Stat	3.27	
20	6	3	3		P(T<=t) one-tail	0.006	
19	4	3	1		t Critical one-tail	1.860	
average	4.33	3	1.11		P(T<=t) two-tail	0.011	
					t Critical two-tail	2.306	

Appendix B: User Studies

Cooking with the Elements

Questionnaire pages 1-4

INTRO

Welcome to the kitchen of the future. Now that you have signed the consent form, please answer the following questions:

1. Are you a native speaker of English? **Yes/No**

   If No, how many years have you spoken English? ______years

2. How many times per week do you cook in your kitchen?

   0 1 2 3 4 5 6 7 8 9 10+

3. What is your favorite dish to prepare? ____________________

4. Do you often forget steps in the cooking process? **Yes/No**

   If **Yes**, what steps do you forget most often?____________________

5. Do you think that the kitchen can benefit from new interfaces? **Yes/No**

   If Yes, what improvements can you suggest?

FREEZER

Open the freezer to find a tub of Haagen-Dazs Ice Cream and put it on the countertop.

1. What happened when you opened the freezer?

2. How did it make you feel?

Please tell the investigator when you have finished and wait for instruction.

RANGE

The *range* is the black glass surface above the stove where pans are heated.

a) What do you think is the status of the range? **On/Off**

How did you decide the temperature of the range?

Please tell the investigator when you have finished and wait for instruction

b)What do you think is the status of the range? **On/Off**

How did you decide the temperature of the range?

Please tell the investigator when you have finished and wait for instruction.

c)What do you think is the status of the range? **On/Off**

How did you decide the temperature of the range?

Please tell the investigator when you have finished and wait for instruction

FAUCET

Without touching the water or the faucet, do the following:
-Fill one cup with VERY hot water
-Fill another cup with VERY cold water

How did you decide if the water was hot or cold?

Please tell the investigator when you have finished and wait for instruction

Without touching the water or the faucet, do the following
-Fill one cup with VERY hot water
-Fill another cup with VERY cold water.

How did you decide if the water was hot or cold?

Please tell the investigator when you have finished and wait for instruction.

Appendix B: User Studies

Cooking with the Elements

Questionnaire pages 5-7

CABINET

A. In the cabinets indicated to you, please find the **ketchup** and place it on the countertop.

Please tell the investigator when you have finished and wait for instruction.

B. In the same cabinets, please find the **mustard** and place it on the countertop.

Please tell the investigator when you have finished and wait for instruction.

C. In the same cabinets, please find the can of **coca-cola** and place it on the countertop.

Please tell the investigator when you have finished and wait for instruction.

CONCLUSION

Thank you for participating in our study of new interfaces in the kitchen of the future. **Please take time to answer the following questions. Your suggestions** will be greatly valued.

1 How **useful** did you find the following interfaces?

	Not effective						Very Effective
Freezer	1	2	3	4	5	6	7
Range	1	2	3	4	5	6	7
Faucet	1	2	3	4	5	6	7
Cabinet	1	2	3	4	5	6	7

2 How **intuitive** did you find the following interfaces?

	Not Intuitive						Very Intuitive
Freezer	1	2	3	4	5	6	7
Range	1	2	3	4	5	6	7
Faucet	1	2	3	4	5	6	7
Cabinet	1	2	3	4	5	6	7

3 How **enjoyable** did you find the following interfaces?

	Not enjoyable						Very enjoyable
Freezer	1	2	3	4	5	6	7
Range	1	2	3	4	5	6	7
Faucet	1	2	3	4	5	6	7
Cabinet	1	2	3	4	5	6	7

Please give us suggestions and ideas for improving kitchen interfaces

____

____

____

____

____

____

While filling out this questionnaire did you notice the lights flicker (turn on and off quickly)? Yes/No

If Yes, how many times? ______

Thank you for participating in our study.

Appendix B: User Studies

Cooking with the Elements

Results

Freezer study: 18 users aged 18-35.

