Taking the Internet to the Next Physical Level

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Our physical universe has been transformed by computing's ubiquity. The authors describe the challenges and delights we'll find in a future enabled by the Internet of Things.

FROM THE EDITOR

With the realization of the ideas behind the Internet of Things (IoT)—a network of everyday items with embedded computers that can connect directly or indirectly to the Internet—we're entering the era of ubiquitous computing. As the IoT takes root, the number of devices connecting to the Internet is likely to increase 10- or even 100-fold over the next 10 years, forever changing our relationship with "things"—now they'll be smart: smart devices, smart homes, smart buildings, and smart cities.

Although its origins date back to 1999, the IoT's core ideas were first described in Mark Weiser's vision of ubiquitous computing in 1988. Although these ideas have been around for more than 25 years, it has only recently become practical for high-performance processing and networking to be built into everyday products. We now have the ability to augment our things' capabilities at a reasonable cost and size: this embedded computing—with the equivalent performance of a complete 1980s-era workstation—can be added to products for less than $10.

To kick off the inaugural installment of "The IoT Connection," a bimonthly forum bringing *Computer* readers exciting developments from the IoT field, it seems appropriate to invite one of the fathers of the Internet, Vint Cerf, and one of Google's in-house philosophers, Max Senges, to get the ball rolling. Vint's perspective, spanning his considerable experience in networking from the early days of Internet design at DARPA to its modern instantiation, is combined with Max's expertise in building both sociotechnological innovation around a "good IoT" and a vibrant multistakeholder IoT ecosystem.

Please contact me with your content suggestions, especially regarding IoT standards development, applications, protocols, security and privacy, and novel human–computer interaction requirements for new modes of use. —*Roy Want*

We've come a long way since the article in which Mark Weiser envisioned small, ubiquitous, connected computers that enhanced all aspects of our lives.[1] Here, we present our analysis of the architectural leitmotifs that should be pursued so the Internet of Things (IoT) ecosystem can enjoy the staggering success of the Internet, which resulted in the World Wide Web. By success, we mean the economic value and the social and technological innovation these platforms have brought to the world.

THE IOT IS HERE

As with the Internet, it's difficult to pin down the dimensions of value creation through the IoT because it's essentially a general-purpose platform. So, we'll start by highlighting some examples of how the IoT already helps society in many different ways, through applications ranging in scope from the individual to the

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Figure 1. The scope of the Internet of Things (IoT). (Source: Copenhagen Wheel [http://senseable.mit.edu/copenhagenwheel] photo by Max Tomasinelli; www.maxtomasinelli.com. Aclima photo courtesy of Aclima [http://aclima.io].)

planetary (as shown in Figure 1), as well as across ventures in a variety of industries.

IoT ventures are rooted in and advance all kinds of professional spheres, including entertainment (for example, mixed-reality ventures like Magic Leap; www.magicleap.com), science (such as scientific data sharing), education (for example, connected platforms like SAM Labs; http://samlabs.me), health (such as the smart contact lens developed at Google X), and civic innovation (for example, participatory smart city initiatives; https://smartcitizen.me).

UNDERSTANDING THE CHALLENGES

Although we're already reaping so many of the IoT's exciting benefits and anticipating much more from the promising forecasts of its future, mainstream users and organizations aren't yet craving the majority of IoT devices and services. Indeed, some of its potential applications and complexities stir public fears over privacy and security risks—an aspect the media tends to revel in reporting about. Additionally, many IoT products have a level of complexity that limits their appeal for users unwilling to invest time and resources to learn to configure them.

However, its greatest limitation is arguably the lack of open standards, because the IoT's growth will bring many incompatible IoT solutions. Even if standards are used, consumers are hesitant to pay a premium for IoT-enabled devices, particularly if these devices aren't compatible with products and devices they already own. As many IoT products—such as home appliances and cars—have a product lifetime of more than a decade, consumers need to be confident that technical support and security updates are available long term.

LESS IS MORE

Tech companies have generally pursued business models in which successful products and services are constantly updated. This translates to technology-rich environments where devices and services constantly compete for consumers' attention; thus, technology tends to distract rather than add value. Will the addition of more networked devices add more screens to this cacophony? We have no doubt that IoT technology will profoundly impact our lives. If these devices are to fit into our lives comfortably, they shouldn't require more screens or keyboards.

