Supervisory Control of Discrete-Event Systems for Infinite-Step Opacity

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2020 American Control Conference

July 1-3, 2020, Denver, CO, USA

上海交通大學

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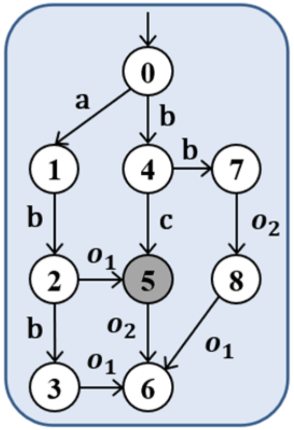
Motivation

- Security and privacy concerns in Cyber-Physical Systems
- Opacity: An information-flow property
- Application: Web services, Location-based services…
- Current-state opacity & Infinite-step opacity

System Model and Intruder



The system has secrets

Information-Flow
$P(\mathcal{L}(G)) \in \Sigma_o^*$

Intruder

- The system is modeled as a FSA $G = (X, \Sigma, \delta, x_0)$
- The system has secrets, modeled a set of states $X_s \subseteq X$
- $\Sigma = \Sigma_o \,\dot{\cup}\, \Sigma_{uo}$, $P: \Sigma^* \rightarrow \Sigma_o^*$ is the natural projection
- The intruder is a passive observer seeing $P(\mathcal{L}(G))$
- System G is opaque if the intruder cannot infer for sure that the system is in a secret state

Delayed State Estimate

Definition: (Delayed State Estimate).

Let $\alpha\beta \in P(\mathcal{L}(G))$ be an observable string. Then the delayed state estimate associated with (α, β), denoted by $\hat{X}_G(\alpha \mid \alpha\beta)$, is defined as the set of states the system could have been in $|\beta|$-steps earlier, after observing $\alpha\beta$.

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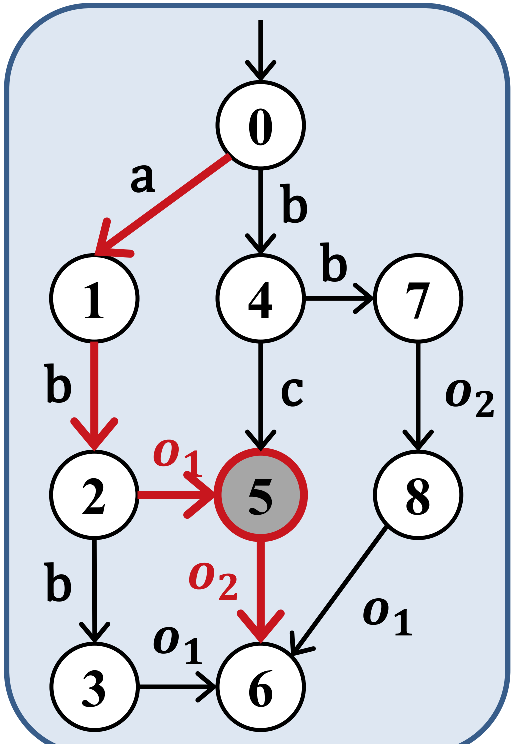

$\hat{X}_G\,(o_1 \mid o_1 o_2)$={5}

- $\Sigma_o = \{o_1, o_2\}$
- Suppose string $s = abo_1o_2$ with $P(s) = o_1o_2$ is observed

Infinite-Step Opacity

Definition: (Infinite-Step Opacity).

System G is said to be infinite-step opaque w.r.t. G and X_s if

$$\forall \alpha\beta \in P\big(L(G)\big): \hat{X}_G(\alpha \mid \alpha\beta) \not\subseteq X_S$$

