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The Four Phases of Pervasive Computing: From Vision-inspired to Societal-Challenged

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Abstract

This paper reflects on the visions and motivations underlying Pervasive Computing and advances made ending with considering future directions for the field. It describes these in terms of four phases: (i) vision-inspired, (ii) the design of engaging experiences, (iii) innovation-based, and (iv) addressing societal challenges. It is proposed that in the future we will need to embrace a paradigm shift that will be far more challenging than previously. While we can continue to harness pervasive computing advances to augment ever more aspects of ourselves and the environment, we will need in the current climate to be more mindful and responsible of our aspirations. This may mean, paradoxically, contemplating how the field scales down its technology innovation in order to scale up its impact. The paper sets out how to achieve this.

Keywords: Pervasive computing, vision, green computing, ubicomp, ethical challenges

1. Introduction

Compared with other new fields that have emerged in computer science (e.g. cybersecurity, quantum computing) - that have been driven by a combination of factors including the pursuit of scientific goals and industrial concerns - Pervasive Computing was heavily influenced by Weiser's vision of a techno-utopian future. His dream was to create an easier, calmer way of living; computers would seamlessly appear when needed and disappear when not. Following many gallant, but disappointing efforts to achieve this nirvana, researchers began branching out, proposing an alternative framing of the field, with a move towards designing for experience. As the field came of age, it became dominated more by technology innovation, market forces and enterprise. Where will it go next? It is proposed, here, that like many other academic disciplines, it is imperative for the field to become more challenge-led. By this is meant carrying out research that addresses pressing societal needs, such as global warming, through developing more sustainable and ethically accountable computing.

2. The beginning: Weiser's Vision-led Ubiquitous computing

When pervasive computing came to the fore in the early 90s, one man's vision led the way, that of Mark Weiser, shaping and informing the research agenda that subsequently followed. His Scientific American paper, "The Computer for the 21st Century", proved to be hugely influential [20]. Everyone read it and talked about how it could inspire a new world order of having computers everywhere, breaking away from the existing paradigm of desktop computing. Such was its persuasiveness and universal appeal, that it was rare to find a pervasive or ubiquitous computing project that was not motivated by Weiser's words. Many publications that followed began by mentioning some aspect of his vision, often including a quote from his paper. Two of the most cited ones that became a mantra were:

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

"Machines that fit the human environment instead of forcing humans to enter theirs will make using a computer as refreshing as taking a walk in the woods"

A fundamental idea that everyone aspired to was that the next generation of technology could be designed to fit into our everyday lives, like a breath of fresh air. This notion was in sharp contrast to those who had grown up with tethered, very visible, humming PCs, sat on their desks, that needed to be booted up every time they wanted to use them and which crashed all too often. The vision was very seductive; it made perfect sense to imagine a time and place where using technology was no longer equated with a frustrating user experience but could become as enjoyable as a walk in the woods.

Droves of researchers at the time tasked themselves with figuring out what, when, and how to achieve this. In particular, they preoccupied themselves with how to design contextually-aware 'content' that could appear when needed and disappear when not. To achieve this needed considerable technical capability and many research groups worldwide preoccupied themselves with developing all manner of systems, infrastructures and middleware. Meanwhile the first commercial mobile devices were released (personal digital assistants and mobile phones) followed by the arrival of the much heralded, multi-touch shared displays. WiFi entered the ether at a global scale enabling connectivity. The nascent field grew rapidly, with many experimenting with how to build wearable tech, design handheld tech, and projecting digital visualizations and data onto situated displays on buildings and other places in the environment.

The field of UbiComp (as it was affectionately shortened to in those days) was established; governments, researchers and developers, from all over the world, got involved. The European Community, for example, funded a huge initiative called the Disappearing Computer in the late 90s and early 2000s, where the disappearance was viewed as being either *physical miniaturization* of devices and their integration into everyday artifacts (e.g., wearables) or *mental disappearance*, where computers were no longer perceived as computers but were transformed into everyday artefacts, such as interactive walls or interactive furniture [19]. Other blue-skies projects included MIT's Project Oxygen, HP's CoolTown, IBM's BlueEyes and Philips Vision of the Future. A particular strand of research that gained much traction was to embed technologies into people's homes with a view to making living in them easier, convenient and more comfortable. The 'smart home' agenda was born. Iconic projects were the Aware Home and Orange-at-Home. Sensors were placed in 'living lab' type homes [2] to detect and monitor people's everyday activities. An inhabitant need only have to walk into a room, make a gesture or speak and the smart room would bend to their will; responding or reacting as deemed appropriate at a given point in time.

