Monitoring Security Policies

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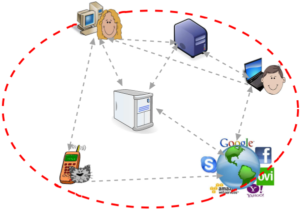
Story so far . . .

- Which policies are **enforceable**?
  - Characterization for an abstract setting
  - Enforcement via execution monitoring



policies

system

allowed action?

enforcement mechanism

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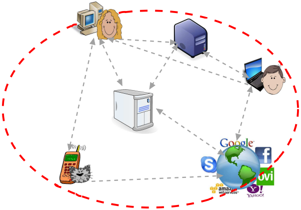


policies

system

allowed action?

enforcement mechanism

- In the following:
  How to check **policy compliance** of system behavior?

$$\text{behavior} \overset{?}{\models} \text{policy}$$

Why relevant?

- Policies are omnipresent but not all are enforceable

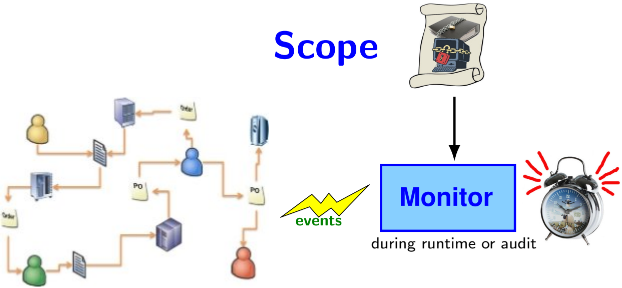
- Even when enforceable, the enforcement mechanism might be missconfigured or corrupted

- Strengthen security controls, audits, system debugging, . . .
  See NIST SP 800-92: "Guide to Computer Security Log Management"

Why different?

- **Policy enforcement and monitoring are related but ...**
- *Monitoring is simpler!*
  A monitor only needs to observe the system and report the violations
  * Events must only be observable
  * When monitoring online, violations can be reported possibly with a delay
  * Monitoring a trace offline is also possible
- *Monitoring is more generally applicable!*
  * For $P \subseteq \Sigma^\infty$, if P is enforceable then P is "monitorable"
  * Pnueli & Zaks (2006):
    "A verdict for an infinite sequence is always possible by an observation."
  * Examples: ω-safety properties and also some ω-liveness properties (e.g., *eventually p*)
  * Nonexamples: some ω-liveness properties (e.g., *always eventually p*)
  * Alternative characterizations/views exist (e.g., [Falcone et al. '12])

Scope



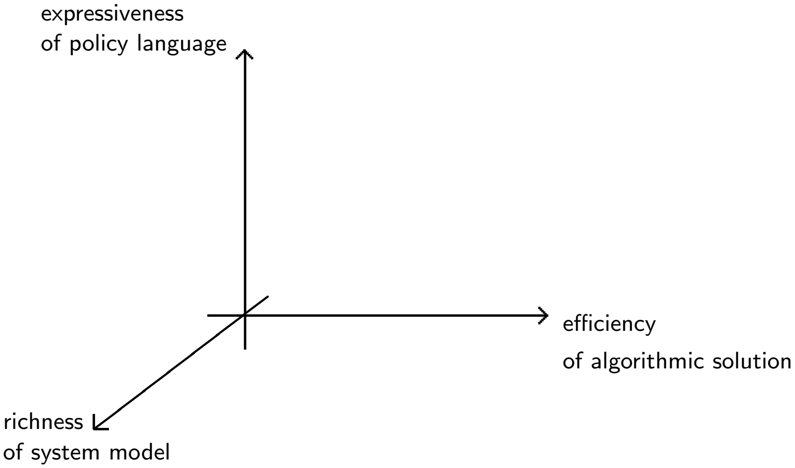
- **Setting:** policies stipulate data usage and agent behavior in IT systems or business processes

  HIPAA, SOX, separation of duty, etc.

- **Objective:** detect policy violations

- **Focus:** **policy specification** and **monitoring**

Why challenging?



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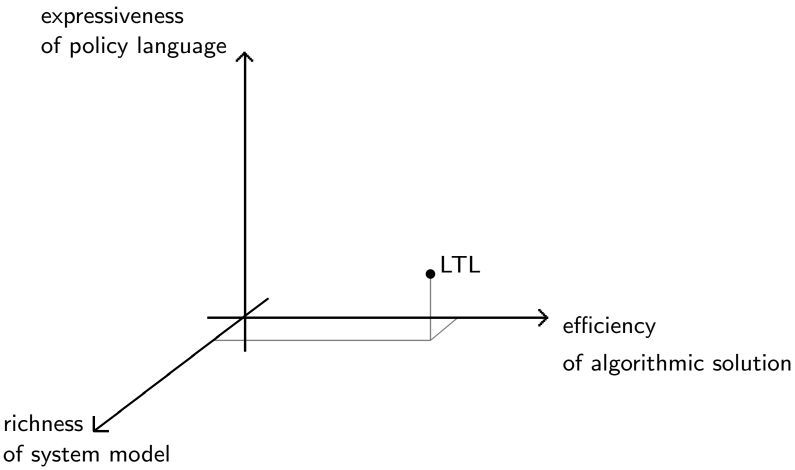

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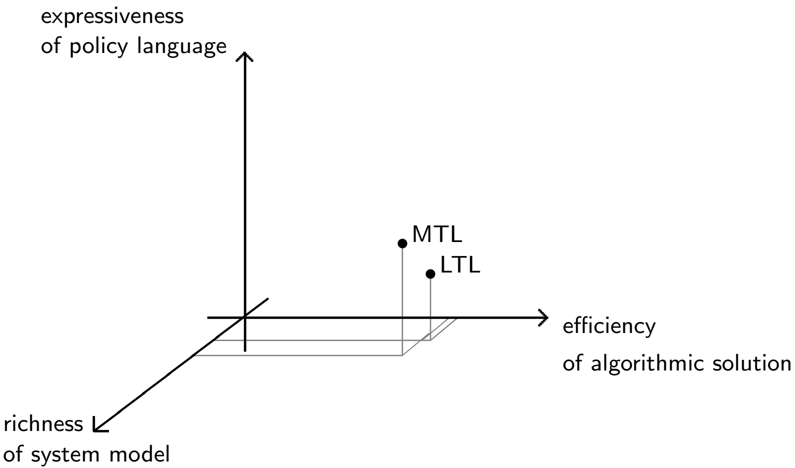

