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Achieving Ubiquity: The New Third Wave

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Mark Weiser, a chief scientist at world-renowned Xerox Palo Alto Research Center, envisioned a third wave of computing, one with hundreds of wireless computers in every office, which would come about as the cost of electronics fell:

> *Ubiquitous computing names the third wave in computing, just now beginning. First were mainframes, each shared by lots of people. Now we are in the personal computing era, person and machine staring uneasily at each other across the desktop. Next comes ubiquitous computing, or the age of calm technology, when technology recedes into the background of our lives.*[1-2]

Indeed, from his perspective in the late 1980s and early 1990s, this prediction made imminent sense. Technologists had seen a dramatic shift in computing from many-to-one environment of mainframes to the one-to-one relationship of the personal computer. Drawing this trend out, Weiser foresaw the emergence of a world where one person would interact seamlessly with many computers—a development that he believed would lead to the age of ubiquitous computing.

Two decades later, some in the ubiquitous computing community point to the pervasiveness of microprocessors as a realization of this dream. Without a doubt, many of the objects we interact with on a daily basis are digitally augmented. They contain microchips, buttons, and even screens. But is this the one-to-many relationship of people to computers that Weiser envisioned?

Editor's Note

In this article, Chris Harrison, Jason Wiese, and Anind K. Dey discuss the predictions of Mark Weiser, the father of ubiquitous computing, who envisioned that we would have smart personal environments, with numerous computational devices embedded within each environment. The authors point out that, rather than this happening, what we have currently are personalized computational devices, for example, smart phones, tied to users rather than embedded in the environment. The interesting development of this observation is the crux of their article. Even though multimedia, per se, is not specifically addressed in the article, what the authors have to say is certainly relevant to our community, as smart computational devices and sensors of various sorts are certainly siblings under the skin.

—William I. Grosky

What's in a name?

To understand where Weiser's dream has and has not been realized, we need to define what makes a computational device. Many definitions exist, and, for better or worse, this is partially why the success of the ubiquitous-computing vision has diverse interpretations. Although Weiser never defines computers explicitly, we need look no further for a definition than his core realization that the PC era was marked by a one-to-one, person-to-computer experience.

In the late 1980s (and certainly by the 1990s), people were surrounded by digital devices: thermostats, televisions, alarm clocks, wristwatches, microwaves, and even mobile phones. Critically, Weiser didn't include these in his count of computers. Why? These devices certainly used computation. After all, they contained a microprocessor capable of crunching thousands of numbers per second. But they did not expose this computational ability to the user, and thus it's hard to view them as computational platforms.

For example, a simple DVD player has a better processor than that of the first Apple computer. However, it would be hard to argue that a DVD player is a better computing platform than the Apple I. To generalize, a computer is much less about the presence of

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computing power, and much more about how that power can be wielded by the user. Computers, in our view, are those that provide functions that aid in creation, communication, and information.

Indeed the key motivation behind the microprocessor revolution was not about adding computation, but rather replacing unwieldy, unreliable, and costly analog electronics and mechanical systems. In other words, it wasn't about making more capable thermostats; it was about making them less expensive and more reliable. The fact is, we could replace the electronic innards of your thermostat with a mechanical equivalent, and functionally it wouldn't be tremendously different. In fact, you might not even notice. There are scores of devices like this where the move to microprocessors did not greatly enable us—a core tenet of computing.

Returning to Weiser, his vision of the simplest scrap computing device was a tab (see Figure 1). Even by today's standards, this is a fairly sophisticated and capable computer. This post-it-note-sized device contained a processor, solid-state memory, and a screen capable of pen input. It could connect to wireless networks to access documents and information, as well as computational and communication resources in the cloud. If this was considered the lowest common denominator computer, Weiser set the bar quite high indeed.

Figure 1. A ParcTab, the inch-scale computer that Weiser foresaw sprinkled in offices by the hundreds. (Photo courtesy of Palo Alto Research Center, PARC; http://www.parc.com.)

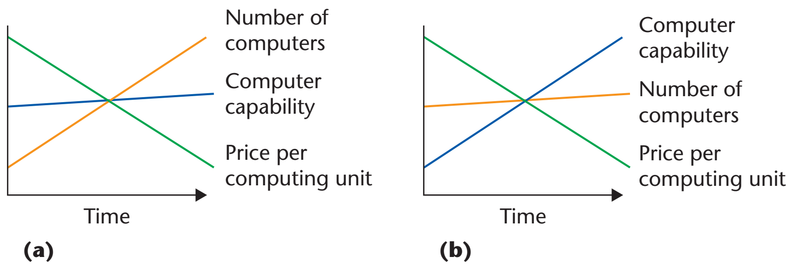

Figure 2. Both (a) quantity and (b) quality computing paradigms assume the cost of computing falls over time (for example, in terms of speed, storage, screen quality, and so on). If the same total amount of money is spent, two paths are possible: increase the number of computing devices or increase the quality of a few select devices.

