Enforcing Opacity in Modular Systems

Graeme Zinck, Laurie Ricker, Hervé Marchand, Loïc Hélouët

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Mount Allison University, New Brunswick, Canada
Inria Rennes-Bretagne Atlantique, Rennes, France

Motivation

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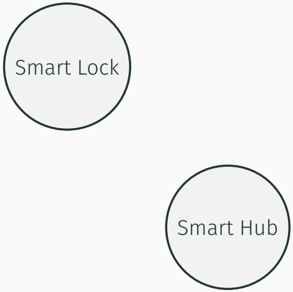

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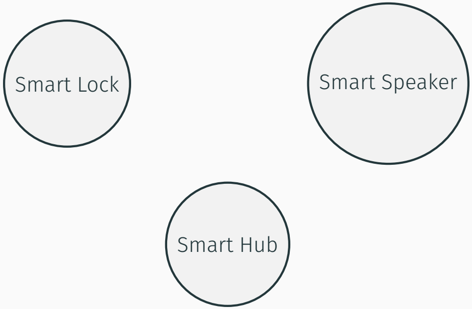

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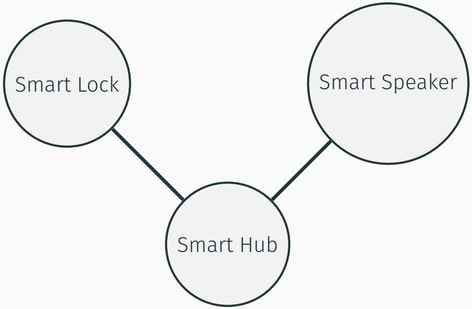

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Model

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1. System has multiple **modules** (automata)
2. Each module has its a set of **secret states**
3. Modules interact with **shared events**

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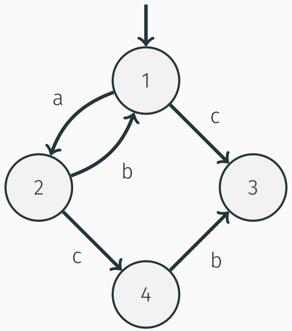
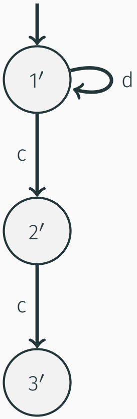


(a) G_1



(b) G_2

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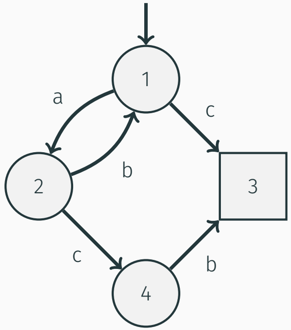

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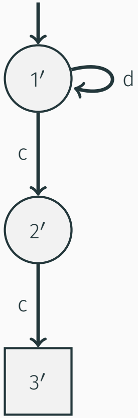

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Model

We construct the global system with the **parallel composition**

1. Synchronize on common events
2. Private events are interleaved

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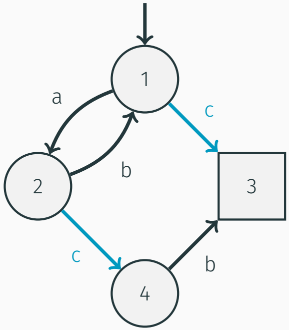

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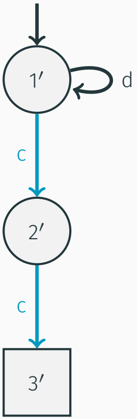

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(c) $G_1||G_2$

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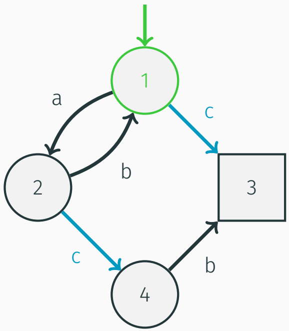

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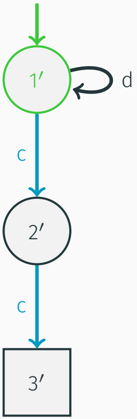

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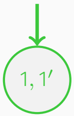

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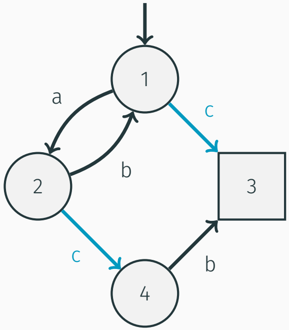

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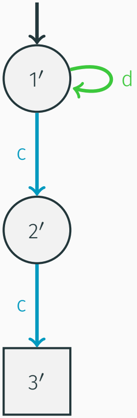

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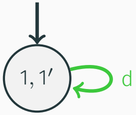

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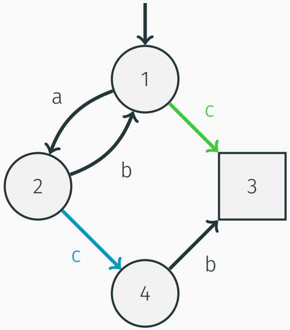

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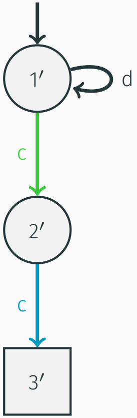

