To appear in Kaptelinin, V. & Czerwinski, M. (Eds.), *Beyond the desktop metaphor: Designing integrated digital work environments* (pp. 195–222). Cambridge, Massachusetts: MIT Press, 2007.

Supporting Activity in Desktop and Ubiquitous Computing

Stephen Voida, Elizabeth D. Mynatt, and Blair MacIntyre

The emergence of the ubiquitous computing paradigm in the early 1990s marked the beginning of a new era of computation in the workplace. Weiser envisioned a world in which we no longer focus our attention on a single box while we work with information; rather, the proliferation of small, powerful, connected computing devices would allow computation to "vanish into the background" (Weiser, 1991).

Although Weiser's vision of "ubicomp" is not yet commonplace, mainstream computing technology has begun to evolve in many of the ways that Weiser predicted over a decade ago. Computation has become an integral part of many personal information appliances such as PDAs, cell phones, and digital music players that are carried throughout the day. A recent surge in interest in the tablet computer form factor has led some business professionals and students to abandon use of pen and paper for electronic ink while taking notes and annotating documents. The desktop computer itself is spreading beyond its traditional beige-case-and-monitor boundaries—information that was once stored primarily on the PC hard drive is making its way onto web sites and web services; multiple monitor use is now becoming quite commonplace, and in many domains such as financial trading, virtual walls of tiled monitors are entirely replacing traditional displays; and experiments in wearable computing and augmented reality are evolving into commercial enterprises seeking to bring the functionality of a desktop computer to users at any place and at any time.

At the intersection of all these developments, *ubicomp environments* have themselves become a reoccurring fixture in the research community. Tangible workbenches for designers (e.g., Ishii & Ullmer, 1997; Leibe et al., 2000), smart kitchens (e.g., Tran & Mynatt, 2002), context-aware classrooms (e.g., Abowd, 1999), and reconfigurable meeting spaces (e.g., Johanson, Fox & Winograd, 2002; Streitz et al., 1999) all demonstrate the advanced interaction techniques and social collaboration that become possible when small, inexpensive computation permeates a space, coupled with sensors, cameras, projectors, and various networking technologies.

Although the ubicomp paradigm shift is having a dramatic impact on the design and deployment of new devices and applications, it is also affecting the study of technology and work practice as well. In general, the migration of the computer off the desktop and into the world has drawn greater attention from interrogating *users' dialogue with the computer* to the *contexts in which computers are used.* Field studies of how users carry out their work, from the ways in which they organize the information around them (e.g., Kidd, 1994; Malone, 1983; Mander, Salomon & Wong, 1992) to the ways in which they use existing office technologies such as whiteboards (Mynatt, 1999) to the ways in which they juggle multiple simultaneous tasks and handle interruptions (e.g., Gonzàlez & Mark, 2004), are becoming even more of a prerequisite for the design of new ubicomp technologies than they were during the PC era. The ubicomp vision breaks with the previous tradition of creating application designs based on a single, universal metaphor such as the graphical user interface's "desktop;" instead, ubiquitous computing technologies can only achieve their goal of becoming "invisible" when their design is informed by and well-matched to the context in which they are used.

In this chapter, we outline our agenda and approach for supporting the concept of "activity" from a user's perspective in an integrated digital and physical workplace. This perspective encompasses the context in which computers are used, the multitude of work artifacts that make up and activity, and the historical trajectory of an activity over time. We describe five challenges for matching computation to activity. These are:

- **Activities are multifaceted,** involving a heterogeneous collection of work artifacts;
- **Activities are dynamic,** emphasizing the continuation and evolution of work artifacts in contrast to closure and archiving;
- **Activities are collaborative,** in the creation, communication, and dissemination of work artifacts;
- **Activities exist at different levels of granularity,** due to varying durations, complexity and ownership; and
- **Activities exist across places,** including physical boundaries, virtual boundaries of information security and access, and fixed and mobile settings.

We examine ubiquitous computing support for activities in the workplace from two complementary angles. In the first, we describe our experiences designing the Kimura system, an integrated desktop and interactive whiteboard environment that supports individual knowledge workers in managing and shifting among multiple work activities. Following a description of Kimura, we critique its design with respect to the five challenges. We then examine support for activities from the theoretical perspective of Activity Theory. In particular, we note how recent extensions to Activity Theory have addressed theoretical shortcomings similar to our five challenges and suggest directions for bridging the gap between everyday practice and systems support. We conclude by considering ways in which a combination of theoretical and pragmatic perspectives can provide solutions to the five challenges for future system designs.

KIMURA: AN ACTIVITY-CENTERED WORK ENVIRONMENT

Our research seeks to design an office that better supports knowledge workers—business professionals who interpret and transform information (Drucker, 1973). Successful knowledge workers manage multiple tasks, collaborate effectively among several colleagues and clients, and manipulate information that is most relevant to their current task by leveraging the spatial organization of their work area (Kidd, 1994; Malone, 1983; Mynatt, 1999; Grudin, 2001). The diversity of these work practices and the complexity of implementing flexible computing tools make it difficult to meet all of these workers' needs.

We have spent several years developing technologies that support knowledge workers. Our work on the Kimura system has allowed us to begin exploring different notions of activity both on and off the desktop (MacIntyre et al., 1999; Voida, Mynatt, MacIntyre & Corso, 2002). Our experiences suggest that activity may be a useful, unifying framework for ubiquitous computing environments, but also foregrounds several challenges for future research in ubicomp environments.

In order to explain the fundamental concepts underlying the design of the Kimura system, we begin with a brief scenario highlighting unique aspects of an imagined interaction with the system on a typical workday. Scenarios like this one have served to focus our designs and define key user interactions in an activity-centered digital work environment.

Kimura in Practice: A Scenario

Wendy, a knowledge worker, walks into her office Monday morning following a week's vacation. She scans the piles of paper on her desk and the contents of her whiteboard, recalling the work that has been waiting for her.

After quickly surveying the various whiteboard montages that represent ongoing activities, she annotates the budget plan with "Work on Wed., Due Friday" and throws it to the whiteboard's far side.

The calendar image in the Acme design project montage reminds her of a design briefing later that day.

She studies the montage for a moment, trying to remember how far into the design briefing activity she was before she left on vacation. She sees opaque images of the documents she worked with most recently: her calendar, an illustration, a presentation file, and a Web search page. The montage also includes several translucent images of past documents—two important email messages from her group's client and the original project proposal. She taps on the montage to load it onto her desktop. The design briefing documents reappear on her desktop computer, just as she left them.

After a quick perusal, she resumes her Web search for details on an interesting technology and fine-tunes one of her sketches. After sending the new sketch to the printer,

Figure 1
The Kimura system in an office environment, including the monitor and peripheral displays.

she decides to spend some time catching up on the theme ideas for the upcoming open house. Using the desktop controls to switch activities (and virtual desktops), the montage for the Acme design activity reappears on her whiteboard, now annotated with a printer icon, to indicate that a print job is in progress.

