Hybrid Attack Graphs for Modeling Cyber-physical Systems

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Overview

- Introduction and Motivation
  - Cyber-physical systems
  - Attack graphs
- Background
  - Related formalisms
  - Attack graphs
- Enhanced Discrete Attack Graph
- Hybrid Attack Graph
- Performance
- Conclusions and Future Work

Introduction – Cyber-physical systems (CPS)

- Systems with tight physical-digital-network coupling
- Security threats can come from both sides
- Serious security challenges (Crenshaw and Beyer, 2010):
  - Concentration in safety critical domains
  - **Integration of many third-party or unrelated components**
  - Dependence upon unreliable data collection
  - Pervasiveness

Introduction – Attack graphs

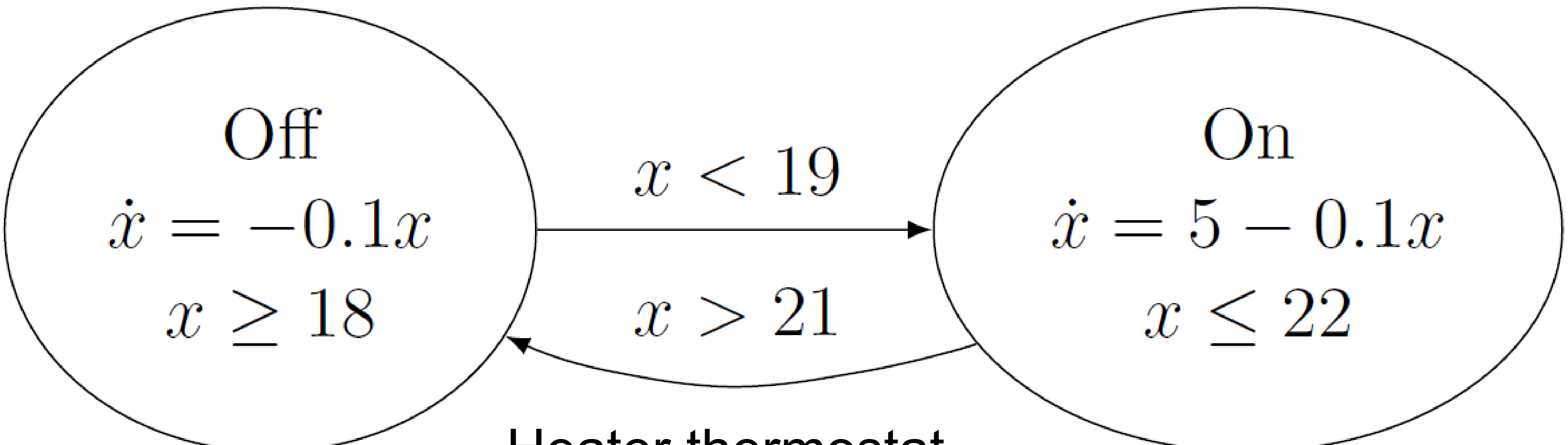
- Discrete domain formalism grounded in graph theory
- Model networks, systems, and attacks
- Excel at highlighting systems' and attacks' interactions

Introduction – Motivation

- Why a formal model for CPS security?
- Safety criticality calls for verification
- Dearth of useful models for the cyber-physical boundary
    - Need a common language for these systems
- Why attack graphs, specifically?
    - System heterogeneity makes them a natural fit

Background – Hybrid systems modeling

- Typical hybrid system model: Hybrid Automata (HA)
- State transition system paired with differential equations
- Operational "modes" and "switches" between them
- Guarded by conditions that govern state variables
- Great for modeling "micro" scale, bad for "macro"

