Enforceable Security Policies

David Basin
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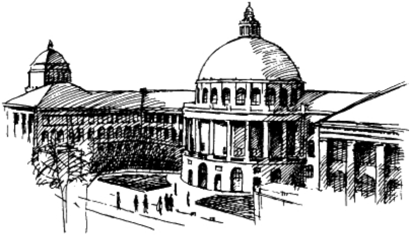


Structure and Credits

- Tutorial in two parts, with two speakers

  Enforcement: David Basin
  Monitoring: Felix Klaedtke

- Tutorial focus: partial survey, with primary focus on our work

- Material online

  Slides: www.inf.ethz.ch/personal/basin/teaching/teaching.html
  Papers: www.inf.ethz.ch/personal/basin/pubs/pubs.html

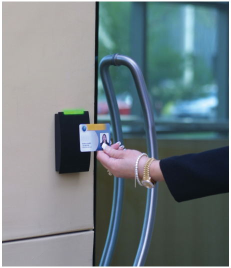
- Collaborators

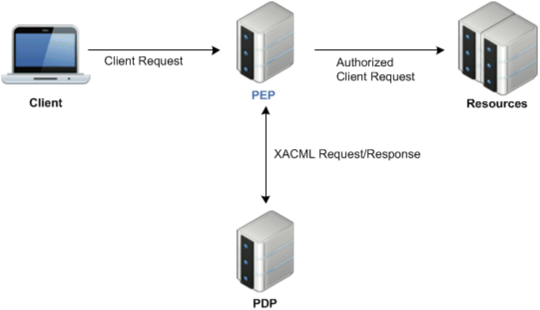
  Enforcement: Vincent Jugé, Eugen Zălinescu
  Monitoring: Matúš Harvan, Srdjan Marinovic, Samuel Müller, Eugen Zălinescu

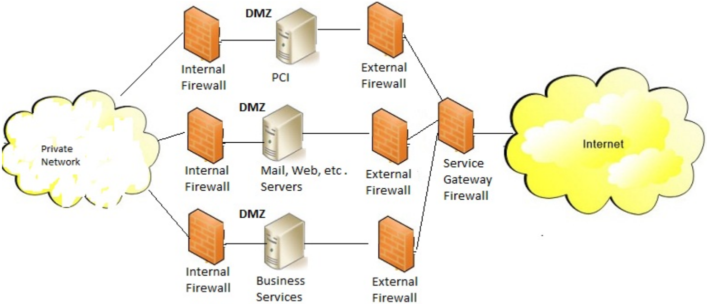
Road Map

1. **Motivation**
2. Enforcement by execution monitoring
3. Generalized setting
4. Conclusions

Policy Enforcement Mechanisms are Omnipresent

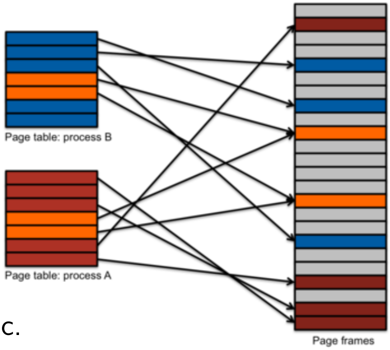






Enforcing Policies at all Hardware/Software Layers

- Memory management hardware
- Operating systems and file systems
- Middleware and application servers
- Network traffic: firewalls and VPNs
- Applications: databases, mail servers, etc.



Policies Come in all Shapes and Sizes

History-based Access Control

Chinese Wall

Information Flow

Separation of Duty

Business Regulations

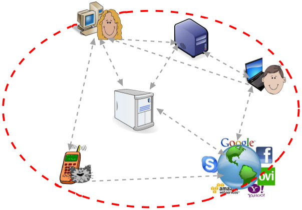
Data Usage

Privacy

...

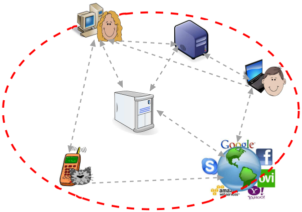
So Which Policies can be Enforced?

Examples
AC / General



- Only **Alice** may update **customer data**.
- **Employees** may overspend their **budget** by 50% provided they previously received **managerial approval**.
- **Bob** may make up to most 5 copies of **movie XYZ**.

Examples
AC / General



policies

- Only **Alice** may update **customer data**.
- **Employees** may overspend their **budget** by 50% provided they previously received **managerial approval**.
- **Bob** may make up to most 5 copies of **movie XYZ**.