As Wendy contemplates her reply to an interesting theme idea from one of her colleagues, she notices that his face has appeared on her whiteboard. Ah, Joe must be in the coffee room. Deciding that a face-to-face discussion would be more useful than sending another message, she goes to join Joe for coffee and brainstorming.

Later that day, she decides to go ahead and start working on some budget numbers. From the corner of her eye, she notices the softly changing calendar in the Acme design montage. It is time for the meeting. As she runs out of the office, she sees the icon for the completed print job. Grateful that someone—or something—is on top of things, she heads to the printer on the way to the meeting.

System Design and Implementation

Kimura separates the user's "desktop" into two regions: the focal region, on the desktop monitor; and peripheral displays, projected on the office walls. Each work activity is associated with a unique virtual desktop that is displayed on the monitor while the user is engaged in the activity. Background activities are projected as visual montages on the peripheral display, as shown in figure 1.

From Kimura's point of view, a work activity—such as managing a project, participating in a conference, or teaching a class—is modeled as a cluster of documents and a collection of cues representing ongoing interactions with people and objects related to that activity. We refer to this cluster as the activity's *working context*. Each working context may have numerous documents—including text files, Web pages, and other application files. A working context may also have iconic indications of ongoing activity—including email messages without replies and outstanding print jobs. Kimura automatically tracks the contents of each working context and tags documents based on their relative importance. As in previous systems, such as Rooms (Henderson & Card, 1986), users define the boundaries of working contexts manually—in our case, by creating virtual desktops. We chose this strategy because these operations are easy for the user to perform and can be easily monitored to detect working-context changes, and because this strategy avoids relying on the system to infer these transitions.

Each working context is displayed as a *montage* of images garnered from system activity logs (see figure 2). These montages are analogous to the "room overviews" provided by other multi-context window managers. But where these systems show the exact layout of the windows in each room, our goal is to provide visualizations of past activity in context. These visualizations help remind the user of past actions; the arrangement and transparency of the component images automatically create an icon for the working context. Additionally, montages can serve as anchors for background awareness information that is gleaned from a context-aware infrastructure.

The electronic whiteboard—the primary display surface for the montage

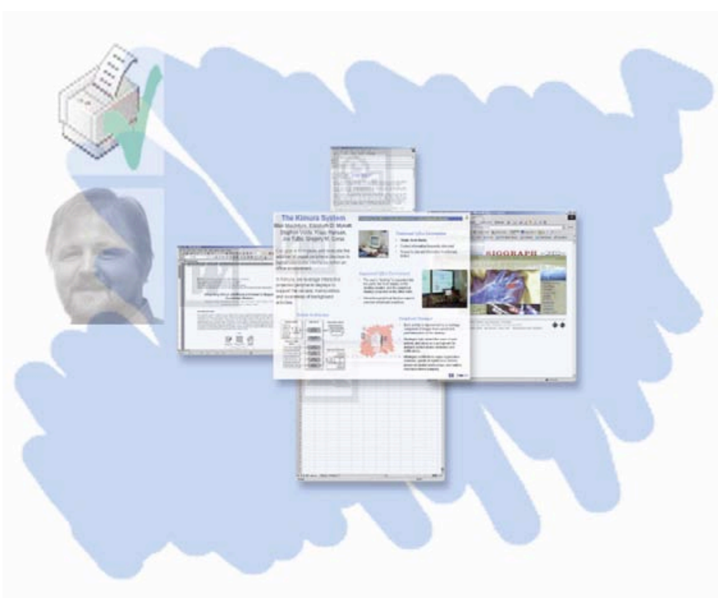

Figure 2
A montage of a working context, including a number of application windows and two external context notification cues, representing both virtual (completion of a print job) and physical context information (the availability of a colleague).

visualizations—supports common whiteboard practices (Mynatt, 1999). Whiteboards feature an intuitive user interface and are well-suited to supporting informal information management activities. Our system implementation incorporates existing electronic whiteboard interaction techniques with montages and notification cues (Igrashi, Edwards, LaMarca & Mynatt, 2000; Mynatt, Igrashi, Edwards & LaMarca, 1999, 2000; Hong & Landay, 2000). This allows the user to annotate montages with informal reminders and reposition montages to indicate the respective priority of background activities. Additionally, the whiteboard's large display area is an ideal, unobtrusive location to show contextually relevant information about the user's work activities and the context information sensed from around the office.

The whiteboard lets users monitor each ongoing work activity, transition smoothly between activities, access a wide variety of contextual information designed to facilitate collaboration, and maintain awareness about relevant activity changes. Additionally, the interactivity provided by the electronic whiteboard allows the user to informally annotate and spatially organize the montages.

The montage design relieves the user of burdens associated with maintaining a large amount of information—information about each work activity and its related contextual information—and with synthesizing that information on the fly from a potentially overwhelming number of sources. The montages are designed to present this information without intruding on the user's focal activity and in a manner that supports the needs of knowledge workers.

Activity and Context-Awareness in Kimura

The Kimura system allows its users to continue using whatever tools and practices they would normally use in the course of their work while providing activity-level support by sensing and responding to virtual and physical context surrounding the user's activities. Unlike the majority of context-aware systems that have generally focused solely on the acquisition and interpretation of physical context—primarily location—to adapt an application to a user's social and physical surroundings, Kimura leverages virtual context—the processes and resources involved in manipulating digital information—as well.

Our system uses several monitoring components and proxies to acquire virtual context about the user's ongoing activities. Our focus is on capturing the users' interactions with the application and document windows that are associated with each activity. We have developed a desktop monitoring system for Microsoft Windows using the Win32 system hooks API. When the Kimura system is running, Windows sends notification of low-level user actions (e.g., opening a window, changing the window focus, pressing a key, clicking the mouse) to a desktop monitoring process. The monitoring process encodes the event and forwards it to a distributed activity log. Additionally, the desktop monitor creates a screenshot of each window each time the window system's input focus changes. The context interpreter integrates these screenshots into the montages so that the visual representations of the user's activity can include actual images of the user's work. The images, similar to thumbnails, provide more relevant visual reminders than generic icons or labels. We use metrics, such as the amount of time a particular window has been in focus and the number of focus switches between open windows, to determine the size and placement of the screenshot images in the montage visualizations displayed on the electronic whiteboard.

Kimura also acquires virtual context through an email monitoring system, tracking the user's interaction with colleagues during work activities. A small process running on the user's mail server monitors changes in each of the user's mailboxes. It monitors all email messages that the user sends and associates each mail recipient with the active working context. The process also adds the recipient to a list of individuals with whom the Kimura user might be trying to connect, and instructs the location-monitoring component to actively monitor the availability of that individual by watching for their presence in public areas of the office.

