Software Foundations of Security & Privacy 15315 Spring 2017 Lecture 5: Execution Monitoring, Security Automata

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Runtime enforcement (review)

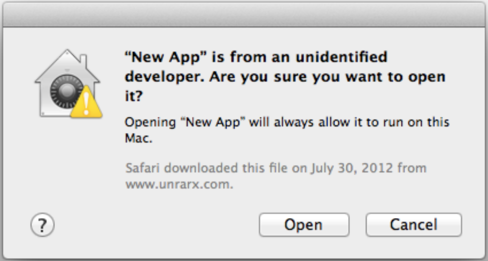
Our focus: policies enforceable by **execution monitors**

Execution Monitor (EM)

An execution monitor is a coroutine that executes in parallel with a **target** program or system.

- Monitor steps of a *single* execution
- Compare observed behavior against a policy
- Terminate the program when policy is violated

Execution monitor examples (review)



- Filesystem access control
- Firewall
- Stack inspection
- Dynamic bounds checking

What's *not* EM? (review)

anything that uses more information than what's available from a single execution of the program/system

In particular, this excludes:

- Information about *future* steps
- Alternative *hypothetical* executions
- *All possible* executions

As we'll see this excludes some important properties

Formalizing execution (review)

A target S is characterized by:

- A set of **atomic actions** A
- A set of sequences Σ_S of elements from A

Sequences in Σ_S can be finite or infinite

What might A look like?

- Set of program states: mappings from *variables* to *values*
- Set of all system calls: `open`, `send`, ...
- Set of primitive commands in server scripting language

Example

How might we model the following program?

Ultimately, our goal is to enforce the policy:

"No `send` after `read`"

```
while(read(&buf, &len, fp)) {
  if(buf[0] == 255)
    send(sock, buf, len);
  printf("%s", buf);
}
```

$$A = \{\mathtt{read}, \mathtt{send}\}$$

$$\Sigma_S = \left\{ \begin{array}{l} [\mathtt{read}, \mathtt{read}, \ldots] \\ [\mathtt{read}, \mathtt{send} \ldots] \\ [\mathtt{read}, \mathtt{send}, \mathtt{read} \ldots] \\ \ldots \end{array} \right\}$$

Formalizing policies (review)

Let Ψ denote the universe of all possible executions in A

- Note: Ψ is not the same as Σ_S
- It contains executions that may not be possible in S
- In particular, $\Sigma_S \subseteq \Psi$

Policy

A **policy** P is a predicate on *sets* of executions. In other words,

$$P \subseteq 2^{\Psi}$$

A target S satisfies P if and only if $\Sigma_S \in P$.

Aside: predicates

A **predicate** f over domain D is a Boolean-valued function:

$$f : D \mapsto \{0, 1\}$$

Predicates specify subsets of their domain

- Let D_f denote the subset of D specified by f
- In set builder notation, D_f is the set:

$$D_f = \{d \in D \mid f(d) = 1\}$$

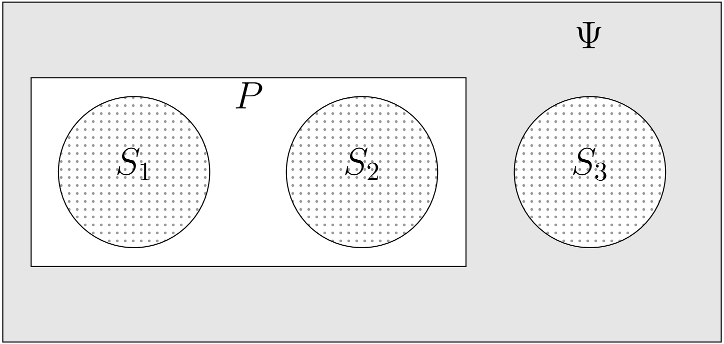
- Often, we don't distinguish between the function symbol f and the set that it represents

So, you can think of a policy P as either

- A subset of the *set of all sets* of executions: $P \subseteq 2^\Psi$
- Or, a Boolean function $P : 2^\Psi \mapsto \{0, 1\}$

