Withdrawn Draft

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National Institute of Standards and Technology
U.S. Department of Commerce

Draft NISTIR 8228

Considerations for Managing Internet of Things (IoT) Cybersecurity and Privacy Risks

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Michael Fagan
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U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
Walter Copan, NIST Director and Under Secretary of Commerce for Standards and Technology

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Organizations are encouraged to review all draft publications during public comment periods and provide feedback to NIST. Many NIST cybersecurity publications, other than the ones noted above, are available at https://csrc.nist.gov/publications.

Public comment period: *September 24, 2018* through *October 24, 2018*

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All comments are subject to release under the Freedom of Information Act (FOIA).

Reports on Computer Systems Technology

The Information Technology Laboratory (ITL) at the National Institute of Standards and Technology (NIST) promotes the U.S. economy and public welfare by providing technical leadership for the Nation's measurement and standards infrastructure. ITL develops tests, test methods, reference data, proof of concept implementations, and technical analyses to advance the development and productive use of information technology. ITL's responsibilities include the development of management, administrative, technical, and physical standards and guidelines for the cost-effective security and privacy of other than national security-related information in federal information systems.

Abstract

The Internet of Things (IoT) is a rapidly evolving and expanding collection of diverse technologies that interact with the physical world. Many organizations are not necessarily aware of the large number of IoT devices they are already using and how IoT devices may affect cybersecurity and privacy risks differently than conventional information technology (IT) devices do. The purpose of this publication is to help federal agencies and other organizations better understand and manage the cybersecurity and privacy risks associated with their IoT devices throughout their lifecycles. This publication is the introductory document providing the foundation for a planned series of publications on more specific aspects of this topic.

Keywords

cybersecurity risk; Internet of Things (IoT); privacy risk; risk management; risk mitigation

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Audience

The primary audience for this publication is personnel at federal agencies with responsibilities related to managing cybersecurity and privacy risks for IoT devices, although personnel at other organizations may also find value in the content. Personnel within the following Workforce Categories and Specialty Areas from the National Initiative for Cybersecurity Education (NICE) Cybersecurity Workforce Framework [1] are most likely to find this publication of interest, as are their privacy counterparts:

- Securely Provision (SP): Risk Management (RSK), Systems Architecture (ARC), Systems Development (SYS)
- Operate and Maintain (OM): Data Administration (DTA), Network Services (NET), Systems Administration (ADM), Systems Analysis (ANA)
- Oversee and Govern (OV): Cybersecurity Management (MGT), Executive Cyber Leadership (EXL), Program/Project Management (PMA) and Acquisition
- Protect and Defend (PR): Cybersecurity Defense Analysis (CDA), Cybersecurity Defense Infrastructure Support (INF), Incident Response (CIR), Vulnerability Assessment and Management (VAM)
- Investigate (IN): Digital Forensics (FOR)

In addition, IoT device manufacturers and integrators may find this publication useful for understanding concerns regarding managing cybersecurity and privacy risks for IoT devices.

Trademark Information

Note to Reviewers

NIST welcomes feedback on any part of the publication, but there is particular interest in the following:

1. Our approach has been to articulate the differences from our perspective between managing cybersecurity and privacy risk for conventional IT and for IoT. This is so personnel can more easily adapt their conventional IT risk mitigation practices for IoT, no matter what risk management practices or methodologies they currently use. Is this approach helpful? Does the publication emphasize these differences too much, not enough, or the right amount? Would a different approach be more effective?
2. This publication focuses on mitigating risk and does not address other forms of risk response (accepting, avoiding, sharing, and transferring.) Our analysis has shown that mitigation options may be significantly different for IoT devices than conventional IT devices, but other forms of risk response are generally not different. Is this a reasonable assertion?
3. There has been a great deal of interest from many organizations in establishing cybersecurity and privacy baselines[1] for IoT device risk mitigation. NIST analysis of existing standards and guidelines for IoT device cybersecurity and privacy has determined that because IoT devices and their uses and needs are so varied, few recommendations can be made that apply to all IoT devices. NIST is creating a high-level, widely applicable baseline, with the first examples shown in Appendix A of this publication, and also developing more specific and actionable recommendations for particular types of IoT devices. Therefore, feedback on the Appendix A examples is particularly important.
4. This publication is the introductory document providing the foundation for a planned series of publications on more specific aspects of this topic. The intention is to develop one publication defining a high-level baseline and one or more publications defining baselines and other recommendations for particular IoT device types. Additional publications can be developed if needed. Which aspects of managing cybersecurity and privacy risks for IoT devices would be most beneficial to address in future publications?

[1] The term “baseline” has different meanings to different people and organizations. Some want flexible general recommendations; some want specific, prescriptive guidance; and the rest want something in between. In this publication, “baseline” is used in the generic sense of a set of requirements or recommendations. It should not be confused with the low, moderate, and high control security baselines set forth in NIST Special Publication 800-53 to help federal agencies meet their obligations under the Federal Information Security Modernization Act (FISMA) and other federal policies.

Executive Summary

The Internet of Things (IoT) is a rapidly evolving and expanding collection of diverse technologies that interact with the physical world. IoT devices are an outcome of combining the worlds of information technology (IT) and operational technology (OT). Many IoT devices are the result of the convergence of cloud computing, mobile computing, embedded systems, big data, low-price hardware, and other technological advances. IoT devices can provide computing functionality, data storage, and network connectivity for equipment that previously lacked them, enabling new efficiencies and technological capabilities for the equipment, such as remote access for monitoring, configuration, and troubleshooting. IoT also adds the ability to analyze data about the physical world and use the results to better inform decision making, alter the physical environment, and anticipate future events.

While the full scope of IoT is not precisely defined, it is clearly vast. Every sector has its own types of IoT devices, such as specialized hospital equipment in the healthcare sector and smart road technologies in the transportation sector, and there is a large number of enterprise IoT devices that every sector can use. Also, versions of nearly every consumer electronics device, many of which are also present in organizations' facilities, have become connected IoT devices—kitchen appliances, thermostats, home security cameras, door locks, light bulbs, and TVs. [2]

Many organizations are not necessarily aware they are using a large number of IoT devices. It is important that organizations understand their use of IoT because many IoT devices affect cybersecurity and privacy risks differently than conventional IT devices do. Once organizations are aware of their existing IoT usage and possible future usage, they need to understand how the characteristics of IoT affect managing cybersecurity and privacy risks, especially in terms of risk response—accepting, avoiding, mitigating, sharing, or transferring risk.

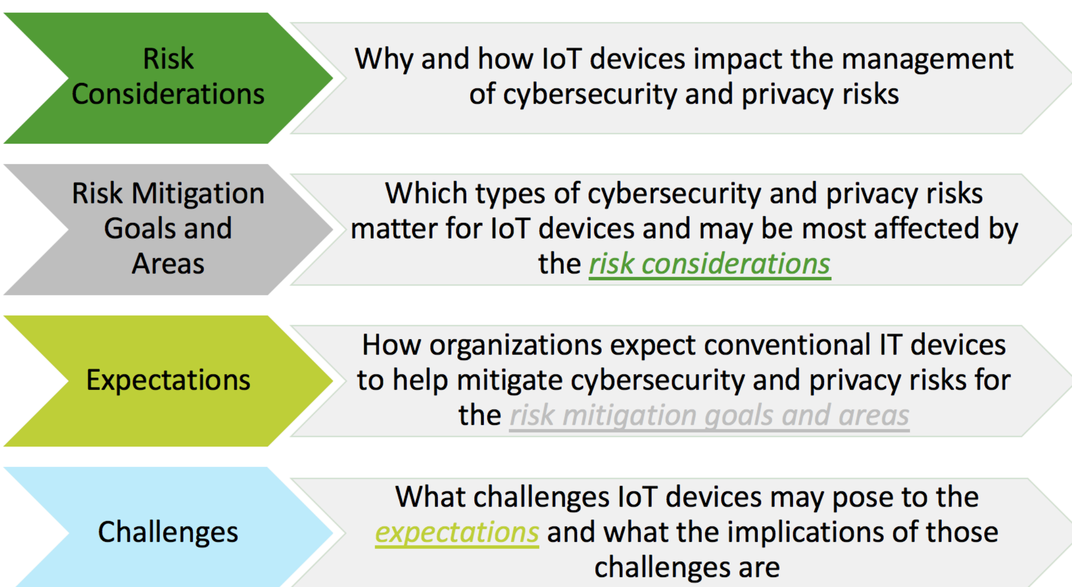
This publication identifies three high-level considerations that may affect the management of cybersecurity and privacy risks for IoT devices as compared to conventional IT devices:

1. **Many IoT devices interact with the physical world in ways conventional IT devices usually do not.** The potential impact of some IoT devices making changes to physical systems and thus affecting the physical world needs to be explicitly recognized and addressed from cybersecurity and privacy perspectives. Also, operational requirements for performance, reliability, resilience, and safety may be at odds with common cybersecurity and privacy practices for conventional IT devices.
2. **Many IoT devices cannot be accessed, managed, or monitored in the same ways conventional IT devices can.** This can necessitate doing tasks manually for large numbers of IoT devices, expanding staff knowledge and tools to include a much wider variety of IoT device software, and addressing risks with manufacturers and other third parties having remote access or control over IoT devices.
3. **The availability, efficiency, and effectiveness of cybersecurity and privacy capabilities are often different for IoT devices than conventional IT devices.** This means organizations may have to select, implement, and manage additional controls, as well as determine how to respond to risk when sufficient controls for mitigating risk are not available.

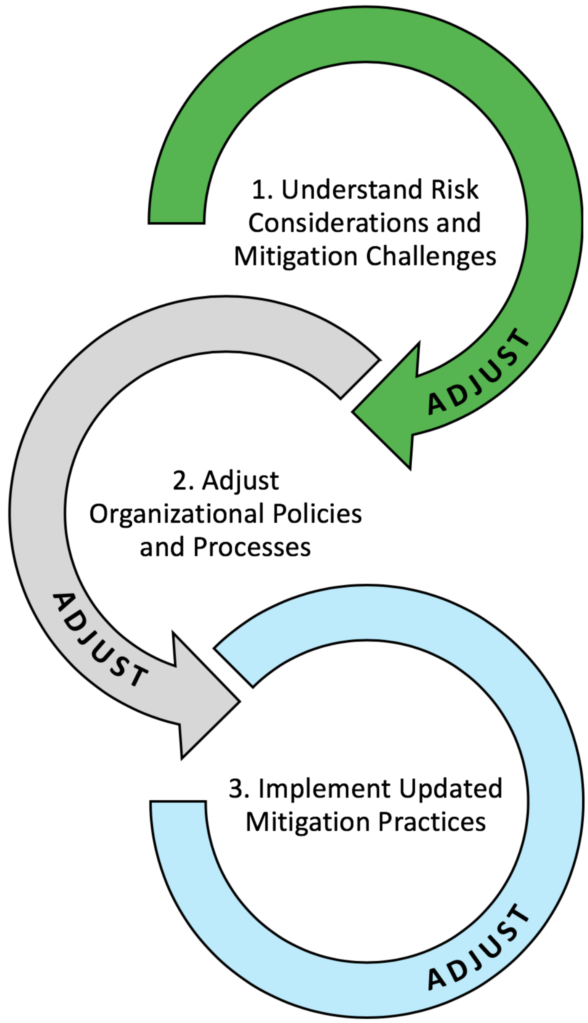
Cybersecurity and privacy risks for IoT devices can be thought of in terms of three high-level risk mitigation goals:

1. **Protect device security**. In other words, prevent a device from being used to conduct attacks, including participating in distributed denial of service (DDoS) attacks against other organizations, and eavesdropping on network traffic or compromising other devices on the same network segment. This goal applies to all IoT devices.
2. **Protect data security.** Protect the confidentiality, integrity, and/or availability of data (including personally identifiable information [PII]) collected by, stored on, processed by, or transmitted to or from the IoT device. This goal applies to each IoT device with one or more data capabilities unless it is determined that none of the device's data needs its security protected.
3. **Protect individuals' privacy.** Protect individuals' privacy impacted by PII processing beyond risks managed through device and data security protection. This goal applies to all IoT devices that process PII or directly impact individuals.

Meeting each of the risk mitigation goals involves addressing a set of risk mitigation areas. Each risk mitigation area defines an aspect of cybersecurity or privacy risk mitigation thought to be most significantly or unexpectedly affected for IoT by the risk considerations. For each risk mitigation area, there are one or more expectations organizations usually have for how conventional IT devices help mitigate cybersecurity and privacy risks for the area. Finally, there are one or more challenges that IoT devices may pose to each expectation. The end result of these linkages is the identification of a structured set of potential challenges with mitigating cybersecurity and privacy risk for IoT devices that can each be traced back to the relevant risk considerations.



Organizations should ensure they are addressing the cybersecurity and privacy risk considerations and challenges throughout the IoT device lifecycle for the appropriate risk mitigation goals and areas. This publication provides the following recommendations for accomplishing this:



1. Understand the IoT device risk considerations and the challenges they may cause to mitigating cybersecurity and privacy risks for IoT devices in the appropriate risk mitigation areas.
2. Adjust organizational policies and processes to address the cybersecurity and privacy risk mitigation challenges throughout the IoT device lifecycle. This publication cites many examples of possible challenges, but each organization will need to customize these to take into account mission requirements and other organization-specific characteristics.
3. Implement updated mitigation practices for the organization's IoT devices as you would any other changes to practices.

