

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

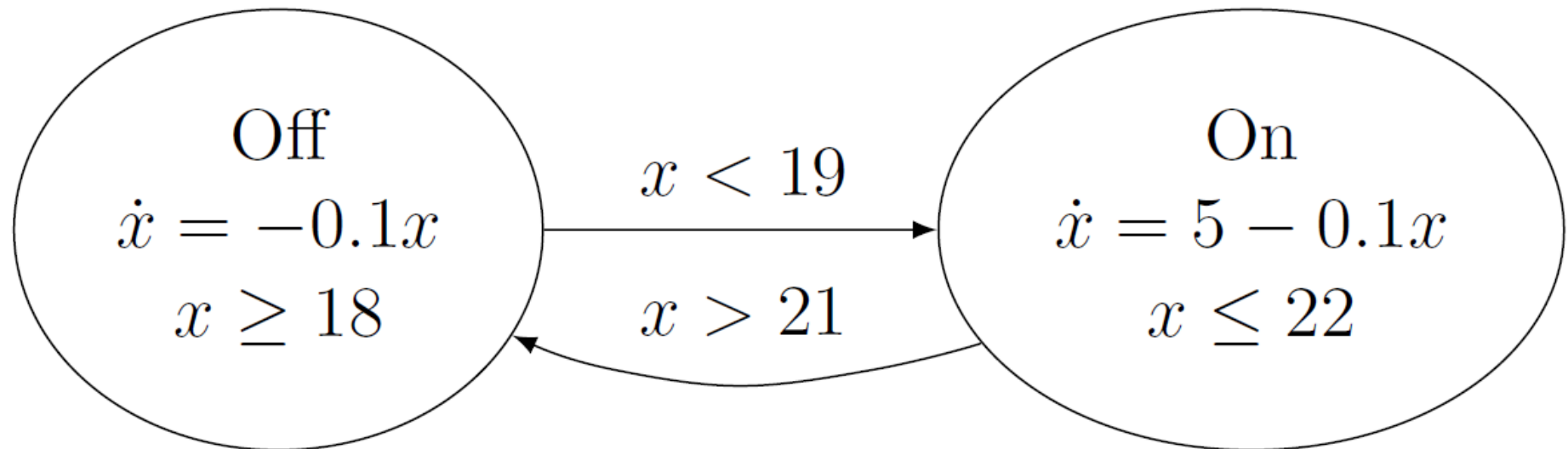
- Discrete domain formalism grounded in graph theory
- Model networks, systems, and attacks
- Excel at highlighting systems' and attacks' interactions

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



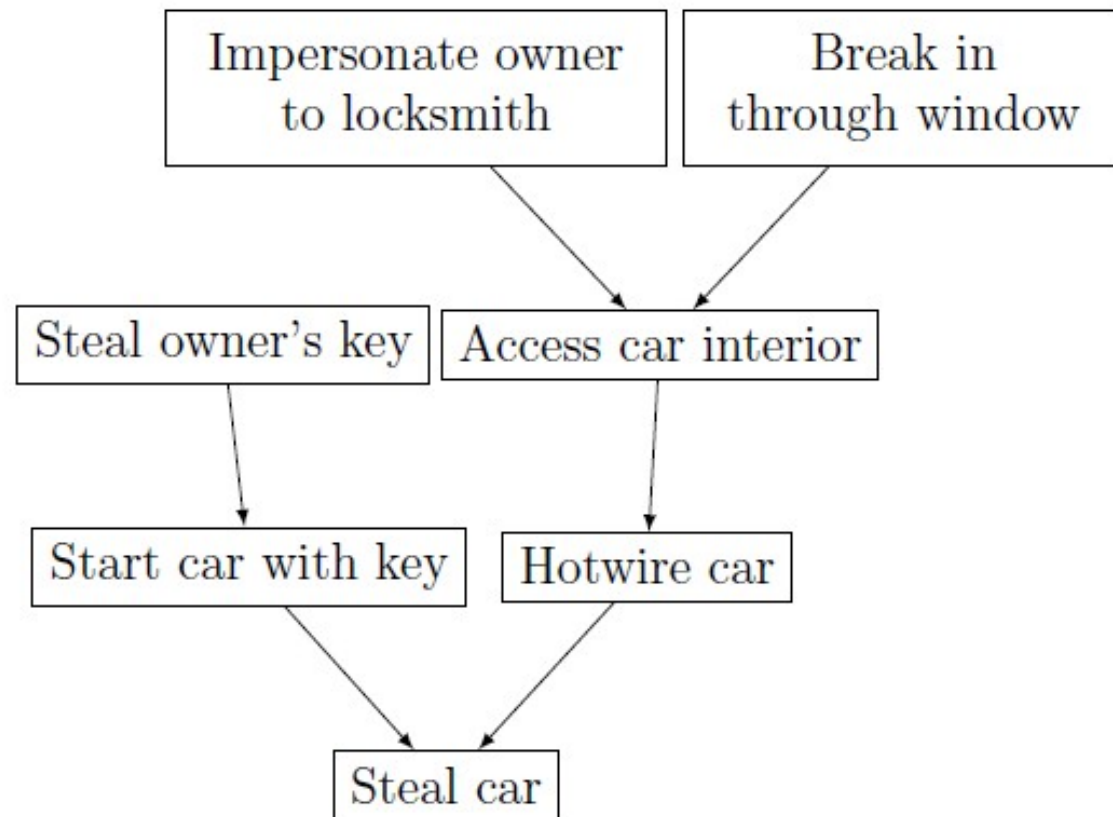
Background – HAs

- Idiomatic of hybrid systems modeling
 - Differential equations
 - Operating modes with guards
 - Limited composition capability
- Idea:
 - Model “micro” scale with HA like strategy
 - Model “macro” scale with AGs

