Labscape: A Smart Environment for the Cell Biology Laboratory

A user-driven system, although technologically conservative, embraces a central goal of ubiquitous computing: to enhance the ability to perform domain tasks through fluid interaction with computational resources. Smart environments could soon replace the pen and paper commonly used in the laboratory setting.

Larry Arnstein, Chia-Yang Hung, Robert Franza, and Qing Hong Zhou
University of Washington

Gaetano Borriello, Sunny Consolvo, and Jing Su
Intel

Labscape is a smart environment that we designed to improve the experience of people who work in a cell biology laboratory. Our goal in creating it was to simplify laboratory work by making information available where it is needed and by collecting and organizing data where and when it is created into a formal representation that others can understand and process. By helping biologists produce a more complete record of their work with less effort, Labscape is designed to foster improved collaboration in conjunction with increased individual efficiency and satisfaction.

Many of the smart environments that the ubiquitous computing research community has built so far have served primarily as platforms for technology evaluation.[1–4] These environments are crucial to the research enterprise because they provide a sandbox in which to safely test and evaluate experimental technologies. In contrast, our emphasis on meeting an authentic user community's rigorous requirements has produced insights into the design approaches, evaluation methods, and implementation challenges associated with creating usable, extensible environments. These insights in turn help guide and influence our technology-based research.

The application domain

A cell biology experiment involves observing how cell states change in response to some form of stimulus or treatment. Experiment outcomes usually take the form of charts or images associated with measurements corresponding to cell state features. For example, the image in Figure 1 indicates the effect on gene expression (ribonucleic acid, or RNA, production) that 10 different drug candidates had on otherwise similar cells. Columns correspond to the cells treated by different drug candidates, and rows correspond to gene activity expressed in the form of molecular concentrations. The darkness of the band at each row–column intersection indicates a specific gene's activity level under the drug candidate's influence. A technique called *gel electrophoresis*, in which researchers use an electric field to sort molecules by size, produces the readout. When genes produce different-sized RNA molecules, this technique can help discriminate between them.

In the common biochemical procedure called *polymerase chain reaction* (PCR), genetic material (RNA, in this case) is amplified (repeatedly duplicated) so we can detect the molecules' presence by using the electrophoresis technique. Thus, the entire experiment consists of

- Exposing cells to drug candidates
- Destroying the cells and performing PCR on their molecular components
- Applying electrophoresis
- Taking an image of the gel to capture the results

A biologist must communicate many details of such a procedure for a third party to understand the experiment's results: some examples are the identities of the drug candidates, the history and state of the cells, and the details of the PCR chemistry. Even the camera's exposure setting might be important for comparing the results of two different experiments.

Labscape shares many of the objectives and characteristics that are important to the ubiquitous computing community. Like classroom 2000,[5] we seek to "automate the capture of live experiences and provide flexible and universal access to those experiences later on."[6] In our case, we must capture formal, detailed representations of laboratory procedures as the work is performed. And it must be accomplished in an environment that is characterized by significant user and device dynamics and the need for users to stay focused on both physical and intellectual tasks.

Figure 2 shows a map of a biologist's movements within the first 60 minutes of an experiment in the pre-Labscape laboratory. We produced the map from extensive video recorded to support detailed analysis of where and when information access and physical activity occur during an experiment's course. In addition to the high degree of physical movement evident in the map, several characteristics of laboratory work influenced our design:

- Experimentation requires interleaving of physical and mental tasks.
- Information needs arise throughout the environment.
- Laboratory work involves interaction and interoperation of heterogeneous devices, including instrumentation and traditional computer and human interface components.

The single laboratory workstation in Figure 2b exemplifies the information management challenge that we're addressing: the lab bench is a place where information is both created and needed, yet it remains a largely computer-free zone. This separation exists because the traditional tools biologists use, such as spreadsheets and other desktop applications and computing devices, are suited neither to the interaction nor information needs of someone managing complex physical procedures. Instead, biologists tend to rely on paper-based support systems that, although limited in many ways, have simple, reliable, and familiar interfaces. However, the number of concurrent laboratory activities that a researcher can manage is frequently limited by how much procedural information he or she can mentally track. Beyond basic inefficiency and the potential for error, reliance on paper systems results in significant human effort for documenting laboratory work and for transforming such records into a form that others can understand and apply.

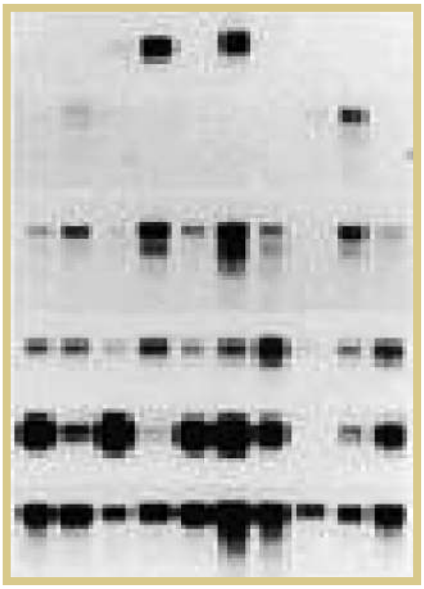


Figure 1. An example of an electrophoresis gel image.