In addition, Kimura observes the user's interactions with distributed peripheral devices over the course of a work activity. We have implemented a printer proxy that records the ID and status of pending print jobs in a working context. As the status of each print job changes (for example, a print job is sent to the spooler, prints after being buried in a long queue, or stalls because the printer is out of paper), the context interpreter adds a notification cue to the appropriate montage.

Kimura also helps the user reconstruct the environmental circumstances surrounding a working context and provides cues about the user's colleagues' location and availability using physical context. In our current prototype, we simulate a pervasive, location-aware infrastructure (e.g., Dey, Abowd & Salber, 2001) with a series of Dallas Semiconductor i-Button docks distributed throughout the office environment. We designed our sensor network to detect the arrival and departure of known individuals in our augmented office environment, in public areas of the office, and near peripheral devices (that is, next to the printer). This functionality lets the system determine the general location of the Kimura user and her colleagues, and allows the system to infer when those colleagues might be available for collaboration or when they have joined the user in the augmented office for an informal meeting.

THE CHALLENGES OF SUPPORTING ACTIVITY IN UBICOMP ENVIRONMENTS

The design of the Kimura system was based on our understanding of *activity*, supplanting the traditional "desktop," application-and-document metaphor and allowing users to manage their ongoing activities in the same way that they conceive of and manage their tasks in the real world. It also built upon the findings of previous studies of knowledge work, allowing users to organize their work spatially and without needing to explicitly name or label information in order to work with it. We developed our designs with the belief that even though ubiquitous computing is changing how, where, and when we work, the desktop computer will still play a key role in office computing for the foreseeable future.

However, we made several explicit design decisions to limit the scope, and therefore the complexity, of our design space for the Kimura project. For example, we opted to design a system that would be used in one worker's personal office, and primarily by that single user. We also represented activities as "flat" collections of documents, as opposed to hierarchical representations or representations with variable perspectives, so that we would be able to more readily evaluate the montage visualizations for each activity.

As we continue to work on the next-generation version of the Kimura system, we are looking to extend the system in ways that emphasize the *mediating* role of the digital work environment. Our informal experiences in using the system suggest that having a mechanism for organizing and managing one's own short-term activities is useful, but Kimura would be even more useful if it could allow users to manage substantially more numerous and complex activities over the course of months or years and enable users to coordinate activities among members of a project team.

We are confident that many of the design decisions we initially made will continue to prove useful as we move forward with the project. For example, the explosion of recent work on multiple displays in the workplace (Grudin, 2001; Tan & Czerwinski, 2003) and large-display groupware (Fass, Forlizzi & Pausch, 2002; Huang, Russell & Sue, 2004; Johanson et al., 2002; Moran et al., 1996; Streitz et al., 1999) indicate that our intuitions about leveraging the electronic whiteboard as an organizing space will continue to prove fruitful. However, the side effects of our limited design space, such as our system's relatively simple representation of activities, the lifecycle of those activities, and the current means of populating and managing those activity representations over time may need drastic reconsideration if we are to be successful.

We have identified five challenges for representing and supporting activity in integrated digital work environments, based on our experiences with the Kimura system and our attempts to extend its capabilities. The challenges exist due in large part to the inherent complexity of human activity, the technical affordances of the computing tools used in work practice, and the nature of (and culture surrounding) knowledge work.

Activities are Multifaceted

One of the primary departures of activity-centered computing from use of the traditional "desktop" metaphor is the recognition that one activity often spans several applications, and includes many types of documents and information resources. Although the "desktop" metaphor provided users with interface-level support for multitasking, application software has become so specialized and information sources so diverse that a typical desktop window layout, organized to support a single activity, might consist of dozens of windows spanning multiple applications—in addition to any real-world artifacts that are referenced over the course of the activity.

The Kimura system allowed users to organize and manage their work at the level of activities, as opposed to manually manipulating applications and documents. Our design was intended to lower the overhead of activity switching by allowing the user to simply switch between relevant groups of applications and documents as needed—much the same motivation as in systems like Rooms (Henderson & Card, 1986), Task Gallery, and GroupBar (Robertson et al., this volume; Robertson et al., 2000, Smith et al., 2003). Kimura initially associated activities with individual virtual desktops on the primary desktop computer; the number and contents of a user's virtual desktops were used to identify the user's current activities and associate applications, documents, and external resources with those activities.

Supporting the multifaceted aspects of activity in a ubicomp environment becomes a much more complex proposition. If activity is to be used as a unifying organizational structure across a wide variety of devices such as traditional desktop and laptop computers, PDAs, mobile telephones, personal-server style devices (Want et al., 2002), shared public displays, etc., then those devices must all be able to share a common set of activity representations and use those representations as the organizational cornerstone for the user experience they provide. Additionally, the activity representations must be versatile enough to encompass the kinds of work for which each of these kinds of devices are used. Although this may sound like an unattainable vision, we have already demonstrated that support for activity can be added to a platform without dramatically changing the fundamental nature of its operating system or application software.

Activities are Dynamic

User studies and intuition both suggest that the activities that a knowledge worker engages in change—sometimes dramatically—over time. Projects and milestones come and go, and the tools and information resources used within an activity often change over time as well. Furthermore, activities completed in the past and their outcomes often impact activities in the present, and ongoing activities will, in turn, affect activities that will be undertaken in the future. Capturing activity over the course of time has long been a problem for desktop computing. For example, saved files frequently contain only the most recent state of a document and users must often adopt unusual work practices to capture and access the history of a document, such as tracking changes using an auxiliary change-management system such as CVS[1]. Another often-cited observation is that hierarchical filing systems do not readily reflect the fact that a single resource might be used in different contexts (e.g., Dourish et al., 2000).

One of our central design decisions in the Kimura system was to base our representations and visualizations of activity on users' actual, ongoing work. As users created new virtual desktops, opened and closed applications, referenced documents, and interacted with colleagues electronically, Kimura's model of the user's activity would automatically reflect these changes. Our approach in representing the history of activities was to provide visualizations that reflected the state of an activity throughout the entire course of its existence, rather than simply providing a snapshot of its current state. The document thumbnails within each montage are sampled both from the most current *and* the most significant components of each activity, even if the most significant components are documents that are no longer open and therefore no longer immediately accessible. Additionally, the integration of external context notification cues allowed our visualizations to reflect the dynamic nature of activities as impacted by changes sensed from the "real world." We felt that in order to provide an accurate representation of the activity, this holistic view of the activity's contents would be invaluable, particularly for resumption of an activity that had not been active for an extended period of time.