What was there not to like about this world? Well, in my mind, quite a lot.

What puzzled me at the time was why so few people ever questioned or challenged Weiser's vision of calm and ubiquitous computing. Most people seemed to buy into the idea that tech was there to make our lives calmer, convenient and more comfortable. While I could understand how this kind of techno-utopian thinking was attractive, I was troubled by the tacit assumption it was based on. Namely, that humans are essentially lazy creatures who would rather avoid the hassle of doing menial tasks, themselves, and where our relationship with technology is viewed as largely one-sided: it is there to serve us. It was as if we were harking back to Victorian England, where millions of servants were expected to take over all manner of mundane chores, letting the gentry get on with the more enjoyable pursuits in life. And just like servants were told to make themselves invisible as much as possible, so, too, was it assumed that the new generation of pervasive tech would do the same. We would never have to worry or remember to do everyday tasks, like buy more milk when needed, as the new technology would remind us in a timely fashion, and where possible, order it on our behalf.

Surely, I thought, there must be more to ubiquitous computing than acting as our techno-servant. I yearned for the field to broaden its horizons and to think differently, widening its research questions to investigate new ways of extending humans rather than replacing them – such as provoking curiosity in people, helping them learn better, be more creative, discover more about the world and themselves, and ultimately be more engaged with the world. This gap spurred me on to write my first ever 'call for arms' paper, setting the world to right, if you will. It was called "Engaging Ubicomp" and I wrote it with a view not to put down Weiser's vision of having computers 'so embedded, so fitting and so natural' (which I did not have a problem with *per se*) but to inspire and pave the way for the research community to move on from calm computing [14].

Other researchers also began to critique how UbiComp had turned out, relative to the vision, pointing out how since Weiser's publication, computing had taken quite different turns from being calm [1, 4, 12]. Concerns were voiced and observations made as to how little progress had actually been achieved. More recently, Schöning [17] wrote about the failure of UbiComp to deliver on the vision, pointing out how instead it has created a world full of too many "dumb smart" technologies, where new solutions may look cool but solve problems that do not exist.

3. Engaging Ubicomp Experiences

15 years on from Weiser's initial vision, I recast UbiComp in the context for what computers were originally designed for, namely, as tools to extend and engage people in their activities and pursuits [14]. I pointed out how *"calm computing wraps us in cotton wool rather than challenges us"* and that what we needed was actually the opposite, namely, that *"computers should be visible, playful and used to help humans become even more creative and proactive."* I argued that ubiquitous computing should be exciting, provocative, stimulating, visible, engaging, playful and even uncomfortable, enabling people to be active, creative and reflective in their work, learning and living. The paper was well received in the community and many people have commented since on how influential it was in helping them reimagine new possibilities for pervasive computing. New questions, frameworks, infrastructures, methods, and prototypes entered the stage. A sea change was in our midst.

A growing interest was how pervasive technologies could be designed to engage with the everydayness of life. There was a move towards experimenting with new technological possibilities that could change and even disrupt behaviour. The arrival of a cornucopia of affordable "plug and play" technologies, tools, and materials — for example, Arduino tool kits, e-textiles, mobiles, actuators, ultrasonics, infrared, user-friendly programming languages, sensors, and different display types enabled a wider range of designers and researchers (other than computer scientists) to imagine, create, and build new possibilities.