Where technology has taken us

A key aspect of Weiser's vision was that the number of devices (smart or dumb) would increase as the cost of electronics fell, and not just double, but multiply by tens or hundreds. A quick survey of your home or office would immediately reveal this hasn't come to fruition. In fact, for the most part we have a similar number of devices as people did in Weiser's day—that is, thermostats, microwaves, televisions, and so on. In some cases, we've seen device convergence; peoples' smart phones also serve as their alarm clocks and audio players.

Armed with a better understanding of what makes a computing platform, we can see the growth in computers is fairly muted as well. Most families have a personal computer; a subset have laptops as well. Many people have mobile phones; dramatically fewer have smart phones. Tablets, ebook readers, and similar devices remain relatively uncommon. Finally, there are a few examples of special-purpose, shared-computing devices, such as DVRs and gaming consoles in the home, and conference room computers and perhaps multifunction print machines in the office.

At best, we've moved from the one-to-one PC era to the one-to-four contemporary era—and that's being generous. Regardless of how you do the counting, it's hard to argue that we're anywhere close to the two orders of magnitude change that Weiser envisioned. So what happened? Instead of using the falling cost of electronics to have more devices, we've just reinvested these advances to make better devices. It's analogous to the quantity or quality maxim—and all indications point to quality computing triumphing over quantity computing, illustrated in Figure 2.

This trend is apparent if we look at the evolution of desktops, laptops, PDAs, and mobile phones, which are arguably the four most successful classes of computer. Although factors such as processor speed, storage space, and wireless bandwidth have improved by two or three orders of magnitude, these platforms have become only nominally less expensive (one order of magnitude at the most). In many cases, price has stayed relatively constant: the first-generation Palm Pilot cost about as much as an iPod Touch does today, and they occupy a remarkably similar role.

So why is quality computing winning?

Coalescing computation

According to Weiser, ''The technology required for ubiquitous computing comes in three parts: cheap, low-power computers that include equally convenient displays, a network that ties them all together, and software systems implementing ubiquitous applications.'' Consider the following question: would you rather have 10 computers in your office, or one computer 10 times more capable? Given that people tend to use only one computer at any given time, the single superior device is probably the best choice. It's not that we're lazy; it's how our brain works. Attention is the scarce commodity and we work best when we dedicate our faculties to a single task. Thus, we would want to wield the most capable tool.

We've collectively made this choice many times during the evolution of computing. The truth is, devices approaching Weiser's tab are available. We could sprinkle low-end digital organizers (which cost as little as $5 today) all over the home and office. But would you really want scores of these limited devices or an iPhone in your pocket? There is really no contest. That's not to say there isn't value in having more computers. It would be nice (although mostly convenient) to have 10 iPhones lying around the house. But the economic reality is that we'd prefer to concentrate power so we can wield it all at a given instant, making us maximally efficient.

Quantity computing would make sense if we reach a computing plateau, where devices just couldn't get any better. However, the long history of technological innovation casts doubt that this will ever occur: things can always be made better. If devices only cost a dollar to manufacture, people would just go out and buy the $2 version for personal use, even if it were only imperceptibly superior. Maybe for their homes, they would buy a few $10 versions. And by the time you get to this reality, maybe people would just buy the super $100 version to keep in their pocket, instead of having to use the inferior $1 devices on the train.

Because of these economic and technical factors, quantity computing can only exist if the computing experience is made holistic. That is, the whole computing experience is more than the sum of its individual devices. Imagine a task where the more tabs you placed on your desk, the exponentially more efficient you became. This would dramatically shift the economics back in favor of Weiser's quantity-computing vision. However, we don't have an interface and interaction paradigm that achieves this holistic computing experience. Clearly using two laptops at once is only marginally superior to using one, and using 10 laptops at once certainly doesn't make you 10 times more efficient. It's this diminishing return that has driven the economics towards quality computing.

In general, although more than 20 years have passed since Weiser proffered his grand vision, no one has a solid grasp of how to achieve a generalized, holistic, multicomputer experience. Moreover, even if a critical mass of killer applications were found for quantity computing—hundreds of devices in every office—there are several significant challenges that would have to be overcome.

Quantity computing in practice

Weiser mostly got it right when he said, ''Ubiquitous computing envisions a world of fully connected devices, with cheap wireless networks everywhere ... it postulates that you need not carry anything with you, since information will be accessible everywhere.'' We have fully realized his vision of inexpensive wireless networks blanketing our world, allowing us to transmit and receive voice, video, and data wherever we happen to be. This unprecedented level of information access has undeniably changed the way we socialize, work, learn, and play.