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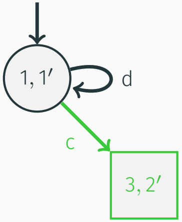

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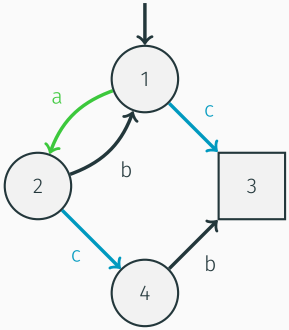

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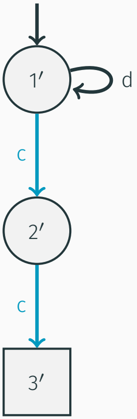

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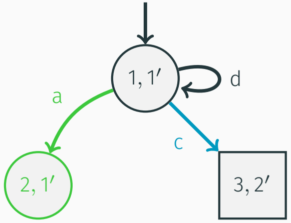

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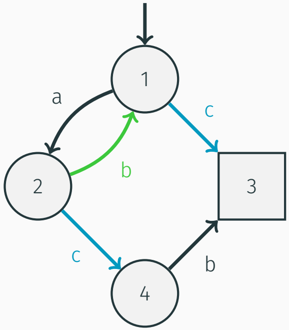

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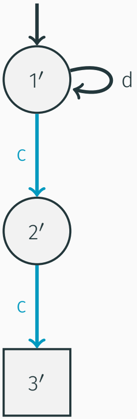

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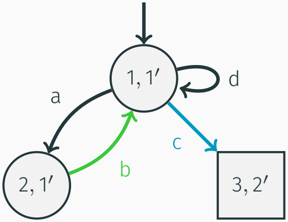

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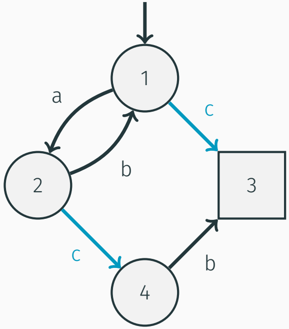

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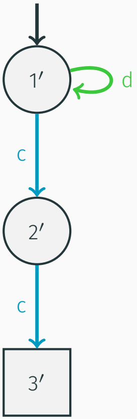

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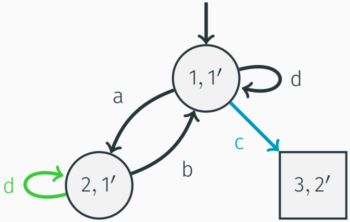

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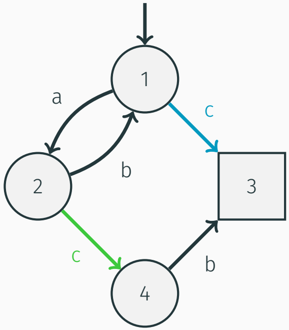

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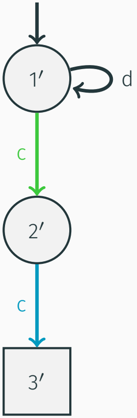

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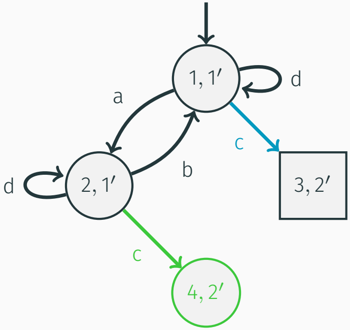

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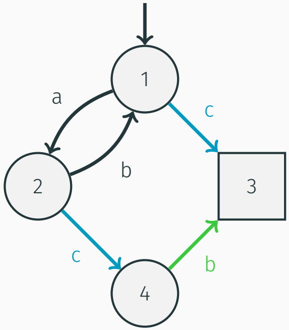

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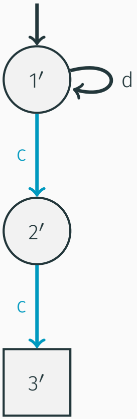

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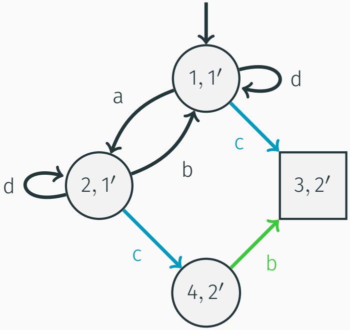
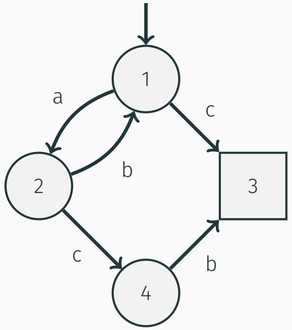


(c) $G_1||G_2$

Attacker

- Modules are under **partial observation**
- Full knowledge of system architecture
- Has an **observable alphabet**

Model



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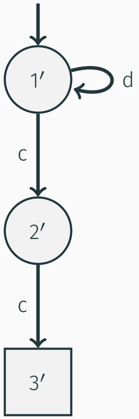

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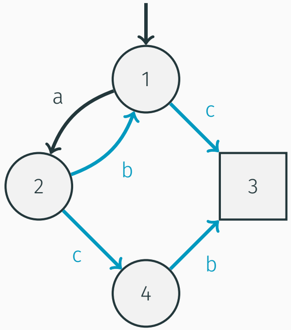