Two large-scale research programmes stood out for how they shaped the field: (i) Equator – which was a UK multi-university interdisciplinary collaboration that ran for six years, and (ii) MobileLife - a Swedish multi-site centre that ran for 10 years. The focus of both was to create new *user experiences* with an emphasis on designing for different human values other than ease and convenience. These included 'ludic engineering' (promoting learning through novel, playful visions of technology) and curiosity. Driving the Equator agenda was a mission (and *not* a vision) to develop systems, applications, and understandings that could promote the synthesis of the physical environment and digital spaces to improve the quality of life. Many domains were explored with new ways of augmenting them including learning, entertainment and community care. For example, the pioneering Ambient Wood project designed and deployed a diversity of ubiquitous and mobile technologies that moved learning with technology outside of the classroom [13]. Other values were also promoted, such as non-utilitarian ones, that inspired the design of highly unusual and original artefacts, such as the 'drift table' – which was intended to enable people, while at home, to let their minds wander and wonder and, in doing so, question traditional views of the domestic role of technology [6]. The MobileLife Centre also researched novel applications of mobile and ubiquitous technology to create new user experiences, spanning a diversity of areas, including entertainment and socialization to work and society. A further emphasis was to consider how to create a society where happiness, playfulness and creativity were central to peoples' everyday lives. It drew inspiration from the social sciences, design thinking, aesthetics and value-based concerns. In so doing, the large body of research conducted pushed the boundary of what was considered a user experience, including the development of wearable biosensors for wellbeing and health; engaging animals in interaction; and designing with felt life and bodily engagement.

The cumulative knowledge from both ventures led to new ways of thinking about the relationship between humans and technology, expanding the scope of pervasive computing. Next, we consider the third phase that followed on from these halcyon days; which was a turn to being innovation-based pervasive computing.

4. Innovation-based Pervasive Computing

The third phase of pervasive computing, starting circa 2010, was much more concerned with innovation compared with the earlier phases of research-driven and vision-inspired developments. By this is meant the arrival of significant commercial developments that had widespread uptake, including the smartphone in 2007, the wireless internet, Bluetooth, RFID, GPS and QR codes. Each acted as a catalyst, paving the way for significant advances in how the public *experienced* and *used* technology. For many, it was a whole new way of being. Ironically, the ubiquitous smartphone became an extension of ourselves, rather than disappearing into the environment; acting as a guide, a remote controller, a connector, a recorder, a reminder and much, much more. UbiComp had truly arrived. And so, too, did new framings enter the fray, most notable was the idea of the Internet of Things (IoT) that took the field by storm – which referred specifically to embedding physical artefacts with sensors, processing ability and software, that could connect and exchange data via the Internet with other devices and systems.

Monitoring and tracking technologies came of age through the arrival of commercial IoT systems. Sensors began to be placed everywhere, becoming the eyes and ears of society, for example, remotely checking up on elderly relatives, and, in so doing, extending the reach of caregiving services. IoT was also employed to monitor wildlife and many aspects of the environment (e.g., air quality). Citizen science was empowered through IoT capabilities and mobile technology; greatly expanding what it could accomplish, where members of the general public joined up with scientists to advance their knowledge.

IoT systems were also engineered and embedded into our homes and other buildings. Affordable home automation systems came into being; where people started controlling their domestic appliances and artefacts remotely using a smartphone/tablet app, such as turning on the washing machine or opening the blinds. Smart office buildings were also designed that could automatically control their internal systems, such as ventilation, lighting, security and heating. While being more efficient and less prone to human error (e.g. leaving the heating and the lights on all night), a downside was that they ended up being frustrating for many inhabitants, who discovered they were no longer able to control them, for example, not even being able to open a window to let some fresh air in.

Notwithstanding, the innovation-based phase led to significant improvements in the workplace. Many industrial solutions came into being, integrating pervasive computing with other technological advances, such as robotics, AI and cloud computing. Transformational changes took place in the manufacturing, automobile and logistics industries. Ocado, for example, a UK online grocery company developed sophisticated swarms of physical bots that were programmed to move around, navigating a ginormous warehouse, picking up bins and delivering them to pick stations where other robots and humans packed and completed individual customer orders. This was achieved by overlaying a warehouse with a grid that enabled the bots to act like a swarm, picking up the groceries in the best order, starting from the top and moving systematically to the bottom of the grid. Sophisticated algorithms were also used to determine which of their fleet of road vehicles should deliver orders and the optimal routes for their drivers to take.

Smart supermarkets then appeared, fitted out with a sophisticated network of cameras in the ceiling, and shelves embedded with weight sensors, that together with AI, determined what a customer had picked up and put in their bag/pocket, billing them as soon as they had left the store. Amazon Go pioneered this transformation of shopping, with other supermarkets following suit. The smarts were in how the computer vision, sensor fusion and deep learning were combined to track customers and what they took from or replaced on a shelf.

