Emergent Behavior in Cybersecurity

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ABSTRACT
We argue that emergent behavior is inherent to cybersecurity.

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1. INTRODUCTION
The human-created cyberspace is a very large-scale complex system of cybersystems. Its security properties are difficult to understand and characterize. We attribute this difficulty to its complexity, a manifestation of which is the so-called emergent behavior in Complexity Science [6]. Although there is no universally accepted definition of emergent behavior [11], the basic idea is intuitive. The simplest example of emergent behavior may be the well known “1 + 1 > 2” effect. For our purpose, it is sufficient to use the following informal definition of emergent behavior in cybersecurity domain.

DEFINITION 1. A security property of a cybersystem exhibits emergent behavior if the property is not possessed by the underlying lower-level components of the cybersystem.

A direct consequence of emergent behavior is that at least some security properties cannot be understood by solely considering the lower-level components; instead, we must explicitly consider the interactions between the lower-level components. Although emergent behavior of cybersystems has been discussed from a function or constructional perspective [10, 7], emergent behavior in cybersecurity is not systematically examined until now.

2. EMERGENT BEHAVIOR
We demonstrate emergent behavior in cybersecurity through three examples.

Example 1: Emergent behavior exhibited by cybersecurity dynamics. We refer to [15] for an exposition of the emerging field of cybersecurity dynamics. In order to explain how emergent behavior is exhibited by cybersecurity dynamics, we consider the perhaps simplest model [4]. For our purpose, it suffices to consider two cybersystems that respectively induce attack-defense structures (or graphs) $G_i = (V_i, E_i)$, where $V_i$ is the node (vertex) set and $E_i$ is the edge set for $i = 1, 2$. Let $\lambda_1(G)$ denote the largest eigenvalue of the adjacency matrix of a graph $G$, $\beta$ denote the defense capability in detecting and cleaning compromised nodes (e.g., the probability that a compromised node gets cleaned at a time step), and $\gamma$ denote the attack capability in compromising secure nodes (e.g., the probability that this event occurs over an edge at a time step). For simplicity, suppose $G_1$ is a complete graph with $n_1$ nodes for $i = 1, 2$. It is well known that $\lambda_1(G_1) = n_1 - 1$ and $\lambda_1(G_2) = n_2 - 1$. For $i = 1, 2$, if $\lambda_1(G_i) < \beta/\gamma$, the attacks will eventually be wiped out in the cybersystem that induces $G_i$; if $\lambda_1(G_i) > \beta/\gamma$, the attacks cannot be wiped out [4].

Now we consider a new cybersystem that is obtained by interconnecting the aforementioned two cybersystems that induced $G_1$ and $G_2$. Consider the simplest case that any node can attack any other node in the interconnected cybersystem, which effectively induces attack-defense structure, a complete graph, $G_{1,2}$ with $n_1 + n_2$ nodes and $\lambda_1(G_{1,2}) = n_1 + n_2 - 1$. In many (if not all) cases, the defense capability $\beta'$ and the attack capability $\gamma'$ associated to $G_{1,2}$ are respectively the same as the defense capability $\beta$ and the attack capability $\gamma$ associated to $G_1$ and $G_2$. Since $\lambda_1(G_{1,2}) > \beta/\gamma$, we conclude that the attacks can be wiped out in the two underlying component cybersystems, but cannot be wiped out in the interconnected cybersystem as long as $\lambda_1(G_{1,2}) > \beta/\gamma$. This phenomenon can be naturally extended to more sophisticated settings (e.g., [17, 16, 18, 19]). This implies that cybersecurity dynamics cannot be determined by looking at the component cybersystems alone. Rather, we need to look into how the component cybersystems interact with each other.

Example 2: Emergent behavior exhibited by security properties in the extended trace-property framework. In the field of program verification, it was known that specifications that are sufficient for sequential programs are not sufficient for concurrent programs. For dealing with concurrent programs, Lamport proposed the safety-liveness framework of trace properties [12]. Intuitively, a trace is a finite or infinite sequence of states corresponding to an execution of a program. A trace property is a set of traces such
that every trace, in isolation, satisfies the same predicate. A safety property says that no “bad thing” happens during the course of a program execution, while a liveness property says that “good thing” will eventually happen during the course of a program execution. Both safety and liveness are trace properties. A beautiful result is that every trace property is the intersection of a safety property and a liveness property [12].

Given the above history, it is appealing to specify a cybersystem as a set of traces, and therefore as a subset of a security property that is also specified as a set of traces. Unfortunately, security properties are not trace properties as shown in [8] and [4] and refreshed below. First, noninterference is a security property that captures the intuition that system security is preserved as long as high-clearance (or high-privilege) processes cannot influence the behavior of low-clearance (low-privilege) processes. It is no trace property because it cannot be verified without examining the other traces. Second, information-flow captures some kind of correlation between the values of variables in multiple traces. It is no trace property because it cannot be verified by examining each trace alone. Third, average service response time is an availability property. It is no trace property because it depends on the response time in all traces.

In an effort to overcome the above limitation of the safety-liveness framework, Clarkson and Schneier extended the notion of trace properties to the notion of trace hyperproperties [5]. Basically, hyperproperties are sets of trace properties. In parallel to the safety-liveness framework, a hyperproperty is also the intersection of a safety hyperproperty and a liveness hyperproperty. It is now known that information-flow, integrity and availability can be hypersafety or hyperliveness [5]. Exactly because hyperproperties capture that the verification procedure must examine across multiple traces, which may accommodate interactions between the component systems, we say that hyperproperties exhibit the emergent behavior. This means that we need to study the emergent behavior in cybersecurity, which may explain why it took so long to realize the importance of hyperproperties.

**Example 3: Emergent behavior exhibited by cryptographic security properties.** Cryptographic secure multiparty computation allows multiple parties $P_1, \ldots, P_m$, each having a respective secret $x_1, \ldots, x_m$, to compute a function $f(x_1, \ldots, x_m)$ such that no information about the $x_i$’s is leaked except for what is implied by the output of the function. This manifests a confidentiality property. A beautiful feasibility result is that any polynomial-time computable function $f(\cdot, \ldots, \cdot)$ can be securely computed [20, 9], as long as the protocol executes in isolation (the stand-alone setting) and trapdoor permutations exist. When such cryptographic protocols are used as building-blocks for constructing larger cybersystems, we need to make extra assumptions, such as that majority of the parties $P_1, \ldots, P_m$ are not compromised [2]. This manifests emergent behavior. (It is interesting to note that whether or not it is reasonable to assume that majority of the parties are not compromised may be addressed by the cybersecurity dynamics framework [15].)

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3. **REFERENCES**

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