The design strategies that we ultimately applied to these problems have let us begin to establish authentic user communities in two separate institutions: the immunology laboratory of the Cell Systems Initiative — a part of the University of Washington's Department of Bioengineering—and Immunex Corporation in Seattle. The system has reached a level of stability and usability at CSI that supports rigorous, quantitative evolution of how well Labscape is integrated into the laboratory's physical and intellectual workflow.

Design strategy

We originally aimed to capture experiments without distracting the biologist. Emphasizing flexibility, we based our first approach on sensors and recognition systems that attempted to construct a representation of the experiment while minimizing explicit interaction with the biologist—limiting such interactions to error detection and correction as needed.

This approach failed to lead to a useful system for two reasons. One, we could not identify sensor technologies that would provide the detail, completeness, and reliability sufficient to produce a useful record of the experiment without dramatically altering the physical working environment or constraining the biologists' actions. As an example, the logical structure of an entire experiment could be exquisitely sensitive to fine-grained sensing errors, such as those that might occur when trying to determine over which square-centimeter area a pipette tip is hovering when a small volume of liquid is dispensed. Two, although error correction for a hypothetical, reliable recognizer might require little or infrequent user input, error detection still requires the user to extensively monitor system output. This might not be a problem when the user would be monitoring system output anyway, as in a speech or gesture interface to a graphics editor or other typical desktop application. But, in the laboratory, monitoring a recognition-based capture system would be a new and difficult task to perform in conjunction with the experiment's physical and intellectual demands.

Realizing that we could not rely on sensors and recognizers to automatically capture structured representations of experiments, we arrived at the following restatement of our objectives: capture experiments through fluid interactions that help meet the experimenter's immediate information needs. We call this system a *ubiquitous laboratory assistant*. We designed it using the following guidelines:

- The system should be compatible with almost any cell biology laboratory (meaning it should rely only on basic computing equipment and networking infrastructure rather than on a rich, sophisticated sen-

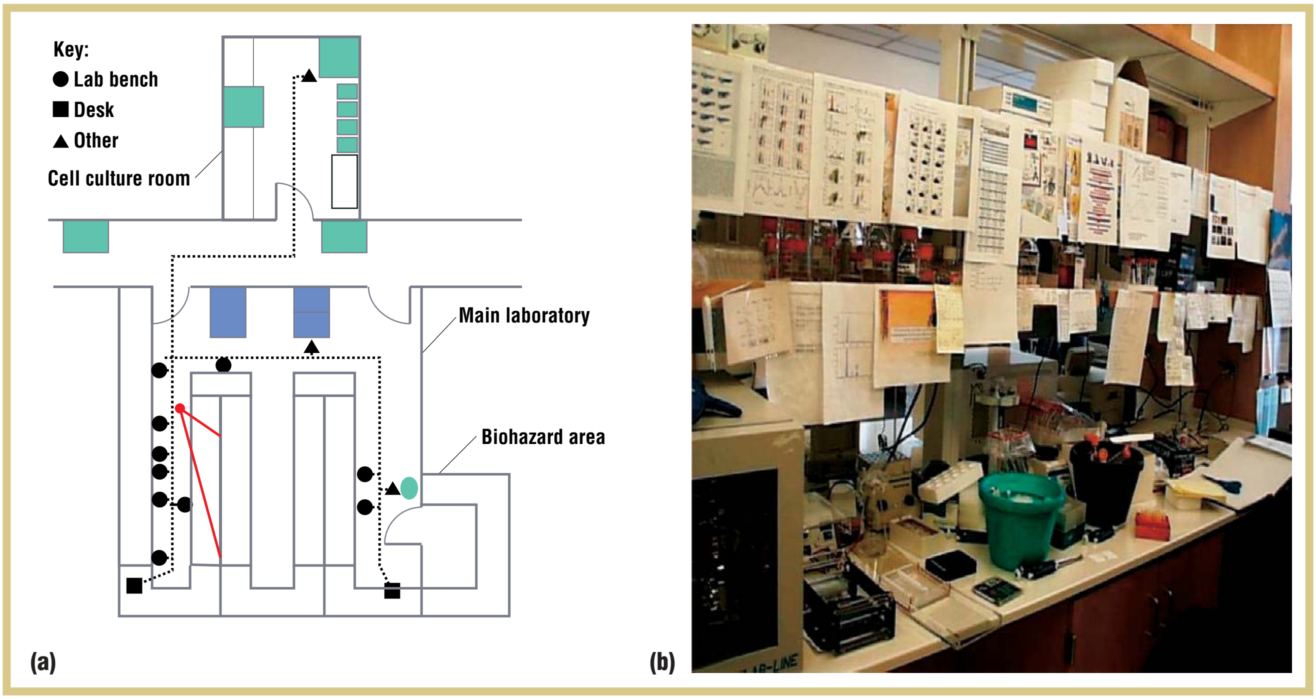


Figure 2. (a) A simplified map of a laboratory that shows a biologist's location for 60 minutes of a typical session. This map does not show the complexity of movement throughout the lab; it merely shows the different locations that the biologist visited. During the 60 minutes, the biologist changed locations a total of 76 times and used information resources in several locations. We show the camera's viewpoint in red. (b) A single laboratory workstation.

sor base and deep integration with existing instrumentation).

