Interacting with 21st-Century Computers

This discussion reflects on four themes from Weiser's original vision from a human-computer interaction perspective: computing everywhere, personal computing, the social dimension of computing, and privacy implications. The authors review developments both in accordance with and contrasting this vision.

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Over the past 20 years, we've seen how technology can become invisible and provide services that ease people's lives, "invisibly enhancing the world that already exists."[1] While Mark Weiser's vision was formulated with the user at the center, technical challenges still must be resolved to realize his vision. This becomes even more obvious when looking at the prototypes Weiser and his group created, the skill sets of the people involved at Xerox PARC, and the resulting publications and patents. At the same time, the importance of designing for the "user experience" has been widely acknowledged both in research and industry, including manufacturers of mobile devices and computers alike.[2,3]

Today, mobile phones are the prime computing platform worldwide,[4] tablet computers are a fast-growing market, and many schools are installing digital whiteboards in their classrooms. Furthermore, processors have become a part of many devices. Some TVs are now computers enhanced with hard drives, networking capabilities, and special user interfaces, and smart home appliances can be networked and wirelessly controlled. High-end cars also include many networked processors. When we talk about ubiquitous computing (ubicomp), we refer to all these types of developments. Even though mobile phones are ubiquitous, they're only one, albeit important, part in the ubicomp infrastructure currently emerging.

Here, we discuss ubicomp's impact on users and their interaction with devices. Traditionally, new technologies open up opportunities for new types of applications and forms of human-computer interaction (HCI).[5] A prominent example was the transition from text-based user interfaces to graphical systems in the 1990s, and more recently the rise of tangible user interfaces.[6] In the last decade, ubicomp has similarly inspired and enabled new approaches to HCI.

Focusing on four themes from Weiser's original article—computing everywhere, personal computing, computing beyond the individual, and privacy implications—we discuss these themes from an HCI perspective and reflect on remaining research challenges.[1]

Computing Everywhere for Everyone

Ubiquitous access to computing and mobile communication technologies and to the Internet hasn't just enhanced the world but also changed it. When Weiser wrote his article, the World Wide Web as we know it didn't exist, but the Web has significantly influenced how people interact with computers and use ubicomp technologies.

Published by the IEEE CS ■ 1536-1268/12/$31.00 © 2012 IEEE

Ubiquitous access to knowledge (such as farming advice or medical information) and up-to-date information (about weather forecasts or current market prices, for example) is increasingly available. People who previously didn't have Internet access can now obtain such information through kiosks and mobile phones. Additionally, digital banking systems have been created on top of the mobile phone infrastructure,[7] and groups have found ways to use mobile communication technologies to organize themselves (even to topple regimes[8]).

The Web's impact has been significant in reducing the complexity of creating distributed applications. An early approach to combining the Web with ubicomp systems used a Web browser and Web protocols to control smart environments.[9] Nowadays, creating a distributed information application (basically a webpage) has become trivial; even having an interactive, distributed multiuser application requires little expertise (using Web forms or a Web 2.0 platform).

We have thus witnessed two major ubicomp drivers: cheap availability of technology and services, and easy-to-use computing devices and systems (especially mobile phones and smartphones). These are now making possible the realization of what Weiser suggested in his seminal article, saying that "embodied virtuality will bring computers to the presidents of industries and countries for nearly the first time. Computer access will penetrate all groups in society."[1]

Ease of Use is Key

Ubiquitous technology use requires simple, easy-to-use interfaces and a positive user experience. These are prerequisites for enabling technology access for the masses. People expect to use devices without engaging with the underlying concepts or technical details. In particularly, this trend has developed over the last decade as computer-based consumer devices have penetrated people's lives and enabled them to concentrate on how they can exploit a device's power without worrying about how it works.

Ubicomp has three major dimensions relating to ease of use: deployment, maintenance, and end-user interaction.

Deployment. This is an important dimension in ubicomp systems.[10] As "ordinary" (nontechnical) people become the target users, the required expertise for using, deploying, and installing systems must be minimized. If construction workers want to deploy sensor networks in buildings, or if farmers plan to apply monitoring systems to their cattle, we must reduce the (technical) complexity for installation and ensure that the required knowledge fits in with the users' skill set.

This aligns well with Weiser's discussion of embodied virtuality. People who will install and deploy systems are often experts about the object of embodiment (for example, buildings or cows) and their own everyday tasks. In an optimal design, knowing about the embodiment (domain expertise) should be sufficient for people to successfully deploy a ubicomp system.