- A **login** must not happen within 3 seconds after a **fail**
- Each **request** must be followed by a **deliver** within 3 seconds

Relevance of Research Question

- Fundamental question about **mechanism design**.
  - **Focus:** conventional mechanisms that operate by **monitoring execution** and **preventing** actions that violate policy.
  - Given **omnipresence of such mechanisms** and **diversity of policies** it is natural to ask: **which policies can be enforced?**
- Enforce versus monitor
  - Enforcement often combined with system monitoring.
  - Why do both? Defense in depth? Accountability? Something deeper?
- Fun problem. Nice example of applied theory.
  - Temporal reasoning, logic, formal languages, complexity theory

Road Map

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2. **Enforcement by execution monitoring**
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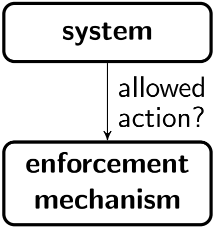
Enforcement by Execution Monitoring

Enforceable Security Policies
Fred B. Schneider, ACM Trans. Inf. Syst. Sec., 2000

Abstract Setting

- System iteratively executes actions
- Enforcement mechanism intercepts them (prior to their execution)
- Enforcement mechanism terminates system in case of violation



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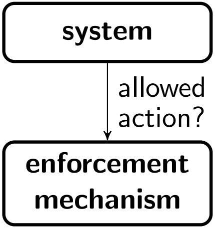
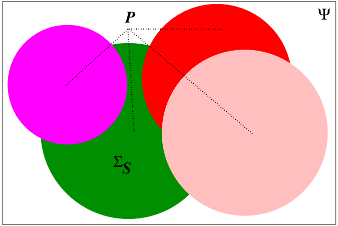


So which policies are enforceable?

Characterizing EM enforceability — formal setup

- Let Ψ denote universe of all possible finite/infinite sequences.
  - Represents executions at some abstraction level.
  - E.g., sequences of actions, program states, state/action pairs, ...
  - **Example:** **request** $\cdot$ **tick** $\cdot$ **deliver** $\cdot$ **tick** $\cdot$ **tick** $\cdot$ **request** $\cdot$ **deliver** $\cdot$ **tick** ...
- A **security policy** P is specified as a predicate on **sets** of executions, i.e., it characterizes a **subset of** 2^{Ψ}.
- A system S defines a set $\Sigma_S \subseteq \Psi$ of actual executions.
- S **satisfies** P iff $\Sigma_S \in P$.



Characterizing EM enforceability: trace properties

- EMs work by monitoring target execution. So any enforceable policy P must be specified so that

$$\Pi \in P \iff \forall \sigma \in \Pi.\, \sigma \in \hat{P}\,.$$

  $\hat{P}$ formalizes criteria used by EM to decide whether a trace σ is acceptable, i.e., whether or not to abort ("execution cutting").

- Hence **Requirement 1**: P must be a **property** formalizable in terms of a predicate $\hat{P}$ on executions.

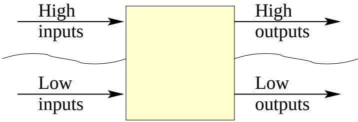
  A set is a **property** iff set membership is determined by each element alone and not by other elements of the set.

- Contrast: properties of behaviors versus properties of **sets** of behaviors (**hyper-properties**).

Not all security policies are trace properties

Noninterference (Goguen & Meseguer, 1982)

- **Noninterference** states that commands executed by users holding high clearances have no effect on system behavior observed by users holding low clearances.



- Not a trace property.

  Whether a trace is allowed by a policy depends on whether another trace (obtained by deleting command executions by high users) is also allowed.

- It is a **property** of **systems**, but a **hyper-property** of **behaviors**.

Characterization (cont.)

- Mechanism cannot decide based on possible future execution.

$$\textbf{tick} \cdot \textbf{tick} \cdot \textbf{BadThing} \cdot \textbf{tick} \cdot \textbf{tick} \cdot \textbf{GreatThing} \cdot \textbf{tick} \ldots$$

$$\Uparrow \textbf{???}$$

- Consequence: (Recall $\Pi \in P \Leftrightarrow \forall \sigma \in \Pi.\, \sigma \in \hat{P}$)
  * Suppose σ' is a prefix of σ, such that $\sigma' \notin \hat{P}$, and $\sigma \in \hat{P}$.
  * Then policy P is not enforceable since we do not know whether system terminates before σ' is extended to σ.

