Emergent Behavior in Cybersecurity

HotSoS'14

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Abstract

We argue that emergent behavior is inherent to cybersecurity.

Informal Definition and Implication

Emergent behavior is a core concept in Complexity Science, although there is no universally accepted definition.

Definition (informal): A security property of a cybersystem exhibits ***emergent behavior*** if the property is not possessed by the underlying lower-level components of the cybersystem. (Simplest example: "1 + 1 > 2" effect)

Implication: At least some security properties cannot be understood by considering the lower-level components individually; instead, we must explicitly consider the interactions between the lower-level components. In other words, the composition approach has some fundamental limitations (like reductionism in Physics).

Inspiration from Cryptography

Complexity Science Comes to Rescue Again?

The (envisioned) Science of Cybersecurity:

- **Soul: Security (concepts)**
- **Brain: (Cybersecurity) Dynamics (kind of Complexity Science)**
- **Muscle & Blood: Complex System/Network, Stochastic Process, Dynamical System, Statistical Physics, Control Theory, Game Theory, Statistics, Algebraic Graph Theory, Algorithms, Software, Programming Language, etc.**

The Science of Cryptography:

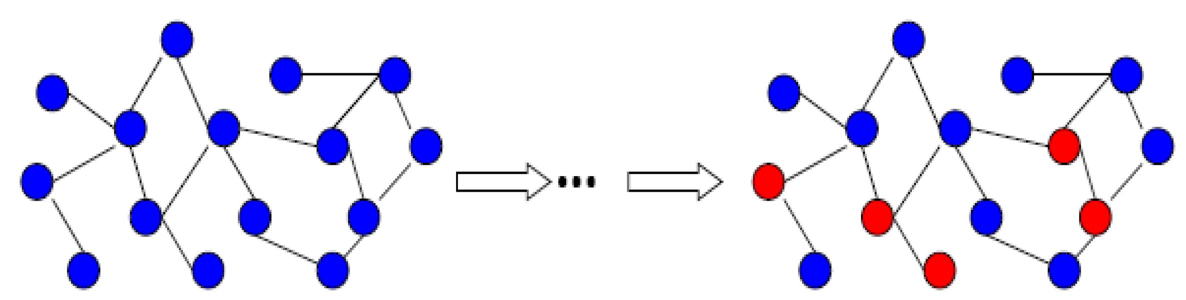
- **Soul: Security (concepts)**
- **Brain: Comp. Complexity Theory (kind of Complexity Science)**
- **Muscle & Blood: Probability Theory, Number Theory, Abstract Algebra, etc.**

For information about Cybersecurity Dynamics, see

http://www.cs.utsa.edu/~shxu/socs/

Example 1: Cyber Epidemics

Scenario: Illustration of cyber epidemics model (which is a specific kind of Cybersecurity Dynamics model).



(secure node compromised node)

Consider the simplest cyber epidemic model in two component networks: $G_i = (V_i, E_i)$, where V_i is the node set and E_i is the edge set for $i = 1, 2$.

$\lambda_1(G)$: the largest eigenvalue of the adjacency matrix of graph G
β: the defense capability in detecting and cleaning infected nodes
γ: the attack capability in infecting secure nodes

Suppose G_i is a complete graph with n_i nodes for $i = 1, 2$. Then, $\lambda_1(G_1) = n_1 - 1$ and $\lambda_1(G_2) = n_2 - 1$.

$$\lambda_1(G_i) < \beta/\gamma \quad \Rightarrow \quad \text{spreading dies out in } G_i$$
$$\lambda_1(G_i) > \beta/\gamma \quad \Rightarrow \quad \text{spreading does not die out in } G_i$$

Consider cybersystem $G_{1,2}$ obtained by interconnecting G_1 and G_2.

Suppose $G_{1,2}$ is also a complete graph with $n_1 + n_2$ nodes. Then, $\lambda_1(G_{1,2}) = n_1 + n_2 - 1$.

In many (if not all) cases, the defense capability β' and the attack capability γ' in $G_{1,2}$ are respectively the same as the defense capability β and the attack capability γ in G_1 and G_2. Since

$$\left.\begin{array}{lll} \lambda_1(G_i) & < & \beta/\gamma \\ \lambda_1(G_2) & < & \beta/\gamma \end{array}\right\} \not\Rightarrow \lambda_1(G_{1,2}) < \beta'/\gamma' = \beta/\gamma,$$

the spreading dies out in the two underlying component cybersystems, but does not die out in the interconnected cybersystem as long as $\lambda_1(G_{1,2}) > \beta/\gamma$.

This phenomenon applies to a class of cyber epidemic models.

Insight: Cyber epidemics properties exhibit emergent behavior because properties of cyber epidemics in a greater cybersystem cannot be determined by properties in the component cybersystems alone.

Example 2: Program Verification

Trace properties: In the field of program verification, Lamport proposed the safety-liveness framework of trace properties for analyzing concurrent programs. 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; a liveness property says that ``good thing" will eventually happen during the course of a program execution. **Both safety and liveness are trace properties**; every trace property is the intersection of a safety property and a liveness property (Alpern and Schneider).

Security properties are not (necessarily) trace properties (Goguen and Meseguer, Clarkson and Schneider, etc): (I) **Noninterference** is no trace property because it cannot be verified without examining the other traces in question. (II) **Information-flow** is no trace property because it cannot be verified by examining each trace alone. (III) **Average service response time** is no trace property because it depends on the response time in all traces.

Security properties can be trace hyperproperties: Clarkson and Schenider extended the concept of trace properties to trace hyperproperties, which are **sets of trace properties**. For example, information-flow, integrity and availability are trace hyperproperties (and intersections of some safety hyperproperties and some liveness hyperproperties).

Insight: Hyperproperties exhibit emergent behavior because the verification procedure must examine across multiple traces, which can accommodate interactions between component systems.

Example 3: Cryptography

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.

Feasibility result (Yao; Goldreich et al.): Under some standard cryptographic assumptions, any polynomial-time computable function f(.,…) can be securely computed in the ***standalone*** setting (i.e., the protocol executes in isolation).

Standalone vs. concurrent execution: When cryptographic protocols are used as building-blocks in larger applications/systems, they may execute concurrently (rather than in isolation). Are the cryptographic protocols, which are provably secure when executed in isolation, still secure when they are concurrently called by larger applications/systems?

Impossibility result: There exist classes of functions that can be securely computed by running some cryptographic protocols in isolation, **but cannot be securely computed when the protocols execute concurrently**. In order to make cryptographic multiparty computation protocols secure when they are used as building-blocks for constructing larger cybersystems, we need to make extra assumptions, such as that majority of the parties P_1, …, P_m are not compromised.

Insight: Cryptographic properties exhibit emergent behavior because there are functions that can be securely computed in the standalone setting but cannot be securely executed in the concurrent setting.

Acknowledgement

AFOSR Grant # FA9550-09-1-0165 and ARO Grant # W911NF-13-1-0370.