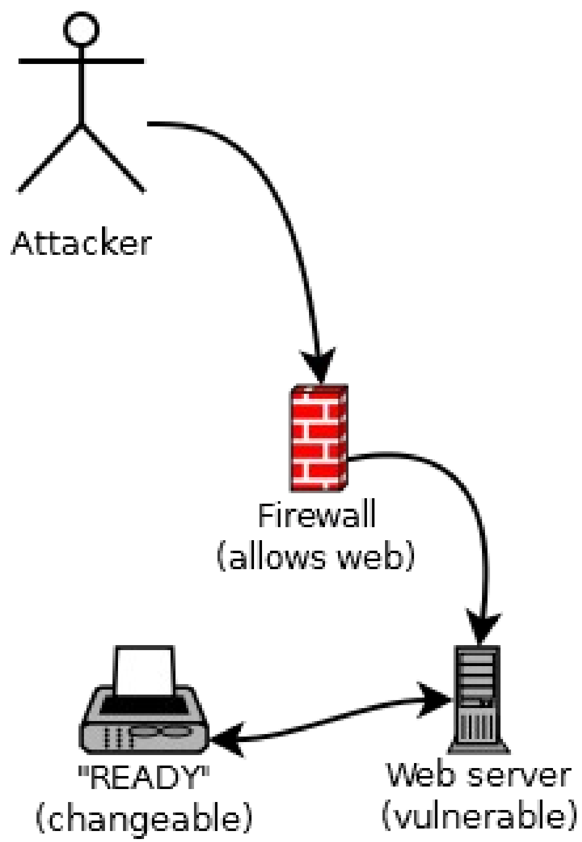


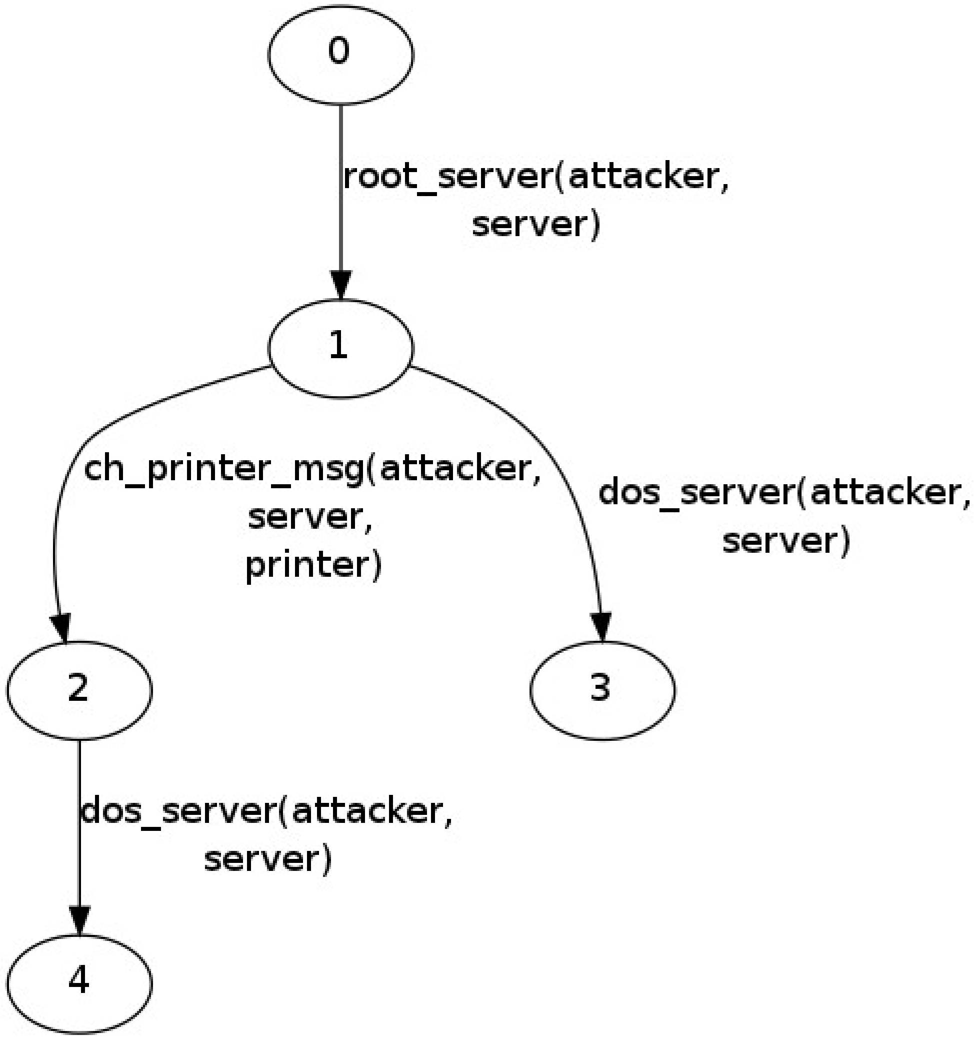
Heater thermostat

Background – Attack Graphs

- Formal model for network attacks
- State transition system
- Automatic generation: matches “exploit patterns” to network objects to create new states
- Network model + exploit patterns + generator = attack graph

Background – Attack Graphs – Example





Background – Attack Graphs – Approaches

- Free form vs. domain driven
  - *Free form – liberal specification semantics, arbitrary keywords, properties, qualities, assets (requires standardized vocabulary)
  - Domain driven – specification uses networking specific concepts (requires heavy lifting in the generator)
- Other mixins:
  - Metrics
  - Likelihood weights
  - Adversary characterization
  - Cost ($$$) of mitigation

Background – Attack Graphs – Domains

Network Model (state)

Facts

- Asset
  - Security principal
- Quality
  - Property of an asset
- Topologies
  - Relation on two assets
  - Directed
- Exploits (free) / Attacks (bound)
  - Function-like
  - Parameters
  - Preconditions
  - Postconditions

```
assets=
 asset1; asset2;
facts=
 quality:asset1,q1=v;
 topology:asset1->asset2,t;
```

```
ex(a1, a2)=
 preconditions:
  topology:a1,q1,v;
 postconditions:
  insert quality:asset1,q2=v;
```

Enhanced Discrete Attack Graphs

- Stepping stone to Hybrid attack graphs (HAGs)
- Contributions
  - Lexicon
    - Access topologies
    - Connection topologies
    - Host status qualities
  - Syntactic improvements
  - Platform facts
  - Global/grouped exploits

Enhanced Discrete Attack Graphs - Lexicon

- Free-form modeling capability requires conventions
- Based upon Common Vulnerability Enumeration and National Vulnerability Database specifications
- NVD/CVE specify useful characteristics of vulnerabilities:
  - “Security Protection” (unauthorized access) types:
    - User access
    - Administrative access
    - Other access (e.g. service account)
  - Access vector:
    - Local
    - Adjacent (same broadcast or collision domain)
    - Network (e.g. Internet)