Background – Attack graphs

- Best understood in relation to attack *trees*
- Attack trees:
 - Goal-oriented model of a system abuse
 - Root is “goal”
 - Children encode prerequisites

Background – AGs – Attack Tree example

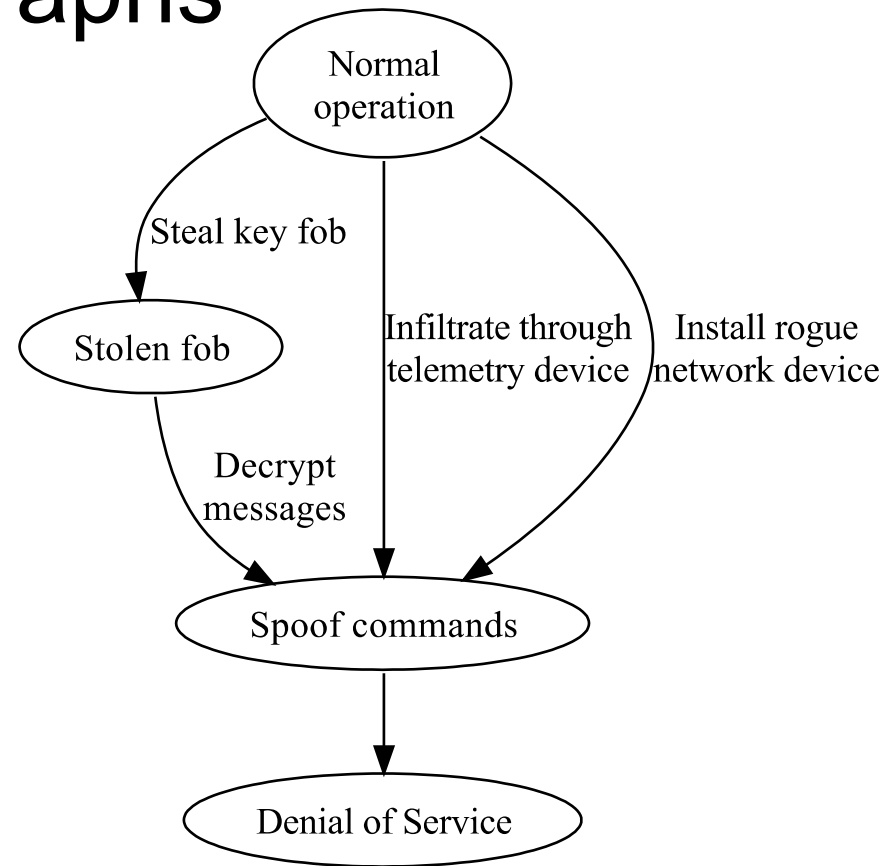


Background – Attack Graphs

- What if we want to “work forwards” – start with a system characterization and explore its possible abuses?
- What about automating this (basically a formal, simulated penetration test)?
- Attack graphs

