Designing a Home of the Future

An interdisciplinary team is developing technologies and design strategies that use context-aware sensing to empower people by presenting information at precisely the right time and place. The team is designing a living laboratory to study technology that motivates behavior change in context.

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People spend more time in their homes than in any other space. The home ideally provides a safe, comfortable environment in which to relax, communicate, learn, and be entertained. Increasingly, it is where people connect with friends and family, conduct business, manage resources, learn about the world, and maintain health and autonomy as they age. People invest extraordinary amounts of time, money, and emotional energy to mold their homes into living spaces that meet their needs.

Unfortunately, homes today are ill-suited to exploiting the pervasive computing applications being developed in laboratories. Most homes do not easily accommodate even the simplest new technologies, let alone embedded sensor infrastructures and ubiquitous display technologies. Moreover, homeowners generally believe that computer devices make life more complex and frustrating rather than easier and more relaxing. They are wary of the aesthetic, financial, and cognitive challenges of bringing new technologies into their homes.

Researchers in the Changing Places/House_n: MIT Home of the Future Consortium (http://architecture.mit.edu/house_n) at the Massachusetts Institute of Technology are investigating how the home and its related technologies, products, and services should evolve to better meet the opportunities and challenges of the future. Our team's researchers have backgrounds in computer science, user interface design and usability, architecture, mechanical engineering, psychology, and materials science. The "n" in House_n represents a variable; we believe there is no single "home of the future." In particular, we aim to create design strategies for more flexible environments that better meet occupants' physical and cognitive needs than current environments. Based on discussions with medical professionals, patients, educators, and homeowners, we believe that the home of most value in the future will not use technology primarily to automatically control the environment but instead will help its occupants *learn how to control the environment on their own*.

This shift is the focus of this article. As a byproduct of this shift, new tools are required to study technology in the context of home life. To address this need, our team has designed and is planning to construct a "living laboratory" that will support qualitative and quantitative studies investigating the relationships between spaces, the behaviors of people, and pervasive computing technologies.

Envisioning homes of the future

If we are to believe most movies, television, and popular press articles that mention home life in the future, we will have complete control over our spaces at the touch of a button. In fact, our homes will be so fully automated and "smart" that we will rarely have to think about everyday tasks at all. We will spend nearly all our time in the home engaged in leisure activities because digital and robotic agents will have taken over the mundane chores of day-to-day life.

Researchers and technologists are more cautious in predicting the future of the home. A survey of ongoing work shows, however, that there is a bias toward creating automatic (smart) home environments that eliminate the need to think about tasks such as controlling heating and light-

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ing, going to the grocery store, scheduling home appliances, and cooking.[1–3]

Although our team might use automation to help people accomplish tasks they cannot perform on their own because of a disability or frailty, our primary vision is not one where computer technology ubiquitously and proactively manages the details of the home. Technology should require human effort in ways that keep life as mentally and physically challenging as possible as people age. We are designing and building prototypes demonstrating how to create environments that help people

- Live long and healthy lives in their homes
- Reduce resource consumption
- Integrate learning into their everyday activity in the home

To accomplish these goals, we envision computer technology as ever-present but in a more subtle way. Information will be presented to people at precisely the time and place they need it. We want our pervasive technologies to empower people with information that helps them make decisions; we do not want to strip people of their sense of control, which has been shown to be psychologically and physically debilitating.[4]

Control versus empowerment: An example

To illustrate this shift in thinking, imagine that our goal is to create an environment that uses pervasive computing technology to save energy by automatically controlling the heater-vent-air conditioning system. We assume that the environment's embedded sensors can infer context such as where people are, what they are doing, and what the inside environmental conditions are. We also assume that the home contains computer-controlled HVAC appliances, windows, and blinds.

The automated home

One way to reduce resource consumption is to design a home environment that controls environmental conditions. The home's occupant informs the system via some type of user interface that he or she wishes to stay comfortable while saving as much energy or money as possible. The home then uses a set of optimization algorithms to simultaneously maximize savings and comfort by automatically controlling the HVAC systems, windows, and blinds. For instance, on a day when the temperature is predicted to shift from warm to cool, the home might determine that the optimal cooling strategy is to shut down the AC and automatically open a set of blinds and windows so as to create an efficient cross breeze.

