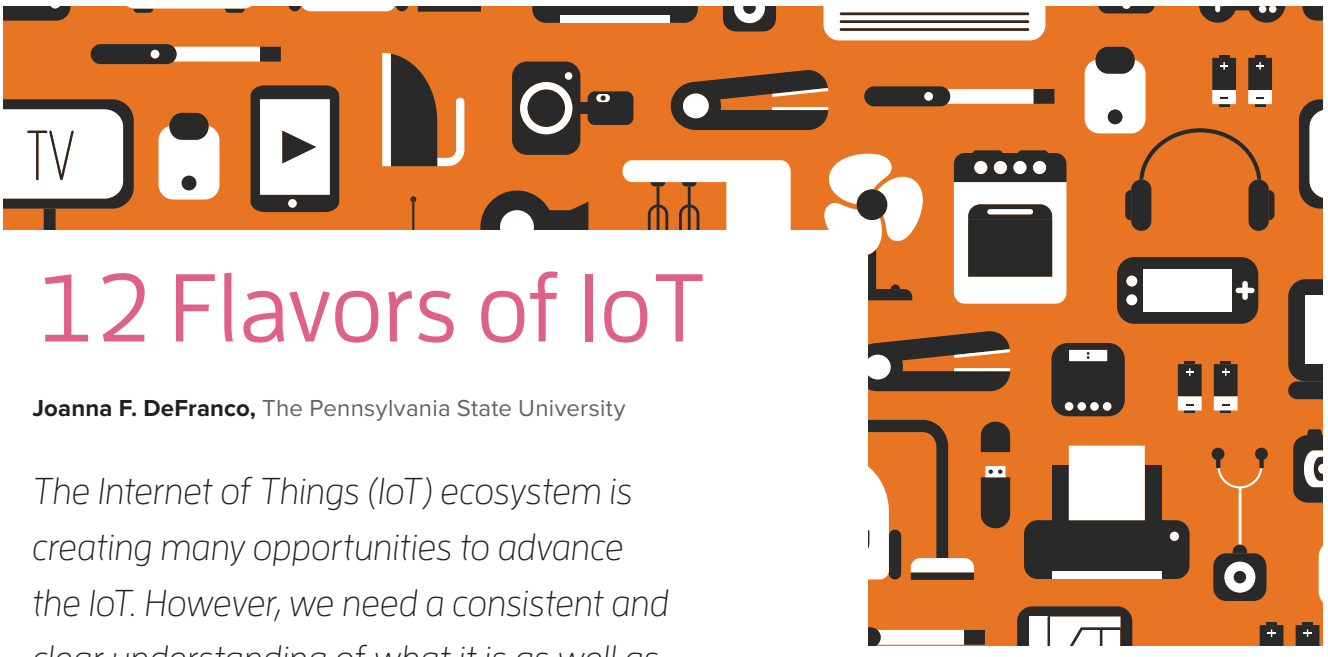
EDITOR JOANNA F. DEFRANCO
Pennsylvania State University; jfd104@psu.edu




# 12 Flavors of IoT

**Joanna F. DeFranco,** The Pennsylvania State University

*The Internet of Things (IoT) ecosystem is creating many opportunities to advance the IoT. However, we need a consistent and clear understanding of what it is as well as the complexities to be considered to design, develop, and adopt any IoT system.*

The term *Internet of Things (IoT)* has been around for two decades. But 20 years after its introduction, does the public really understand what the term means? The genesis of the term started in 1999 by Kevin Ashton, the founder of Auto-ID Labs, a research group in the field of networked sensors and radio frequency identification (RFID). A summary of his original definition is "a system where the Internet is connected to the physical world via ubiquitous sensors, including RFID."[1] An interesting fact is that Ashton regretted not calling it "Internet for things."[2]

Another interesting fact is that the credit for the first IoT device is given to a few students at Carnegie Mellon in 1982, who rigged a vending machine with a microswitch to report on the status of Coca-Cola availability and its coldness.[3] In 2021, IoT technology is now being applied to everything from light bulbs to critical systems such as smart grids that determine a city's energy consumption for increased safety and efficiency.

