Software Foundations of Security & Privacy 15315 Spring 2017 Lecture 4: Enforceable Security Policies

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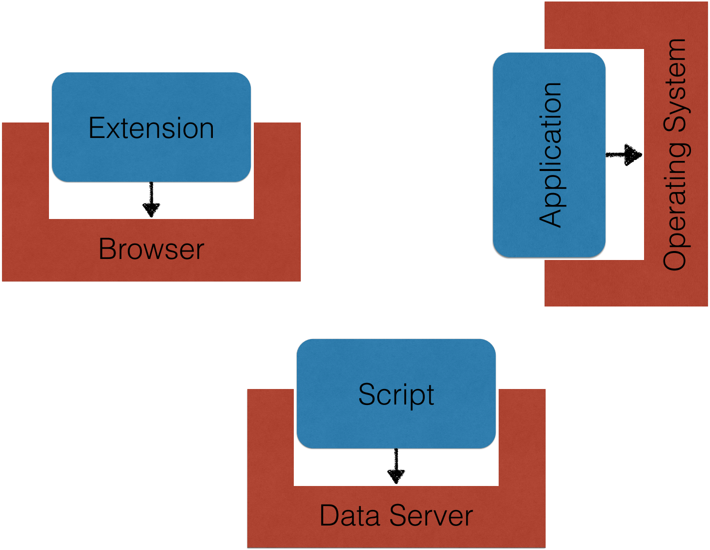
Securing Extensible Systems



Key Questions

What security policies can we enforce?

- Topic of today's lecture

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What mechanisms can we use?

- Type checking
- Static verification
- Program rewriting
- **Runtime enforcement**

Runtime enforcement

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

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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

Execution monitor examples

- Filesystem access control
- Firewall
- Stack inspection
- Dynamic bounds checking
- Malware detectors
- Chrome's *Content Security Policies* (CSP)
- ...

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Later, we'll talk about techniques that aren't limited in this way

- Verifying compilers, type systems
- Anything classified as "static analysis"

Formalizing execution

A target S is characterized by:

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

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- Set of all system calls: `open`, `send`, …
- Set of primitive commands in server scripting language

Example

How do we model the following program?

$$
\textbf{while}(x < y)\ \{ \\
\quad x := x + 1; \\
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How might we model the following program?

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while(read(&buf, &len, fp)) {
  if(buf[0] == 255)
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Formalizing policies

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

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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 $\Sigma_S \in P$.

Example

Suppose that we want a simple policy

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while(read(&buf, &len, fp)) {
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Does the program satisfy this policy?

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- These are called **properties**

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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

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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.

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- 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 (in principle) detect it

Enforceable policies

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

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- **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 enforced
"no send after read"

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while(read(&buf, &len, fp)) {
  if(buf[0] == 255)
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Safety and information flow

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We wanted to prevent:

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

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  memset(buf, 0, len);
  send(sock, , len);
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}
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Does this flow `fp` to `sock`?

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This policy *approximates* information flow

- Prevents a flow from happening
- Also prevents other things

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Information flow isn't EM-enforceable

Suppose x and y are bits

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if(x)
  y = 0;
else
  y = 1;
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With executions:

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

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Changes to x cause changes in y

A thought experiment

Let S_1:

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And S_2:

```
x, y = 0, 1;
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And S_3:

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Suppose I give you:

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

How to distinguish between S_1 and S_2?

A (modified) thought experiment

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Now you win every time

Hyperproperties

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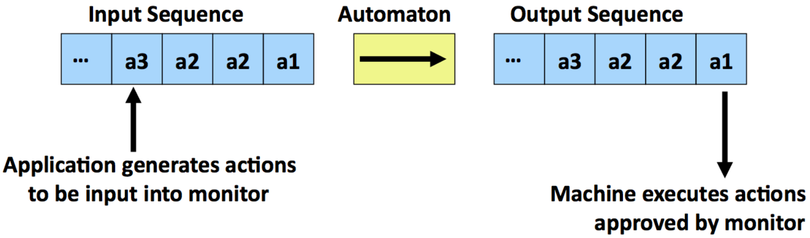
Can generalize to k-safety

- 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

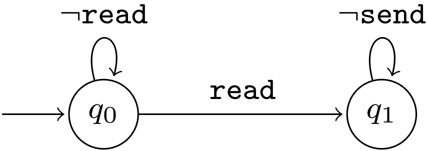
Security automaton

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**
- A: a countable set of **input symbols**
- $\delta : (Q \times I) \mapsto 2^Q$: a **transition function**

Security automata: semantics

Notice: no accepting states



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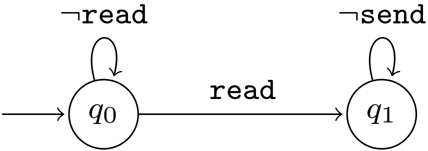

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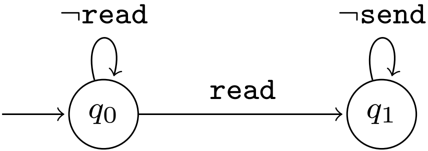

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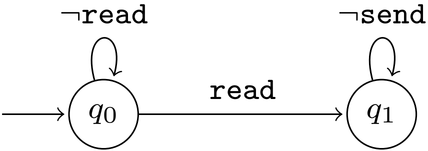

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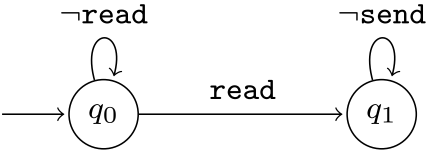
3. If Q' ever becomes empty, the input is rejected



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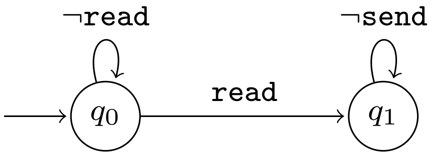
$$\bigcup_{q \in Q'} \delta(q, s_i)$$
3. If Q' ever becomes empty, the input is rejected



An action is allowed if a transition exists for it

Security automata: semantics

Notice: no accepting states

Let Q' be the *current states*

To process execution $s_1 s_2 \ldots$:

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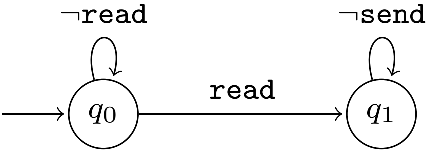


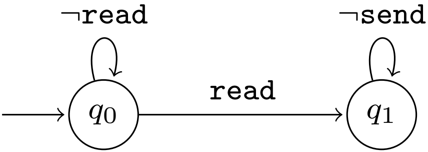
An action is allowed if a transition exists for it

Can process both finite and infinite sequences!

Security automata: input symbols

We label edges with *transition predicates*

- Boolean-valued and total
- Domain: A



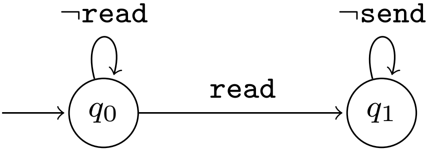
Security automata: input symbols

We label edges with *transition predicates*

- Boolean-valued and total
- Domain: A

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

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



Using security automata for enforcement

Security automata can be implemented to form the basis 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

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We allowed automata to have (countably) infinite states

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- The amount of memory needed to remember the past grows without bound

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- 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

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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.

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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 time cannot be stopped!

Assumption: mechanism integrity

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

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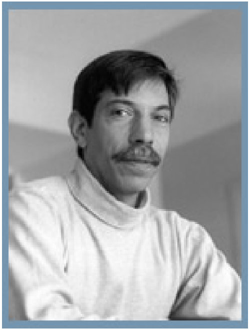
Address this with two strategies

- **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

Further reading

Enforceable Security Policies

FRED B. SCHNEIDER
Cornell University



Further reading

Recognizing safety and liveness *

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

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