There has been a great deal of interest from many organizations in establishing cybersecurity and privacy baselines[2] to aid with IoT device risk mitigation. NIST analysis of existing standards and guidelines for IoT device cybersecurity and privacy has determined the following:

1. Most efforts have focused on specifying pre-market cybersecurity and privacy capabilities—the capabilities manufacturers should build into their IoT devices. Although these efforts are important and helpful, organizations are already using many IoT devices without these capabilities, and it will take time for manufacturers to improve pre-market capabilities for future devices, if that can be done without making them too costly.
2. Some efforts have assumed that organizations will only want to use pre-market capabilities. Organizations acquiring IoT devices may want to use pre-market

[2] The term "baseline" has different meanings to different people and organizations. Some want flexible general recommendations; some want specific, prescriptive guidance; and the rest want something in between. In this publication, "baseline" is used in the generic sense of a set of requirements or recommendations. It should not be confused with the low, moderate, and high control security baselines set forth in NIST SP 800-53 to help federal agencies meet their obligations under FISMA and other federal policies.

capabilities, post-market capabilities (capabilities added by the organization after device acquisition), or a combination of these for a variety of reasons.

3. For some IoT devices, only the security of the device itself needs protected. Other IoT devices might need data security protected in addition to device security, and a subset of those devices might also need privacy protected in ways that data security protection cannot. Existing efforts have not distinguished requirements and recommendations in this way, leaving organizations to determine which ones apply to any particular IoT device implementation and usage.

Because IoT devices and their uses and needs are so varied, few recommendations can be made that apply to all IoT devices; Appendix A provides examples of possible universal recommendations. More specific and actionable recommendations can be made for particular types of IoT devices in specific use cases.

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1 Introduction

1.1 Purpose and Scope

The purpose of this publication is to help organizations better understand and manage the cybersecurity and privacy risks associated with Internet of Things (IoT) devices throughout their lifecycles. This publication emphasizes what makes managing these risks different for IoT devices than conventional information technology (IT) devices, and it omits all aspects of risk management that are largely the same for IoT and conventional IT.

The publication provides insights to inform organizations' risk management processes. After reading this document, an organization should be able to improve the quality of its risk assessments for IoT devices and its response to the identified risk through the lens of cybersecurity and privacy.

For some IoT devices, additional types of risks, including safety, reliability, and resiliency, need to be managed simultaneously with cybersecurity and privacy risks because of the effects addressing one type of risk can have on others. Only cybersecurity and privacy risks are in scope for this publication. Readers who are particularly interested in better understanding other types of risks and their relationship to cybersecurity and privacy may benefit from reading NIST Special Publication (SP) 800-82 Revision 2, *Guide to Industrial Control Systems (ICS) Security*, which provides an operational technology (OT) perspective on cybersecurity and privacy. [3]

Readers do not need a technical understanding of IoT device composition and capabilities, but a basic understanding of cybersecurity and privacy principles is expected.

1.2 Publication Structure

The remainder of this publication is organized into the following major sections and appendices:

- Section 2 defines capabilities IoT devices can provide that are of primary interest in terms of potentially affecting cybersecurity and privacy risk.
- Section 3 describes considerations that may affect the management of cybersecurity and privacy risks for IoT devices.
- Section 4 explores how the risk considerations may affect mitigating cybersecurity and privacy risk for IoT devices. The section lists expectations for how these risks are mitigated in conventional IT environments, then explains how IoT presents challenges to those expectations and what the potential implications of those challenges are.
- Section 5 provides recommendations for organizations on how to address the cybersecurity and privacy risk mitigation challenges for their IoT devices.
- Appendix A provides examples of possible cybersecurity and privacy capabilities that organizations may want their IoT devices to have.
- Appendix B provides an acronym and abbreviation list.
- Appendix C contains a glossary of selected terms used in the publication.
- Appendix D lists the references for the publication.

Figure 1 provides a roadmap depicting the topics covered in each section and subsection of the publication.

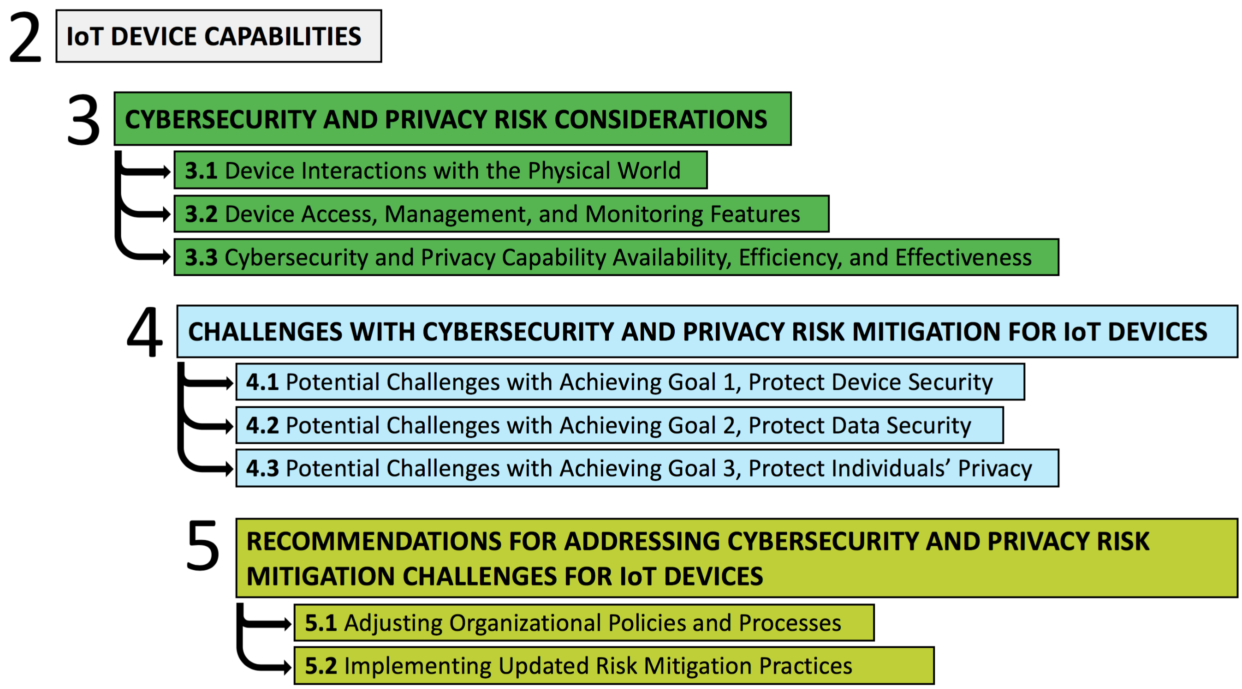

Figure 1: Publication Roadmap

2 IoT Device Capabilities

Each IoT device provides one or more *capabilities*—features or functions—it can use on its own or in conjunction with other IoT and non-IoT devices to achieve one or more goals. This publication references the following types of capabilities IoT devices can provide that are of primary interest in terms of potentially affecting cybersecurity and privacy risk. This is not a comprehensive list of all possible IoT device capabilities.

- *Transducer capabilities* interact with the physical world and serve as the edge between digital and physical environments. Transducer capabilities provide the ability for computing devices to interact directly with physical entities of interest. Every IoT device has at least one transducer capability. The two types of transducer capabilities are:
  - *Sensing*: the ability to provide an observation of an aspect of the physical world in the form of measurement data. Examples include temperature measurement, computerized tomography scans (radiographic imaging), optical sensing, and audio sensing.
  - *Actuating*: the ability to change something in the physical world. Examples of actuating capabilities include heating coils, cardiac electric shock delivery, electronic door locks, unmanned aerial vehicle operation, servo motors, and robotic arms.
- *Data capabilities* are typical digital computing functions involving data: *data storing* and *data processing*.
- *Interface capabilities* enable device interactions (e.g., device-to-device communications, human-to-device communications). The types of interface capabilities are:
  - *Application interface*: the ability for other computing devices to communicate with an IoT device through an IoT device application. An example of an application interface capability is an application programming interface (API).
  - *Human user interface*: the ability for an IoT device and people to communicate directly with each other. Examples of human user interface capabilities include keyboards, mice, microphones, cameras, scanners, monitors, touch screens, touchpads, speakers, and haptic devices.
  - *Network interface*: the ability to interface with a communication network for the purpose of communicating data to or from an IoT device—in other words, to use a communication network. A network interface capability includes both hardware and software (e.g., a network interface card and the software implementation of the networking protocol that uses the card). Examples of network interface capabilities include Ethernet, Wi-Fi, Bluetooth, Long-Term Evolution (LTE), and ZigBee. Every IoT device has at least one enabled network interface capability and may have more than one.
- *Supporting capabilities* provide functionality that supports the other IoT capabilities. Examples are device management, cybersecurity, and privacy capabilities. [2]

Figure 2 summarizes these IoT device capabilities.

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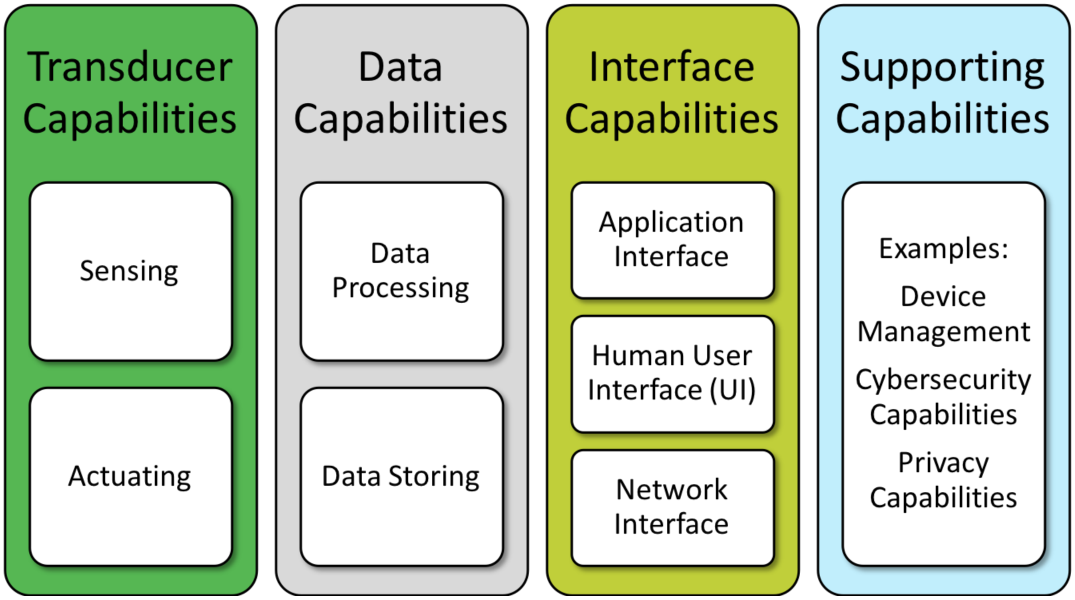

403 **Figure 2: IoT Device Capabilities Potentially Affecting Cybersecurity and Privacy Risk**

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3 Cybersecurity and Privacy Risk Considerations

Cybersecurity risk and privacy risk are related but distinct concepts. *Risk* is defined in draft NIST Special Publication (SP) 800-37 Revision 2 as "a measure of the extent to which an entity is threatened by a potential circumstance or event, and typically is a function of: (i) the adverse impact, or magnitude of harm, that would arise if the circumstance or event occurs; and (ii) the likelihood of occurrence." [4] For cybersecurity, risk is about threats—the exploitation of vulnerabilities by threat actors to compromise device or data confidentiality, integrity, or availability. For privacy, risk is about *problematic data actions*—operations that process personally identifiable information (PII) through the information lifecycle to meet mission or business needs of an organization or "authorized" PII processing and, as a side effect, cause individuals to experience some type of problem(s). As Figure 3 depicts, privacy and cybersecurity risk overlap with respect to concerns about the cybersecurity of PII, but there are also privacy concerns without implications for cybersecurity, and cybersecurity concerns without implications for privacy. [5]

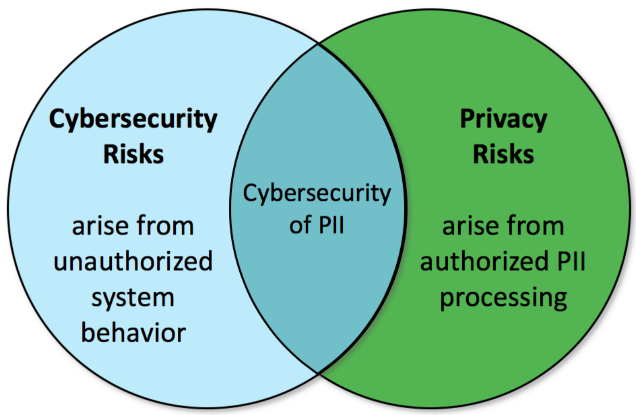

Figure 3: Relationship Between Cybersecurity and Privacy Risks

IoT devices generally face the same types of cybersecurity and privacy risks as conventional IT devices, though the prevalence and severity of such risks often differ. For example, data security risks are almost always a significant concern for conventional IT devices, but for some IoT devices, there may not be data security risks because the devices lack data capabilities.