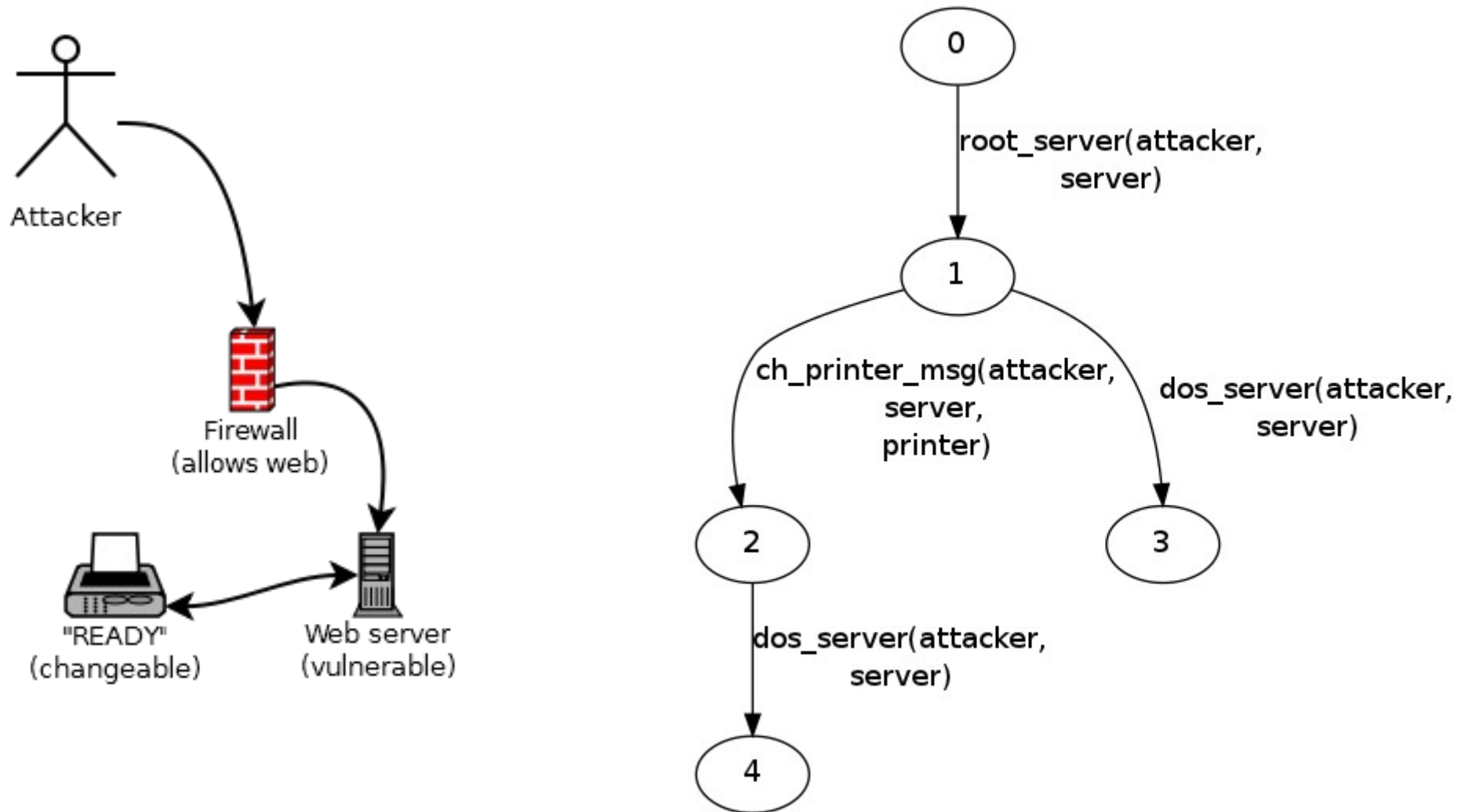
Background – Attack Graphs

- Formal model for network attacks
- Uses graph theory to represent attacks
- Automatic generation: matches “exploit patterns” to network objects to create chains
- Network model + exploit patterns + generator = attack graph



Hand-generated attack graph for locking a driver out of a car

Background – Attack Graphs – Example

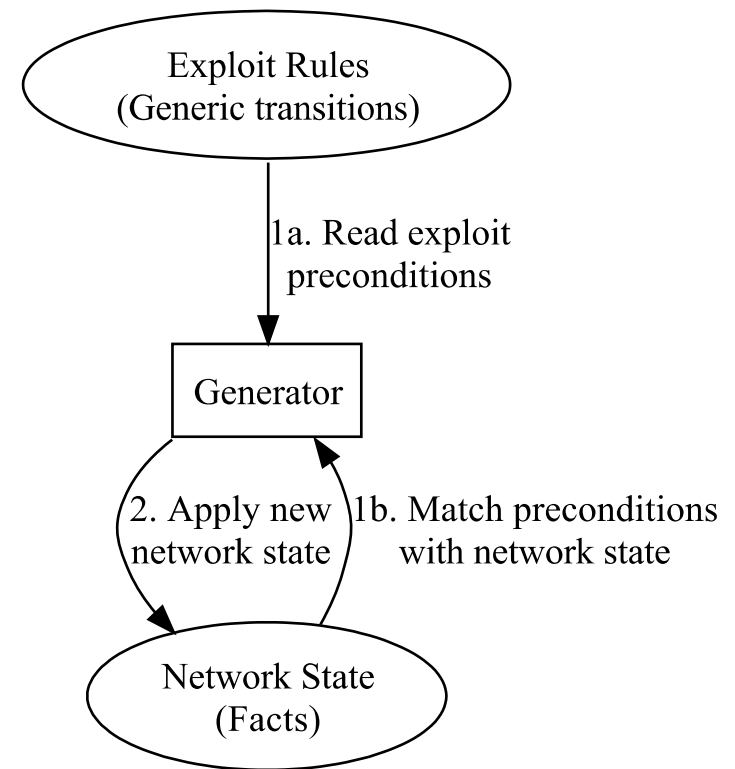


Background – Attack Graphs – Approaches

- 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 model)
- Other mixins:
 - Metrics
 - Likelihood weights
 - Adversary characterization
 - Cost (\$\$\$) of mitigation

Background – Attack Graphs – Framework

- Underlying model based on “assets” and “facts”
 - Assets – network objects
 - Qualities – property facts about assets
 - Topologies – relationship facts between assets
- Set of assets + set of facts = state
- Exploits match states' facts and generate new states



Automated attack graph
generation process

Background – Attack Graphs – Domains

Network
Model

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)