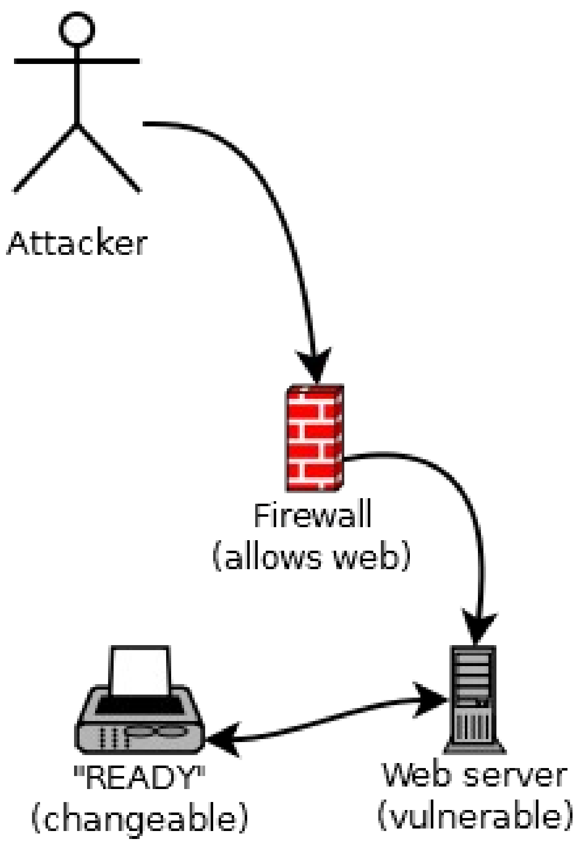
Enhanced Discrete Attack Graphs - Lexicon

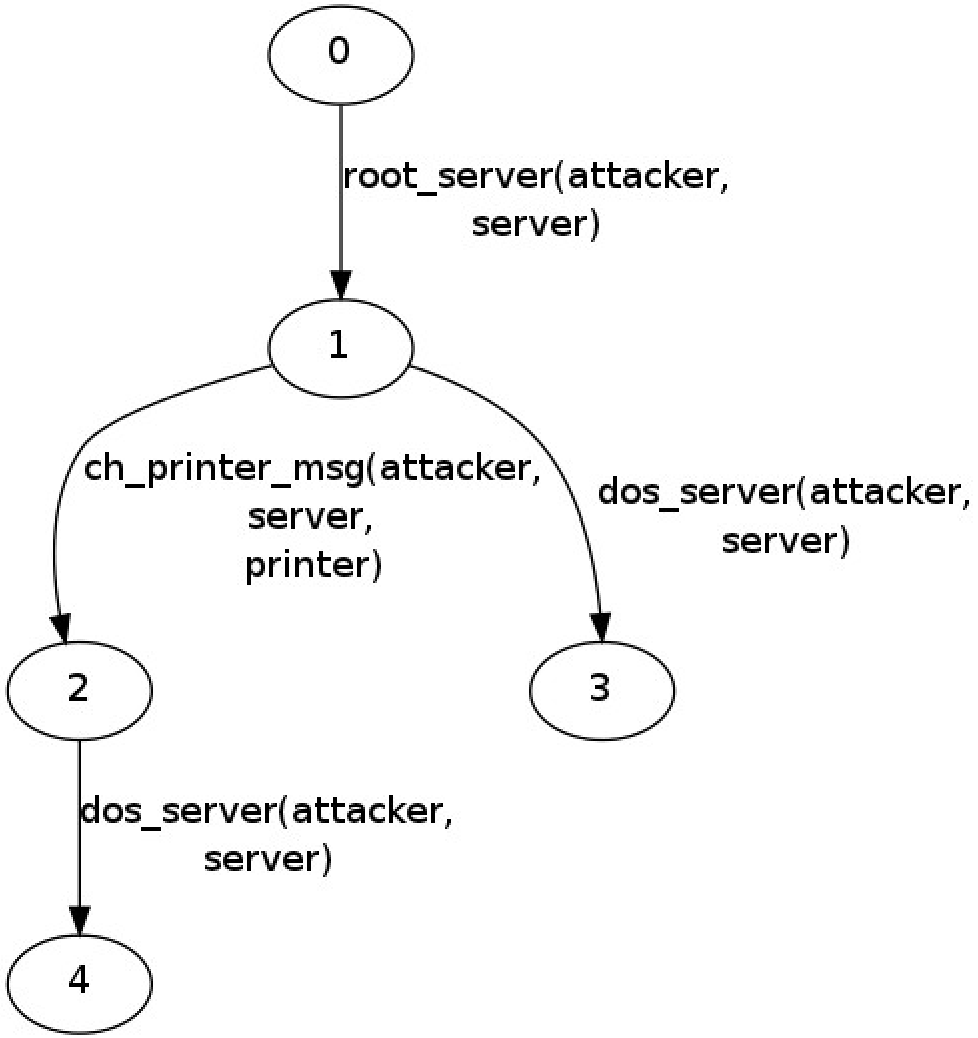
- Status qualities
  - Denote hosts that are up or down
  - Quality name: “status”, values “up” or “down”
- Access topologies
  - Denote (possibly legitimate) trust relationships
  - Topology name: “access_<type>”
  - Type = “user” | “root” | “other” | “other_<name>”
- Connection topologies
  - Denote communication relationships
  - Topology name: “connected_<type>”
  - Type = “adjacent” | “local” | “network_<protocol>”