A Google Trends analysis for worldwide Internet queries showed that the interest in the IoT grew rapidly from 2014 to 2016.[4] However, there was no universally accepted definition. It is also safe to say that, even after many attempts to define the IoT, there is a population that would simply describe it as a noun prefaced with the word "smart."

Here are some examples of IoT definitions from 2015 (with key IoT components in bold):

> *The term Internet of Things generally refers to scenarios where* ***network connectivity*** *and* ***computing capability*** *extends to objects,* ***sensors*** *and everyday items not normally considered computers, allowing these devices to generate,* ***exchange and consume data*** *with minimal human intervention.*[5]

> *Although there is no single definition for the Internet of Things, competing visions agree that it relates to the integration of the physical world with the virtual world—with any object having the potential to be* ***connected to the Internet*** *via short-range* ***wireless technologies****, such as radio frequency identification (RFID), near field communication (NFC), or wireless sensor networks (WSNs). This merging of the physical and virtual worlds is intended to increase instrumentation, tracking, and measurement of both natural and social processes.*[6]

*Digital Object Identifier 10.1109/MC.2021.3099049*
*Date of current version: 24 September 2021*

*In what's called the Internet of Things,* ***sensors and actuators*** *embedded in physical objects—from roadways to pacemakers—are linked through* ***wired and wireless networks****, often using the same Internet Protocol (IP) that connects the Internet.*[7,8]

(software or hardware to execute algorithms and processes, for example, a database), and a decision trigger (establishes an action or command, for example, an actuator).

Six years later, even after this comprehensive definition, there are still many disparate, incomplete IoT definitions. Most IoT definitions miss at least one important piece. Table 1 shows a sample of a dozen current IoT definitions from organizations in the IoT domain. The table further includes an analysis of the definitions via a mapping to the NIST NoT primitives.

> The world desperately needed a simple, actionable, and universally accepted definition for the IoT.

These definitions were on the right track; however, there was no consistent, clear definition. The world desperately needed a simple, actionable, and universally accepted definition for the IoT. As a result, in 2016, the National Institute of Standards and Technology (NIST) provided a definition for the IoT in SP-183.[9] They opted to call it "Networks of Things" (NoT) instead of "Internet of Things" because the Internet is an unbounded network versus a bounded network. It is technically a network of networks. Essentially, this NIST special publication describes the building blocks of the IoT that offer an underlying and foundational science to the IoT based on five core IoT primitives that are the "Lego-like" building blocks for any IoT-based system.

In general, system primitives allow for descriptions of system behavior as well as formalisms, reasoning, simulations, reliability, and security risk tradeoffs to be discussed, formulated, and argued. These primitives also apply well to systems with large amounts of data and quality concerns such as scalability, heterogeneity, performance, security, and privacy. As defined, the five primitives of all NoT systems include sensors (measures physical properties, for example, RFID), aggregators (software to transform data collected by a sensor), a communication channel (data transmission), an eUtility

Table 1 shows that, even in 2021, IoT definitions are not only inconsistent—they are missing key elements. It is of the utmost importance that any IoT definition conveys an accurate understanding for society to continue to build and advance IoT systems that are integrated into many aspects of daily life.