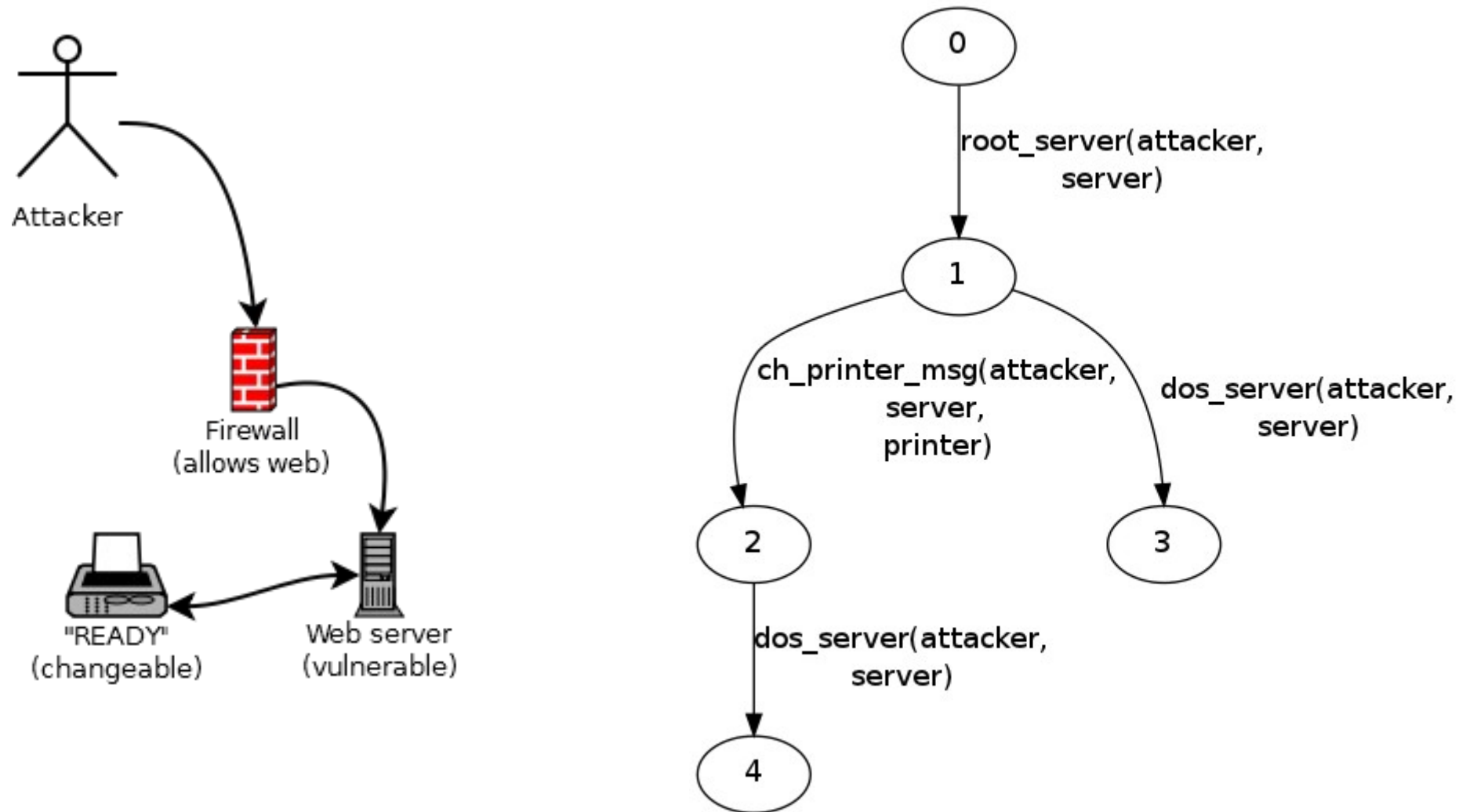
Enhanced Discrete Attack Graphs - Lexicon