Enhanced Discrete Attack Graphs - Platforms

- Uses Common Platform Enumeration (CPE)
  - Provides a language for specifying platform hardware, software, version, language, etc.
  - Format: “cpe:/<part>:<vendor>:<version>:<update>:<edition>:<language>”
  - Example: “cpe:/a:adobe:reader:8.1::en”
  - Prefix and wildcard properties apply
- New fact type: platforms (special case of quality)
  - `platform:asset1,cpe:/a:adobe:reader:8.1;`

Enhanced Discrete Attack Graphs – Example





Enhanced Discrete Attack Graphs – Example

NETWORK MODEL

```
network model =
    assets :
        attacker;
        server;
        printer;

    facts:
        topology:attacker->server,connected_network_web;
        topology:server<->printer,connected_local;
        platform:server,cpe:/a::VulnerableWebServer;
        platform:printer,cpe:/h::printer;
        quality:server,status=up;
        quality:printer,ready_message=READY;
.
```

EXPLOIT PATTERNS

```
exploit root_server(a, s)=
    preconditions:
        topology:a->s,connected_network_web;
        platform:s,cpe:/a::VulnerableWebServer;
    postconditions:
        insert topology:a->s,access_admin;
.

exploit ch_printer_msg(a, s, p)=
    preconditions:
        topology:a->s,access_admin;
        topology:s<->p,connected_local;
        platform:p,cpe:/h::printer;
        quality:s,status=up;
    postconditions:
        update quality:p,ready_message=OUT_OF_TONER;
.

exploit dos_server(a, s)=
    preconditions:
        topology:a->s,access_admin;
        quality:s,status=up;
    postconditions:
        update quality:s,status=down;
```

Enhanced Discrete Attack Graphs - Grouping

- It is useful to cause attacks to fire simultaneously
- Aggregate AG edge transition to include multiple attacks
- **Group** exploits
  - `group(group1) exploit ex1(ap) = ...`
  - `group (group1) exploit ex2(ap) = ...`
  - When possible, ex1(a) and ex2(a) use same edge
- **Global** exploits
  - `global exploit ex3(a) = ...`
  - When possible, ex2(a), ex2(b), etc. use same edge
- **Global group** exploits
  - `global group(group2) exploit ex4(ap)`
  - Combines both mechanics

Hybrid Attack Graphs (HAGs)

- AGs excel at modeling disparate components' interactions
  - Recall that this is a principal challenge in CPS
- HAGs extend AGs with real-values, physical reasoning:
  - RFID inventory tag distance to reader
  - Generator temperature or pressure
  - Centrifuge speed

Hybrid Attack Graphs (HAG)

- What does a hybrid attack look like?
  - System placed into harmful **mode** (think HAs)
    - Centrifuge spins too fast
    - Brakes stop working, accelerator stuck
    - Power consumption increased
- Requires *time*
  - Enabled by global/group exploits

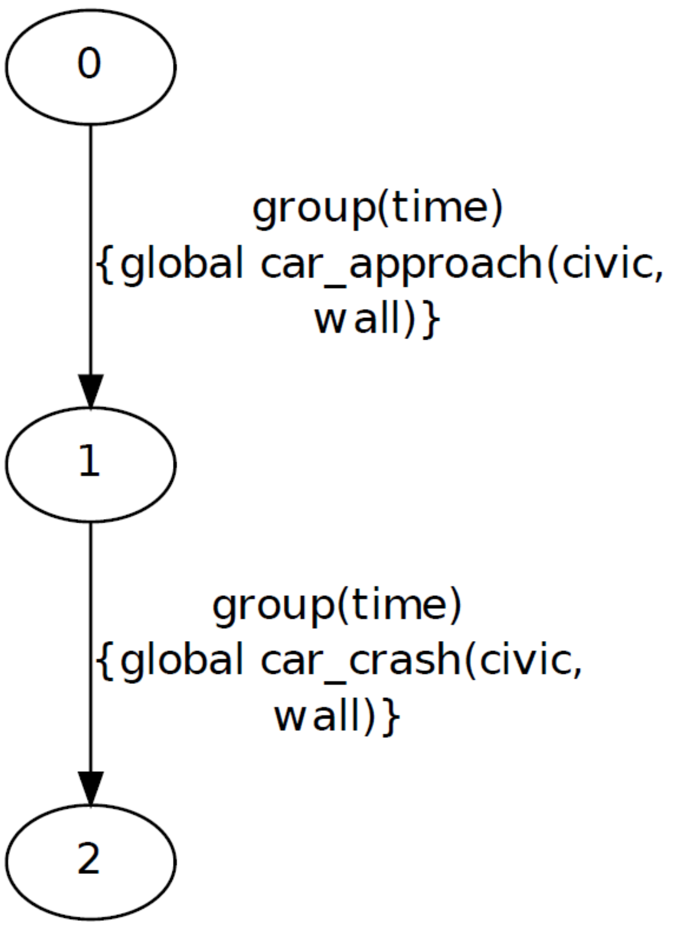
Additions

- Type system
  - Facts are “token” (string) or “real” valued
  - Types denoted by operators
    - Token
      - Assignment: =
      - Relational: =, !=
    - Real
      - Assignment: :=, +=, -=, *=, /=
      - Relational: ==, <>
  - Every test or assignment has an explicit type
- Real (but not token) values for topologies