However, some of our implementation decisions also made it difficult to work with many long-lived activities. In order to maximize compatibility with all desktop applications and not force users to adopt a small set of custom-built, "Kimura-aware" applications, we initially opted to track and manage activity using only window handles, application types, and window captions. Unfortunately, this imposed the limitation that activities could be resumed only if their windows were still open and available (albeit hidden) on the desktop computer. A design decision that was originally intended to enable more realistic evaluation—system users would be able to use whatever applications with Kimura that they already used in the course of their work—actually undermined long-term study of the system since even powerful, modern computers have practical limitations about the number of applications and documents that can be open at a given time.

There are a number of other systems that have been quite successful at capturing user activity as a function of time and exposing this record to the user. Although these systems have provided different means for navigating through the temporal record—Designers' Outpost via a "global timeline" at the bottom of the display (Klemmer, Thomsen, Phelps-Goodman, Lee & Landay, 2002), Flatland through snappable, per-"segment" time sliders (Mynatt et al., 1999), and TimeScape by presenting several interactive desktop visualizations (Rekimoto, 1999)—all indirectly support the notion of activity in the interface by allowing users to restore the interaction state to that of a previous point in time. Regardless of the specific user interface technique or techniques used to expose the interaction history to the user, this general approach is successful in allowing users to immerse themselves in the context of an activity from the past *and* have access to the content that they were using to accomplish that activity.

Activities are Collaborative

Most knowledge work is inherently collaborative. If activities aren't centered around synchronous interaction between multiple members of a project team or the user and some number of individuals external to his or her immediate workgroup, they almost certainly draw upon information that was created by others at some earlier point in time. Recognizing the *mediating* role of the digital work environment in enabling users to meaningfully collaborate is a critical step to ensuring the success of these systems.

However, as the large, diverse body of literature in the computer-supported collaborative work (CSCW) community suggests, supporting effective collaboration is rarely a trivial undertaking. Technical issues involving the exchange of information, preservation of state, and graceful operation in the face of network failures, coupled with social issues regarding awareness, negotiation about the roles that collaborators will play, and privacy—just to name a few—abound.

We initially limited the scope of Kimura to one user in order to simplify our design space and allow us to iterate on our infrastructure implementation and montage designs with fewer CSCW-related constraints. However, Kimura was able to detect certain patterns of electronic communication and associate individuals with ongoing tasks. We also provided a visualization technique that presented colleague availability as a component of the montages on the electronic whiteboard, based on information gleaned from the context-aware infrastructure. This appeared to be a useful initial step during our informal evaluations of the system.

Looking beyond our single-user implementation of the Kimura system, there are several design considerations that will be critical in enabling more robust collaboration support for work activities. First and foremost, other individuals must be represented as first-class objects in computational models of activity. One potentially useful way to incorporate colleagues into activity representations is to leverage and visualize the relationships between ongoing work activities and naturally-occurring virtual and real world social networks (e.g., Nardi, Whittaker & Schwarz, 2002; Fisher & Nardi, this volume). Additionally, activities need to be represented in such a way that their contents can be shared, with the caveats that individual participants in an activity may have very different perceptions of the activity, they may bring different resources to play over the course of the activity, and, particularly for large activities in which many individual users participate, users themselves may come and go over the life of the activity.

Moreover, such systems must be designed with the social context of the workplace in mind; providing support for collaboration requires somewhat more subtlety than simply exposing all participants' activity representations and constituent resources to one another. Participants may wish to exercise varying degrees of control over how and when their resources and work processes are shared with their colleagues. They may also wish to specify how their availability is shared with different colleagues. Finally, the organizational structure of the workplace may cause each collaborator to play different roles in the activity; as a result, each may need access to different activity representations or meta-information about the activity and contributions of its participants (Shen & Dewan, 1992; Sikkel, 1997).

Activities Exist at Different Levels of Granularity

At any given point in time, a single user may report being involved in several different activities, each specified at a slightly different level of granularity. For example, she might be in the midst of writing a conference paper review, compiling a list of references for a proposal submission, and working towards a promotion. The paper review activity lasts only a short time and requires a unique set of resources—namely, the paper under review. It also might resemble other activities, for example, a conference review at about the same time last year, and it might take advantage of some resources affiliated with other activities, such as a repository of research papers often used for project literature reviews. The proposal submission might be a substantially longer task involving a broader spectrum of resources and, often, the input of several colleagues. Striving for the promotion might require years of work and encompass many other, subordinate activities.

The idea that activities may exist at different levels of granularity is not a new one. Boer, van Baalen & Kumar (2002) provide a model explaining how an *activity* at one level of analysis may be modeled as an *action*—a component of an activity—at another. This holds true for individual users, as in the example provided above, but is even more pronounced when a single activity is viewed from multiple participants' perspectives. For example, a manager and a principal investigator might both be involved in the activity of completing a research project, but their perceptions of the importance of the activity, the tools, the actors involved, and specific goals might be quite different.

The Kimura system represented activities based on the contents of a single virtual desktop on a primary desktop computer, placing few limitations on the contents or lifespan of a tracked activity. Our montage visualizations were also designed to apply across activities specified at different levels of granularity. The visualization algorithm simply displayed the longest-used and most recently used window thumbnails associated with each activity; regardless how long- or short-lived the activity or the level of granularity at which the user conceptualized it, the documents with which they would most likely associate the activity were displayed on the whiteboard.

Of course, supporting activities shared among two or more users complicates the situation. Suppose one user manages their tasks at a high, project-oriented level, e.g., *annual project review* and *teaching*, and another user participating in the same activities manages their tasks at a much finer granularity, e.g., *project review demonstration debugging* and *preparing computer graphics guest lecture*. This scenario is particularly likely when colleagues with different roles (such as a team member and a manager) collaborate on a single activity. Although it would be relatively straightforward to provide activity-level support for either of these users on their own, maintaining a shared representation of each of the users' collaborative activities at their preferred granularity, providing each user with appropriate views of the activities, generating notifications to each user for relevant changes in the activities, and coordinating changes in the structure of the activities over time becomes a very complex undertaking.

Activities Exist Across Places

Activities also span place; that is, it is common for work to take place outside of the immediate office environment. However, current office technologies sometimes present a very different view of information across different physical and virtual settings. For example, resources affiliated with a work activity may not be visible to users that are physically located outside of the workplace due to the presence of a corporate firewall. Even when physically located within the workplace, collaboration on an activity might not be possible between colleagues whose computers are connected on different network subnets, that is, when one is plugged into a wired network and the other is connected wirelessly.

Furthermore, portable devices currently operate with very different interfaces and hierarchies than their office environment counterparts. Where a desktop computer might store complex, detailed representations of user activities and the resources affiliated with them (and even more so when augmented with activity-aware applications), PDAs and mobile phones often store very simple, flat collections of information and require explicit user action to maintain information synchronization among devices.

We implemented the Kimura system using the Java programming language and enabled distributed computing using common TCP/IP networking protocols so that it would be easy to implement visualization clients and context-awareness providers on a wide variety of devices. Although we have not yet created information managers for use on PDAs and cell phones, it would be easy to do so using J2ME virtual machines or by creating WAP-based web interfaces to the Kimura system using our existing servers.

