Pervasive Computing Revisited

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In 2001, Mahadev Satyanarayanan (Satya) published a paper, "Pervasive Computing: Vision and Challenges," in *IEEE Personal Communications*.[1] This was the first paper to substantively explore the implications of Mark Weiser's 1991 vision for a real-world systems infrastructure.[2] It provided the conceptual foundations for what much of the computing industry now calls the Internet of Things (IoT). It also developed a taxonomy showing the deep relationships between distributed systems, mobile computing, and pervasive computing (IoT). You might not realize it, but the paper also inspired the creation of our own publication, *IEEE Pervasive Computing*, with Satya serving as the founding Editor in Chief.

A Look Back

Satya's paper has earned almost 3,000 citations and has inspired many well-known authors whose names are synonymous with the pervasive computing field, including Victor Bahl, Gaetano Borriello, Nigel Davies, Hans Gellersen, Jason Hong, Liviu Iftode, Anupam Joshi, David Kotz, James Landay, Marc Langheinrich, Dejan Milojicic, and Dan Siewiorek. It has also inspired at least nine papers with more than 500 citations each (see the "Inspiring Others: Related Work" sidebar).

Looking back at the vision Satya outlined and comparing it to today's reality, we see that our community has made progress, but we still have a long way to go. For example, in two scenarios he outlines, we can see aspects of everyday pervasive computing—we use cloud storage services that automatically sync our electronic documents between devices, and we identify which documents to maintain on each of our devices. But many aspects of his scenarios are more distant. For example, my smartphone has never told me to move to a different area to get better network service.

Last year, the *IEEE Pervasive Computing* editorial board decided that after slightly more than 15 years, this would be a good time to look back at Satya's vision, review the challenges he laid out for our community, and evaluate what has been achieved in making the vision a

Inspiring Others: Related Work

T he following important works were all inspired by Satya's 2001 paper, "Pervasive Computing: Vision and Challenges," in *IEEE Personal Communication*:

- D.S. Milojicic et al., *Peer-to-Peer Computing*, tech. report HPL-2002-57 (R.1), HP Labs, 2002; www.hpl.hp.com/techreports/2002/HPL-2002-57R1.pdf.
- D. Garlan et al., "Project Aura: Toward Distraction-Free Pervasive Computing," *IEEE Pervasive Computing*, vol. 1, no. 2, 2002, pp. 22–31; http://ieeexplore.ieee.org/abstract/document/1012334.
- D. Saha and A. Mukherjee, "Pervasive Computing: A Paradigm for the 21st Century," *Computer*, vol. 36, no. 3, 2003, pp. 25–31; http://ieeexplore.ieee.org/abstract/document/1185214.
- M. Pantic and L.J.M. Rothkrantz, "Toward an Affect-Sensitive Multimodal Human-Computer Interaction," *Proc. IEEE*, vol. 91, no. 9, 2003, pp. 1370–1390; http://ieeexplore.ieee.org/abstract/document/1230215.

- J.I. Hong and J.A. Landay, "An Architecture for Privacy-Sensitive Ubiquitous Computing," *Proc. 2nd Int'l Conf. Mobile Systems, Applications, and Services* (MobiSys), 2004, pp. 177–189; http://dl.acm.org/citation.cfm?id=990087.
- D. Cook and S.K. Das, *Smart Environments: Technology, Protocols and Applications*, John Wiley & Sons, 2004.
- L. Kagal, T. Finin, and A. Joshi, "A Policy Language for a Pervasive Computing Environment," *Proc. IEEE 4th Int'l Workshop Policies for Distributed Systems and Networks*, 2003; http://ieeexplore.ieee.org/abstract/document/1206958/.
- D.J. Cook and S.K. Das, "How Smart Are Our Environments? An Updated Look at the State of the Art," *Pervasive and Mobile Computing*, vol. 3, no. 2, 2007; https://doi.org/10.1016/j.pmcj.2006.12.001
- E. Aarts, J. Korst, and W.F.J. Verhaegh, "Algorithms in Ambient Intelligence," *Phillips Research Book Series*, vol. 2, Springer, 2004; https://link.springer.com/chapter/10.1007/978-94-017-0703-9_1.

reality. This special issue is a retrospective on that vision.

