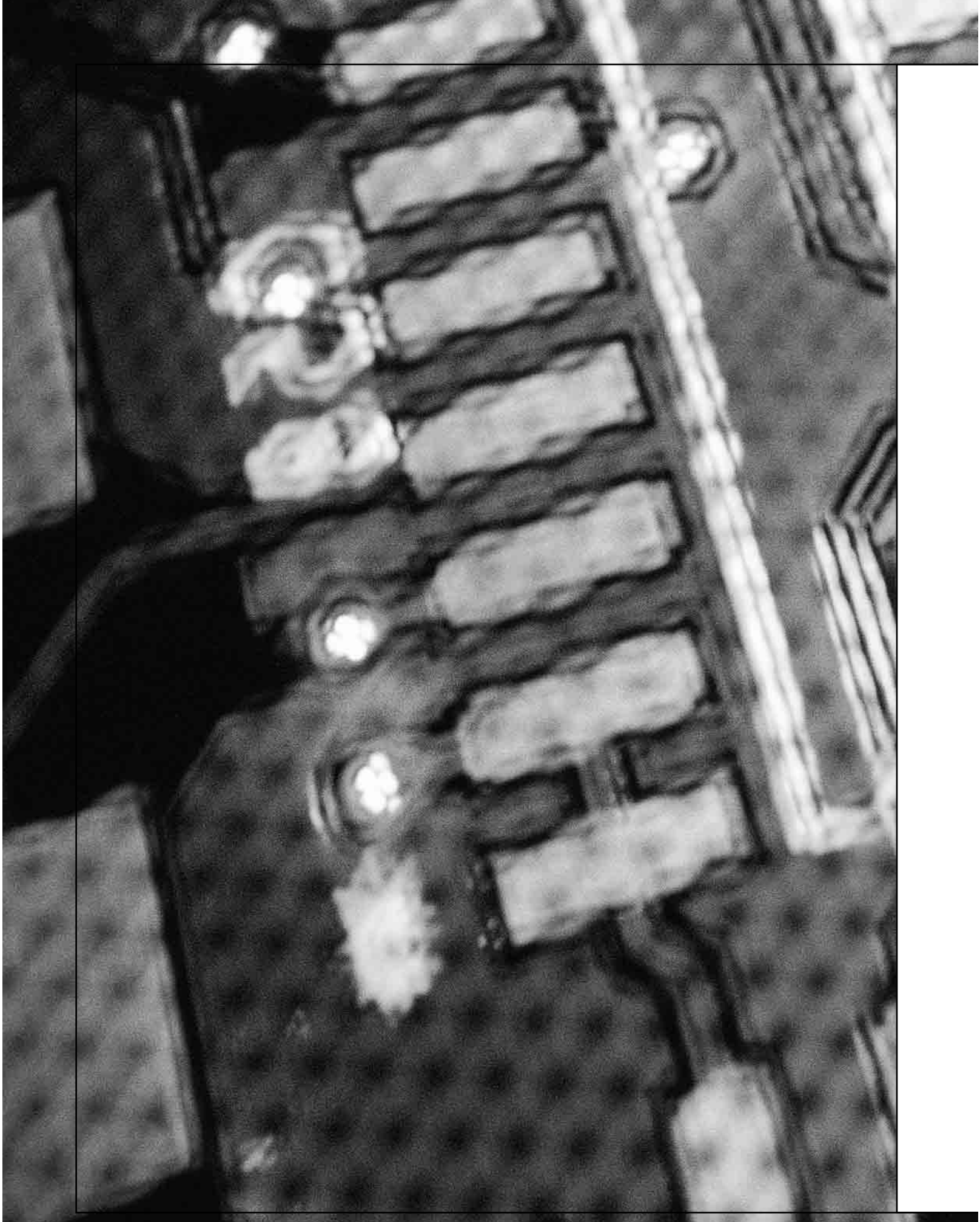


By Kalle Lyytinen and Youngjin Yoo

Issues and Challenges in Ubiquitous Computing

A fundamental measure of progress in computing *involves rendering it as an inseparable part of our everyday experience while simultaneously making it disappear [2]. Radical improvements in microprocessor cost-performance ratios have pushed this process forward while drastically reducing computing-device form factors, enabling us to embed computers in many parts of our environments. In 40 years this change has transformed the early large "computing machines" into compact devices that enable, mediate, support, and organize our daily activities.*

