Supervisory Control for Opacity and other analysis problematics (Drafty version)

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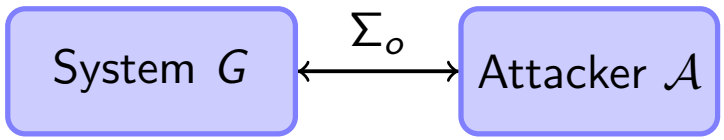
Security of Information Systems

- Emergence of new services
  - (E-)voting system
  - Medical card (medical information storage)
  - E-passport (biometric & person. information)
  - Web-services : E-Bancking, on-line payment, travel agency, etc
- Have to deal with critical information that should not flow, be erased or corrupted
- Security Aspects for information systems are classified into 3 categories :
  1. *Integrity* : something illegal cannot be performed by a user
  2. *Confidentiality* : some secret information cannot be inferred by a user
  3. *Availability* : a user can always perform the actions that are allowed by the other security policies

Information flow

- Context : Given a system $\mathcal{G}$ and an attacker $\mathcal{A}$ who
  - knows the model of $\mathcal{G}$ and
  - observes $\mathcal{G}$ and interacts with $\mathcal{G}$ through Σ_o



- Confidentiality information : secret properties
  - State configurations (values of secret variables)
  - Occurrence of an event (e.g. password file is unlocked), Trajectories
- Information flow : an attacker is able to infer confidential information based on observations and the knowledge of the system.

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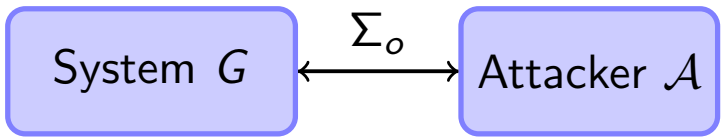

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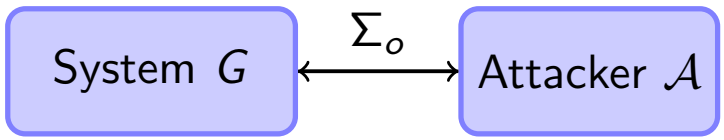

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Outline

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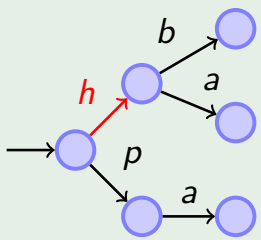
State-Based (language-Based) Opacity

Definition (State-Based opacity)

On $\mathcal{G}$, the secret S is opaque under the projection P_{Σ_o} or $(\mathcal{G}, P_{\Sigma_o})$-opaque if

$$\forall t \in \mathcal{L}_S(\mathcal{G}), \exists s \in \mathcal{L}(\mathcal{G}) : s \approx_{\Sigma_o} t \wedge s \notin \mathcal{L}_S(\mathcal{G}).$$

Example



$$\Sigma = \{h, p, a, b\},\ \Sigma_o = \{a, b\}$$

$$L_\varphi = \Sigma^*.h.\Sigma^*$$

Verification of Opacity

Theorem

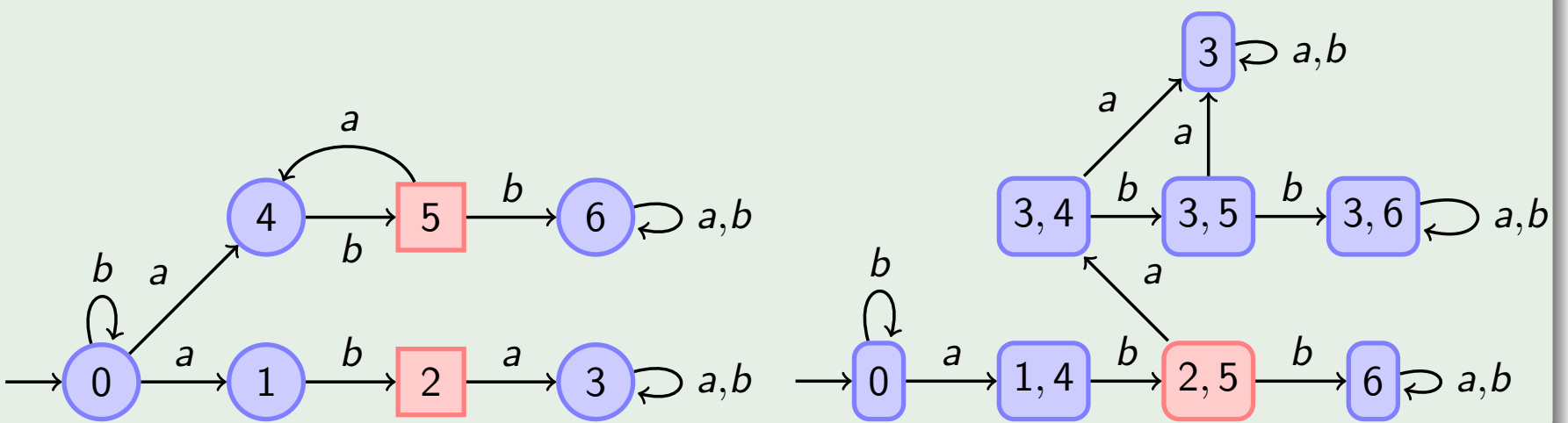
Checking opacity is PSPACE complete

$\Rightarrow$ Reduction of universality problem

Algorithm to Check Opacity

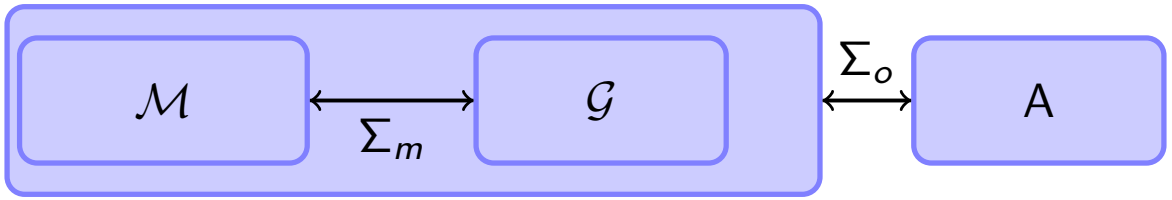
1. Subset construction of $\mathcal{G}$
2. check whether a macro-state $F \subseteq S$ is reachable