Additions

- Modeling time
    - Implemented with exploits: `global group(time)`
    - Discretize time into steps of equal size
    - Each time attack is one timestep
- Automotive example

```
global group(time) exploit car_approach(c,w)=
    preconditions:
        platform:c,cpe:/h:honda;
        quality:c,compromised=true;
        platform:w,cpe:/h::wall;
        quality:c,status=up;
        topology:c<->w,distance>25;
    postconditions:
        update topology:c<->w,distance-=25;
.

global group(time) exploit car_crash(c,w)=
    preconditions:
        platform:c,cpe:/h:honda;
        quality:c,compromised=true;
        platform:w,cpe:/h::wall;
        quality:c,status=up;
        topology:c<->w,distance<=25;
    postconditions:
        update topology:c<->w,distance:=0;
        update quality:c,status=down;
.
```



RFID Example

- ISO 18000-7 RFID system used by DOD and DOE for inventory tracking
- Tags are active and battery powered
- Usage includes inventory on nuclear material containers
- Tags have “active” and “sleep” modes
- A “denial of sleep” attack from a rogue or compromised reader causes battery drain

RFID Example

```
network model =
    assets :
        attacker;
        reader;
        tag0;

    facts :
        # Reader:
        platform:reader,cpe:/h::VulnerableReader;
        quality:reader,status=up;

        # Tag:
        platform:tag0,cpe:/h::Tag;
        quality:tag0,status=up;
        quality:tag0,power:=100;
        quality:tag0,mode=sleep;

        # Topologies:
        topology:attacker -> reader,connected_netv
        topology:reader -> tag0,connected_rfid;
.
```

```
exploit own_reader(a, r)=
    preconditions:
        platform:r,cpe:/h::VulnerableReader;
        quality:r,status=up;
        topology:a->r,connected_network;
    postconditions:
        insert topology:a->r,access_admin;
.

exploit deny_sleep(a, r, t)=
    preconditions:
        platform:r,cpe:/h::VulnerableReader;
        quality:r,status=up;

        platform:t,cpe:/h::Tag;
        quality:t,status=up;
        quality:t,mode=sleep;

        topology:a->r,access_admin;
        topology:r->t,connected_rfid;
    postconditions:
        update quality:t,mode=wake;
.
```

Discrete exploits

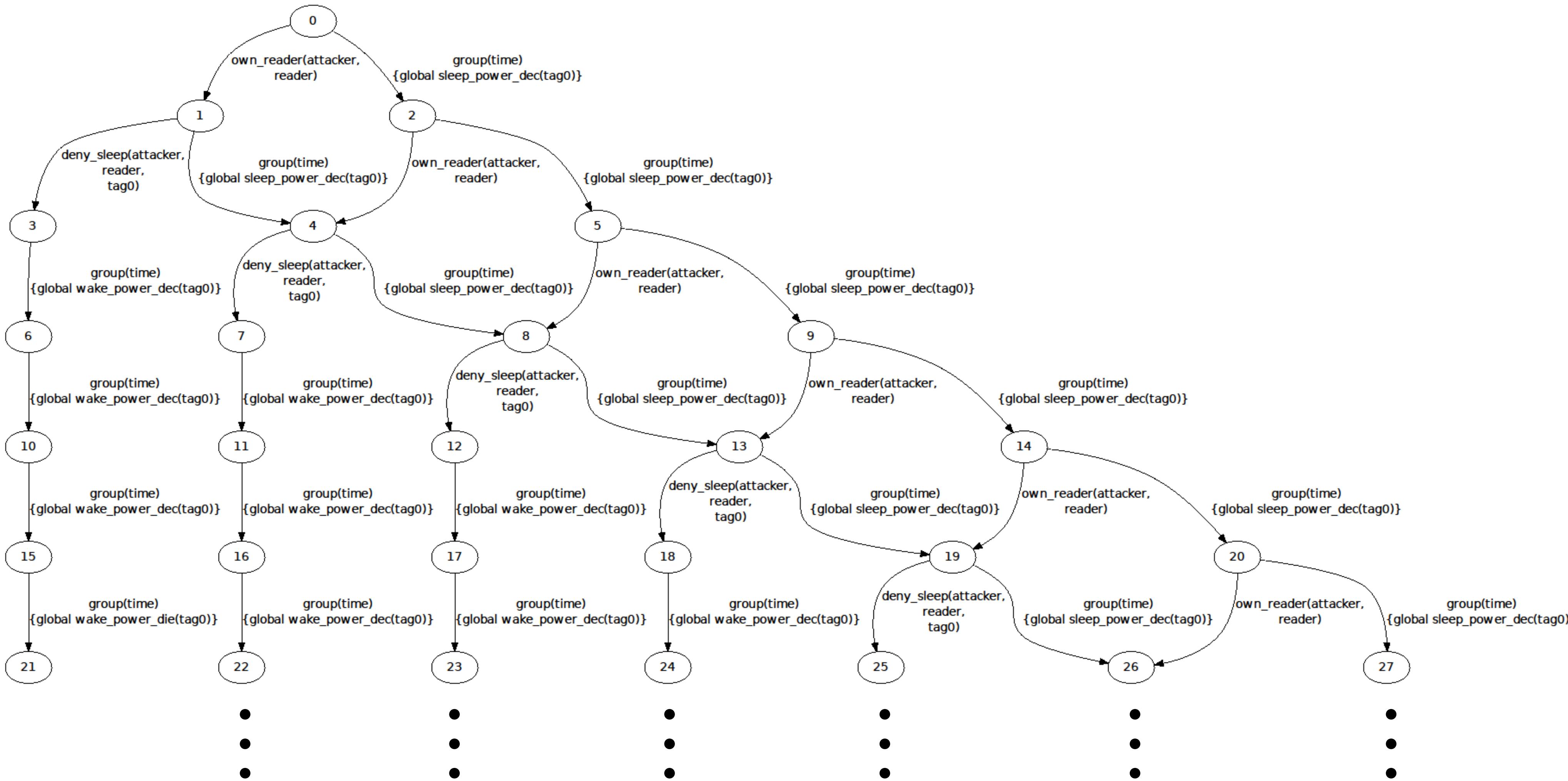
RFID Example

```
global group(time) exploit wake_power_dec(t)=
    preconditions:
        platform:t,cpe:/h::Tag;
        quality:t,status=up;
        quality:t,mode=wake;
        quality:t,power>25;
    postconditions:
        update quality:t,power-=25;
.

global group(time) exploit sleep_power_dec(t)=
    preconditions:
        platform:t,cpe:/h::Tag;
        quality:t,mode=sleep;
        quality:t,status=up;
        quality:t,power>10;
    postconditions:
        update quality:t,power-=10;
.
```

```
global group(time) exploit wake_power_die(t)=
    preconditions:
        platform:t,cpe:/h::Tag;
        quality:t,mode=wake;
        quality:t,status=up;
        quality:t,power<=25;
    postconditions:
        update quality:t,power:=0;
        update quality:t,status=down;
.

global group(time) exploit sleep_power_die(t)=
    preconditions:
        platform:t,cpe:/h::Tag;
        quality:t,mode=sleep;
        quality:t,status=up;
        quality:t,power<=10;
    postconditions:
        update quality:t,power:=0;
        update quality:t,status=down;
.
```