Figure 2 illustrates what our colleagues at Nest Labs—a home automation producer of programmable, Internet-connected thermostats, smoke detectors, and security systems—came up with when their CEO, Tony Fadell, asked them to envision the living room of the future. What's important is

Figure 2. Nest's vision of the living room of the future. (Source: Nest Labs)

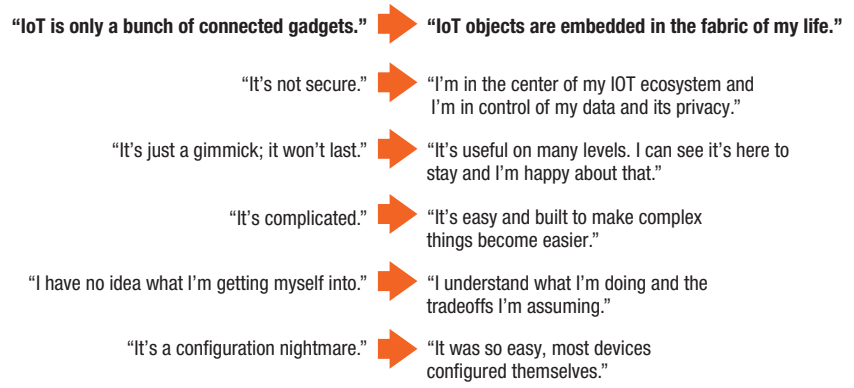


Figure 3. From resisting to embracing the IoT. Our assessment of current user perception of the IoT and where we believe the value propositions should be.

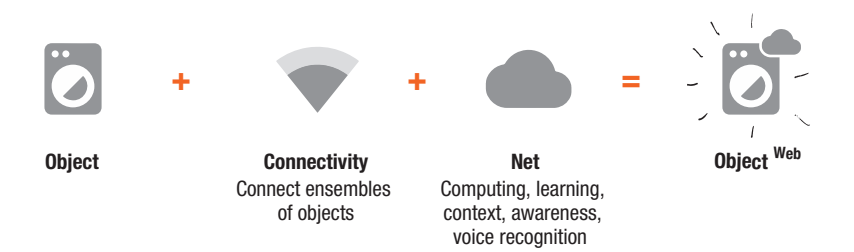


Figure 4. How connectivity changes "things."

what's missing—where's the collection of screens and keyboards? We might interact with future devices through voice requests, gestures, or perhaps inputs mediated through smartphones.

As Weiser espoused, technology will (or should) fade into the background, supporting us in our private and professional lives in many subtle and effective ways.

THE PROMISE OF GOOD IOT TECHNOLOGY

How can we guide technologists, entrepreneurs, and user-experience designers to shift their perspectives? Let's start by comparing current user perceptions with the experiences we'd like to provide (see Figure 3).

When thinking about the IoT, we like the dualism of *hard IoT* versus *soft IoT*—an idea put forward by Usman Haque in 2002.[2] Hard IoT is traditionally understood as a network of electronic gadgets, software, and sensors that are connected so objects can collect and exchange data. In contrast, soft IoT focuses on the value that can be derived from the collection of fluid relationships among people, objects, and spaces.

The following three maxims can inform good IoT design:

- reimagine ordinary objects with the power of the Internet,
- foster ensembles of objects and services, and
- match relevant objects and services for genuine user benefit.

Reimagining ordinary objects with the power of the Internet

How useful will objects be when they're amplified by everything the Internet can do? Figure 4 shows how a traditional "offline" object is enhanced by being connected to the online ecosystem.

Imagine a washing machine with the power of the Web (see Figure 5). Whereas traditional washing machines have all the features they'll ever have once they're installed in a home—they're