Example



Monitoring an information flow

Compute a monitor in charge of detecting an information flow



- Set of observations for which there is an information flow

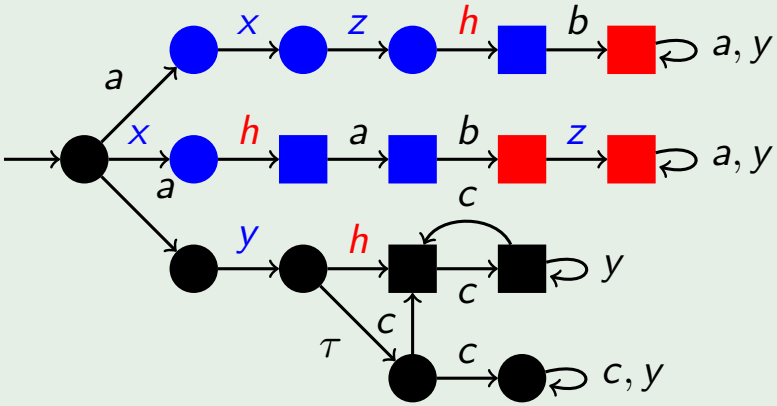
$$\mathcal{F} = \mathcal{L}_{2^S}(Det_{\Sigma_o}(\mathcal{G}))$$

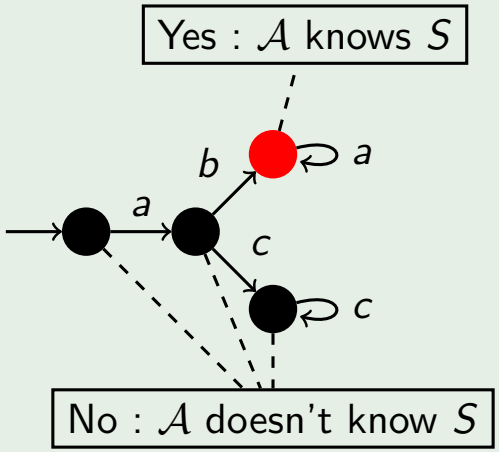
- $\mathcal{M}$ M has to diagnose/predict the occurrence of the trajectories of $\mathcal{I} = \mathcal{L}(\mathcal{G}) \cap P_{\Sigma_o}^{-1}(\mathcal{F}).\Sigma^*$ by observing Σ_m.

- Some information flows might not be detected by the monitor

Monitoring an information flow

Example ($\Sigma_o = \{a, b, c\}$, $\Sigma_m = \{x, y\}$)





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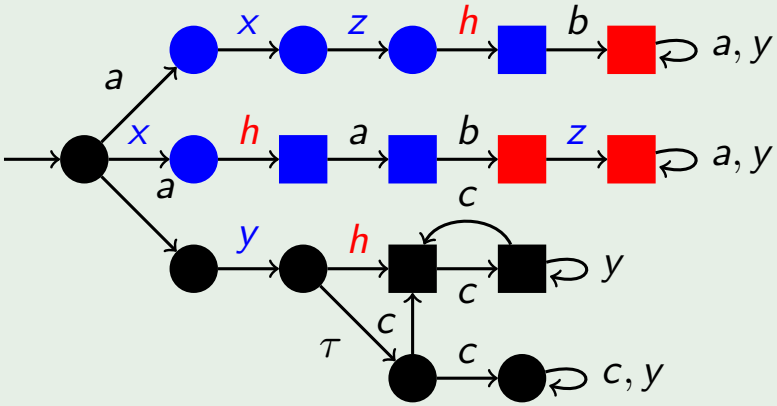
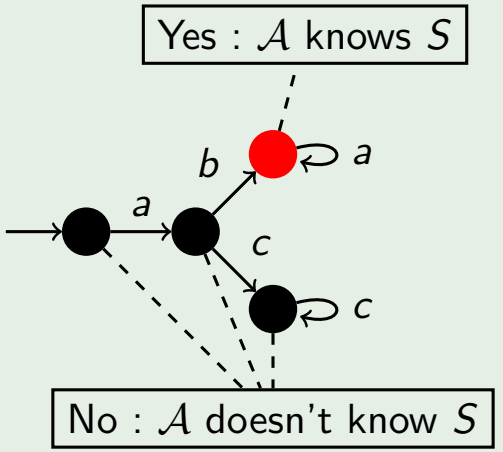
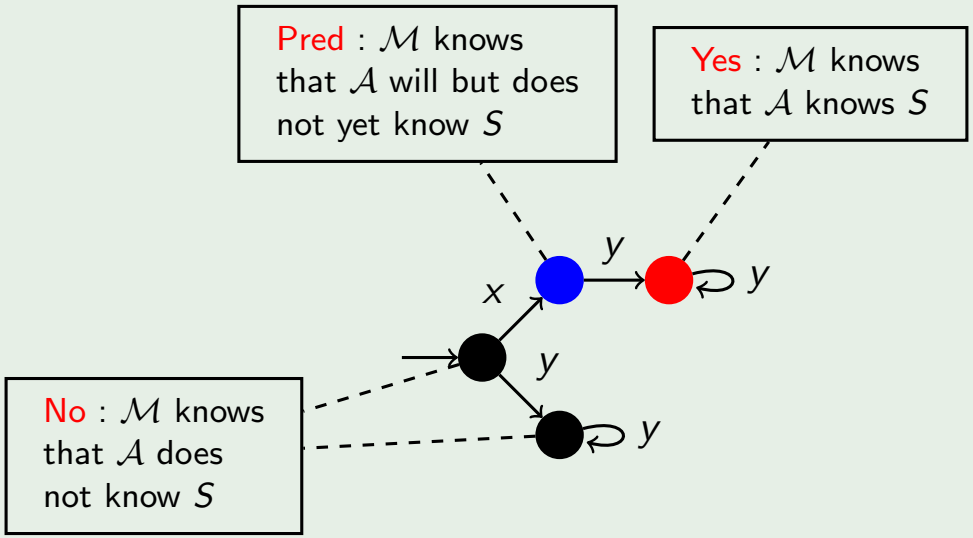
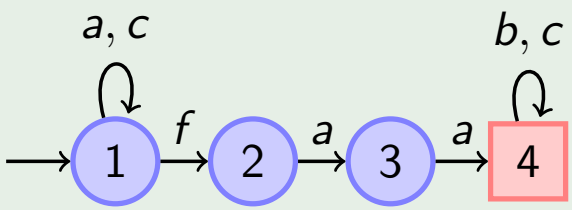