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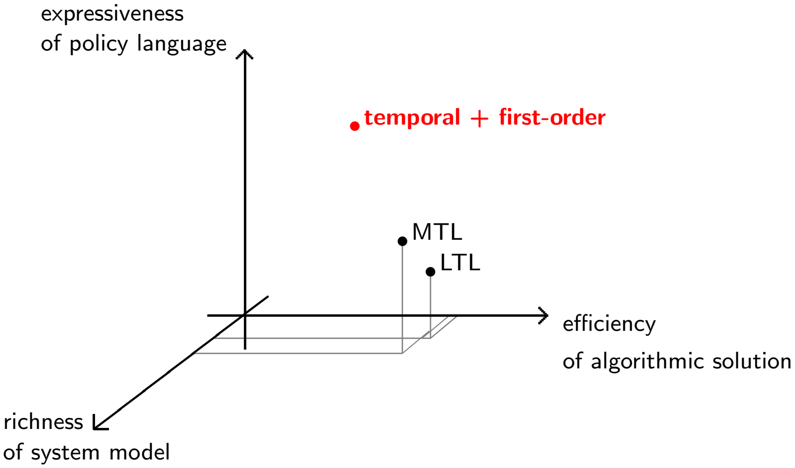
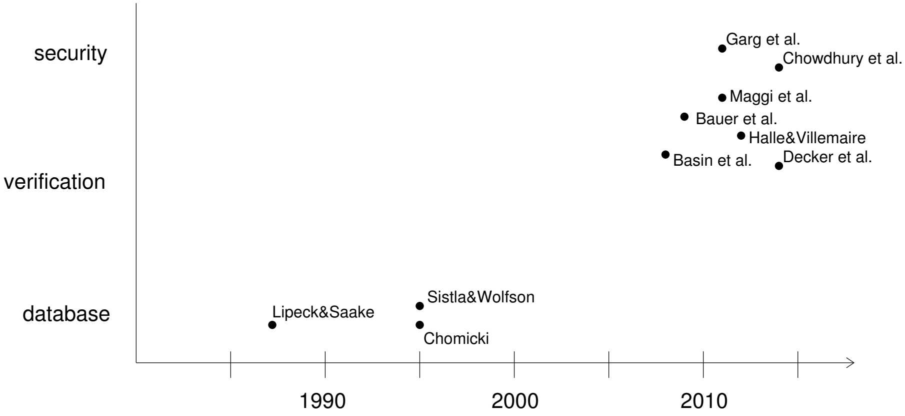


Monitoring first-order temporal properties



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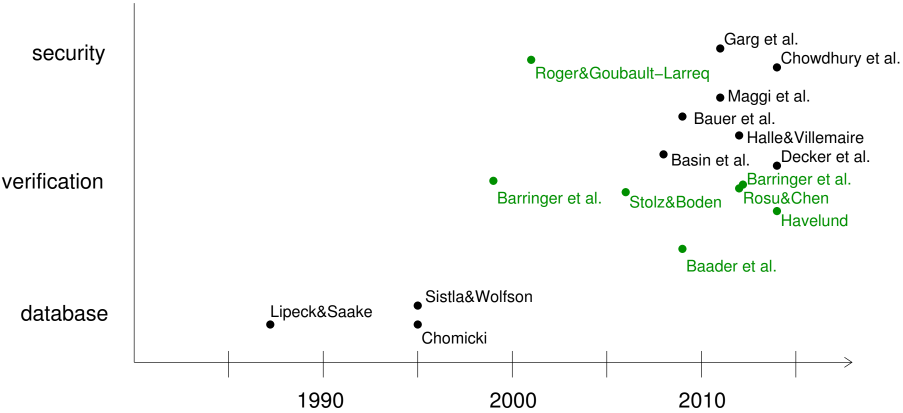
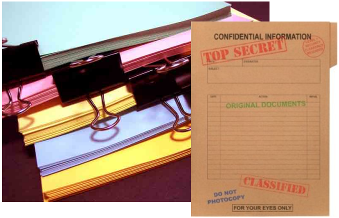


Policy Specification

Example



- Consider a financial or research institute
  - Employees write and publish reports
  - Reports may contain confidential data
- Report-must-be-approved policy

  1. *Reports must be approved before they are published.*
  2. *Approvals must happen at most 10 days before publication.*
  3. *The employees' managers must approve the reports.*

- IT system logs events

```
2013-03-03    publish_report (Charlie, #234)
2013-03-04    archive_report (Alice, #104)
    ⋮               ⋮
2013-03-09    approve_report (Alice, #248)
2013-03-13    publish_report (Bob, #248)
    ⋮               ⋮
```

- Is system trace policy compliant?

Policy elements

1. *Reports must be approved before they are published.*
2. *Approvals must happen at most 10 days before publication.*
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Policy elements

Subjects

- **reports** and **employees**
- unbounded over time

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Temporal aspects

- qualitative: **before** and **always**
- quantitative: **at most 10 days**

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- happen at a point in time
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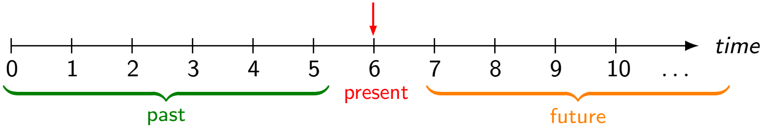
Temporal aspects

- qualitative: **before** and **always**
- quantitative: **at most 10 days**

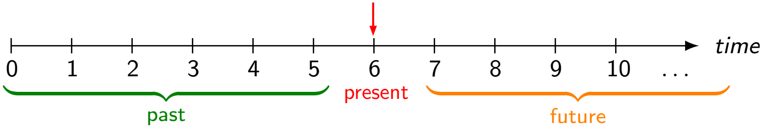
State predicates

- **being someone's manager**
- have a duration

Linear-time temporal logic



Linear-time temporal logic



- At each time point $i \in \mathbb{N}$, a proposition P is either true or false

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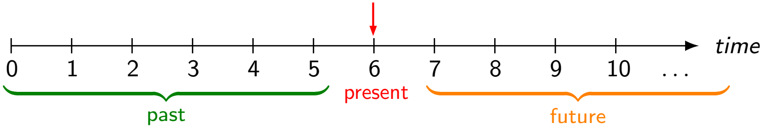

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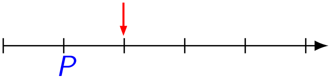
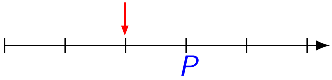
$\bullet P$



$\circ P$



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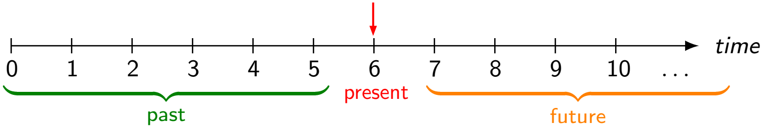

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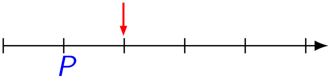
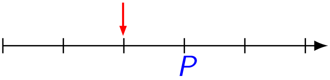
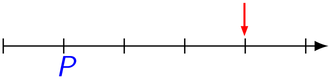
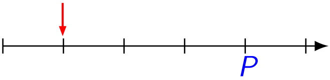
$\bullet P$ 

$\bigcirc P$ 

- **Once** and **Eventually** (including **present**)

$\blacklozenge P$ 

$\Diamond P$ 

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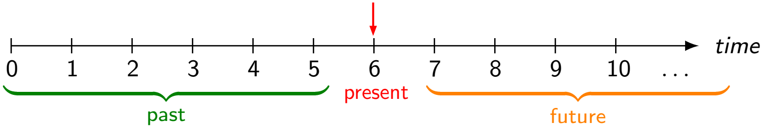

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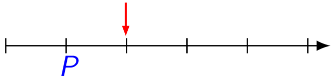

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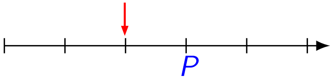

- **Once** and **Eventually** (including **present**)