Network connectivity-related problems, although beyond the scope of our current research agenda, constitute a challenge for many ubiquitous computing efforts. Technologies like virtual private networks (VPNs), which allow users outside of a corporate domain to pass traffic through a secure tunnel to their company's internal network; zero configuration networking protocols such as Apple's Bonjour[2], which allow users to see and use nearby resources without incurring network set-up cost for the user; and research platforms like Speakeasy, which fosters service interoperability and enables *ad hoc* network bridging (Edwards et al., 2002), are all helping to lessen the impact of network topology on visibility and availability of networked resources for mobile users.

UNDERSTANDING THE CHALLENGES: A THEORETICAL FRAMEWORK

In order to address the challenges that we identified for the design of activity-centered ubicomp work environments, we are conducting more in-depth field studies to understand the subtleties of users' conceptualization of activity in their day-to-day work practices. However, we are also looking to theoretical frameworks to understand the role of activity in these types of environments.

We have already noted that the emergence of ubicomp and integrated digital work environments has had a dramatic impact on the way that researchers in human-computer interaction (HCI) and related fields think about the design of computing environments. Historically, HCI adopted and adapted knowledge, processes and techniques from artificial intelligence (AI), cognitive science, and cognitive psychology in service of understanding and modeling user behavior, and applied those findings to the creation of new interfaces and technologies through design practice. As a result of this lineage, many of the theories and techniques used in HCI to model users have exhibited a markedly cognitive, "agents as information processors" flavor. As a result, much of the research literature on user modeling in HCI has been based on the Model Human Processor (Card, Moran & Newell, 1983), which has its roots in the physical symbol system hypothesis. Other important user models, such as Norman's Seven Stages of Action model (Norman, 1990), can trace their heritage back to Gibson's systems school of perception (Gibson, 1979).

Over the last decade, the focus of the HCI community began to shift away from the quantitative evaluation of user interfaces based on cognitive models and towards more ecologically informed techniques, including contextual and participatory design (Beyer & Holtzblatt, 1998; Kyng, 1994). This "user-centered design" movement foregrounded the social context of technology use and incorporated user feedback and participation throughout the design process. While this transition has been invaluable in producing traditional computer systems that exhibit both *usability* and *usefulness*, ubiquitous computing is providing its own set of challenges for HCI practitioners. In particular, the fact that most users are only now beginning to experience the ubicomp vision and integrate this new, unique class of technology into their work practices suggests that another change in focus may be on the horizon: "[T]he shift from user-centered design to context-based design corresponds with recent developments in pervasive, ubiquitous computing networks and in the appliances that connect with them, which are radically changing our relationships with personal computing devices" (Gay & Hembrooke, 2003).

The changes in how HCI researchers and practitioners are examining the relationships between users and their devices are not limited to cutting-edge tangible media computing or immersive environments, however. Throughout the field, much more work is being done in understanding users' existing work practices, often involving traditional desktop computer systems, and in developing better models of users' interactions with a variety of computing devices.

One of the frameworks for asking these kinds of questions that has garnered a great deal of attention in recent years is Activity Theory. Activity Theory places a strong focus on the mediating role of tools and social practices in the service of accomplishing goals.

Because this seems to echo the sentiment of the challenges we uncovered in developing activity-based computing tools, we believe that Activity Theory can serve as a useful framework to inform the design of activity-centered digital work environments.

Activity Theory and Activity-Centered Design

The origins of Activity Theory can be traced back to the former Soviet Union as part of the cultural-historical school of psychology founded by Vygotsky, Leont'ev, and Luria. Rather than focusing on *action* as a unit of analysis, Activity Theory focuses at the broader level of an *activity* and incorporates the social and cultural context of cognition (Halverson, 2001; Leont'ev, 1978; Vygotsky, 1978).

In their well-known "activity checklist," Kaptelinin, Nardi, and Macaulay (1999) identified five basic principles of Activity Theory:

1. *Hierarchical structure of activity*
   In Activity Theory, the unit of analysis is an *activity* which is directed at an *object* that motivates the activity. Activities are composed of conscious, goal-directed *actions*; different actions may be taken to complete any given goal. Actions are implemented through automatic *operations*, which do not have goals of their own. This hierarchical structure is dynamic and can change throughout the life of an activity.

2. *Object-orientedness*
   Activity Theory holds that humans exist in an broadly-defined objective reality, that is, the things around us have properties that are objective both to the natural sciences and society and culture.

3. *Internalization/externalization*
   Activity Theory considers both *internal* and *external* actions and holds that the two are tightly interrelated. *Internalization* is the process of transforming an external process into an internal one for the purposes of planning or simulating an action without affecting the world. *Externalization* transforms internal actions into external ones and is often used to resolve failures of internal actions and to coordinate actions among independent agents.

4. *Mediation*
   A central tenet of Activity Theory is that activity is *mediated* by tools, and that these tools are created and transformed over the course of the activity so that the culture and history of the activity becomes embedded in the tools. Vygotsky's definition of *tool* is very broad; one of the tools he was most interested in was language.

5. *Development*
   Activity Theory relies upon development as one of its primary research methodologies; that is, "experiments" often include consist of a subject's participation in an activity and observation of developmental changes in the subject over the course of the activity. Ethnographic methods that identify the cultural and historical roots of activity are also frequently used.

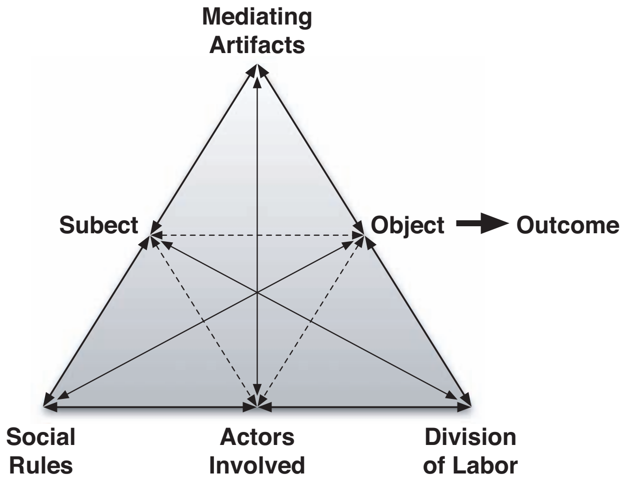

Figure 3
An adaptation of Engeström's analysis of activity and mediating relationships.

Engeström (1987) provides a classic visualization summarizing the structure of an activity (figure 3). This model is based around three mutual relationships: that between the actor (*subject*) and the community (other *actors involved*), that between subject and the object (in the sense of *objective*) of the activity, and that between the object and the community. These mutual relationships are *mediated* by the other components of activity. For example, the relationship between subject and object is mediated by tools (*mediating artifacts*); because of this, the subject's experience of the object is constrained by the tools used, and the tools that are created as a by-product of the activity are directly shaped by the subject and the object. (The tools also embed the culture and history of the other components of the activity, such as the social rules governing the community, the community itself, and the organization of that community (e.g., the roles of its members), sometimes referred to as the *division of labor*.