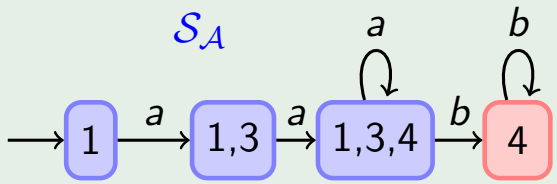


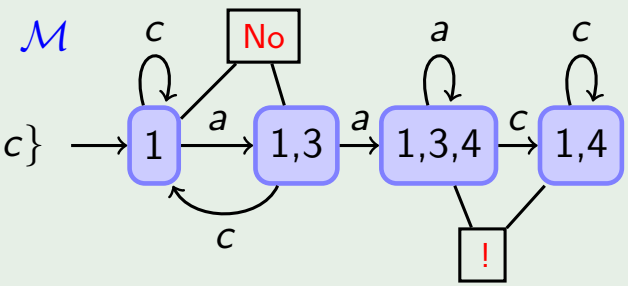
How to be sure that $\mathcal{A}$ knows the secret

Example



$\Sigma_o = \{a, b\}$





$\Sigma_m = \{a, c\}$

$s = aabc \Rightarrow \begin{cases} P_{\Sigma_o}(s) = aab \\ P_{\Sigma_m}(s) = aac \end{cases}$

Proposition

- *Every information flow is detectable iff $\mathcal{G}$ is $\mathcal{I}$-diagnosable w.r.t. Σ_m.*
- *Every information flow is detectable strictly before its occurrence iff $\mathcal{G}$ is $\mathcal{I}$-predictable w.r.t. Σ_m.*

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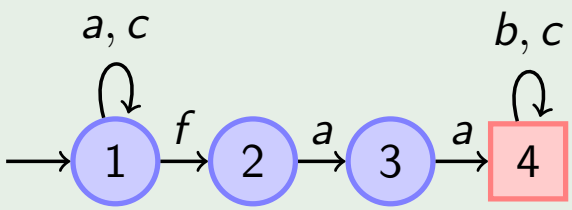

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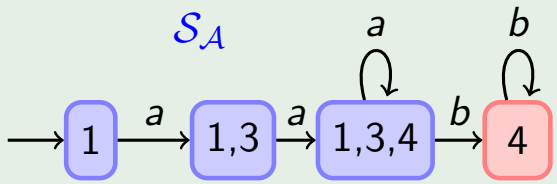

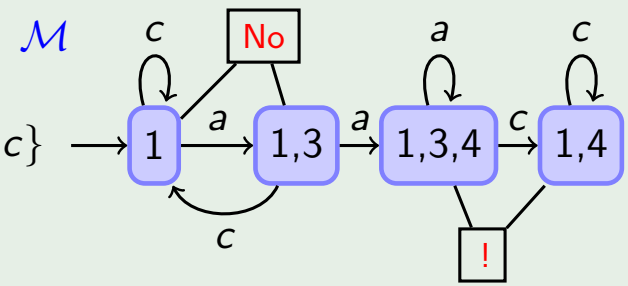

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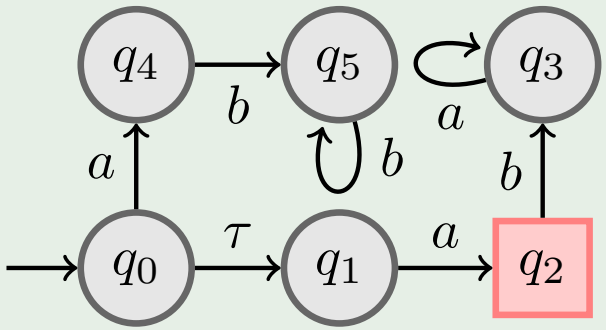
K-step Weak Opacity (introduced in (Sabori, 2009))

Example



$\Sigma = \{\tau, a, b\}$, $\Sigma_o = \{a, b\}$
observation $a.b.a : \mathcal{G}$ was in the secret two observations ago