This scenario is relatively simple compared with other smart-home visions. In practice, however, it would be an immense challenge to achieve this simple scenario in an actual home setting. The sophistication of commonsense reasoning and context awareness that is required is daunting, given the current state of our understanding of these fields. There are many situations in which the automatic system might succeed in optimizing temperature comfort yet fail in "doing the right thing": something noisy is occurring outside, someone is smoking outside the window, someone in the home is allergic to pollen and the pollen count is high, it is raining outside, it is too quiet for a person reading when the hum of the air conditioner is off, someone did not want the blinds open because it throws glare on a computer screen, and so on. No matter how hard the system designer tries to program contingency plans for all possible contexts, invariably the system will sometimes frustrate the home occupant and perform in unexpected and undesirable ways. A learning algorithm would also have difficulty because a training set will not contain examples of appropriate decisions for all possible contextual situations.

There is a fundamental problem here: the more complexity the algorithms consider when making decisions, the less transparent those decisions will be to the homeowner.[5] The system will actually become less predictable as it acquires more expertise, and the system's success some or most of the time will raise user expectations about what the system is capable of doing. Inevitably, the system will violate the user's high expectations given the unexplainable "intelligence" the system sometimes shows when making these control decisions. Because the system is so complex, the user will be left feeling frustrated—helpless to understand the behavior. Why does it keep opening the windows when, clearly, the user wants and needs them closed?

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The home that uses subtle reminders

Consider an alternative scenario. In this home of the future, the windows include a tiny light that is either embedded in the window frame (for example, a light-emitting diode) or projected on the window using display technology (for example, an IBM Everywhere Display[6]). The home's embedded sensors and optimization algorithms compute a strategy for cooling the home by opening a particular set of windows, but they do not proactively implement the strategy.

In this example, imagine that the light on the window subtly illuminates. It does not interrupt the home occupant. When someone in the home notices it, he or she knows the light means "it might be a good idea to open this window right now." The home thereby unobtrusively informs the user of actions that might be taken to conserve energy or money. In this way, the home teaches the occupant, in an unobtrusive way, how to achieve the optimal settings. The home can take a similar approach when the goal is to improve health or introduce learning into everyday life.

This scenario has several advantages over proactive control:

- Information can be presented that the occupant can react to without interrupting ongoing activity in potentially irritating ways; this is especially true if information can be "augmented" onto the physical environment itself.
- Leaving occupants in control of making decisions allows the home to present options based on partial information without confusing them; they will naturally consider contexts that the home has not and adjust their actions accordingly.

- Algorithms that make suggestions can degrade gracefully; algorithms that make decisions typically do not.
- Lack of control over aspects of life has been shown to diminish health[4]; this strategy empowers the home occupant.

The user ultimately decides whether to open the window. Therefore, the task of interpreting the suggestion in context rests with the user: if it is noisy outside, the user will simply decide not to open the window, realizing that this is not a good time. This is a pervasive computing application with an exceptionally simple user interface. Could such a system actually influence behavior? Yes. Controlled studies in homes show that using such a small, simple light on an AC unit can lead to 15 percent reductions in AC use.[7,8]

The teaching home

Pervasive computing can be used not only to motivate behavior but to teach at the moment when the behavior is undertaken. Systems that automatically make control decisions generally miss this opportunity—users can become complacent if the system functions perfectly. Although a computer system might try to present the user with educational messages to explain the actions it is taking, to do this without interrupting and irritating the user is a challenge. The system must compute a reasonable time to present the information. Even for relatively simple help applications, this has proven to be difficult to do (for example, ClipIt, the Microsoft paperclip, attempts just-in-time help but does so in ways that often require the user to divert attention from the current task). On the other hand, if a user is unhappy with a control decision the home has made, he or she will feel annoyed and primarily interested in counteracting the home's actions. This is not the best time for the home to present explanatory information to promote learning. A home that leaves control to the occupant avoids this tricky issue.