Time exploits

RFID Example



Performance

Domain	Symbol
Facts	$F = \lvert \mathcal{Q} + \mathcal{T} \rvert$
Fact names	f
Exploits	$E = \lvert \mathcal{E} \rvert$
Depth	d
Assets	$A = \lvert \mathcal{A} \rvert$
Qualities	$Q = \lvert \mathcal{Q} \rvert$
Topologies	$T = \lvert \mathcal{T} \rvert$
Most preconditions in any exploit	p
Most postconditions in any exploit	P
Most parameters in any exploit	a
Possible asset bindings	B

Build attack graph $O(1)$

$$O\left(\left(\left(\frac{A!}{(A-a)!}\right)E\right)^d\right)$$

- **Load initial state** $O(F)$
- **Load exploits** $O(E)$
- **Generate attack graph (recursive)** $O(d)$
  - **For each analysis state** $O(states)$
    - **Copy network model** $O(A) + O(F)$
    - **Get valid attacks** $O(1)$
      - **For attack in attack bindings** $O(BE)$
        - **Validate attack** $O(p)$, which is technically bounded by $O(A^2) \cdot O(F)$ but is in practice quite small
        - **Process groups and globals** $O(1)$
    - **For each valid attack** $O(BE)$
      - **Get successor state** $O(1)$
        - **Build network model** $O(A) + O(F)$
        - **Add postconditions** $O(P)$, which is technically bounded by $O(A^2F)$ but is in practice quite small.

Performance

Domain	Symbol
Facts	$F = \|\mathcal{Q} + \mathcal{T}\|$
Fact names	f
Exploits	$E = \|\mathcal{E}\|$
Depth	d
Assets	$A = \|\mathcal{A}\|$
Qualities	$Q = \|\mathcal{Q}\|$
Topologies	$T = \|\mathcal{T}\|$
Most preconditions in any exploit	p
Most postconditions in any exploit	P
Most parameters in any exploit	a
Possible asset bindings	B

