The Web of Things: Challenges and Opportunities

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As billions of devices connect to the Internet, a new Web of Things is emerging, with virtual representations of physical or abstract realities increasingly accessible via Web technologies. Achieving a new phase of exponential growth, comparable to the earliest days of the Web, will require open markets, open standards, and the vision to imagine the potential for this expanding WoT.

I got involved with the Web in 1992 as part of work I was doing at Hewlett-Packard's corporate laboratories on a graphical hypertext-based application for creating quotes on HP computer systems. Tim Berners-Lee's original vision for the Web focused on documents and their interrelationships, but it was soon clear that the future lay in a Web of applications. The Web has since become the world's most successful vendor-independent open application platform.

Today, we are poised for a major transition, as billions of devices connected to the Internet fuel an explosive growth in services based on an Internet of Things (IoT). Continuing improvements in electronics have led to a staggering number of new devices—albeit, often having only limited interoperability with other devices and services. For example, maker enthusiasts now have access to readily available hardware platforms, such as Raspberry Pi and Arduino, along with various associated sensors and actuators. Potential application domains range from consumer electronics (including wearables and home automation) for retail consumption and products for manufacturing and construction to complex devices for building management, transportation logistics, control of major utilities (including smart grids),

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healthcare and assisted living, and scientific research.

All of this is opening the way to a Web of Things (WoT), with "things" as proxies for physical or abstract realities and "Web" referring to the idea that these "things" are accessible via Web technologies, such as HTTP at the protocol layer and scripting APIs at the services layer. As these things move from simple to complex and really smart, and as Web services themselves become smarter, we can expect techniques to emerge for embedding in them an almost human understanding of what we consider everyday reality, including personal emotions and individual impulses—essential if these things and services are to provide a "human touch."

This will be made possible through interdisciplinary work combining cognitive psychology and linguistics, along with traditional notions of artificial intelligence, and through an immersive 3D Web realized as computers' increasing power allows minute facial gestures to be tracked in real time and compelling projections to be shared in virtual environments.

For this transition to achieve its full potential, however, we will need open markets based on open standards. The sidebar "The Web of Things Framework" provides an overview.

THE WEB OF THINGS FRAMEWORK

There are already many Internet of Things (IoT) platforms, and this presents increasing challenges for those creating applications that span them. The solution is to enable worldwide discovery and interoperability by exposing these platforms through the Web with a new class of webservers that support an open framework for the Web of Things (WoT), analogous to the open Web of pages as originally conceived by Tim Berners-Lee, the Web's inventor. Figure A diagrams such a framework.

This open WoT would require

- URIs as addresses for things serving as proxies for physical and abstract entities;
- a way to retrieve metadata for things in a standard format, such as JavaScript Object Notation for Linked Data (JSON-LD);
- owner, purpose, access control, and terms and conditions relationships to other things;
- things modeled as events, properties, and actions;
- discrete property values that can smoothly change between data points;
- bindings to scripting APIs and multiple protocols; and
- a variety of communication patterns: pull, push, publish-subscribe, and peer-to-peer.

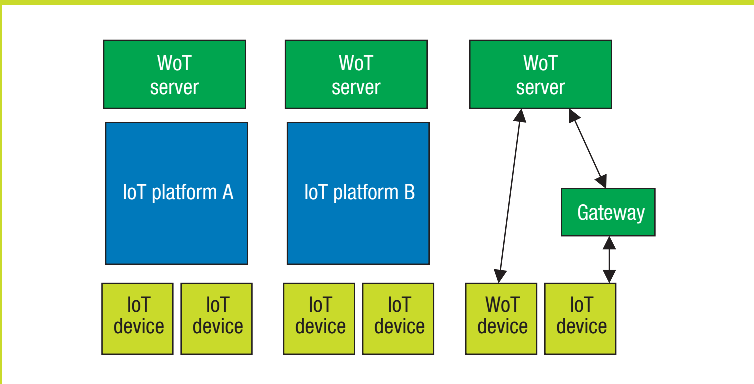

Figure A. Framework for an open Web of Things (WoT) that bridges multiple Internet of Things (IoT) platforms.