The extraordinary potential power of pervasive computing comes into play when a user decides to take an action such as opening the window. This is a "point of behavior" that the home can easily identify by detecting a specific event (the opening of the window). The user has already decided to stop whatever he or she was doing to perform a recommended task. The home can safely infer directly from sensor data that the user is opening the window and therefore is likely to be receptive to information that helps the user determine how to do so. The user is also likely to be curious about why the home is making this recommendation. Finally, the user will have moved to the object's physical location; this presents a good opportunity to teach by overlaying digital information on the physical space. In this scenario, precisely when the system determines that the user has decided to act, it can overlay information on the real world to educate the user about how to create the most effective cross breeze.

Even if the user does not have time to stop and study information, it is possible to present feedback that results in learning. For example, as the window is opened, the system might project information onto the nearby wall that estimates the magnitude of the breeze to be created. The person might notice that, counterintuitively, opening the window further does not always result in a stronger cross breeze. The user's task has not been interrupted, so even if the user is completely uninterested in the information, no attentional disruption has been created. Immediately after the point of action, the system could remove the information.

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Our project

It is the potential impact of this nonintrusive, just-in-time learning on behavior that our group has begun to explore. We are interested in three points in time: the point of decision, the point of behavior, and the point of consequence.[9] How can we use sensors that automatically detect these specific (and sometimes fleeting) moments in time to educate people about controlling their environment? In this example, as the occupants occasionally follow the home's recommendation, they will gradually learn how to efficiently control the temperature in the environment in sophisticated ways. Occupants will understand that lights appear on their windows because it is cool enough outside to set up a cross breeze. They will also gradually learn how to create a cross breeze given the geometry of their house and the prevalent wind direction:

- Using window inlets and outlets that maximize cooling and air flow through the home
- Understanding how long it will take for cooling to occur
- Recognizing the best times to establish intake air
- Knowing how to use fans to facilitate cross-breeze cooling

Most people do not know how to do these things because no one is there to teach them when they need guidance at the point of behavior. A pervasive computing system presenting information at the point of behavior can fill this need.

To measure the impact of point-of-decision messaging, we are developing prototypes on two platforms: "augmented reality" Everywhere Display technology that can place information directly onto objects in a home[6] and portable computing devices such as PDAs and cell phone hybrids. (Based on trends in miniaturization,[10] within five to 10 years we will likely be able to buy an affordable and stylish wrist computer that will convey information to us whenever it is appropriate.) Either method can easily present information at the right place. The challenge then becomes to develop algorithms that can recognize the right time and select a presentation strategy suitable for the given context.

We have been conducting small user studies with mock-up displays and are now implementing prototypes of some of the examples. Figure 1 shows two displays that might appear on a wearable PDA device and convey the same type of information in different ways. An open question that we plan to explore is how the presentation of information and the current context influence the persuasive impact of educational messages.

An important consequence of using such technology for just-in-time teaching rather than control is that the information people learn is transferable to other environments where there