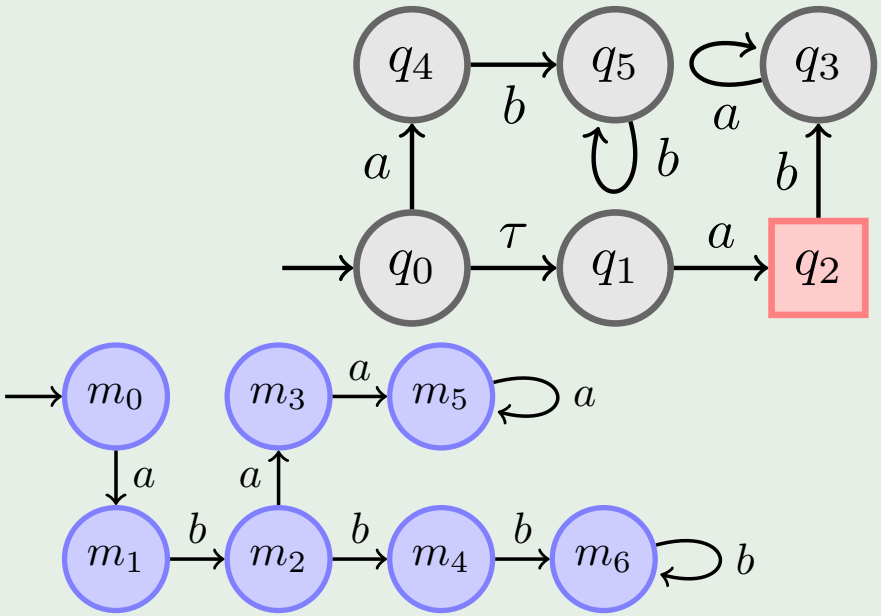
Definition (K-step weak opacity)

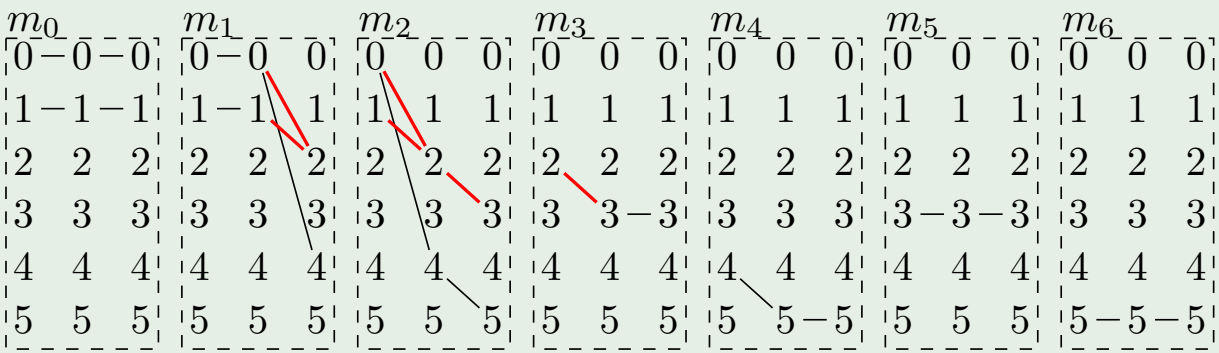
For $K \in \mathbb{N}$, the secret S is K-step weakly opaque on $\mathcal{G}$ under the projection P_{Σ_o} or $(\mathcal{G}, P_{\Sigma_o}, K)$-weakly opaque if

$$\forall t \in \mathcal{L}(\mathcal{G}), \forall t' \preceq t : |t - t'|_{\Sigma_o} \leq K \wedge t' \in \mathcal{L}_S(\mathcal{G})$$
$$\Rightarrow \exists s \in \mathcal{L}(\mathcal{G}), \exists s' \preceq s : s \approx_{\Sigma_o} t \wedge s' \approx_{\Sigma_o} t' \wedge s' \notin \mathcal{L}_S(\mathcal{G}).$$

Verification of K-step weak opacity

Example





Other notions of Opacity

- K-step strong opacity
  $\Rightarrow$ the system traversed the secret less that K observations ago

- infinite step opacity
  $\Rightarrow$ the system traversed the secret in the past

- Initial opacity
  $\Rightarrow$ similar to infinite opacity but the secret is a subset of the initial states.

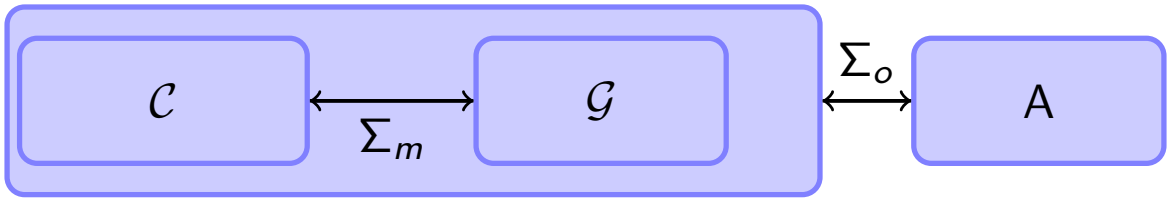
- Initial & Final State-Based opacity

- etc.

Outline

Supervisory Control for opacity

Compute an Access Control using Supervisory Control Theory



Control problem

Hyp : $\mathcal{C}$ observes $\Sigma_m \subseteq \Sigma$ and controls $\Sigma_c \subseteq \Sigma$,
Pb : Compute a maximally permissive access control C observing Σ_m and controlling $\Sigma_c \subseteq \Sigma_m$ s.t. φ is opaque w.r.t. $\mathcal{G} \times \mathcal{C}$ and Σ_o.

Maximality : $\forall \mathcal{C}'$, $L(\mathcal{G} \times \mathcal{C}') \models \psi \implies L(\mathcal{G} \times \mathcal{C}') \subseteq L(\mathcal{G} \times \mathcal{C})$

Supervisory Control for Opacity

Problem

Compute a maximally permissive access control $\mathcal{C}$ observing Σ_m and controlling $\Sigma_c \subseteq \Sigma_m$ s.t. φ is opaque w.r.t. $\mathcal{G} \times \mathcal{C}$ and Σ_o.

