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The Rocky Road to Sustainable Security

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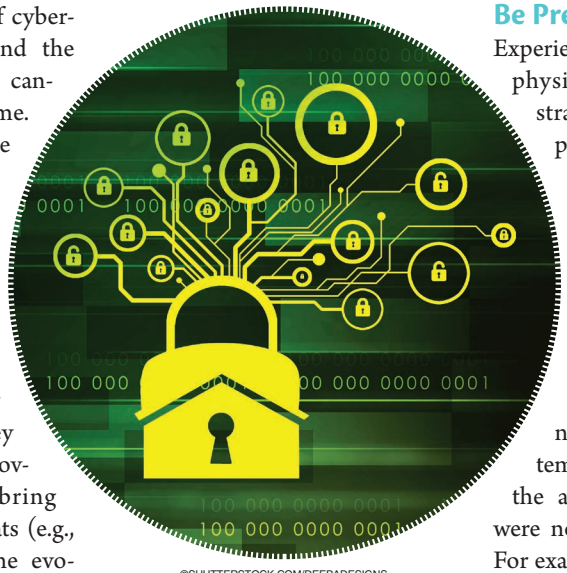
In this column, we illustrate real-world scenarios in which modern systems cannot preserve security during operation. We examine the notion of sustainable security and discuss the challenges to engineering sustainably secure systems.

With software systems permeating our lives, we are entitled to expect that such systems are secure by design and can preserve security throughout their use and subsequent evolution. However, the complexity of cyberphysical systems can extend the attack surface in ways that cannot be foreseen at design time. Thus, it is difficult to ensure that systems are secure by design, and alternative ways to preserve security during system operation must be considered.

We argue that modern, cyberphysical, systems should preserve security during their operation. They should be capable of discovering changes that may bring unanticipated security threats (e.g., anomalies) and manage the evolution of security requirements and controls to mitigate such threats. Human intervention can also be beneficial and sometimes essential to preserve security. For example, humans can monitor security-relevant data[1] or support the diagnosis of anomalies.[2]



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However, the success of such interventions depends on human attention and engagement, which are difficult to replenish once depleted. Thus, modern systems should be *sustainably secure*: they should not only preserve security but also sustain human engagement and attention.

Why Security Cannot Be Preserved

Experience with real-world cyberphysical systems has demonstrated that it is difficult to preserve security due to vulnerable system configurations, unforeseen and third-party vulnerabilities, and the human factor.

Vulnerable system configurations: In a cyberphysical system, users could add potentially vulnerable devices during system operation. This can extend the attack surface in ways that were not expected at design time. For example, smart home users can plug in different devices during system operation (e.g., smart speakers or cameras). Even if the individual devices are secure by design, unauthorized access to one of these devices may harm other devices, the

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home, and its users. For example, in November 2018, a Google Nest camera was added to a household. A vulnerability in this device allowed an attacker to control the thermostat and turn up the temperature to 90 degrees.[3]

Unforeseen vulnerabilities: Newly discovered vulnerabilities can also arise. For example, an unforeseen vulnerability in Log4J[4] allowed attackers to break into systems, steal passwords and logins, extract data, and infect networks with malicious software. Blind spots are another example of unforeseen vulnerabilities. They may be known to the security community and have fixes, but they occur due to developers' insufficient security knowledge and delayed updates. Another example of unforeseen vulnerabilities may arise when manufacturers stop shipping software updates for older devices.[5] For example, most mobile phone vendors usually stop shipping patches for phones older than three years, making them highly vulnerable. This is also a problem for specialized medical equipment, often controlled by obsolete computers.

Third-party vulnerabilities: Most systems rely on third-party software, which can evolve unexpectedly and introduce vulnerabilities outside the software provider or original equipment manufacturer's control to fix. Software supply chain attacks, like the infection of SolarWind's Orion platform,[6] aim to inject malicious code into software components to compromise downstream users. The European Union Agency for Cybersecurity identified highly complex supply chains, particularly their software dependencies, as the number one threat in its forecast of cyber threats up to 2030.[7]

The human factor: People can use technology in unexpected ways that were not considered during design. For example, in a smart home, users can accidentally disclose sensitive information while using a smart speaker.[8] Existing threat models rarely factor in how people can misuse technologies.[9]

Human intervention could mitigate some of these vulnerabilities. For example, a home tenant could be warned about a vulnerable device and temporarily disconnect it from other critical devices until the vulnerability is fixed. Security engineers could analyze data about anomalous behavior and network traffic of smart home devices to diagnose anomalies and identify appropriate security controls. Software engineers could be encouraged to develop more maintainable software systems, which will facilitate the implementation of security patches when such systems become outdated. User interfaces that provide notifications and nudges could motivate people to behave securely and avoid misuse.