- **Requirement 2**, above, is called **prefix closure**.
  * If a trace is not in $\hat{P}$, then the same holds for all extensions.
  * Conversely if a trace is in $\hat{P}$, so are all its prefixes.

- Moreover, **Requirement 3, finite refutability:** If a trace is not in $\hat{P}$, we must detect this based on some finite prefix.

Characterization (cont.)

- Let $\tau \leq \sigma$ if τ is a **finite prefix** of σ.
- **Requirement 2:** prefix closure.

$$\forall \sigma \in \Psi .\, \sigma \in \hat{P} \rightarrow (\forall \tau \leq \sigma .\, \tau \in \hat{P})$$

- **Requirement 3:** finite refutability.

$$\forall \sigma \in \Psi .\, \sigma \notin \hat{P} \rightarrow (\exists \tau \leq \sigma .\, \tau \notin \hat{P})$$

- Sets satisfying all three requirements are called **safety properties**.

Safety properties — remarks

- **Safety properties** are a class of trace properties.
  Essentially they state that **nothing bad ever happens**.

- **Finite refutability** means if bad thing occurs, this happens after finitely many steps and we can immediately observe the violation.

- **Examples**
  - Reactor temperature never exceeds $1000^o\ C$.
  - If the key is not in the ignition position, the car will not start.
  - You may play a movie at most three times after paying for it.
  - Any history-based policy depending on the present and past.

- **Nonexample** (liveness): If the key is in the ignition position, the car will start eventually.

  Why?

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  * Reactor temperature never exceeds $1000^o\ C$.
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- **Nonexample** (liveness): If the key is in the ignition position, the car will start eventually.

  Why? This cannot be refuted on any finite execution.

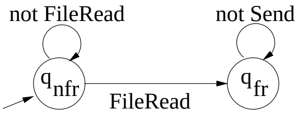
Formalization consequences

- Formalization shows all EM-enforceable properties are safety.
  - So if set of executions for a security policy P is not a safety property, then no EM enforcement mechanism exists for P.
  - E.g., mechanism grants access if a certificate is delivered in future.
- EM-enforceable policies can be (conjunctively) composed by running mechanisms in parallel.
- EM mechanisms can be implemented by automata.
  - Büchi automata are automata on infinite words.
  - A variant, **security automata**, accept safety properties.

Security automata

- A **security automaton** $A \equiv \langle Q, Q_0, I, \delta \rangle$ is defined by:
  * A countable set Q of **automaton states**.
  * A set $Q_0 \subseteq Q$ of **initial states**.
  * A countable set I of **input symbols**.
  * A **transition function**, $\delta : (Q \times I) \to 2^Q$.
- Sequence $s_1, s_2, \ldots$ of input symbols processed by run $Q_0, Q_1, \ldots$ of automaton, where:
  * Q_0 is set of initial states (as above).
  * $Q_{i+1} = \bigcup_{q \in Q_i} \delta(q, s_i)$, defines set of states reachable from those in Q_i by reading input symbol s_i.
  * If Q_{i+1} empty, then input s_i is rejected, otherwise accepted.
- Language accepted by A is set of finite and infinite sequences.
  Set is prefix closed and any rejected string has a rejected finite prefix.

Example: a simple information flow policy



- Example (e.g., for mobile code): messages cannot be sent after files have been read.
- Automaton
  * States: "no file read" (initial state) and "file read".
  * δ specified by edges labeled by (computable) predicates on the set I.
  * Transition in state Q on symbol $s \in I$ to $\{q_j \mid q_i \in Q \wedge p_{ij}(s)\}$, where p_{ij} denotes predicate labeling edge from node q_i to q_j.
- Input here determined by problem domain.
  E.g., transition predicate *FileRead* satisfied by input symbols (system execution steps) that represent file read operations.

Security automata as an enforcement mechanism

- EM-enforceable policies can be specified by security automata.

state vars	*state*:{nfr,fr} **initial** nfr	
transitions	**not** *FileRead* $\wedge$ *state* = nfr	$\rightarrow$ **skip**
	FileRead $\wedge$ *state* = nfr	$\rightarrow$ *state* := fr
	not *Send* $\wedge$ *state* = fr	$\rightarrow$ **skip**

Schneider suggests the use of guarded commands here.

- Policy enforced by running automaton in parallel with system. Each step system is about to make generates an input symbol for automaton.
  1. If automaton can make a transition, then system may perform corresponding step and automaton state is updated.
  2. If automaton cannot make transition, then system execution is aborted (or an exception is thrown or ...).