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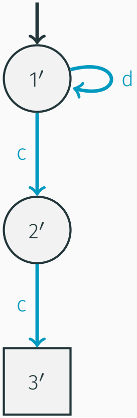

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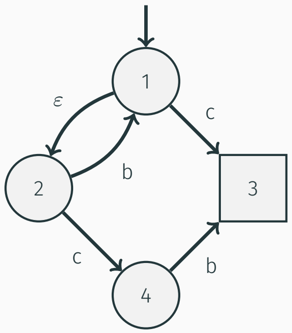
- Attacker should not be able to distinguish a **secret state** from a **non-secret state**
- *How can we verify that the attacker cannot distinguish secret states?*
- **Determinization**: we treat events not in the attacker’s alphabet as epsilon events and determinize the system

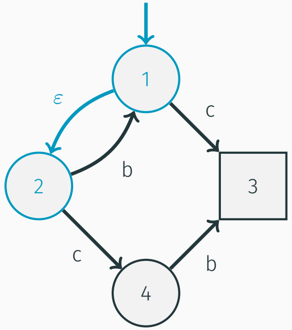
Determinizing G_1



(a) G_1

(b) $Det_{\Sigma_a}(G_1)$

Determinizing G_1



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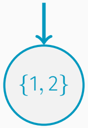

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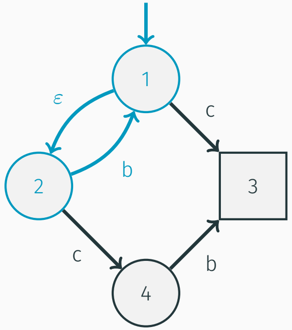

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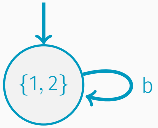

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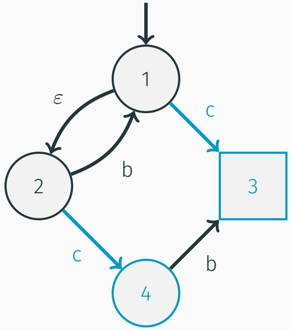

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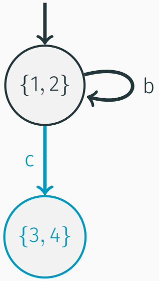

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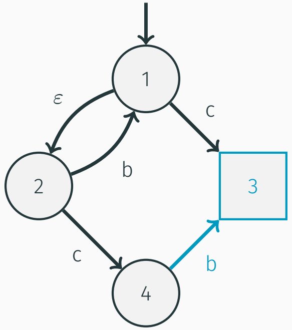

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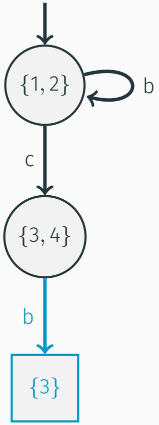
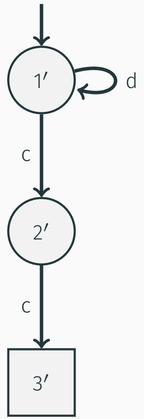


(b) $Det_{\Sigma_a}(G_1)$

Determinizing G_2



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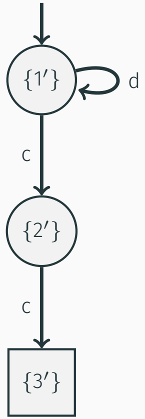

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- This implies a simple PSPACE-complete verification algorithm

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Traditionally, we verify opacity in the global system as follows:

- Compose all modules
- Determinize the result
- Check if there are states that are a subset of the set of secret states

Opacity

What if we could check opacity locally, allowing us to avoid constructing the full system?

Verifying Opacity in Modular Systems

Verifying Opacity

- Can we verify opacity in a local module instead of verifying it globally?

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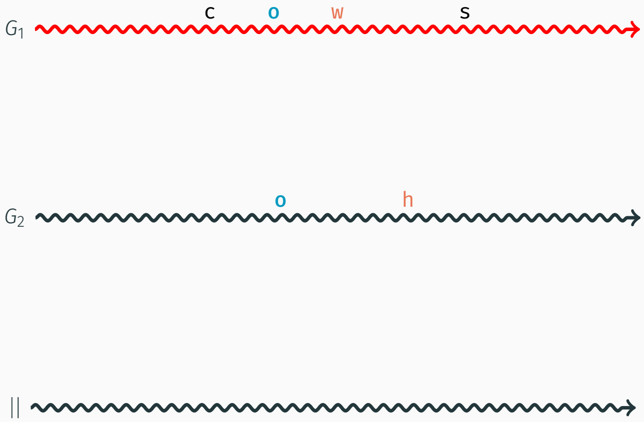
Verifying Opacity

- Can we verify opacity in a local module instead of verifying it globally?
- **Not necessarily...** but there is a sufficient condition which enables us to verify locally
- We can assume the **attacker observes the interface** between modules
- Assuming this allows us to check opacity of the local module's secret
    - If opaque locally, it's opaque for the composed system
    - Otherwise, we need to check the global system