Question 1: What happened when you opened the freezer?

fridge screen had swirling snow and wind noises
lights flash on fridge when I got close
(no sound) lights flashed on fridge
sound, lights
Sound/Images appeared, sounds of wind
sound of a winter breeze, as well some projected snow or ice
Weird noise
sound/video on fridge
noise like an ocean, didn't stop til I was done
buzzing noise, noticed flashing colors
lights/sound, backgournd special FX to my actions
white lights flashed, sound of noise similar to wind
sound of wind, lights on freezer door
wind-like sound
movie with frozen landscape, sound of wind blowing
blizzard noises, light
images/sounds, indicate freezer open
Projection light (abstract pattern) sound

Question 2: How did it make you feel?

cold, plus I had to dig through the over frosted freezer to the back, plus a little rushed, like I had the door open too long.
Confused
Excited
feel I knew what was in the freezer
surprised, uneasy
arctic, seemed pointless
kind of bizarre, made me feel cold
didn't pay attention
wondered what was going on, tried to make it stop. Did I break something?
didn't pay too much attention, concentrating on getting ice cream. A little startling.
trekking across arctic to get ice cream
Disorienting
in a cold place, a little bit scary
thought it wasn't related, but more of a cheesy sound effect
Dry and cold
Like I should probably close the freezer eventually, also amused
ambivalent, useful for blind people
initially did something wrong, but then figured out warning of freezer door open

Appendix B: User Studies

Cooking with the Elements

Results

Range study: 18 users aged 18-35.

When range was ON *without projection*:

Question a) What do you think is the status of the range? How did you decide?

off/fire display off, same as before
off/flames gone away
off/used to gas stovetops, couldn't see heat/fire
off/assumed fire indicated its state
on/light is on
off/no animation
on/assumed wouldn't have left the stove on, so must have been turned on
off/no visuals, but unsure
off/no obvious signs something is turned on
off/no longer image of fire
off/cannot decide, investigator doing something close to range, so probably off
off/no flames, white light like other ones, located near things not hot
on/assuming turning on after pressing buttons
off/nothing to indicate on, lights above it look normal
off/'blue light' indicate off
off/temperature not visible, no way of knowing

When range was ON *with projection*:

Question b) What do you think is the status of the range? How did you decide?

off/color of it, black, no sound
on/really big flames above it
on/although no fire, the visuals suggested on
on/I assumed that the fire indicates its on
on/must be on because of fire picture. Looks hot very hot.
on/video off, fire in back
on/flame image projected
on/fire visual
on/special effect, obvious stove is on
on/image fo fire
on/animated fire rising when investigator pushing buttons, on - temperature high
on/flames behind range
on/flames showign a warning of heat
on/fiery pictures of background indicate hotness
on/image of fire indicates range on
on/fires projection

Appendix B: User Studies

Cooking with the Elements

Results

Faucet study: 16 users aged 18-35 (protocol was changed after first 2 users)

Without *Heat Sink*:

Question: How did you decide if the water was hot or cold?

faucet tradition, hot left, cold right
guessed based on previous faucet use, waited for a while
assume hot left, cold right
I assumed the standard - left hot, right cold
how the cup felt in my hand by feeling the first one. For the second, it should turn in the opposite way
one had more bubbles, thought it was hot.
touched metal under handle
Traditional
traditional, waiting
guessing based on tradition
feel water in glass, felt temperature, but not ot or cold
traditional, water cloudy and air bubbles when I thought it was hot
traditional, waited - hot water more bubbles
guessed based on previous knowledge of sinks
tradition, but lights blinking (noise)
feeling cup temperature

With *Heat Sink*:

Question: How did you decide if the water was hot or cold?

when water was hot spout was red
red light for hot, blue for red
faucet was initially red, turned to blue
based on color of faucet end/little slow,though
lights on the faucet – assumed red for hot, blue for cold
colors suggested temperature
light on faucet told me everything – no waiting, no guessing
color of lights around faucet
noticing change of color in faucet, blue=cold, red=hot
i assumed the red indicated hot and blue indicated cold
color in faucet seemed to change, still unsure, went with control
led color red=hot blue=cold
color of light around the faucet
color of the faucet head
red light indicates hot, blue indicates cold
faucet turned red or blue