An Adaptive View on Sustainable Security

Sustainable security is the cost-effective development and maintenance of "code that will go on working dependably for decades in environments that change and evolve."[5] It

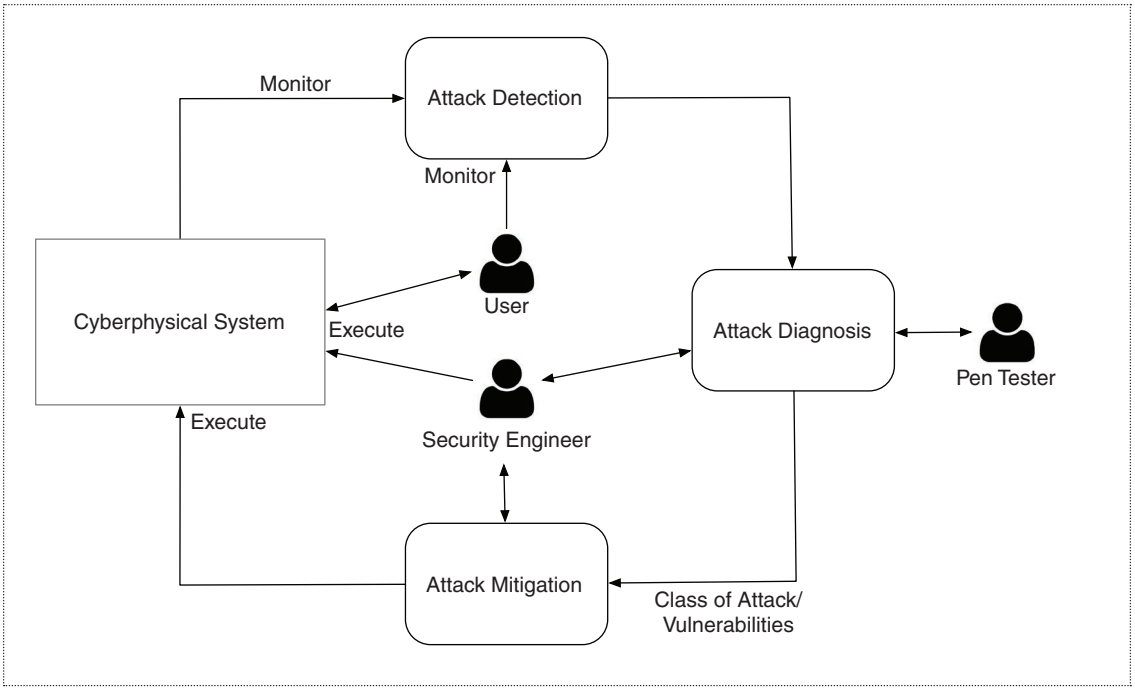

Figure 1. Our view on sustainable security.

has also been considered as the property of a network intrusion detection system to ensure continuous, reliable operation[10] or the capability of organizational processes to be more resilient to insider threats.[11] Unlike previous work, we suggest considering sustainable security as the capability of a system to preserve security requirements throughout its use and evolution while sustaining human engagement and attention.

To be sustainably secure, systems must continuously detect, diagnose, and mitigate attacks by adapting their security controls (see Figure 1). *Attack detection* should identify potentially unanticipated attacks using data monitored during system operation. For example, in a smart home, an anomaly detector can identify an abnormal packet rate to a device, indicating the suspected presence of an attack. *Attack diagnosis* should explain the attack by, for example, identifying the type of attack and the vulnerabilities it could exploit. For example, an abnormal packet rate can be linked to a DDoS or a botnet attack. *Attack mitigation* should use information about the type of attack to select short-term actions that stop harm (e.g., block traffic to or from malicious endpoints or reduce the traffic rate to or from a device). It should also use the information about the vulnerabilities exploited during the suspected attack to select long-term actions that fix the vulnerabilities and prevent the recurrence of the same attack. For example, CVE-2023-1389 is a vulnerability in the firmware of some Wi-Fi routers that has been exploited for a long time to deploy botnet attacks.

