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ORIGINAL ARTICLE

The motivations of ubiquitous computing: revisiting the ideas behind and beyond the prototypes

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Abstract Ask anyone in the field, "What is ubiquitous computing?" and you'll get a different answer from each person. The one definition of ubicomp that nearly everyone points to (as an almost obligatory citation) is Mark Weiser's 1991 Scientific American article: "The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it." While this vision was clearly inspiring, many readers miss the point that ubicomp was not simply a dream of putting computers everywhere. Weiser was deeply concerned about what it would be like to live in a world of ubiquitous computing. Those human issues were compressed to a single paragraph of his *Scientific American* article, citing Herbert Simon, Michael Polanyi, James Gibson, Hans Georg Gadamer, and Martin Heidegger. By unpacking this dense paragraph, tracing connections between ideas through his library archives, and interviewing many of Weiser's professional and personal influencers from the early days of ubicomp (late 1980s at Xerox PARC), we get a sense for the philosophical history behind ubiquitous computing. This broader understanding of the influencers and ideas can serve as a source for inspiration for exploration and innovation that refocuses upon the first-person human experience of ubicomp systems: (1) leveraging human experience below the level of focused, conscious attention, (2) bringing back embodiment, and (3) simultaneously supporting and getting out of the way of human interpersonal interactions and relationships.

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1 Introduction

> *The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it.*

Ubiquitous computing is often defined by Mark Weiser's *Scientific American* article, "The computer for the twenty-first century" (1991). He argued that computers should recede into the background of life, just as written language, paper, and electricity have "disappeared" from our conscious attention, despite the fact that we use them all the time. The term "ubiquitous computing" was coined at Xerox Palo Alto Research Center (Xerox PARC) in April 1989 among members and affiliates of the Computer Science Laboratory (CSL). It is unclear whether Mark Weiser was the first to utter the phrase or to scribble it down in his notebook [1], but it is very clear that he became the most vocal advocate of the vision to the wider Computer Science and human–computer interaction communities.

Weiser believed that the personal computer's "basic problem was that it took people away from other people—not only from other people, but from the world and the environment that we live in." He envisioned ubicomp as the third paradigm of computing [2, 3], addressing these social issues raised by personal computers (the second paradigm of computing). Weiser argued that we should use computation in a way that "would not take us away from our loved ones, not take us away from the environment, not take us away from the world around us, but be part of our world instead" [4]. He attributes the articulation of this problem with personal computers to his social science colleague at Xerox PARC, Lucy Suchman. This goal manifests itself through several key aspects of ubicomp:

- Computers should be attended *from* rather than attended *to*. This idea comes from Michael Polanyi's concept of tacit knowing [5]. Another way to say this is that computation should be *ready-to-hand*, not only *present-at-hand*, in Martin Heidegger's terms [6]. Weiser reasoned that "only when things disappear in this way are we freed to use them without thinking and so to focus beyond them to new goals" [7].
- Ubicomp is "diametrically opposed to" virtual reality (VR) in that it brings computation into the everyday world rather than immersing humans in a computational world. That is why ubicomp has the alternative name of "embodied virtuality" [7] in many of Weiser's notes and presentations. In fact, "embodied virtuality" was the original title of his *Scientific American* manuscript [8]. However, his colleagues discouraged him from focusing too much upon the anti-VR aspects of ubicomp in that article.
- Ubicomp is also the opposite of interface agents [9]. It seeks to fade into the background rather than force itself as a character in the foreground of a user's attention.

The name "ubiquitous computing" suggests that computers can, should, and will be everywhere. As such, we find spins on the name such as "everyware" [10]. However, putting computers everywhere was not the ultimate nor primary goal of ubicomp. Because the vast majority of the article focused upon the technical prototypes intended to demonstrate the ideas of ubiquitous computing, it is understandable that subsequent work focuses upon similar prototyping experiments. Out of seven pages of describing demo systems and system usage scenarios, only one paragraph was dedicated to many (but not all of the) actors and ideas involved in this formulation of ubiquitous computing:

> Computer scientist, economist and Nobelist Herbert A. Simon calls this phenomenon 'compiling'; philosopher Michael Polanyi calls it the 'tacit dimension'; psychologist J. J. Gibson calls it 'visual invariants'; philosophers Hans Georg Gadamer and Martin Heidegger call it the 'horizon' and the 'ready-to-hand'; John Seely Brown of PARC calls it the 'periphery.' All say, in essence, that only when things disappear in this way are we freed to use them without thinking and so to focus beyond on new goals. (94).

Starting from this paragraph, the current work traces the ideas that contributed to this landmark publication so that we can better grasp on the more amorphous constellation of concepts called "ubiquitous computing." This constellation includes visions of computers being pervasive (e.g., IEEE's Pervasive Computing community), being transparent [e.g., 11], being unremarkable [12], being embedded [13], being everyday [14], and, most notably, being calm [3, 15]. The broader community of players includes members of Xerox Palo Alto Research Center (Xerox PARC), the Institute for Research on Learning (IRL), and Stanford University's Center for the Study of Language and Information (CSLI)—all located in Palo Alto, California, and led by a circle of influencers, including Rich Gold and John Seely Brown [15]. This community was heavily influenced by phenomenological concepts, including embodiment, indexicality, situated action [16, 17], and situated learning [18].