- The Labscape interaction model should suffice even when it can only use unambiguous interface modalities (mouse, keyboard, touch screen) rather than recognition-based modalities (speech, gesture, handwriting).

These guidelines do not preclude the use of sensors and recognizers; they only state that the system must be usable and effective without them. They also ensure that the system can provide appropriate user feedback and input methods that let users continue to work even in the presence of recognition errors, sensor limitations, or component failures.

The focus on a minimal system lets us more easily determine the system's baseline effectiveness, against which we can further measure refinements and enhancements. Thus, we can quantitatively assess our efforts to create an increasingly proactive and collaborative environment.[7]

Given our new objectives, we embarked on a user-centered design approach that consisted of extensively observing laboratory behavior, interviewing biologists, transcribing biologists' narrations of their work, and coding and analyzing over 18 hours of video. Our findings strongly influenced our design decisions and fall into two major categories:

- Although laboratory work appears complex and the tools and instruments are highly diverse, biologists perform only a few types of abstract operations, although in many different ways.
- Lab workers have information needs that current approaches don't address well. Some examples include the need to capture information in a variety of formats, refer to historical data, keep track of progress against a plan, and share information with others.

Let's examine these findings in detail. We'll describe how they helped us arrive at a design for Labscape that achieves experiment capture through voluntary, explicit, and task-appropriate interaction.

Abstraction for laboratory procedures

Anything that happens in a laboratory environment has a plausible impact on an experiment's outcome: ambient room temperature, how long a sample sits on a lab bench, how far out of calibration a particular tool or instrument was at the time of use, and so on. Thus we are forced to trade off between the difficulty of obtaining such details and their potential utility. The key to rapidly developing and deploying a useful system is to discover the highest level of procedural abstraction in the captured record that still provides significant value to the biologist.

For example, flow-cytometers, mass spectrometers, and electrophoresis systems perform different tasks. Flow-cytometers sort whole cells in a moving stream into bins based on several properties, including the fluorescence of cells when a laser stimulates them. A mass spectrometer sep-