Attack detection, diagnosis, and mitigation cannot always be fully automated and should be supported by stakeholders, such as users, security engineers, and pen testers. For example, in a smart home, a user can complement the activities of a network anomaly detector to flag situations when a device does not exhibit instructed behavior (e.g., a smart speaker unexpectedly playing audible sounds), indicating the presence of an ultrasonic voice command attack. Users and security engineers can also execute security controls that cannot be automated. For example, users can update specific vulnerable devices. Security engineers can modify the network configuration for groups of households to prevent specific attacks. Moreover, users have agency in the physical world. They may also need to override the system due to requirements stronger than security, which cannot be incorporated into the system (e.g., personal safety and exceptional/emergency situations). Security engineers could support the diagnosis by identifying plausible attacks that could occur, considering the data monitored during system execution.

Bridging the gap among attack detection, diagnosis, and mitigation is essential to address previously unknown attacks.

The discovery of the vulnerabilities exploited by an attack cannot always be performed automatically, so regular pen testing activities should be conducted for this purpose. For example, information about the type of attack obtained during the diagnosis can inform pen testers who could launch this attack and identify the vulnerabilities exploited.

Human attention and engagement are critical to ensure the success of stakeholder interventions. However, maintaining human attention and engagement can be challenging, and once depleted, these resources are difficult to replenish. Also, stakeholders' security expertise, personality traits, experienced cognitive load, or motivation can influence their attention and engagement.[12] Thus, sustainable security requires preserving security and sustaining a positive experience for stakeholders interacting with the system. Although interactive security tools (e.g., Krüger et al.[13]) hold promise to sustain human attention, they cannot adapt their interactions and notifications depending on their stakeholders' personality, expertise, and cognitive capabilities.

The Road Ahead

Several challenges should be addressed when engineering sustainably secure systems.

Coupling attack detection, diagnosis, and mitigation: Bridging the gap among attack detection, diagnosis, and mitigation is essential to address previously unknown attacks. Although anomaly detection techniques are effective for detecting previously unknown attacks, they cannot typically diagnose the type of attack and identify appropriate security controls automatically. Also, attack diagnosis techniques are not usually linked to automated approaches that can select security controls based on the attack diagnosis. Moreover, software vendors cannot always perform pen testing during system use, especially for smart homes. When performed, pen testing is not informed and configured based on the anomalies discovered during system operation and the diagnosed suspected attacks.

Managing evolving security requirements: Anomalies discovered from runtime data may not always indicate that an attack is underway, but they can suggest a change in the system configuration (added or removed components) without requiring a diagnosis of an attack. In such cases, it can be necessary to identify and manage evolving security requirements during system operation. For example, adding a vulnerable (outdated) system component to a smart home may require changing the system security requirements by, for example, changing the network topology to avoid communication among this device and other critical devices and appliances in the smart home. Logic-based learning, particularly inductive learning, identifying general rules from examples, can be useful for this purpose. For example, inductive learning has been successfully used to learn security policies from anomaly detection traces.[14] Similarly, it can be used to reason about the security requirements that should be satisfied when system components change and trigger their evolution.

Sustaining human engagement: A human–machine collaborative approach would instill a culture of continuous improvement and resilience against evolving threats and attacks. An increased engagement of the stakeholders supporting attack detection, diagnosis, and mitigation can ultimately contribute to enacting effective security controls and increasing system security. To support the engagement of users, security engineers, and pen testers, there is a need to increase their situational awareness and design human–machine interactions supporting different levels of agency depending on the stakeholders' roles and expertise. This promising research direction requires multidisciplinary collaboration among cybersecurity, AI, HCI, and psychology disciplines.

Measuring sustainable security: Finally, it is still unclear how to measure sustainable security. For example, taking inspiration from software maintenance metrics, we could evaluate sustainable security as a system's robustness to attacks (e.g., measuring the mean time to mitigate an attack or the mean time between attacks). From an ecological perspective, we could measure the reduced manual effort induced by attack detection, diagnosis, and mitigation activities. Since stakeholders' participation in the attack detection, diagnosis, and mitigation cycle is critical to preserve security, measuring their engagement and attention is also critical to assess sustainable security.[15] Finally, as systems become increasingly sociotechnical, representing complex human interactions with technological and social systems, we argue that sustainable security should also aim at improving the security experience of users (e.g., personalized security to individual needs and sustained engagement that improves user awareness of security). Thus, experiential trust, security, and usability should be explored to evaluate sustainable security. ■

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