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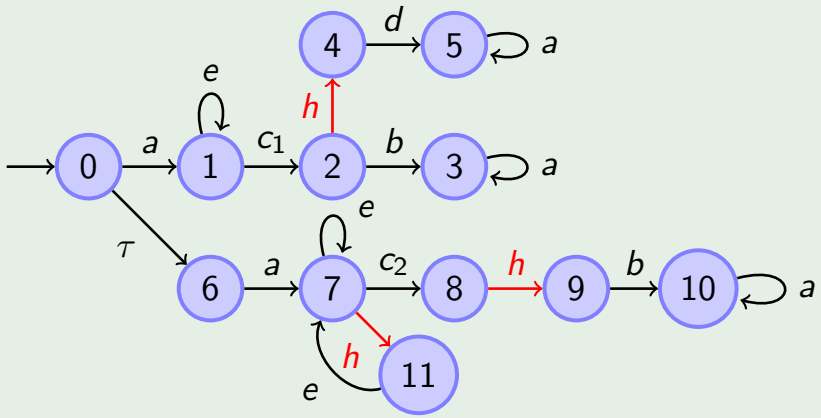

$\Sigma_o = \{a, b, d, e\}$
$\Sigma_m = \{a, c_1, c_2, b, d, e\}$
$\Sigma_c = \{b, c_1, c_2, e\}$

Secret : $L_\varphi = \Sigma^*.h.\Sigma^*$

Theorem

If φ is opaque w.r.t. $\mathcal{L}(\mathcal{G}) \cap \Sigma^*_{uc}$ and Σ_o, and $\Sigma_m \subseteq \Sigma_o$, or $\Sigma_o \subseteq \Sigma_m$, there exists a maximal access control $\mathcal{C}$ s.t. φ is opaque w.r.t. $\mathcal{G} \times \mathcal{C}$ and Σ_o

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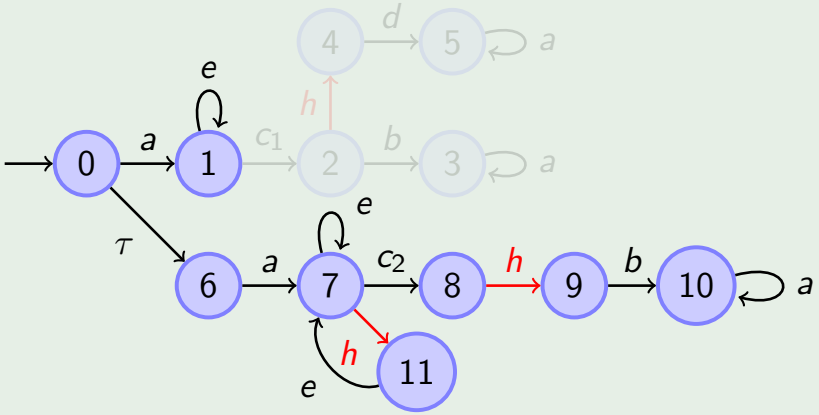

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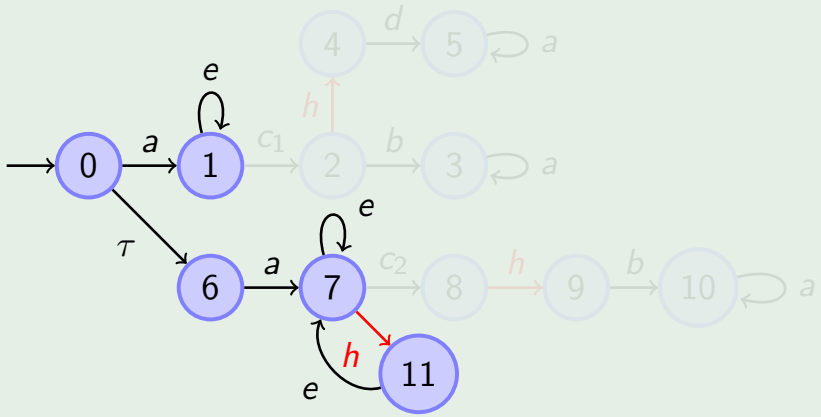

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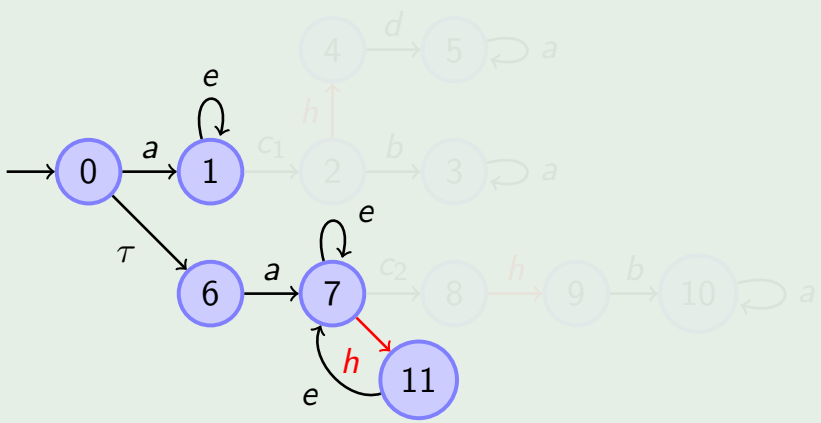

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Enforcing Opacity on Modal Transition Systems

Classical Opacity control Problem

1. The controller knows exactly the model of the system
2. The model is exact w.r.t. the implementation

In reality

- The model $\equiv$ an implementation with different versions.
- The implementation should fulfill some requirements with a certain flexibility.