Another technological innovation, that no-one predicted, was the emergence of drones. After being taken up by hobbyists, they soon found other commercial uses. Several companies experimented with dropping drinks off to people at outdoor festivals. Since then, flying deliveries have literally taken off, dropping off medicines and groceries that people order on their phone apps. Drones have also increasingly been built and programmed to light up our skies replacing conventional firework displays, such as Firefly Drone Shows, by being pre-programmed, choreographed, and automated by a computer. However, while there are many good uses that drones have been used for, they have also begun to be used in more nefarious ways, such as spying on people (e.g., filming remotely inside people's homes without their permission) and as lethal autonomous weapons (i.e., killer robots). These latest developments are raising new ethical concerns about the impact such technologies are having on society, especially regarding privacy, safety and human rights.

But it is not just drones. Other devices that are connected to the internet, such as baby monitors, interactive dolls and smart speakers, that collect and can use personal data without the users knowing, are increasingly considered an invasion of a person's privacy. This has resulted in the general public becoming more concerned about whether this kind of technology is safe, and in response whether more 'parental controls' are needed to ensure it does not violate human values. What can be done? It does not make sense to stop innovation - since most technologies are designed with good intentions in mind. It is only after they have been released, when others appropriate them for different uses, that they become seen as unethical or even creepy. It is at this point that governments need to get involved and instigate new regulations and policies – which many are doing.

Much of the innovation in the last 20 years has been led by market forces and business drivers. It is now reaching a point where serious questions need to be asked by society about the impacts they are having on society, including personal privacy to resource, environmental and societal impacts. Another negative consequence of the growth in tech innovation during the last 20 years is the vast amount of energy that is needed to develop, run and maintain it. It is without doubt played a role in global warming. The current generation, not surprisingly, is unhappy with being 'dumped' with this. While they try to navigate the current crisis using grassroots initiatives, it is an opportunity and a responsibility, for the field of pervasive computing to face the music.

5. Challenge-led Pervasive Computing

While advances in technology innovation will continue to persist into the future, the consequences of creating ever more technology for technology's sake is leading many to question its sustainability, especially in light of the size of the carbon footprint it leaves behind. There have been new call to arms that are promulgating a change in research direction; namely to address head-on pressing and global issues [16]. These include tackling the 'Grand Challenges' facing society, which emphasize *"a difficult but important, systemic and society-wide problem with no 'silver bullet' solution"* [11]. Examples include achieving no poverty, zero hunger, quality education, gender equality and sustainable cities and communities. What will it mean for Pervasive Computing to become part of this challenge-led agenda? To begin, there are many opportunities to join other researchers who are addressing the United Nation's Sustainable Development Goals (https://sdgs.un.org/goals). Below, we focus on the goal of climate change: embracing the 'green computing' agenda which argues for finding ways of significantly reducing the environmental impact of pervasive technology.

5.1 Green computing

Until now, researchers have not really worried about how much energy, IoT, computation, public displays, WiFi, smartphones and the like uses or its impact on the earth's resources. However, recently, the growing concern worldwide with climate change has led many to consider how computing itself can change to a low carbon future. There is also a growing awareness of just how much electricity is used to make, run and use computers. For example, within the AI community there is a move towards Green AI which promotes a research agenda that takes into account the computational cost of running algorithms while encouraging a reduction in resources spent [18].

In the last few years, some in-roads have been made towards developing low energy computing. Another idea gaining popularity is to challenge the values designed into IoT objects that influence the end-user practices of disposal, recycling and upcycling [8]. Most devices are designed to have a short lifespan. Users are constantly under pressure to get the latest model – be it a smartwatch, smartphone, smart TV, ebike or other. By instilling alternative design values in society, it may be possible to support the continuity of the material life of IoT objects for longer. However, this also requires the tech companies buying into an alternative view of tech; coming up with different business models, production cycles and investing more in re-usable materials.