Verifying Opacity



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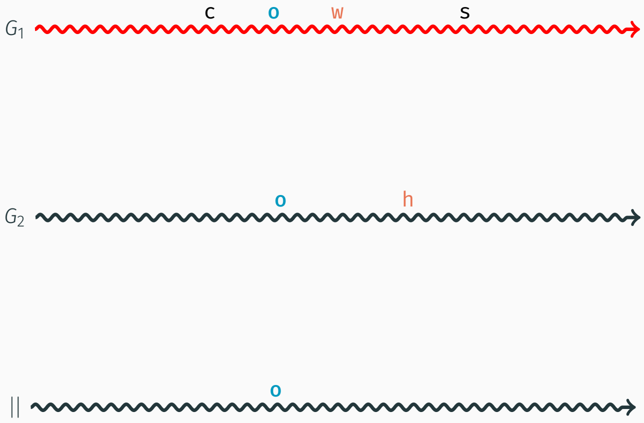

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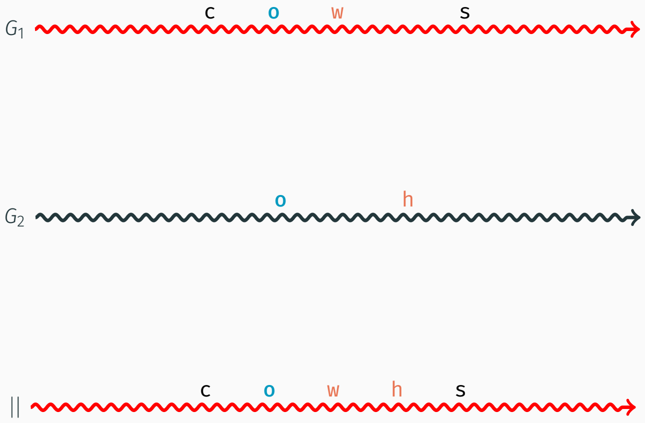

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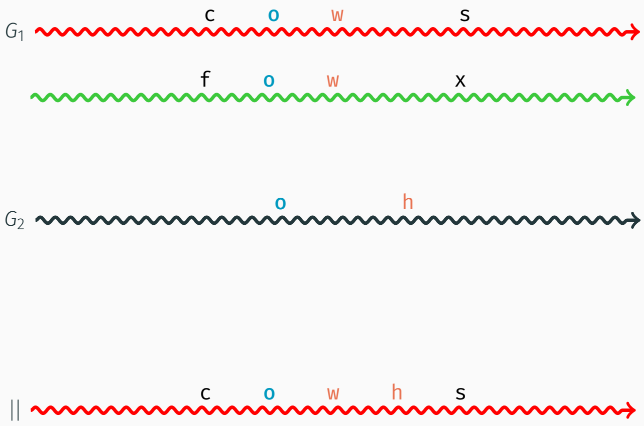

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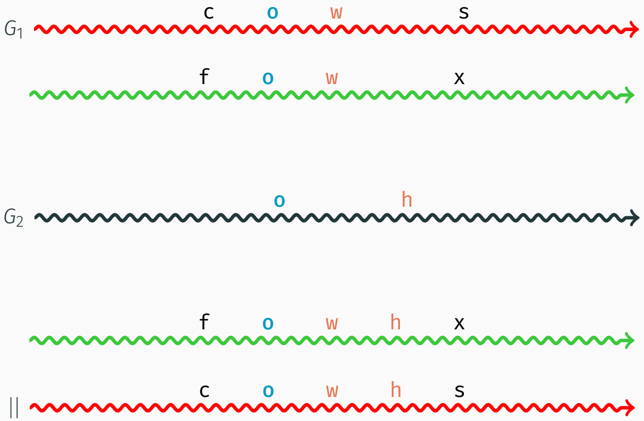

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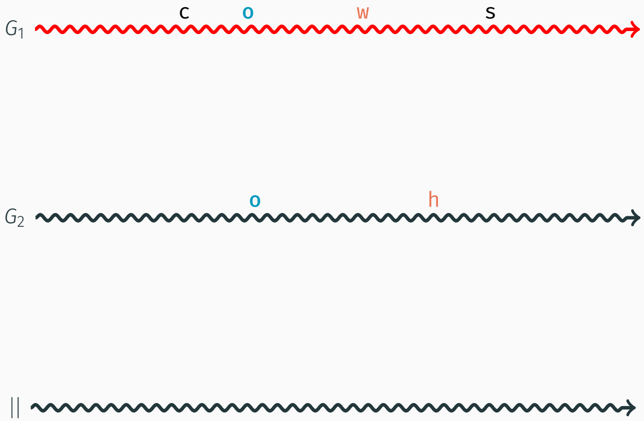

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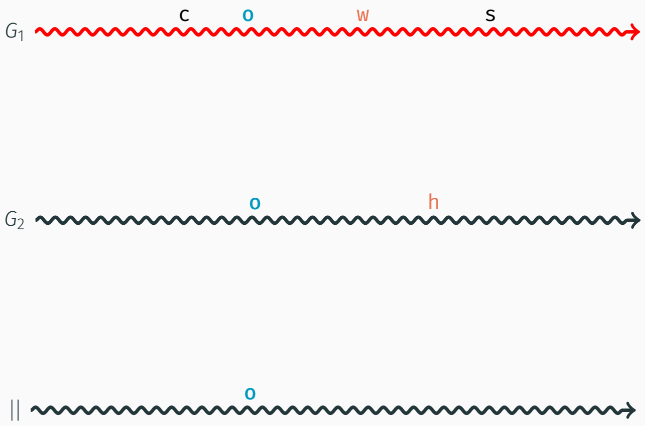