The intruder can never know that the system was at a secret state

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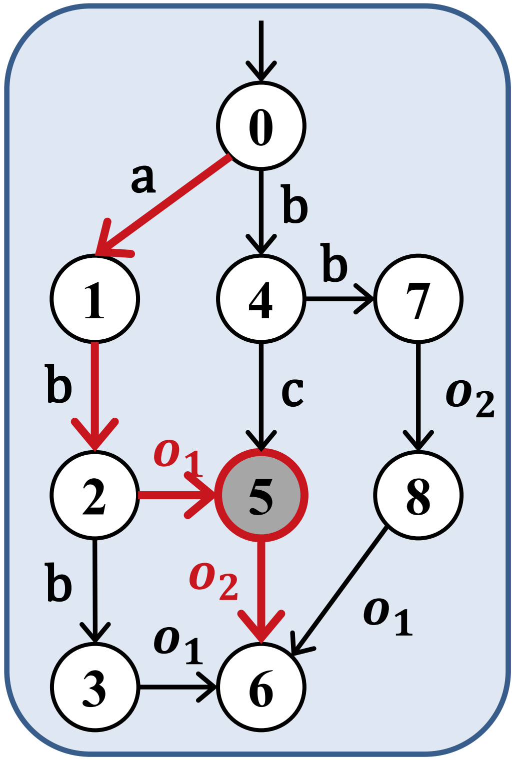
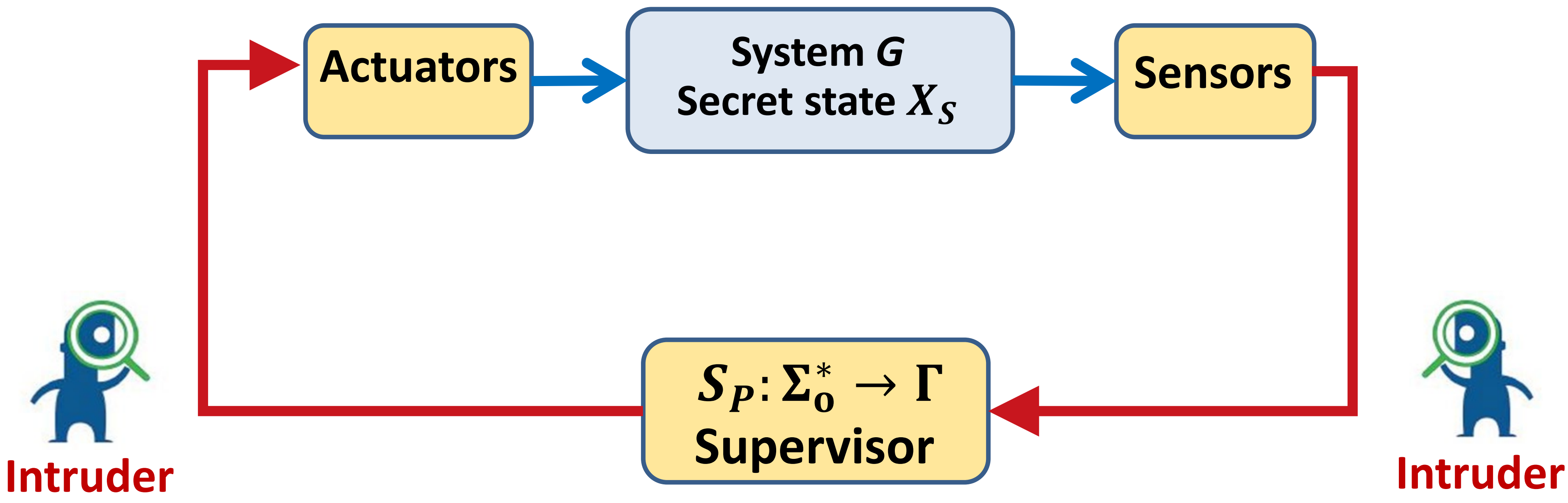


$\hat{X}_G\ (o_1 \mid o_1 o_2)=\{5\}\subseteq X_S$

Not infinite-step opaque

- $\Sigma_o = \{o_1, o_2\}$, $X_S = \{5\}$
- **Suppose string** $s = abo_1o_2$ **with** $P(s) = o_1o_2$ **is observed**

Supervisory Control Systems



- **Sensors:** $\Sigma = \Sigma_o \dot\cup \Sigma_{uo}$ and $P: \Sigma^* \to \Sigma_o^*$
- **Actuators:** $\Sigma = \Sigma_c \dot\cup \Sigma_{uc}$ and $\Gamma := \{\gamma \in 2^{\Sigma}: \Sigma_{uc} \subseteq \gamma\}$
- **Supervisor:** $S_P: P(\mathcal{L}(G)) \to \Gamma$ updates decisions dynamically
- **Intruder:** System model G, Observable events Σ_o^* , Control policy Γ

Definition: (Delayed State Estimate).