OPTIMIZING WEB TECHNOLOGY–BASED SERVICES

Until recently, most efforts in the field have focused on devices—mainly sensors and actuators—and the communication technologies used to access them. Gartner expects IoT vendors to top US$309 billion in direct revenue by 2020, with most of that money deriving from services (www.gartner.com/newsroom/id/2636073). Add Web technologies into the mix, and it is clearly time to consider how to expand the IoT beyond product silos into Web-scale open ecosystems based on open standards, including those for identification, discovery, and service interoperability across platforms from different vendors.

Rich descriptions and shared data models will also be needed, along with close attention to matters of security, privacy, scalability, and accessibility. Open ecosystems will stimulate growth, establishing larger markets for developers and mitigating the burden of tailoring products to vendor-specific platforms.

Current open ecosystems

There is plenty of potential to exploit existing languages like JavaScript, data encoding methods like JSON and Efficient XML Interchange (EXI), data and metadata formatting tools like those being developed in the Linked Open Data community, and protocols such as HTTP and WebSockets—to name only a few. JavaScript, for example, could be used to communicate with IoT sensors and actuators directly from a browser—whether in a cloud service platform or at the network edge—via device drivers in gateways that use IoT protocols to access embedded or constrained devices and Web protocols to expose these devices to service platforms.

Smartphones and tablets can easily be used for this purpose, with operating systems like iOS and Android already offering APIs for native apps to access embedded sensors and nearby devices via Bluetooth or near-field communications (NFC). Work has already begun on defining standards for browser-based APIs; examples include the W3C Web Bluetooth Community Group (www.w3.org/community/web-bluetooth) and the W3C NFC Working Group (www.w3.org/2012/nfc). Future work may cover APIs for additional protocols such as the Constrained Application Protocol (CoAP) and MQTT (Message Queue Telemetry Transport). Bluetooth low energy can be used for advertising devices to other devices in their neighborhood. Google is exploring this with its proposed "physical web" (https://google.github.io/physical-web). The 3rd Generation Partnership Project (3GPP; www.3gpp.org) is developing a similar approach for cellular networks based on device-to-device proximity services.[1]

Home hubs

Home hubs provide another opportunity for hosting services. Many people today have a home hub that functions as a Wi-Fi access point for broadband Internet access. It is reasonable to expect these devices to evolve into service platforms for accessing IoT devices around the home. To succeed fully, these hubs will need to support open standards that allow users the freedom to install services from any vendor they choose. Also required will be gateway devices that can be positioned around the home to reach IoT devices outside the hub's range.

Cloud platforms

Cloud-based platforms can be designed to scale flexibly with the platform's load. An example is the open source Compose platform (www.compose-project.eu), based on top of Cloud Foundry (www.cloudfoundry.org/index.html). With this platform, service compositions are authored with Node-RED (http://nodered.org) and then deployed to the Compose cloud. Service owners can define security policies that are enforced through a mix of access control, static flow analysis, and dynamic monitoring.

Standard vocabularies and repositories

An open market for services requires a standard way to describe the interfaces the services expose as well as the interfaces they depend on. A useful analogy is Linux package management, where packages have names and version numbers, and declare the names and the number ranges they depend on to work.

But how can we encourage reuse of data and metadata vocabularies? One answer is to support repositories of existing vocabularies that developers can browse and search—and where they are encouraged to upload new vocabularies when existing ones are not a good match. Schema.org provides one such repository.

Monetizing services

Service monetization is clearly important in creating healthy ecosystems like these, but how to do so? For Web-scale ecosystems, we will need open standards independent of particular vendors. The W3C recently launched a Web Payments Interest Group (www.w3.org/Payments/IG) seeking to decouple Web applications from the means of payment. In principle, this could take the form of upfront payments, subscription-based payments, per-use payments, or out-of-bound mechanisms that grant particular users or groups of users the rights to use a given service. Contract law is roughly similar across countries and could form the basis for legally binding agreements between suppliers and consumers of services. In addition to payment arrangements, such agreements could apply to policies that give data owners control over how data is used and for what purposes.