Enforcement remarks

- Specification using guarded commands is rather primitive
  - Lacks abstractions for specifying, structuring, and composing designs and support for refinement and transformation.
  - Alternative: use process calculi and data-type specification languages See D.B./Olderog/Sevinc paper in references.

- Enforcement (PEP) can be formalized as synchronous parallel composition in processes calculi

$$SecSys = (UnProtectedSys\ [|A|]\ SecAut) \setminus B$$

  Question: how useful is this separation of concerns in practice?

- Enforcement in practice by running automata in trusted reference monitor or weaving automaton checks into target system.

  See Erlingsson, Schneider, *SASI Enforcement of Security Policies: a Retrospective*, NSPW 1999.

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Story so far...

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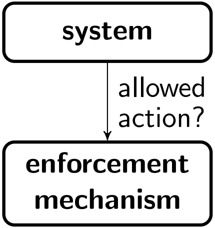

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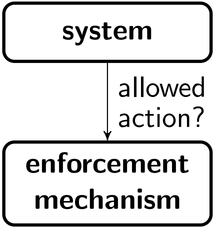

Main Concerns

- enforceable policy $\Longrightarrow$ / $\not\Longleftarrow$ safety property
- match with reality?

Follow-Up Work

- *SASI enforcement of security policies*
  Ú. Erlingsson and F. Schneider, NSPW'99
- *IRM enforcement of Java stack inspection*
  Ú. Erlingsson and F. Schneider, S&P'00
- *Access control by tracking shallow execution history*
  P. Fong, S&P'04
- *Edit automata: enforcement mechanisms for run-time security properties*
  J. Ligatti, L. Bauer, and D. Walker, Int. J. Inf. Secur., 2005
- *Computability classes for enforcement mechanisms*
  K. Hamlen, G. Morrisett, and F. Schneider, ACM Trans. Inf. Syst. Secur., 2006
- *Run-time enforcement of nonsafety policies*
  J. Ligatti, L. Bauer, and D. Walker, ACM Trans. Inf. Syst. Secur., 2009
- *A theory of runtime enforcement, with results*
  J. Ligatti and S. Reddy, ESORICS'10
- *Do you really mean what you actually enforced?*
  N. Bielova and F. Massacci, Int. J. Inf. Secur., 2011
- *Runtime enforcement monitors: composition, synthesis and enforcement abilities*
  Y. Falcone, L. Mounier, J.-C. Fernandez, and J.-L. Richier, Form. Methods Syst. Des., 2011
- *Service automata*
  R. Gay, H. Mantel, and B. Sprick, FAST'11
- *Cost-aware runtime enforcement of security policies*
  P. Drábik, F. Martinelli, and C. Morisset, STM'12
- ...

Match with reality ???

- A **login** must not happen within 3 seconds after a **fail**
- Each **request** must be followed by a **deliver** within 3 seconds

Both are safety properties.

Can we enforce both by preventing events causing policy violations from happening?

Some Auxiliary Definitions

- Σ^* and Σ^ω, are the finite and infinite sequences over alphabet Σ. $\Sigma^\infty := \Sigma^* \cup \Sigma^\omega$.
- For $\sigma \in \Sigma^\infty$, denote set of its **prefixes** by $\mathsf{pre}(\sigma)$ and set of its **finite prefixes** by $\mathsf{pre}_*(\sigma)$. I.e., $\mathsf{pre}_*(\sigma) := \mathsf{pre}(\sigma) \cap \Sigma^*$.
- The **truncation** of $L \subseteq \Sigma^*$ is the largest prefix-closed subset of L.

$$\mathsf{trunc}(L) := \{\sigma \in \Sigma^* \mid \mathsf{pre}(\sigma) \subseteq L\}$$

- Its **limit closure** contains both the sequences in L and the infinite sequences whose finite prefixes are all in L.

$$\mathsf{limitclosure}(L) := L \cup \{\sigma \in \Sigma^\omega \mid \mathsf{pre}_*(\sigma) \subseteq L\}$$

- For $L \subseteq \Sigma^*$ and $K \subseteq \Sigma^\infty$, their **concatenation** is defined by:

$$L \cdot K := \{\sigma\tau \in \Sigma^\infty \mid \sigma \in L \text{ and } \tau \in K\}$$

Refined Abstract Setting Accounting For Controllability

Actions

Set of actions $\Sigma = \mathbf{O} \cup \mathbf{C}$:

- $\mathbf{O} = \{\text{observable actions}\}$
- $\mathbf{C} = \{\text{controllable actions}\}$

Traces

Trace universe $\mathbf{U} \subseteq \Sigma^\infty$:

- $\mathbf{U} \neq \emptyset$
- $\mathbf{U}$ prefix-closed

Example: **request** · **tick** · **deliver** · **tick** · **tick** · **request** · **deliver** · **tick** . . . $\in \mathbf{U}$

Refined Abstract Setting
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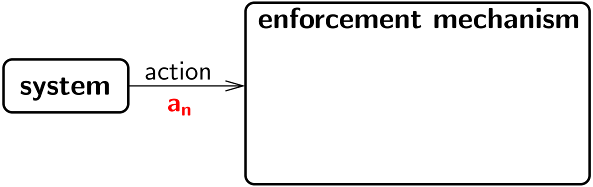
Example: **request** · **tick** · **deliver** · **tick** · **tick** · **request** · **deliver** · **tick** . . . $\in \mathbf{U}$

Requirements (on an Enforcement Mechanism)

- **Soundness**: prevents policy-violating traces
- **Transparency**: allows policy-compliant traces
- **Computability**: makes decisions

Formalization



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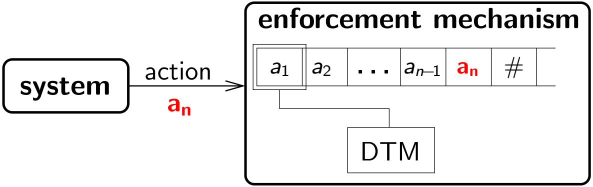

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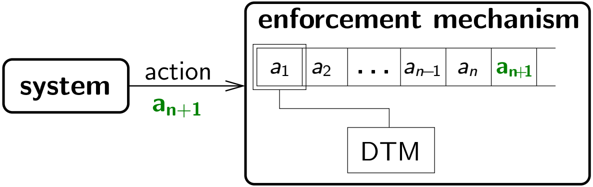

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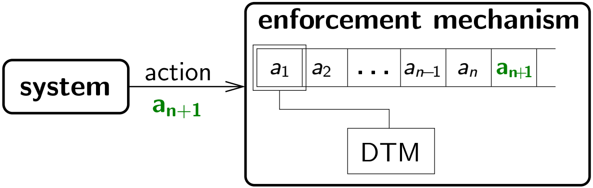


Definition

$P \subseteq (\mathbf{O} \cup \mathbf{C})^\infty$ is **enforceable** in $\mathbf{U}$ $\overset{\text{def}}{\iff}$ exists DTM $\mathcal{M}$ with

1. $\varepsilon \in L(\mathcal{M})$
   "$\mathcal{M}$ accepts the empty trace"
2. $\mathcal{M}$ halts on inputs in $\big(\mathit{trunc}(L(\mathcal{M})) \cdot (\mathbf{O} \cup \mathbf{C})\big) \cap \mathbf{U}$
   "$\mathcal{M}$ either permits or denies an intercepted action"
3. $\mathcal{M}$ accepts inputs in $\big(\mathit{trunc}(L(\mathcal{M})) \cdot \mathbf{O}\big) \cap \mathbf{U}$
   "$\mathcal{M}$ permits an intercepted observable action"
4. $\mathit{limitclosure}\big(\mathit{trunc}(L(\mathcal{M}))\big) \cap \mathbf{U} = P \cap \mathbf{U}$
   "soundness ($\subseteq$) and transparency ($\supseteq$)"

Examples

Setting

- Controllable actions: $\mathbf{C} = \{\mathbf{login}, \mathbf{request}, \mathbf{deliver}\}$
- Observable actions: $\mathbf{O} = \{\mathbf{tick}, \mathbf{fail}\}$
- Set of actions: $\Sigma = \mathbf{C} \cup \mathbf{O}$
- Trace universe: $\mathbf{U} = \Sigma^* \cup (\Sigma^* \cdot \{\mathbf{tick}\})^\omega$

Policies

P_1. A **login** must not happen within 3 seconds after a **fail**

P_2. Each **request** must be followed by a **deliver** within 3 seconds

P_1 is Enforceable

A login must not happen within 3 seconds after a fail

- Trace universe $U \subseteq \Sigma^\infty$ consists of all traces containing infinitely many **tick** actions and their finite prefixes.

  For simplification, assume actions do not happen simultaneously and, when time progresses by 1 time unit, system sends **tick** action. However, more than 1 action can happen in time unit.