$\Rightarrow$ The model determines the events that the implementation may or must allow after a given run.

- The model : Modal transition systems (MTS) can be used to model this uncertainty with regards to the implementation(s)
- Problem : How extending the Opacity Control problem results to MTS ?

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Larsen's modal transition systems

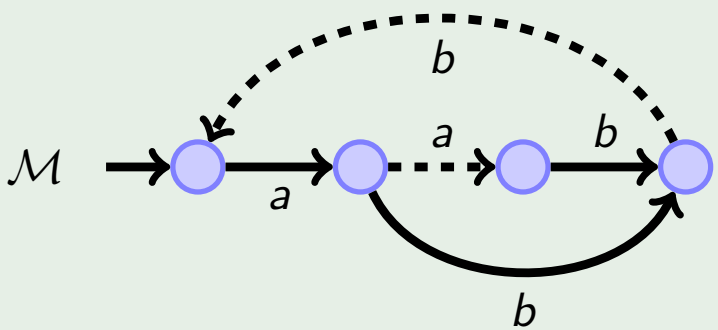
An MTS $\mathcal{M}$ is used to model a non-empty and possibly infinite set of LTS models $(\mathcal{G} \models \mathcal{M})$, each of them being seen as a possible implementation.

Definition

$\mathcal{M} = (S, \Sigma, \delta^{\Box}, \delta^{\Diamond}, s_0)$ where $\delta^{\Box} \subseteq \delta^{\Diamond} \subseteq S \times \Sigma \times S$

- $\delta^{\Diamond}$: May transition (could be present in $\mathcal{G} \models \mathcal{M}$)
- $\delta^{\Box}$: Must transition (must be present in all $\mathcal{G} \models \mathcal{M}$)

Example



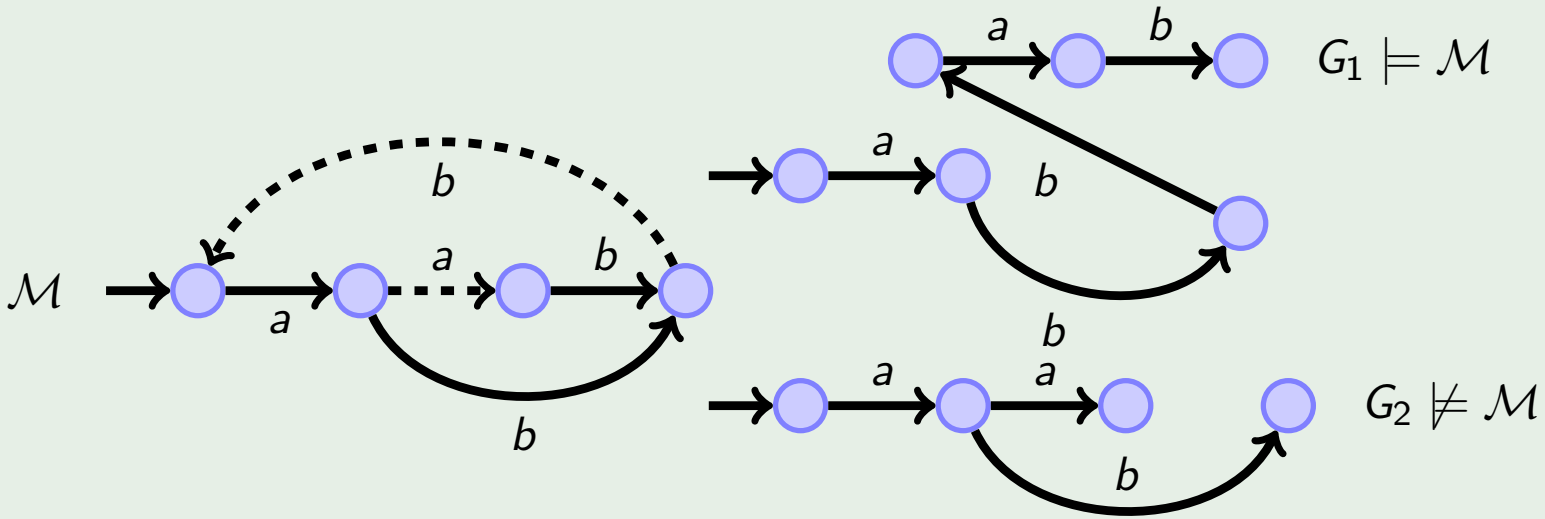
must ($\Box$) = plain edges,
may ($\Diamond$) = dotted edges

LTS associated to an MTS

Each MTS $\mathcal{M}$ determines a corresponding family of finite LTS that preserves the modality conditions and models $\mathcal{M}$ ($\mathcal{G} \models \mathcal{M}$)

$\Rightarrow$ $\models$ is based on an equivalence relation between states of the LTS and the ones of the MTS

Example



Note that G_i might be an unfolding of $\mathcal{M}$

The problem, formally

Given :

- $\mathcal{M} = (S, \Sigma, \delta^{\Box}, \delta^{\Diamond}, s_0)$, a modal transition system
- $Sec \subseteq \Sigma^*$, a regular secret
- Subsets of events :
  - $\Sigma = \Sigma_c \cup \Sigma_{uc}$
  - $\Sigma = \Sigma_m \cup \Sigma_{uo}$ (controller) and $\Sigma_o \subseteq \Sigma$ (attacker)

Construct (regular) controller K s.t.

- K is admissible w.r.t. Σ_c and Σ_m for every $G \models \mathcal{M}$,
- Sec is opaque w.r.t. Σ_o in K/G
- K is maximally permissive with these properties.