A special case: cyber-physical systems

Cyber-physical systems are essentially control loops that bridge sensors and actuators to achieve system-wide goals such as managing traffic on city streets, maintaining comfortable environments in large buildings, and monitoring smart grids for electricity. Control over such systems

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can be expressed at multiple levels of abstraction and must be distributed at the network edge to address requirements for low latency and to tightly coordinate synchronization among multiple actuators.

This means that protocols will need to be matched to fulfill latency and jitter requirements, and the service layer may need to pass quality-of-service requirements down to the network layer. In addition, latency may be subordinate to transactional robustness, so requirements are likely to vary at different levels of abstraction.

SECURITY

Security will be an essential requirement for the WoT.[2] As sensors proliferate all around us, we will want to be assured that our privacy is protected from snooping and that our identity and financial resources are safe from malicious attack. Data encryption is important, but best security practices and strong authentication procedures for users, devices, services, and applications are also required.

IoT protocols

There is currently considerable variety among IoT protocols, and their ongoing rapid evolution suggests the need for abstraction layers that couple loosely with underlying IoT technologies to simplify services development, lessen the learning curve for developers, and increase overall robustness. Abstraction layers can also help with the heterogeneous mix of device vendors and versions available.

IoT devices are often constrained and may not be software-upgradeable, which puts them at risk when security flaws are identified.[3] One workaround for this is to use device gateways that are software-upgradeable—this can actually offer stronger security than is practical on hardware-constrained devices. In principle, gateways could use scripts for device drivers, but doing so raises the problem of identifying which driver will be needed for each specific device, and also will require standard APIs for drivers to use in accessing IoT protocols.

Identity verification

Verifying identity is important for devices, users, applications, and services as part of end-to-end security and for trust management. Unlike regular Web application users, we cannot assume that "users" in the WoT are present and able to authenticate themselves. Therefore, trust management will entail developing means for verifying metadata: the provenance of data, a given sensor's location, and various other identifiers (processes analogous to "know your customer" requirements in the banking world). Such trust can be built based on known brands, strong vetting processes, and even crowdsourcing in terms of reputation management.

RESILIENCE

With increasing dependence on systems based in the WoT, we will need to pay careful attention to overall resilience, and services will need to cope with rapidly peaking demand loads. I'm reminded of 1994 when the Web was very young: servers were unable to cope as large numbers of people wanted to see new images of Comet Shoemaker-Levy 9 as it collided with Jupiter, producing Earth-sized fireballs. We are now much more experienced with designing server farms for scalability.

Although dealing with a heterogeneous mix of device vendors and versions can be addressed through abstraction layers and best practices, as mentioned earlier, with so many devices at work it is inevitable that some will fail, either through hardware faults or software bugs such as botched upgrades. Services will have to be designed to tolerate failures, including the ability to employ appropriate workarounds when sensor readings are interpreted as implausible.

Cyberthreats from criminals and hostile states can further challenge resilience. Countering these will require careful attention to fixing security flaws, closely monitoring anomalous behavior, and employing in-depth defenses such as trip wires and security zones.

THINGS AND AVATARS

Applications and services often need data at a higher level than the raw data sensors provide. Moreover, data needs to be interpreted in the context of other sources of information. The same applies to control systems, whose actions need to be translated contextually into actions on lower-level entities. The WoT needs to be able to model the real world at different levels of abstraction, enabling open markets with free competition of services across these levels.

Because, as I noted in my initial definition, the things in the WoT are virtual representations of objects, they are not limited to connected devices. They can also include things that are not (and even cannot be) connected the way devices are: people, places, and abstract ideas such as organizations, events, and time periods. They can also have histories: a car, say, can include a record of previous owners.

Things can have one or more virtual representations, or avatars. Avatars have identities, rich descriptions, and their own services, as well as access control and data handling policies. In addition, avatars have URIs and are accessible via Web technologies. Avatars facilitate building applications and services that combine information from different sources and at different levels of abstraction.

SMARTER SEARCHES

Open standards for services would further increase opportunities for smart, intent-based searches. This process starts in the usual way, with a user typing in a search string. The search engine uses rules of thumb to recognize the intent, extract the associated search parameters, and then pass them on to registered services via the interface associated with the particular intent.