Sample IoT domains with supporting examples are listed here:

- *Smart home systems*: detect resident activity using sensors, learn inhabitant activity/inactivity patterns, floor vibration sensors, and wearables to determine if intervention is needed[10]
- *Autonomous farming equipment*: robotic farm vehicle equipment with increased safety, such as having the ability to react to unexpected hazards (https://asirobots.com/farming)
- *Health care*: wearable health monitors such as closed-loop insulin pumps and smart heart-monitoring sensors inserted into clothing fabric[11]
- *Smart factory equipment*: increased automation and optimization with real-time analytics (https://tulip.co/glossary/what-is-a-smart-factory-and-what-it-means-for-you/)
- *Inventory trackers:* improved visibility of inventory to reduce excess stock and shipping container/vehicle and logistics tracking to improve supply chain management
- *Cities:* collecting, evaluating, and making decisions to develop new traffic patterns, have effective speed limits and traffic lights or smart grids that enable a two-way flow of electricity and data with digital communications technology for detection and reaction to power usage and issues
- *Education:* support the pedagogical processes for faculty, students, and staff as well as all educational assets such as libraries, classrooms, and labs.[12]

## MAJOR CONSIDERATIONS FOR THE IoT

Although some IoT definitions imply there is no human interaction, this is not accurate. The IoT certainly involves connections between humans as well as physical and cyber "things." These numerous connections inherently are complex, causing a core set of trust concerns that need to be considered and improved when adopting IoT systems. NIST wrote an internal report (8222) that describes a core set of 17 technical trust concerns and ways to mitigate the effects of these concerns in the rapidly changing IoT industry.[13] The list of trust concerns with a summarized explanation of each includes

1. *scalability*: complexity is increased every time a new "thing" is added to a system

**TABLE 1.** IoT definition analyses.

| IoT Definition | Pro | Con | Actionable? |
|---|---|---|---|
| "The Internet of Things (IoT) describes the network of physical objects—"things"—that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the Internet."—Oracle.com | Data are collected and exchanged using sensors and software | Data analytics are not discussed | No. Do the data trigger an event? What happens with the data that are exchanged? |
| "The Internet of Things, or IoT, is a system of interrelated computing devices, mechanical and digital machines, objects animals or people that are provided with unique identifiers (UIDs) and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction."—internetofthingsagenda.techtarget.com | Data are transferred over a network | Sensors/data collection not discussed. Data analytics not discussed | No. Do the data trigger an event? What happens with the data that are exchanged? |
| "The Internet of Things connects billions of devices that collect and share data, while integrating the physical and digital worlds."—ACM.org | Data collected (sensors assumed) and shared | Data analytics not discussed | No. Do the data trigger an event? What happens with the data that are exchanged? |
| "The Internet of Things (IoT) is the network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment."—Gartner.com | Communication using sensors and software | Data analytics not discussed | No. Do the data trigger an event? What happens with the data that are exchanged? |
| "Internet of Things is the concept of connecting any device (so long as it has an on/off switch) to the Internet and to other connected devices. The IoT is a giant network of connected things and people—all of which collect and share data about the way they are used and about the environment around them."—IBM.com | Data are collected (sensors assumed) and shared | Data analytics are not discussed | No. Do the data trigger an event? What happens with the data that are exchanged? |
| "It's your equipment, machines, products, and devices that are connected to the cloud and outfitted to collect and securely transmit data."—azure.microsoft.com | Data are collected (sensors assumed) and shared | Data analytics are not discussed | No. Do the data trigger an event? What happens with the data that are exchanged? |
| The IoT is "the use of network-connected devices, embedded in the physical environment, to improve some existing process or to enable a new scenario not previously possible. These devices, or things, connect to the network to provide information they gather from environment through sensors, or to allow other systems to reach out and act on the world through actuators."—cloud.google.com | Data collected and shared via sensors | Data analytics are not discussed | Yes—"acting on the world through actuators" |
| "The networking capability that allows information to be sent to and received from objects and devices (such as fixtures and kitchen appliances) using the Internet."—Merriam-Webster.com | Data collected (sensors assumed) and shared | Data analytics are not discussed | No. Do the data trigger an event? What happens with the data that are exchanged? |
| "The interconnection via the Internet of computing devices embedded in everyday objects, enabling them to send out and receive data."—Google Dictionary | Data shared | Sensors/data collection and data analytics not discussed | No. Do the data trigger an event? What happens with the data that are exchanged? |
| "The Internet of Things (IoT) refers to a system of interrelated, internet-connected objects that are able to collect and transfer data over a wireless network without human intervention."—Aeris.com | Data are collected (sensors assumed) and shared | Data Analytics are not discussed | No. Do the data trigger an event? What happens with the data that are exchanged? |