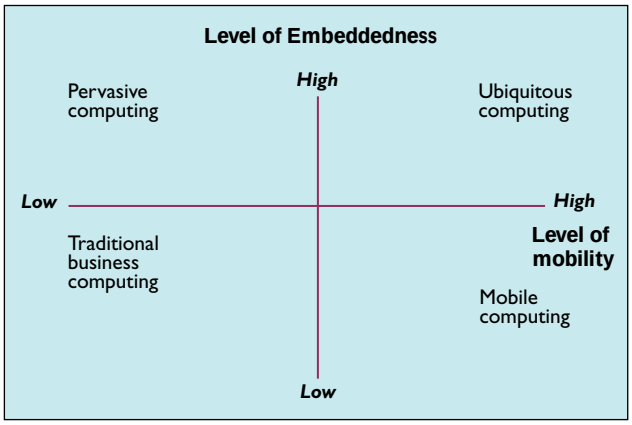
The next step in this evolution involves the move toward ubiquitous computing, in which computers will be embedded in our natural movements and interactions with our environments—both physical and social. Ubiquitous computing will help organize and mediate social interactions wherever and whenever these situations might occur. The idea of such an environment emerged more than a decade ago in Weiser's [2] seminal article and its evolution has recently been accelerated by improved wireless telecommunications capabilities, open networks, continued increases in computing power, improved battery technology, and the emergence of flexible software architectures. Consequently, during the next five to ten years, ubiquitous computing will come of age and the challenge of developing ubiquitous services will shift from demonstrating the basic concept to integrating it into the existing computing infrastructure and building widely innovative mass-scale applications that will continue the computing evolution.

The movement into the ubiquitous computing realm will integrate the advances from both mobile and pervasive computing. Though these terms are often used interchangeably, they are conceptually different and employ different ideas of organizing and managing computing services (see the accompanying figure). Mobile computing is fundamentally about increasing our

ILLUSTRATION BY RICHARD TUSCHMAN

The shift toward ubiquitous computing poses multiple novel technical, social, and organizational challenges.

capability to physically move computing services with us. As a result, the computer becomes a taken-for-granted, ever-present device that expands our capabilities to inscribe, remember, communicate, and reason independently of the device's location. This can happen either by reducing the size of the computing devices and/or providing access to computing capacity over a broadband network through lightweight devices. In principle, this evolution has been marked by the movement of computers from insulated and sealed rooms to our offices, to our laps, and finally to our pockets, clothing, and body. Combined with access capability, this has transformed computing into an activity that can be carried to a beach, a jungle, or an airport to support a wide array of human activities. In mobile computing, however, an important limitation is that the computing model does not considerably change while we move. This is because the computing device cannot seamlessly and flexibly obtain information about the context in which the computing takes place and adjust it accordingly. The only way to accommodate the needs and possibilities of changing environments is to have users manually control and configure the applications while they move—a task most users do not want to perform.



Dimensions of ubiquitous computing.

Another dimension in making the computer invisible is the idea of pervasive computing. This concept implies the computer has the capability to obtain the information from the environment in which it is embedded and utilize it to dynamically build models of computing. The process is reciprocal: the environment can and should also become "intelligent" in that it also has a capability to detect other computing devices entering it. This mutual dependency and interaction results in a new capacity of computers to act "intelligently" upon and within the environments in which we move. This is the very idea of pervasive computing, an area populated with sensors, pads, badges, and virtual or physical models of the physical and social/cognitive environments.

Pervasive computing services can be built either by embedding models of specific environments into dedicated computers or, more generally, by building generic capabilities into computers to inquire, detect, explore, and dynamically build models of their environments. Currently, the main challenge of pervasive computing is the limited scope and large effort involved to teach a computer about its environment. This makes the availability and usefulness of such services limited and highly localized because of the large effort required to design and maintain such services, thus preventing users from effectively exploiting the computing resources of their environments.