2 Research approach

This research began as two separate studies of New Media and American Culture with Frederick Turner and Phenomenological Foundations of Cognition, Language, and Computation with Terry Winograd. It grew into a larger project, involving several years of library archives research at the Stanford University Library Special Collections for Mark D. Weiser (M1069), which included papers from Rich Gold. Those library archive notebooks, recordings, and artifacts raised many questions, which could not be answered by the objects themselves so the research turned to structured interviews with people whose names kept coming up in the archives. They included John Seely Brown, David Goldberg, Marina LaPalma, Vicky Reich, Bill Schilit, and Roy Want. These interviews were conducted under Stanford IRB Protocol #82997: Interviews for Ubiquitous Computing History Study. Both the library archives and interviews were invaluable to understanding the richer history behind the people, ideas, and values that culminated into a vision of ubiquitous computing.

Although this study of ubiquitous computing focuses upon Mark Weiser and Rich Gold, there were clearly many actors who contributed to these particular articulations of ubiquitous computing. Those people included a broader diversity of genders, ages, ethnicities, and disciplines. Lucy Suchman was an important researcher at Xerox PARC, who Mark Weiser and John Seely Brown mention repeatedly in their recollections of the inspirations for looking at the issues of computing getting in the way of interpersonal interaction. Natalie Jeremijenko was an important artist-in-residence at Xerox PARC, who created the most memorable demo of ubiquitous computing that moved beyond the original three prototypes. Marina LaPalma has thoroughly edited and published many of Rich Gold's explorations and hard questions asked of ubiquitous computing in *The Plenitude* [19]. Many colleagues inside and outside of Xerox PARC at the time, who might not feel that they directly contributed to ubiquitous computing, actually inspired the few who wrote that early *Scientific American* article; this becomes evidence in the copious notes, video recordings, and readings in Weiser's library archives. Those people included Terry Winograd (Stanford University, Computer Science), Clifford Nass (Stanford University, Communication), and Stuart Card (Xerox PARC). While this is not a social history, it is important to note that the ideas traced throughout this philosophical history do not represent the thoughts of an individual person. Instead, they represent the culmination of discussions, debates, readings, and public discourse between a much more diverse, distributed community of thinkers and doers.

3 Ubicomp artifacts

The ultimate goal of ubicomp was to fade into the fabric of everyday life. This is an inherently difficult goal to communicate in the form of demonstrations because demonstrations typically aim to be remarkable and memorable. Ubiquitous computing aimed to be exactly the opposite. The CSL team took up this challenge and built several prototype systems to experiment with various manifestations of ubiquitous computing. The ubicomp prototypes at Xerox PARC during the late 1980s and early 1990s were the PARC Tabs, Pads, and Boards [15, 20]. These prototypes were designed on the physical scale of existing ubiquitous (analog) technologies: post-it notes, paper notepads, and whiteboards. They were networked in such a way that people would share information across devices in various form factors and distributed locations. Documents resided on the network instead of on a single device so that they could be shared among several devices, projected onto large, shared displays, and edited from any location. The ubicomp prototype devices served as terminals to provide document access from anywhere as opposed to being servers where documents were stored. This networked form of computation was key to the ubiquitous computing vision, explicitly shifting away from the personal, monolithic machine.

Most of the current research in ubicomp picked up on particular aspects of the ubicomp PARC Tabs, Pads, and Boards. The ideas of portability and "smart" objects of the PARC Tabs and Pads were taken up by mobile computing, while the invisible networks that connected these prototypes were picked up by pervasive computing. The Active Badge project [21, 22] that Roy Want brought from Olivetti to Xerox PARC also became part of the ubicomp systems canon. The Active Badge looked like a corporate identification badge. It contained a microprocessor that broadcasted the identity of the wearer to computers in the environment such that it would trigger appropriate opening of doors, routing of telephone calls, and customizing of proximate computer displays [7]. This project inspired much of the sensor-based work today in pervasive and context-aware computing areas.

Several years after the original ubicomp studies, Natalie Jeremijenko's Live Wire (aka: Dangling String) captured the essence of a ubicomp cousin concept, calm computing [3, 23, 24]. An eight-foot string hung from the ceiling and twitched with each bit that passed through the Ethernet cable to which it was attached. When network traffic was heavy, the string whirled around frantically, becoming an attention-demanding pull cue. When the traffic was light, the string twitched every few moments and could easily be ignored [23, 25]. In this way, "[c]alm technology engages both the *center* and the *periphery* of our attention, and in fact moves back and forth between the two" [3]. Calm computing is one of two visions that are most tightly aligned with Weiser's original goals; the other vision is unremarkable computing [12], which was a rearticulation of ubicomp as making computers "invisible in use." Unlike the other ubicomp areas, there are no annual workshops or conferences on calm or unremarkable computing, probably because these do not map well to specs for computer system design. It is also extremely difficult to build flashy and memorable demos of systems that aspire to be more like wallflowers.

Though there are already several thriving threads of technology-centered research under the umbrella of ubicomp, they are loosely connected threads. They could reconnect with the many aspects of the ubicomp vision that were lost in translation from philosophies to prototypes. Even Weiser thought they would get it wrong on the first try [26] (see Fig. 1).