This section defines three risk considerations that may affect the management of cybersecurity and privacy risks for IoT devices. Organizations should ensure they are addressing these risk considerations throughout the IoT device lifecycle for their IoT devices. Section 4 provides more information on how the risk considerations may affect risk mitigation, and Section 5 provides recommendations for organizations on how to address the risk mitigation challenges.

3.1 Consideration 1: Device Interactions with the Physical World

Many IoT devices interact with the physical world in ways conventional IT devices usually do not.

The interactions with the physical world that IoT devices enable may affect cybersecurity and privacy risks in several ways. Here are examples:

- IoT sensor data, representing measurements of the physical world, always has uncertainties associated with it. Effective management of IoT sensor data, including understanding uncertainties, is necessary to assess data quality and meaning so the organization can make decisions regarding the data's use and avoid introducing new risks. Without this, error rates may be unknown for the different contexts in which an IoT device might be used.
- The ubiquity of IoT sensors in public and private environments can contribute to the aggregation and analysis of enormous amounts of data about individuals. These activities can be used to influence individuals' behavior or decision-making in ways they do not understand, or lead to information being revealed that individuals did not want revealed, including the re-identification of previously de-identified PII—and may be beyond the originally intended scope of the IoT device's operation.
- IoT devices with actuators have the ability to make changes to physical systems and thus affect the physical world. The potential impact of this needs to be explicitly recognized and addressed from cybersecurity and privacy perspectives. In a worst-case scenario, a compromise could allow an attacker to use an IoT device to endanger human safety, damage or destroy equipment and facilities, or cause major operational disruptions. Privacy concerns and related civil liberties concerns could arise through authorized changes to physical systems that could impact individuals' physical autonomy or behavior in personal and public spaces. For example, law enforcement or other authorized third parties could take control of automated vehicles with individuals inside, or environmental controls such as lighting or temperature could be used to influence individuals' movement in buildings.
- IoT network interfaces often enable remote access to physical systems that previously could only be accessed locally. Manufacturers, vendors, and other third parties may be able to use remote access to IoT devices for management, monitoring, maintenance, and troubleshooting purposes. This may put the physical systems accessible through the IoT devices at much greater risk of compromise. Further, these decentralized data processing functions can exacerbate many privacy risks, making it harder for individuals to develop reliable assumptions about what is happening with the system to be able to participate in decision making about the processing of their information and their interactions with the systems.

Another important aspect of IoT device interactions with the physical world is the operational requirements devices must meet in various environments and use cases. Many IoT devices must comply with stringent requirements for performance, reliability, resilience, safety, and other objectives. These requirements may be at odds with common cybersecurity and privacy practices for conventional IT. For example, practices such as automatic patching are generally considered essential for conventional IT, but these practices could have far greater negative impacts on some IoT devices with actuators, making critical services unavailable and endangering human safety. An organization might reasonably decide that patches should be installed at a date and time chosen by the organization with the appropriate staff onsite and ready to react immediately if a problem occurs. An organization might also reasonably decide to avoid patching certain IoT devices under normal circumstances and instead tightly restrict logical and physical access to them to prevent exploitation of unpatched vulnerabilities.

Another way to think of this is in terms of general cybersecurity objectives: confidentiality, integrity, and availability. For conventional IT devices, confidentiality often receives the most attention because of the value of data and the consequences of a breach of confidentiality. For many IoT devices, availability and integrity are more important than confidentiality because of the potential impact to the physical world. Imagine an IoT device that is critical for preventing damage to a facility. An attacker who can view the IoT device's stored or transmitted data might not gain any advantage or value from it, but an attacker who can alter the data might trigger a series of events that cause an incident.

3.2 Consideration 2: Device Access, Management, and Monitoring Features

Many IoT devices cannot be accessed, managed, or monitored in the same ways conventional IT devices can.

Conventional IT devices usually provide authorized people, processes, and devices with hardware and software access, management, and monitoring features. In other words, an authorized administrator, process, or device can directly access a conventional IT device's firmware, operating system, and applications, fully manage the device and its software throughout the device's lifecycle as needed, and monitor the internal characteristics and state of the device at all times. Authorized users can also access a restricted subset of the access, management, and monitoring features.

In contrast, many IoT devices are opaque, often referred to as "black boxes." They provide little or no visibility into their state and composition, including the identity of any external services and systems they interact with, and little or no access to and management of their software and configuration. The organization may not know what capabilities an IoT device can provide or is currently providing. In extreme cases, it may be difficult to determine if a black box product is actually an IoT device because of the lack of transparency.

Authorized people, processes, and devices may encounter one or more of the following challenges in accessing, managing, and monitoring IoT devices that affect cybersecurity and privacy risk:

- **Lack of management features.** Administrators may not be able to fully manage an IoT device's firmware, operating system, and applications throughout the IoT device's lifecycle. Unavailable features may include the ability to acquire, verify the integrity of, install, configure, store, retrieve, execute, terminate, remove, and replace, update, and patch software. In addition, an IoT device's software may be automatically reconfigured when an adverse event occurs, such as a power failure or a loss of network connectivity.
- **Lack of interfaces.** Some IoT devices lack application and/or human user interfaces for device use and management. When such interfaces do exist, they may not provide the functionality usually offered by conventional IT devices. An example is the challenge in notifying users about an IoT device's processing of their PII so they can provide meaningful consent to this processing. An additional issue is the lack of universally

accepted standards for IoT application interfaces, including expressing and formatting data, issuing commands, and otherwise fostering interoperability between IoT devices.

- **Difficulties with management at scale.** Most IoT devices do not support standardized mechanisms for centralized management, and the sheer number of IoT devices to be managed may be overwhelming.
- **Wide variety of software to manage.** There is extensive variety in the software used by IoT devices, including firmware, standard and real-time operating systems, and applications. This significantly complicates software management throughout the IoT device lifecycle, affecting such areas as configuration and patch management.
- **Differing lifespan expectations.** A manufacturer may intend for a particular IoT device to only be used for a few years and then discarded. An organization purchasing that device might want to use it for a longer time, but the manufacturer may stop supporting the device (e.g., releasing patches for known vulnerabilities) either by choice or because of supply chain limitations (e.g., supplier no longer releases patches for a particular IoT device component). The problem of differing lifespan expectations is not new and is not specific to IoT, but it may be particularly important for some IoT devices because of the safety, reliability, and other risks potentially involved in using devices past their intended lifespan.
- **Unserviceable hardware.** IoT device hardware may not be serviceable, meaning it cannot be repaired, customized, or inspected internally.
- **Lack of inventory capabilities.** IoT devices brought into an organization may not be inventoried, registered, and otherwise provisioned via the normal IT processes. This is especially true for types of devices that did not previously have networking capabilities.
- **Heterogeneous ownership.** There is often heterogeneous ownership of IoT devices. For example, an IoT device may transfer data to manufacturer-provided cloud-based service processing and storage because the IoT device lacks these processing and storage capabilities. Data may also be sent to a cloud service to aggregate data from multiple IoT devices in a single location. These cloud services may have access to portions or all of the devices’ data, or even access to and control of the devices themselves for monitoring, maintenance, and troubleshooting purposes. In some cases, only manufacturers have the authority to do maintenance; an organization attempting to install patches or do other maintenance tasks on an IoT device may void the warranty. Also, in IoT there may be little or no information available about device ownership, especially in black box IoT devices. This could exacerbate existing privacy redress difficulties because the lack of accountability limits individuals’ abilities to locate the source of and correct or delete information about themselves, or to address other problems. Another concern with heterogeneous ownership is the effect on device re-provisioning—what data may still be available after transferring control of a device.

3.3 Consideration 3: Cybersecurity and Privacy Capability Availability, Efficiency, and Effectiveness

The availability, efficiency, and effectiveness of cybersecurity and privacy capabilities are often different for IoT devices than conventional IT devices.

For the purposes of this publication, built-in cybersecurity and privacy capabilities are called *pre-market capabilities*. Pre-market capabilities are integrated into IoT devices by the manufacturer or vendor before they are shipped to customer organizations. *Post-market capabilities* are those capabilities that organizations select, acquire, and deploy themselves in addition to pre-market capabilities. Pre-market and post-market cybersecurity and privacy capabilities are often different for IoT devices than conventional IT. The main reasons for this are:

- Many IoT devices do not or cannot support the range of cybersecurity and privacy capabilities typically built into conventional IT devices. For example, a "black box" IoT device may not log its cybersecurity and privacy events or may not give organizations access to its logs. If pre-market capabilities are available for IoT devices, they may be inadequate in terms of strength or performance—e.g., using strong encryption and mutual authentication to protect communications may cause unacceptable delays.[3] Post-market capabilities cannot be installed onto many IoT devices. Also, existing pre-market and post-market capabilities may not be able to scale to meet the needs of IoT—for example, an existing network-based cybersecurity appliance for conventional IT devices may not be able to also process the volume of network traffic and generated data from a large number of IoT devices.
- The level of effort needed to manage, monitor, and maintain pre-market capabilities on each IoT device may be excessive. Especially when IoT devices do not support centralized management, it may be more efficient to implement and use centralized post-market capabilities that help protect numerous IoT devices instead of trying to achieve the equivalent level of protection on each individual IoT device. One example is having a single network-based IoT gateway or IoT security gateway protecting many IoT devices instead of having to design, manage, and maintain a unique set of protection capabilities within each IoT device.
- Some post-market capabilities for conventional IT, such as network-based intrusion prevention systems, antimalware servers, and firewalls, may not be as effective at protecting IoT devices as they are at protecting conventional IT. IoT devices often use protocols that cybersecurity and privacy controls for conventional IT cannot understand and analyze. Also, IoT devices may communicate directly with each other, such as through point-to-point wireless communication, instead of using a monitored infrastructure network.

An IoT device may not need some of the cybersecurity and privacy capabilities conventional IT devices rely on—an example is an IoT device without data storage capabilities not needing to protect data at rest. An IoT device may also need additional capabilities that most conventional IT devices do not use, especially if the IoT device enables new interactions with the physical world.

[3] For more information on low-resource computing devices, see Internet Engineering Task Force (IETF) Request for Comments (RFC) 7228, "Terminology for Constrained-Node Networks," May 2014 (https://doi.org/10.17487/RFC7228).

4 Challenges with Cybersecurity and Privacy Risk Mitigation for IoT Devices

Cybersecurity and privacy risks for IoT devices can be thought of in terms of three high-level *risk mitigation goals*, as shown in Figure 4:

1. **Protect device security**. In other words, prevent a device from being used to conduct attacks, including participating in distributed denial of service (DDoS) attacks against other organizations, and eavesdropping on network traffic or compromising other devices on the same network segment. This goal applies to all IoT devices.
2. **Protect data security.** Protect the confidentiality, integrity, and/or availability of data (including PII) collected by, stored on, processed by, or transmitted to or from the IoT device. This goal applies to each IoT device with one or more data capabilities unless it is determined that none of the device's data needs its security protected.
3. **Protect individuals' privacy.** Protect individuals' privacy impacted by PII processing beyond risks managed through device and data security protection. This goal applies to all IoT devices that process PII or directly impact individuals.

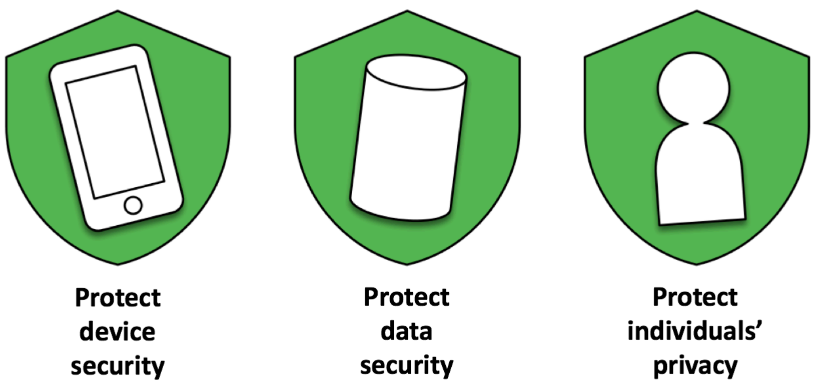

Figure 4: Risk Mitigation Goals

Meeting each of the risk mitigation goals involves addressing a set of *risk mitigation areas*, which are defined below. Each risk mitigation area defines an aspect of cybersecurity or privacy risk mitigation thought to be most significantly or unexpectedly affected for IoT by the risk considerations defined in Section 3.

Risk mitigation areas for Goal 1, Protect Device Security:

- **Asset Management:** Maintain a current, accurate inventory of all IoT devices and their relevant characteristics throughout the devices' lifecycles in order to use that information for cybersecurity and privacy risk management purposes.
- **Vulnerability Management:** Identify and eliminate known vulnerabilities in IoT device software and firmware in order to reduce the likelihood and ease of exploitation and compromise.
- **Access Management:** Prevent unauthorized and improper physical and logical access to, usage of, and administration of IoT devices by people, processes, and other computing devices.

- **Device Security Incident Detection:** Monitor and analyze IoT device activity for signs of incidents involving device security.

