Enforceable Security Policies Revisited

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POST 2012

Security Policies Come in all Shapes and Sizes

History-Based Access Control

Chinese Wall

Information Flow

Separation of Duty

Business Regulations

Data Usage

Privacy

Estonian Law

...

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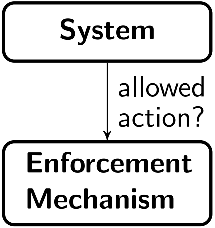
Which of these are enforceable?

Enforcement by Execution Monitoring

Enforceable Security Policies
F. Schneider, TISSEC 2000

Abstract Setting

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



Main Concerns

- match with reality?
- enforceable $\Rightarrow$ / $\not\Leftarrow$ safety

Follow-Up Work

- *SASI Enforcement of Security Policies*
  Ú. Erlingsson and F. Schneider, NSPW 1999
- *IRM Enforcement of Java Stack Inspection*
  Ú. Erlingsson and F. Schneider, S&P 2000
- *Access Control by Tracking Shallow Execution History*
  P. Fong, S&P 2004
- *Edit Automata: Enforcement Mechanisms for Run-Time Security Properties*
  J. Ligatti, L. Bauer, and D. Walker, IJIS 2005
- *Computability classes for enforcement mechanisms*
  K. Hamlen, G. Morrisett, and F. Schneider, TISSEC 2006
- *Run-Time Enforcement of Nonsafety Policies*
  J. Ligatti, L. Bauer, and D. Walker, TISSEC 2009
- *A Theory of Runtime Enforcement, with Results*
  J. Ligatti and S. Reddy, ESORICS 2010
- *Do you really mean what you actually enforced?*
  N. Bielova and F. Massacci, IJIS 2011
- *Runtime Enforcement Monitors: Composition, Synthesis and Enforcement Abilities*
  Y. Falcone, L. Mounier, J.-C. Fernandez, and J.-L. Richier, FMSD 2011
- *Service Automata*
  R. Gay, H. Mantel, and B. Sprick, FAST 2011
- *Enforceable Policies Revisited*
  D. Basin, V. Jugé, F. Klaedtke, and E. Zălinescu, POST 2012
- ...

Enforcement by Execution Monitoring (Fundamental Open Question)

Match with Reality

- Can we refine Schneider's abstraction?

Limited Understanding

- Schneider: enforceable $\Rightarrow$ safety
- Necessary and sufficient condition?

Our Solution

Refined abstract setting by distinguishing between **observable** and **controllable** actions:

- **clock tick**
- **administrative actions**
- **user actions**

Contributions

1. **Formalization and Characterization of Enforceability**
2. Realizability of Enforcement Mechanisms

Refined Abstract Setting

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: $\textbf{request} \cdot \textbf{tick} \cdot \textbf{deliver} \cdot \textbf{tick} \cdot \textbf{tick} \cdot \textbf{request} \cdot \textbf{deliver} \cdot \textbf{tick} \ldots \in \mathbf{U}$

Refined Abstract Setting

Actions

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

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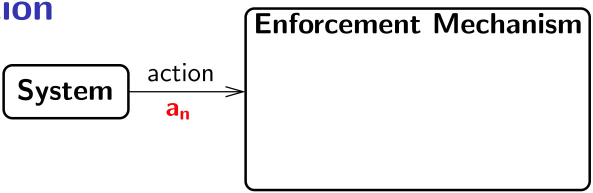
Example: **request** · **tick** · **deliver** · **tick** · **tick** · **request** · **deliver** · **tick** . . . $\in \mathbf{U}$

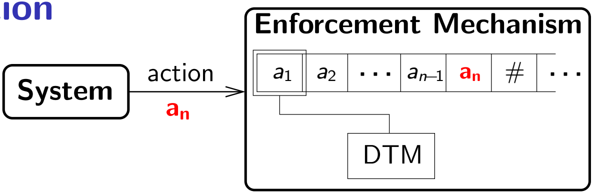
Requirements (on the Enforcement Mechanism)

- **Computability**: Make decisions
- **Soundness**: Prevent policy-violating traces
- **Transparency**: Allow policy-compliant traces

Formalization



Formalization



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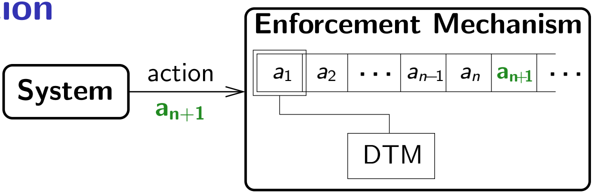

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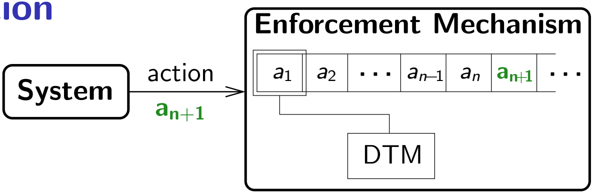

Definition

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

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

1. "**login** must not happen within 3 time units after a **fail**."
2. "each **request** must be followed by a **deliver** within 3 time units."