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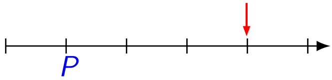

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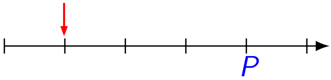
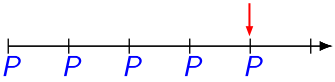
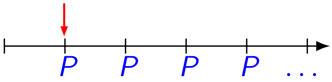


- **Historically** and **Generally** (including **present**)

$\blacksquare P$

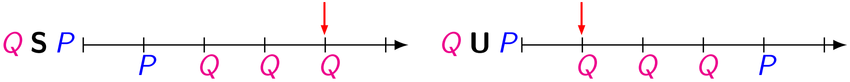


$\Box P$



Since and Until

- Temporal operators: **Since** and **Until**



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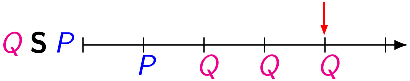
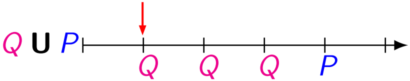




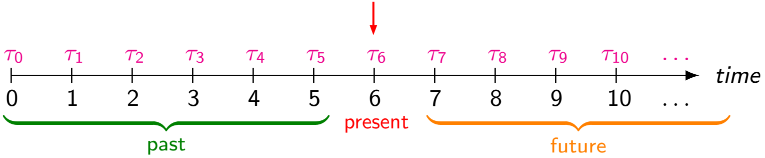
- Examples:

$$\Box\, access \rightarrow \blacklozenge\, login \qquad\qquad \neg\big((\neg login)\ \mathbf{U}\ (access \wedge \neg login)\big)$$

$$\Box\, access \rightarrow \big((\neg logout)\ \mathbf{S}\ login\big)$$

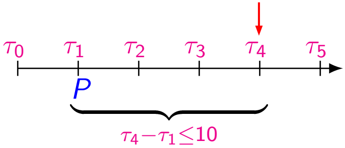
“a user is not allowed to acccess a file before he has not logged in”

Metric temporal operators



- Each time point $i \in \mathbb{N}$ is **timestamped** $\tau_i \in \mathbb{N}$
  - ∗ *monotonically increasing*: for all $i \in \mathbb{N}$, $\tau_i \leq \tau_{i+1}$
  - ∗ *progressing*: for every $\kappa \in \mathbb{N}$, there is some $i \in \mathbb{N}$ such that $\tau_i > \kappa$
- Attach timining constraints to temporal operators

$\blacklozenge_{\leq 10}\, P$



Propositional MTL

- **Syntax:** P an atomic proposition from AP and I an interval over $\mathbb{N}$

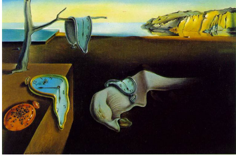
$$\phi ::= P \;\big|\; \neg\phi \;\big|\; \phi \vee \phi \;\big|\; \bullet_I\, \phi \;\big|\; \bigcirc_I\, \phi \;\big|\; \phi\, \mathbf{S}_I\, \phi \;\big|\; \phi\, \mathbf{U}_I\, \phi$$

- **Semantics:** $\bar{D} = (D_0, D_1, \dots)$ with $D_0, \dots \subseteq AP$, $\bar{\tau} = (\tau_0, \tau_1, \dots)$, and $i \in \mathbb{N}$

$$\begin{array}{lll}
(\bar{D}, \bar{\tau}, i) \models P & \text{iff} & P \in D_i \\
(\bar{D}, \bar{\tau}, i) \models \neg\phi & \text{iff} & (\bar{D}, \bar{\tau}, i) \not\models \phi \\
(\bar{D}, \bar{\tau}, i) \models \phi \vee \psi & \text{iff} & (\bar{D}, \bar{\tau}, i) \models \phi \text{ or } (\bar{D}, \bar{\tau}, i) \models \psi \\
 & & \\
(\bar{D}, \bar{\tau}, i) \models \bullet_I\, \phi & \text{iff} & i > 0,\ \tau_i - \tau_{i-1} \in I,\ \text{and } (\bar{D}, \bar{\tau}, i-1) \models \phi \\
(\bar{D}, \bar{\tau}, i) \models \bigcirc_I\, \phi & \text{iff} & \tau_{i+1} - \tau_i \in I \text{ and } (\bar{D}, \bar{\tau}, i+1) \models \phi \\
 & & \\
(\bar{D}, \bar{\tau}, i) \models \phi\, \mathbf{S}_I\, \psi & \text{iff} & \text{there is some } j \leq i \text{ with } \tau_i - \tau_j \in I,\ (\bar{D}, \bar{\tau}, j) \models \psi, \\
 & & \text{and } (\bar{D}, \bar{\tau}, k) \models \phi,\ \text{for all } k \text{ with } j < k \leq i \\
(\bar{D}, \bar{\tau}, i) \models \phi\, \mathbf{U}_I\, \psi & \text{iff} & \text{there is some } j \geq i \text{ with } \tau_j - \tau_i \in I,\ (\bar{D}, \bar{\tau}, j) \models \psi, \\
 & & \text{and } (\bar{D}, \bar{\tau}, k) \models \phi,\ \text{for all } k \text{ with } i \leq k < i
\end{array}$$

- **Syntactic Sugar:** $\blacklozenge_I\, \phi := \mathit{true}\, \mathbf{S}_I\, \phi$, $\blacksquare_I\, \phi := \neg \blacklozenge_I \neg\phi$, ...

Remarks on time model



- Zoo of temporal logics: CTL, LTL, PSL, ITL, MTL, TPTL, ...
  - Dedicated temporal operators; temporal reasoning restricted to a few cases
  - Underlying time models differ [Alur&Henzinger '92]
- Why time-points with time-stamps?
  - Event-based view
  - Temporal reasoning with points is “simpler” than with intervals (see [Basin et al. '11])
  - State predicates can often be mimicked with the **S** operator
- Why a discrete time domain?
  - Clocks have limited precision
  - Minor impact on monitoring
- Linear time versus branching time
  - In monitoring, we observe a single trace

Policy specification language

Metric First-Order Temporal Logic [Koymans '90]

$$\Box \forall e. \forall r.\, \mathit{publish\_report}(e, r) \rightarrow \blacklozenge_{\leq 10} \exists m.\, \underline{\mathit{manager}}(m, e) \wedge \mathit{approve\_report}(m, r)$$

- **First-order** for expressing relations on data
- **Temporal operators** for reasoning about time
- **Metric information** adds timing constraints

Syntax

- A *signature* S is a tuple (C, R)

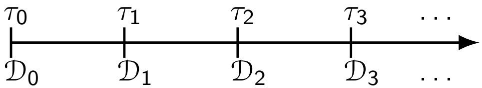
  C is a finite set of constant symbols and R is a finite set of predicates, each with an associated arity