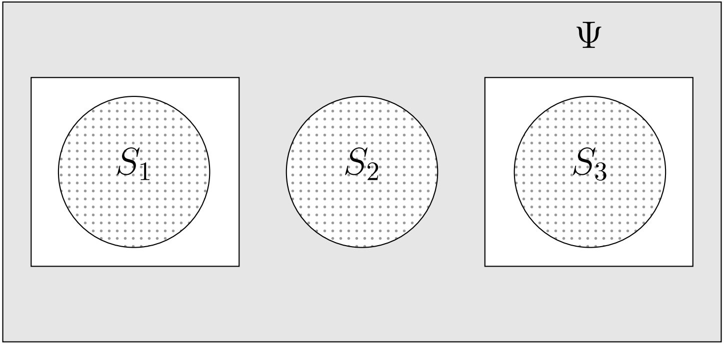
Formalizing policies: intuition

Intuition: a policy is a set whose elements correspond to *systems that are allowed to execute*



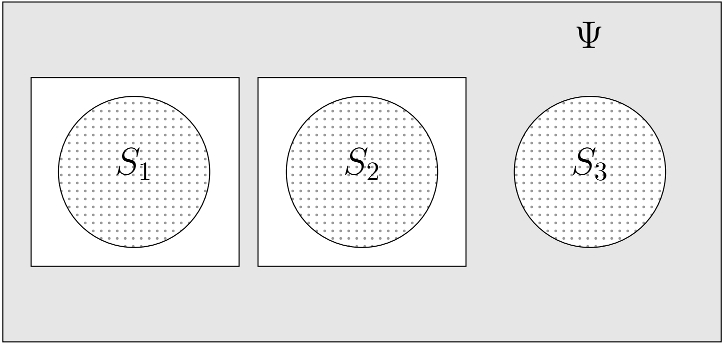
Formalizing policies: intuition

Policies can specify *any* subset of systems



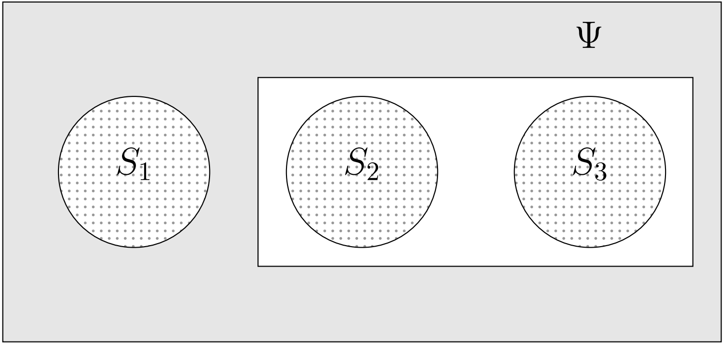
Formalizing policies: intuition

Policies can specify *any* subset of systems



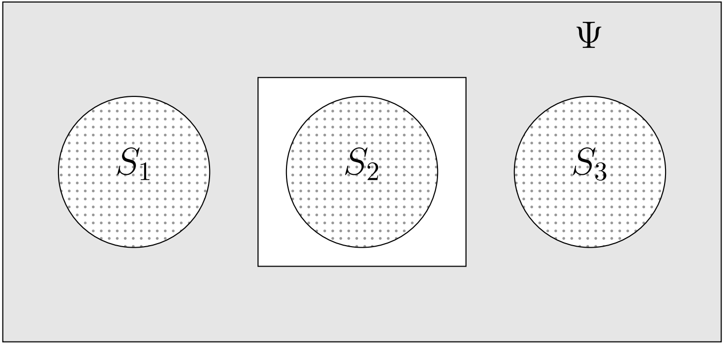
Formalizing policies: intuition

Policies can specify *any* subset of systems



Formalizing policies: intuition

Policies can specify *any* subset of systems



Example

Suppose that we want a simple policy

```
while(read(&buf, &len, fp)) {
  if(buf[0] == 255)
    send(sock, buf, len);
  printf("%s", buf);
}
```