However, Gay and Hembrooke point out a weakness in the original formulation of Activity Theory: "The model of activity theory…has traditionally been understood as a synchronic, point-in-time depiction of an activity. It does not depict the transformational and developmental processes that provide the focus of much recent activity theory research" (Gay & Hembrooke, 2003).

Boer et al. (2002) provide an interesting suggestion for how the scope of Activity Theory can be expanded across time and the levels of an organization to explain connections between different activities as well as the influence that an activity may exert upon itself:

> Besides the fact that an activity is situated in a network of influencing activity systems, it is also situated in time….In order to understand the activity system under investigation, one therefore has to reveal its *temporal interconnectedness*….Rather than analyzing an activity system as a static picture of reality, the developments and tensions within the activity system need to be

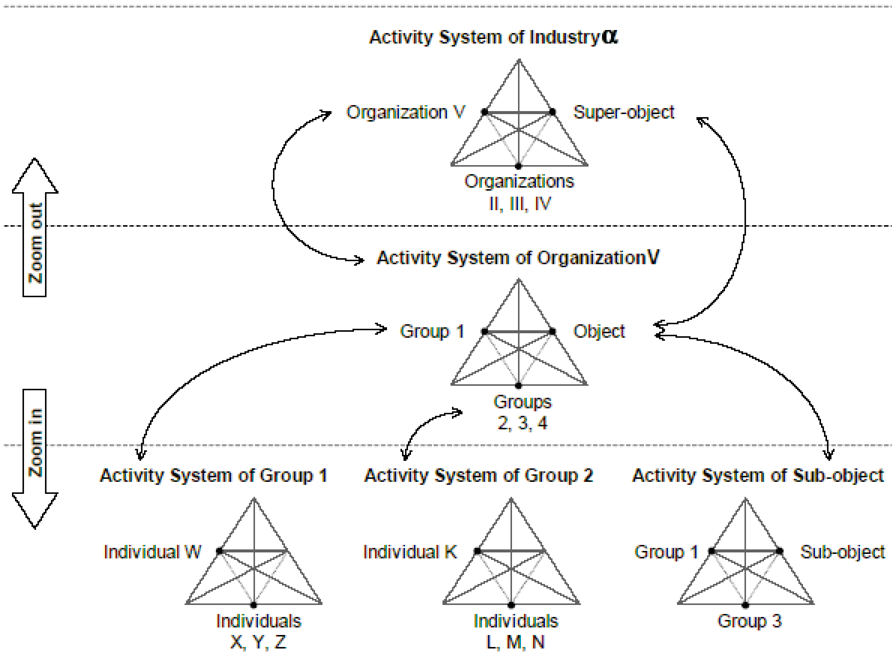

Figure 4
Relationships between different levels of analysis (from Boer et al., 2002, reprinted with permission ©2002 IEEE).

> described and analyzed….When analyzing an activity system at a particular contextual level, one should also take into account its relations with activity systems at other contextual levels (e.g., economic system, industry, supply chain, organization, department or production process)….The activity system under investigation is not only affected by activity systems at other contextual levels, it also exerts influence on them itself (bi-directional twisted arrows in figure [4]). This is in line with Giddens' theory of structuration which assumes that on the one hand human action is restricted by institutional properties of social systems, while on the other hand these institutional properties are the product of human action (Boer et al., 2002, authors' emphasis).

Boer et al. also consider the role that an activity may play in other activities at different levels of analysis. They suggest that the components of one activity system may play different roles in more broadly- or narrowly-scoped activities that exist in different cultural contexts, e.g., on a project team, in a department, or in an entire corporation (e.g., figure 4).

These extensions increase the complexity of the Activity Theory model but also help to explain tensions present in real-world systems such as when one agent plays different roles in two systems that have divergent goals. Furthermore, this approach provides Activity Theory with a similar degree of agility in representing complex, distributed cognition as competing theoretical approaches, such as Distributed Cognition (Hutchins, 1995).

Nardi (1996) argues that one of the inherent strengths of Activity Theory is in its ability to capture the idea of *context* in user models for HCI, a notion that is gaining momentum particularly with respect to the ubiquitous computing paradigm and as its own design movement, so-called *activity-centered design* (Gay & Hembrooke, 2003). The world that Gay and Hembrooke envision relies upon design that is not user-centered (which is currently the dominant view in the HCI community) but activity-centered, since Activity Theory provides the right "orientation" for future classes of interactions mediated by ubiquitous computing devices.

THE INTERSECTION OF THE PRAGMATIC AND THE THEORETIC

Activity Theory is described both as a guiding framework for analyzing observations of work practice and a language for communicating those findings within the community of practitioners (Halverson, 2001). In the case of designing activity-centered ubicomp environments, Activity Theory can help to shape the definition of *activity* that such systems seek to support. It can help to focus and organize field observations of work practice and smooth the transition from those observations into design specifications. It can also suggest solutions to some of the most difficult challenges in supporting activity in these integrated digital work environments.

At its core, Activity Theory provides a useful model of a single user's perspective on the process of completing some objective. This model reflects many of the same underlying assumptions that we made going into our work with the Kimura system, most notably the idea of *object-orientedness*—that users mentally organize their work around activities (and their constituent actions) and that they use a variety of tools in the service of achieving the objects of those activities. This perspective contrasts with traditional principles held by the HCI community, which emphasize the dialogue between the user and the system rather than emphasizing the system's role as one of many mediating tools in the context of an activity. Kimura reflected this change in perspective by playing down the application-document metaphor, which presumes that the user will be able to complete a task within a single application. Instead, Kimura presented the user with clusters of applications and documents augmented with contextual cues sensed from the other virtual and physical aspects of the work activity. These clusters became the user's central point of interaction for managing activity, allowing them to interact at a level of abstraction above applications and documents but without requiring adoption of new and unfamiliar tools.

The Activity Theory framework also helps to expand the ways in which we study work practices in situ and seek to understand the roles that new technologies might play as part of users' activities. Although it is certainly useful to investigate how tools are being used and the aspects of collaboration that are critical in the workplace, Activity Theory encourages researchers to examine activity from the perspectives of each participant and to understand the role of social rules and participant roles, in addition to the use of artifacts and information resources.