These intent services can invoke other services as needed but must be able to pass back the result in a fraction of a second for integration on the search engine's results page. Note that the result could embed a more complex query that the user can then activate via clicking on the link or icon. This allows tasks that take substantial computation time to be delivered to users as out-of-band notifications.

LEGAL IMPLICATIONS

What are the legal implications for the WoT? One issue involves who accepts liability for errors or disruptions to services. With free or low-cost services, this is likely to be the end user. For premium services, it may be the other way around, as determined by the contracts between service providers and consumers. For trust and delegation, there will likely be disputes about the vetting procedures. There are also likely to be upheavals in the insurance industry as the WoT increases the likelihood of accidents.

THE WEB OF THINGS AND VIRTUAL REALITY

At the First International Conference on the World Wide Web, hosted in 1994 by CERN near Geneva, Tim Berners-Lee and I organized a session on the potential for virtual reality (VR) as a richer way to support networked applications. I suggested the term "VRML"—by analogy with HTML (the hypertext markup language)—and presented ideas for using scripts and objects for a scalable, immersive 3D Web formed from a federation of servers.

That proved too ambitious, and work on VRML tapered off. Since then, network and computer speed has improved dramatically. We have also seen work on extending the Web for peer-to-peer real-time communications (WebRTC). These trends make it increasingly practical to capture detailed human facial expressions and speech and to project them with low latency into a compelling 3D-immersive shared virtual environment—something Neal Stephenson foresaw in his 1992 novel *Snow Crash*.[4] The challenge now will be to enable a cohesive 3D Web based on an open federation of servers, linked by open standards, and not controlled by a single vendor.

A MUCH SMARTER WEB

Web applications and services are based on scripts designed for specific tasks. However well designed, though, they lack the flexibility we expect when interacting with humans (except in instances where humans are forced to act like machines). Over the next 20 years, we can look forward to virtual things that exhibit common sense and even understand human emotions and drives. This will be made possible through interdisciplinary work combining cognitive psychology, linguistics, and traditional notions of artificial intelligence.

I recommend looking at progress in the field of cognitive science, particularly pioneering work by John R. Anderson. He and his colleagues have had great success in developing quantitative models of how people perform tasks ranging from playing games and performing simple algebraic calculations to driving a car. These models provide accurate predictions for BOLD (blood oxygenation level dependent) responses shown by brain scans taken when people are carrying out the tasks. In essence, we now have functional accounts for what different parts of the brain are doing in symbolic terms. If this interests you, I recommend Anderson's book *How Can the Human Mind Occur in the Physical Universe?*.[5] We need more cross-fertilization of ideas among different research fields and less of the compartmentalization that is common today.

A major challenge for creating such systems is to capture the everyday knowledge that humans find effortless, but which has proved immensely difficult for computers. Common sense includes knowledge about people and personal relationships, space, time, causality and naive physics, tools, the natural and urban worlds, storytelling, humor, emotions, empathy, personality traits, and more. A promising direction is to establish an evolving taxonomy of common sense and use it to create a sequence of "lesson plans" for training the cognitive models needed to replicate human understanding. The cognitive architecture depicted in Figure 1 combines symbolic with sub-symbolic reasoning,

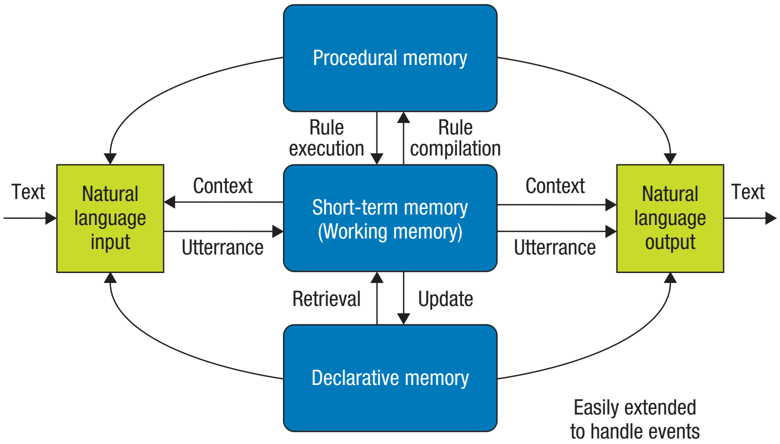

FIGURE 1. Proposed cognitive architecture for an evolving taxonomy of common sense that could provide a basis for models to replicate human understanding in computing systems. Adapted from J.R. Anderson, How Can the Human Mind Occur in the Physical Universe?, Oxford Univ. Press, 1997.