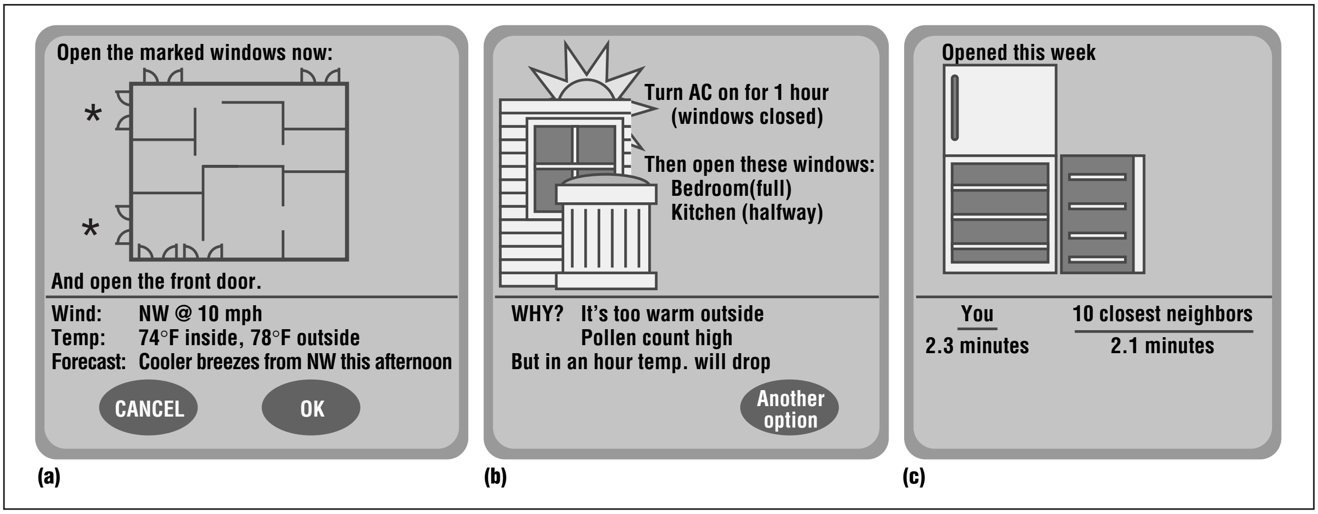


Figure 1. The messages in (a) and (b) might appear on a person's PDA device the moment he or she opens or closes a window. The message in (c) could be displayed on the refrigerator or on a wearable wrist computer just as someone closes the refrigerator door.

is no computer technology. Additionally, the just-in-time teaching scenario might still use automatic control of the windows but in a way that encourages people to use their physical abilities: a young healthy person would be encouraged (using ubiquitous messaging) to exercise muscles by opening the window, whereas a frail, elderly person who cannot lift the window would be encouraged to go to the window and push a real or virtual automatic button. We are also studying how to present persuasive, pervasive messages to motivate small behavior changes during everyday activities. For instance, Figure 1c shows a message that could be displayed on a refrigerator door (or on a wearable wrist computer) just after the door has been closed to encourage awareness of energy conservation. People who are informed that their behavior is out of line with community standards will often naturally change their activity; in this case, a greater awareness of the need to keep the door shut might result.

A living laboratory

Our team's focus affects not only the type of technology we are designing but also our outlook on how we must conduct research to evaluate our work. We cannot evaluate the technologies we develop independently of the people using them. We need to study people using the technology in realistic, nonlaboratory settings for long periods of time and then measure whether our interventions lead to learning and behavior change.

To address this need, we have designed a full-scale single-family home with an integrated and ubiquitous sensor architecture. This facility will serve as a "living laboratory" to study how people live with technology. Applications will use this architecture to acquire information about context. One existing living lab, the Georgia Institute of Technology's Aware Home, is being used for such studies.[1] We will use our lab infrastructure to quantitatively measure and qualitatively study the impact of new technologies on people's behavior in a real living environment. This facility will not be a traditional home that has been retrofitted with technology but an entirely new type of home structure designed from the ground up to serve three functions:

- Demonstrate a new type of building methodology that lets us embed technology within the infrastructure of environments and then easily change and upgrade it.
- Provide an environment in which to scientifically study home life, particularly the relationships between space and information.
- Provide a means for evaluating whether new types of pervasive computing interventions have a long-term and meaningful impact on behavior in the home.

Demonstrating a building methodology

Migration of pervasive computing technology from the lab to the home will require systems that provide value to homeowners without unreasonable cost and disruption to their living environments. For example, technologies such as wall-sized displays will be slow to migrate to the home if they require skilled labor on site to conduct disruptive procedures such as tearing out drywall or installing digital and electrical cables.

We are developing a component-based building system for new homes that will be used to construct the living laboratory. The flexible nature of the methodology will let us transform the lab's physical and digital infrastructure quickly at low cost to study different spatial and sensor configurations. We will use the lab to identify the technologies that are most suitable for retrofitting existing environments.

Eighty percent of the cost of building a new home in the US is spent on field labor and 20 percent on materials. We are interested in reversing this ratio so that four times as much money can be devoted to materials, design, engineering, safety, and technologies in the home. Borrowing from recent innovations in the automobile industry, House_n researchers led by project director and architect Kent Larson have proposed an integrated "chassis–infill" construction system that can be rapidly installed with minimal labor. In one integrated assembly, composite beams and columns provide structure, insulation, sensor arrays, lighting, signal and power cable raceways, and ductwork. The beams use special connectors that lock together easily. Infill sections that form the structure's interior and exterior walls are then "snapped in" to the chassis structure without requiring skilled labor. Finally, interior finishes are snapped on to cover joints and wiring raceways. The resulting structure will be easier to change than conventional housing, require less expensive labor during construction, allow more money to be spent on higher-quality materials and technologies, and easily accommodate sensing infrastructure and new output technologies.