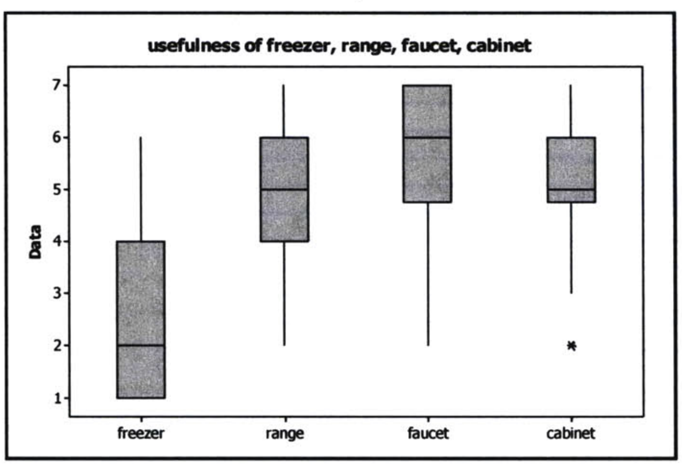
Cooking with the Elements

Results

Concluding questionnaire: 18 users aged 18-35.

Question 1. How **useful** did you find the following interfaces?
(on a scale of 1 to 7, 1 is least useful and 7 is most useful)

user	freezer	range	faucet	cabinet
1	2	4	7	5
2	1	5	3	3
3	1	5	7	4
4	2	6	6	4
5	4	4	2	5
6	1	6	5	5
7	2	2	5	6
8	1	3	4	7
9	2	5	7	5
10	4	7	7	5
11	4	7	7	6
12	1	5	5	2
13	4	6	7	5
14	2	5	6	6
15	2	3	7	5
16	6	7	7	5
17	1	6	6	7
18	5	6	3	7



Appendix B: User Studies

Cooking with the Elements

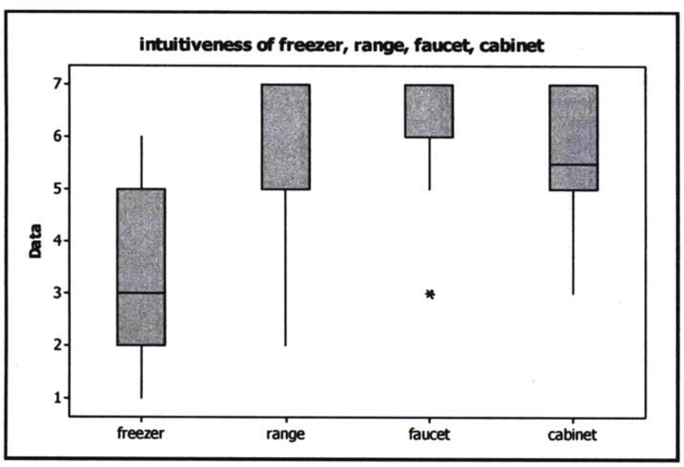
Results

Concluding questionnaire: 18 users aged 18-35.

Question 2. How **intuitive** did you find the following interfaces?

(on a scale of 1 to 7, 1 is least intuitive and 7 is most intuitive)

user	freezer	range	faucet	cabinet
1	3	5	7	5
2	1	5	3	5
3	5	7	7	7
4	5	7	7	7
5	4	5	3	5
6	6	6	6	7
7	2	2	5	6
8	5	6	7	7
9	1	7	7	5
10	2	7	7	5
11	2	7	7	4
12	3	7	7	3
13	5	7	7	5
14	2	7	6	7
15	2	4	7	7
16	6	7	6	5
17	1	7	6	7
18	5	7	6	6



Appendix B: User Studies

Cooking with the Elements

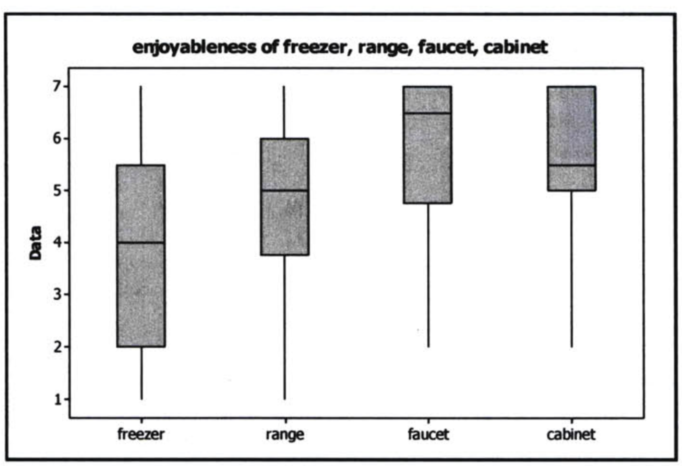
Results

Concluding questionnaire: 18 users aged 18-35.