and embodies ideas developed by Anderson and his team in their work on the architecture they call ACT-R, along with the layered thinking model proposed by Marvin Minsky (see Figure 2).[6] In principle, sub-symbolic processes could be sped up through the use of hardware accelerators. Can achieving this exploit existing graphics accelerators, or will a new breed of hardware be needed?

Cognitive psychology also points the way for handling emotions and moods, which is critical for services with a human touch. Jerry Lin and his colleagues provide a 2012 survey of research in computational emotions and cognition.[7] Appraisal theory, for instance, treats emotions as effects of reactions to situations. How one understands a situation influences one's emotions, and this in turn influences how one reacts. Humor, on the other hand, can be considered in terms of incongruities and puns.[8] In principle, emotions and humor could be handled as part of the lesson plans, including examples and assessments, and result in iterative refinements to the cognitive architecture.

It will likely take many years to bring all of this work to fruition, but the impact will be immense, especially when the potential result is self-aware, intelligent avatars on the Web.

USING THE WEB TO BENEFIT SOCIETY

A separate topic for discussion is how advances in the WoT could enable humanity to overcome the challenges we currently face from resource depletion, climate change, and overpopulation. Increasing automation at progressively higher levels of skill would concentrate value production into the hands of a small, elite minority. What does this mean for the rest of the population? And how, then, do we create stable, civil societies? Although not directly germane to computer science, questions like these are nonetheless something we all need to consider in grappling with the increasing inequality within and among societies.

W3C AND THE WEB OF THINGS

To explore what is needed to realize these various potentialities, the W3C held a workshop on the WoT in June 2014 (www.w3.org/2014/02/wot). This was followed by the chartering of a W3C Interest Group for the Web of Things (www.w3.org/WoT/IG), whose aim is to accelerate development of open markets for applications and services based on the role Web technologies will play as the IoT intersects with the Web of data.

The new Interest Group will start with a survey of use cases across industry sectors and a concurrent study of existing solutions and standards relevant to the WoT. These surveys are essential for ensuring a shared understanding and will be a prerequisite for dividing work into separate task forces that can proceed in parallel.

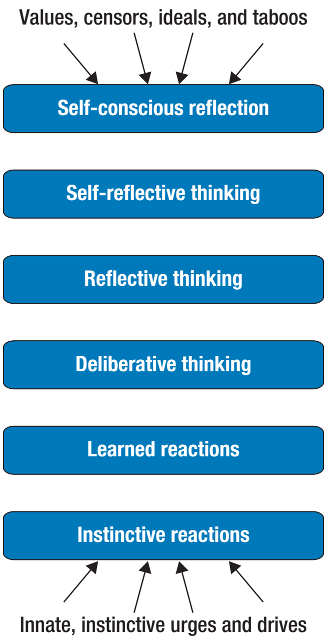

FIGURE 2. Marvin Minsky's six-layer model of thinking. From *The Emotion Machine: Commonsense Thinking, Artificial Intelligence, and the Future of the Human Mind*, Simon & Schuster, 2006.

The most important criterion for the Interest Group's success is whether it can establish consensus to focus the W3C's work, defining the possible actions and study areas that are within the organization's scope and then driving these into existing or new working groups as appropriate.

With Gartner predicting some 26 billion units for the IoT by 2020, it is likely that the Web is going to get a great deal bigger than it is now. As it evolves from a Web of pages to a WoT, it will provide a basis for discovery and interoperability on a worldwide scale. We can look forward to a new phase of exponential growth just as we saw in the early days of the Web. In the process, new Internet giants will appear and old ones will decline. We live in exciting times!

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