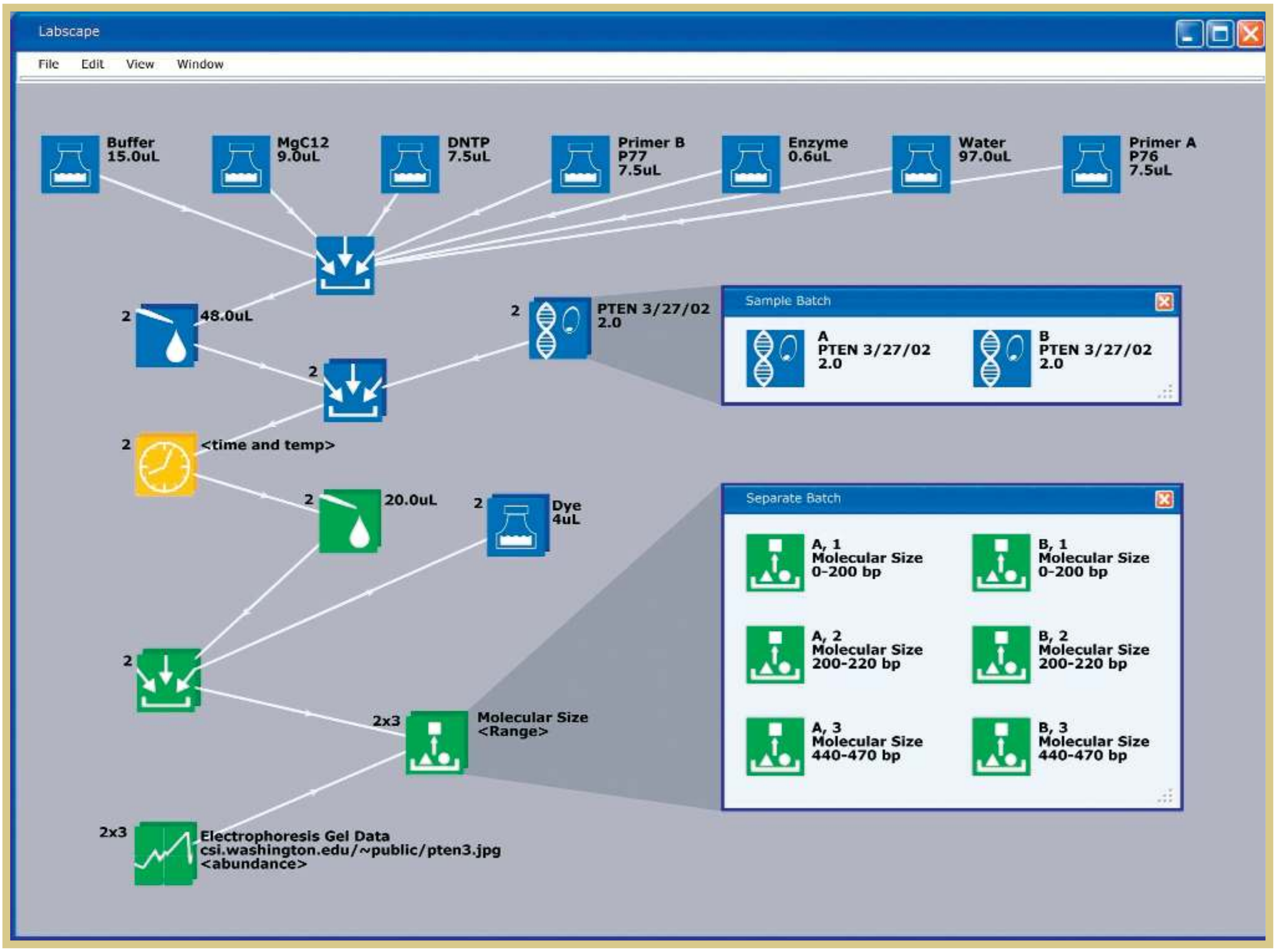


Figure 3. A graphical representation of a complete sample flow graph for a polymerase chain reaction procedure. The URL attached to the detection operation at the end of the procedure represents the image of the electrophoresis gel produced by the separation step. The numbers at the upper-left corner of some of the icons indicate the sizes and dimensionality of batches of operations. The insets show contents of two of the batches. Icon colors correspond to states of completion of each step (blue for completed, green for ready, and yellow for in progress).

arates molecules by the ratio of mass and charge, and gel electrophoresis is typically applied to genetic material or proteins to select by size or electric charge. We can describe the operation of all these instruments as *separation*—sorting cells or molecules into bins according to value ranges of the physical properties. In fact, the essential procedural information for all the laboratory work we have observed can be represented by flow-graph arrangements of simple abstract operations:

- *Combination*. Forming a single, possibly heterogeneous, collection of entities from two or more collections.
- *Incubation*. Exposing a collection of entities to specific, possibly changing, environmental conditions over time. We can specify such conditions in terms of temperature, acidity, salinity, humidity, physical vibration, and so on.
- *Dispensing*. Extracting a collection of entities from another collection non-selectively, where both collections exhibit the same relative distributions of entities.
- *Separation*. Extracting a collection of entities from another collection selectively, based on some physical property and a particular value range for that property.
- *Detection*. Recording the physical properties of an entity or collection. Such a recording can take the form of an image, number, table, natural-language description, movie, spectrum, or other data types.
- *Storage and retrieval*. Naming a collection for later retrieval or reference.

Although we do not claim to have identified all possible abstract operations, we are confident that our list will remain short even as the diversity of techniques and devices increases. Figure 3 shows how we organize these operations into a directed acyclic graph (DAG) structure that we refer to as a *sample flow graph* (SFG). The nodes in the graph represent the operations, whereas the arcs (or arrows) represent the flow of collections between them. Operations produce, at most, one outgoing arc, so they can be identified with the collections that they produce. Each node has appropriate parameters specified.

The SFG can accommodate the physical world's actual complexity and diversity in two ways: by annotating the operations in the flow graph with parameter values or by defining numerous, specific operation types that inherit the semantics of one or more of the base set of abstract operations. Institutions only have to agree on the base set of operations to ensure interoperability and mutual understandability between their databases. We have confirmed through interviews and direct observation of post-Labscape behavior that the level of abstraction we have chosen suffices for record-keeping purposes.

If a biologist can produce an SFG representation of each procedure as it is performed in the laboratory, we have met our basic capture requirements. Fortunately, the SFG also provides a convenient contextual framework for presenting and capturing information during laboratory work.

The information needs of laboratory workers

Our findings about biologists' information needs, and the associated design implications, are best understood in terms of the three not necessarily distinct phases that we have observed in the typical laboratory workflow: preparation, execution, and documentation.

The preparation phase

The outcome of the preparation phase is a working document that the biologist carries into the laboratory where it serves as the primary information support system during the execution phase. The working document could contain details of how to do the procedure along with space to record data obtained in the laboratory. The key observation is that the working document is usually not a complete, stand-alone representation of the planned work. Biologists tend to make small changes to basic procedures over time, so the working document typically consists of only the details that change from one instance of a procedure to another. Because lab workers, like most people, try to minimize the amount of information they must write down, they tend to rely on memory for the bulk of the procedure's details.

When using Labscape, the biologist's goal in the preparation phase is to produce or modify an SFG representation of the planned work. Input is minimized without loss of flexibility by letting the biologist use any previously completed procedure (an existing SFG) as a starting point. Consistent with the biologist's need to minimize input, the amount of user interaction necessary in planning is proportional to the extent that the planned work differs from previous experiments or from established template procedures (protocols). However, unlike the paper system, the outcome is always a complete, self-contained description of the procedure that is electronically accessible and widely comprehensible. Thus, we expect our system to be at least equivalent in terms of interaction overhead while offering additional benefits in collaboration and reduced reliance on memory. The SFG structure serves the dual purpose of presenting procedural details while providing a logical context into which we can place data and observations.