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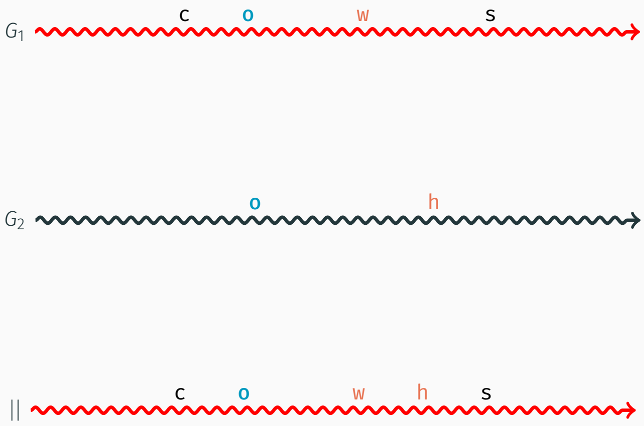

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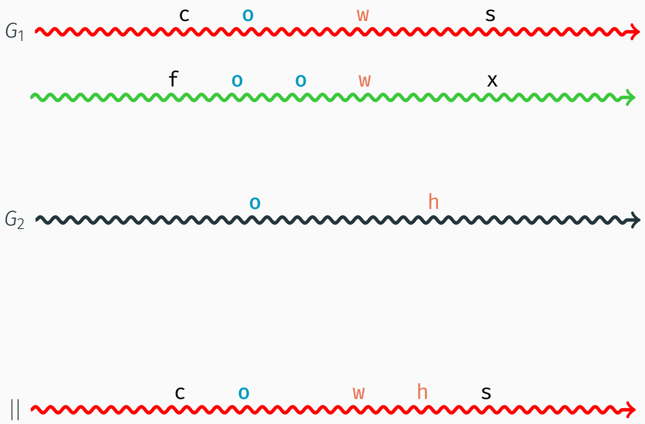

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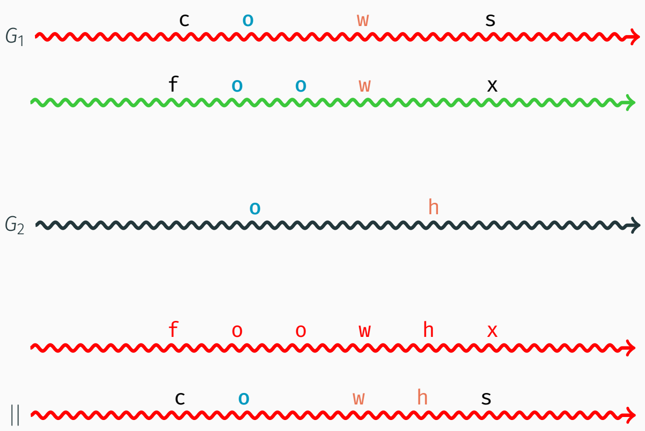

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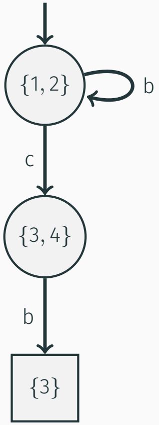
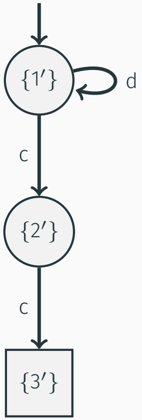
Opacity holds over composition when the attacker observes the interface, and we can verify opacity locally instead of doing it for the whole system.

- Check opacity of the local module’s secret
  - If opaque locally, it’s opaque for the composed system
  - Otherwise, iterate by composing the system with another module. If no other modules remain, it is not opaque for the composed system

Verifying Opacity



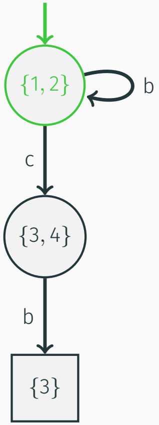
(a) $Det_{\Sigma_a}(G_1)$



(b) $Det_{\Sigma_a}(G_2)$

(c) Full system

Verifying Opacity



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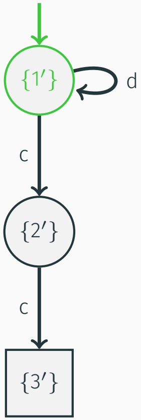
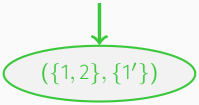
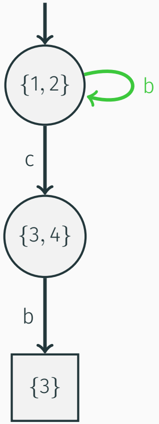