- Define P_1 as the complement with respect to U of limit closure of

$$\left\{a_1 \dots a_n \in \Sigma^* \,\middle|\, \exists i, j \in \{1, \dots, n\} \text{ with } i < j \text{ such that } a_i = \textbf{fail}, a_j = \textbf{login}, \text{ and } a_{i+1} \dots a_{j-1} \text{ contains} \leq 3 \textbf{ tick} \text{ actions}\right\}$$

- Straightforward to define a Turing machine $\mathcal{M}$ as required
  * Whenever the enforcement mechanism observes a **fail** action, it prevents all **login** actions until it has observed sufficiently many **tick** actions.
  * This requires that **login** actions are controllable, whereas **tick** and **fail** actions need only be observed by the enforcement mechanism.

P_2 is not Enforceable

Each request must be followed by a deliver within 3 seconds

- Define P_2 as the complement with respect to U of limit closure of

$$\left\{a_1 \ldots a_n \in \Sigma^* \;\middle|\; \begin{array}{l} \exists i, j \in \{1, \ldots, n\} \text{ with } i < j \text{ such that } a_i = \textbf{request} \text{ and} \\ a_{i+1} \ldots a_j \text{ contains no } \textbf{deliver} \text{ action and} > 3 \textbf{ tick} \text{ actions} \end{array}\right\}$$

- P_2 not (U, O)-enforceable.
  Intuition: Mechanism observing a **request**, cannot terminate the system in time to prevent a policy violation when no **deliver** occurs within the given time bound as time's progression is uncontrollable.

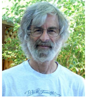
- More precisely:
  * Assume exists TM $\mathcal{M}$ as required, which must accept **request tick**$^3 \in P_2$.

    N.B. $\mathcal{M}$ must accept this since terminating system before observing the fourth **tick** action would violate transparency requirement.
  * By condition (ii) of Def. $\mathcal{M}$ must also accept **request tick**$^4 \notin P_2$

Example: Separation of Duties in RBAC

- **(Dynamic) SOD:** a user may be a member of any two exclusive roles as long as he has not activated both in the same session.
- **Formalization:** user **activates** roles and admin **changes** exclusiveness relation for roles.
- Policy enforceable only if both **actions** are controllable
  * Mechanism must prevent an admin action that makes two roles exclusive whenever these roles are both currently activated in some user's session
- Simpler to enforce the following slightly weaker policy
  * **(Weak dynamic) SOD:** a user may only activate a role in a session if he is currently a member of that role and the role is not exclusive to any other currently active role in the session.
  * Enforcement requires only **activates** action to be controllable.
  * **Changes** action just observed and used to update exclusiveness relation.

The Evolution of Safety



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$$\forall \sigma \in \Sigma^\omega .\, \sigma \notin P \to \exists i \in \mathbb{N} .\, \forall \tau \in \Sigma^\omega .\, \sigma^{<i} \cdot \tau \notin P$$

  * Violations are finitely observable and irremedial.
  * Reformulates what we previously saw.

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- Folklore: A property $P \subseteq \Sigma^\infty$ is **∞-safety** if

$$\forall \sigma \in \Sigma^\infty .\, \sigma \notin P \rightarrow \exists i \in \mathbb{N}.\, \forall \tau \in \Sigma^\infty .\, \sigma^{<i} \cdot \tau \notin P$$

The Evolution of Safety

- L. Lamport, 1977: "A **safety property** is one which states that something bad will *not* happen."

- B. Alpern and F. Schneider, 1986: A property $P \subseteq \Sigma^\omega$ is **ω-safety** if

$$\forall \sigma \in \Sigma^\omega .\, \sigma \notin P \to \exists i \in \mathbb{N}.\, \forall \tau \in \Sigma^\omega .\, \sigma^{<i} \cdot \tau \notin P$$

  * Violations are finitely observable and irremedial.
  * Reformulates what we previously saw.