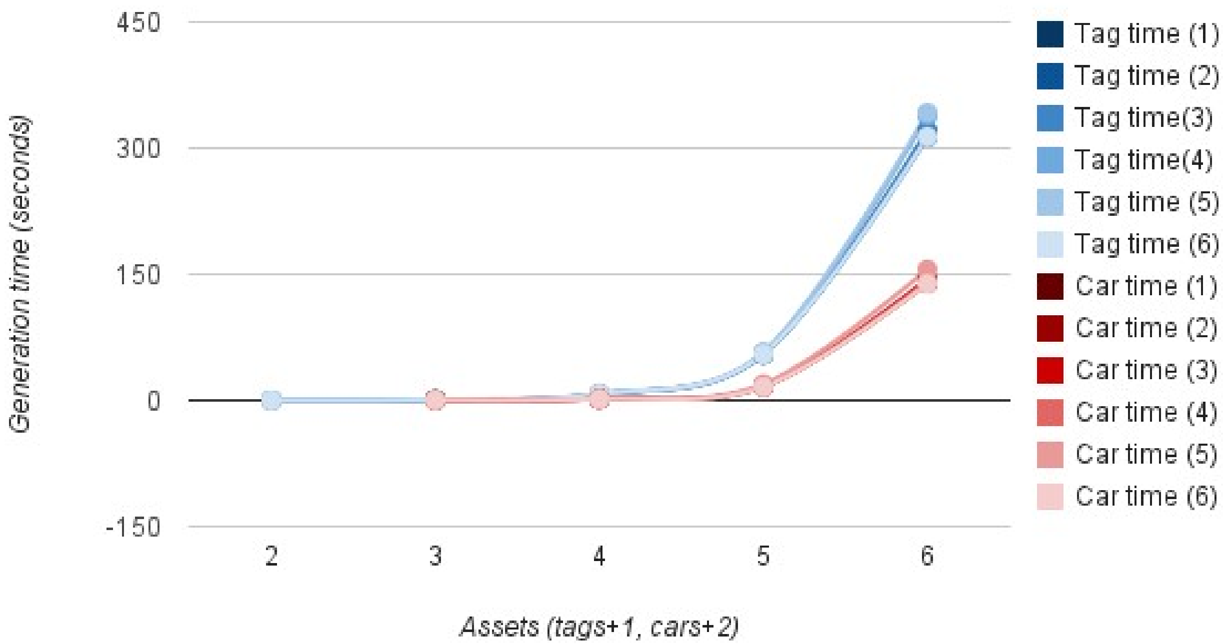
$$O((A^A E)^d((A + A^2 f) + A^A E A + A^A E(A + A^2 f + A)))$$

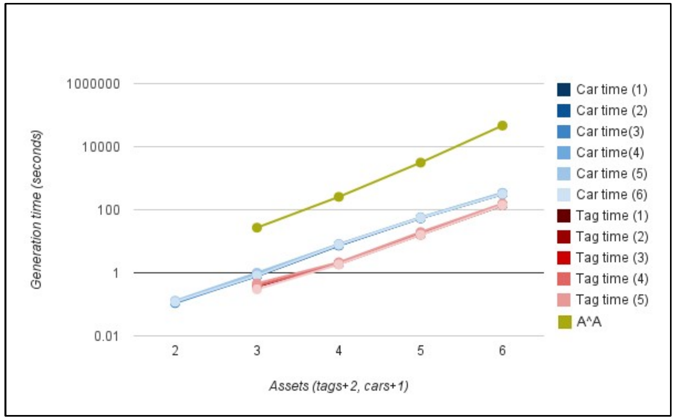
$$= O(f E A^{Ad+A+2})$$

$$= O(E^{d+1} f A^{A(d+1)+2})$$

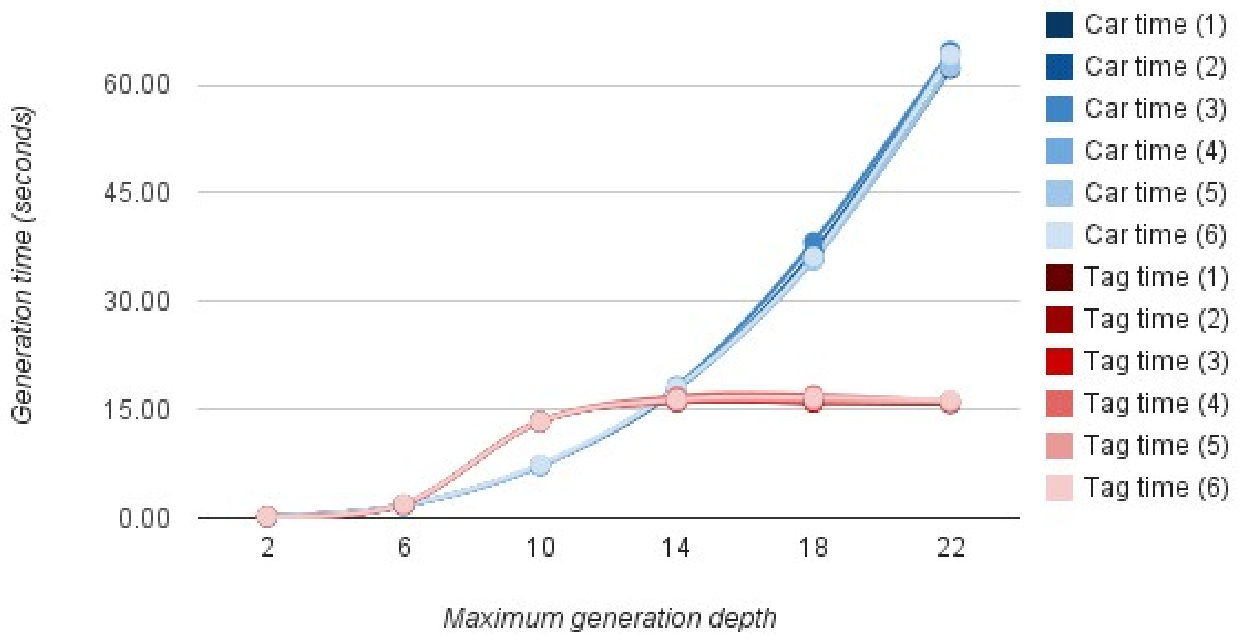
$$\approx O(E^{d+1} f A!^d) \text{ (in a mild abuse of notation)}$$