But perhaps most compelling are the ways in which Activity Theory models interact with the challenges that we identified in our experiences with Kimura and our survey of other activity-centered ubicomp environments. Activity Theory casts a wide but well-defined net around the multifaceted nature of activity, suggesting that the user's colleagues and the object of the activity are of the utmost importance, but that the tools, social rules, and roles of collaborators within the community must also be reflected back to the user as critical components of that activity. The idea that components of activity reflect their history of use through time suggest several ways for activity-centered systems to support a dynamic working landscape; for example, they might capture past activities in an archive for quick—and potentially automated—reference during related tasks in the future, and that the tools used in previous and ongoing activities (e.g., documents and information resources) both be available at all times and tagged with meta-information about how they have been used in the past. The hierarchical structure of the Boer et al. adaptation of the Activity Theory model can help to reconcile the differences in granularity and the difficulties of supporting collaboration identified in our work; future activity-centered user interfaces might take advantage of the zoomable user interface paradigm or feature control over the level of detail (LOD) represented in the interface to more accurately reflect the depth at which a given user conceptualizes their own tasks or the tasks of their colleagues.

While Activity Theory provides a useful lens for understanding users' work practices and a language for communicating models of users' behavior, there are some aspects of work practice that have been shown to be critical for knowledge work but are not captured in the Activity Theory framework. For example, knowledge workers have been shown to rely on the organization of information used in ongoing activities to accomplish their work, particularly when the value or role of that information has not yet been fully determined (Kidd, 1994; Malone, 1983; Mynatt, 1999). Activity Theory alludes to the fact that tools reflect the history of their use, but does not place a strong emphasis on this critical component of knowledge work. This observation implies that supporting activity well in ubicomp environments will likely require us to draw upon a variety of activity models and inquiry techniques for understanding how work is accomplished in the real world.

However, theoretical frameworks provide only one perspective on understanding the role of activity in ubicomp environments. Another invaluable resource is the growing body of research literature describing design decisions related to and practical experience resulting from integrating activity into other kinds of computational tools. Activity is increasingly being used to organize and manage overloaded communication channels like email (e.g., Bellotti, Ducheneaut, Howard & Smith, 2003; Gwizdka, 2002), as an index into personal information management on desktop computers (e.g., Kaptelinin, 2003;

Kaptelinin & Boardman, this volume), and as a means for coordinating action among groups of users (e.g., Bardram, 2005, this volume). The results of these experiments will further help to clarify the issues and challenges related to representing activity in the user interface and provide the community with a more diverse portfolio of approaches for modeling activity and exposing those models to system users.

As designers are faced with creating the next generation of integrated digital work environments, theoretical frameworks such as Activity Theory and pragmatic perspectives like those gained from our work on the Kimura system will both play a key role in informing the design of these systems and overcoming the challenges that supporting real-world work practices present.

NOTES

1. http://www.cvshome.org

2. http://developer.apple.com/networking/bonjour/

REFERENCES

Abowd, G.D. (1999, October). Classroom 2000: An experiment with the instrumentation of a living educational environment. *IBM Systems Journal: Special Issue on Pervasive Computing, 38*(4), 508–530.

Bardram, J.E. (2005, September). Activity-based computing: Support for mobility and collaboration in ubiquitous computing. *Personal and Ubiquitous Computing, 9*(5), 312–322.

Bellotti, V., Ducheneaut, .N., Howard, M. & Smith, I. (2003). Taking email to task: The design and evaluation of a task management centered email tool. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI 2003).* New York: ACM Press. pp. 345–352.

Beyer, H. & Holtzblatt, K. (1998). *Contextual Design: Defining Customer-Centered Systems*. San Francisco: Morgan Kaufmann.

Boer, N., van Baalen, P.J. & Kumar, K. (2002). An activity theory approach for studying the situatedness of knowledge sharing. In *Proceedings of the 35th Annual Hawaii International Conference on System Sciences (HICSS-35'02)*.

Card, S.K., Moran, T.P. & Newell, A. (1983). *The Psychology of Human-Computer Interaction.* Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Dey, A.K., Abowd, G.D. & Salber, D. (2001). A conceptual framework and a toolkit for supporting the rapid prototyping of context-aware applications. *Human-Computer Interaction Journal, 16*(2–4), 97–166.

Dourish, P., Edwards, W.K., LaMarca, A., Lamping, J., Petersen, K., Salisbury, M., Terry, D.B. & Thornton, J. (2000, April). Extending document management systems with user-specific active properties. *ACM Transactions on Information Systems, 18*(2), 140–170.

Drucker, P.F. (1973). *Management Tasks, Responsibilities and Practices*. New York: Harper & Row.

Edwards, W.K., Newman, M.W., Sedivy, J.Z., Smith, T.F., Balfanz, D., Smetters, D.K., Wong, H.C. & Izadi, S. (2002). Using Speakeasy for ad hoc peer-to-peer collaboration. In *Proceedings of the ACM 2002 Conference on Computer Supported Cooperative Work (CSCW 2002).* New York: ACM Press. pp. 256–265.

Engeström, Y. (1987). *Learning by Expanding.* Helsinki: Orienta-konsultit.

Fass, A.M., Forlizzi, J. & Pausch, R. (2002). MessyDesk and MessyBoard: Two designs inspired by the goal of improving human memory. In *Proceedings of the Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques (DIS 2002)*. New York: ACM Press. pp. 303–311.

Gay, G. & Hembrooke, H. (2003). *Activity-Centered Design: An Ecological Approach to Designing Smart Tools and Usable Systems.* Cambridge, Mass.: MIT Press.

Gibson, J.J. (1979). *The Ecological Approach to Visual Perception.* Boston: Houghton Mifflin.

Gonzàlez, V.M. & Mark, G. (2004). "Constant, constant multi-tasking craziness": Managing multiple working spheres. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI 2004)*. New York: ACM Press.

Grudin, J. (2001). Partitioning digital worlds: Focal and peripheral awareness in multiple monitor use. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI 2001)*. New York: ACM Press. pp. 458–465.

Gwizdka, J. (2002). TaskView: Design and evaluation of a task-based email interface. In *Proceedings of the IBM Centers for Advanced Studies Conference (CASCON 2002)*. Toronto, Canada. pp. 136-145.

Halverson, C.A. (2001). Activity theory and distributed cognition: Or what does CSCW need to do with theories? *Computer Supported Cooperative Work (CSCW), 11*(1-2), 243-267.

Henderson, J.D.A. & Card, S.K. (1986, July). Rooms: The use of multiple virtual workspaces to reduce space contention in window-based graphical user interfaces. *ACM Transactions on Graphics, 5*(3), 211–241.

Hong, J.I. & Landay, J.A. (2000). SATIN: A toolkit for informal ink-based applications. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST '00)*. New York: ACM Press. pp. 63–72.

Huang, E.M., Russell, D.M. & Sue A.E. (2004). IM Here: Public instant messaging on large, shared displays for workgroup interactions. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI 2004).* New York: ACM Press. pp. 279–286.

Hutchins, E. (1995). *Cognition in the Wild.* Cambridge, Mass.: MIT Press.