"No `send` after `read`"

$$P = \left\{ \begin{array}{l} \{[\mathtt{read}], [\mathtt{read}, \mathtt{read}], \ldots\} \\ \{[\mathtt{send}], [\mathtt{send}, \mathtt{read}], [\mathtt{send}, \mathtt{send}, \mathtt{read}], \ldots\} \\ \ldots \end{array} \right\}$$

All sets of sequences where `send` only comes after `read`

Formalizing execution monitoring (review)

Recall the key feature of EM:

- Must work by *monitoring the execution of a single execution*

We should be able to express P using simpler means

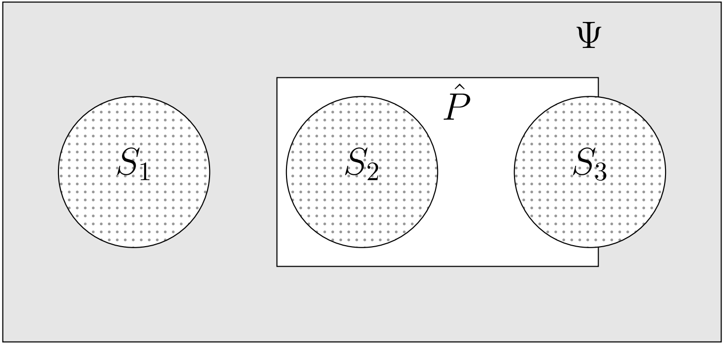
- Let $\hat{P} \subseteq \Psi$ be a set of executions
- We can define $\hat{P}$ so that:

$$\Sigma_S \in P \iff \sigma \in \hat{P} \text{ for all } \sigma \in \Sigma_S$$

Intuition: think of $\hat{P}$ as something like a *regular expression* over executions

Execution monitoring: intuition

Now policies can't necessarily specify any subset of systems



A system is allowed if it is a *subset* of $\hat{P}$

Example

Let's revisit the policy from before

```
while(read(&buf, &len, fp)) {
  if(buf[0] == 255)
    send(sock, buf, len);
  printf("%s", buf);
}
```

"No `send` after `read`"

$$\hat{P} = \left\{ \begin{array}{l} [\mathtt{read}, \mathtt{read}, \ldots], \\ [\mathtt{send}, \mathtt{read}, \ldots], \\ [\mathtt{send}, \mathtt{send}, \mathtt{read}], \\ \ldots \end{array} \right\}$$

We only have a *single* set

Don't need to specify a different set for each allowed system

Which policies are enforceable? (review)

We know they have to be expressible in terms of $\hat{P}$

- i.e., policies determined by each element in Σ_S alone
- These are called **properties**

Are all properties enforceable?

- Recall: can't use information about *future* steps
- So if σ' is a **prefix** of σ and $\sigma' \notin \hat{P}$, but $\sigma \in \hat{P}$
- ...then P isn't enforceable

Prefix closure

Enforceable policies are **prefix-closed**:

- If a trace is in $\hat{P}$ then so are all its prefixes
- If a trace isn't in $\hat{P}$, then none of its extensions are

Prefix closure

Suppose that $\sigma = bad$ is **disallowed**: $\sigma \notin \hat{P}$

- All possible extensions of σ' are also disallowed!
- $badd$, $bada$, $badb$, $badda, \ldots \notin \hat{P}$
- The sequence bad is a **bad thing**
- Once it occurs, there's no way to fix it
- Ex.: leaking password over network, overwriting a file, ...

Suppose that $\sigma = good$ is **allowed**: $\sigma \in \hat{P}$

- All prefixes of σ are also allowed
- g, go, goo, $good$
- But an extension of $good$ **might** be disallowed
- Ex.: `send`,`read` is allowed in policy from before
- But `send`,`read`,`send` is not

More prefix closure

What about the policy:

> "No `send` after `read`, unless `send` is followed by `close`"

This does not have prefix closure

- `read,send,close` is **allowed**
- `read,send` is **disallowed**

To enforce this policy at runtime, we have two options:

- Look into the future to see if the next symbol is `close`
- Wait to see the next symbol after `send` to decide

Why prefix closure is desirable

The “wait and see” approach doesn’t seem too unreasonable

Why do we forbit it by insisting on prefix closure?