Looking at those three prototypes, it is easy to understand why people would focus upon the novel technical approaches of mobile, networked, context-aware devices that broke away from the standard desktop personal computer. The problem with having such technically challenging and interesting prototypes was that it was easy to lose sight of the deeper motivations behind the prototypes. The question at hand now is how we might move forward with a new ubicomp that does better justice to its original ideals of making the first-person experience of computational systems more calming, less socially distracting, and less physically intrusive.

4 Weiser's ubicomp

Mark Weiser embodied the much larger social and philosophical milieu from which ubiquitous computing emerged as a computerization movement—a process that includes

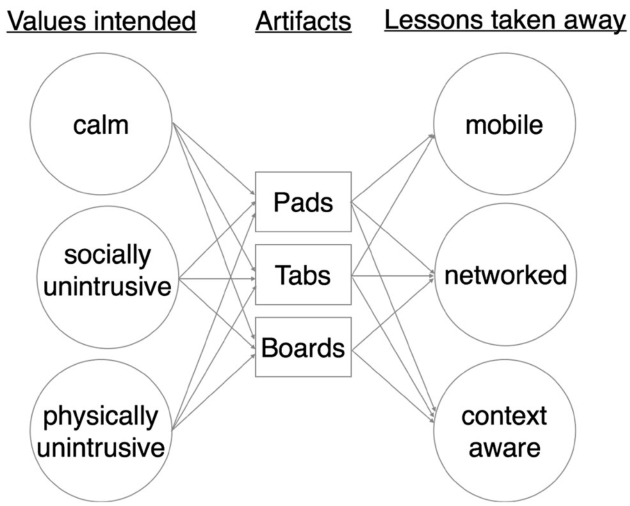

Fig. 1 Ubicomp values lost in translation through the Xerox PARC Pads, Tabs, and Boards artifacts

technological frames and public discourses [27]. Weiser played a major role in both forming the technological frame[1] of ubiquitous computing and instigating the public discourses of ubiquitous computing (see Table 1). The key problem with the personal computing paradigm and the promises of virtual reality was that the computers took too much focused attention from people, drawing people away from interacting with one another. This problem is still highlighted in today's concerns raised about our technologies driving us apart [29], e.g., a couple sits at a restaurant table, intently gazing into their mobile phones, completely ignoring each other. Similarly, the re-popularization of head-mounted virtual reality (VR) devices has re-invigorated discussions around the social implications of such individualized experiences, e.g., walking through an entire conference center full of people, who are each wearing their own head-mounted VR devices, exploring their own individual virtual worlds (Fig. 2).

Through this technological frame, Weiser engaged in the public discourses—"both written and spoken public communications—which develop around a new technology… [that is] necessary for particular understandings about new technologies to widely circulate" [27]. Presenting the frame of ubiquitous computing to audiences all around the world, from industry to academia, from purely technical audiences to religious ones, Weiser instigated and engaged much of the public discourses of ubiquitous computing. The 1991 *Scientific American* article was the main text that Weiser provided to these communities; after his passing, two major publication venues reprinted the article in memoriam [30, 31]. One of the more revealing presentations he gave about ubiquitous computing was actually at UC Berkeley in 1998 called, "The Distinctiveness of Being Human: How Science Informs the Spiritual Quest".

> "Ubiquitous computing grew out of a deep dissatisfaction I had a number of years ago with the state of the personal computers in our lives… They are life-distorting devices… Basically, the idea we worked on was to put the computer into the environment so that instead of having to turn away from the environment, or turn away from other people, you could have it in your life while doing other things".

> "Think of yourself as an iceberg. And there's a little bit of you above the surface, the conscious part, the part that at any moment is having this thought or that thought, is listening to my words, or maybe even listening to the concepts I'm trying to convey to you… There is a flow of conscious thought—the part above the water line—above the line in this picture–the center—apparent center—of our attention. And then there is a much larger part of us that we are unconscious of".

This iceberg model of human experience can also be found in many other presentations done by John Seely Brown, who talks about the iceberg in terms of knowledge—explicit knowledge above the surface (e.g., what exists in books and heads) and tacit knowledge below the surface (e.g., what exists in practice and interactions between people). Brown's concept of "periphery" was a key component of ubicomp [24], similarly influenced by the philosophers and ideas swirling around Xerox PARC in the 1980s. Regardless of exactly who first sketched out this framework, it was clearly an important model that motivated the ideas around ubiquitous computing.

Weiser was a major driving force behind the computerization movement of ubiquitous computing. As lead of the CSL at Xerox PARC, he was charged with the job of defining the laboratory's vision that would capture the imagination the best and the brightest of the computer engineering community. In essence, he wanted computing to become phenomenologically invisible: "the experience of direct interaction with artifacts and tools largely free of conscious monitoring" [32].

[1] A technological action frame is a "multi-dimensional composite understandings—constituted and circulated in language—that legitimate high levels of investment for potential users, and form the core ideas about how a technology works and how a future based on its usage should be envisioned"… "Bijker [28] lists the major dimensions of technological frames as goals, key problems, problem-solving strategies, requirements to be met by problem solutions, current theories, tacit knowledge, perceived substitution function, user practices and exemplary artifacts. Taken together, these dimensions constitute the meaning of a particular technology and frame it in specific ways" [27]. This work includes some, but not all, of those dimensions.