The execution phase

During execution, roles of the information support system include presenting the biologist with a clear representation of the plan, providing a means for keeping track of progress, and helping record data and observations that occur during the procedure. In a traditional environment, the individual biologist's experience suffers because information is tied to physical objects (notebooks and working documents) that support a limited set of interaction models and data types. The collaborative experience suffers from these limitations as well and from the fact that information is not represented in a complete, structured, and standardized way.

Directly addressing these issues, we designed our system to migrate structured information about procedural plans and records to the point of need, as the biologist moves about the laboratory environment. For a minimal Labscape configuration, we assume that each biologist has a modern computer in his or her personal office environment, and that each shared work area in the laboratory is equipped with a touch-tablet computer (for example, Futjitsu Sylistic 3400 or Intel Celeron 400 MHz), a USB numeric keypad, a small wireless IR keyboard that can be tucked away, and both wired and wireless networking to allow the tablet to be physically removed from its mount without losing connectivity. Some of the work areas might also be equipped with scanners (barcode or RFID). The touch screen can be operated by finger, stylus, or using the pipettes that are ubiquitously available in the laboratory (see Figure 4). The current system can support several laboratory workers migrating their own Labscape interface to and from sufficiently equipped shared and personal work areas. To adequately cover the work areas our subjects most often used required five tablet computers distributed throughout the laboratory.

Figure 4. A minimally configured Labscape work area, including a touch-tablet computer, barcode scanner, numeric keypad, and small wireless keyboard.

In execution, the biologist's principal goal is to transform the plan representation (the SFG) into a record of the actual work performed. At a minimum, this only requires indicating to the system that all the work was completed as planned. However, a biologist will likely want to use Labscape to access more information, change the plan, track progress, and record observations and data produced by laboratory instruments.

We aim to offer benefits over the traditional environment with respect to all three requirements of the information support system described earlier.

Plan access and presentation. Paper-based systems have several limitations with respect to access: they tend to compete for space on the lab bench with the materials and tools needed for the experiment; transporting them between work areas when the biologist's hands are busy with samples and tools is difficult; and as mobile physical objects, they pose contamination risks when transported in and out of sensitive areas. Permanent notebooks might actually be banned from certain laboratories that contain radioactivity and biohazards. In contrast, touch-panel displays mounted upright, behind a work area, occupy the biologist's natural view without obscuring his or her work. Moreover, by moving only data and state, Labscape eliminates the burden of transporting physical objects while reducing contamination risk.

Figure 3 shows the type of information that is always available to the biologist with Labscape. We find that users can frequently get the information they need with a quick glance at the nearest screen. However, Labscape's main advantage with respect to access is that the SFG provides a window into a database that can answer a variety of questions on the spot, which would otherwise require an interruption of the workflow. As examples, biologists raised two questions during our trials that required reference to a not-readily-available information source, but which a Labscape database could have answered directly: "Show me if this control sample I am using was positive or negative in the original assay" and "Show me the volume scaling factor that I used the last time I had a low DNA concentration reading on the spectrophotometer."

For presentation and access, Labscape offers unique capabilities for both interaction overhead and utility. Because of the ubiquitous database access, benefits increase with more users, although a single user can realize the system's full benefits.

Progress tracking. In the traditional workflow, biologists use notations on paper to keep track of progress in a procedure during breaks and interruptions or when the next step in the procedure cannot be deduced by looking at the physical setup. For example, when transferring clear liquids from one set of containers to another, telling which transfers are complete and which are still pending might be difficult. Depending on the situation, the biologist could record progress at varying levels of granularity. In Labscape, the user indicates progress through simple touch interactions that visually transform the plan into a record of the experiment, so finer granularity of interaction results in better temporal resolution in the record. The Labscape user is free to trade off between precision in the experimental record and the number of interactions required. For simple progress tracking purposes, the ability to record temporal information through touch interactions counts as an increase in utility with the same or reduced interaction overhead.

In our formal user study, biologists tracked progress with finer granularity when they used Labscape than they did in the original environment. As an example, one of our subjects would mark operations in the graph as completed just before switching to a different task. In a later interview, the subject stated that without Labscape, she would have either postponed the other activity or tried to manage it mentally, thus reducing efficiency and increasing the potential for error.

The standard electronic representation of progress in Labscape lets scientists more easily cooperate with colleagues, laboratory technicians, or students at a finer level of granularity. In the case of the small team of closely cooperating biologists that we observed, we expect the plan's visual transformation to eliminate confusion and reduce the potential for mistakes.

Recording information. Labscape offers two major advantages over the traditional workflow with respect to data capture: recorded information can take the most appropriate form (such as freehand drawings, text, audio clips, videos, or images), and we can attach such information to a specific component of the SFG representation, thus providing the context for later retrieval. Attaching a drawing or a spoken comment to a particular sample at a specific point in the procedure ensures that the note can resurface during a data analysis phase that occurs long after the physical experiment is completed. Note that multimedia annotation does not require the system to interpret or recognize free-form user input.