Question 2. How **enjoyable** did you find the following interfaces?

(on a scale of 1 to 7, 1 is least enjoyable and 7 is most enjoyable)

user	freezer	range	faucet	cabinet
1	4	4	6	5
2	1	3	3	5
3	4	4	7	7
4	4	5	6	7
5	2	2	2	2
6	5	6	4	7
7	2	2	5	6
8	4	5	7	5
9	7	5	7	7
10	3	7	7	5
11	7	6	7	5
12	5	5	4	3
13	4	6	6	5
14	2	5	7	7
15	1	1	7	4
16	7	7	7	6
17	4	4	6	7
18	7	7	7	7



Appendix B: User Studies

Cooking with the Elements

Results

Concluding questionnaire: 18 users aged 18-35.

Question: Please give us suggestions and ideas for improving kitchen interfaces.

snow for freezer good if I walked away after leaving it open, cabinet pics more helpful if live updated shot, stove top should still light up, fire noise quite loud
nto really sure what firdge was supposed to do. Range neat idea. Don't understand what faucet lights were doing. Clear cabinets more useful than projector.
everything you made was easy to use and useful, cabinet projections on the fridge.
Cabinets don't need the image because they could just be made of glass. May be useful for fridge/freezer though. Faucet warning when water is at burning temperature
a lot of the interfaces would be best suited if they were learned whi;le growing up
faucet could look better, freezer noise frivolous, range could indicate more about state, such as temperature or number of burners on, that might be cool
none
faucet change faster, lights old and dim
seem useful, but may not blen in well with a normal kitchen.
freezer unecessary, faucet great idea. Good for black cabinets to help find things.
cabinets pointless, clear door better. Projection used to ';redecorate' kitchen. Faucet/range useful, sound superfluous. (freezer too - unless you are Shackleton)
improve aesthetics,
color in faucet changes too slowly, needed 'a few secondss'
cabinet good interface, but a lot of energy. Clear doors better idea. Faucet temp indicator good idea, but greater range. Also less energy usage.
temp sensing faucet useful, incorporate into pots and pans
faucet range and freezer very good and effective. Cabinet projection - confusing, but might enforce organization, does it change when items chagned?
cabinets amazing! Leave as is. Faucet great second time. Noise confused user...range only mildy necessary, fridge/freezer cabinets
freezer - just sound effective, cant see projection above you (projcetion on floor?), range - less absract fire, faucet faster, cabinet perfect without flaws

Appendix B: Pilot Studies

Cooking with the Elements

Results

Lights study: 18 users aged 18-35.

Each user had the lights flicker 5 times.

Question: While filing out this questionnaire, did you notice the lights flicker (turn on and off quickly)?

If Yes, how many times?

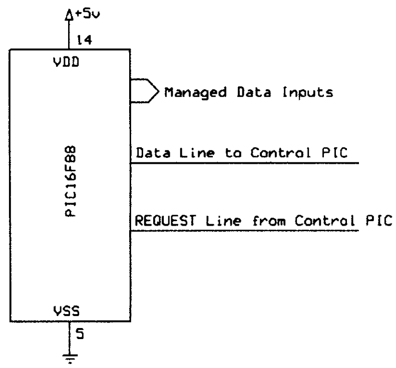
yes/5
yes/5ish
yes/4-5
yes/4-5
no
yes/5+
yes/5
yes/2?
yes/3-4, not sure
no
yes/2
no, but maybe once or twice
yes/2
no/actually I did notice after the question - 4 times
yes/3
yes/1
yes/3
no

