2017 NSF CYBER-PHYSICAL SYSTEMS PRINCIPAL INVESTIGATORS' MEETING

Information Flow Analysis for Cyber-Physical System Security

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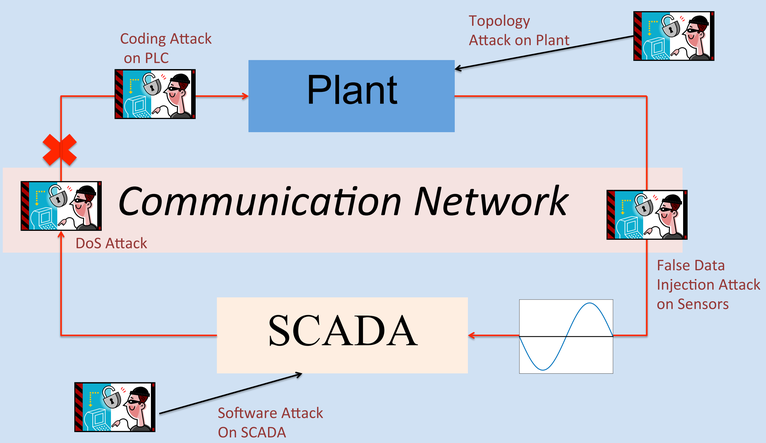
Challenge

The Resiliency of CPS Must Be Addressed

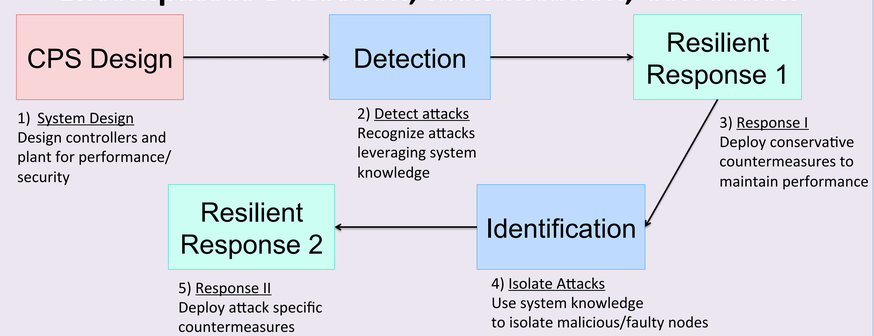


We Lack a Unifying Framework

Cyber + Software Security + System Theory

A Framework of Accountability

Encompasses Detection, Identification, Correction



Information Flow Anaysis: A Language for CPS Security

An information flow exists from *x* to *y* when information in *x* is transferred to, or used to or derive information transferred to *y*

Traditionally used to restrict flows for secrecy/privacy

Example: US Intelligence: Unclassified ≤ Confidential ≤ Secret ≤ Top Secret → **Valid Information Flow**

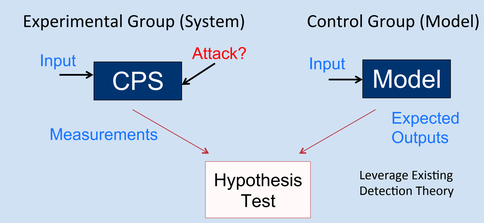
Noninterference: the absence of information flow can be used to express diverse security policies

Multi Level Security | Discretionary Access Control | Capability Passing | Confinement

Information Flow for Detection

Detecting Flows of Information: ***Example Web Data Usage Detection***

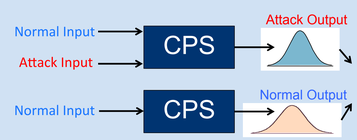
Does browser history affect the Ads one receives? **Answer Via Information Flow Experiment**



In CPS Security we wish to detect an information flow from the attacker's inputs to the defender's outputs.

Desire a Causal Measure of Information Flow: The KL Divergence

Causal Measures: Quantify cause and effect. Useful for detection.



Metric: KL Divergence — Quantify the effect of the attacker's inputs on system outputs

$$IF_k = \frac{1}{k+1} D_{KL}\left(\mathbb{D}^{\mathcal{F}_{-1},\mathcal{U},\mathcal{U}^a}_{y_{0:k}} \| \mathbb{D}^{\mathcal{F}_{-1},\mathcal{U},0}_{y_{0:k}}\right)$$

Relates to fundamental limits on attack detectability

Analyzing Attacks and Defenses

Large Information Flow ⟷ Attack is Detectable

$\limsup_{k\to\infty} IF_k > \epsilon > 0 \longrightarrow$ There exists $0 < \delta < 1$, such that $\beta_k > \delta\ \forall k$, α_k converges to 0 with rate greater than ϵ

Converse holds if attack outputs are ergodic. Also, $IF_k = 0\ \forall k \implies \alpha_k = \beta_k\ \forall k$

Ua generates an **Unconditional ε - Weak Information Flow**

Feasible Design Space → Any Defender Strategy ⟹ $IF_k \le \epsilon$ For attack strategy *Ua*

Illustrated Examples: Zero Dynamics, False Data Injection Attacks

Ua generates a **U conditional ε - Weak Information Flow**

U → Defender Strategy in **U** ⟹ $IF_k \le \epsilon$ For attack strategy *Ua*

Illustrated Examples: Replay Attack against certain State Feedback Policies, Motivates ***Active Detection Policies***

U generates a **Ua conditional ε - Strong Information Flow**

Ua → Attacker Strategy in **Ua** ⟹ $IF_k > \epsilon$ For defense strategy *U*

Illustrated Examples: Watermarking against Replay Attacks

Design Methodology

Goal: Be able to detect new attack vector by designing IF > **ε**

1) Attacker Policy | Current Defender Policy | Defender Degrees of Freedom → Categorize Information Flow

2) Do the Following

Type of Information Flow	Detectability of Attack	Action Required
Unconditional ε - weak information flow	Attack is stealthy for all admissible defender policies: **IF ≤ ε**	Nothing can be done without increasing the available DOF for the defender
Conditional ε - weak information flow	Attack is stealthy for some defender policies (including current): **IF ≤ ε**	Change Policy: Balance Information Flow and System Performance
ε – strong information flow	Attack is detectable for current defender policy: **IF > ε**	None

3) If necessary, increase degrees of freedom and/or change the defender policy. Ensure prior attack vectors generate sufficient Information Flow

Extensions

Tools and Analytical Methods can be Applied to **Attack Identification**

Design Measures | Node *i* attacked → Large IF(i) | Node *i* normal → Small IF(i) | Use Traitor Tracing research to develop efficient algorithms

Information Flow Analysis can help us bridge the gap between mainstream security + privacy and system theory

Ex 1: Compositional Security | Ex 2: Apply privacy related information flow techniques to system theory

Impact: By integrating information flow, a traditional cyber security centric notion, and resilient control of physical systems, this project will enable unified foundations of CPS security for researchers.

Affects: traditional CPS such as the Smart Grid and Transportation Systems as well as emerging fields such as network science and the Internet-of-Things (IoT). Benefits operators, researchers, society at large.

Education and Outreach: A course of CPS security/Information flow, Aid to Minority Serving Institutions, SEE Program for High School Students