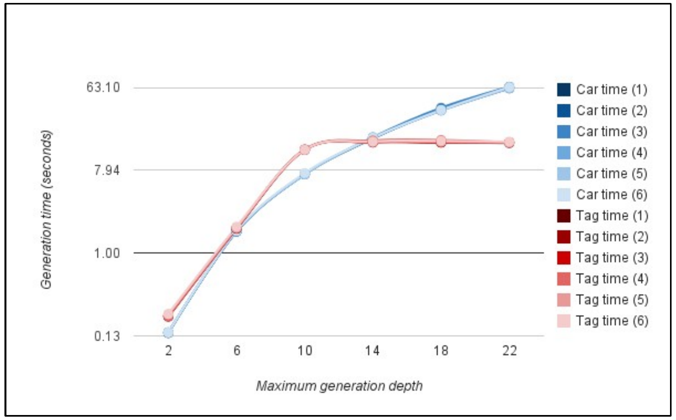
Performance – Number of assets





Performance – Generation depth





Performance Summary

- Execution time scales factorially with input assets and exponentially with maximum depth
- Falls well short of the state of the art
  - This is expected
  - This is fine

Conclusions – Summary

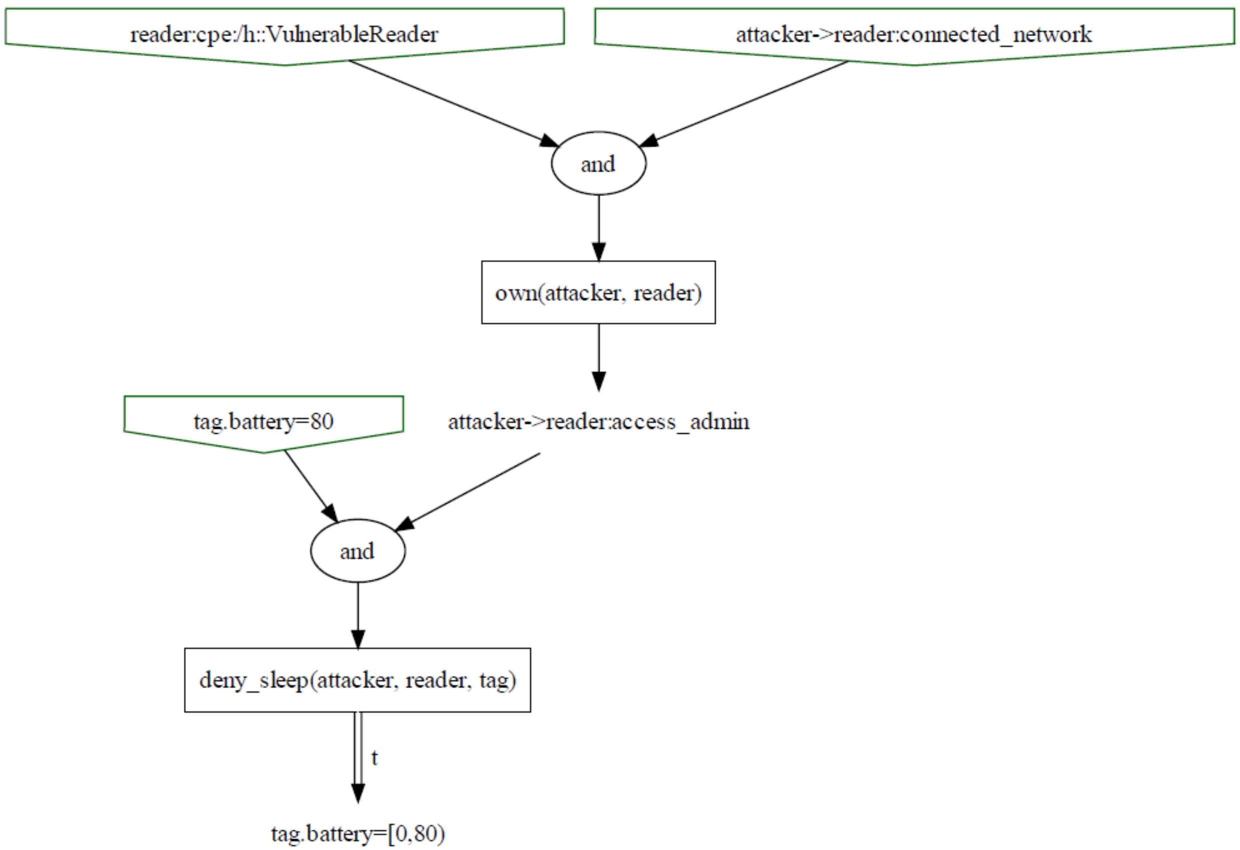
- Enhanced discrete attack graph with applications to information systems (IS)
- Expanded attack graph with applications to CPS, possibly to IS as well
- Faithfully model well-behaved subset of hybrid systems
- Falls short of the state of the art in performance

Conclusions - Challenges

- Performance
  - HAGs make little changes to algorithmically expensive portions of the generation process, however
- Cognitive scalability
  - Even more marked in time driven HAGs
- Model acquisition
- Less serious:
  - Separation of concerns (exploits vs. network)
  - Wildcard and pivot exploits
  - Complex preconditions
  - Variable hybrid postconditions (HA applications)

Future Work

- Hybrid attack dependency graphs



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