- *(MFOTL) formulas* over a signature S and set of variables V

$$\begin{array}{rcl} \phi & ::= & t_1 \approx t_2 \;\big|\; t_1 \prec t_2 \;\big|\; r(t_1, \ldots, t_n) \;\big|\; \exists x.\, \phi \;\big| \\ & & \neg\phi \;\big|\; \phi \vee \phi \;\big|\; \CIRCLE_I\, \phi \;\big|\; \Circle_I\, \phi \;\big|\; \phi \,\mathbf{S}_I\, \phi \;\big|\; \phi \,\mathbf{U}_I\, \phi \end{array}$$

  where I is an *interval* of $\mathbb{N}$

Semantics



- A *temporal structure* (over S) is a pair $(\bar{\mathcal{D}}, \bar{\tau})$.
  - Sequence $\bar{\tau} = (\tau_0, \tau_1, \dots)$ of timestamps, $\tau_i \in \mathbb{N}$
    monotonically increasing and progressing
  - Sequence of structures $\bar{\mathcal{D}} = (\mathcal{D}_0, \mathcal{D}_1, \dots)$
    constant domains and rigid interpretation of constant symbols
- $(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models \phi$ denotes *MFOTL satisfaction*

  $(\bar{\mathcal{D}}, \bar{\tau})$ is a temporal structure, v a valuation, $i \in \mathbb{N}$, and ϕ a formula
- Standard semantics for first-order part

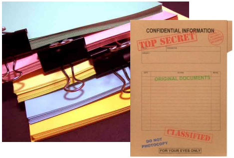
Differences to other FO monitoring approaches

- Temporal **past** and **future** operators
  As we will see, the operator **S** will be particularly handy
- **Fixed (infinite) domain** $|\bar{\mathcal{D}}|$
  But multiple (finite) events at each time point

$$(\mathsf{Alice}, 234) \in \mathit{approve\_report}^{\mathcal{D}_i} \quad \text{and}$$
$$(\mathsf{Bob}, 248), (\mathsf{Charlie}, 249) \in \mathit{publish\_report}^{\mathcal{D}_i}$$

- **Quantification**
  $\left(\bar{\mathcal{D}}, \bar{\tau}, v, i\right) \models \exists x.\, \phi \quad \text{iff} \qquad \left(\bar{\mathcal{D}}, \bar{\tau}, v[x \mapsto d], i\right) \models \phi,$ for some $d \in |\bar{\mathcal{D}}|$
  Alternatives:
  - freeze quantification ("half-order" [Henzinger '94])
  - guarded quantification [Garg et al. '11, Chowdhury et al. '14]
  - range restricted to data items occurring at current time point [Hallé&Villemaire '12, Bauer et al. '09]
- For monitoring, we will impose syntactic restrictions

Policy revisited and simplified



1. *Reports must be approved before they are published.*
2. *Approvals must happen at most 10 days before publication.*
3. ~~*The employees' managers must approve the reports.*~~