- Folklore: A property $P \subseteq \Sigma^\infty$ is **∞-safety** if

$$\forall \sigma \in \Sigma^\infty .\, \sigma \notin P \to \exists i \in \mathbb{N}.\, \forall \tau \in \Sigma^\infty .\, \sigma^{<i} \cdot \tau \notin P$$

- T. Henzinger, 1992: A property $P \subseteq \Sigma^\omega$ is **safety in $\mathbf{U} \subseteq \Sigma^\omega$**

$$\forall \sigma \in \mathbf{U} .\, \sigma \notin P \to \exists i \in \mathbb{N}.\, \forall \tau \in \Sigma^\omega .\, \sigma^{<i} \cdot \tau \notin P \cap \mathbf{U}$$

Safety

(with Universe and Observables)

- Intuition
  - P is safety in $\mathbf{U}$ *and*
  - Bad things are not caused by elements from $\mathbf{O}$.
- Formalization: A property $P \subseteq \Sigma^\infty$ is **($\mathbf{U}$,$\mathbf{O}$)-safety** if

$$\forall \sigma \in \mathbf{U}.\, \sigma \notin P \rightarrow \exists i \in \mathbb{N}.\, \sigma^{<i} \notin \Sigma^* \cdot \mathbf{O} \wedge \forall \tau \in \Sigma^\infty.\, \sigma^{<i} \cdot \tau \notin P \cap \mathbf{U}$$

  - Generalizes previous defs: $\mathbf{O} = \emptyset$ and Σ^ω and Σ^∞ are instances of $\mathbf{U}$.
  - As $\mathbf{U}$ and $\mathbf{O}$ become smaller it is more likely a trace set P is ($\mathbf{U}$,$\mathbf{O}$)-safety. (Indeed, for $\mathbf{U} = \emptyset$, P is always ($\mathbf{U}$,$\mathbf{O}$)-safety).

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- Liveness also generalizes to this setting
  ("something good can happen in $\mathbf{U}$ after actions not in $\mathbf{O}$")

Example

P_1**.** A **login** must not happen within 3 seconds after a **fail**

P_2**.** Each **request** must be followed by a **deliver** within 3 seconds

- P_1 is ∞-safety.
  - If trace τ violates P_1 then violation has position where *login* is executed.
  - So $\exists i \geq 1$ with $\tau^{<i-1} \in P_1$, $\tau^{<i} \notin P_1$, and $\tau^{<i}$ ends with a *login* action.
  - All extensions of $\tau^{<i}$ still violates P_1.
- P_2 is also ∞-safety. Argument analogous with violations due to *tick*.
- But P_1 is (U, O)-safety & P_2 is not (U, O)-safety, for $\mathbf{O} = \{\mathbf{tick}, \mathbf{fail}\}$
  - P_1 violated by executing $login \in \mathbf{C}$. No policy compliant extensions.
  - For P_2 simply consider:

$$\mathbf{request} \cdot \mathbf{tick} \cdot \mathbf{tick} \cdot \mathbf{tick} \cdot \mathbf{tick} \ldots$$

Aside on other Notions of Safety

Model-checking community has looked at numerous **fragments** and **variants** of safety properties.

- Language $L \subseteq \Sigma^\omega$ is **k-checkable** for $k \geq 1$ if there is a language $R \subseteq \Sigma^k$ (of allowed subwords) such that w belongs to L iff all length k subwords of w belong to R. (Kupferman, Lustig, Vardi, 2006)
  - A property is **locally checkable** if its language is k-checkable for some k.
  - Results in practice, e.g., from bounded past/future constraints.
  - Good for runtime verification: memory use bounded as monitor only requires access to last k computation cycles.
- **Safety** in **reactive** (or **open**) **system** setting.
  - Designed for systems interacting with an environment.
  - **Reactive safety** (Ehlers and Finkbeiner, 2011): system stays in allowed states from which environment cannot force it out.
  - See related **environment-friendly safety** (Kupferman and Weiner, 2012).

Safety and Enforceability

Theorem

Let P be a property and $\mathbf{U}$ a trace universe with $\mathbf{U} \cap \Sigma^*$ decidable.

$$P \text{ is } (\mathbf{U}, \mathbf{O})\text{-enforceable} \iff \begin{array}{ll} (1) & P \text{ is } (\mathbf{U}, \mathbf{O})\text{-safety}, \\ (2) & \text{pre}_*(P \cap \mathbf{U}) \text{ is a decidable set, and} \\ (3) & \varepsilon \in P. \end{array}$$

Proof uses characterization that

$$P \text{ is } (\mathbf{U}, \mathbf{O})\text{-safety iff limitclosure}(\text{pre}_*(P \cap \mathbf{U}) \cdot \mathbf{O}^*) \cap \mathbf{U} \subseteq P.$$

Schneider's "characterization:" only $\Longrightarrow$ for (1)
where $\mathbf{U} = \Sigma^\infty$ and $\mathbf{O} = \emptyset$

Realizability of Enforcement Mechanisms

Fundamental Algorithmic Problems

Given a specification of a policy.