Table 1 Technological frame of ubiquitous computing for Mark Weiser

Technological frame	Technological frame of ubiquitous computing for Mark Weiser
Goals	Less intrusive interactions with computing that keep people present in their physical and social environment
Key problems	Computers demand too much focused attention from us
	Computers are going to be increasingly pervasive in everyday life
Problem-solving strategies	Leverage peripheral, unconscious perception and action by putting computing into the physical environment instead of pulling people into a virtual environment
Requirements to be met by problem solutions	Computing must enable people without getting in the way
Current theories	Phenomenology, ecological psychology, and model human processor
Exemplary artifacts	Xerox PARC Pads, Tabs, Boards
	Live Wire

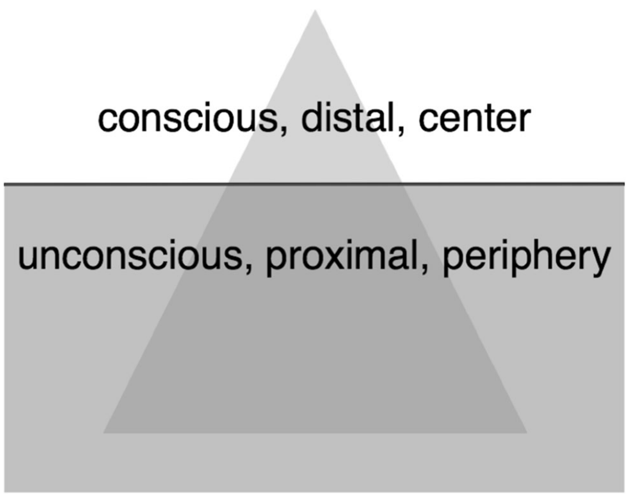

Fig. 2 Weiser's iceberg model of human experience (based on an audio recording of his 1998 UC Berkeley presentation)

5 Ideas that influenced ubicomp

Weiser was deeply concerned about what it would be like to live in a world of ubiquitous computing. His close colleague, Rich Gold, raised many poignant concerns throughout his presentations and writing, e.g., "How smart does your bed have to be before you are afraid to go to bed at night?" [19]. Many of those human issues were compressed to a single paragraph of his Scientific American article, citing Herbert Simon, James Gibson, Martin Heidegger, Hans Georg Gadamer, and Michael Polanyi. By unpacking this dense paragraph, we get a sense for the philosophical history of ubiquitous computing. Figure 3 depicts the theories and concepts that fed into the model of human experience that Weiser used in his thinking about ubiquitous computing.

Mark Weiser was very interested in philosophy in his earlier years at school when cybernetic theories were popular. In graduate school, he recorded a letter to his father about his current courses and potential advisors; after having talked with Bernie Zeigler, who was interested in system modeling, Weiser reflected upon his own intellectual contributions: "I really believe that the philosophical side of my ideas is more earthshaking, as it were… is really where the difficulty is. That the mathematics of it are not so important" [33]. In 1975, he installed a 12-foot-wide PDP-9 computer in his living room for creating art installations, which were well aligned with ideas that would later become ubiquitous computing. Along with some friends, Weiser founded a nonprofit company called Cerberus, which was funded by a National Endowment for Humanities grant. He described Cerberus as "a collective of artists and programmers working together in video and related visual information systems evolving a synthesis of media consistent with the energies and consciousness of man in a cybernetic culture" [34]. They used that PDP computer to power interactions between people at museums, performing "works of dance and large screen projection of live and delayed video mix." Rather than making the computer the center of attention, it was used to create the exhibits and experiences elsewhere, e.g., Power Center for the Performing Arts in Ann Arbor, Michigan, and the National Computer Conference in Chicago, Illinois.

This interest in philosophy and using computing to create experiences was re-kindled during the late 1980s within the communities of thinkers in Palo Alto at Xerox PARC, IRL, and Stanford's CSLI. In the human–computer interaction community, Herb Simon and James Gibson were already prominent thinkers, especially around Xerox PARC. Through his work on human problem solving and books such as *Sciences of the Artificial* [35], Simon made an intellectual impact upon Xerox PARC that was further carried through his close collaborations with Alan Newell [36] and mentorship of Stuart Card [37], who joined Xerox PARC in 1974 and remained an influential researcher and