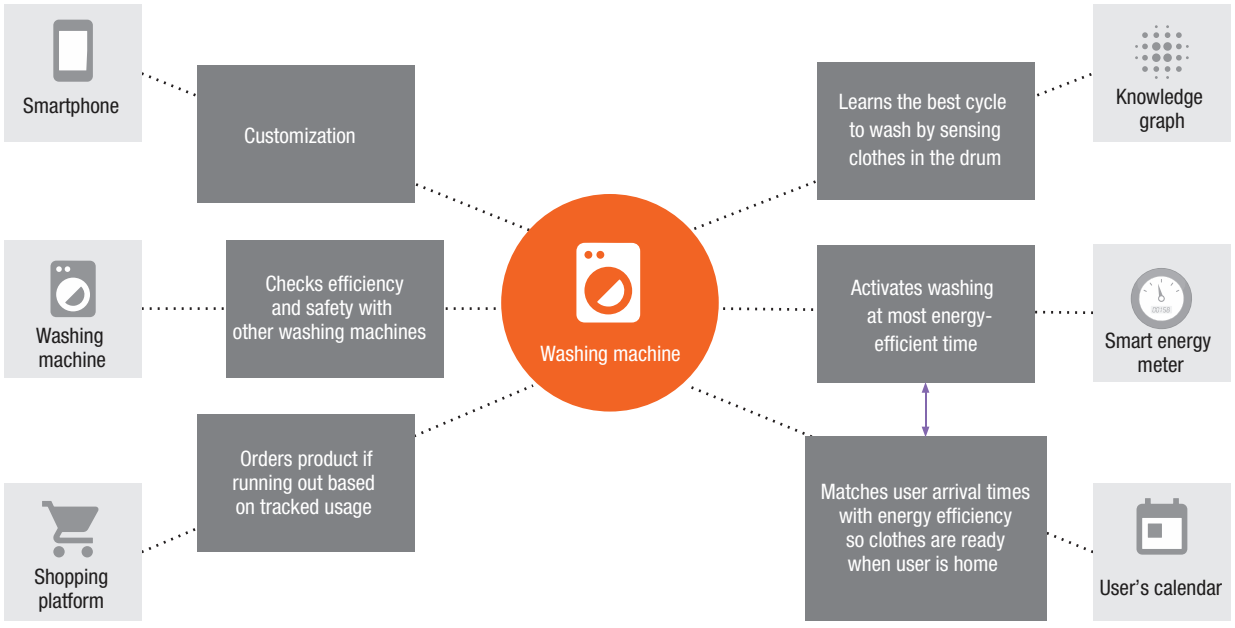


Figure 5. The various features and benefits enabled by connectivity and access to an online ecosystem.

neither customizable nor aware of the resources they consume—a Web-enabled machine is able to acquire new safety or security features and services (for example, programs designed to clean innovative textiles, such as Google's Project Jacquard [http://levistrauss.com/unzipped-blog/2015/05/google-levis-project-jacquard]). Connecting to cloud services and the Internet ecosystem enables the washing machine, for example, to link to other objects and build ensembles that complement and cooperate with one another.

In such configurations, Web-enabled appliances benefit from continuous machine learning, improving their understanding and consideration of context and enabling their access to ecosystem services (such as weather data), markets (such as placing an order to replenish washing detergent; www.youtube.com/watch?v=U1XOPIqyP7A [at 3:02]), and APIs and protocols that allow full cooperation with other devices. Thus, network-enabled objects embody smart behaviors that make them adaptive to new circumstances, more resource efficient, and generally user optimized.

Fostering ensembles of objects and services

Orchestration among an ensemble of objects can add to their usefulness and value—it facilitates rich, intuitively interactive or standardized environments. In the washing machine example shown in Figure 5, users can customize and save personal preferences via their smartphone. The machine can compare efficiency and learn about safety hazards from other machines, track usage and order replenishment of supplies, access knowledge bases to learn the most suitable programs for washing clothes, and find the best price for energy.

Although this is a very simplistic example, such IoT innovations can allow for resource conservation and energy efficiency in a scalable way. It follows that such efficiencies can be realized at a much larger scale, and in industrial IoT ecosystems that can result in huge cost reductions along with green efficiency benefits.

Matching relevant objects and services for genuine user benefit

So far we've considered mainly static actors, but the IoT's true benefits will be felt when we connect contextually relevant objects to the right information and services.

Figure 6 shows how the IoT extends the information graph created by the Web, the social graph created by user-generated media, and the physical graph that links objects and their functionalities. Only when these three knowledge domains are combined can products and services be truly "smart."

PREREQUISITES FOR A GOOD IOT

There are already many successful IoT products and services, and even some (limited) domain-specific ecosystems on the market. Nevertheless, we identify three areas that require significant R&D investment and cooperation before an ecosystem can emerge to universally interconnect all industries, people, and spaces (see Figure 7):

- data, access-control, and identity management;
- standardized and modular system architecture (including protocols and IoT schema); and
- new human–device interaction paradigms and techniques.