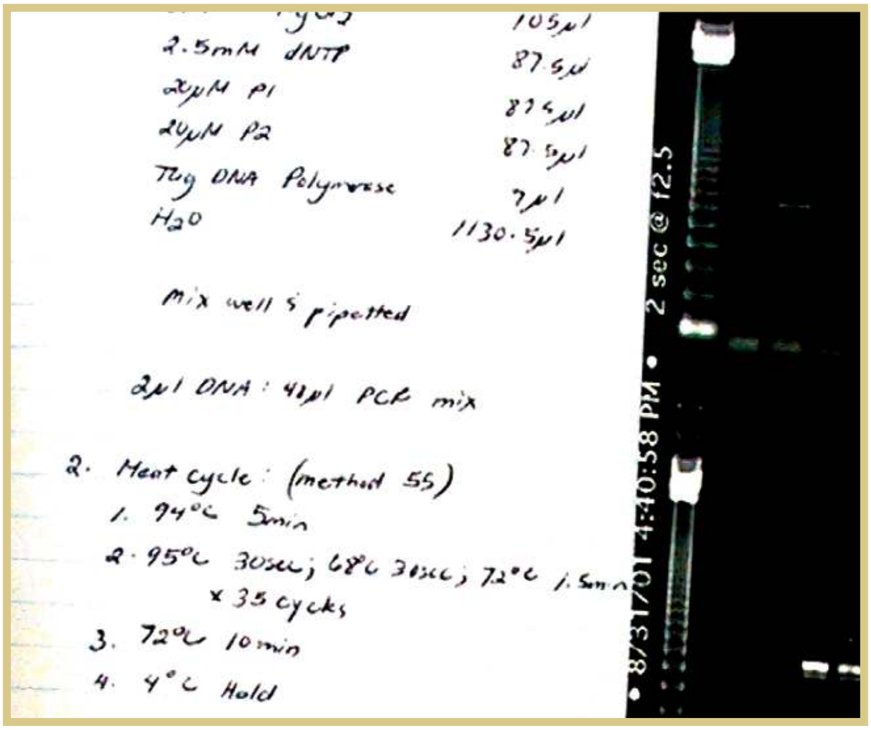
Figure 3 shows how the SFG representation provides an organizing structure for all data and observations produced during the experiment. Data produced by instruments are linked to specific *detection* operations in the SFG, sample identifying information (or tags) coming from scanners or direct user input are attached to *storage* and *retrieval* operations, and unstructured annotations and sensor data can be attached to any node in the SFG. Data such as scanned ID tags or URLs pointing to new data files can be linked to operations in the SFG through a touch on the screen. The URLs are created automatically and forwarded to the appropriate user's interface when the data files are created. The result of working in the laboratory is a complete, accurate, widely understandable representation of the experiment.

By lowering the barriers, we believe biologists will be more likely to record information that might not be immediately needed. For example, when contamination problems arise in a laboratory, being able to trace tools and the reagent lot numbers involved is important. We have observed biologists recording this information only after such problems arose—when it might be too late to diagnose the problem quickly and cheaply.

Documentation phase

In the documentation phase, the biologist enters a formal record of the laboratory work into the laboratory notebook (see Figure 5). Although in some cases the working document serves directly as the formal record, we have observed that documentation is often a completely separate task that could occur up to several days after the actual work is completed. A typical notebook entry might involve transcribing information from working documents, adding references, and physically cutting and pasting printed results. Because this is a manual process, the amount of detail in the record is proportional to the amount of effort expended and could include

Figure 5. A laboratory notebook entry for the PCR procedure without Labscape.



only what the experimenter thinks is important at the time. References to other documents might be included, but some details could be simply assumed or omitted. In some cases, the working document is used directly as the formal notebook entry.

In the ideal Labscape scenario, documentation and execution are indistinguishable tasks. Figure 6 shows a spontaneous laboratory notebook entry that resulted from a biologist's first use of Labscape. Without direction from us, the biologist used two screenshots from Labscape as the bulk of the formal notebook entry. The lower screenshot shows details associated with a batch of samples represented by a single icon in the top-level flow graph view. The gel image pasted on the page can also be accessed by the URL associated with the last step in the flow graph from anywhere in the laboratory. This result strongly supports our hypothesis that the abstract representation suffices for understanding and communicating laboratory results.

Lessons learned

Based on our Labscape experience, we think a certain set of strategies might be generally applicable to the design of smart environments.

UI precedes AI

Having built our system to deliver adequate utility through a graphical user interface alone, we can now incrementally augment the experience by selectively adding sensing and AI technologies. For example, we have shown that it is possible to enable a handheld electronic pipette to wirelessly transmit aspiration and dispensation events. We could imagine flagging the user when a sequence of such actions does not correlate with the user-level task representation, thereby catching a difficult-to-trace source of error without placing a new burden on the user. Such effective use of sparse sensing data would not be possible without the task context provided by the SFG representation.