- 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;
```

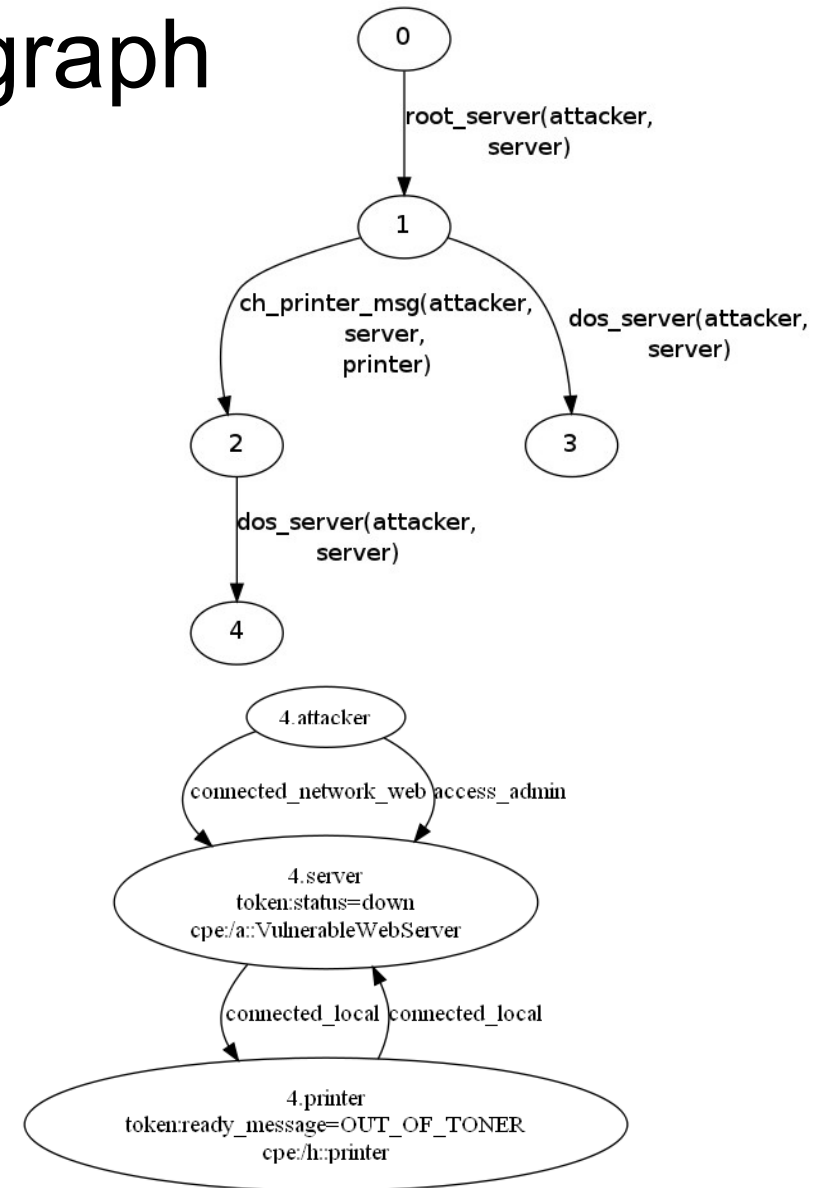
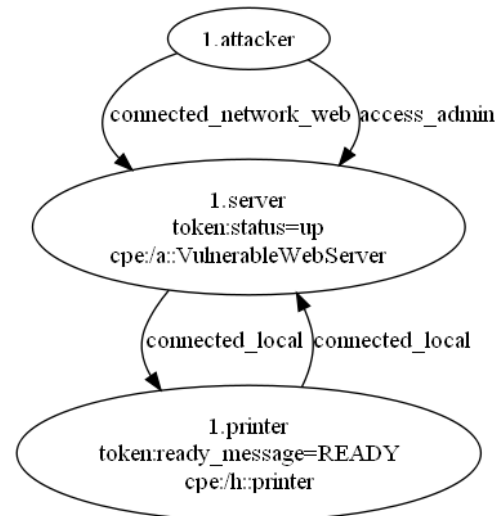
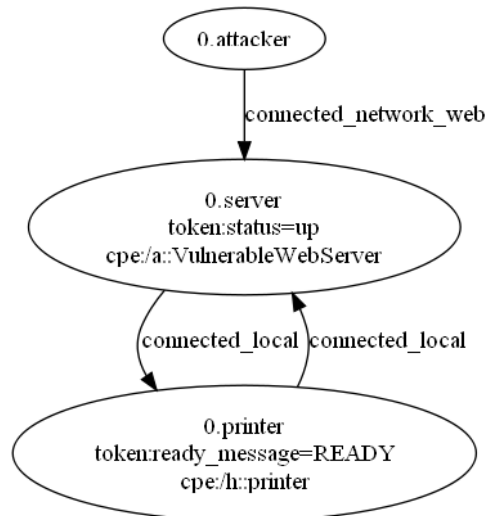
EXPLOIT PATTERNS

```
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;
```


Scenario example – Attack graph



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 (HAG)

- AG excel at modeling disparate components' interactions
 - Recall that this is a principal challenge in CPS
- HAG extend AG 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)=
```

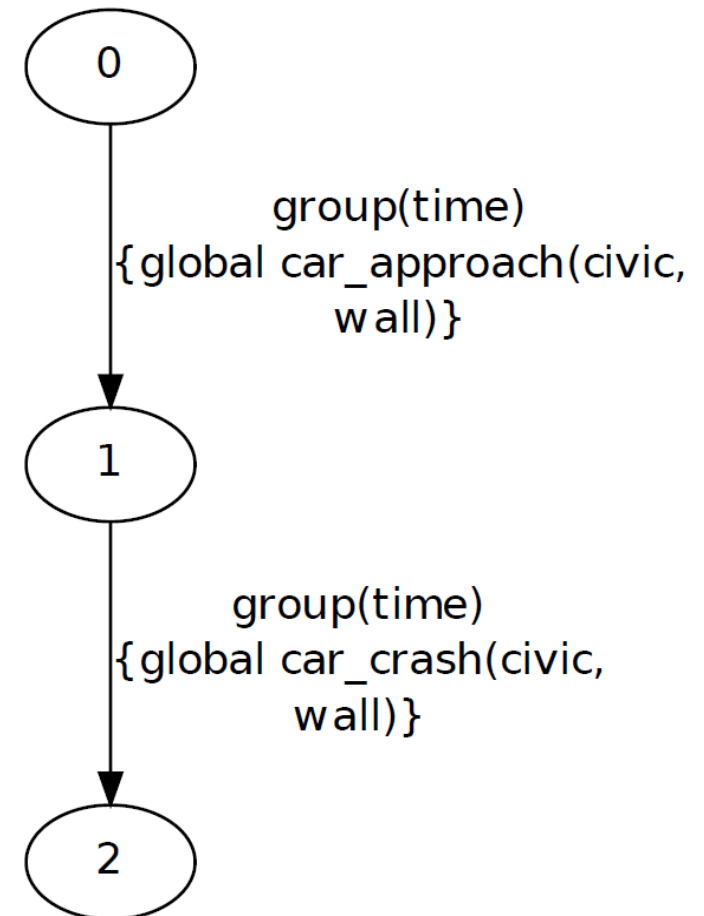
```
preconditions:
```

```
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_network;
    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;
  .