- Publishing and approving events are logged with time-stamps

```
    ⋮              ⋮
2013-03-04    archive_report (Alice, #104)
2013-03-04    approve_report (Alice, #248)
    ⋮              ⋮
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              publish_report (Bob, #248)
    ⋮              ⋮
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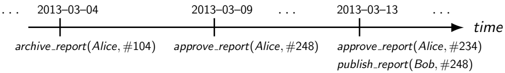
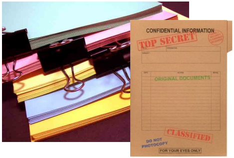


- Simplified policy in MFOTL:

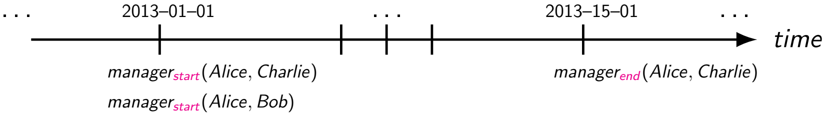
$$\Box\, \forall e.\, \forall r.\, \mathit{publish\_report}(e, r) \rightarrow \blacklozenge_{\leq 10}\, \exists m.\, \mathit{approve\_report}(m, r)$$



Policy revisited

1. *Reports must be approved before they are published.*
2. *Approvals must happen at most 10 days before publication.*
3. *The employees' managers must approve the reports.*

- Being someone's manager is a state property, with a duration
  - ∗ Log events that mark start and end points



  - ∗ State predicate as syntactic sugar

$$\underline{manager}(m, e) = \neg manager_{end}(m, e) \ \mathbf{S} \ manager_{start}(m, e)$$

- Policy in MFOTL:

$$\Box \forall e. \forall r.\ publish\_report(e, r) \rightarrow$$
$$\blacklozenge_{\leq 10} \exists m.\ \underline{manager}(m, e) \wedge approve\_report(m, r)$$

Separation of duty requirements

Principle for preventing fraud and errors

- Requires involvement of multiple users in critical processes.
- Usually formulated on top of Role-Based Access Control.
  - Users are assigned to roles, which have associated permissions.
  - SoD constraints specified in terms of mutually exclusive roles.

Separation of duty requirements

Principle for preventing fraud and errors

- Requires involvement of multiple users in critical processes.
- Usually formulated on top of Role-Based Access Control.
  - Users are assigned to roles, which have associated permissions.
  - SoD constraints specified in terms of mutually exclusive roles.
- Signature (formalizing both RBAC and SoD)
  - $\underline{U}$, $\underline{R}$, $\underline{A}$, $\underline{O}$, and $\underline{S}$ represent the sets of users, roles, actions, objects, and sessions associated with a (RBAC) system
  - $\underline{UA}(u, r)$: user u assigned role r
  - $\underline{PA}(r, a, o)$: role r can carry out action a on object o
  - $\underline{roles}(s, r)$: role r is active in session s
  - $\underline{X}(r, r')$: roles r and r' are mutually exclusive
  - $exec(s, a, o)$: action a is executed on object o in session s

Formalizing SoD requirements

- *Static SoD*: no user may be assigned to two mutually exlusive roles

$$\Box\, \forall r.\, \forall r'.\, \underline{X}(r, r') \rightarrow \neg \exists u.\, \underline{UA}(u, r) \wedge \underline{UA}(u, r')$$

(Assumption: X irreflexive and symmetric)

- *Simple dynamic SoD*: a user may be assigned to two exclusive roles provided he does not activate them both in the same session

$$\Box\, \forall r.\, \forall r'.\, \underline{X}(r, r') \rightarrow \neg \exists s.\, \underline{roles}(s, r) \wedge \big(\neg S_{end}(s)\ \mathbf{S}\ \underline{roles}(s, r')\big)$$

(Assumptions: session always associated with one user who remains constant over the session's lifetime, ...)

SoD requirements (cont.)

- *Object-based SoD*: a user may be assigned to two exclusive roles and also activate them both in the same session, but he must not carry out actions on the same object through both.

$$\begin{aligned}\Box\,\forall r.\,\forall r'.\,\underline{X}(r,r') \;\rightarrow\; & \\ \neg\exists s.\,\exists o.\big(&\exists a.\,exec(s,a,o) \wedge \underline{roles}(s,r) \wedge \underline{PA}(r,a,o)\big) \wedge \\ &\big(\neg S_{end}(s)\;\mathbf{S}\;\exists a'.\,exec(s,a',o) \wedge \\ &\qquad \underline{roles}(s,r') \wedge \underline{PA}(r',a',o)\big)\end{aligned}$$

Chinese Wall

- Policy to avoid conflict-of-interest situations

  "Subject s must not access object o when s has previously accessed another object in a different dataset than o and both datasets are in the same conflict-of-interest class"

- A possible formalization (with timing constraints):

$$\begin{aligned}\Box\, \forall s.\, \forall o.\, \forall d.\, \forall d'.\ & access(s,o) \wedge \underline{dataset}(o,d) \wedge \\ & \big(\exists o'.\, (\blacklozenge_{<4}\, access(s,o')) \wedge \underline{dataset}(o',d')\big) \ \rightarrow \\ & \neg \underline{conflict}(d,d')\end{aligned}$$

  Assume that:
  - At each time point, *conflict* is irreflexive and symmetric
  - At each time point, *dataset* is a partial function from objects to datasets

- Different types of predicates:
  - Event predicate: accessing an object happens at a time point
  - State predicate: being in a dataset has a duration (start and finish)
  - Datasets and conflict-of-interest classes might change over time

Experience

MFOTL is well suited to formalize a wide range of policies

But:

- Precision must precede formalization
  - *"Data must be securely stored."*
- Gap between high-level policies and system information
  - *"Data must be deleted within 30 days."*
  - *"Data should be used for statistical purposes only."*
- Not all policies are trace properties
  - *"Average response time, over all executions, should be less than 10ms."*
  - *"Actions of high users have no effect on observations of low users."*

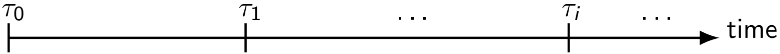
Monitoring

Monitoring Objective

- For a policy given as an **MFOTL formula** ϕ

$$\Box \forall c.\, \forall t.\, \forall a.\, \mathit{trans}(c,t,a) \wedge \mathit{th} < a \rightarrow \Diamond_{<6}\, \mathit{report}(t)$$

- and a **prefix of a temporal structure** given by system events or logs



trans	cID	tID	amount
	Bob	#34	$100'000
	Eve	#37	$1'000

report	tID

trans	cID	tID	amount
	Eve	#45	$999'999

report	tID
	#34

trans	cID	tID	amount
	Bob	#78	$24
	Mallory	#99	$333'333

report	tID

- monitor should **report all policy violations** (either online or offline)

Monitoring Objective

- For a policy given as an **MFOTL formula** ϕ

$$\Box \forall c.\, \forall t.\, \forall a.\, \mathit{trans}(c,t,a) \land \big(\blacklozenge_{<31} \exists t'.\, \exists a'.\, t \not\approx t' \land \mathit{trans}(c,t',a') \land \Diamond_{<6}\, \mathit{report}(t') \big) \\ \rightarrow \\ \Diamond_{<3}\, \mathit{report}(t)$$