(*Continued*)

**TABLE 1.** IoT definition analyses. (*Continued*)

| IoT Definition | Pro | Con | Actionable? |
|---|---|---|---|
| "The Internet of Things (IoT) is a catch-all term for the growing number of electronics that aren't traditional computing devices, but are connected to the Internet to send data, receive instructions or both."—Networkworld.com | Data shared | Sensors/data collection and data analytics not discussed | No. Do the data trigger an event? What happens with the data that are exchanged? |
| "The Internet of Things is to connect any object to the Internet through radio frequency identification, infrared sensors, global positioning systems, laser scanners and other information sensing equipment according to an agreed protocol. It is a kind of network that realizes the intelligent identification, positioning, tracking, monitoring and management of items through information exchange and communication."—Alibabacloud.com | Data collected and shared via sensors | Data analytics are not discussed | No. Do the data trigger an event? What happens with the data that are exchanged? |

2. *heterogeneity*: interoperability as well as integration causing unexpected emergent behaviors
3. *ownership and control*: lack of transparency with third-party black-box devices
4. *composability, interoperability, integration, and compatibility*: each of these requirements needed to be critically analyzed before adding new hardware and software components to the system to determine the impact on the major system requirements
5. *"ilities"*: nonfunctional or quality requirements need to be prioritized and evaluated for technical conflict
6. *synchronization*: address the anomalies that occur due to the timing of computations/events occurring in parallel
7. *measurement*: improve upon the metrics and measures for the adoption and integration of "things" in the system
8. *predictability*: establish predictability of the system component interactions
9. *testing and assurance*: address the increased difficulty in testing due to system interdependencies
10. *certification*: address the questions that arise for any type of certification to confirm things such as system lifespan and time to market
11. *security*: increased security is required as more connections may cause increased accessibility by unauthorized parties
12. *reliability*: increase system resiliency by being able to handle anomaly from events and data
13. *data integrity*: ensure system data accuracy, fidelity, availability, and confidence
14. *excessive data*: ensure the integrity of the excessive amounts of data due to the dynamic and rapidly changing system dataflow and workflow
15. *performance*: require increased performance to be able to recover from faults and failures
16. *usability*: improved user "friendliness" to limit user constraints
17. *visibility and discoverability*: address increased privacy concerns, as an IoT system can become so ingrained in a user's life as users may, for example, forget about the systems sensing their every move and listening to every word.

Six years later, even after this comprehensive definition, there are still many disparate, incomplete IoT definitions.

The world has grown into an IoT ecosystem, creating many further opportunities to advance the IoT. For example, we have a long way to go to improve connections of domain specific critical systems such as in the areas of smart cities, health care, and law enforcement. Improvements in the connections within and between these domains would advance care, efficiency, and decision making for all. Thus, similar to the turn of the 19th century when the world needed electrical engineers due to the invention of the electric motor or in the late 1950s when aerospace engineering appeared to develop vehicles

operating in the earth's atmosphere, the world may need official IoT engineers to address the trust concerns that come with IoT system design. Continued focus and improvement of the trust concerns in IoT device and system design is critical. In addition, educating professionals to design effective and efficient IoT system will certainly pay off to address this immediate need.

> The world has grown into an IoT ecosystem, creating many further opportunities to advance the IoT.