Maintenance. Ordinary users should similarly be able to perform their own maintenance tasks. Exchanging an IP-based light bulb shouldn't be more complicated than exchanging a regular light bulb. The goal, especially considering hundreds of computers per room, is zero maintenance or, where more complex services are required, administration that can be done remotely or automatically.

End-User Interaction. User interaction with the system should also be invisible, at least to an extent where the person can focus on performing the tasks, albeit mediated by the system, without worrying about the technology itself. To achieve this, we must explicitly consider interaction with ubicomp systems.

Authors have variously suggested that these interactions can be embedded,[11] natural,[12] intuitive, or reality based.[13] The terms "natural" and "intuitive" aren't well defined and typically refer to an interaction that conforms to the users' expectations. Daniel Wigdor and Dennis Wixon describe a natural user interface as an "interface that makes your user act and feel like a natural."[12] Matthew Chalmers and Areti Galani used another interpretation of invisibility, arguing that total technical invisibility might be an unrealistic goal.[14] Instead, they suggest "seamful interweaving," where people can rationally interact with infrastructure "seams" and heterogeneity in the everyday course of their interaction. In all of these definitions, the key point is that invisibility is about not getting in the way and not drawing attention away from the task; as Weiser said, "People will simply use them unconsciously to accomplish everyday tasks."[1]

Many of the expectations people will have with regard to easy and intuitive interaction (and maintenance) of ubicomp systems will directly come from their experiences using the Web. When dealing with a problematic webpage, users simply hit "reload." Large amounts of information can be available in an instant entering everyday language terms. Even with email, the increasing sophistication of search tools means there's less need to sort email, because emails can be queried on the fly to provide ad hoc orderings. Such expectations are likely to transfer over to the standards that people will also expect of ubicomp systems. (See the sidebar for a small collection of ubicomp technologies strongly related to HCI that we expect will become pervasive over the next 20 years. These technologies should greatly impact future ubicomp interactions and what we think about the user's experience.)

Ubicomp Inside

Although many of the early visions of interacting with ubicomp systems assumed multiple devices, the convergence

Promising Ubicomp Technologies

Many technologies are currently being explored in human-computer interaction (HCI). We predict that the following technologies for implicit and explicit interaction will become ubiquitous over the next 20 years.

Pico Projectors

Visual feedback for ubiquitous devices is still mainly given using traditional displays integrated into the device itself. Mobile pico projectors will extend the interaction space massively, making projection technology ubiquitous. These pico projectors can be integrated into mobile and wearable devices and can convert any surface—walls, ceilings, desks, floors, or even a t-shirt or the palm of your hand—into an interactive display. Some interaction concepts[1] and prototypes, such as the Sixth Sense Project,[2] are first examples that illustrate the power for applications.

Digital Signage and Public Displays

As prices for display technologies decrease, painted signs in public spaces are being replaced with their digital counterparts (see Figure A1). Whereas nowadays digital signage often shows mere adaptations of traditional content, networking capabilities as well as sensors will allow content to be easily updated and adapted to the audience, potentially making public displays a future communication medium.[3] A key challenge is to create a pleasant and convenient user experience that fosters people's engagement with public displays.

Spatial Gestural Interaction

As gestures and emotion are essential information cues in human-to-human communication, they've recently received increasing attention in HCI. The idea is to enable users to interact based on natural gestures with computing devices, allowing explicit gestures as well as implicit observation. Technologies, ranging from multitouch surfaces to 3D motion tracking (such as Microsoft's Kinect), have been a major focus lately—and decreasing costs will allow for ubiquitous use.

Brain-Computer Interfaces

Brain-computer interfaces for explicit interaction could become feasible in the future; however, using electronencephalography (EEG) as a source for contextual information is already feasible. With many cheap devices available that sense and classify brain activity, ubiquity use can be expected for implicit interaction. Monitoring the user's brain signals can improve support for activities (see Figure A2).[4]

Physiological (Self-)Monitoring

Sensors that monitor health parameters (such as heart rate, electrocardiography, and muscle activity) are becoming smaller, cheaper, and more robust. With those sensors vanishing into the background (by being integrated in undergarments, for example), continuous monitoring of health and fitness information becomes possible without the extra burden to the user. This information can serve as contextual input for ubicomp applications and could become a means for health prevention. Thus, "underwear that's like a helmet for your heart" might be the norm in several years, allowing for early detection of trends and patterns—such as early warning signs of heart disease.