Appendix C: Technical Documentation

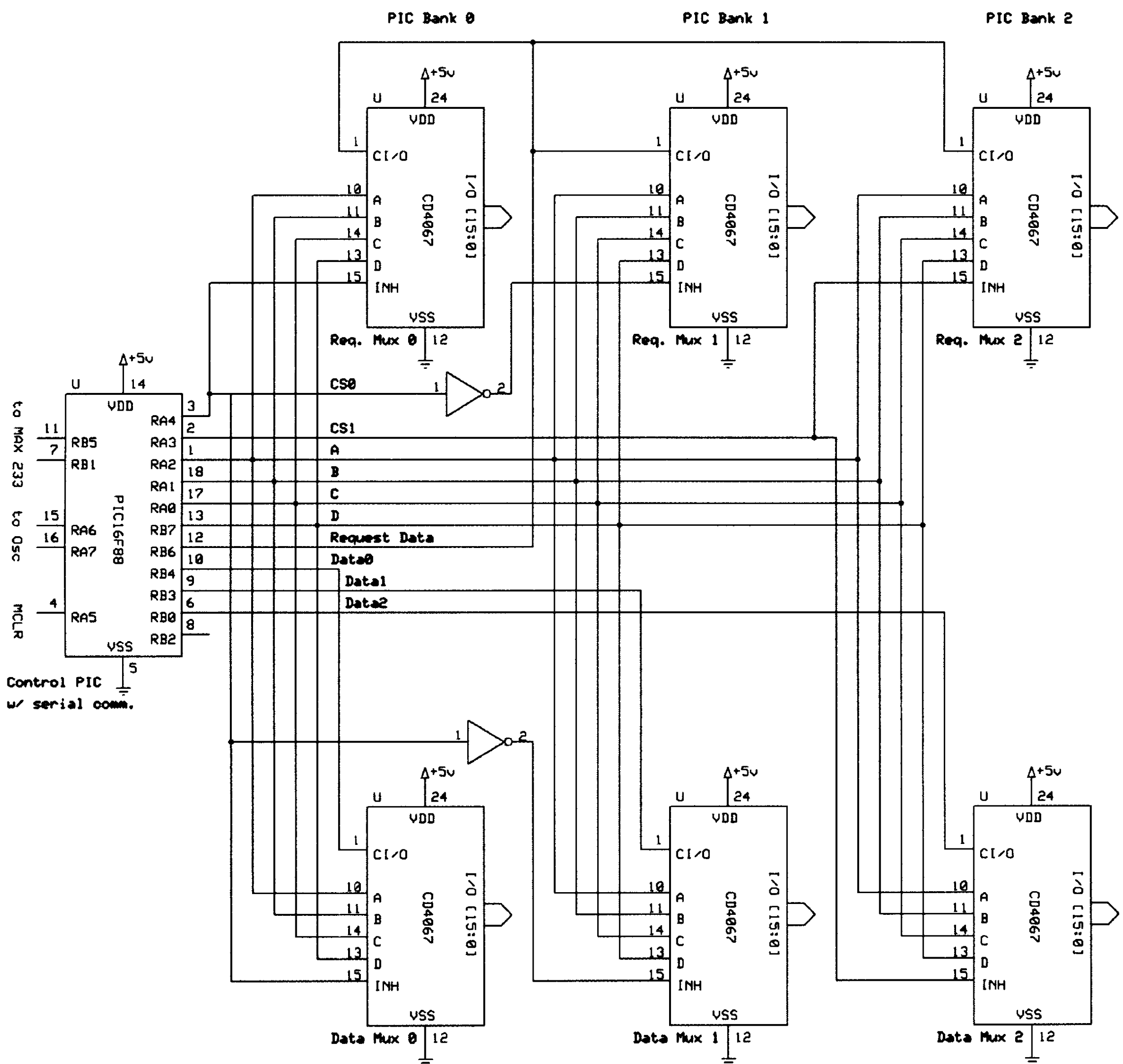
HeatSink circuit board designed by the author (actual size 1.5" x 1.5")

```
#include "C:\Program Files\PICC\Devices\12F675.h"
#device ADC=10

// Configure PIC to use: HS clock, no Watchdog Timer,
// no code protection, enable Power Up Timer

#fuses INTRC_IO,NOWDT, PUT, NOMCLR, NOPROTECT, BROWNOUT
#use delay (clock=4000000)
#use fast_io(A)

#define LED_RED  PIN_A0
#define LED_BLUE PIN_A1
#define WATER_PIN PIN_A2
#define CH_H20 2
#define CH_TEMP 3
#define VDD 5.0
#define INPUT_MIN 2.8
#define INPUT_MAX 3.1
#define INPUT_MIN2 2.6
#define INPUT_MAX2 2.8

float volts_read;
long  adc_value;

int main()
{
  float temp,r_data, r_data2;
  float v_int,v_min,v_int2,v_min2; float i;

            SET_TRIS_A(0b11100);
            //PIN_A3 is always an Input
            PORT_A_PULLUPS(TRUE);
            DISABLE_INTERRUPTS(GLOBAL);
            setup_comparator(NC_NC_NC_NC);
            SETUP_TIMER_1(T1_DISABLED);

            setup_adc_ports(AN3_ANALOG | VSS_VDD); //setup adc
  setup_adc(ADC_CLOCK_DIV_64);
  set_adc_channel(3);

  v_int = (float)((INPUT_MAX-INPUT_MIN)*1024/VDD);
  v_min = (float)(INPUT_MIN*1024/VDD);

  v_int2 = (float)((INPUT_MAX2-INPUT_MIN2)*1024/VDD);
  v_min2 = (float)(INPUT_MIN2*1024/VDD);

while (1)                                                   //main loop
{
 if ( input(WATER_PIN) )     // if water is detected turn on LEDs
            {
            temp = read_adc() ;
            r_data = temp - v_min;
  r_data2= temp- v_min2;

      if(temp<= v_min)
         {
         for(i=0.0;i<v_int2;i=i+1.0)
         {
                  output_low(LED_RED);
            if(i>r_data2)
            {
               output_high(LED_BLUE);
            }
            else
            {
               output_low(LED_BLUE);
            }
            delay_us(100);
         }
         else
         {
         for(i=0.0;i<v_int;i=i+1.0)
         {
            output_low(LED_BLUE);
            if(i<r_data)
            {
               output_high(LED_RED);
            }
            else
            {
               output_low(LED_RED);
            }
            delay_us(100);
         }
         }
            }
 else  //if there is no water
            {
            OUTPUT_LOW(LED_RED);
            OUTPUT_LOW(LED_BLUE);
            }
}
}
```