Risk mitigation areas for Goal 2, Protect Data Security:

- **Data Protection:** Prevent access to and tampering with data at rest or in transit that might expose sensitive information or allow manipulation or disruption of IoT device operations.
- **Data Security Incident Detection:** Monitor and analyze IoT device activity for signs of incidents involving data security.

Risk mitigation areas for Goal 3, Protect Individuals' Privacy:

- **Information Flow Management:** Maintain a current, accurate mapping of the information lifecycle of PII, including the type of data action, the elements of PII being processed by the data action, the party doing the processing, and any additional relevant contextual factors about the processing to use for privacy risk management purposes.
- **PII Processing Permissions Management:** Maintain permissions for PII processing to prevent unpermitted PII processing.
- **Informed Decision Making:** Enable individuals to understand the effects of PII processing and interactions with the device, participate in decision-making about the PII processing or interactions, and resolve problems.
- **Disassociated Data Management:** Identify authorized PII processing and determine how PII may be minimized or disassociated from individuals and IoT devices.
- **Privacy Breach Detection:** Monitor and analyze IoT device activity for signs of breaches involving individuals' privacy.

Sections 4.1, 4.2, and 4.3 examine how the risk considerations introduce challenges with meeting each of the three risk mitigation goals for an organization's IoT devices—in other words, how mitigation may differ for IoT versus conventional IT. Section 5 provides recommendations on how organizations should address these challenges.

4.1 Potential Challenges with Achieving Goal 1, Protect Device Security

Table 1 lists common expectations for the pre-market capabilities of conventional IT devices that are often used to help mitigate their device security risk. Although these expectations are not always true for conventional IT devices, they are usually true and have greatly influenced common device security practices for conventional IT devices. For each expectation, Table 1 defines one or more potential challenges individual IoT devices may pose to the expectation. Each challenge has its own row in the table:

- First column: a brief statement of the challenge, with each challenge uniquely numbered to make it easy to reference, and the numbers of the risk considerations from Section 3 that cause the challenge

- Second column: examples of draft NIST SP 800-53 Revision 5 [7] controls that might be negatively affected for some individual IoT devices[4]
- Third column: the potential implications for the organization if a substantial number of IoT devices are affected by the challenge
- Fourth column: examples of Cybersecurity Framework Subcategories [6] that might be negatively affected by the implications

Figure 5 shows the relationships among the Section 3 and Section 4 concepts. Section 3 defines the three risk considerations, which explain why and how IoT devices impact the management of cybersecurity and privacy risks. Next, the Section 4 introduction defines the risk mitigation goals and areas, which specify which types of cybersecurity and privacy risks matter for IoT devices and may be most affected by the risk considerations. The rest of Section 4 lists expectations, which are how organizations expect conventional IT devices to help mitigate cybersecurity and privacy risks for the risk mitigation goals and areas, and the challenges IoT devices may pose to those expectations, along with the implications of those challenges. The end result of these linkages is the identification of a structured set of potential challenges for mitigating cybersecurity and privacy risk for IoT devices that can each be traced back to the relevant risk considerations.

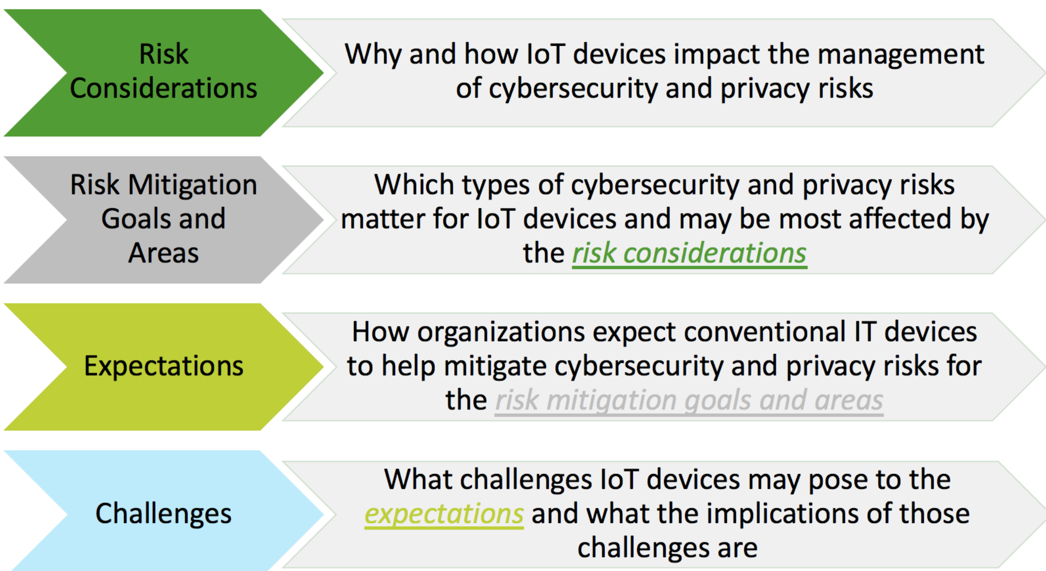

Figure 5: Relationships Among Section 3 and Section 4 Concepts

The tables in this section do not define or imply equivalence between the NIST SP 800-53 controls and the Cybersecurity Framework Subcategories in each row. In many cases, a challenge affects just parts of one or more SP 800-53 controls, the implications of that challenge affect just parts of one or more Cybersecurity Framework Subcategories, and the two sets of parts are not equivalent.

[4] These examples will be updated as needed once draft NIST SP 800-53 Revision 5 is finalized.

Table 1: Potential Challenges with Achieving Goal 1, Protect Device Security

Challenges for Individual IoT Devices, and Risk Considerations Causing the Challenges	Affected Draft NIST SP 800-53 Revision 5 Controls	Implications for the Organization	Affected Cybersecurity Framework Subcategories
Asset Management			
Expectation 1: The device has a built-in unique identifier.			
1. The IoT device may not have a unique identifier that the organization's asset management system can access or understand. Risk Consideration 2	• CM-8, System Component Inventory	• May complicate device management, including remote access and vulnerability management.	• ID.AM-1: Physical devices and systems within the organization are inventoried
Expectation 2: The device can interface with enterprise asset management systems.			
2. The IoT device may not be able to participate in a centralized asset management system. Risk Consideration 2	• CM-8, System Component Inventory	• May have to use multiple asset management systems. • May have to perform asset management tasks manually.	• ID.AM-1: Physical devices and systems within the organization are inventoried • ID.AM-2: Software platforms and applications within the organization are inventoried • PR.DS-3: Assets are formally managed throughout removal, transfers, and disposition
3. The IoT device may not be directly connected to any of the organization's networks. Risk Consideration 2	• CM-8, System Component Inventory	• May have to use a separate asset management system or service, or manual asset management processes, for external IoT devices.	• ID.AM-1: Physical devices and systems within the organization are inventoried • ID.AM-2: Software platforms and applications within the organization are inventoried • PR.DS-3: Assets are formally managed throughout removal, transfers, and disposition
Expectation 3: The device can provide the organization sufficient visibility into its characteristics.			
4. The IoT device may be a black box that provides little or no information on its hardware, software, and firmware. Risk Consideration 2	• CM-8, System Component Inventory	• May complicate all aspects of device management and risk management.	• ID.AM-1: Physical devices and systems within the organization are inventoried • ID.AM-2: Software platforms and applications within the organization are inventoried • ID.AM-4: External information systems are catalogued

Challenges for Individual IoT Devices, and Risk Considerations Causing the Challenges	Affected Draft NIST SP 800-53 Revision 5 Controls	Implications for the Organization	Affected Cybersecurity Framework Subcategories
Expectation 4: The device or the device's manufacturer can inform the organization of all external software and services the device uses, such as software running on or dynamically downloaded from the cloud.			
5. Not all of the IoT device's external dependencies may be revealed. Risk Consideration 2	• AC-20, Use of External Systems	• Cannot manage risk for the external software and services.	• DE.CM-8: Vulnerability scans are performed • PR.IP-1: A baseline configuration of information technology/industrial control systems is created and maintained incorporating security principles (e.g. concept of least functionality) • PR.PT-3: The principle of least functionality is incorporated by configuring systems to provide only essential capabilities
Vulnerability Management			
Expectation 5: The manufacturer will provide patches or upgrades for all software and firmware throughout each device's lifespan.			
6. The manufacturer may not release patches or upgrades for the IoT device. Risk Consideration 3	• SI-2, Flaw Remediation	• Cannot remove known vulnerabilities.	• PR.IP-1: A baseline configuration of information technology/industrial control systems is created and maintained incorporating security principles (e.g. concept of least functionality)
7. The manufacturer may stop releasing patches and upgrades for the IoT device while it is still in use. Risk Consideration 3	• SI-2, Flaw Remediation	• May not be able to remove known vulnerabilities in the future.	• PR.IP-1: A baseline configuration of information technology/industrial control systems is created and maintained incorporating security principles (e.g. concept of least functionality)
Expectation 6: The device either has its own secure built-in patch, upgrade, and configuration management capabilities, or can interface with enterprise vulnerability management systems with such capabilities.			
8. The IoT device may not be capable of having its software patched or upgraded. Risk Considerations 2 and 3	• SI-2, Flaw Remediation	• Cannot remove known vulnerabilities.	• PR.IP-1: A baseline configuration of information technology/industrial control systems is created and maintained incorporating security principles (e.g. concept of least functionality)

Challenges for Individual IoT Devices, and Risk Considerations Causing the Challenges	Affected Draft NIST SP 800-53 Revision 5 Controls	Implications for the Organization	Affected Cybersecurity Framework Subcategories
9. It may be too risky to install patches or upgrades or to make configuration changes without extensive testing and preparation first, and implementing changes may require operational outages or inadvertently cause outages. Risk Consideration 1	• CM-3, Configuration Change Control • CM-6, Configuration Settings • SI-2, Flaw Remediation	• May be significant delays in removing known vulnerabilities.	• PR.IP-1: A baseline configuration of information technology/industrial control systems is created and maintained incorporating security principles (e.g. concept of least functionality)
10. The IoT device may not be able to participate in a centralized vulnerability management system. Risk Consideration 2	• CM-3, Configuration Change Control • SI-2, Flaw Remediation	• May have to use numerous vulnerability management systems instead of one. • May have to perform vulnerability management tasks manually and periodically (e.g., manually install patches, manually check for software configuration errors).	• PR.IP-1: A baseline configuration of information technology/industrial control systems is created and maintained incorporating security principles (e.g. concept of least functionality)
11. The IoT device may not offer the ability to change the software configuration or may not offer the features organizations want. Risk Consideration 2	• CM-2, Baseline Configuration • CM-3, Configuration Change Control • CM-6, Configuration Settings • CM-7, Least Functionality • SC-42, Sensor Capability and Data	• Cannot remove known vulnerabilities. • Cannot achieve the principle of least functionality by disabling unneeded services, functions. • Cannot restrict sensor activation and usage.	• PR.IP-1: A baseline configuration of information technology/industrial control systems is created and maintained incorporating security principles (e.g. concept of least functionality) • PR.IP-3: Configuration change control processes are in place • PR.PT-3: The principle of least functionality is incorporated by configuring systems to provide only essential capabilities
Expectation 7: The device either supports the use of vulnerability scanners or provides built-in vulnerability identification and reporting capabilities.			
12. There may not be a vulnerability scanner that can run on or against the IoT device. Risk Consideration 3	• RA-5, Vulnerability Scanning	• Cannot automatically identify known vulnerabilities.	• DE.CM-8: Vulnerability scans are performed

Challenges for Individual IoT Devices, and Risk Considerations Causing the Challenges	Affected Draft NIST SP 800-53 Revision 5 Controls	Implications for the Organization	Affected Cybersecurity Framework Subcategories
13. The IoT device may not offer any built-in capabilities to identify and report on known vulnerabilities. Risk Consideration 3	• RA-5, Vulnerability Scanning	• Cannot automatically identify known vulnerabilities.	• DE.CM-8: Vulnerability scans are performed
Access Management			
Expectation 8: The device can uniquely identify each user, device, and process attempting to logically access it.			
14. The IoT device may not support any use of identifiers. Risk Considerations 2 and 3	• IA-2, Identification and Authentication (Organizational Users) • IA-3, Device Identification and Authentication • IA-4, Identifier Management • IA-8, Identification and Authentication (Non-Organizational Users) • IA-9, Service Identification and Authentication	• Cannot identify or authenticate users, devices, and processes.	• PR.AC-1: Identities and credentials are issued, managed, verified, revoked, and audited for authorized devices, users and processes • PR.AC-7: Users, devices, and other assets are authenticated (e.g., single-factor, multi-factor) commensurate with the risk of the transaction (e.g., individuals' security and privacy risks and other organizational risks)
15. The IoT device may only support the use of one or more shared identifiers. Risk Considerations 2 and 3	• IA-2, Identification and Authentication (Organizational Users) • IA-3, Device Identification and Authentication • IA-4, Identifier Management • IA-8, Identification and Authentication (Non-Organizational Users) • IA-9, Service Identification and Authentication	• Cannot uniquely identify users, devices, and processes. Complicates credential management because of shared credentials.	• PR.AC-1: Identities and credentials are issued, managed, verified, revoked, and audited for authorized devices, users and processes
16. The IoT device may require the use of identifiers but only in certain cases (for example, for remote access but not local access, or for administration purposes but not regular usage). Risk Considerations 2 and 3	• IA-2, Identification and Authentication (Organizational Users) • IA-3, Device Identification and Authentication • IA-4, Identifier Management • IA-8, Identification and Authentication (Non-Organizational Users) • IA-9, Service Identification and Authentication	• Cannot identify or authenticate some users, devices, and processes.	• PR.AC-1: Identities and credentials are issued, managed, verified, revoked, and audited for authorized devices, users and processes • PR.AC-7: Users, devices, and other assets are authenticated (e.g., single-factor, multi-factor) commensurate with the risk of the transaction (e.g., individuals' security and privacy risks and other organizational risks)