- and a **prefix of a temporal structure** given by system events or logs

τ_0 — τ_1 — $\dots$ — τ_i — $\dots$ → time

At τ_0:

trans	cID	tID	amount
	Bob	#34	$100'000
	Eve	#37	$1'000

report	tID

At τ_1:

trans	cID	tID	amount
	Eve	#45	$999'999

report	tID
	#34

At τ_i:

trans	cID	tID	amount
	Bob	#78	$24
	Mallory	#99	$333'333

report	tID

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- and a **prefix of a temporal structure** given by system events or logs

τ_0 $\quad$ τ_1 $\quad$ ... $\quad$ τ_i $\quad$ ... $\quad$ time

τ_0:

trans	cID	tID	amount
	Bob	**#34**	**$100'000**
	Eve	#37	$1'000

report	tID

τ_1:

trans	cID	tID	amount
	Eve	#45	$999'999

report	tID
	#34

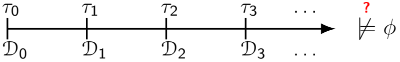
τ_i:

trans	cID	tID	amount
	Bob	**#78**	**$24**
	Mallory	#99	$333'333

report	tID

- monitor should **report all policy violations** (either online or offline)

Restrictions



Not every MFOTL-definable property can be effectively monitored on a temporal structure

- **Structures** $\mathcal{D}_0, \mathcal{D}_1, \ldots$ have only finite relations
- **Formula** ϕ must be of the form $\Box\,\phi'$
  - Temporal future operators in ϕ' only refer finitely into the future
    So ϕ describes an ***ω*-safety property**
  - Further restrictions on ϕ' to guarantee finiteness of intermediate results

$$r(x) \wedge \blacksquare_{<7} \neg q(x) \qquad \rightsquigarrow \qquad r(x) \wedge \neg \blacklozenge_{<7}\, q(x)$$

Related to domain independence of database queries
(see, e.g., [Fagin 1982])

Preprocessing: Negation and Rewriting

- Input formula ϕ

$$\square \forall t.\, \forall c.\, \forall a.\, \mathit{trans}(t, c, a) \wedge \big(\blacklozenge_{<31} \exists t'.\, \exists a'.\, t \not\approx t' \wedge \mathit{trans}(t', c, a') \wedge \lozenge_{<6}\, \mathit{report}(t') \big) \\ \rightarrow \\ \lozenge_{<3}\, \mathit{report}(t)$$

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- Negate, rewrite, and drop outermost $\Diamond$ and $\exists$ quantifier(s), yielding ψ

$$\cancel{\Diamond \exists t.}\, \exists c.\, \exists a.\, \mathit{trans}(t,c,a) \land \left(\blacklozenge_{<31} \exists t'.\, \exists a'.\, t \not\approx t' \land \mathit{trans}(t',c,a') \land \Diamond_{<6}\, \mathit{report}(t') \right) \\ \land \\ \neg \Diamond_{<3}\, \mathit{report}(t)$$

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- **For monitoring:** for each $i \in \mathbb{N}$, determine elements satisfying ψ:

$$\big\{ \bar{a} \;\big|\; (\bar{\mathcal{D}}, \bar{\tau}, v[\bar{x}/\bar{a}], i) \models \psi \big\}$$

These are the transactions that should have been reported at time point i

Preprocessing: Reduction to First-Order Queries

- For each temporal subformula α in ψ, introduce an auxiliary predicate p_α

$$\exists c.\, \exists a.\, \mathit{trans}(t, c, a) \land \underbrace{\left(\blacklozenge_{<31}\, \exists t'.\, \exists a'.\, \ldots \land \underbrace{\lozenge_{<6}\, \mathit{report}(t')}_{p_{\alpha_1}}\right)}_{p_{\alpha_2}} \land \neg \underbrace{\lozenge_{<3}\, \mathit{report}(t)}_{p_{\alpha_3}}$$

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- Replace each α by a corresponding p_α, yielding first-order formula $\hat{\psi}$

$$\exists c.\, \exists a.\, \mathit{trans}(t, c, a) \land p_{\alpha_2}(c, t) \land \neg p_{\alpha_3}(t)$$

Preprocessing: Reduction to First-Order Queries

- For each temporal subformula α in ψ, introduce an auxiliary predicate p_α

$$\exists c.\, \exists a.\, \mathit{trans}(t, c, a) \land \underbrace{\left(\blacklozenge_{<31} \exists t'.\, \exists a'.\, \ldots \land \underbrace{\Diamond_{<6}\, \mathit{report}(t')}_{p_{\alpha_1}}\right)}_{p_{\alpha_2}} \land \neg \underbrace{\Diamond_{<3}\, \mathit{report}(t)}_{p_{\alpha_3}}$$

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$$\exists c.\, \exists a.\, \mathit{trans}(t, c, a) \land p_{\alpha_2}(c, t) \land \neg p_{\alpha_3}(t)$$

- **For monitoring:**
  - For each $i \in \mathbb{N}$, extend $\mathcal{D}_i$ to $\hat{\mathcal{D}}_i$, where for each temporal subformula α

$$p_\alpha^{\hat{\mathcal{D}}_i} = \left\{ \bar{a} \;\middle|\; (\bar{\mathcal{D}}, \bar{\tau}, v[\bar{x}/\bar{a}], i) \models \hat{\alpha} \right\}$$

  - For each $i \in \mathbb{N}$, query extended first-order structure $\hat{\mathcal{D}}_i$

$$\left\{ \bar{a} \;\middle|\; (\hat{\mathcal{D}}_i, v[\bar{x}/\bar{a}]) \models \hat{\psi} \right\}$$

Preprocessing: Reduction to First-Order Queries

- For each temporal subformula α in ψ, introduce an auxiliary predicate p_α

$$\exists c.\, \exists a.\, \mathit{trans}(t,c,a) \wedge \Big(\underbrace{\blacklozenge_{<31}\, \exists t'.\, \exists a'.\, \ldots \wedge \underbrace{\lozenge_{<6}\, \mathit{report}(t')}_{p_{\alpha_1}}}_{p_{\alpha_2}}\Big) \wedge \neg \underbrace{\lozenge_{<3}\, \mathit{report}(t)}_{p_{\alpha_3}}$$

- Replace each α by a corresponding p_α, yielding first-order formula $\hat{\psi}$

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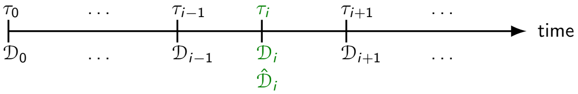
$$\{\bar{a} \mid (\hat{\mathcal{D}}_i, v[\bar{x}/\bar{a}]) \models \hat{\psi}\}$$

Next: how to construct $p_\alpha^{\hat{\mathcal{D}}_i}$ for each $i \in \mathbb{N}$

Constructing the Auxiliary Relations



- Construct auxiliary relations $p_\alpha^{\hat{\mathcal{D}}_i}$ inductively over α's formula structure and using also relations from both **previous** and **subsequent** structures
- Case where α has form $\bullet_I\, \beta$: $$p_\alpha^{\hat{\mathcal{D}}_i} = \begin{cases} \hat{\beta}^{\hat{\mathcal{D}}_{i-1}} & \text{if } i > 0 \text{ and } \tau_i - \tau_{i-1} \in I \\ \emptyset & \text{otherwise} \end{cases}$$
- Case where α has form $\bigcirc_I\, \beta$: $$p_\alpha^{\hat{\mathcal{D}}_i} = \begin{cases} \hat{\beta}^{\hat{\mathcal{D}}_{i+1}} & \text{if } \tau_{i+1} - \tau_i \in I \\ \emptyset & \text{otherwise} \end{cases}$$
  - ∗ Construction depends on relations in $\hat{\mathcal{D}}_{i+1}$ for which the predicates occur in $\hat{\beta}$
  - ∗ Monitor constructs $p_\alpha^{\hat{\mathcal{D}}_i}$ with a delay of at least one time step

Construction for $\mathbf{S}_{[0,\infty)}$

- The construction for $\alpha = \beta \, \mathbf{S}_{[0,\infty)} \, \gamma$ reflects the logical equivalence