Continuous Capture and Extended Human Memory

Wearable cameras and continuous audio capture can easily record everything we see and hear. Combined with contextual annotation and data mining, this will provide extended (personal) "memories." Capture technology and storage are available for the ubiquitous use of devices to extend human memory, but social and ethical implications of such data capture are still an open issue. The SenseCam (see Figure A3) has demonstrated the power of such systems in the context of people with disabilities, because it can continuously capture a person's surroundings.[5]

of multiple capabilities into one device opens up a new version of ubicomp interaction. The phone, for example, is one device that has seen a massive transition from an electronic device into a computer-based appliance, where many of the functionalities perceived in a ubicomp scenario are now available within the smart phone—such as location awareness and embedded sensors.

The changes to many machines in industry and the transformation of manufacturing processes have been less visible in public but similarly revolutionary. Ubicomp is fundamentally changing many engineering disciplines as mechanical and electromechanical devices and systems are being replaced by computing technologies with multiple embedded capabilities. In modern cars, for example, many functions are nowadays being realized in software.[15]

Increasingly Intimate Computing

Although for most people, the age of personal computing isn't gone (yet), the nature of "personal" computing as envisioned by Weiser in the early

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Figure A. Examples of (1) a public display, (2) a brain-computer interface, and (3) the Microsoft SenseCam (photo courtesy of Microsoft Research).

days of the PC has radically changed.[16] People nowadays have a much closer relationship with their personal computing devices. In particular, mobile phones—and increasingly other portable devices, such as pads and tablets—have become ubiquitous and, at the same time, very personal. This trend is in contrast to one of Weiser's forecasts:

> *The idea of a "personal" computer itself is misplaced and … the vision of laptop machines [is] only a transitional step toward achieving the real potential of information technology. Such machines cannot truly make computing an integral, invisible part of people's lives. We are therefore trying to conceive a new way of thinking about computers, one that takes into account the human world and allows the computers themselves to vanish into the background.*[1]

The new form of personal computing that many users initially experienced when they received their first smart phone exemplifies how nontechnical people now perceive and experience computing in the 21st century and how our understanding of "invisible" has evolved. For many people, smartphones are increasingly the "personal computer" that they rely on the most—and they have become an integral, highly visible part of their lives. The device itself and its many converged functionalities have become part of people's self-expression and even a status symbol in many cases. It's as though consumers have "fashioned" themselves with a particular phone as an accessory and—similar to the fashion industry—competing phone companies work hard to ensure that the latest smartphones are considered even more cutting edge and desirable than the previous ones, and that the devices themselves don't vanish into the background.

Invisible Technologies

When considering the experience of using new generations of personal devices, the "vanishing into the background" step Weiser predicted has been clearly made by the majority of users. We recently conducted a study of mobile-phone-camera use. As we asked users about their phone, we received answers that were mainly related to the mobile phone's functional capabilities (how they use the phone for social networking or to show off photos or access their favorite apps). They knew little about the phone's built-in processor or networking specifications. Many users didn't even know the model of their phone. However, hardware properties were better known if they directly impacted the user experience (such as the camera or screen resolution). We suggest that the smartphone has enabled a major change in how we interact with computers, as it has become for many users, in Weiser's words, "a pleasant and effective 'place' to get things done."[1]

The interesting paradox is that in being clearly visible as a device or "place," the technologies and devices are also invisible in the way they seem to blend into everyday practices of use and in how people have evolved practices around them. Typing emails on an iPhone might be viewed as inefficient owing to the slower typing speed. However, users have compensated by developing new email practices, such as shorter emails, thereby in a way increasing the efficiency of the overall medium.

Also seemingly contradicting the vision of the disappearing computer, advertising could become ubicomp's killer app.[17] Pervasive advertising is finally ready to leave the labs, and we're currently at a crossroad in terms of determining advertising's future. On the Web, pop-up windows and unsolicited banners strive for user attention, as do static displays. Initial experiments show that the use of traditional poster advertising can be combined with mobile and context-aware devices to create links between static content and dynamic information.[18]

The potential for changing how advertising is implemented in ubicomp settings has also been explored with a variety of options for interaction with yard-scale computing and public displays.[19] Many visions of the advertising future see personalized ads bombarding users with spam, spying on them, and manipulating them to make them buy products they don't need. However, there's also the positive future of calm and engaging advertising where "advertisements strike a balance between being calm when we do not need them and being engaging and inspiring when we want to participate."[20]

Extremely Personal Data

Looking at the data many people organize and store on their personal devices, it's also clear that these devices have become intimate companions. Cherished personal photos; intimate communication traces in SMS and email; contacts and interactions with those contacts; private calendar entries and logs of personal activities, websites accessed, notes taken, and various applications installed are all examples of sensitive and valuable personal information.[21] With current technologies, such as Near-Field Communication (NFC) and other means for electronic payment[22] and authentication,[23] phones have become even more personal. Given this intimate link between the person and the device's data, how much would you need to trust someone—a family member, friend, or colleague—before lending them your mobile phone?