As a more generally applicable example, we deployed an active badge-like system for location tracking to control application migration and to allocate laboratory resources.[8] Enforcing our design constraint of always enabling a minimal system, users can touch an icon on the most convenient display that is labeled with their name. This manual system is adequate but not ideal because it requires user interaction and cannot provide intermediate movement data, which would also be useful. However, a system that relies only on the active badge might be worse because the user could not correct system mistakes. By running both systems in parallel, explicit user interactions can train the location system, possibly eliminating the need for the extensive configuration typically associated with such systems. As sensing systems improve, Labscape will become increasingly proactive without ever eliminating the user interface.

Values matter

HP Labs' CoolTown Exploratorium[9] application shares an important characteristic with Labscape: both support mobile individuals engaged in tasks that demand physical and intellectual involvement. Despite this similarity, the two projects have different outcomes because of user values. In a science museum, interaction with the physical exhibit is the point of the experience—a captured record of the experience has value, but not at the expense of distraction from the exhibit. In biology research, the value is much more in the record than in the experience. Interaction requirements that contribute to a better experiment record could be acceptable, especially if the laboratory work is simplified as a result. As a consequence of these divergent values, HP's interface has become increasingly implicit whereas ours has become increasingly explicit. We are in the process of installing Labscape into a Seattle public high school biology laboratory, where the value system is more like that of a museum than that of our research laboratory. In this setting, Labscape will be cast in a tutorial role to reinforce the skills and techniques associated with a process. The SFG's organizing structure will be used to present multimedia demonstrations of the biochemistry explanations. This deployment will provide an interesting counterpoint to our professional laboratory applications.

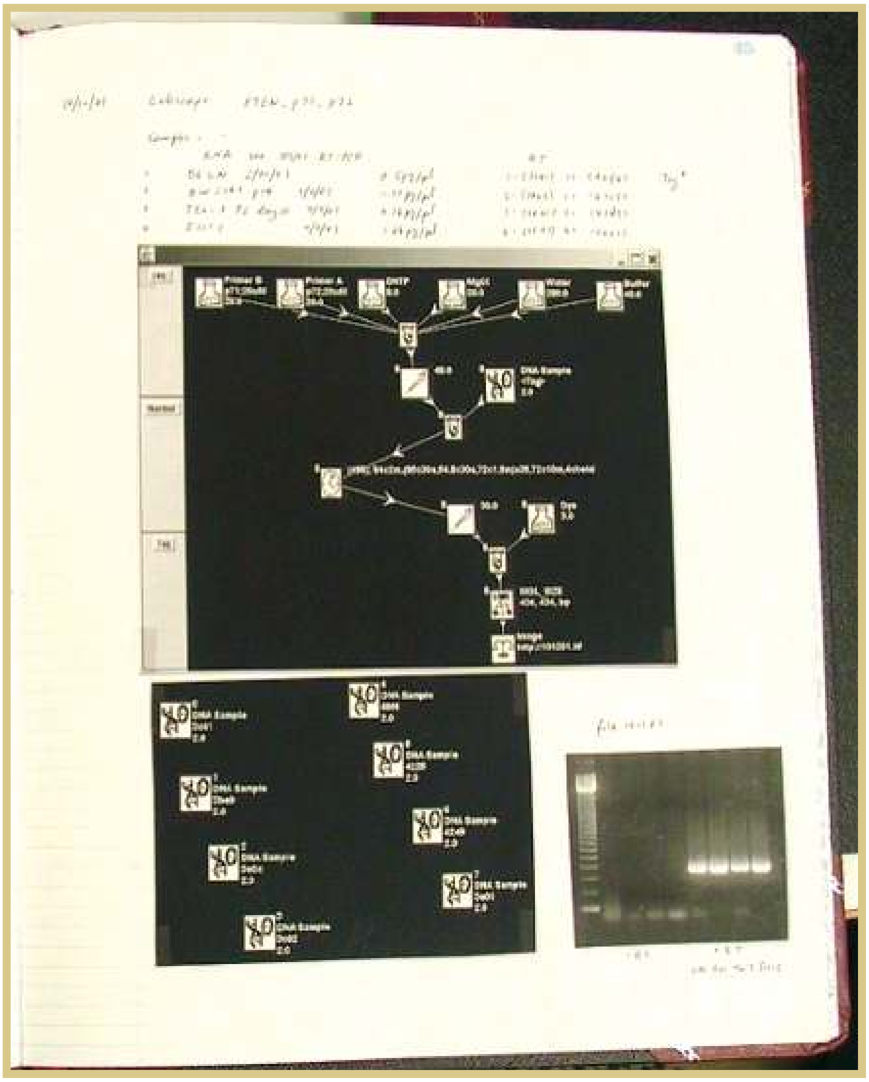


Figure 6. A laboratory notebook entry for the PCR procedure with Labscape.

We have completed one round of informal user studies at the University of Washington and are now engaged in a formal evaluation that will quantify the benefits and costs of using Labscape.[7] Using coded video observation, interaction logs, and interviews, we are attempting to quantify characteristics of the working environment (how information and physical activity are interleaved before and after Labscape, how much physical movement is due to information retrieval, and how collaborative behavior changes as a result of using Labscape). At the same time, we are deploying Labscape in two more sites: the immune cell purification laboratories of the Immunex Corporation and a Seattle public high school biology laboratory. Immunex is interested in the quality control potential that Labscape offers in a procedure that is crucial to its scientific mission. The high school is interested in Labscape for its potential to help students see the big picture of an experiment without losing important details.