$$\alpha \leftrightarrow \gamma \vee (\beta \wedge \bullet \alpha)$$

- Assume that β and γ have the same free variables. Then

$$p_\alpha^{\hat{\mathcal{D}}_i} = \hat{\gamma}^{\hat{\mathcal{D}}_i} \cup \begin{cases} \emptyset & \text{if } i = 0 \\ \hat{\beta}^{\hat{\mathcal{D}}_i} \cap p_\alpha^{\hat{\mathcal{D}}_{i-1}} & \text{if } i > 0 \end{cases}$$

- Uses relations just for subformulas and previous time point

- Constructions for metric $\mathbf{S}_I$ and $\mathbf{U}_I$ slightly more involved

Monitoring Algorithm

$i \leftarrow 0$ *% lookahead index in sequence $(\mathcal{D}_0, \tau_0), (\mathcal{D}_1, \tau_1), \ldots$*

$q \leftarrow 0$ *% index of next query evaluation in sequence $(\mathcal{D}_0, \tau_0), (\mathcal{D}_1, \tau_1), \ldots$*

$Q \leftarrow \big\{ \big(\alpha, 0, \mathit{waitfor}(\alpha)\big) \,\big|\, \alpha \text{ temporal subformula of } \psi \big\}$

loop

  Carry over constants and relations of $\mathcal{D}_i$ to $\hat{\mathcal{D}}_i$.

  for all $(\alpha, j, \emptyset) \in Q$ **do** *% can build relation for α in $\hat{\mathcal{D}}_j$*

    Build auxiliary relation for α in $\hat{\mathcal{D}}_j$.

    Discard auxiliary relation for α in $\hat{\mathcal{D}}_{j-1}$ if $j - 1 \geq 0$.

    Discard relations $p_\delta^{\hat{\mathcal{D}}_j}$, where δ is a temporal subformula of α.

  while all relations $p_\alpha^{\hat{\mathcal{D}}_q}$ are built for $\alpha \in \mathit{tsub}(\psi)$ **do**

    Output violations $\hat{\psi}^{\hat{\mathcal{D}}_q}$ and time-stamp τ_q.

    Discard structure $\hat{\mathcal{D}}_{q-1}$ if $q > 0$.

    $q \leftarrow q + 1$

  $Q \leftarrow \big\{ \big(\alpha, i+1, \mathit{waitfor}(\alpha)\big) \,\big|\, \alpha \text{ temporal subformula of } \psi \big\} \cup$
  $\big\{ \big(\alpha, j, \bigcup_{\alpha' \in \mathit{update}(S, \tau_{i+1} - \tau_i)} \mathit{waitfor}(\alpha')\big) \,\big|\, (\alpha, j, S) \in Q \text{ and } S \neq \emptyset \big\}$

  $i \leftarrow i + 1$ *% process next element in input sequence $(\mathcal{D}_{i+1}, \tau_{i+1})$*

end loop

Counters q (query) and i (lookahead) into input sequence

Monitoring Algorithm

$i \leftarrow 0$ *% lookahead index in sequence* $(\mathcal{D}_0, \tau_0), (\mathcal{D}_1, \tau_1), \ldots$
$q \leftarrow 0$ *% index of next query evaluation in sequence* $(\mathcal{D}_0, \tau_0), (\mathcal{D}_1, \tau_1), \ldots$
$Q \leftarrow \big\{ \big(\alpha, 0, \mathit{waitfor}(\alpha)\big) \,\big|\, \alpha \text{ temporal subformula of } \psi \big\}$
loop
  Carry over constants and relations of $\mathcal{D}_i$ to $\hat{\mathcal{D}}_i$.
  for all $(\alpha, j, \emptyset) \in Q$ **do** *% can build relation for* α *in* $\hat{\mathcal{D}}_j$
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    $q \leftarrow q + 1$
  $Q \leftarrow \big\{ \big(\alpha, i+1, \mathit{waitfor}(\alpha)\big) \,\big|\, \alpha \text{ temporal subformula of } \psi \big\} \cup$
    $\big\{ \big(\alpha, j, \bigcup_{\alpha' \in \mathit{update}(S, \tau_{i+1} - \tau_i)} \mathit{waitfor}(\alpha')\big) \,\big|\, (\alpha, j, S) \in Q \text{ and } S \neq \emptyset \big\}$
  $i \leftarrow i + 1$ *% process next element in input sequence* $(\mathcal{D}_{i+1}, \tau_{i+1})$
end loop

Q **maintains list of unevaluated subformula** (α, j, S) **for past time points**

Monitoring Algorithm

$i \leftarrow 0$ *% lookahead index in sequence* $(\mathcal{D}_0, \tau_0), (\mathcal{D}_1, \tau_1), \ldots$
$q \leftarrow 0$ *% index of next query evaluation in sequence* $(\mathcal{D}_0, \tau_0), (\mathcal{D}_1, \tau_1), \ldots$
$Q \leftarrow \{ (\alpha, 0, \mathit{waitfor}(\alpha)) \mid \alpha \text{ temporal subformula of } \psi \}$
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    Carry over constants and relations of $\mathcal{D}_i$ to $\hat{\mathcal{D}}_i$.
    for all $(\alpha, j, \emptyset) \in Q$ **do** *% can build relation for* α *in* $\hat{\mathcal{D}}_j$
        Build auxiliary relation for α in $\hat{\mathcal{D}}_j$.
        Discard auxiliary relation for α in $\hat{\mathcal{D}}_{j-1}$ if $j - 1 \geq 0$.
        Discard relations $p_\delta^{\hat{\mathcal{D}}_j}$, where δ is a temporal subformula of α.
    while relations $p_\alpha^{\hat{\mathcal{D}}_q}$ are built for all temporal subformulas α of ψ **do**
        Output violations $\hat{\psi}^{\hat{\mathcal{D}}_q}$ and time-stamp τ_q.
        Discard structure $\hat{\mathcal{D}}_{q-1}$ if $q > 0$.
        $q \leftarrow q + 1$
    $Q \leftarrow \{ (\alpha, i+1, \mathit{waitfor}(\alpha)) \mid \alpha \text{ temporal subformula of } \psi \} \cup$
        $\{ (\alpha, j, \bigcup_{\alpha' \in \mathit{update}(S, \tau_{i+1} - \tau_i)} \mathit{waitfor}(\alpha')) \mid (\alpha, j, S) \in Q \text{ and } S \neq \emptyset \}$
    $i \leftarrow i + 1$ *% process next element in input sequence* $(\mathcal{D}_{i+1}, \tau_{i+1})$
end loop

Given relations for all temporal subformulas, output policy violations

Finite Relations

- In each iteration, monitor stores auxiliary relations
- **Problem:** must restrict negation and quantification
  - Consider the formula $p(x) \wedge \bullet \neg q(x)$
  - In $(i+1)$st iteration, monitor constructs auxiliary relation $p^{\hat{\mathcal{D}}_i}_{\bullet \neg q(x)}$
- **Solution:** rewrite to a formula so that auxiliary relations are finite
  - $p(x) \wedge \bullet \neg q(x)$ is rewritten to $p(x) \wedge \bullet \big(\neg q(x) \wedge \bigcirc\, p(x)\big)$
  - Heuristic!
  - Related to domain independence of database queries, e.g., [Fagin '82]

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  - Heuristic!
  - Related to domain independence of database queries, e.g., [Fagin '82]

- Under reasonable assumptions, the size of the finite relations is **polynomially bounded** w.r.t. to input

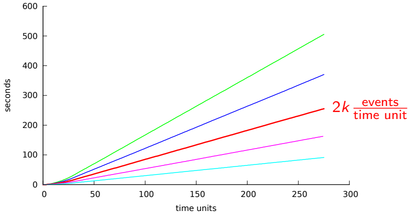
MONPOLY

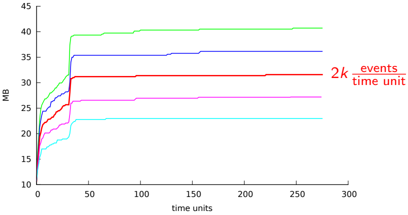
- Implementation of our monitoring algorithm for MFOTL
  - Usage: `monpoly -sig` *signature* `-formula` *policy* `-log` *logfile*
  - Output: policy violations
- Open source, GNU public license
  - Available at `http://sourceforge.net/projects/monpoly`
  - Written in OCaml
- Also handles policies with aggregations:

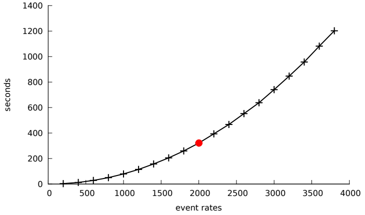