Challenges for Individual IoT Devices, and Risk Considerations Causing the Challenges	Affected Draft NIST SP 800-53 Revision 5 Controls	Implications for the Organization	Affected Cybersecurity Framework Subcategories
Expectation 9: The device can conceal password characters from display when a person enters a password for a device, such as on a keyboard or touch screen.			
17. The IoT device may not support concealment of displayed password characters. Risk Considerations 2 and 3	• IA-6, Authenticator Feedback	• Increases the likelihood of credential theft.	• PR.AC-7: Users, devices, and other assets are authenticated (e.g., single-factor, multi-factor) commensurate with the risk of the transaction (e.g., individuals' security and privacy risks and other organizational risks)
Expectation 10: The device can authenticate each user, device, and process attempting to logically access it.			
18. The IoT device may not support use of non-trivial credentials (e.g., does not support the use of identifiers, does not allow default passwords to be changed). Risk Considerations 2 and 3	• IA-5, Authenticator Management	• Cannot identify or authenticate users, devices, and processes, which increases the chances of unauthorized access.	• PR.AC-7: Users, devices, and other assets are authenticated (e.g., single-factor, multi-factor) commensurate with the risk of the transaction (e.g., individuals' security and privacy risks and other organizational risks)
19. The IoT device may not support the use of strong credentials, such as cryptographic tokens or multifactor authentication, for the situations that merit them. Risk Consideration 3	• IA-5, Authenticator Management	• Increases the chances of unauthorized access through credential misuse.	• PR.AC-7: Users, devices, and other assets are authenticated (e.g., single-factor, multi-factor) commensurate with the risk of the transaction (e.g., individuals' security and privacy risks and other organizational risks)
Expectation 11: The device can use existing enterprise authenticators and authentication mechanisms.			
20. The IoT device may not support the use of an existing enterprise user authentication system. Risk Consideration 3	• IA-2, Identification and Authentication (Organizational Users) • IA-5, Authenticator Management • IA-8, Identification and Authentication (Non-Organizational Users)	• Need one or more additional accounts and credentials for each user.	• PR.AC-1: Identities and credentials are issued, managed, verified, revoked, and audited for authorized devices, users and processes • PR.AC-7: Users, devices, and other assets are authenticated (e.g., single-factor, multi-factor) commensurate with the risk of the transaction (e.g., individuals' security and privacy risks and other organizational risks)

Challenges for Individual IoT Devices, and Risk Considerations Causing the Challenges	Affected Draft NIST SP 800-53 Revision 5 Controls	Implications for the Organization	Affected Cybersecurity Framework Subcategories
Expectation 12: The device can restrict each user, device, and process to the minimum logical access privileges necessary.			
21. The IoT device may not support use of logical access privileges within the device that is sufficient for a given situation. Risk Consideration 3	• AC-3, Access Enforcement • AC-5, Separation of Duties • AC-6, Least Privilege	• Allows authorized users, devices, and processes to intentionally or inadvertently use privileges they should not have. • Allows an attacker who gains unauthorized access to an account to have even greater access than the account should have.	• PR.AC-4: Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties • PR.DS-5: Protections against data leaks are implemented • PR.MA-1: Maintenance and repair of organizational assets are performed and logged, with approved and controlled tools
22. The IoT device may not support use of logical access privileges to restrict network communications into and out of the device that is sufficient for a given situation. Risk Consideration 3	• AC-3, Access Enforcement • AC-4, Information Flow Enforcement • AC-5, Separation of Duties • AC-6, Least Privilege • AC-17, Remote Access • SC-7, Boundary Protection	• Allows authorized users, devices, and processes to intentionally or inadvertently conduct network communications they should not be able to. • Allows an attacker to have greater network access than intended.	• PR.AC-3: Remote access is managed • PR.AC-5: Network integrity is protected (e.g., network segregation, network segmentation) • PR.DS-5: Protections against data leaks are implemented • PR.MA-2: Remote maintenance of organizational assets is approved, logged, and performed in a manner that prevents unauthorized access

Challenges for Individual IoT Devices, and Risk Considerations Causing the Challenges	Affected Draft NIST SP 800-53 Revision 5 Controls	Implications for the Organization	Affected Cybersecurity Framework Subcategories
Expectation 13: The device can thwart attempts to gain unauthorized access, and this feature can be configured or disabled to avoid undesired disruptions to availability. (Examples include locking or disabling an account when there are too many consecutive failed authentication attempts, delaying additional authentication attempts after failed attempts, and locking or terminating idle sessions.)			
23. The IoT device's use of these security features may not be sufficiently modifiable. Risk Considerations 1 and 3	• AC-7, Unsuccessful Logon Attempts • AC-11, Device Lock • AC-12, Session Termination • IA-11, Re-Authentication	• Cannot gain immediate access to IoT devices when needed to use or manage them.	• PR.AC-3: Remote access is managed • PR.AC-4: Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties • PR.MA-1: Maintenance and repair of organizational assets are performed and logged, with approved and controlled tools • PR.MA-2: Remote maintenance of organizational assets is approved, logged, and performed in a manner that prevents unauthorized access
Expectation 14: The device has adequate built-in physical security controls to protect it from tampering (e.g., tamper-resistant packaging).			
24. The IoT device may be deployed in an area where people who are not authorized to access the device may do so or where authorized people can access the device in unauthorized ways. Risk Considerations 1 and 2	• MP-2, Media Access • MP-7, Media Use • PE-3, Physical Access Control	• Allows an attacker to have direct physical access to devices and tamper with them, including adding or removing storage media, connecting peripherals, etc.	• PR.AC-2: Physical access to assets is managed and protected • PR.PT-2: Removable media is protected and its use restricted according to policy • PR.MA-1: Maintenance and repair of organizational assets are performed and logged, with approved and controlled tools
Incident Detection			
Expectation 15: The device can log its operational and security events.			
25. The IoT device may not be able to log its operational and security events at all or in sufficient detail. Risk Consideration 3	• AU-2, Audit Events • AU-3, Content of Audit Records • AU-12, Audit Generation • SI-4, System Monitoring	• Increases the likelihood of malicious activity going undetected. • Cannot confirm and reconstruct incidents from log entries.	• DE.CM-7: Monitoring for unauthorized personnel, connections, devices, and software is performed • PR.PT-1: Audit/log records are determined, documented, implemented, and reviewed in accordance with policy • RS.AN-1: Notifications from detection systems are investigated

Challenges for Individual IoT Devices, and Risk Considerations Causing the Challenges	Affected Draft NIST SP 800-53 Revision 5 Controls	Implications for the Organization	Affected Cybersecurity Framework Subcategories
26. The IoT device may continue operating even when a logging failure occurs. Risk Consideration 3	• AU-5, Response to Audit Processing Failures	• Increased likelihood of malicious activity going undetected.	• DE.CM-7: Monitoring for unauthorized personnel, connections, devices, and software is performed • PR.PT-1: Audit/log records are determined, documented, implemented, and reviewed in accordance with policy
Expectation 16: The device can interface with existing enterprise log management systems.			
27. The IoT device may not be able to participate in an enterprise log management system. Risk Consideration 2	• AU-6, Audit Review, Analysis, and Reporting • SI-4, System Monitoring	• May have to use numerous log management systems instead of one. • May have to perform log management tasks manually. • Increases the likelihood of malicious activity going undetected.	• DE.AE-3: Event data are collected and correlated from multiple sources and sensors • DE.CM-7: Monitoring for unauthorized personnel, connections, devices, and software is performed • PR.PT-1: Audit/log records are determined, documented, implemented, and reviewed in accordance with policy
Expectation 17: The device can facilitate the detection of potential incidents by internal or external controls, such as intrusion prevention systems, anti-malware utilities, and file integrity checking mechanisms.			
28. The IoT device may not be able to execute internal detection controls or interact with external detection controls without adversely affecting device operation. Risk Considerations 1 and 3	• SI-3, Malicious Code Protection • SI-7, Software, Firmware, and Information Integrity	• Increases the likelihood of malicious code infections and other unauthorized activities occurring and going undetected.	• DE.CM-1: The network is monitored to detect potential cybersecurity events • DE.CM-4: Malicious code is detected • PR.DS-6: Integrity checking mechanisms are used to verify software, firmware, and information integrity
29. The IoT device may not provide controls with the visibility needed to detect incidents efficiently and effectively. Risk Considerations 2 and 3	• IR-4, Incident Handling • SI-4, System Monitoring	• Increases the likelihood of malicious code and other unauthorized activities going undetected.	• DE.CM-1: The network is monitored to detect potential cybersecurity events • DE.CM-4: Malicious code is detected • PR.DS-6: Integrity checking mechanisms are used to verify software, firmware, and information integrity

Challenges for Individual IoT Devices, and Risk Considerations Causing the Challenges	Affected Draft NIST SP 800-53 Revision 5 Controls	Implications for the Organization	Affected Cybersecurity Framework Subcategories
Expectation 18: The device can support event and incident analysis activities.			
30. The IoT device may not provide analysts with sufficient access to the device's resources in order to do the necessary analysis. Risk Considerations 2 and 3	• SI-4, System Monitoring	• Cannot use forensic tools for information gathering and analysis.	• RS.AN-1: Notifications from detection systems are investigated • RS.AN-3: Forensics are performed

4.2 Potential Challenges with Achieving Goal 2, Protect Data Security

Table 2 follows the same conventions as Table 1, but for protecting data security. It is assumed that if data security needs to be protected, device security needs protected as well, so the challenges in both tables would need to be considered.

Note that the Incident Detection section of Table 1 is also applicable for protecting data security. Table 1 assumes only device security incidents need to be protected; the same potential challenges, affected controls, implications, and Cybersecurity Framework subcategories also apply to detecting data security incidents. The Incident Detection rows are omitted from Table 2 for brevity.

Table 2: Potential Challenges with Achieving Goal 2, Protect Data Security

Challenges for Individual IoT Devices	Affected Draft NIST SP 800-53 Revision 5 Controls	Implications for the Organization	Affected Cybersecurity Framework Subcategories
Data Protection			
Expectation 19: The device can prevent unauthorized access to all sensitive data on its storage devices.			
31. The IoT device may not provide sufficiently strong encryption capabilities for its stored data. Risk Consideration 3	• MP-4, Media Storage • SC-28, Protection of Information at Rest	• Increases the likelihood of unauthorized access to sensitive data.	• PR.DS-1: Data-at-rest is protected • PR.PT-2: Removable media is protected and its use restricted according to policy
32. The IoT device may not provide a mechanism for sanitizing sensitive data before disposing of or repurposing the device. Risk Consideration 3	• MP-6, Media Sanitization	• Increases the likelihood of unauthorized access to sensitive data.	• PR.IP-6: Data is destroyed according to policy

Challenges for Individual IoT Devices	Affected Draft NIST SP 800-53 Revision 5 Controls	Implications for the Organization	Affected Cybersecurity Framework Subcategories
Expectation 20: The device has a mechanism to support data availability through secure backups.			
33. The IoT device may not provide a secure backup and restore mechanism for its data. Risk Consideration 3	• CP-9, System Backup	• Increases the likelihood of loss of data.	• PR.IP-4: Backups of information are conducted, maintained, and tested
Expectation 21: The device can prevent unauthorized access to all sensitive data transmitted from it over networks.			
34. The IoT device may not provide sufficiently strong encryption capabilities for protecting sensitive data sent in its network communications. Risk Consideration 3	• AC-18, Wireless Access • SC-8, Transmission Confidentiality and Integrity	• Increases the likelihood of eavesdropping on communications.	• PR.DS-2: Data-in-transit is protected
35. The IoT device may not verify the identity of another computing device before sending sensitive data in its network communications. Risk Consideration 3	• SC-8, Transmission Confidentiality and Integrity • SC-23, Session Authenticity	• Increases the likelihood of eavesdropping, interception, manipulation, impersonation, and other forms of attack on communications.	• PR.DS-2: Data-in-transit is protected

4.3 Potential Challenges with Achieving Goal 3, Protect Individuals' Privacy

Table 3 lists potential challenges with achieving goal 3, protecting individuals' privacy by mitigating privacy risk arising from authorized PII processing. It follows the same conventions as the previous tables, but it omits mappings to Cybersecurity Framework Subcategories since the Cybersecurity Framework does not address privacy risks from authorized PII processing.

It is assumed that if individuals' privacy needs to be protected, device and data security need to be protected as well, so the challenges in all three tables would need to be considered. However, organizations may use information from Table 2 to address privacy risks arising from the loss of confidentiality, integrity, or availability of PII.