Examples

Setting

- Controllable actions: $\mathbf{C} = \{\mathbf{login}, \mathbf{request}, \mathbf{deliver}\}$
- Observable actions: $\mathbf{O} = \{\mathbf{tick}, \mathbf{fail}\}$
- Set of actions: $\Sigma = \mathbf{C} \cup \mathbf{O}$
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Policies

1. "**login** must not happen within 3 time units after a **fail**."
   $\Rightarrow$ **enforceable**
2. "each **request** must be followed by a **deliver** within 3 time units."
   $\Rightarrow$ **not enforceable**

Evolution of Safety

Early Definitions

- 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 $\forall \sigma \in \Sigma^\omega .\, \sigma \notin P \rightarrow \big(\exists i \in \mathbb{N}.\, \forall \tau \in \Sigma^\omega .\, \sigma^{<i} \cdot \tau \notin P\big)$
- Folklore: A property $P \subseteq \Sigma^\infty$ is ∞-**safety** if $\forall \sigma \in \Sigma^\infty .\, \sigma \notin P \rightarrow \big(\exists i \in \mathbb{N}.\, \forall \tau \in \Sigma^\infty .\, \sigma^{<i} \cdot \tau \notin P\big)$
- T. Henzinger, 1992: A property $P \subseteq \Sigma^\omega$ is **safety in** $U \subseteq \Sigma^\omega$ if $\forall \sigma \in U .\, \sigma \notin P \rightarrow \big(\exists i \in \mathbb{N}.\, \forall \tau \in \Sigma^\omega .\, \sigma^{<i} \cdot \tau \notin P \cap U\big)$

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Refined Definition

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Refined Definition

A property $P \subseteq \Sigma^\infty$ is **U-safety** if
$\forall \sigma \in \mathbf{U} .\, \sigma \notin P \rightarrow \big(\exists i \in \mathbb{N}. \forall \tau \in \Sigma^\infty .\, \sigma^{<i} \cdot \tau \notin P \cap \mathbf{U}\big)$

Evolution of Safety

Early Definitions

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Refined Definition

A property $P \subseteq \Sigma^\infty$ is **(U, O)-safety** if
$\forall \sigma \in \mathbf{U} . \sigma \notin P \rightarrow \big(\exists i \in \mathbb{N} . \sigma^{<i} \notin \Sigma^* \cdot \mathbf{O} \wedge \forall \tau \in \Sigma^\infty . \sigma^{<i} \cdot \tau \notin P \cap \mathbf{U}\big)$

Intuition: "P is safety in **U** *and* bad things are not caused by an **O**"

Safety and Enforceability

Theorem

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

P is $(\mathbf{U}, \mathbf{O})$-enforceable $\iff$

1. P is $(\mathbf{U}, \mathbf{O})$-safety,
2. $\mathrm{pre}_*(P \cap \mathbf{U})$ is a decidable set, and
3. $\varepsilon \in P$.

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

Contributions

1. Formalization and Characterization of Enforceability
2. **Realizability of Enforcement Mechanisms**

Realizability of Enforcement Mechanisms

Fundamental Algorithmic Problems

Given a specification of a policy.

- Is this policy 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

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

Checking Enforceability and Safety (PDA and FSA)

Checking Enforceability

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

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

Checking Safety

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

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

Checking Enforceability and Safety (LTL and MLTL)

Checking Enforceability

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

1. $\mathrm{pre}_*(L(\varphi_P) \cap L(\varphi_{\mathbf{U}}))$ 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 formulæ $\varphi_{\mathbf{U}}$ 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

Conclusion

Summary

- Formalization of enforceability in a refined abstract setting
- Characterization of enforceability
- Realizability problem for enforcement

Future Work

- Investigate more powerful enforcement mechanisms
- Investigate more expressive specification languages
- Provide tool support