$\Rightarrow$ Need to ensure
- Controllability, Observability,
- Opacity

$\Big\}\ \forall G \models MTS$

Some Solutions

$\Sigma_c \subseteq \Sigma_m \subseteq \Sigma_o = \Sigma$

- NS Condition : $\mathcal{L}(K/G) \subseteq \Sigma^* \setminus Sec;\ \forall G \models \mathcal{M}$
- Solution : $K^\dagger$ is the max perm. solution of the SCP for $\overline{\mathcal{M}}$ and the prop. $\mathcal{L}(\overline{\mathcal{M}}) \setminus Sec$ with $\overline{\mathcal{M}} = (S, \Sigma, \delta^\Diamond, s_0)$

$\Sigma_o \subseteq \Sigma_c \subseteq \Sigma_m = \Sigma$

- $Sec = Sec.\Sigma^*$ and is encoded w.l.o.g in $\mathcal{M} = (S, \Sigma, \delta^\Box, \delta^\Diamond, s_0, S_F)$
- $K^\dagger$ computed from H s.t. $X_H \subseteq S \times \mathcal{P}(S)$, $\mathcal{L}(\mathcal{M}) = \mathcal{L}(H)$ and δ_H is build according to Σ_o and the modality of the transitions in $\mathcal{M}$.
  - NS Condition : Sec is opaque w.r.t. Σ_a in every $G \models \mathcal{M}$ if and only if $\forall w : \delta_H((s_0, E_0), w) = (s, E) \ \Rightarrow\ E \not\subseteq S^F$.
  - Solution : $K^\dagger$ is obtained by removing all access (w.r.t. controllabilty) paths to $(s, E),\ E \subseteq S^F$

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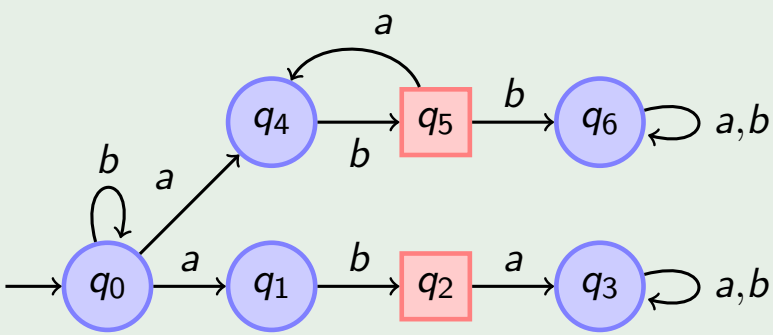
Add a filter between the attacker and the system

Example

- Static Filter : $\Sigma_o = \{a\}$ or $\Sigma_o = \{b\} \Rightarrow F$ is opaque
- Dynamic Filter : Hide "b" after the observation of a "a" and keep everything observable after the observation of a "a"

Add a filter between the attacker and the system

Example



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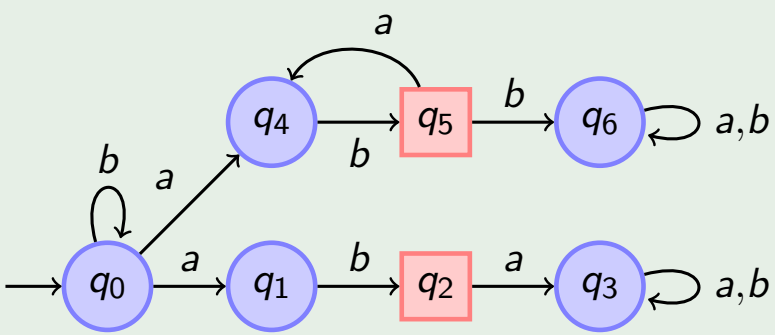

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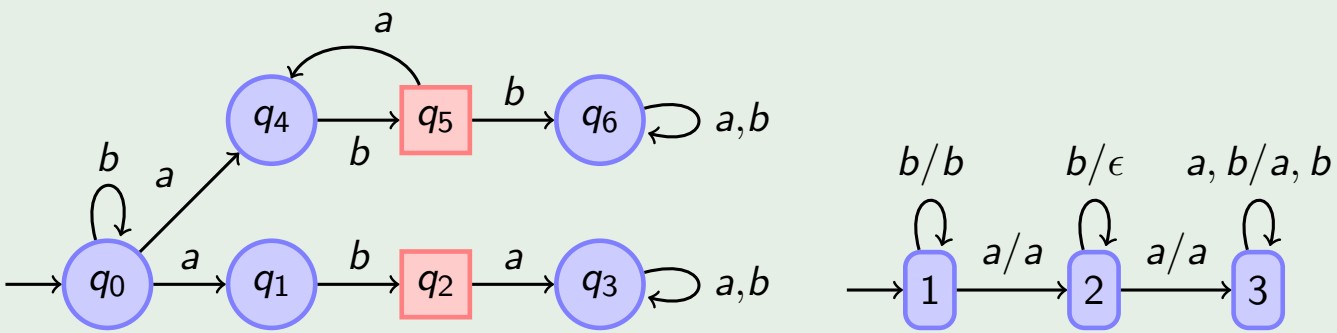