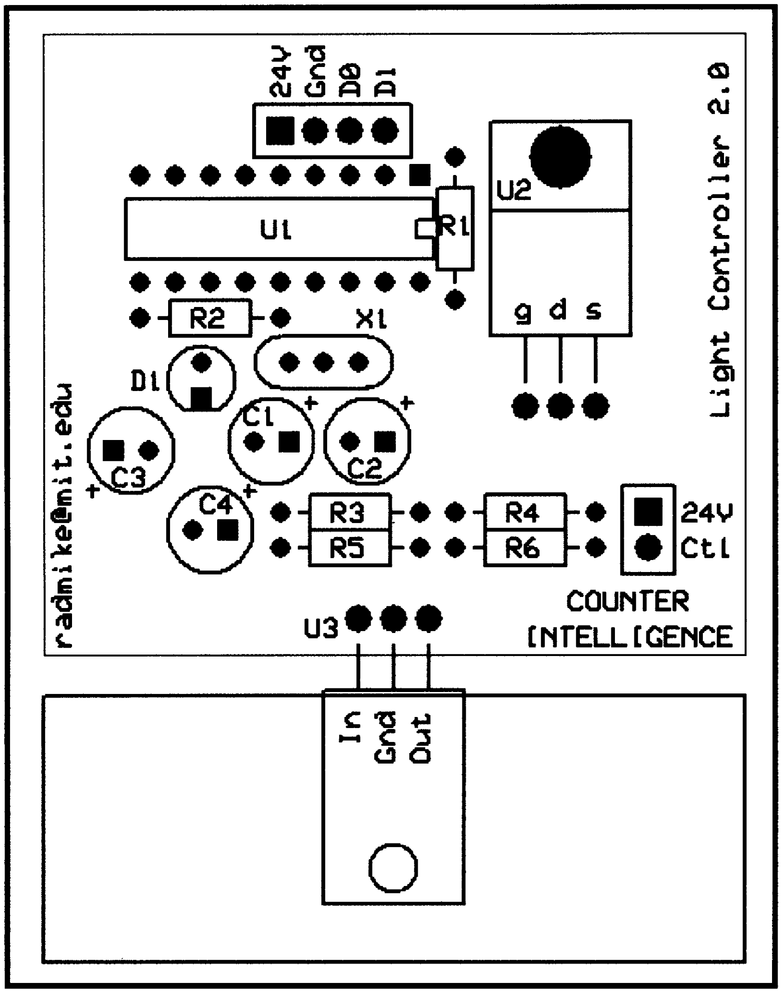
Code for Heat Sink board with PIC12F675



General input scheme for Cooking with the Elements PIC by Michael Barrett.



Multiplexer input scheme for Cooking with the Elements data acquisition board by Michael Barrett.



Soft Lights controller with power supply and heat sink by Michael Barrett.