(b) $Det_{\Sigma_a}(G_2)$

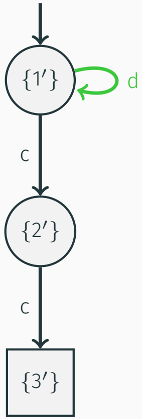


(c) Full system

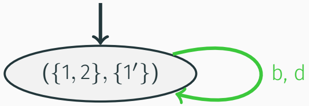
Verifying Opacity



(a) $Det_{\Sigma_a}(G_1)$



(b) $Det_{\Sigma_a}(G_2)$



(c) Full system

Verifying Opacity

$$\begin{tikzcd}
{} \arrow[d] \\
\{1,2\} \arrow[loop right, "b"] \arrow[d, "c"'] \\
\{3,4\} \arrow[d, "b"'] \\
\boxed{\{3\}}
\end{tikzcd}$$

(a) $Det_{\Sigma_a}(G_1)$

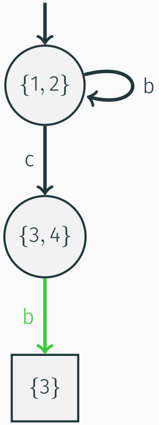
$$\begin{tikzcd}
{} \arrow[d] \\
\{1'\} \arrow[loop right, "d"] \arrow[d, "c"'] \\
\{2'\} \arrow[d, "c"'] \\
\boxed{\{3'\}}
\end{tikzcd}$$

(b) $Det_{\Sigma_a}(G_2)$

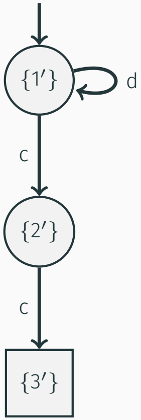
$$\begin{tikzcd}
{} \arrow[d] \\
(\{1,2\},\{1'\}) \arrow[loop right, "{b, d}"] \arrow[d, "c"'] \\
(\{3,4\},\{2'\})
\end{tikzcd}$$

(c) Full system

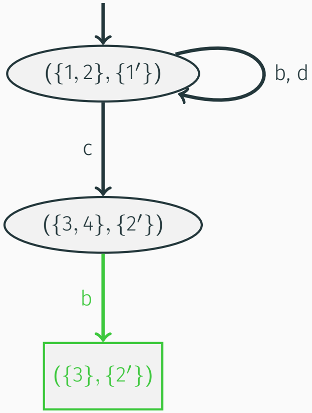
Verifying Opacity



(a) $Det_{\Sigma_a}(G_1)$



(b) $Det_{\Sigma_a}(G_2)$



(c) Full system

Enforcing Opacity in Modular Systems

Enforcing Opacity

- We can enforce opacity within each module separately to enforce it for the global system

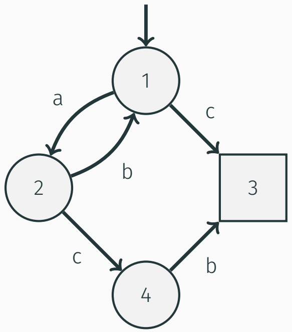
Enforcing Opacity

- We can enforce opacity within each module separately to enforce it for the global system
- Can observe some events

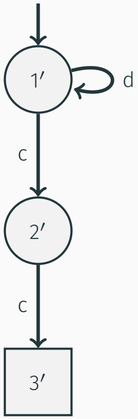
Enforcing Opacity

- We can enforce opacity within each module separately to enforce it for the global system
- Can observe some events
- Can control some events