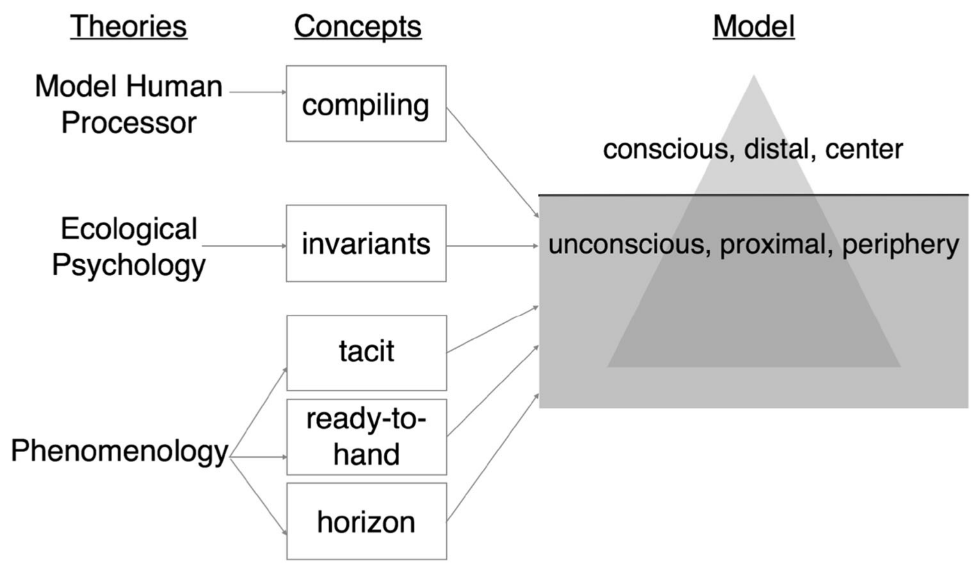

Fig. 3 Theories and concepts that flowed into Weiser's iceberg model of human experience

thinker there for several decades. Gibson's ecological psychology formed the basis for talking about the affordances offered by different types of designed objects (e.g., Norman's doors [38]). This was also the time when Winograd and Flores' 1986 book [39] hit the human–computer interaction community, particularly JSB, Weiser's boss; this book presented a phenomenological approach to understanding computing systems and their relations to people. These pointed researchers to more situated rather than abstracted approaches of investigation. Heidegger reading groups began at Xerox PARC, where dreams of making computers ready-to-hand began to percolate through the research teams. We will trace the ideas and influences of each of these scholars in turn.

5.1 Model human processor: Simon

Herb Simon was a professor at Carnegie Mellon University in the 1970s when he was presented the A. M. Turing Award (1975) along with Allen Newell for their work on artificial intelligence [35] and cognitive psychology. He was later awarded the Nobel Prize in economics (1978) for his work on rational decision making, including his notion of bounded rationality [40, 41], which raised the issue of the limited resources of human attention and showed how people actually heuristics and satisficing to make decisions. His work on human problem solving [36] inspired work in the *Psychology of human–computer interaction* [37], which centered around a model of humans as information processors. His student and mentee, Stuart Card, graduated from CMU and went to Xerox PARC to lead their research on human–computer interaction in 1974, where he worked until 2010. Through Card's work at Xerox PARC, Simon and Newell's ideas around the model human processor bloomed into not only theories of human–computer interaction, but also practical applications of the theories in the design of prototypes such as the mouse and graphical user interfaces.

In Computer Science terminology, "compiling" refers to converting source code (e.g., written in a programming language) code into a lower-level form (e.g., assembly or machine code) that can be executed by the computer. If you think of human cognition as computation (as in the Model Human Processor point of view), then people "compile" information into lower-level forms of cognition (e.g., the unconscious, bottom part of the iceberg). Since humans have a bounded rationality, we sometimes rely upon those unconscious stores of information to make quick or complex decisions, i.e., heuristics rather than rational rule-driven decisions. Although they did not work directly together on Xerox PARC's ubiquitous computing projects, Stuart Card's work and words of wisdom influenced both Mark Weiser and Rich Gold's thinking around ubicomp. Gold's book on his adventures in what he called "The Plenitude" [19] ends with an often cited quote from Card about ubicomp: "We should be careful to make a world we actually want to live in".

5.2 Ecological psychology: Gibson

James Gibson is another major figure, who influenced theories of human–computer interaction, most notably through his concept of affordances [42] in the context of Ecological Psychology. He approached human cognition from an interactionist view (i.e., interactions between observer and the environment) in which "perception is a system that picks up information that supports coordination of the agent's actions with the systems that the environment provides" [43] (e.g., to a human, chairs afford sitting). His work on *The Senses Considered as Perceptual*

Systems [44] pushed back against the human information processing theory in that he saw information as relating to what people (or animals) can *do*, not merely information that exists independent of the perceiver. Gibson believed that "animal behavior is best understood in terms of alertness to opportunities for action" [45]. Norman popularized Gibson's concept of affordances in his book, *The Psychology of Everyday Things* [38], which is a common entry point for new students of human–computer interaction. This idea is important for HCI in that users should readily perceive affordances so they know how to interact with the designed object (e.g., without thinking too hard, I should be able to tell that the door affords opening and that I should push it, not pull it, to make it open).

Gibson discussed a similar notion of direct perception (i.e., information perceived without much higher-order cognitive processing) when he talked about the "invariant" information [46], the concept that Weiser cited in relation to ubicomp. An example of a visual invariant is a texture gradient; if you are looking down a set of train tracks, the ties closer to you appear larger and spaced further apart (expanding) and the ties further away from you become progressively smaller and spaced closer together (contracting). The same is true for looking down a long brick wall or a row of pine trees. These invariants give us bottom-up perceptual depth cues. In a sense, this invariant information is operating below the surface of conscious experience. It is not surprising that many connections have been drawn between Gibson's work and phenomenologists like Martin Heidegger [47]. In his later work, Gibson even talked about the affordances of cars in much the same way that Heidegger talked about the carpenter's hammer [46]. Before diving into those similarities, it is important to get a broader picture of phenomenology, which included some of the most influential thinkers upon Mark Weiser's work.