However, the second part of Weiser's dream has not materialized. Information is only accessible to us today through special-purpose and highly personalized devices. If we want information access on the go, we carry a device with us. We don't have the smart computational environments and scrap computers Weiser predicted. Two significant technical challenges have stymied this future: infrastructure and privacy.

Infrastructure and hardware

In Weiser's vision, "The pad that must be carried from place to place is a failure. Pads are intended to be 'scrap computers' that can be grabbed and used anywhere; they have no individualized identity or importance." The first question one might ask is who is buying all of these devices to sprinkle around? Even at a dollar apiece, this cost would be staggering to make them ubiquitous. Certainly a large corporation could afford to distribute them in controlled environment such as an office. But what do people do when they are out for a walk, at the local pub, or riding the subway? You could certainly hope to snag devices sort of like you might do with a discarded newspaper during your train ride into work—but would you risk it? Or would you just carry a device with you to be assured?

Even if we assume inexpensive devices were sprinkled everywhere, who's maintaining them? Hundreds per person no less. Not only kept in good repair, but batteries charged. And much like how office staplers seems to coalesce in certain colleagues' offices, we'd need a class of workers whose full time job was to simply redistribute them. Admittedly, we're taking a somewhat extreme view and reaching out beyond Weiser's original vision. But these examples do serve to underscore, albeit humorously, significant challenges that would develop.

Unfortunately, device infrastructure is only half the story—what about wireless communication? Reliable access breaks down quickly when the number of devices increases dramatically—an issue that Weiser noted and that continues to be an imposing obstacle despite two decades of intense research. Concurrent with this problem is battery technology, which has seen limited advancement. Processors can be engineered to be energy efficient, and power consumption for each million instructions per second has seen tremendous improvement.

Unfortunately, the physics of electromagnetic radiation for communication purposes mandates a certain level of energy consumption. We can't engineer ourselves out of the laws of nature. The notion of hundreds of devices all talking with each other, accessing cloud resources, and not needing to be charged for days at a time seems unlikely. The battery alone would cost $5, breaking the whole economic model.

Weiser also discussed environments augmented with robust sensing capabilities. To make applications that rely on sensing work reliably, every location would have to implement a standard suite of sensors. Unlike wireless communication, which can blanket acres, many sensors would have to be deployed at room level. This would be a massive, if not impossible undertaking. If this ubiquity cannot be achieved, users are unlikely to tolerate applications that become diminished in capability or entirely unusable in some areas. Far more practical is for devices to be self-sufficient, containing their own sensors, and to guarantee a consistent level of operation, which is a model we see today in smart phones with cameras, microphones, and accelerometers.

Privacy and security

A myriad of questions arise in a world that knows you and everything you do. Is privacy possible? Who owns the sensors? Where is personal information stored? How is it transmitted securely? Who can access your data? How do you access your own data? Weiser recognized the desire for privacy and the need for users to be (and feel) in control of their data:

> *Hundreds of computers in every room, all capable of sensing people near them and linked by high-speed networks, have the potential to make totalitarianism up to now seem like sheerest anarchy. Just as a workstation on a local-area network can be programmed to intercept messages meant for others, a single rogue tab in a room could potentially record everything that happened there.*

He offered a partial solution: personal data should be centralized, even going so far as to say it should be centralized onto each person's individual PC—a curious backpedaling of the ubiquitous vision. Even if data could be centralized, the very fact that it's collected in a ubiquitous manner—by untrusted sensors and computers and sent over unknown communication links—instantly dissolves any hope of data protection.

A quality-computing model sidesteps some of theses issues (certainly not all; privacy is a grand challenge problem). Instead of having a smart environment track you, you can have your smart device track the dumb environment. For example, instead of every book in the bookstore sensing you, your smart device senses every book (perhaps through dumb RFID tags). This immediately centralizes the data on a single device, where you can view it, ask questions of it, and delete it.

Having a single device sense the world doesn't fully remedy the problem. If that device happens to be a scrap computer you picked up on your way to work, how can you be guaranteed it does what is says? Is it key logging all of your passwords? Forwarding all of your emails to a third party? Really deleting the files you're asking it to?

These issues suggest that a better way forward is to have a single device that you control, more effectively guaranteeing an expectation of centralization and operation. This is essentially the model we see today.

Realization versus implementation

Ubiquitous computational power for creation, information, and communication is massively empowering and has forever changed our way of life. This was the heart of Weiser's dream, and in the most significant ways, he has been vindicated. The biggest divergence was in the implementation—instead of achieving computing ubiquity through proliferation, we've achieved it through mobility.

Thus, two grand challenges arise. To realize the potential of quantity computing, the challenge is to develop a holistic interaction and interface paradigm that augments a wide range of tasks and experiences. To capitalize on quality computing, we need to be bold in our clairvoyance, inventing the future by assuming tomorrow's mobile computers are 10 times more powerful than our desktops today. **MM**

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