After waiting, *the damage might already be done*

- Think of “send after read”: once the data is sent, there’s no taking it back
- We’d like to terminate execute **before** the bad thing happens

With that said, some reasonable policy ideas might need “speculative” enforcement

- Ex.: transactional semantics in assignment 1
- For now, we’re focusing on a simpler notion of enforcement
- Later, we’ll consider more complicated ones

Practical matters

Our goal: define policies that can be enforced *for real*

- We need to know if a policy violation is underway
- We have finite time to wait around for this to happen

Finite refutability

A property P is **finitely refutable** if whenever a trace σ is *not* in $\hat{P}$, there exists some *finite prefix* σ' of σ that is also not in $\hat{P}$.

$$\sigma \notin \hat{P} \Longleftrightarrow \exists i . \sigma[..i] \notin \hat{P}$$

where $\sigma[..i]$ corresponds to the subsequence of σ from its beginning to position i.

Finite refutability

Intuition: We can always write down a **witness** that explains why an execution violates the policy

- The witness is the finite prefix σ'
- The fact that it is finite allows us to write it down

In the "no send after read" example:

- Given `send`,`read`,`send`,`read`,`read`
- `send`,`read`,`send` is the witness
- It ends with the "bad thing", is sufficient to prove violation

More pragmatics

Prefix closure and **finite refutability** simplify matters further:

- We don't need to specify *all allowed executions*
- Instead, specify a set of finite prefixes

These prefixes are "bad things" disallowed by the policy

- Because our policies are properties, we look for bad things in "real time" on a single execution
- By prefix closure, once we see the bad thing happen, we know the policy is permanently violated
- By finite refutability, if a policy violation happens we will detect it in finite time
- Plus, we can give a witness to prove that it was violated

Enforceable policies

Properties satisfying prefix closure and finite refutability are called **safety properties**

What policies are safety properties?

- **Access control**, defined broadly as policies that proscribe unacceptable operations. This includes filesystem permissions, bounds checking, read-xor-execute, ...
- **Information flow** is *not* safety: it cannot be defined in terms of individual executions. Did we define information flow with "no send after read"?
- **Availability** is *not* safety: any partial execution can be *extended* to grant access to the resource in question, so we can't define a set of finite prefixes to characterize availability.

Safety and information flow

Before, we actually enforced
"no send after read"

Ideally, we wanted to prevent:

$$\texttt{fp} \longrightarrow \texttt{sock}$$

How is our *actual* policy *not* the same?

This policy *approximates* information flow

- Prevents flow from happening
- Also prevents other things

```
while(read(&buf, &len, fp)) {
  if(buf[0] == 255)
    send(sock, buf, len);
  printf("%s", buf);
}
```

```
while(read(&buf, &len, fp)) {
  memset(buf, 0, len);
  send(sock, buf, len);
  printf("%s", buf);
}
```

Does this flow `fp` to `sock`?

Information flow isn't EM-enforceable

Suppose x and y are bits

```
if(x)
  y = 0;
else
  y = 1;
```

With executions:

$$\left\{\begin{array}{c} [(x \mapsto 0, y \mapsto 0), (x \mapsto 0, y \mapsto 1)] \\ [(x \mapsto 0, y \mapsto 1), (x \mapsto 0, y \mapsto 1)] \\ [(x \mapsto 1, y \mapsto 0), (x \mapsto 1, y \mapsto 0)] \\ [(x \mapsto 1, y \mapsto 1), (x \mapsto 1, y \mapsto 0)] \end{array}\right\}$$

What *is* information flow from x to y?

Changes to x cause changes in y

A thought experiment

Let S_1:

```
if(x)
  y = 0;
else
  y = 1;
```

And S_2:

```
x, y = 0, 1;
```

And S_3:

```
x, y = 1, 0;
```

What's going on?