5.3 Phenomenology: Heidegger

Phenomenology is generally construed as a philosophical approach ontology and epistemology from the elements of *human experience* rather than from the concept of truth. Edmund Husserl (1859–1938) was the founding father of phenomenology; his original ideas of phenomenology were altered and further elucidated by his student, Martin Heidegger, who pushed against its dualism in favor of focusing on the world and ourselves as part of that world. From his undergraduate years of studying philosophy, Mark Weiser drew upon Heidegger's form of phenomenology to inform future visions of ubiquitous computing. His interest in phenomenology carried through his college studies, professional career, and even came out when he spoke to audiences full of engineers (e.g., USENIX'95). Hans-Georg Gadamer (1976) wrote, "One's own philosophical standpoint always shines through his description of the basic meaning of phenomenology… Every phenomenologist had his own opinion about what phenomenology really was. Only one thing was certain: that one could not learn the phenomenological approach from books" [48], p. 143. While there may be no definitive elevator pitch that summarizes phenomenology, it is helpful to see how people have tried to distill it for non-philosophers, particularly those working in the area of computing. Winograd and Flores (1986) briefly describe phenomenology as "the philosophical examination of the foundations of experience and action" [39]. Dourish describes Heidegger's type of phenomenology as turning "from an epistemological question, a question about knowledge, to an ontological question, about question about forms and categories of existence. Instead of asking, 'How can we know about the world?' Heidegger asked, 'How does the world reveal itself to us through our encounters with it?'" [49].

"Invisible computers" and "disappearing computers" are both misnomers in the sense that ubicomp was not about visually concealing computers, but about making computers less attentionally demanding, calmer, and easily able to slip in and out of our center of awareness. They would only be invisible in that they would be ignorable and taken for granted—ready-at-hand as opposed to present-at-hand. Martin Heidegger emphasized the importance of studying everyday experiences of being in the world [6]. He most clearly influenced ubiquitous computing in discussions of "modes of being" for equipment. He uses the example of a hammering, where the hammer is ready-to-hand (aka: available), versus just learning to use the hammer or merely observing the hammer, where it is present-at-hand (aka: occurrent). The idea of computers being ready-to-hand is similar to the ubicomp idea of making computers invisible-in-use. Dreyfus [50] writes, "When we are using equipment, it has a tendency to 'disappear'. We are not aware of it as having any characteristics at all". Similarly, when one is learning how to drive a car, the controls and the machine are quite present-at-hand. After years of practice, driving feels much more like just driving [51], not like operating a machine by manipulating the steering wheel, pedals, and switches.

5.4 Phenomenology: Gadamer

Weiser's version of ubicomp was also influenced by Hans-Georg Gadamer's concept of the horizon. Gadamer was a student of Heidegger. He believed that each of us has our own set of prejudices that constitute our horizon, and "there is undoubtedly no understanding that is free of all prejudices, however much the will of our knowledge must be directed towards escaping their thrall" [52]. Similar to our own everyday notion of prejudice, Gadamer used the concept of a horizon to refer to those parts of our own history, culture, and experiences that invisibly shape the way we perceive the world; it often works at a level below consciousness. Howard [53] writes:

> …the horizon we occupy, has its own past and future, independently both of ourselves and of the text or culture we wish to understand, for neither of us chose them by intentional act. The attainment of understanding is actually a "fusing of horizons," an event in which what seemed to be frontiers dividing two horizons vanishing, so that only one human community of thought and action remains. Sometimes this fusion of horizons can take place without our noting it, especially in the experience of great art. It happens, as it were, "behind our back", and we realize it in a deliberate consciousness only afterward. (p. 152)

Gadamer's horizon is the conceptual tool Weiser offers for thinking about what shapes those interpretations with which we approach the world. He saw language as the universal horizon of human hermeneutical experience though he believed that "[t]he possibilities of our knowledge seem to be far more individual than the possibilities of expression offered by language" [52] (p. 362).

While ubicomp can be seen as trying to leverage our horizons such that we don't have to exert much effort to use computers, the concept of horizons encompasses much more than just coping with equipment. Rather, our horizons influence our openness to the world as a whole. Computing systems are just one part of the world. Ideally, the way that ubicomp systems present information to users would fuse so well with the users' horizons that the system's communication would be perfectly transparent.

An example of how the concept of a horizon could be designed for in a ubicomp application is the ParcTab, which could be held with one hand. It wirelessly communicated with other Tabs and locations via infrared communications [20]. Like the ParcPad and LiveBoard, the ParcTab was designed to be non-intrusive and easy to use, leveraging pen-based interaction techniques. One particularly interesting application built for the ParcTab was its Auto Diary, which logged co-occurring people and places where the Tab had been throughout the day, implying events in the user's day, but not explicitly trying to interpret them. Individuals at Euro PARC carried tabs around, which communicated via infrared with sensors located in rooms, and the Pepys system [54] automatically recorded activities such as two or more people being present in a space for some short duration of time (e.g., meetings), people moving around or between buildings with the goal of helping people to remember what they did in the past day. This information was available to others in the Euro PARC organization.