Enforcing Opacity

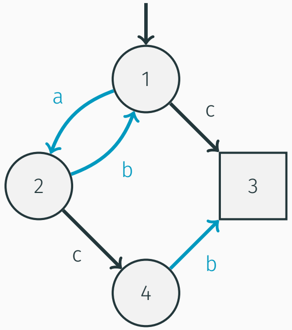


(a) G_1

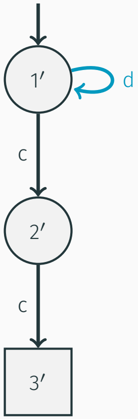


(b) G_2

Enforcing Opacity

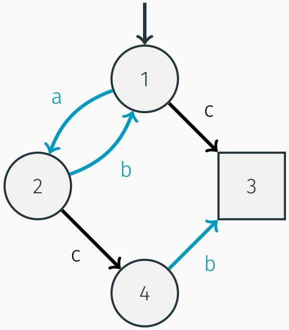


(a) G_1

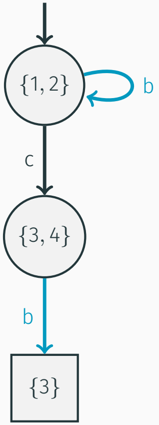


(b) G_2

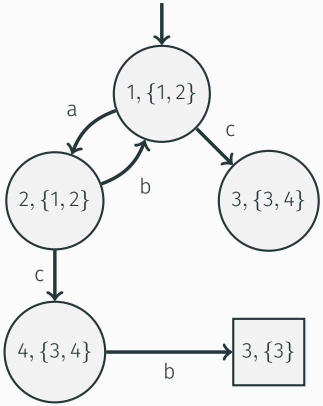
Enforcing Opacity



(a) G_1

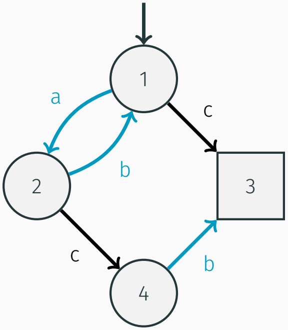


(b) $Det_{\Sigma_a}(G_1)$

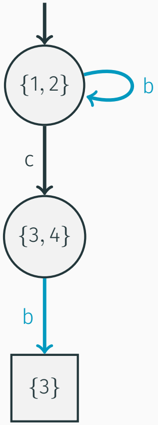


(c) Controller View

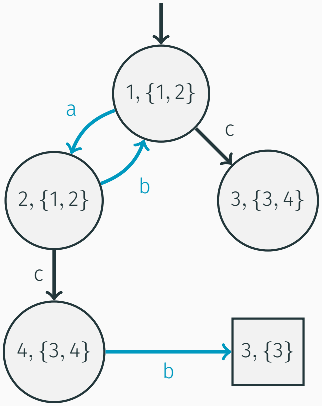
Enforcing Opacity



(a) G_1

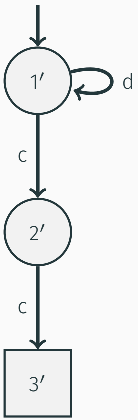


(b) $Det_{\Sigma_a}(G_1)$

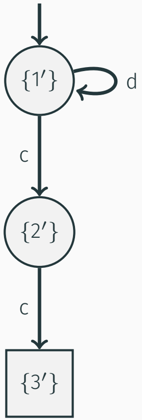


(c) Controller View

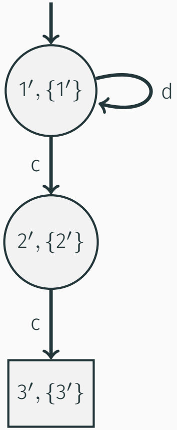
Enforcing Opacity



(a) G_2

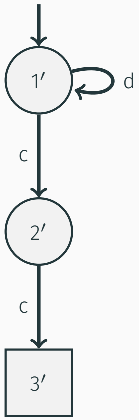


(b) $Det_{\Sigma_a}(G_2)$

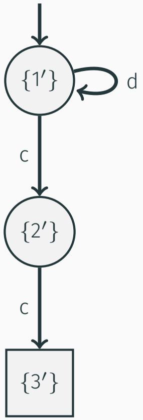


(c) Controller view

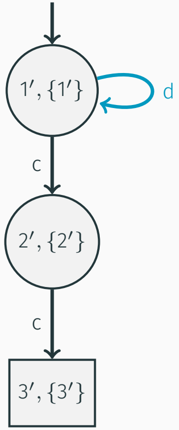
Enforcing Opacity



(a) G_2



(b) $Det_{\Sigma_a}(G_2)$

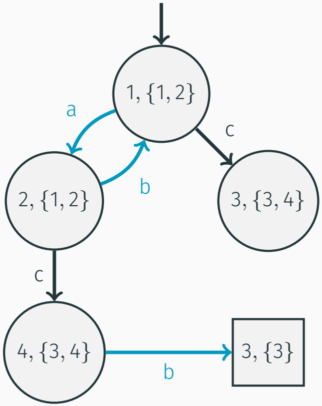


(c) Controller view

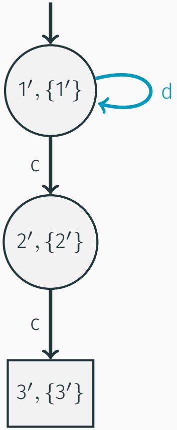
Enforcing Opacity

Naive approach: enforce opacity locally without considering other modules.