- S_1 flows information from x to y
- S_2, S_3 do not
- Together, S_2, S_3 can replicate all executions of S_1

$$\left\{ \begin{array}{c} [(x \mapsto 0, y \mapsto 0), (x \mapsto 0, y \mapsto 1)] \\ [(x \mapsto 0, y \mapsto 1), (x \mapsto 0, y \mapsto 1)] \\ [(x \mapsto 1, y \mapsto 0), (x \mapsto 1, y \mapsto 0)] \\ [(x \mapsto 1, y \mapsto 1), (x \mapsto 1, y \mapsto 0)] \end{array} \right\}$$

A thought experiment

Let S_1:

```
if(x)
  y = 0;
else
  y = 1;
```

And S_2:

```
x, y = 0, 1;
```

And S_3:

```
x, y = 1, 0;
```

Experiment as follows:

1. You pick an initial value for x, show it to me.
2. I (secretly) pick $i \in \{1, 2, 3\}$, run S_i on your input to get execution σ.
3. You see σ, try to guess i.

Suppose you pick $x = 0$ initially

Now I show you:

$$\sigma = [(x \mapsto 0, y \mapsto 0), (x \mapsto 0, y \mapsto 1)]$$

How to distinguish between S_1 and S_2?

A (modified) thought experiment

Let S_1:

```
if(x)
  y = 0;
else
  y = 1;
```

And S_2:

```
x, y = 0, 1;
```

And S_3:

```
x, y = 1, 0;
```

New experiment as follows:

1. You pick **two** initial values for x.
2. I (secretly) pick $i \in \{1, 2, 3\}$, run S_i on your inputs.
3. You see the executions σ_1, σ_2, try to guess i.

Now you win every time

Hyperproperties

Information flow is a *hyperproperty*

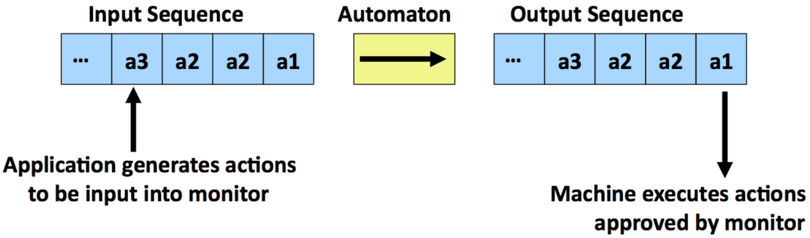
In particular, it is *2-safety*:

- Finitely refutable over *pairs* of traces

Can generalize to k-safety

- Lots of interesting properties...
- Quantitative privacy
- Statistical availability

Security automata



- Formal model of an execution monitor
- "Language" for specifying policies
- Corresponds to $\hat{P}$ from before

Image credit: Lujo Bauer

Security automata

Security automaton

A **security automaton** is a non-deterministic finite or infinite-state automaton defined by:

- Q: a countable set of **automaton states**
- $Q_0 \subseteq Q$: a countable set of **initial states**
- I: a countable set of **input symbols**
- $\delta : (Q \times I) \mapsto 2^Q$: a **transition function**

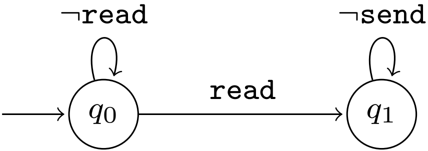
Security automata: semantics

Notice: no accepting states

Let Q' be the *current states*

To process execution $s_1 s_2 \ldots$:

1. Read the next input symbol s_i
2. Change Q' to
$$\bigcup_{q \in Q'} \delta(q, s_i)$$
3. If Q' ever becomes empty, the input is rejected



An action is allowed if a transition exists for it

Can process both finite and infinite sequences!