Rather than trying to make the Tab "understand" the user's day, it laid out its data to the user with simple information like date, place, and people encountered in the place. This kind of low-level information both exposes the Auto Diary's minimal "understanding" of the events that took place by displaying raw data to the users, thereby communicating the Auto Diary's horizon of its infrared proximity sensors. This kind of data presentation also allows for multiple people with different horizons to approach the information with their own interpretations, e.g., "Mark had a meeting with John at 1 pm on Friday" versus "Mark and John took an extended their lunch hour to chat in Mark's office." Designing for the various interpretations that different users will draw from an event is another way of designing in ambiguity [55, 56] not only for the sake of plausible deniability, which may be extremely useful for dealing with issues of privacy in ubicomp, but also designing for intersubjectivity (i.e., facilitating the fusing of horizons).

5.5 Phenomenology: Polanyi

Like Gadamer, Polanyi considered "human knowledge by starting from the fact that we can know more than we can tell." Polanyi's main contribution to the vision of ubiquitous computing was what he called the proximal and distal terms [5]:

> …in the act of tacit knowing we *attend from* something for attending to something else; namely, *from* the first term *to* the second term of the tacit relation. In many ways the first term of this relation will prove to be nearer to us, the second further away from us… Using the language of anatomy, we may call the first term *proximal*, and the second term *distal*. It is the proximal term, then, of which we have a knowledge that we may not be able to tell. (p. 10)

The proximal term, the one we are least aware of, is closest to us the same way that the horizons we occupy are so close to us that we are usually unaware of their influence on our interpretations of the world. This concept of a tacit relation of attending to the distal from the proximal is a central concept in ubicomp. Ubicomp aims to put the computer in the realm of the proximal, where it may be pushed off of as part of an infrastructure rather than attended to. Polanyi further discussed the use of tools and how we can "make them function as the proximal term of tacit knowing" (p. 16):

> Anyone using a probe for the first time will feel its impact against his fingers and palm. But as we learn

> to use a probe, or to use a stick for feeling our way, our awareness of its impact on our hand is transformed into a sense of its point touching the objects we are exploring… We become aware of the feelings in our hand in terms of their meaning located at the tip of the probe or stick to which we are attending. This is so also when we use a tool. (pp. 12–13)

Somewhat like Heidegger's hammer example, demonstrating ready-to-hand versus present-at-hand [50], Polanyi's concept of tacit knowing describes our way of using the proximal ubicomp system in order to do our task of holding a meeting, taking notes, etc. Weiser described the way that street signs are invisible in that "you absorb its information without consciously performing the act of reading" [7]. Ubicomp aimed at embedding computers into our world such that we could go about our lives, doing what we do, without concentrating on performing the act of computing.

6 Ubicomp today

Most of ubicomp's progress has moved along the lines of those ideas encoded in the original prototypes—mobile, networked, context aware—can be seen in research on mobile computing. The constellation of philosophies that influenced ubicomp include visions of computers being pervasive (e.g., IEEE's Pervasive Computing community), being transparent [e.g., 11], being unremarkable [12], being embedded [13], being everyday [14], and, most notably, being calm [3, 15]. These descriptions beg the question: If that was the vision of ubicomp then, what is it now? The frustrating answer is: "There are many ubiquitous computings" [10] and "none of [them are] necessarily pursuing anything that Mark Weiser would have recognized as fully cognate with his ubiquitous computing" (p. 14). Table 2 presents descriptions and representative project examples to provide a sense of what ubicomp research areas look like today. These are far from being mutually exclusive domains. The ACM and IEEE libraries abound with hybrids such as context-aware mobile phone applications, smart objects that interface with the larger environment, and social examinations of mobile phone use. Individual researchers often publish a cross a range of these research venues. The purpose of this taxonomy is not to provide an exhaustive set of current research, but to illustrate the wide range of research that is drawn from ubicomp today.

These lines of ubicomp research have taught us many lessons in the past couple of decades. By prototyping smart coffee makers that update us on the news, walls that dynamically respond to a person's proximity, and orbs that ambiently update us on the state of the stock market, we have been building up a knowledge base of experiences, themes, risks, opportunities, and insights across the many different subcommunities. Among these insights are notions of ubicomp being better off "seamful" than "seamless" so that users might appropriate the technologies in their own ways [78]. Ubicomp has turned out to be much messier than we expected. As with other infrastructures, it is still incredibly complicated to deal with heterogeneous network access, coverage, and interoperability, let alone figure out how to bill and pay for services [79]. With the increasing pervasiveness of sensors in environments and devices, we are experiencing the need to responsibly handling privacy. The sensors to enable the interpretation of deictic gestures in commands such as, "Put that [point] there [point]," could also enable strangers to intrude upon the privacy of our homes. As such, we have been developing toolkits [80] and frameworks [81, 82] for managing ubicomp privacy. Although there has been significant progress across the many areas of ubicomp, there is still a long way to go if these communities are to reach ubicomp's deeper philosophical goals.

Ubiquitous computing researchers have been saying that ubicomp is already here [79] and that it may have already disappeared as a research agenda [83]. Indeed, computation is seeping out into the world in ways that look much like the original Tabs, Pads, and Boards. In revisiting the ideas behind those early prototypes, it is unclear that we could claim success in reaching ubicomps' philosophical goals. Rather than getting out of the way of face-to-face interpersonal communication and connection, people walk around with their faces buried in their mobile phones. Rather than fading into the background of experience, people are putting IoT agents Front and Center in their interactions at home. Rather than leveraging the cognitive unconscious, users actively struggle to set up and make sense of their smart home smoke detectors and security systems. While we have made technological progress in networks, sensing, mobility, and more, there is still much room for improvement in terms of the first-person user experiences of today's ubiquitous computing systems.