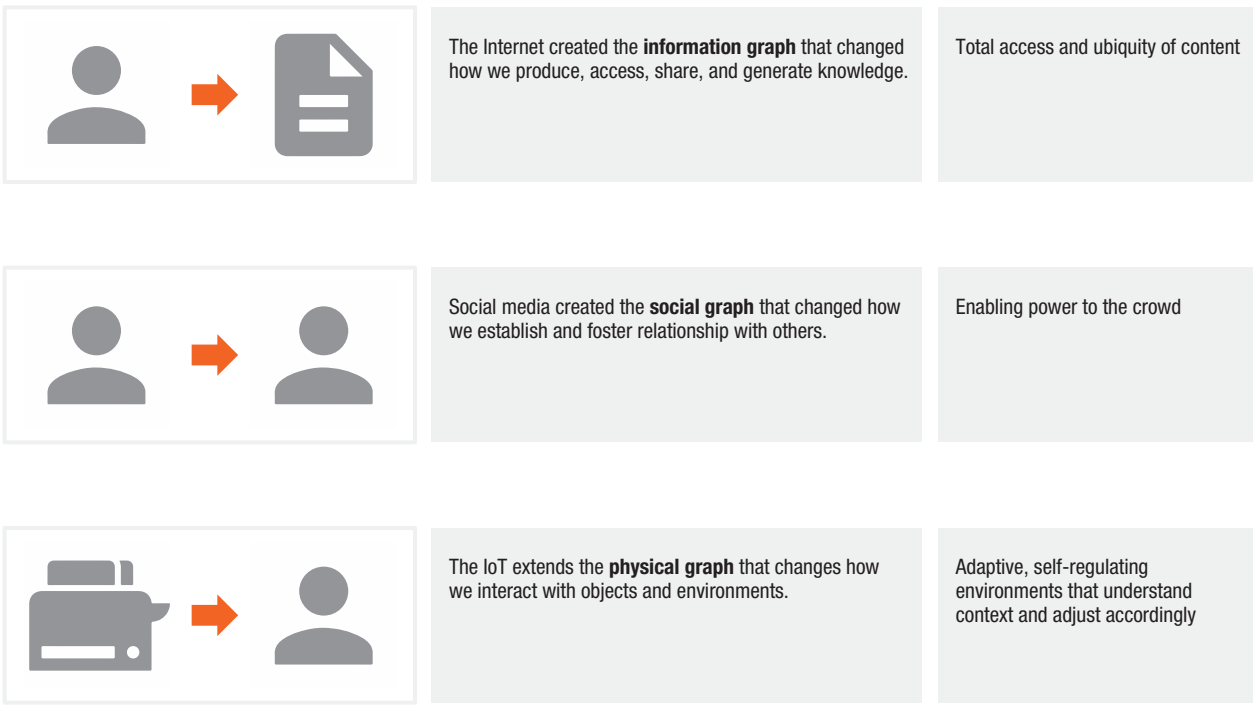


Figure 6. How the IoT extends the Web-created information graph, the user-generated media–based social graph, and the object–functionality physical graph to create "smart" ecosystems.

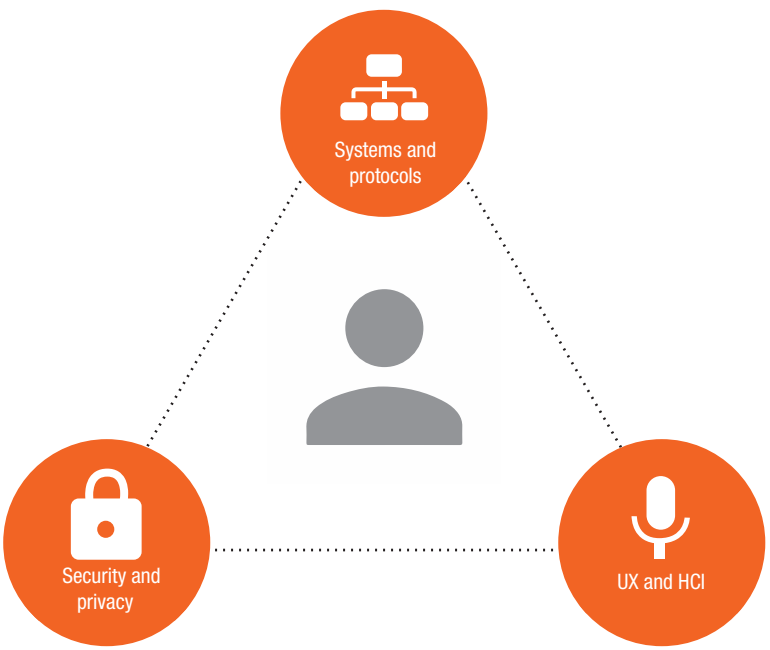


Figure 7. Components of an IoT ecosystem. HCI: human–computer interaction; UX: user experience.