The reason for our intense focus on users (biologists, students, lab administrators, and so forth) is to create a sustainable test bed for evaluating new ubiquitous computing technologies in terms of their impact on real users' experiences. Although Labscape might appear to be simply a traditional application that migrates, it is in fact the ground floor of a ubiquitous computing environment that breaks down the digital divide between office and laboratory environments. By establishing a user base and by carefully characterizing the baseline environment, we can continue to iteratively augment the environment and assess the impact of ubiquitous computing technologies and interaction design.

Invisible infrastructure

Although the Labscape interface is explicit and will likely remain so to some degree, we have gone to great lengths to ensure that the computing infrastructure is invisible. Our goal is to ensure that the biologist does not have to cross the semantic Rubicon that Tim Kindberg and Armando Fox describe.[10] For example, we did not want our users to worry about persistence and lost work, so there should be no need for explicit file I/O or for defensive backups of the application's state. Nor should the biologist be acutely aware of network topology, including how various I/O devices connect to host computers embedded in the laboratory. Delivering a flexible, dynamic user experience along with a high degree of reliability proved to be a challenging problem. We implemented Labscape twice: once using only standard tools for distributed systems (TCP sockets and shared file systems) and once using one.world,[11] a runtime system designed specifically to support ubiquitous applications. Although the two implementations are functionally and architecturally similar, we found a significant difference in the degree to which they each exhibited the required properties.[12] That one.world was not designed specifically with Labscape in mind suggests ubiquitous applications have many requirements in common and can thus benefit from a system support layer for coping with dynamic environments.

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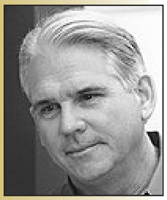
the AUTHORS

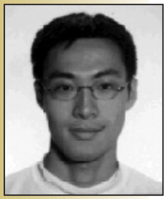
Larry Arnstein is a research assistant professor in the Department of Computer Science and Engineering of the University of Washington and is affiliated with the University's Cell Systems Initiative. His research interests include the design of ubiquitous computing systems with applications in biotechnology. He received a PhD in electrical and computer engineering from Carnegie Mellon University. He is a member of the IEEE and ACM. Contact him at the Dept. of Computer Science and Eng., Univ. of Washington, Box 352350, Seattle, WA 98195; larrya@cs.washington.edu.

Gaetano Borriello is the director of the Intel Research Laboratory in Seattle, on leave from his appointment as a professor in the University of Washington's Department of Computer Science and Engineering. His research interests include design, development, and deployment of computing systems, with particular emphasis on mobile and ubiquitous devices and their application. He has a BS in electrical engineering from the Polytechnic Institute of New York, an MS in electrical engineering from Stanford University, and a PhD in computer science from the University of California, Berkeley. He is a member of the IEEE and ACM. Contact him at Intel Research Lab., 1100 NE 45th St. 6th Floor, Seattle, WA 98105; gaetano.borriello@intel.com or gaetano@cs.washington.edu.

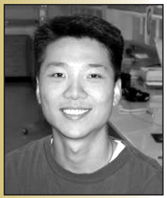
Sunny Consolvo is a member of the research staff at Intel Research, Seattle. Her research interests include user-centered design and user study techniques. She is a member of the ACM and ACM SIGCHI. Contact her at Intel Research Seattle, 1100 NE 45th St., 6th Floor, Seattle, WA 98105; sunny@intel-research.net.



Robert Franza is research professor and director of the Cell Systems Initiative in the University of Washington's Department of Bioengineering. His research focuses on understanding dynamic information systems in cells. He received his BS in philosophy of science at St. Mary's University in San Antonio and his MD from Georgetown University. Contact him at the Dept. of Bioengineering, Univ. of Washington, Box 358070, Seattle, WA, 98195; bfranza@u.washington.edu.



Chia-Yang Hung is a member of the research staff of the Cell Systems Initiative at the University of Washington. His research interests include ubiquitous computing applications and middleware for Internet computing. He has a BS in computer engineering from the University of Washington. Contact him at the Cell Systems Initiative, Dept. of Bioengineering, Univ. of Washington, Box 358070, Seattle, WA 98195; cyhung@u.washington.edu.



Jing Su is an intern at Intel Research Laboratories in Seattle. His interests include software for embedded systems, distributed applications, and ubiquitous software systems. He has a BS in computer engineering from the University of Washington and is a member of the ACM. Contact him at Intel Research Seattle, 1100 NE 45th St., 6th Floor, Seattle, WA, 98105; jingsu@cs.washington.edu.

Qing Hong Zhou is a a senior research scientist in the Department of Bioengineering at the University of Washington. Her research interests include T cell signaling and T cell-antigen-presenting cell interactions. She has an MS in pathobiology from the University of Washington and an MD from Hunan Medical University. Contact her at the Dept. of Bioengineering/Cell Systems Initiative, Box 358070, Univ. of Washington, Seattle, WA 98195; qinghong@u.washington.edu.

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