The goal of the system is to empower home-

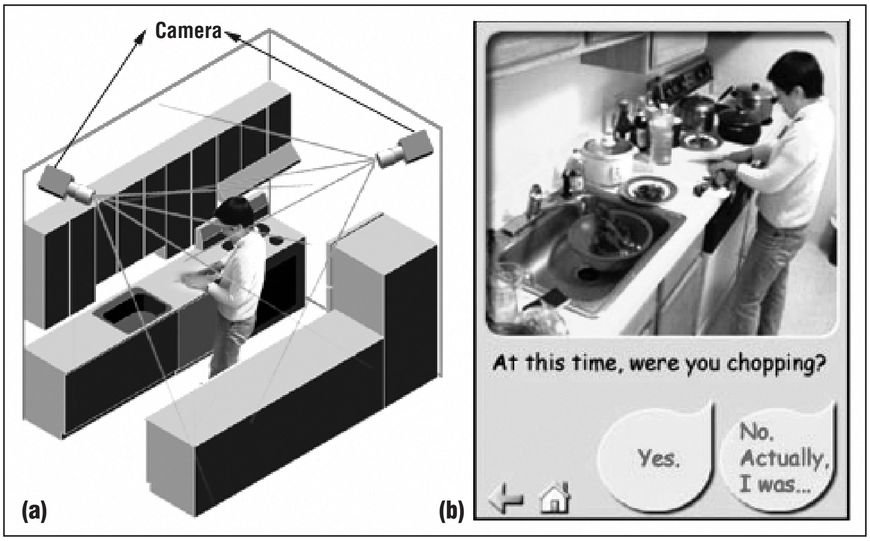


Figure 2. (a) Sensor packs in the beams of the living lab chassis structure will contain tiny cameras that can periodically snap images of the activity in the environment. (b) Image-based experience sampling and reflection algorithms will use a combination of ubiquitous sensing, context awareness, and user interfaces for portable computing technologies to acquire information from home occupants about how they perceive their environment.

owners so that they can replace interior and exterior infill panels at will without costly and messy custom work. Infill components might include integrated wall–floor assemblies, specialty millwork with transformable elements, display systems, networked appliances and devices, and so on. The House_n research team is establishing criteria that might inform industry standards.

The team is designing the chassis components to incorporate multipurpose "sensor packs." These are standardized sets of sensors that easily plug into the chassis beams at regular intervals (one every six to eight feet on average) and can provide computing applications with access to data on interior and exterior environmental conditions to support context-aware computing. The beams are nine feet above the floor. Each pack will minimally consist of a fixed, wide-angle color camera, a microphone, and temperature sensors, but other sensors can also be included (for example, an infrared camera or a particulate sensor). We are developing the sensor packs so that as costs drop they can be retrofitted into existing environments with only a small amount of labor.

Using this construction methodology, we will build a laboratory facility that has visual and auditory input sensors at regular intervals in every room. Researchers will be able to use this infrastructure to both enable and study new context-aware applications. We are currently creating visually based, real-time people- and object-tracking algorithms for environments that use these sensor packs.