Table 3: Potential Challenges with Achieving Goal 3, Protect Individuals' Privacy

Challenges for Individual IoT Devices	Affected Draft NIST SP 800-53 Revision 5 Controls	Implications for the Organization
Disassociated Data Management		
Expectation 22: The device operates in a traditional federated identity environment.		
36. The IoT device may contribute data that is used for identification and authentication, but is outside of traditional federated environments. Risk Consideration 3	IA-8 (6), Identification and Authentication (non-organizational users) | Disassociability	Techniques such as the use of identifier mapping tables and privacy-enhancing cryptographic techniques to blind credential service providers and relying parties from each other or to make identity attributes less visible to transmitting parties may not work outside a traditional federated environment.
Informed Decision Making		
Expectation 23: Traditional interfaces exist for individual engagement with the device.		
37. The IoT device may lack interfaces that enable individuals to interact with it. Risk Consideration 2	IP-2, Consent	Individuals may not be able to provide consent for the processing of their PII or condition further processing of specific attributes.
38. Decentralized data processing functions and heterogenous ownership of IoT devices challenge traditional accountability processes. Risk Consideration 3	IP-3, Redress	Individuals may not be able to locate the source of inaccurate or otherwise problematic PII in order to correct it or fix the problem.
39. The IoT device may lack interfaces that enable individuals to read privacy notices. Risk Consideration 2	IP-4, Privacy Notice	Individuals may not be able to read or access privacy notices.
40. The IoT device may lack interfaces to enable access to PII, or PII may be stored in unknown locations. Risk Consideration 2	IP-6, Individual Access	Individuals may have difficulty accessing their information, which curtails their ability to manage their information and understand what is happening with their data, and increases compliance risks.
PII Processing Permissions Management		
Expectation 24: There is sufficient centralized control to apply policy or regulatory requirements to PII.		
41. The IoT device may collect PII indiscriminately or analyze, share, or act upon the PII based on automated processes. Risk Consideration 2	PA-2, Authority to Collect	PII may be processed in ways that are out of compliance with regulatory requirements or an organization's policies.
42. IoT devices may be complex and dynamic with sensors being frequently added and removed. Risk Consideration 1	PA-3, Purpose Specification	PII may be hard to track such that individuals, as well as device owners/operators, may not have reliable assumptions about how PII is being processed, causing informed decision making to be more difficult.

Challenges for Individual IoT Devices	Affected Draft NIST SP 800-53 Revision 5 Controls	Implications for the Organization
43. The IoT device may be accessed remotely, allowing the sharing of PII outside the control of the administrator. Risk Consideration 2	PA-4, Information Sharing with External Parties	PII may be shared in ways that are out of compliance with regulatory requirements or an organization's policies.
Information Flow Management		
Expectation 25: There is sufficient centralized control to manage PII.		
44. IoT devices may be complex and dynamic, with sensors being frequently added and removed. Risk Consideration 1	PM-29, Inventory of Personally Identifiable Information	PII may be difficult to identify and track using traditional inventory methods.
45. IoT devices may not support standardized mechanisms for centralized data management, and the sheer number of IoT devices to manage may be overwhelming. Risk Consideration 2	SC-7 (24), Boundary Protection | Personally Identifiable Information	Application of PII processing rules intended to protect individuals' privacy may be disrupted.
46. The IoT device may not have the capability to support configurations such as remote activation prevention, limited data reporting, notice of collection, and data minimization. Risk Consideration 3	SC-42, Sensor Capability and Data	Lack of direct privacy risk mitigation capabilities may require compensating controls and may impact an organization's ability to optimize the amount of privacy risk that can be reduced.
47. The IoT device may indiscriminately collect PII. Heterogenous ownership of devices challenges traditional data management techniques. Risk Consideration 2	SI-12 (1), Information Management and Retention | Limit Personally Identifiable Information Elements	It is more likely that operationally unnecessary PII will be retained.
48. Decentralized data processing functions and heterogenous ownership of IoT devices challenge traditional data management processes with respect to checking for accuracy of data. Risk Consideration 2	SI-19, Data Quality Operations	It is more likely that inaccurate PII will persist, with the potential to create problems for individuals.
49. Decentralized data processing functions and heterogenous ownership of IoT devices challenge traditional de-identification processes. Risk Considerations 2 and 3	SI-20, De-Identification	Aggregation of disparate data sets may lead to re-identification of PII.

5 Recommendations for Addressing Cybersecurity and Privacy Risk Mitigation Challenges for IoT Devices

This section provides recommendations for addressing the cybersecurity and privacy risk mitigation challenges for IoT devices. Figure 6 summarizes the recommendations, which are listed below and, if indicated, described in more detail elsewhere in the publication:

1. Understand the IoT device risk considerations (Section 3) and the challenges they may cause to mitigating cybersecurity and privacy risks for IoT devices in the appropriate risk mitigation areas (Section 4).
2. Adjust organizational policies and processes to address the cybersecurity and privacy risk mitigation challenges throughout the IoT device lifecycle. Section 5.1 provides more information on this. Section 4 of this publication cites many examples of possible challenges, but each organization will need to customize these to take into account mission requirements and other organization-specific characteristics.
3. Implement updated mitigation practices for the organization's IoT devices as you would any other changes to practices (Section 5.2).

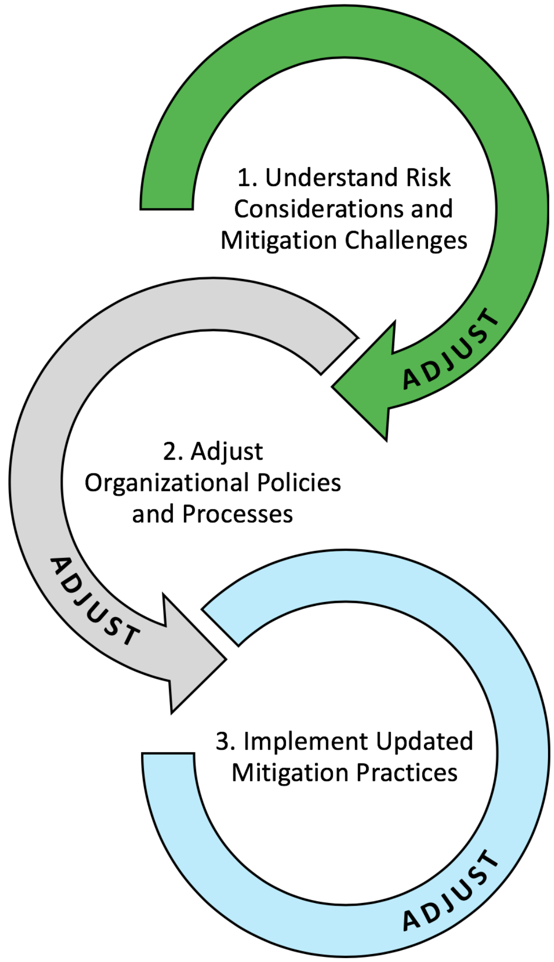

Figure 6: Recommendation Summary

5.1 Adjusting Organizational Policies and Processes

Organizations should ensure they are addressing the considerations throughout the IoT device lifecycle in their cybersecurity and privacy policies and processes. Organizations should ensure they clearly state how they scope IoT in order to avoid confusion and ambiguity. This is particularly important for organizations that may be subject to laws and regulations with differing definitions of IoT.

Similarly, organizations should ensure their cybersecurity, supply chain, and privacy risk management programs take IoT into account appropriately. This includes the following:

- Determining which devices have IoT device capabilities. Have mechanisms in place to determine whether a device that might be procured or has already been procured is an IoT device, if that is not apparent.

- Identifying IoT device types. Know which types of IoT devices are in use, which capabilities each type supports, and what purposes each type supports.
- Assessing IoT device risk. It is important to take into consideration the particular IoT environment the IoT devices reside within, and not just assess risks for IoT devices in isolation. For example, attaching an actuator to one physical system may affect risks much differently than attaching the same actuator to another physical system.
- Determining how to respond to that risk by accepting, avoiding, mitigating, sharing, or transferring it. As previously discussed, some risk mitigation strategies for conventional IT may not work well for IoT. Section 4 of this publication discusses risk mitigation challenges for IoT devices in considerable detail.

Managing cybersecurity and privacy risks for some IoT devices may affect other types of risks and introduce new risks to safety, reliability, resiliency, performance, and other areas. Organizations should be sure to consider the tradeoffs among these risks when making decisions about cybersecurity and privacy risk mitigation. For example, suppose a particular IoT device is critical for safety. Requiring personnel in a physically secured area to enter a password in order to gain local access to the IoT device could delay intervention during a malfunction. Additional requirements involving password length, password complexity, and automatic account lockouts after consecutive failed authentication attempts could cause far greater delays, increasing the likelihood and magnitude of harm. Organizations should leverage their existing programs for managing other forms of risk when determining how IoT device cybersecurity and privacy risks should be managed.

Based on the potential mitigation challenges and the implications of those challenges, the implementations of the following Cybersecurity Framework Subcategories [6] are most likely to need adjusted so the organizational policies and processes adequately address cybersecurity risk throughout the IoT device lifecycle:

- ID.AM (Identify—Asset Management)
  - ID.AM-1: Physical devices and systems within the organization are inventoried
  - ID.AM-2: Software platforms and applications within the organization are inventoried
- ID.BE (Identify—Business Environment)
  - ID.BE-4: Dependencies and critical functions for delivery of critical services are established
  - ID.BE-5: Resilience requirements to support delivery of critical services are established for all operating states (e.g. under duress/attack, during recovery, normal operations)
- ID.GV (Identify—Governance)
  - ID.GV-1: Organizational cybersecurity policy is established and communicated
  - ID.GV-2: Cybersecurity roles and responsibilities are coordinated and aligned with internal roles and external partners
  - ID.GV-3: Legal and regulatory requirements regarding cybersecurity, including privacy and civil liberties obligations, are understood and managed
  - ID.GV-4: Governance and risk management processes address cybersecurity risks

- ID.RA (Identify—Risk Assessment)
  - ID.RA-1: Asset vulnerabilities are identified and documented
  - ID.RA-3: Threats, both internal and external, are identified and documented
  - ID.RA-4: Potential business impacts and likelihoods are identified
  - ID.RA-6: Risk responses are identified and prioritized
- ID.RM (Identify—Risk Management Strategy)
  - ID.RM-2: Organizational risk tolerance is determined and clearly expressed
  - ID.RM-3: The organization's determination of risk tolerance is informed by its role in critical infrastructure and sector specific risk analysis
- ID.SC (Identify—Supply Chain Risk Management)
  - ID.SC-2: Suppliers and third party partners of information systems, components, and services are identified, prioritized, and assessed using a cyber supply chain risk assessment process
  - ID.SC-3: Contracts with suppliers and third-party partners are used to implement appropriate measures designed to meet the objectives of an organization's cybersecurity program and Cyber Supply Chain Risk Management Plan
- PR.IP (Protect—Information Protection Processes and Procedures)
  - PR.IP-3: Configuration change control processes are in place
  - PR.IP-9: Response plans (Incident Response and Business Continuity) and recovery plans (Incident Recovery and Disaster Recovery) are in place and managed
  - PR.IP-12: A vulnerability management plan is developed and implemented

Similarly, the implementations of the tasks listed below from draft NIST SP 800-37 Revision 2[5] [4] are most likely to need adjusted so the organizational policies and processes adequately address cybersecurity and privacy risk throughout the IoT device lifecycle. Note that although the Cybersecurity Framework can be used to manage the aspect of privacy relating to PII cybersecurity, draft NIST SP 800-37 Revision 2 can be used to manage the full scope of privacy because it integrates authorized PII processing into the NIST Risk Management Framework (RMF).

- Prepare, Organization Level, Task 1: Risk Management Roles
- Prepare, Organization Level, Task 2: Risk Management Strategy
- Prepare, Organization Level, Task 3: Risk Assessment—Organization
- Prepare, System Level, Task 1: Mission or Business Focus
- Prepare, System Level, Task 6: Information Life Cycle
- Prepare, System Level, Task 7: Risk Assessment—System
- Prepare, System Level, Task 8: Protection Needs—Security and Privacy Requirements

5.2 Implementing Updated Risk Mitigation Practices

An organization's cybersecurity and privacy risk mitigation practices may need significant changes because of the sheer number of IoT devices and the large number of IoT device types. For conventional IT devices, most organizations have dozens of types—desktops, laptops,

[5] These examples will be updated as needed once draft NIST SP 800-37 Revision 2 is finalized.

servers, smartphones, routers, switches, firewalls, printers, etc. Conventional IT devices within a single type tend to have similar capabilities. For example, most laptops have similar data storage and processing capabilities; human user interface and network interface capabilities; and supporting capabilities, such as centralized management. This enables organizations to determine how to manage risk for each of the dozens of conventional IT device types, with some customizations for particular devices and device models, and organizations are generally accustomed to this level of effort.

In contrast, most organizations may have many more types of IoT devices than conventional IT devices because of the single-purpose nature of most IoT devices. An organization may need to determine how to manage risk for hundreds or thousands of IoT device types. Capabilities vary widely from one IoT device type to another, with one type lacking data storage and centralized management capabilities, and another type having numerous sensors and actuators, using local and remote data storage and processing capabilities, and being connected to several internal and external networks at once. The variability in capabilities causes similar variability in the cybersecurity and privacy risks involving each IoT device type, as well as the options for mitigating those risks.