The main challenges in ubiquitous computing originate from integrating large-scale mobility with the pervasive computing functionality. In its ultimate form, ubiquitous computing means any computing device, while moving with us, can build incrementally dynamic models of its various environments and configure its services accordingly. Furthermore, the devices will be able to either "remember" past environments they operated in, thus helping us to work when we reenter, or proactively build up services in new environments whenever we enter them.

The shift toward ubiquitous computing poses multiple novel technical, social, and organizational challenges. At the technology level, there are several unresolved technical issues concerning the design and implementation of computing architectures that enable dynamic configuration of ubiquitous services on a large scale. New challenges will also emerge in terms of how one should design and develop ubiquitous services. This may require

rethinking of feasible architectures, design ontologies and domain models, requirements and interactions scenarios, and analyzing new families of nonfunctional requirements (such as configurability and adaptability). Anticipated new ways of dynamically configuring services will also shift the line between proactive design and tailoring during use. Previously, unexplored challenges will also emerge at the border between the technical and the social: some issues are to be left outside the technical implementation to be addressed by social negotiation and due process; other issues should be addressed during technical design. Finally, the emergence of truly integrated sociotechnical systems will create a wide array of research and policy issues that deal with social organization, impact, and the future of work, organizations, and institutions.

We conducted a workshop at Case Western Reserve University in late 2001 to address these issues with leading researchers in the ubiquitous computing realm from academia and industry. The group included researchers with an interest either in the technical or the social issues associated with this emerging field. Our goal was to examine the status of the field, to formulate new research directions, to explore and refine an emerging research agenda, and to identify topics requiring particular attention in the future. The articles in this special section are derived from material presented at the workshop. The authors provide rich explorations into pending issues surrounding ubiquitous computing and demonstrate diverse and even conflicting ideas of how mobility and embedded computing can and should be integrated, along with giving consideration to associated social ramifications.

The first two articles in this special section complement one another quite effectively. Davis focuses on the potential positive and negative impacts of mobility on individual knowledge work and its organization. Grudin discusses the impact of increased embeddedness on group dynamics and meeting behavior. The next two articles highlight specific design and business challenges affecting ubiquitous computing. Siewiorek's article addresses design challenges of integrating wearable computing with increased mobility in the context of supporting office and factory work. The article by Fano and Gershman explores potential business opportunities and challenges resulting from integrating mobility and embedded computing. The last two articles in the section paint a broader picture of social and technical challenges involved in making progress in ubiquitous computing. Jessup and Robey discuss potential impacts of ubiquitous computing, including its unintended and contradictory outcomes, which require attention by practitioners of several social and technical disciplines at multiple levels of analysis—individual, team, and organizational. Banavar and Bernstein identify key characteristics and functionality of emerging ubiquitous computing environments. They also describe specific technical challenges involved in building supporting infrastructure and applications.

The emergence of ubiquitous computing will provide a rich and exciting opportunity for future research. As evidenced by the articles here, studying ubiquitous computing itself presents many unique challenges—we close by noting three: First, ubiquitous computing is currently in an early stage of development. Therefore, studying it entails studying something that does not yet exist. Researchers in this field are still "dreaming" and "creating problems" as much as they are solving problems and recording and theorizing about effects. Researchers need to find ways to maintain the rigor of scientific research without restraining their ability to imagine. In addition, researchers need to find ways to study personal issues at a global level. For example, how wearable computers interact with environments and how this affects individuals' satisfaction or productivity must be studied in the context of global diffusion of mobile technology. Finally, research in ubiquitous computing requires transcending the traditional barriers between social and technical as well as levels of analysis—individual, team, and organizational [1].

As technology becomes more embedded and integrated with mobility, the barriers between social and technical aspects become blurred. A paradoxical outcome of ubiquitous computing is that it is simultaneously very personal and extremely global. Thus, a complete understanding of its impacts cannot be gained at a single level of analysis. The articles that follow will stimulate the debate on how to address these compelling issues. C

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