Although many aspects of ubicomp are embedded in everyday spaces and objects, there are other aspects that have become more personal and intimate than probably most people have imagined. Computing has become an integral part of life for many users across the world. It has massively changed how people live. Being able to reach and be reached at any time as well as having immediate access to information anytime, anywhere has had a significant impact on the way we work as well as on domestic life. At the same time, phones have become a status symbol, especially among the younger generation, hence contributing to Weiser's vision of ubicomp technologies fitting in well with the world.

Beyond the Individual

Many ubicomp scenarios rely on some forms of artificial intelligence (AI) and a representation of the world—recognizing contexts, understanding activities, and triggering or suggesting applications are some examples. To tackle this, Weiser suggested using AI to make the problem easier to solve:

> *Sal awakens; she smells coffee. A few minutes ago her alarm clock, alerted by her restless rolling before waking, had quietly asked, "Coffee?" and she had mumbled, "Yes." "Yes" and "No" are the only words it [the computer] knows.*[1]

Research laboratories around the world have been developing and testing interesting and useful applications, implementing, in particular, intelligent spaces and smart homes based on AI approaches. The research results suggested that they were feasible, worked properly, and (from a scientific perspective) were successful. Nevertheless, many of these research prototypes have not yet made it out of the lab.

A major challenge is making AI work satisfactorily in the real world. As Genevieve Bell pointed out in her opening keynote at CHI 2010, the real world is messy and unpredictable. Furthermore, plans and actions are situated,[24] there are always exceptions, and behavior can change over time, making pattern detection and predictive interpretation difficult. Identifying how "intelligent" behavior can work in an environment that can change and that might not be fully known is still an open question. The main challenge is finding the "intelligence" balance between the system and people who live in the space. This is where an approach that engages communities rather than individuals offers promise.

Community-Provided Intelligence and Content

Creating anticipatory systems—systems that can anticipate the users' desires without conscious mediation—is still extremely difficult. One way to do this might be to observe a community and its actions. If we consider the task of creating a map of wheelchair-friendly routes around a town, we will quickly realize that this is still not easy. We can either look at all possible routes and manually model it or use available maps and build a heuristic on top of them to find proper paths. The approach of manually modeling routes is time consuming (but is already done in projects such as openstreetmaps.org) and the heuristic-based approach is surely error prone.

Another approach is to directly encourage people to contribute. Alternatively, modeling based on implicitly sensed information can be used. In a simplistic approach, we could accumulate the information from wheelchair users and collect information about the paths they use and how such paths impact the wheelchair (measuring location, speed, and tilt, for example). If there weren't enough wheelchair users, we could also get the same information from walkers (detecting steps and slopes from their gait) and use it to create a map. If we have enough contributed data, we're likely to need less AI, because we can use community intelligence.[25]

Participatory sensing, people-centric sensing,[26] and implicit interactions[27] for contributing content have the potential to fundamentally change how we interact with computers and our environment. Consider an analogy: Children learn from observing grown-ups. Imitation of behavior, even with little understanding of what it means or why it's useful, is key in learning how to deal with the world. At the same time, this also has an interesting effect on the parents, as their behavior changes, too. As soon as they realize that their children will copy their behavior, they become more aware of their actions and their function as a role model. They often change their language and behavior when their children are around.

Users could similarly get into a relationship with ubicomp in which the computer learns and observes their behavior. Imagine the ubicomp infrastructure learning your preferences for parking places or where you like to shop. If you never drive into a parking garage, it wouldn't recommend parking garages. Knowing that the computer is learning from you and others, and potentially sharing what it learned, could lead to different behavior.

Balancing What We Share and Retain

Weiser didn't foresee storage as being an issue:

> *Such enormous stores will not necessarily be filled to capacity with usable information. Abundant space will, however, allow radically different strategies of information management. A terabyte of disk storage will make deleting old files virtually unnecessary.*[1]

This is certainly becoming a reality, as we now have growing sensor networks, devices, and an abundance of computing that will allow massive amounts of data to be collected. Recording everything we see in a high-resolution video and storing everything won't pose a technical problem anymore. As the cost for recording and storing becomes minimal, even if there are only small benefits from such recordings, it can still be useful to do them.[28]

If we now imagine that a large number of people will record and share what they have seen, information access and use is the only remaining problem. For many problems, the solutions will become obvious, similar to the concept of social navigation.[29] Currently, users make deliberate choices about what to record and share. However, consider reversing this approach: what if everything a person saw was by default recorded and shared, and we only had to choose what not to share? How would this impact us?