Appendix A—Examples of Possible Cybersecurity and Privacy Capabilities for IoT Devices

This appendix provides examples of possible cybersecurity and privacy capabilities—features and functions—for IoT devices. These capabilities are often more difficult to achieve for IoT devices than conventional IT devices. Each capability in this appendix has been frequently specified by existing IoT cybersecurity and privacy guidance documents, so the capabilities taken together could be the start of a capabilities baseline.

Figure 7 depicts how an organization might start with a list of capabilities and filter them within the context and risk of a particular situation—a certain type of IoT device being deployed in a particular environment for a stated purpose. This reflects that in many cases, not all capabilities will be applicable. An example of a filter is the risk mitigation goals an IoT device should meet. Suppose an organization is going to acquire a new type of IoT device and wants to determine what capabilities the device should have. If the organization's only cybersecurity and privacy risk mitigation goal for the IoT device is Protect Device Security, then all capabilities corresponding to other goals could be filtered out since they do not apply. Another example of a filter is the organization's existing cybersecurity and privacy capabilities; an organization might not need a type of IoT device to offer certain capabilities because the existing enterprise capabilities will be used instead.

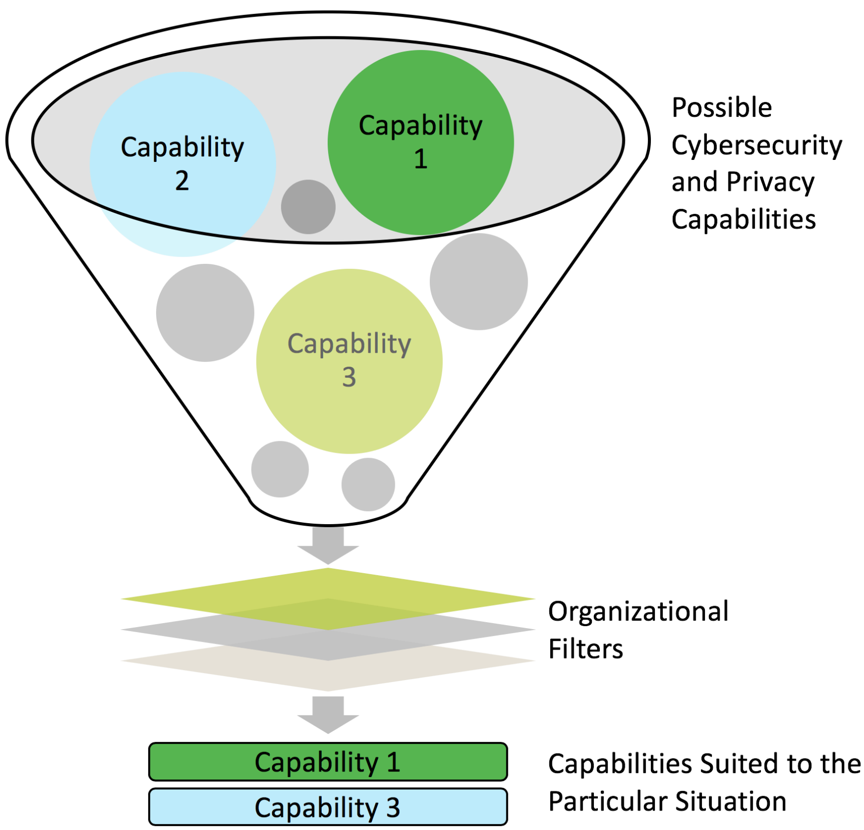

Figure 7: Filtering Capabilities for a Particular Situation

Table 4 lists the capability examples by risk mitigation area. The first column specifies the possible capability and references the related expectations from Section 4. All capabilities in the table apply throughout the IoT device's lifecycle unless otherwise noted. The second and third columns provide examples of Cybersecurity Framework Subcategories and draft NIST SP 800-53 Revision 5 controls[6] potentially affected if the capability is not achieved.[7] The fourth column lists references to requirements and recommendations for the capability from the following selected IoT guidance documents:

- BITAG: Broadband Internet Technical Advisory Group (BITAG), "Internet of Things (IoT) Security and Privacy Recommendations" [8]
- CSA1: Cloud Security Alliance (CSA) Mobile Working Group, "Security Guidance for Early Adopters of the Internet of Things (IoT)" [9]
- CSA2: CSA IoT Working Group, "Identity and Access Management for the Internet of Things" [10]
- CTIA: CTIA, "CTIA Cybersecurity Certification Test Plan for IoT Devices, Version 1.0" [11]
- ENISA: European Union Agency for Network and Information Security (ENISA), "Baseline Security Recommendations for IoT in the context of Critical Information Infrastructures" [12]
- GSMA: Groupe Spéciale Mobile Association (GSMA), "GSMA IoT Security Assessment"[8] [13]
- IIC: Industrial Internet Consortium (IIC), "Industrial Internet of Things Volume G4: Security Framework" [14]
- IoTSF: IoT Security Foundation (IoTSF), "IoT Security Compliance Framework, Release 1.1" [15]
- OTA: Online Trust Alliance (OTA), "IoT Security & Privacy Trust Framework v2.5" [16]
- UKDDCMS: United Kingdom Government Department for Digital, Culture, Media & Sport (DCMS), "Secure by Design: Improving the cyber security of consumer Internet of Things" [17]

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[6] These examples will be updated as needed once draft NIST SP 800-53 Revision 5 is finalized.

[7] Table 4 does not define or imply equivalence between the NIST SP 800-53 controls and the Cybersecurity Framework Subcategories in each row. In many cases, a challenge affects just parts of one or more SP 800-53 controls, the implications of that challenge affect just parts of one or more Cybersecurity Framework Subcategories, and the two sets of parts are not equivalent.

[8] This GSMA document references several other GSMA documents, each of which provides additional detail. All GSMA references in Table 4 are to the cited GSMA document only, and not its supporting documents, which use different identifier schemes.

Table 4: Examples of Possible Cybersecurity and Privacy Capabilities for IoT Devices

Possible Capabilities	Cybersecurity Framework Subcategories	Draft SP 800-53 Revision 5 Controls	References to Selected IoT Guidance Documents
Protect Device Security—Asset Management			
1. The IoT device can be identified both logically and physically. Expectation 1	• ID.AM-1: Physical devices and systems within the organization are inventoried • ID.AM-2: Software platforms and applications within the organization are inventoried • PR.AC-1: Identities and credentials are issued, managed, verified, revoked, and audited for authorized devices, users and processes • PR.DS-3: Assets are formally managed throughout removal, transfers, and disposition • PR.MA-1: Maintenance and repair of organizational assets are performed and logged, with approved and controlled tools • PR.MA-2: Remote maintenance of organizational assets is approved, logged, and performed in a manner that prevents unauthorized access	• CM-8 • IA-3 • PE-20	• BITAG: 7.2, 7.6 • CSA1: 5.2.1.1, 5.3.1, 5.3.4 • CSA2: 11, 14 • CTIA: 4.13 • ENISA: PS-10, TM-21 • GSMA: CLP11_5.2.1, CLP13_6.6.2, 6.8.1, 6.20.1, 8.11.1 • IIC: 7.3, 8.5 • IoTSF: 2.4.14.3-4, 2.4.8.1 • UKDDCMS: 4
2. Information confirming the sources of all the IoT device's software, firmware, hardware, and services is disclosed and accessible. Expectations 3 and 4	• DE.CM-4: Malicious code is detected • ID.SC-2: Suppliers and third party partners of information systems, components, and services are identified, prioritized, and assessed using a cyber supply chain risk assessment process • ID.SC-3: Contracts with suppliers and third-party partners are used to implement appropriate measures designed to meet the objectives of an organization's cybersecurity program and Cyber Supply Chain Risk Management Plan	• AC-20 • CM-8, 10 • IA-9 • SA-9, 12, 19 • SI-7	• BITAG: 7.10 • CSA1: 5.2.2 • CSA2: 14 • CTIA: 3.1.4 • ENISA: OP-14 • GSMA: CLP12_5.1.2.1, 7.1.1.1, CLP13_9.7.1 • IIC: 7.3, 7.5, 10.5.3 • OTA: 9, 11 • UKDDCMS: 7
3. An inventory of the IoT device's current internal software and firmware, including versions and patch status, is disclosed and accessible. Expectation 3	• DE.CM-8: Vulnerability scans are performed	• CM-8, 10, 11 • RA-5	• CSA1: 5.2.2, 5.3, 5.5.3 • CSA2: 14 • CTIA: 3.5, 4.5, 5.5, 5.6 • ENISA: TM-56 • GSMA: CLP12_5.9.1.3, CLP13_6.1.1, 9.7.1.2 • IIC: 7.3, 7.5, 10.5.3 • IoTSF: 2.4.6.2 • OTA: 9 • UKDDCMS: 12

Possible Capabilities	Cybersecurity Framework Subcategories	Draft SP 800-53 Revision 5 Controls	References to Selected IoT Guidance Documents
Protect Device Security—Vulnerability Management			
4. The IoT device's software and firmware can be updated using a secure, controlled, and configurable mechanism. Expectations 5 and 6	• PR.IP-12: A vulnerability management plan is developed and implemented • PR.MA-1: Maintenance and repair of organizational assets are performed and logged, with approved and controlled tools • PR.MA-2: Remote maintenance of organizational assets is approved, logged, and performed in a manner that prevents unauthorized access	• CM-3, 6 • SI-2	• BITAG: 7.1 • CSA1: 5.5.3.1 • CTIA: 3.5, 3.6, 4.5, 4.6, 5.5, 5.6 • ENISA: OP-02, 03, TM-06, 18, 19, 20 • GSMA: CLP11_5.3.3, CLP12_5.8.1, 5.9.1.3, 6.6.1 • IIC: 7.3, 10.5.3, 11.1, 11.2, 11.5 • IoTSF: 2.4.5, 2.4.6, 2.4.13.1 • OTA: 1, 6, 7, 8, 9, 19 • UKDDCMS: 3
5. The IoT device's configuration can be securely changed by authorized users when needed, including restoring a secure default configuration, and unauthorized changes to the IoT device's configuration can be prevented. Expectation 6	• PR.IP-1: A baseline configuration of information technology/industrial control systems is created and maintained incorporating security principles (e.g. concept of least functionality) • PR.IP-3: Configuration change control processes are in place	• CM-2, 6 • SC-42	• BITAG: 7.1 • CSA1: 5.3.3 • CSA2: 02 • CTIA: 4.7, 4.8, 4.12, 5.15 • ENISA: TM-06, 09, 22 • GSMA: CLP12_5.3.1.3, 5.6.2 • IIC: 7.6, 8.10, 11.1, 11.2, 11.5, 11.6 • IoTSF: 2.4.7.7, 2.4.8, 2.4.15 • OTA: 13, 14, 16, 26, 33 • UKDDCMS: 1, 11
6. The IoT device can enforce the principle of least functionality through its design and configuration. Expectation 6	• PR.PT-3: The principle of least functionality is incorporated by configuring systems to provide only essential capabilities	• CM-7	• BITAG: 7.2, 7.3 • CSA1: 5.3.2, 5.3.3 • CSA2: 12, 13, 16 • CTIA: 5.17 • ENISA: TM-05, 08, 12, 27, 28, 43-45, 50 • GSMA: CLP12_7.1.1.2, CLP13_6.7.1, 6.12.1.6, 7.9.1 • IoTSF: 2.4.6, 2.4.7.18, 2.4.13 • OTA: 12 • UKDDCMS: 6, 12

Possible Capabilities	Cybersecurity Framework Subcategories	Draft SP 800-53 Revision 5 Controls	References to Selected IoT Guidance Documents
Protect Device Security—Access Management			
7. Local and remote access to the IoT device and its interfaces can be controlled. Expectations 8, 10, 11, 12, and 13	• PR.AC-3: Remote access is managed • PR.AC-4: Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties • PR.PT-2: Removable media is protected and its use restricted according to policy	• AC-2, 3, 4, 12, 14, 17 • CM-5 • IA-2, 3, 4, 5, 8, 9, 11 • MP-2 • SC-7	• BITAG: 7.2 • CSA1: 5.3.1, 5.3.3, 5.6 • CSA2: 01, 04, 13, 16 • CTIA: 3.2, 3.3, 3.4, 4.2, 4.3, 4.5, 4.7, 4.9, 4.10, 5.2, 5.5, 5.17 • ENISA: TM-09, 21, 23, 27, 29, 40 • GSMA: CLP12_5.6.1, 6.3.1.1, 7.1.1.2, CLP13_6.12.1, 7.10.1, 8.2.1.1 • IIC: 7.3, 8.6, 9.2.7, 11.7 • IoTSF: 2.4.4.5, 2.4.5, 2.4.6, 2.4.7, 2.4.8, 2.4.13, 2.4.15 • UKDDCMS: 4
8. The IoT device is designed to allow physical access to it to be controlled. Expectations 9 and 14	• PR.PT-2: Removable media is protected and its use restricted according to policy	• MP-2, 7 • SA-18 • SC-41	• BITAG: 7.3 • CSA2: 11 • CTIA: 5.16 • ENISA: TM-31, 32, 33 • GSMA: CLP13_7.3.1, 8.2.1.2 • IIC: 7.3, 7.4, 8.3 • IoTSF: 2.4.4 • OTA: 37
Protect Data Security—Data Protection			
9. The IoT device can use cryptography to secure its stored and transmitted data. Expectations 19, 20, 21, and 22	• PR.DS-1: Data-at-rest is protected • PR.DS-2: Data-in-transit is protected	• SC-8, 12, 13, 28, 40	• BITAG: 7.2 • CSA1: 5.3.1, 5.4.1, 5.5.3.2, 5.3.3, 5.7.3 • CSA2: 08 • CTIA: 4.8, 5.15 • ENISA: OP-04, TM-04, 24, 34, 36, 52 • GSMA: CLP12_5.1.5, 5.1.7.1, 5.2.2.1, 5.3.1.1, 6.2.1, 6.3.1.2, CLP13_6.1.1.6, 6.1.1.8, 6.4.1.1, 6.5.1.1, 6.11, 6.12.1.1, 7.6.1, 8.11.1 • IIC: 7.3, 7.4, 7.7, 8.8, 8.11, 9.1 • IoTSF: 2.4.5, 2.4.7, 2.4.8.8, 2.4.9, 2.4.12.2, 2.4.13.16 • OTA: 2, 3 • UKDDCMS: 4, 5, 8