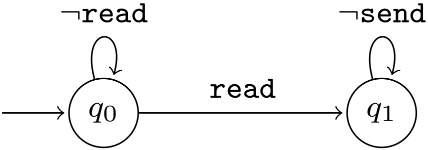
Security automata: input symbols

We label edges with *transition predicates*

- Boolean-valued and total
- Domain: I

Let p_{ij} label edge between states i, j

- p_{ij} specifies a **subset of** I
- $p_{ij}(s)$ is **satisfied** if s is in that subset
- e.g., $\neg$`read` is satisfied by any symbol except `read`



Example

`Goal`: enforce array bounds checking on `a`

- States correspond to $|\texttt{a}|$
- Notice: infinite set of states if $|\texttt{a}|$ is unbounded
- Input symbols I:
  - $\texttt{malloc}(n)$
  - `free`
  - $\texttt{read}(i)$
  - $\texttt{write}(i, v)$

  for all integers n, i, v

Transitions:

- On $\texttt{malloc}(n)$:
  $(|\texttt{a}| = n') \longrightarrow (|\texttt{a}| = n)$
- On `free`:
  $(|\texttt{a}| = n') \longrightarrow (|\texttt{a}| = 0)$
- On $\texttt{read}(i)$:
  $(|\texttt{a}| = n) \longrightarrow (|\texttt{a}| = n)$
  if $0 \leq i < n$
- On $\texttt{write}(i, x)$:
  $(|\texttt{a}| = n) \longrightarrow (|\texttt{a}| = n)$
  if $0 \leq i < n$

Using security automata for enforcement

Security automata as the foundation of an execution monitor:

1. Initialize automaton on program/system startup
2. **Before** the target executes a step, generate the corresponding symbol
3. If the automaton can make a transition, let the target execute the step
4. If the automaton can't transition, terminate the target

This allows termination on *attempted* violation

Assumption: bounded memory

We allowed automata to have (countably) infinite states

This is necessary for recognizing certain safety properties

- Whether a prefix should be rejected might depend on every symbol in the prefix
- The amount of memory needed to remember the past grows without bound

In practice, most security policies don't need this

- Restricting the automaton to a finite set of states is probably fine for most purposes

Assumption: target control

Need ability to terminate the target on policy violation

This makes certain safety properties non-enforceable

Real-time availability

One principal cannot be denied use of a resource for more than M seconds.

Safety characterization: “Bad thing” is an unavailable interval spanning more than M seconds.

Passage of real time is an input symbol

Monitor cannot exert control over passage of time!

Assumption: mechanism integrity

To correctly enforce a policy, we must assume:

- Input symbols correspond to the actual execution
- Transitions correspond to the automaton's true transition function

If target corrupts mechanism, it can violate these assumptions

Address this with two strategies

- **Isolation**: target must be unable to write to the internal representation of the automaton
- **Complete mediation**: make sure that all aspects of execution that might generate input symbols are covered by implementation

Proving correct enforcement

Goal: Show that when S executes under enforcement of SA P,

- S terminates when its execution violates P
- S continues to execute otherwise

This requires a proof that the implementation satisfies:

1. Complete mediation
2. Target control
3. Isolation

We'll see how different implementation strategies lead to different kinds of proof

More pragmatics

Two mechanisms are needed to implement SA:

- **Input Read:** Determines that an input symbol has been produced by the target, forwards that symbol to the automaton simulation
- **Transition:** Determines whether the automaton can make a transition on a given input symbol, and if so, executes that transition by updating automaton state appropriately.

These implementations affect correctness and performance

Further reading

Enforceable Security Policies

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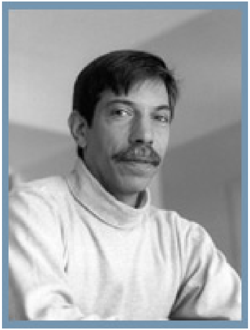

Further reading

Recognizing safety and liveness *

Bowen Alpern[1] **and Fred B. Schneider**[2]

[1] IBM T.J. Watson Research Center, P.O. Box 218, Yorktown Heights, NY 10598, USA
[2] Department of Computer Science, Cornell University, Ithaca, NY 14853, USA