In This Issue

We open with an interview with Satya in which he looks back at the challenges he identified in 2001, noting what he missed and highlighting what has been more difficult than expected. The interview touches on privacy, smart spaces, and user distraction and intent. It also explores the relationship between pervasive computing and both IoT and cloud computing. We think you will find Satya's observations insightful.

One of the key ideas identified in Satya's seminal paper is cyber foraging—he argued that future mobile devices would have to acquire the resources they need from the environment around them. In "Cyber Foraging: Fifteen Years Later," Rajesh Krishna Balan and Jason Flinn examine the progress that has been made in this area. In particular, they discuss seamless cyber foraging and look at what technical challenges remain, how those gaps hamper adoption, and when and

how cyber-foraging systems might reach mainstream deployment.

In "Powering Pervasive Computing Systems," Shwetak Patel and Joshua Smith examine the progress made in power delivery and management over the past 15 years, discussing today's trends in advancing this important area. They examine power-harvesting approaches as well as power transfer through both near-field and far-field mechanisms. They also point out the need to architect pervasive computing systems that recognize and embrace the power limitations of different technologies while minimizing the need for power at the most energy-constrained layers of the system. They also point out that we have biological examples of systems that are millions of times more energy efficient than current technologies, so they're optimistic about the outlook for continued advances in energy efficiency.

Jason Hong shares his thoughts about privacy in pervasive computing systems in his article, "The Privacy Landscape of Pervasive Computing."

In this article, he categorizes pervasive devices into three tiers: the top tier (tablets, smartphones, and so on), middle tier (TVs, refrigerators, thermostats, and so on), and bottom tier (including RFID tags; sensors; and heating, ventilation, and air conditioning systems). He then describes six types of privacy concerns: the ease with which people are aware of what is being sensed, the time scope of the sensing, the number of input and output capabilities the sensing technology can use to interact with users, the amount of software that can run on the device, the existence of third-party software that can be installed and can run on the device, and the amount of support manufacturers provide in terms of fixing bugs and upgrading software. Hong then considers each of these dimensions across each device tier, giving readers a good sense of the range of concerns that must be considered when building a new device or installing a device in a home.

Finally, in "Pervasive Data Science," Nigel Davies and Sarah Clinch make

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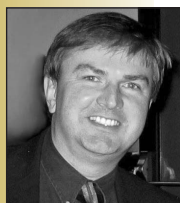
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the case that the intersection between pervasive computing and data science entails some unique challenges that must be addressed. Examples of applications at this intersection, which they discuss, include augmented cognition to improve human abilities, autonomous vehicles to transform our transportation infrastructure, and smart spaces to improve our physical environment. They outline five challenges specific to pervasive data and cover the entire data pipeline. These challenges, like those of pervasive computing more broadly, will require an interdisciplinary approach. The article walks readers through two use cases demonstrating the end-to-end challenges of pervasive data science. Ultimately, Davies and Clinch argue that pervasive data science will transform our ability to achieve the goals of ubiquitous computing outlined by Weiser. Readers looking for a thesis topic should find the challenges presented in this paper inspiring.

Satya's prediction that the "early decades of the 21st century will be a period of excitement and ferment, as new hardware technologies converge with research progress on the many fundamental problems discussed in this paper," was most certainly true. We are well into the second decade of the 21st century, and we continue to see many research initiatives designed to solve the challenges that Satya laid out for us in this one, short article. It's always amazing to see how Satya can keep so many people busy solving difficult and meaty problems, but he seems to do it again and again! ℙ

REFERENCES

1. M. Satyanarayanan, "Pervasive Computing: Vision and Challenges," *IEEE Personal Comm.*, vol. 8, no. 4, 2001, pp. 10–17.

2. M. Weiser, "The Computer for the 21st Century," *Scientific Am.*, Sept. 1991, pp. 66–75.

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