From a research perspective, we can also help by considering new ways of recycling e-waste. We can experiment with discarded tech, repurposing, say, old TVs, phones, coffee machines, smartwatches, etc., into reengineered systems and devices. We can run hackathons that challenge participants to transform their broken-down domestic appliances, for example, turning them into urban irrigation systems that can water the plants on a housing estate. Just like the 'instructables' community came into being, that was set up for sharing ideas among people who like making things, the field of Pervasive Computing can start publishing and promoting efforts that design repurposed pervasive technologies that tackle societal challenges.

How we think about pervasive computing in the home of the future could also be revisited with a new kind of lens [c.f. 7]; this time in terms of how to enable healthy living, reduce resource consumption and integrate learning in the home. The learning could involve discovering how to make an affordable home out of local and recycled materials together with a shift towards bottom-up thinking, providing more affordable sensing and other DIY technologies that local communities can create and use for themselves.

5.2 Engaging communities in research

There has been a growing move towards involving communities throughout the world when deciding how to use and appropriate sensing technologies in their homes [e.g. 7]. Methods used for this 'bottom up' approach include participatory design and co-design. For example, the Bristol approach, developed in the UK, describes how an assortment of community members, including researchers, council officials and IT volunteers from the tech industry, got together to find ways of helping local groups tackle a pressing issue that was of particular concern to them [3]. The problem they identified was damp homes which was prevalent at the time in the city of Bristol. The community combined their resources, expertise and skills to address this. They then explored how best to measure levels of damp in people's homes with the available resources they had, as well as suggesting ways to help them deal with the problem. To this end, they created a simple but effective 3D-printed frog-like, damp-sensing device, that could collect data about the damp conditions in a house. Temperature and humidity sensors were embedded in the middle of each frog's back, connected to a Raspberry Pi computer, that was programmed to collect data every few minutes, then saved to a simple database. The mechanics were simple enough that a frog could be built, understood and used by members of the community, including school children. It also provided the council with empirical evidence of dampness – which was not available before. The project demonstrated how it was possible to come up with a simple IoT sensing device that addressed a pressing societal concern and which involved a cross-section of communities where their engagement was hugely beneficial.

A problem with becoming more community-oriented, however, is it questions what it is that we as researchers should be doing and the academic means by which our work is validated. Coming up with a novel technology intervention - which is what many of us do - may no longer be viewed as important or even needed in a challenge-led approach. A recent community-based research project we were involved in proved to be very humbling in this regard [15]. We were asked to join a consortium, as experts in user engagement, to tackle the challenge of improving food waste recycling amongst inner city housing estates, where the levels were very poor. At the time, we were working as part of a large academic/industrial consortium concerned with sustainable, connected cities (cities.io) innovating with IoT prototypes.

As part of our design process, we proposed a lightweight IoT system, which was to attach weight sensors to the recycling bins to weigh the weekly amount recycled at the depot. This data could then be represented on connected public displays, positioned by the bins on a housing estate, showing various data visualizations of relative food waste recycling levels for different blocks. However, the rest of the consortium viewed our design as being ‘too techy’ and too expensive to implement at scale. Instead, they preferred a simple solution with no tech: to use stickers and fliers. In the end, we settled on a compromise, with some but minimal technology as part of the design (a few LED lights appearing as eyes on each bin that would swivel when approached by someone to lure them to throw their food waste in the bin). This solution, however, presented us with a dilemma: how could we get our work published when there was nothing new about our contribution to knowledge since it no longer demonstrated a novel application of IoT? We ended up writing about the scaling up process that did get published.

5.3 Ethical challenges facing future technology

As touched upon earlier, it is imperative that the Pervasive Computing community find ways of helping address new ethical issues that are surfacing, especially for technologies that are collecting ever-increasing amounts of personal data. Consider home healthcare where this is happening - an area that is likely to grow substantially in the future. It has a very laudable goal of improving the wellbeing of society by empowering people to become more involved in checking up on themselves, through using affordable health monitoring kits, such as smartphone self-examination apps, paper-based sensors, imaging capsules and off-the-shelf medical devices (e.g., ECG readers). These new developments will make it really easy for anyone to collect masses of personal medical data. How do we ensure it is safe, secure, perceived to be trustworthy and importantly valued and is understandable by the general public?

