Ubiquitous Computing 20 Years Later

A Whitepaper for the NSF Sponsored Workshop on Pervasive Computing at Scale (PeCS)

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Background and Experience

Shortly after Mark Weiser was promoted to Manager of the Computer Science Lab (CSL) at Xerox PARC in mid-1988, he tasked members of the lab with developing a research vision that could help focus the lab's activities. As a result of this visioning exercise, various subgroups produced whitepapers proposing radical new directions. I was part of a group that met for several weeks (at the Dutch Goose) and wrote a report called "Ubiquitous Data" outlining our vision of people having access to their personal data from any place at any time using a variety of devices. Mark loved this report but felt that the focus on data access was too narrow, and thus morphed the vision slightly into what he called "Ubiquitous Computing". This did indeed become the unifying theme of much of CSL's research during the 1990s.

Under the ubiquitous computing umbrella at PARC, I led several systems projects. After wrapping up work on the Information Tapestry system, which pioneered the notion of collaborative filtering, I started an effort to define a distributed architecture for ubiquitous computing applications. This effort became the Bayou project. In discussing scenarios concerning ready access to shared data, we quickly realized that replicating data would be necessary in order to tolerate intermittent connectivity among mobile devices. Our work on Bayou was one of the early efforts, along with the Coda work at CMU, to explore replicated data management, support for disconnected operation, weak consistency models, and application-specific conflict handling. In 2000, I left PARC to start a company called Cogenia that developed a commercial platform for (some aspects of) ubiquitous data access; the commercial world was intrigued by the technology but not quite ready to spend its IT budget on such services.

Vision

To this day, I still believe that ubiquitous data access and information sharing is the most important aspect of pervasive computing. In other words, the "computing" part, while interesting, is not what drives human interest; rather, it's the desire to access their data on the go and selectively share it with others. While many innovative systems have been developed

over the past 20 years to facilitate distributed data management, challenges remain in supporting the types of ubiquitous computing applications that we've envisioned.

To some extent, the advent of the "cloud" with its elastic, seemingly unbounded resources has alleviated the concerns of those building scalable pervasive computing applications. But not entirely. While much, if not all, personal and business data will eventually reside in the cloud, it will continue to be accessed by millions of devices, particularly mobile devices, at the edge of the cloud. Such devices will want to cache data locally to ensure low-latency access, continued availability, and perhaps even privacy in some cases. Therefore, issues of communication, consistency, security, and sharing, along with the associated design challenges, will remain for applications that span devices and the cloud. Indeed, even within the cloud where constant connectivity is assumed, replicated services have eschewed strong consistency in favor of performance and availability. The design of scalable systems, services, and applications involves difficult and often subtle trade-offs that affect the system and its users. The core challenge in designing pervasive computing applications at scale, as in designing cloud services, is *how to choose fundamental design tradeoffs that both result in acceptable systems characteristics and are understandable to the end-users of these systems*.

Potential Impact

Users cannot continue to be expected to bear the burden of dealing with applications whose properties are defined by what's doable rather than what's desirable. With new advances in system monitoring, self-adaptive systems, enforceable service-level agreements, data privacy, mobile sensors, contextual awareness, and other emerging technologies, we should be able to develop pervasive computing applications that serve the masses. Twenty years later, the vision presented by Mark Weiser in his Scientific American paper is still attractive and well within our reach, but it will take a concerted effort.