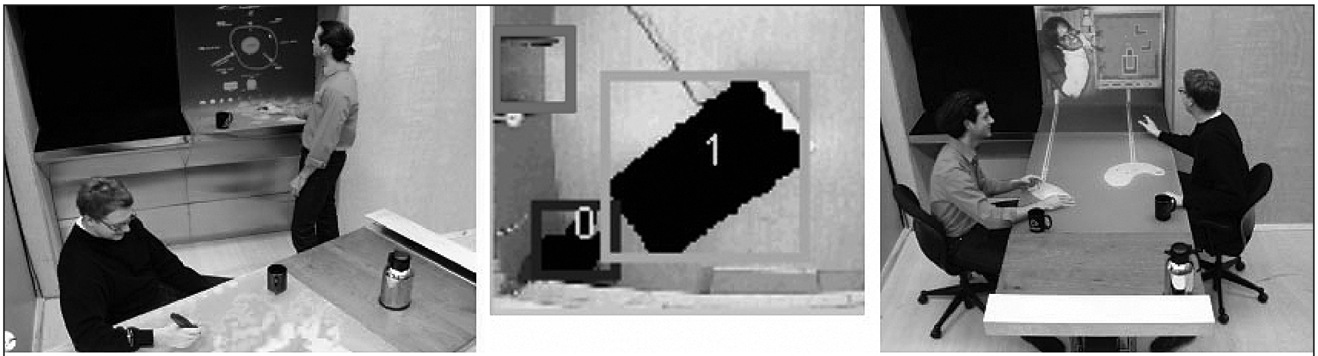
Studying physical–digital interactions in the home

Relatively little research has been done on the relationship between the home and technology, given the importance of the home in life.[11] Once we have constructed a living laboratory, we will use ubiquitous sensing to quantitatively and qualitatively study human behavior in the home—with and without new technologies. To do so, we are developing tools that will use the living lab's sensing infrastructure to acquire and semiautomatically annotate data of interest to researchers.

The lab's infrastructure will make it possible to continuously acquire video, audio, and appliance-level data from every part of the environment. Researchers will be able to identify the types of situations they would like to study and then have access to a variety of data on that activity. For instance, a researcher might be studying television viewing in the home. We are considering the development of tools that will let that researcher make a request such as, "I'd like to see all the video and audio data of activity in rooms where there are television displays and the television was on." The researcher could then manually view only the small subset of relevant data using a video retrieval tool.[12] Other types of data will be available as well, such as positions of people in the environment. An algorithm developer could use the living lab to acquire probabilistic data about people's movement around environments throughout typical days. The lab will provide an excellent resource with which to study, in ways not previously possible, how certain technologies disrupt activity in the home.[5]

For instance, we have built a prototype of a new research tool for a living lab with ubiquitous sensing. The tool queries users for information of value to researchers using a technique we call image-based experience sampling and reflection.[13] Figure 2 shows how it exploits the sensor infrastructure. Suppose a researcher wishes to collect data on the types of activities that a person is engaged in. As the occupants in the living lab go about their business, the system samples and stores images without disrupting the occupants' activity. Then later, at their convenience (for instance, when commuting to work on a bus or waiting in a long line), they can view the images on a portable computing device and easily enter information about what they were doing or how they were feeling about themselves or their environment. The rich contextual information provided by the image or video clip triggers the occupant's memory of the moment when the sample was taken. Researchers can use the data collected directly or through algorithms that respond to user preferences.

Finally, we are studying the relationships between the environment and the use of digital information. For example, by experimenting with displays integrated into devices, we found that physical constraints affect digital design. Figure 3 shows a scenario where a digital table and a digital counter are in an environment that uses computer vision sensing to detect the table's position. From developing such mock-ups, we noticed that the position and surface properties of physical materials in the space implicitly convey meaning about their functionality to users. People generally expect surfaces with the same appearance to have the same digital properties. The user's interaction model is established by seeing one interaction example on a surface and



(a) (b) (c)

Figure 3. A digital table and counter in our lab were (a) designed for edge-to-edge video projection so that they can be abutted against each other. Visual tracking (b) can be used to estimate objects' positions and automatically create larger display surfaces (c) when objects are in close physical proximity.

propagating that model along surfaces with the same "architectural" properties. For instance, users who observe data projected onto one part of a surface or who observe touch sensitivity on one part of a surface assume those properties extend to all parts of that architectural component with similar physical properties.

Similarly, users believe that physical expectations should be matched in the digital world. A kitchen table should move around, and combining two tables should be possible—combining the functionality involves no more than putting the physical objects together. An environment that can automatically track movable objects such as people and tables and that has "edge-to-edge" digital devices can extend the physical metaphor to the digital domain, as in the figure. When physical devices merge, digital interfaces should merge as well.[14] Researchers will be able to study these issues in the living lab.