As part of this challenge, we need to consider the trade-off between the amount of personal information/data a person is expected or willing to provide versus the level of checks needed in order to improve the accuracy of the device. Consider self-examination smartphone apps that use the microphones and cameras embedded in them to act as sensors. SkinVision, for example, is a new commercial app that uses the smartphone camera to enable people to take images of their skin to check up on any strange-looking blemishes or moles. The recorded images are then analysed, with the help of machine learning, for potential lesions. Such self-examination apps currently come with a service that provides personalised health advice and next steps to take, should potential cancer be detected. Having a third party at hand who has expertise in assessing skin lesions (e.g. Skin Analytics), identified by the AI, is reassuring and helps reduce anxiety. However, as new kinds of self-examination apps come into being they may not have such a safety net ecosystem in place, making them less ready for widespread uptake. We need to be mindful of when these new kinds of apps are launched, how reliable they are, and what support structures are in place when people receive bad news.

Hence, the advent of self-examination apps and devices will need to be handled with more care than previous tech that has entered the public domain, where perhaps it did not matter if the sensors were not 100% reliable. How accurate do they need to be before it is considered safe to be let loose on the general public? Recent studies have shown that many current algorithm-based smartphone self-examination apps are in fact unreliable in being able to detect all cases of melanoma or other skin cancers [5]. Clearly, it is not acceptable for people to mistakenly think they have cancer or other serious illness when they don't or overlook a potential health problem which goes undetected using an app. Besides having a support ecosystem in place, the accuracy of these technologies needs to be much higher before they hit the market. A more thorough process of quality control needs to be in place. One strategy is to employ ML classifiers that decide whether or not the data is "valid" before it goes to the analysis component of the ML app [10]. Part of this process, however, is likely to involve gathering demographic, medical history, family history and other risk factor information. How will the general public feel about divulging lots of personal information onto their smartphones for this purpose? More research is needed.

In the future, therefore, we will need to conduct ethically-grounded research, which we have not done before, helping address the kinds of moral dilemmas mentioned above. Clearly, these new kinds of personal technologies offer much potential for being game changers in healthcare and it is important to help find ways of resolving these. Consider another new technology in our midst; that of miniature camera capsules that are currently being trialled to check for certain illnesses. When they are swallowed, they pass through someone's intestines, taking two images per second. The data recorded by the camera is then relayed to a clinician to examine for signs of cancer, gastrointestinal disorders and other conditions, with the aid of trained AI algorithms. Similar to the smartphone self-examination apps, the opportunity here is to switch from the traditional way of looking at the gut through endoscopy, which is time-consuming, expensive and unpleasant, to a home-based one that is much easier to administer, less uncomfortable and considerably cheaper. Similarly, a clinical support eco-system will need to be in place to manage what happens when abnormalities are detected. But, in the future, this process could be handed down to the general public to do, provided the data is accurate, understandable and can reassure people what they should do next.

These new developments also offer opportunities to encourage people to be more curious and engaged with their personal health. By being able to self-examine themselves, they can learn more about and manage their health more effectively. Research is needed, though, to determine how best to present this new kind of health data that is reassuring, informative and helpful. In sum, there is much potential for new technologies to emerge that can address societal challenges. Here we have discussed how we can help in the context of transforming healthcare. The same will be true for the other challenges, like zero poverty and food security.

6. Conclusions

Many of the ubiquitous and mobile technologies that have been developed and deployed in society have been geared towards making our lives more convenient. In the future, it is likely that affordable and far-reaching sensors and devices will come into being that will enable us to examine and augment more aspects of ourselves and the environment, with an emphasis on empowerment. To reassure the general public that the new kind of tech is trustworthy and useful to them, will need us to pay attention to ethical concerns that were not present before. Part of this will involve engaging in new discourses, while also developing new methods and techniques that can operationalize, evaluate and examine specific ethical issues, such as level of creepiness and extent of any invasion of privacy.

In the future, we may become less ‘top-down’ and vision-led in our research directions and alternatively, pivot towards becoming more bottom-up, community-oriented and societal challenge-led. Some researchers are already on this path, having demonstrated how to engage with communities [3,8]. Importantly, it does not mean having to stop imagining how pervasive technology can be ‘exciting, stimulating, and engaging’ but that we also look at how we can make technologies that are more sustainable, more impactful and accountable.

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