$$\Box\, \forall u.\, \forall s.\, \big[\mathrm{SUM}_a\ a, t.\ \blacklozenge_{<31}\ \mathit{withdraw}(u, t, a)\big](s; u) \rightarrow s \preceq 5000$$

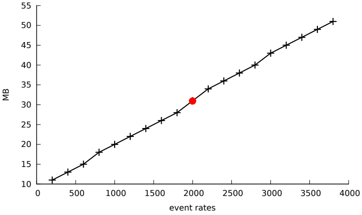
Performance Evaluation

- Generated log files with different event rates for a fixed time span
- Monitoring performance for complex transaction-report policy:



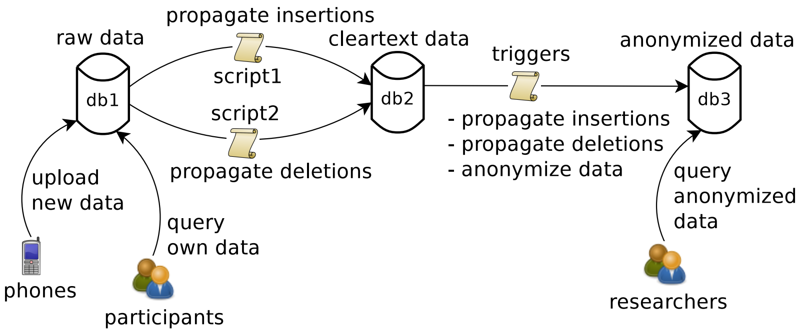






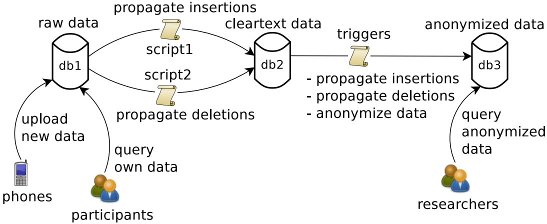
- PostgreSQL does not scale to larger log files

Case study: NOKIA's data-collection campaign



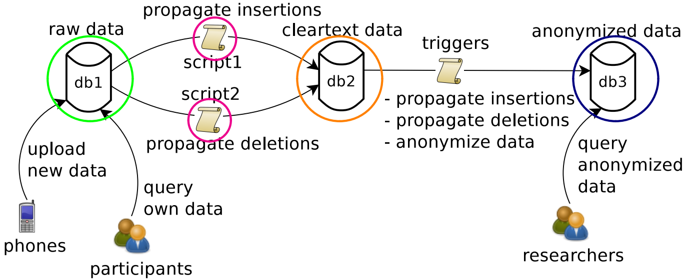
- Phone data collected and propagated to databases: location, call and SMS info, accelerometer, . . .
- Participants can view and delete their data
- Clear-text data used for personalized apps, e.g., location-history maps
- Anonymized data is used for research

Policies (sample)



1. Access-control rules restrict who accesses and modifies data in databases
   (A) Only user *script2* may delete data from *db2*
   (B) Databases *db1* and *db2* are accessed by *script1* account only while *script1* is running
2. Data changes are propagated between databases
   (C) Data deleted from *db2* is deleted from *db3* within 60 seconds
   (D) Data inserted into *db1* is, within 30 hours, either inserted into *db2* or deleted from *db1*

Logs



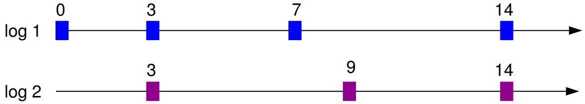
- Log entries are produced at multiple places
- Need to combine logs
- No total order on log entries
- Compliance might depend on order

Log sample

@unix time			
event	*db user*	*db*	*data id*
@1272902328			
insert	(eu.030,	db1,	146368038)
insert	(eu.031,	db2,	122368122)
@1272902355			
delete	(script2,	db2,	108031209)
select	(res.012,	db3,	146368038)
@1273158243			
script_end	(script1)		

Intractability

- Instead of monitoring a single trace, we must monitor a set of traces



- Policy violation: **some** trace/**all** traces

- Even for a very restrictive setting, corresponding decision problems are intractable

Instance:

* propositional, past-only, non-metric linear-time temporal formula ϕ
* prefixes $\bar{D}^1$ and $\bar{D}^2$ of length $n \geq 1$
  with $\bar{D}^i = (D_1^i, \tau_1)\,(D_1^i, \tau_1)\ \ldots\ (D_n^i, \tau_n)$, for $i \in \{1, 2\}$

Question WEAK: $(\bar{D}, 2n) \not\models \phi$, for **some** $\bar{D} \in \bar{D}^1 \,||\, \bar{D}^2$ is NP-complete

Question STRONG: $(\bar{D}, 2n) \not\models \phi$, for **all** $\bar{D} \in \bar{D}^1 \,||\, \bar{D}^2$ is coNP-complete

Collapsed Logs

- Policies should not care about the ordering of events with equal time-stamps

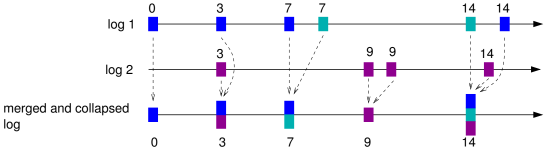
$$\Box\,\forall u.\,\forall d.\,\mathit{delete}(u, db2, d) \rightarrow \blacklozenge_{<1s}\,\Diamond_{<60s}\,\exists u'.\,\mathit{delete}(u', db3, d)$$

Collapsed Logs

- Policies should not care about the ordering of events with equal time-stamps

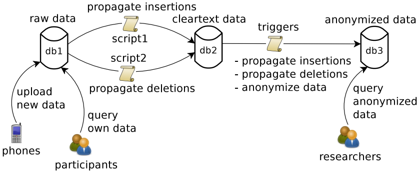
$$\Box\, \forall u.\, \forall d.\, delete(u, db2, d) \rightarrow \blacklozenge_{<1s} \Diamond_{<60s}\, \exists u'.\, delete(u', db3, d)$$

- Monitoring the log in which events with equal time-stamps are merged is sound and complete



- Checking if an MFOTL formula is order-independent is undecidable
  - ∗ Inductive reasoning over formula structure often sufficient
  - ∗ Approximation to order-independent properties possible

Results of Case Study



- **Performance:**
  - One year of logged data: 220 million log entries (8GB)

policy	time / space
easiest	17 minutes / 14 MB
hardest	1 hour / 3.3 GB (mostly within 600 MB)

  - Processing times reasonable and space requirements manageable
- **Compliance:**
  - System users attempted unauthorized actions
  - Testing, debugging, and other improvement activities
  - Bugs in scripts and triggers
- **Value:**
  - Useful even in a benevolent environment where the enterprise is committed to policy compliance
  - Helpful to debug and sharpen controls
  - Can be used to support audits, both internal and external

Conclusion

Conclusion

- Policy enforcement is a challenging and increasingly relevant topic.
  So is policy monitoring!

- Logical methods are well suited for reasoning about policies

  MFOTL: expressive, yet monitoring practically feasible

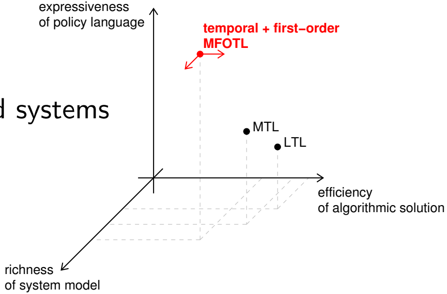
- Tool support publicly available
  MONPOLY at `http://sourceforge.net/projects/monpoly`
  including sanitized log data from NOKIA case study

- No silver bullet
  * Not every policy can be formalized in MFOTL
  * Running times and space consumption is still (always will be!) an issue

Challenges

- **Scaling-up**
  How to monitor terabytes/petabytes of logged data?

- **Distributed monitoring (and enforcement)**
  How to (online) monitor distributed systems in a distributed way?
  What policies are enforceable in a concurrent setting?



- **Incomplete knowledge**
  How account for actions that are not logged (e.g., logging failures)?
  What if observations are contradictory or imprecise?

References

- David Basin, Matúš Harvan, Felix Klaedtke, and Eugen Zălinescu.
  Monitoring usage-control policies in distributed systems.
  IEEE Transactions on Software Engineering, 2013.
- David Basin, Matúš Harvan, Felix Klaedtke, and Eugen Zălinescu.
  MONPOLY: Monitoring usage-control policies.
  Proceedings of the 2nd International Conference on Runtime Verification (RV'11).
- David Basin, Felix Klaedtke, Eugen Zăalinescu.
  Algorithms for monitoring real-time properties
  Proceedings of the 2nd International Conference on Runtime Verification (RV'11).
- David Basin, Felix Klaedtke, and Samuel Müller.
  Policy monitoring in first-order temporal logic.
  Proceedings of the 22nd International Conference on Computer Aided Verification (CAV'10).
- David Basin, Felix Klaedtke, and Samuel Müller.
  Monitoring security policies with metric first-order temporal logic.
  Proceedings of the 15th ACM Symposium on Access Control Models and Technologies (SACMAT'10).
- David Basin, Felix Klaedtke, Samuel Müller, and Birgit Pfitzmann.
  Runtime monitoring of metric first-order temporal properties.
  Proceedings of the 28th IARCS Annual Conference on Foundations of Software Technology and Theoretical Computer Science (FSTTCS'08).