Importantly, in our assessment, all three areas are more likely to result from open peer-production scenarios as described by Yochai Benkler.[3] This will lead to better standards that make it feasible for users to learn nuanced common practices that can be applied internationally across companies, product categories, and industrial and consumer ecosystems. For example, controlling devices with gestures or managing complex dataflows are two new areas where open standards would be beneficial.

Data, access-control, and identity management

In the Internet's early development, user privacy and identity management—and security, to some extent—weren't at the forefront of its inventors' minds, and were only incorporated into the service network much later. User safety has also recently become deeply relevant as devices like cars and door locks become networked.

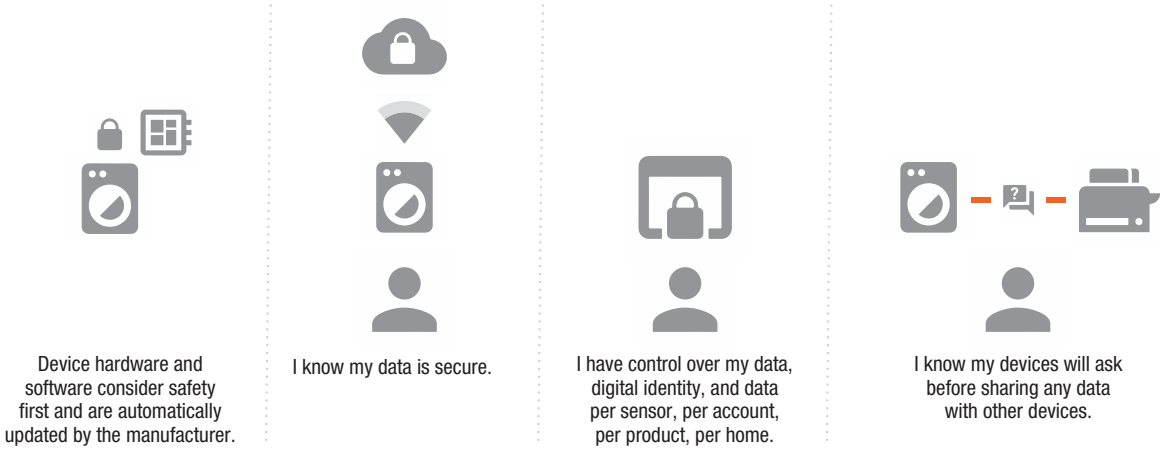


Figure 8. Embedding trust into the IoT.

We believe that a system architected from the ground up, with identity management and data ownership as core features, will better serve users in a world of networked things.

To do this, we'll first need a solid identity management system. All IoT objects—such as door locks and cars—must have deeply ingrained, authority-based usage rights. Establishing preferred usage patterns (personalization) is fundamental, especially to reap the benefits of ensembles and spaces (in other words, to avoid constantly configuring and adapting settings). Because everything creates data, we'll also need to clearly define its flow and ownership to allow for reasonable and effective storage and management.

The key to mainstream IoT acceptance lies in a decentralized, user-controlled system with strong data management and identity controls to elicit greater trust and adequate privacy. Security and safety can be handled mostly by service providers. Figure 8 illustrates the main requirements of a trust-generating identity- and data-management system.

Standardized and modular system architecture

The current IoT landscape is made up of individual solutions, or "walled gardens," that offer special perks for customers who buy from the "product family." Although the Internet was developed around open standards, AOL's and CompuServe's walled gardens were among the first of the Internet's initial development and deployment experiments. We now know that the open ISP model provided superior services to customers, but this experiment needs to be repeated at the beginning of the IoT era.