Enforcing Opacity

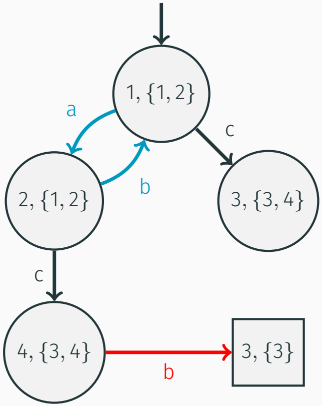


(a) $\mathcal{C}_1$

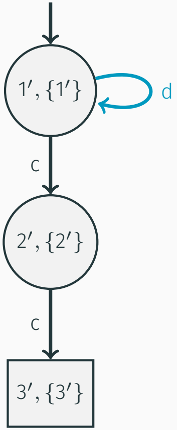


(b) $\mathcal{C}_2$

Enforcing Opacity

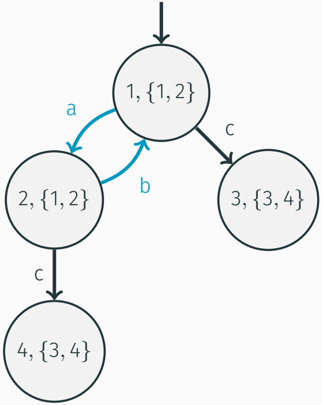


(a) $\mathcal{C}_1$

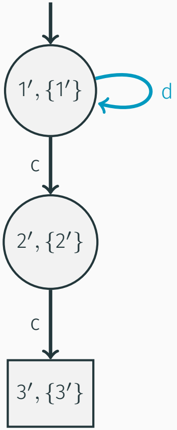


(b) $\mathcal{C}_2$

Enforcing Opacity

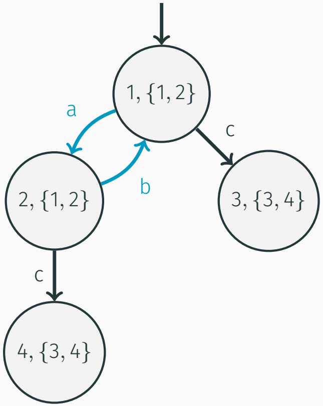


(a) $\mathcal{C}_1$

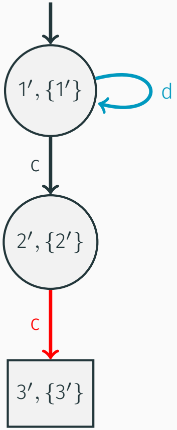


(b) $\mathcal{C}_2$

Enforcing Opacity

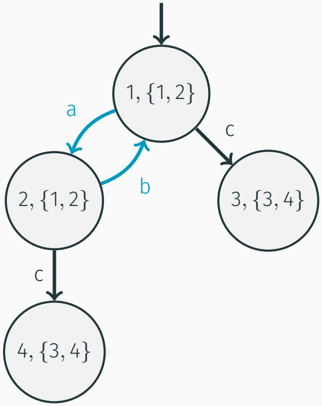


(a) $\mathcal{C}_1$

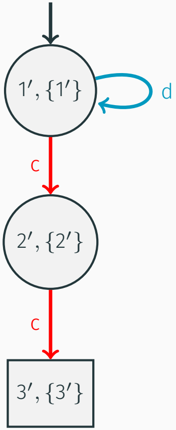


(b) $\mathcal{C}_2$

Enforcing Opacity

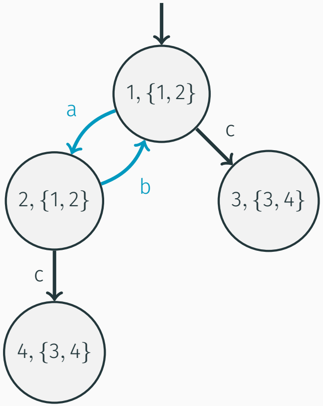


(a) $\mathcal{C}_1$

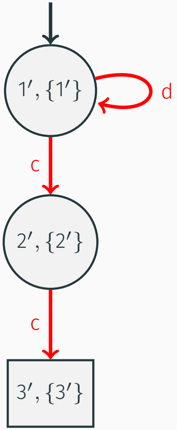


(b) $\mathcal{C}_2$

Enforcing Opacity

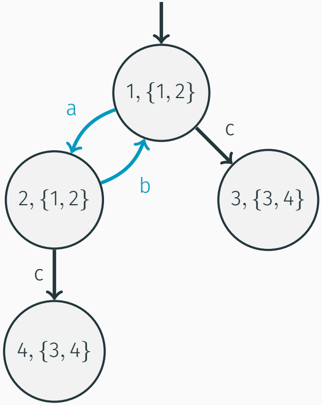


(a) $\mathcal{C}_1$



(b) $\mathcal{C}_2$

Enforcing Opacity



(a) $\mathcal{C}_1$

(b) $\mathcal{C}_2 = \emptyset$

Enforcing Opacity

Better approach:

- Verify if the secret is opaque as previously explained

Enforcing Opacity

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- Verify if the secret is opaque as previously explained
    1. If opaque, use a fully permissive controller
    2. Otherwise, get the supremal controller of the composed system

Enforcing Opacity

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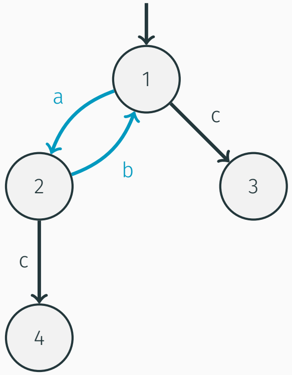
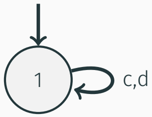
- Verify if the secret is opaque as previously explained
    1. If opaque, use a fully permissive controller
    2. Otherwise, get the supremal controller of the composed system

We observed that $\mathcal{S}_2$ was opaque, so we can use the fully permissive controller for G_2.

Enforcing Opacity



(a) $\mathcal{C}_1$



(b) $\mathcal{C}_2$

Enforcing Opacity

If we assume the attacker knows construction of only the system, **there is an optimal controller** if the controllable alphabet is a subset of the observable alphabet.

Enforcing Opacity

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If we assume the attacker knows the system and the controller, a solution only exists when...

Enforcing Opacity

If we assume the attacker knows construction of only the system, **there is an optimal controller** if the controllable alphabet is a subset of the observable alphabet.

If we assume the attacker knows the system and the controller, a solution only exists when...

1. The controllable alphabet is a subset of the observable alphabet; and
2. The observable and attacker alphabets are comparable:
    2.1 The **observable alphabet is a subset** of the attacker's alphabet
    2.2 The **attacker's alphabet is a subset** of the observable alphabet

Conclusion

- Optimizations for verifying opacity in modular systems

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- New means of **enforcing** opacity in local modules of modular systems

Conclusion

- Optimizations for **verifying** opacity in modular systems
- New means of **enforcing** opacity in local modules of modular systems
- Currently, not possible when attacker knows the controller's architecture

Conclusion

Questions?