Measuring effectiveness

The last function of the living lab is to enable the evaluation of certain types of pervasive computing applications. We are particularly interested in studying how context affects the presentation and motivational impact of information presented in the home environment over long periods of time.

Our group is collaborating with researchers in a variety of fields as we design the living lab. The challenge is to design a facility and infrastructure that lead to verifiable and quantifiable advances in understanding how to use pervasive computing in homes to motivate learning and behavior change. Studies run in this lab will have a limited sample size (that is, one house and a small set of long-term occupants), and must address experimental problems such as the Hawthorne effect (a distortion of research results caused by the subjects' response to the special attention they receive from researchers). However, our discussions with researchers in fields as disparate as preventive medicine and product development have led us to believe the living lab will enable studies that can take place in no other way.

For instance, we have built a prototype system that uses a PDA device and context recognition (in this case location within the environment and proximity to large objects) to detect the onset of congestive heart failure.[15] The software uses a Bayesian framework not only to integrate evidence of heart failure but to select meaningful questions to ask a person in a home given the context. Cameras monitor the environment and detect contextual cues (for example, if someone is probably sleeping because of lack of movement and proximity to the bed). A diagnostic system pools evidence acquired over the last month and, at any moment, can determine which question that is appropriate for the given context will yield the most valuable evidence. The home occupant carries a PDA device. Whenever the person pulls it out to use it, the PDA displays a simple but meaningful question given the user's current context. The person quickly clicks one multiple-choice answer with almost no interruption to the intended task. Meanwhile, the system adds this new evidence to the diagnosis information. If the system detects progression toward CHF onset, it can notify the person that a medical professional should be contacted.

Systems that provide information to people via computerized telephone conversations have proven effective at motivating behavior change.[16] Will systems that present motivational information and acquire data for preventive diagnosis such as our CHF system work when placed in the complex environment of the home? Why or why not and to what degree? How does context affect the way the information is received and attended to? This is the type of investigation we, along with our collaborators, foresee occurring in the living lab.

Different types of studies will require a variety of research protocols. In addition, exactly who lives in the home and for how long will be determined based on the studies that are selected for the home after construction. As an example of how measurement of learning might take place, consider the earlier cross-breeze example. Assume that the set of studies selected for the home (there will be nonconflicting studies running in parallel) require three-week stays of subjects. During each subject's stay, the window could be monitored for open and close events using sensors embedded in the window or visual sensors in the chassis beams. Prior to entering the home, subjects would complete a survey that assesses their understanding of their living environment, including climate control and cross-breeze management. While each set of subjects is living in the home, they will manipulate the windows. If need be, the system could also manipulate the temperature in the home to ensure that the occupants open and shut the windows. The system will log the video, audio, and other (for example, temperature) sensor data for any instance where someone manipulates a window.

The sample size would be small ($n < 24$ for eight sets of subjects where three members of each family can operate the windows). Although some studies might only show trends and not statistically significant results, researchers will be able to qualitatively study the technology's impact using the data automatically collected before, during, and after the point of decision. Does the user appear to be attending to the information at the point of decision? Does the presentation of the information create a disruption? The precise experimental protocols will differ based on the problems being studied. Our goal is to design a tool that lets researchers from various disciplines design and execute studies that cannot be accomplished without the home's ubiquitous sensing infrastructure.

Our proposal for a home that teaches occupants how to take control raises the following three challenges, among others, that would benefit from further exploration:

- *Measuring learning or behavior change*. How can we develop algorithms and systems that use context-aware sensing to measure the impact of new technologies on learning and behavior over long periods of use?
- *Using context-based simulation*. One of the most effective ways to learn is through guided exploration via simulation. Can we create real-time simulations of environments that can be used to show people the impact of their actions at the point of decision? For instance, if I open this window now to this degree, what is the estimated impact on the breeze in my home one hour from now? Also, can these systems exploit the Internet for automatically acquiring required data?
- *Detecting the point of decision*. How can we identify the point of decision for various activities and then detect these moments in time automatically?

We invite researchers who might be interested in conducting studies in a living laboratory to contact us.

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