```

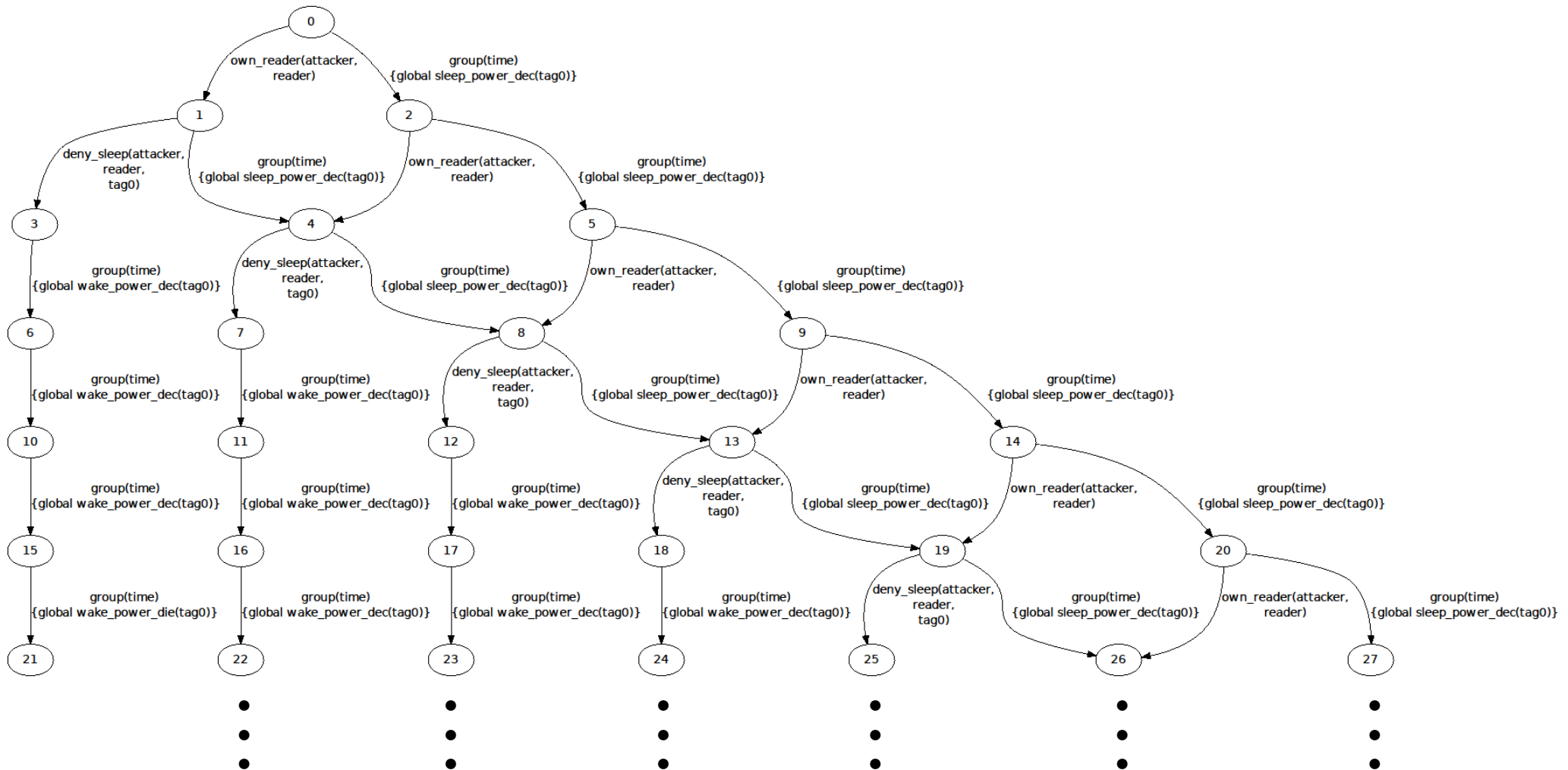
```

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 = \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

Build attack graph $O(1)$

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.

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

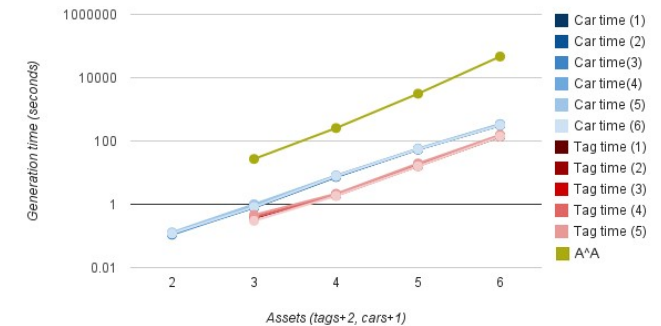
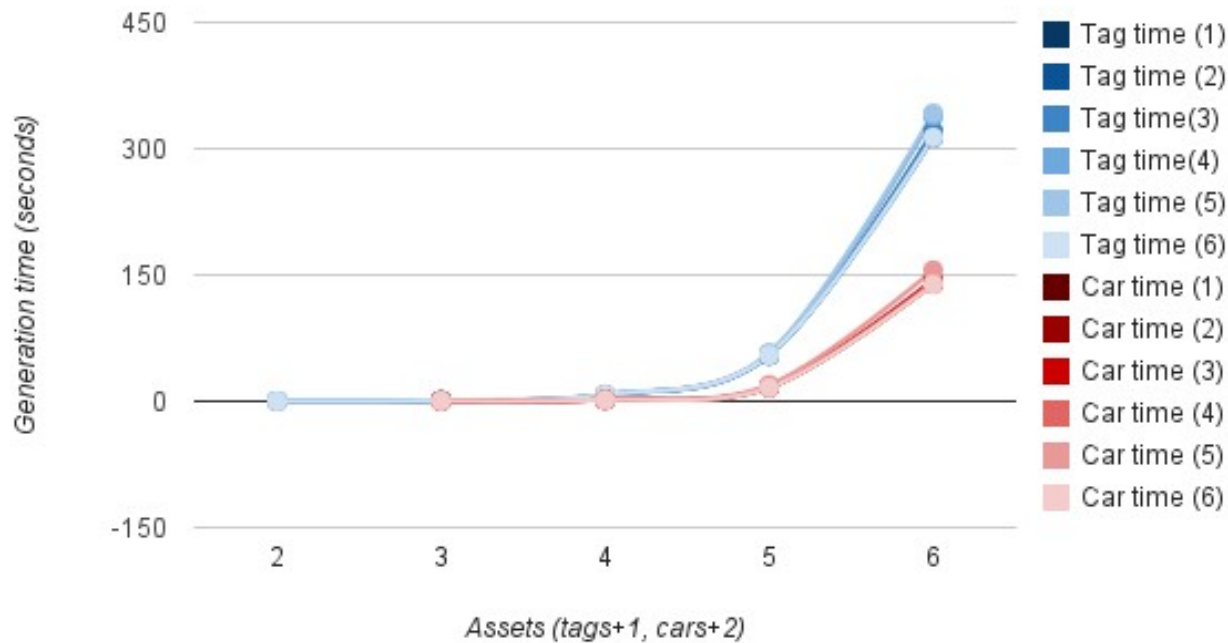


Performance

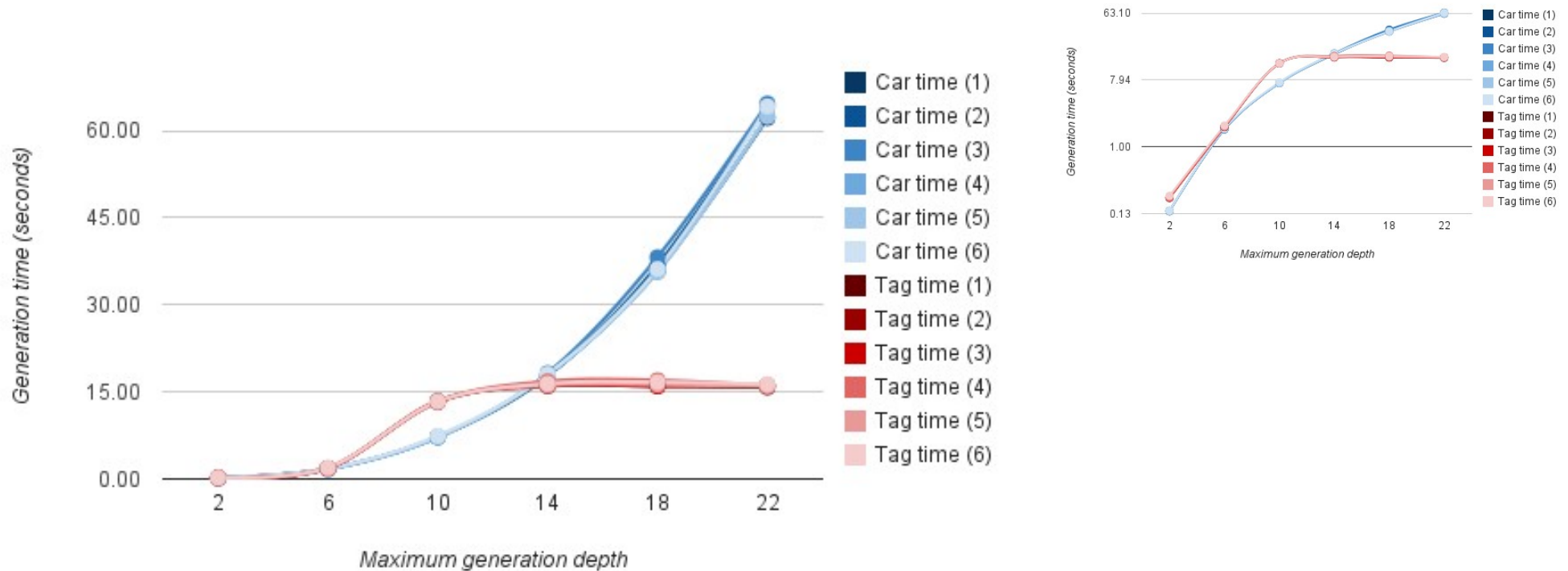
Domain	Symbol
Facts	$F = \mathcal{Q} + \mathcal{T} $
Fact names	f