- Is it enforceable?
- If yes, can we synthesize an enforcement mechanism for it?
- With what complexity can we do so?

Some Results

Deciding if P is (**U**, **O**)-enforceable when both **U** and P are given as

- FSAs is **PSPACE-complete**.
- PDAs is **undecidable**.
- LTL formulas is **PSPACE-complete**.
- MLTL formulas is **EXPSPACE-complete**.

Checking Enforceability and Safety
(PDA and FSA)[1]

Checking Enforceability

Let **U** and P be given as PDAs or FSAs $\mathcal{A}_{\mathbf{U}}$ and $\mathcal{A}_P$.

1. $\mathrm{pre}_*(L(\mathcal{A}_P) \cap L(\mathcal{A}_{\mathbf{U}}))$ is known to be decidable
2. check whether $\varepsilon \in L(\mathcal{A}_P)$
3. check whether $L(\mathcal{A}_P)$ is $(L(\mathcal{A}_{\mathbf{U}}), \mathbf{O})$-safety

Checking Safety

Let **U** and P be given as PDAs or FSAs $\mathcal{A}_{\mathbf{U}}$ and $\mathcal{A}_P$.

- PDAs: undecidable in general
- FSAs: generalization of standard techniques

[1] Automata have 2 sets of accepting states, for finite and for infinite sequences.

Checking Enforceability and Safety

(LTL and MLTL)

Checking Enforceability

Let **U** and P be given as LTL or MLTL formulas $\varphi_{\mathbf{U}}$ and φ_P.

1. $\text{pre}_*(L(\varphi_P) \cap L(\varphi_{\mathbf{U}}))$ is known to be decidable
2. check whether $\varepsilon \in L(\varphi_P)$
3. check whether $L(\varphi_P)$ is $(L(\varphi_{\mathbf{U}}), \mathbf{O})$-safety

Checking Safety

Let **U** and P be given as LTL or MLTL formulas $\varphi_{\mathbf{U}}$ and φ_P.

1. translate $\varphi_{\mathbf{U}}$ and φ_P into FSAs $\mathcal{A}_{\mathbf{U}}$ and $\mathcal{A}_P$
2. use the results of the previous slide on $\mathcal{A}_{\mathbf{U}}$ and $\mathcal{A}_P$
3. perform all these calculations on-the-fly

Beyond a Yes-No Answer

- If **yes** . . .
  synthesize an enforcement mechanism from $\mathcal{A}_P$ and $\mathcal{A}_{\mathbf{U}}$
  (Do so by building FSA security automata for $\mathcal{A}_P \cap \mathcal{A}_{\mathbf{U}}$.)

- If **no** . . .
  return a witness illustrating why P is not $(\mathbf{U}, \mathbf{O})$-enforceable
  (Construct trace in $\mathbf{U} \setminus P$ with suffix in P (violating transparency) or that would not be prevented (violating soundness).)

- If **no** . . .
  return the maximal trace universe $\mathbf{V}$ in which P is $(\mathbf{V}, \mathbf{O})$-enforceable

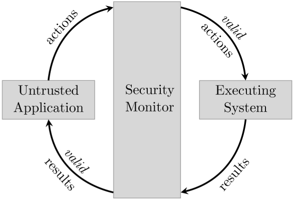
Road Map

1. Motivation
2. Enforcement by execution monitoring
3. Generalized setting
4. **Conclusions**

Summary

- Enforceability is a central problem in information security
  - More generally, in building systems that meet their specification
- Research aims to characterize which policies are enforceable with which mechanisms
  - Here, large class of mechanisms that work by monitoring execution and preventing actions that would result in policy violations
- Important to distinguish controllable and observable actions
  - Leads to refined notion of enforceability
  - And generalized notions of safety and liveness
- For appropriate formalisms, specification languages, and policies, mechanism synthesis is possible

Future Work



- Enforceability for other specification languages
- How best to combine monitoring and enforcement
- Explore connections to control theory and other mechanism classes.
  - *Supervisory Control of a Class of Discrete Event Processes*
    Ramadage, Wonham, SIAM J. Control Optim. 1987
  - *Modeling runtime enforcement with mandatory results automata*
    Dolzhenko, Ligatti, Reddy, IJIS 2014.
  - *Cost-Aware Runtime Enforcement of Security Policies*,
    Dràbik, Martinelli, Morisset, Security and Trust Management, LNCS 7783, 2013.

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