Moving beyond the specific prototypes, products, and services that are being created in each of these areas, there are opportunities for revisiting the motivations behind ubicomp. In doing so, we might get closer to a user experience of ubiquitous computing that might look more like its earlier intentions.

7 Drawing from ubicomp's roots

If we return to the philosophical roots of ubiquitous computing, there are at least a few directions for setting future design goals and research directions:

(1) *Leveraging human experience below the level of focused, conscious attention* (i.e., the submerged base of

Table 2 Current research areas that associate themselves with ubiquitous computing

Research area	Description	Example project(s)
The Internet of Things	Embed computation in everyday objects such as smart appliances [57, 58] and connect them via the Internet [59]	Smart coffee maker that senses individual coffee mugs, customizes orders for the individual, and delivers news [57]
Context-aware computing	Interconnected systems with sensing abilities to enable intelligent environments and context-sensitive interactions [e.g., 60–62]	The Hello Wall displays light patterns to provide information about activity levels of team members in the company; it displays information in higher resolution for people who walk closer to it [63]
Pervasive computing	"[E]nvironments saturated with computing and wireless communication, yet gracefully integrated with human users" [64]	A smart rooms [65] that understands user commands like, "Put that there" [66]
Mobile computing	Mobile phones, text messaging, and general off-the-desktop computing [67]	Location-based applications that recommend nearby coffee shops, traffic conditions, bus tracking, and conference room availability [68]
Ambient computing	Systems that present information in the background of awareness [e.g., 69–71]	The Ambient Orb [72] that delivers stock market trends via softly colored light green for positive change, red for negative change, and yellow for no change
Embodied interaction [49]		
Tangible computing	Merging physical and digital bits to form systems that allow for richer and non-sequential interaction; a physical handle onto a digital world [25, 73–75]	The Marble Answering Machine featured in the movie, "Minority Report"; physical icons (phicons) used on the metaDESK project [25]; inserting computation into Yo-Yo Ma's cello to enable him to play a live concert with additional electronic sounds [57]
Social computing	Sociological, anthropological, and cultural studies of computers in social worlds [e.g., 16, 18, 76, 77]	Ethnographic study of Xerox machine repairmen and how communication technologies played into their work practices [77]

the iceberg). This suggests looking more seriously into unconscious information processing models of human psychology, how to leverage heuristics-based responses and automaticity in interaction design, and developing a better understanding how experience shifts between the center and periphery of attention. These less conscious cognitive processes are likely to inspire design directions for calmer ubicomp systems. Likewise, Dourish points to phenomenology and ethnomethodology as a useful perspectives for "embodied interaction" [49]. In today's world of mobile and cloud computing, we are already experiencing problems caused by chronic multitasking, making this work even more relevant today than it was 30 years ago. The challenge here is: How can we advance and leverage what we know about human social and cognitive sciences to inform the design of ubicomp systems that leverage that unconscious base of the iceberg?

(2) *Bringing back embodiment* Around the same time that Weiser and colleagues published the *Scientific American* article, Katherine Hayles published a chapter on "embodied virtuality" [84], critiquing the many ways that cyberspace and virtual reality are mistakenly conceptualized as being about disembodied information, isolated from the physical world. In her subsequent book, Hayles traces the deeper history of embodied virtuality, drawing from several waves of cybernetics [85], which Weiser had studied in college. Just as contemporary psychology research is examining the influences of body and mind upon each other (e.g., [86–89]), we are exploring ways that embodied experiences can influence and inspire new interaction design approaches, integrating the physical and computational worlds [90]. The challenge here is: How can we embrace embodied experiences in the design of ubicomp systems?

(3) *Supporting and getting out of the way of human interpersonal interactions and relationships* This is one of the most important value-oriented aspects of ubiquitous computing. Ubicomp was, in part, driven by concerns about the impact of computing upon our social world. It was a reaction against the social isolation caused by personal computers and (potentially) virtual reality—issues that are still present today. Even in today's world of social computing, there is still value in creating and nurturing interpersonal connections in face-to-face settings. Weiser's ubicomp aimed to support that kind of future, but some would argue that the mobile computing future we invented is doing just the opposite. HCI research in large, shared displays (e.g., large boards or shared tables) has shown some promise for encouraging human interpersonal interaction and group collaboration. In that vein, the challenge here is:

What ubicomp system design directions the physical world could engage and enrich interpersonal relationships?

8 Conclusion

There are many different ubicomps. This work has traced the Mark Weiser's version of ubicomp because his *Scientific American* article has been so widely influential upon the human–computer interaction community. Because that article so briskly skimmed over the deeper ideas at ubicomp's roots, this work re-traced those conceptual steps so that we can dig deeper for the philosophies and values that motivated that ubicomp vision. This broader understanding of the philosophies behind that version of ubicomp can serve as a source for inspiration for exploration and innovation that refocuses upon the first-person human experience of ubicomp systems: (1) leveraging human experience below the level of focused, conscious attention, (2) bringing back embodiment, and (3) simultaneously supporting and getting out of the way of human interpersonal interactions and relationships.

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