Consider the following example: Have you wondered how to change a bicycle chain or how to make strawberry cupcakes? Someone else has done this before and implicitly recorded and shared it, so you can find a first-person account of how to do it. The remaining problem is how to find it—but here, too, the abundance of resources can help, because we can store meta-information (context) and perform massive data processing and image mining. This also leads to a societal challenge in terms of what we do with all the data, how we make sense of it, who or what makes sense of it, and what this leads to.

Privacy and Profits

Ubiquitous computing enables new opportunities for tracking people's location and activities, which has always been a sensitive issue. When Olivetti Labs described their active badge system, the responses in the scientific community and press were to picture a future of ubiquitous surveillance.[30,31] These are issues that still need to be addressed today.

Acceptance and Perceived Value

User acceptance of technologies that invade privacy is strongly correlated with the perceived value. For mobile phones to work, the operator must know where the user is. This form of ubiquitous location tracking hasn't harmed the adoption of mobile communication technologies. Users accept and usually don't reflect much on the information they must give away in return for the service. This trade-off between convenience and privacy had already emerged in Weiser's initial ubicomp work:

> *Even today the active badges and self writing appointment diaries that offer all kinds of convenience could be a source of real harm in the wrong hands. Not only corporate superiors or underlings but also overzealous government officials and even marketing firms could make unpleasant use of the same information that makes invisible computers so convenient.*[1]

Increasingly over the last few years, companies (such as Google and Facebook) have been successfully exploiting information volunteered by the users (search queries, email content, activity and status messages, and multimedia content) to provide targeted services. So far, this has been more related to Web services, but it's apparent that such companies are moving into the mobile and ubicomp space.

Weiser commented on the use of such information in a very negative undertone ("unpleasant use"). However, today such products are successful in the market, ranging from location sharing to contextual search. Companies profit from providing convenient services, and many users seem to value convenience over privacy. At the same time, it's still an open question whether the reason for accepting this impact on privacy is the consequence of a lack of understanding or a result of products successfully making "invisible" which data they collect in the background. Many researchers, especially in the HCI field, view this loss of privacy as a major risk.

Understanding Risks and Opportunities

Technologies (such as cryptography) alone won't solve the privacy issues at hand. We'll need societal agreements on what's acceptable and how data can be used, implemented within a legal framework. We also need to clarify for people, at least for "self-education" purposes, what's really possible with technology and the risks involved. As a result, we must develop methodologies and approaches that help participants become more informed in these debates and more knowledgeable about their own personal choices. This should affect the design process such that systems are made more accountable to and understandable by users.

The privacy risks considered in early ubicomp research are still perceived as risks today—in particular, the tracking of people and location.[32] On the other hand, ubicomp research has yet to embrace the full potential of available information. Here, it seems general commercial use of available data has moved much faster. More research is required to understand the value of the information we create and own as individuals and as a society, as well as what we can do with it and at what costs.

Reflecting on Weiser's visions 20 years later, it's amazing how the vision foresaw many technological developments that have fundamentally changed how we interact with computers and how we communicate. The cheap availability of technology and services, and of easy-to-use computing devices and systems (especially mobile phones and smartphones), means that computing really is becoming ubiquitous and is already impacting the everyday lives of people around the world. In particular, global, ubiquitous mobile-device use has become the norm and is often seen as the reality of ubicomp. But it's only one aspect of ubicomp. There are more changes to come, as computers become an integral part of many devices and appliances.

Yet how we interact with the "computer" in the 21st century remains a challenging question, precisely because there's no longer a clear, single computer focus, as in the days of the desktop machine. Weiser set out a new vision for a ubicomp world, and the emergence of new technologies are helping us realize evolved versions of this vision. We have single devices that offer multiple ubicomp functionalities and experiences, and we have multiple networked and embedded devices that form part of the fabric of our daily lives. We also have users who are becoming increasingly accustomed to having ubiquitous access to information and computing power, with increasingly discerning expectations about their experiences using these devices. As designers and researchers, we have the challenge and responsibility of creating this new world, while keeping people and their values and interests at the center of the technologies.

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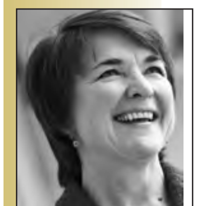

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