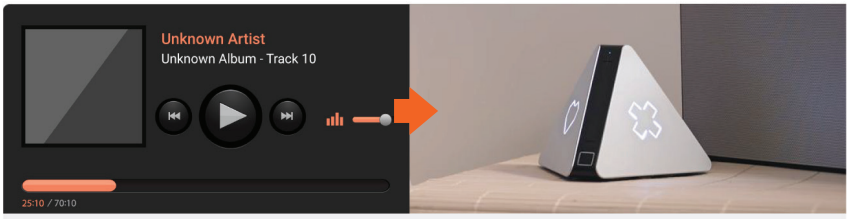
We're not dogmatic about openness, but it seems clear to us that the Internet's success is based on the level playing field created by open standards and interoperability. A successful IoT ecosystem will allow start-ups, established small and midsize businesses (SMBs), and big companies to plug in and play a role in building viable products. For the IoT to become a mainstream success, the IKEAs, Holiday Inns, and Disneys of the world—along with all kinds of SMBs—must join the party and help foment ever more connected hardware and services.

Nearly 100 IoT consortia and standardization efforts are underway. We appreciate the competition to create the best system, but from a strategic perspective, it's more desirable for the architecture of platforms, schemata, and protocols to be modular and for their core elements to be maintained by transparent meritocratic organizations dedicated to the public interest.

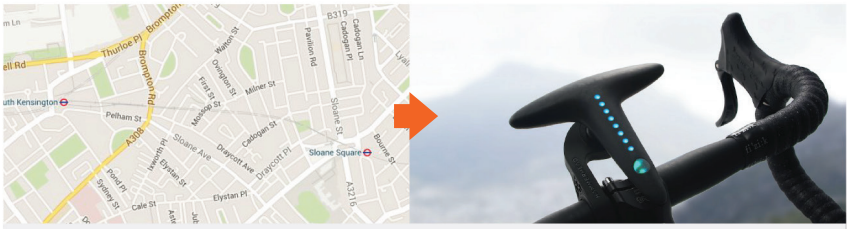
Particularly problematic for the mainstreaming of IoT products and services is the "app trap": the tendency for each connected thing to develop and require its own smartphone application. We need to move away from this paradigm. Single objects or systems shouldn't rely on smartphones as controllers, but should instead use common APIs so that various devices and programs can access and control them (given the right credentials). This will enable an ecosystem in which users interact with multiple devices through voice, gestural, and touch interfaces as devices share contextual information. Standardization will also improve efficiency by enabling competition and user choice for managing and controlling ensembles of devices.

New paradigms for user interface and interaction design

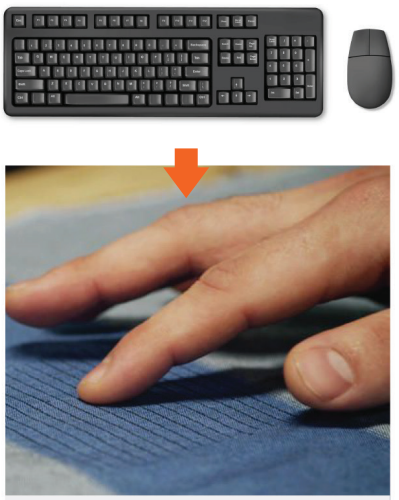
Last but not least, interacting with our connected "things" shouldn't revolve around putting little touchscreens on all of them. Keyboards and mice aren't an effective means to use and orchestrate the devices surrounding us. As neither of us is an expert in human–computer interaction or user-experience design,



Music player reimagined as a physical experience
Prizm



Traditional maps reimagined as smart navigation for bicycles
Hammerhead



Mouse and keyboard reimagined
as an interactive textile
Project Jacquard from Google ATAP

Figure 9. Reimagining interaction with "things" beyond traditional interfaces.

we refrain from making assessments about these challenges and opportunities. Instead, we provide a few examples of nontraditional IoT interfaces in Figure 9.

It's not possible in such a short article to comprehensively analyze the IoT with its multifaceted dimensions. We hope, however, that our analysis here might illustrate the IoT's core potential and articulate some of the barriers to the adoption of a universal, mainstream IoT. As we strongly believe in openness and collaboration, we very much look forward to teaming up and building a good IoT with all of you.

Let's expand the Internet's success story in terms of permissionless innovation and level the playing field for all competing innovators.

Let's promote an interoperable ecosystem based on open standards.

Let's make identity, access-control, and data management an essential part of the technological architecture from the start of the IoT evolution.

Let's take the Internet to the next physical level.

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NOTE

This article is an elaboration on Vint Cerf's keynote address at the IEEE 2nd World Forum on Internet of Things (WF-IoT 15) in Milan, Italy, in December 2015.

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