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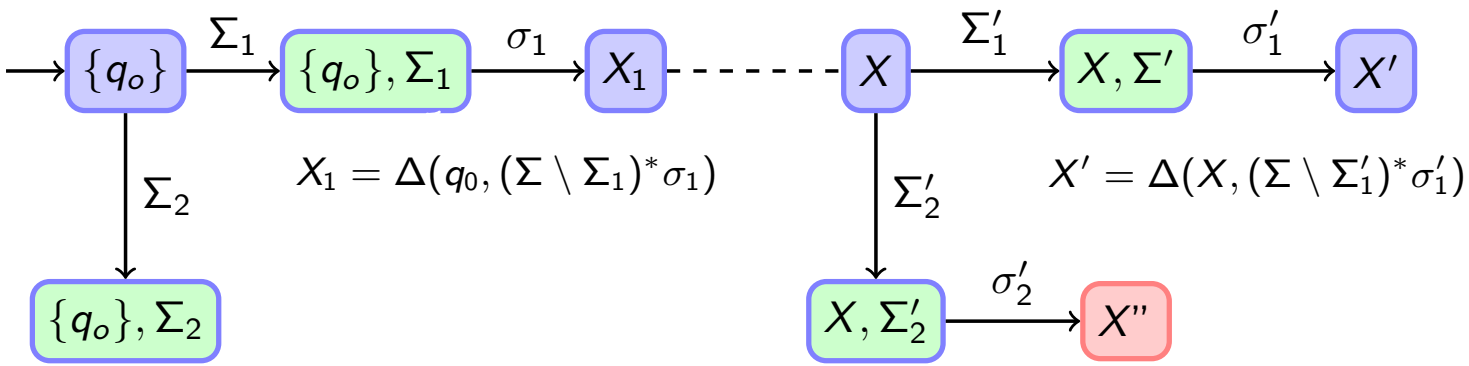
Dynamic Filter Synthesis Problem as a Game Problem

- Reduce the Synthesis Problem to a safety 2-player game
  - Player 1 play the role of a dynamical projection (what remains observable)
    - Player 1 State $\subseteq 2^Q$: estimate of the attacker after an observation
  - Player 2 what the attacker observes.
    - Player 2 State $\subseteq 2^Q\Sigma$: what the attacker could observe in a state of player 1



- Bad states : $Bad = 2^F$
  - Player 2 : find a strategy allowing to reach Bad : *reachability game*
  - Player 1 : find a strategy that avoids Bad : *safety game*

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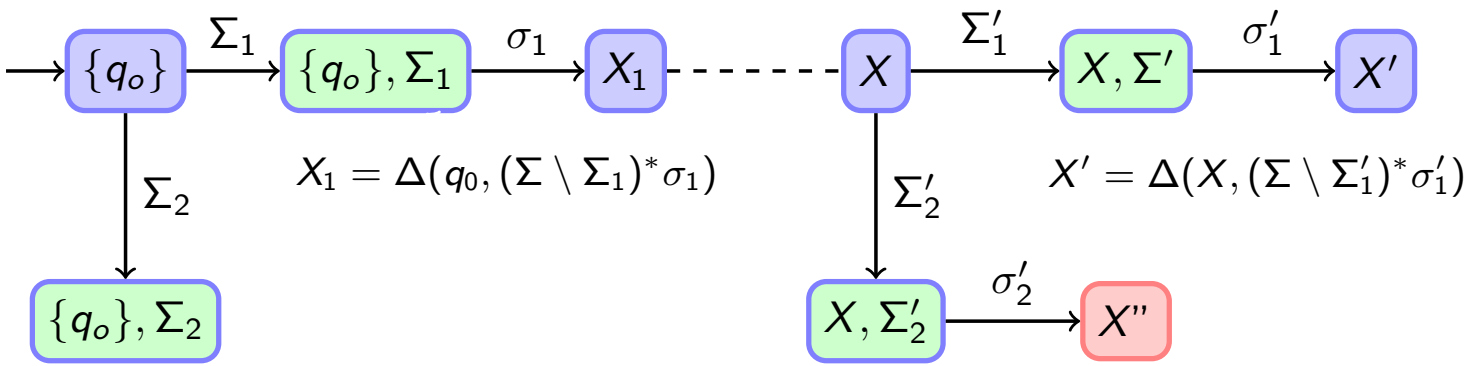

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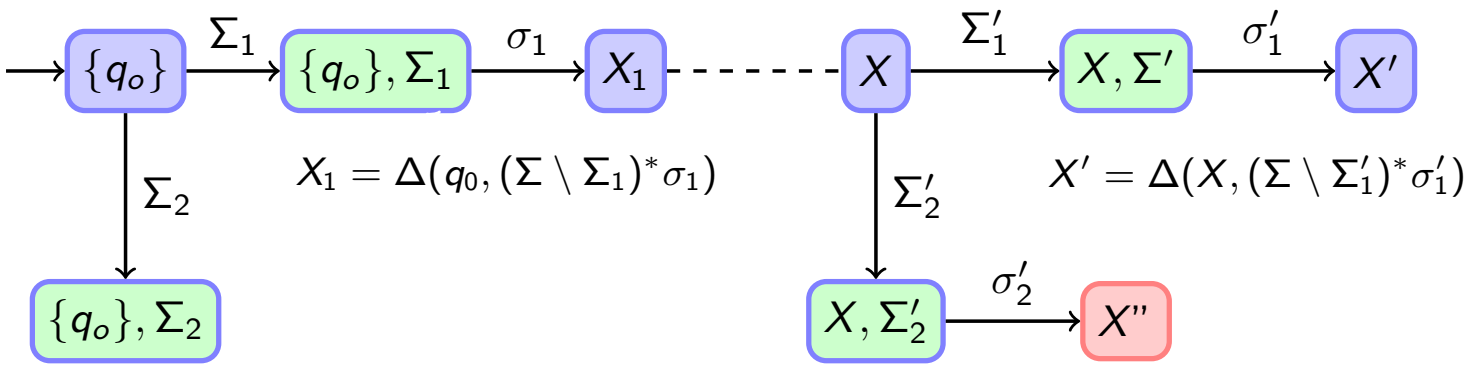

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Outline

Other aspects

- Control :
  - Control of opacity with several attackers
  - Enforcement of opacity
  - Enforcement of opacity properties using insertion
- Other models :
  - Timed automata
  - Petri Nets
  - Recursive tiles systems
- Quantitative aspects ?
  - Stochastic DES
  - Prevent different users to infer secret information from other users