Igrashi, T., Edwards, W.K., LaMarca, A. & Mynatt, E.D. (2000). An architecture for pen-based interaction on electronic whiteboards. In *Proceedings of the Working Conference on Advanced Visual Interfaces*. New York: ACM Press. pp. 68–75.

Ishii, H. & Ullmer, B. (1997). Tangible bits: Towards seamless interfaces between people, bits, and atoms. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI ’97)*. New York: ACM Press. pp. 234–241.

Johanson, B., Fox, A. & Winograd, T. (2002, April–June). The Interactive Workspaces project: Experiences with ubiquitous computing rooms. *IEEE Pervasive Computing, 1*(2), 67–74.

Kaptelinin, V. (2003). UMEA: Translating interacting histories into project contexts. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI 2003)*. New York: ACM Press. pp. 353–360.

Kaptelinin, V., Nardi, B.A. & Macaulay, C. (1999, July–Aug.). The activity checklist: A tool for representing the “space” of context. *Interactions, 6*(4), 27–39.

Kidd, A. (1994). The marks are on the knowledge worker. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI ’94)*. New York: ACM Press. pp. 186–191.

Klemmer, S.R., Thomsen, M., Phelps-Goodman, E., Lee, R. & Landay, J.A. (2002). Where do web sites come from? Capturing and interacting with design history. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI 2002).* New York: ACM Press. pp. 1–10.

Kyng, M. (1994). Scandinavian design: Users in product development. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '94)*. New York: ACM Press. pp. 3–9.

Leont’ev, A.N. (1978). *Activity, Consciousness, and Personality.* Englewood Cliffs, New Jersey: Prentice Hall.

Leibe, B., Starner, T., Ribarsky, W., Wartell, Z., Krum, D., Weeks, J., Singletary, B. & Hodges, L. (2000, November–December). Toward spontaneous interaction with the Perceptive Workbench. *IEEE Computer Graphics and Applications, 20*(6), 54–65.

MacIntyre, B., Mynatt, E.D., Voida, S., Hansen, K.M., Tullio, J. & Corso, G.M. (2001). Support for multitasking and background awareness using interactive peripheral displays. In *Proceedings of the 14th Annual ACM Symposium on User Interface Software and Technology (UIST ’01)*. New York: ACM Press. pp. 41–50.

Malone, T.W. (1983, January). How do people organize their desks? Implications for the design of office information systems. *ACM Transactions on Office Information Systems, 1*(1), 99–112.

Mander, R., Salomon, G. & Wong, Y.Y. (1992). A ‘pile’ metaphor for supporting casual organization of information. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI ’92)*. New York: ACM Press. pp. 627–634.

Moran, T.P., Chiu, P., Harrison, S., Kurtenbach, G., Minneman, S. & van Melle, W. (1996). Evolutionary engagement in an ongoing collaborative work process: A case study. In *Proceedings of the 1996 ACM Conference on Computer Supported Cooperative Work*. New York: ACM Press. pp. 150–159.

Mynatt, E.D. (1999). The writing on the wall. In *Proceedings of INTERACT ’99*. Amsterdam: IOS Press. pp. 196–204.

Mynatt, E.D., Igrashi, T., Edwards, W.K. & LaMarca, A. (1999). Flatland: New dimensions in office whiteboards. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '99)*. New York: ACM Press. pp. 346–353.

Mynatt, E.D., Igrashi, T., Edwards, W.K. & LaMarca, A. (2000, July–August). Designing an augmented writing surface. *IEEE Computer Graphics and Applications, 20*(4), 55–61.

Nardi, B.A. (1996). Studying context: A comparison of activity theory, situated action models, and distributed cognition. In B.A. Nardi, ed., *Context and Consciousness: Activity Theory and Human-Computer Interaction.* Cambridge, Mass.: MIT Press. pp. 69–102.

Nardi, B.A., Whittaker, S. & Schwarz, H. (2002). NetWORKers and their activity in intensional networks. *Computer Supported Cooperative Work, 11*, 205–242.

Norman, D. A. (1990). *The Design of Everyday Things.* New York: Doubleday.

Rekimoto, J. (1999). Time-machine computing: A time-centric approach for the information environment. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST '99).* New York: ACM Press. pp. 45–54.

Robertson, G., van Dantzich, M., Robbins, D., Czerwinski, M., Hinckley, K., Risden, K., Thiel, D. & Gorokhovsky, V. (2000). The Task Gallery: A 3D window manager. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI 2000)*. New York: ACM Press. pp. 494–501.

Shen, H. & Dewan, P. (1992). Access control for collaborative environments. In *Proceedings of the 1992 ACM Conference on Computer Supported Cooperative Work (CSCW 1992)*. New York: ACM Press. pp. 51–58.

Sikkel, K. (1997). A group-based authorization model for cooperative systems. In *Proceedings of the Fifth European Conference on Computer Supported Cooperative Work (ECSCW '97)*. Dordrecht: Kluwer Academic Publishers. pp. 345–360.

Smith, G., Baudisch, P., Robertson, G., Czerwinski, M., Meyers, B., Robbins, D. & Andrews, D. (2003). GroupBar: The TaskBar evolved. In *Proceedings of OZCHI '03 (Australian Computer Human Interaction Conference)*, Brisbane, Australia, Univ. of Queensland. pp. 34–43.

Streitz, N.A., Geißler, J., Holmer, T., Konomi, S., Müller-Tomfelde, C., Reischl, W., Rexroth, P., Seitz, P. & Steinmetz, R. (1999). i-LAND: An interactive landscape for creativity and innovation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '99)*. New York: ACM Press. pp. 120–127.

Tan, D.S. & Czerwinski, M. (2003). Effects of visual separation and physical continuities when distributing information across multiple displays. In *Proceedings of INTERACT 2003*. Amsterdam: IOS Press. pp. 252–265.

Tran, Q. & Mynatt, E.D. (2002). Cook's Collage: Two exploratory designs. Position paper for "New Technologies for Families" Workshop, ACM Conference on Human Factors in Computing Systems (CHI 2002), Minneapolis, Minnesota.

Voida, S., Mynatt, E. D., MacIntyre, B. & Corso, G. M. (2002, July–September). Integrating virtual and physical context to support knowledge workers. *IEEE Pervasive Computing, 1*(3), 73–79.

Vygotsky, L.S. (1978). *Mind in Society: The Development of Higher Psychological Processes.* Cambridge, Mass.: Harvard University Press.

Want, R., Pering, T., Danneels, G., Kumar, M., Sundar, M. & Light, J. (2002). The Personal Server: Changing the way we think about ubiquitous computing. In *Proceedings of the Fourth International Conference on Ubiquitous Computing (UbiComp 2002)*. Berlin: Springer-Verlag. pp. 194–209.

Weiser, M. (1991, September). The computer for the 21st century. *Scientific American, 265*(3), 94–104.