Therefore, in addition to a consistent, accurate definition of the IoT, we need a focus on educating a new generation of IoT engineers. It is all hands on deck, and researchers need to use a consistent IoT definition and engineers need to continue to improve upon the trust concerns of IoT systems while inventing new ways to use the IoT. New and improved engineering curriculums, learning modules, and professional training are needed to develop core skills from multiple engineering disciplines.[14]

In summary, I am the new "Internet of Things" column editor for *Computer*. The goal of this column is to focus on recent advances, trends, novel applications, and technologies in the IoT. If you have ideas for content or you are interested in submitting a column article, please email me at jfd104@psu.edu.

## REFERENCES


1. "Kevin Ashton invents the term 'The Internet of Things'," History of Information, 1999. https://www.historyofinformation.com/detail.php?id=3411
2. "IoT Primer," Action Point Analytics, 2015. https://actionpointanalytics.com/iot-primer/
3. "History of the Internet of Things (IoT)," IT Online Learning, 2020. https://www.itonlinelearning.com/blog-history-iot/
4. C. Greer, M. Burns, D. Wollman, and E. Griffor, "Cyber-physical systems and internet," National Institute of Standards and Technology, Gaithersburg, MD, NIST Special Publication 1900-202, 2019. [Online]. Available: https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1900-202.pdf
5. K. Rose, S. Eldridge, and L. Chapin, "The internet of things (IoT): An overview," Internet Society, Reston, VA, Oct. 2015. [Online]. Available: https://www.internetsociety.org/wp-content/uploads/2017/08/ISOC-IoT-Overview-20151221-en.pdf
6. J. Winter, "Algorithmic discrimination: Big data analytics and the future of the internet," in *The Future Internet: Alternative Visions*, vol. 17, J. Winter and R. Ono, Eds. Cham: Springer-Verlag, Dec. 2015, pp. 125140.
7. M. Chui, M. Löffler, and R. Roberts, "The Internet of Things," McKinsey Quarterly, McKinsey & Company, Mar. 2010. https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/the-internet-of-things
8. T. Samad, "Control systems and the Internet of Things [Technical Activities]," *IEEE Contr. Syst. Mag.*, vol. 36, no. 1, pp. 13–16, Feb. 2016. doi: 10.1109/MCS.2015.2495022.
9. J. M. Voas, "Networks of 'things'," Special Publication (NIST SP), National Inst. of Standards and Technology, Gaithersburg, MD, 2016. Accessed: July 6, 2021. [Online]. Available: https://pages.nist.gov/NIST-Tech-Pubs/SP800.html
10. J. F. DeFranco and M. Kassab, "Smart home research themes: An analysis and taxonomy," in *Proc. Conf. Complex Adaptive Syst.*, 2021, pp. 1–10.
11. J. F. DeFranco and M. Hutchinson, "Understanding smart medical devices," *Computer*, vol. 54, no. 5, pp. 76–80, May 2021. doi: 10.1109/MC.2021.3065519.
12. M. Kassab, J. DeFranco, and P. Laplante "A systematic literature review on internet of things in education: Benefits and challenges," *J. Comput. Assisted Learn.*, vol. 36, no. 2, pp. 115–127, Apr. 2020. doi: 10.1111/jcal.12383.
13. J. Voas, R. Kuhn, P. Laplante, and S. Applebaum, "Internet of things (IoT) trust concerns," National Institute of Standards and Technology, Gaithersburg, MD, White Paper, Oct. 17, 2018. Accessed: July 6, 2021. [Online]. Available: https://csrc.nist.gov/CSRC/media/Publications/white-paper/2018/10/17/iot-trust-concerns/draft/documents/iot-trust-concerns-draft.pdf
14. J. DeFranco, M. Kassab, and J. Voas, "How do you create an internet of things workforce?" *IEEE IT Prof.*, vol. 20, no. 4, pp. 8–12, July/Aug. 2018. doi: 10.1109/MITP.2018.043141662.



**JOANNA F. DEFRANCO** is associate professor of software engineering at The Pennsylvania State University, Malvern, Pennsylvania, 19355, USA. Contact her at jfd104@psu.edu.