Exploits	$E = \mathcal{E} $
Depth	d
Assets	$A = \mathcal{A} $
Qualities	$Q = \mathcal{Q} $
Topologies	$T = \mathcal{T} $
Most preconditions in any exploit	p
Most postconditions in any exploit	P
Most parameters in any exploit	a
Possible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

$$\begin{aligned}
 &O((A^A E)^d((A + A^2 f) + A^A E A + A^A E(A + A^2 f + A))) \\
 &= O(f E A^{Ad+A+2}) \\
 &= O(E^{d+1} f A^{A(d+1)+2}) \\
 &\approx O(E^{d+1} f A!^d) \text{ (in a mild abuse of notation)}
 \end{aligned}$$

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 was expected
 - This is fine

Conclusions – Summary

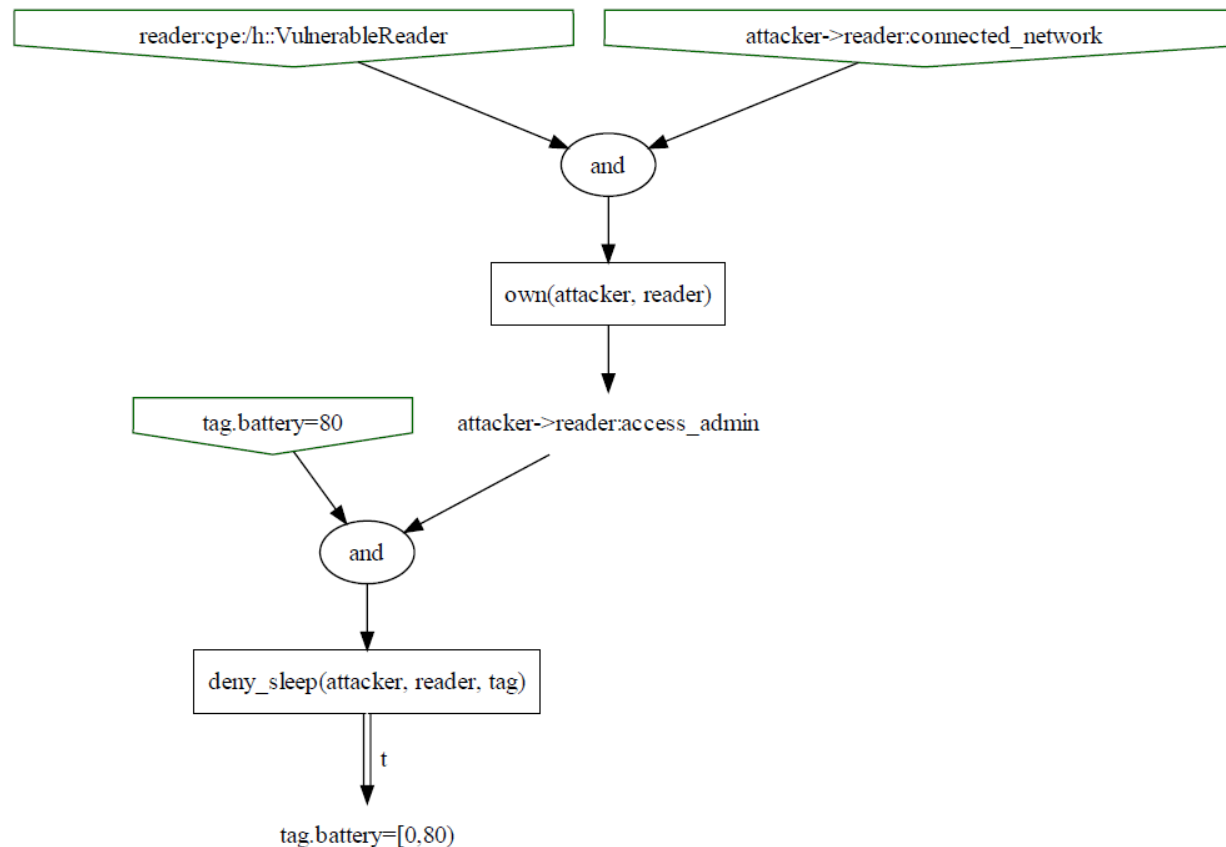
- Enhanced discrete attack graph with applications to information systems (IS)
- Expanded attack graph with applications to CPS, possibly to IS as well
- Faithfully model well-behaved subset of hybrid systems
- Falls short of the state of the art in performance

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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