Possible Capabilities	Cybersecurity Framework Subcategories	Draft SP 800-53 Revision 5 Controls	References to Selected IoT Guidance Documents
10. The IoT device can use well-known and standardized protocols for all layers of the device's data transmissions. Expectation 21	• PR.AC-5: Network integrity is protected (e.g., network segregation, network segmentation) • PR.DS-2: Data-in-transit is protected • PR.DS-5: Protections against data leaks are implemented	• AC-18 • SC-8	• BITAG: 7.2, 7.6 • CSA1: 5.4.1, 5.2.2, 5.3.1 • CSA2: 07, 08 • CTIA: 4.8, 5.14 • ENISA: OP-04, TM-24, 36, 37, 39, 52 • GSMA: CLP12_6.13.1.1, CLP13_6.3.1.2, 6.4.1.1 • IIC: 7.3, 7.4, 7.7, 9.1 • IoTSF: 2.4.5, 2.4.7, 2.4.9, 2.4.10 • OTA: 2, 3, 34 • UKDDCMS: 5
Protect Device Security and Protect Data Security—Incident Detection			
11. The IoT device can log the pertinent details of its security events and make them accessible to authorized users and systems. Expectations 15, 16, 17, and 18	• DE.AE-3: Event data are collected and correlated from multiple sources and sensors • DE.CM-1: The network is monitored to detect potential cybersecurity events • DE.CM-6: External service provider activity is monitored to detect potential cybersecurity events • DE.CM-7: Monitoring for unauthorized personnel, connections, devices, and software is performed • PR.PT-1: Audit/log records are determined, documented, implemented, and reviewed in accordance with policy • RS.AN-1: Notifications from detection systems are investigated	• AU-2, 3, 6, 7, 8, 9, 12 • IR-4, 5 • SI-3, 4, 7	• CSA1: 5.5.4, 5.7 • CSA2: 09 • CTIA: 4.7, 4.12, 4.13, 5.7 • ENISA: OP-05, TM-55-57 • GSMA: CLP11_5.3.4, CLP12_5.7.1.2, 5.7.1.3, CLP13_6.13.1, 7.2.1, 9.1.1.2 • IIC: 7.3, 7.5, 10.1, 10.2, 10.3.2 • OTA: 4 • UKDDCMS: 2, 10
Protect Individuals' Privacy—Informed Decision Making			
12. The IoT device can interact through an interface with individuals regarding the device's processing of the individual's PII. Expectation 23	• N/A	• AC-8 • IP-2, 3, 4, 6	• BITAG: 7.7, 7.8 • CSA1: 5.4.1.5, 5.7.4 • CSA2: 10, 21 • CTIA: 3.1.3, 4.1.3 • ENISA: OP-12, 13, TM-10, 11, 14 • GSMA: CLP11_6, CLP12_6.14, 7.4.1, 8.3.1, 8.11.1 • IIC: 8.8.1, 10.4, 11.9 • IoTSF: 2.4.12 • OTA: 18, 20, 22, 23, 24, 25, 26, 27, 29, 32, 33 • UKDDCMS: 3, 8, 11

Possible Capabilities	Cybersecurity Framework Subcategories	Draft SP 800-53 Revision 5 Controls	References to Selected IoT Guidance Documents
Protect Individuals' Privacy—Information Flow Management			
13. Information about what PII the IoT device is processing and where the PII may be transmitted is disclosed and accessible. Expectation 25	• N/A	• PM-29 • SC-42 • SI-12, 19, 20	• BITAG: 7.3, 7.8 • CSA1: 5.1.2, 5.4.1.5, 5.7.4 • CSA2: 9 • CTIA: 4.1.3 • ENISA: OP-12, 13, TM-11, 12, 13, 14 • GSMA: CLP11_6, CLP12_6.14, 7.4.1, 8.3.1, 8.11.1 • IIC: 8.8.1, 10.4, 11.9 • IoTSF: 2.4.12 • OTA: 20, 23, 25, 26, 30 • UKDDCMS: 4, 5, 8, 11
Protect Individuals' Privacy—PII Processing Permissions Management			
14. The IoT device can read data tags that identify PII processing permission, then conform its processing accordingly. Expectation 24	• N/A	• AC-16 • PA-2, 3, 4	• CSA2: 10 • ENISA: OP-13, TM-10, 11 • GSMA: CLP12_7.4.1.2, 8.3.1 • OTA: 2, 20, 25, 32 • UKDDCMS: 4, 5, 8, 11
Protect Individuals' Privacy—Disassociated Data Management			
15. The IoT device can be configured to minimize the processing of predefined elements of PII. Expectation 22	• N/A	• PA-3	• CSA1: 5.1.1 • ENISA: TM-12 • GSMA: CLP12_6.14 • IIC: 3.6, 10.3.2 • IoTSF: 2.4.12 • OTA: 20, 32 • UKDDCMS: 4, 5, 8, 11

Appendix B—Acronyms and Abbreviations

Selected acronyms and abbreviations used in this paper are defined below.

API	Application Programming Interface
BITAG	Broadband Internet Technical Advisory Group
CSA	Cloud Security Alliance
DCMS	Department for Digital, Culture, Media & Sport
DDoS	Distributed Denial of Service
ENISA	European Union Agency for Network and Information Security
FISMA	Federal Information Security Modernization Act
FOIA	Freedom of Information Act
GSMA	Groupe Spéciale Mobile Association
IETF	Internet Engineering Task Force
IIC	Industrial Internet Consortium
IoT	Internet of Things
IoTSF	IoT Security Foundation
IP	Internet Protocol
IR	Internal Report
IT	Information Technology
ITL	Information Technology Laboratory
LTE	Long-Term Evolution
NICE	National Initiative for Cybersecurity Education
NIST	National Institute of Standards and Technology
OMB	Office of Management and Budget
OT	Operational Technology
OTA	Online Trust Alliance
PII	Personally Identifiable Information
RFC	Request for Comments
RMF	Risk Management Framework
SLA	Service Level Agreement
SP	Special Publication

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Actuating Capability	The ability to change something in the physical world.
Application Interface Capability	The ability for other computing devices to communicate with an IoT device through an IoT device application.
Capability	A feature or function.
Data Actions	"System operations that process PII." [5]
Data Capabilities	Capabilities that are typical digital computing functions involving data: data storing and data processing.
Disassociability	"Enabling the processing of PII or events without association to individuals or devices beyond the operational requirements of the system." [5]
Human User Interface Capability	The ability for an IoT device to communicate directly with people.
Interface Capabilities	Capabilities which enable interactions involving IoT devices (e.g., device-to-device communications, human-to-device communications). The types of interface capabilities are application, human user, and network.
Network Interface Capability	The ability to interface with a communication network for the purpose of communicating data to or from an IoT device. A network interface capability allows a device to be connected to and use a communication network. Every IoT device has at least one network interface capability and may have more than one.
Personally Identifiable Information (PII)	"Information that can be used to distinguish or trace an individual's identity, either alone or when combined with other information that is linked or linkable to a specific individual." [18]
PII Processing	An operation or set of operations performed upon PII that can include, but is not limited to, the collection, retention, logging, generation, transformation, use, disclosure, transfer, and disposal of PII.
Post-Market Capability	A cybersecurity or privacy capability an organization selects, acquires, and deploys itself; any capability that is not pre-market.
Pre-Market Capability	A cybersecurity or privacy capability built into an IoT device. Pre-market capabilities are integrated into IoT devices by the manufacturer or vendor before they are shipped to customer organizations.
Problematic Data Action	A system operation that processes personally identifiable information (PII) through the information lifecycle and as a side effect causes individuals to experience some type of problem(s).

Risk	“A measure of the extent to which an entity is threatened by a potential circumstance or event, and typically is a function of: (i) the adverse impact, or magnitude of harm, that would arise if the circumstance or event occurs; and (ii) the likelihood of occurrence.” [4]
Sensing Capability	The ability to provide an observation of an aspect of the physical world in the form of measurement data.
Supporting Capabilities	Capabilities that provide functionality that supports the other IoT capabilities. Examples of supporting capabilities are device management, cybersecurity, and privacy capabilities.
Transducer Capabilities	Capabilities that provide the ability for computing devices to interact directly with physical entities of interest. The two types of transducer capabilities are sensing and actuating.

899 ## Appendix D—References

[1] W. Newhouse, S. Keith, B. Scribner, and G. Witte, NIST SP 800-181, "National Initiative for Cybersecurity Education (NICE) Cybersecurity Workforce Framework," August 2017, https://doi.org/10.6028/NIST.SP.800-181

[2] E. Simmon, "A Model for the Internet of Things (IoT)," to be published

[3] K. Stouffer, V. Pillitteri, S. Lightman, M. Abrams, and A. Hahn, NIST SP 800-82 Revision 2, "Guide to Industrial Control Systems (ICS) Security," May 2015, https://doi.org/10.6028/NIST.SP.800-82r2

[4] Joint Task Force, Draft NIST SP 800-37 Revision 2, "Risk Management Framework for Information Systems and Organizations: A System Life Cycle Approach for Security and Privacy," May 2018, https://csrc.nist.gov/publications/detail/sp/800-37/rev-2/draft

[5] S. Brooks, M. Garcia, N. Lefkovitz, S. Lightman, and E. Nadeau, NIST IR 8062, "An Introduction to Privacy Engineering and Risk Management in Federal Systems," January 2017, https://doi.org/10.6028/NIST.IR.8062

[6] NIST, "Framework for Improving Critical Infrastructure Cybersecurity, Version 1.1," April 16, 2018, https://doi.org/10.6028/NIST.CSWP.04162018

[7] Joint Task Force, Draft NIST SP 800-53 Revision 5, "Security and Privacy Controls for Information Systems and Organizations," August 2017, https://csrc.nist.gov/publications/detail/sp/800-53/rev-5/draft

[8] BITAG, "Internet of Things (IoT) Security and Privacy Recommendations," November 2016, https://www.bitag.org/documents/BITAG_Report_-_Internet_of_Things_(IoT)_Security_and_Privacy_Recommendations.pdf

[9] CSA Mobile Working Group, "Security Guidance for Early Adopters of the Internet of Things (IoT)," April 2015, https://cloudsecurityalliance.org/download/new-security-guidance-for-early-adopters-of-the-iot/

[10] CSA IoT Working Group, "Identity and Access Management for the Internet of Things," September 2015, https://cloudsecurityalliance.org/download/identity-and-access-management-for-the-iot/

[11] CTIA, "CTIA Cybersecurity Certification Test Plan for IoT Devices, Version 1.0," August 2018, https://api.ctia.org/wp-content/uploads/2018/08/CTIA-IoT-Cybersecurity-Certification-Test-Plan-V1_0.pdf

[12] ENISA, "Baseline Security Recommendations for IoT in the context of Critical Information Infrastructures," November 2017, https://www.enisa.europa.eu/publications/baseline-security-recommendations-for-iot

[13] GSMA, "GSMA IoT Security Assessment," 2017, https://www.gsma.com/iot/iot-security-assessment/

[14] IIC, "Industrial Internet of Things Volume G4: Security Framework," 2016, https://www.iiconsortium.org/IISF.htm

[15] IoTSF, “IoT Security Compliance Framework, Release 1.1,” December 2017, https://www.iotsecurityfoundation.org/best-practice-guidelines/

[16] OTA, “IoT Security & Privacy Trust Framework v2.5,” June 2017, https://otalliance.org/system/files/files/initiative/documents/iot_trust_framework6-22.pdf

[17] United Kingdom Government DCMS, “Secure by Design: Improving the cyber security of consumer Internet of Things Report,” March 2018, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/686089/Secure_by_Design_Report_.pdf

[18] Office of Management and Budget (OMB), Circular No. A-130, “Managing Information as a Strategic Resource,” July 28, 2016 revision, https://www.whitehouse.gov/sites/whitehouse.gov/files/omb/circulars/A130/a130revised.pdf