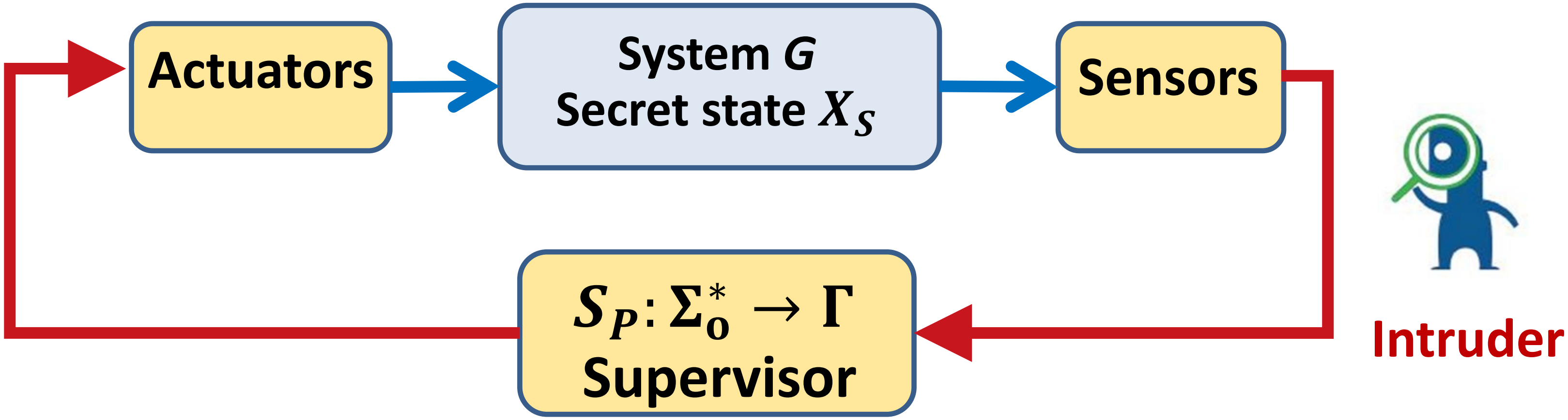
Let $\alpha\beta \in P(\mathcal{L}(S_P/G))$ be an observable string. Then the delayed state estimate in the closed-loop system associated with (α, β), denoted by $\hat{X}_{S_P/G}(\alpha \mid \alpha\beta)$, is defined as the set of states the system could have been in $|\beta|$-steps earlier, after observing $\alpha\beta$.

Definition: (Infinite-Step Opacity).

Closed-loop system S_P/G is said to be infinite-step opaque w.r.t. Σ_o and X_s if

$$\forall \alpha\beta \in P\big(\mathcal{L}(S_P/G)\big): \hat{X}_{S_P/G}(\alpha \mid \alpha\beta) \nsubseteq X_S$$

Synthesis Problem



- **Synthesis Problem:**

How to design a partial observation supervisor $S_P\colon P\big(\mathcal{L}(G)\big) \to \Gamma$?

(1) S_P/G is infinite-step opaque

(2) For any supervisor S_P' satisfying (1), we have $\mathcal{L}(S_P/G) \not\subset \mathcal{L}(S_P'/G)$

The synthesized supervisor is maximal

Review: Enforcement of IFSO

- **Main Idea for Enforcement**

find a supervisor that restricts the behavior of the system dynamically such that the closed-loop system is opaque.

Enforcement Algorithms for Current-state opacity

- J. Dubreil, P. Darondeau, and H. Marchand. Supervisory control for opacity. IEEE Trans. Automatic Control, 55(5):1089–1100, 2010.
- Y. Tong, Z. Li, C. Seatzu, and A. Giua. Current-state opacity enforcement in discrete event systems under incomparable observations. Discrete Event Dynamic Systems: Theory & Appllications, 28(2):161–182, 2018.

$\Sigma_c \subseteq \Sigma_o$

Intruder doesn't know the control policy

Difficulty: need both current information and future information

Information State

Challenge: 2^X **is not sufficient due to the delayed information**

Question: what information we need to synthesize for infinite-step opacity?

Information State

Challenge: 2^X is not sufficient due to the **delayed information**

Question: **what information** we need to synthesize for infinite-step opacity?

$$\xrightarrow{\sigma_1} \underset{\not\subseteq X_S}{\boxed{\hat{X}_{S_P/G}(\sigma_1 \mid \alpha)}} \xrightarrow{\sigma_2} \cdots \xrightarrow{\sigma_{n-1}} \underset{\not\subseteq X_S}{\boxed{\hat{X}_{S_P/G}(\sigma_1 \ldots \sigma_{n-1} \mid \alpha)}} \xrightarrow{\sigma_n} \underset{\not\subseteq X_S}{\boxed{\hat{X}_{S_P/G}(\alpha \mid \alpha)}} \quad \alpha = \sigma_1 \sigma_2 \ldots \sigma_n$$

Information State

Challenge: 2^X **is not sufficient due to the delayed information**

Question: what information we need to synthesize for infinite-step opacity?

$\xrightarrow{\sigma_1} \underbrace{\hat{X}_{S_P/G}(\sigma_1 \mid \alpha)}_{\not\subseteq X_S} \xrightarrow{\sigma_2} \cdots \xrightarrow{\sigma_{n-1}} \underbrace{\hat{X}_{S_P/G}(\sigma_1 \dots \sigma_{n-1} \mid \alpha)}_{\not\subseteq X_S} \xrightarrow{\sigma_n} \underbrace{\hat{X}_{S_P/G}(\alpha \mid \alpha)}_{\not\subseteq X_S}$ $\alpha = \sigma_1\sigma_2 \dots \sigma_n$

Information State

We propose the following information-state space

$$I := \underbrace{2^X}_{\text{Current Estimate}} \times \underbrace{2^{2^{X\times X}}}_{\text{Delayed Estimates for All Possible Previous Instant}}$$

- $\imath = (C(\imath), D(\imath)) \in 2^X \times 2^{2^{X\times X}}$

$C(\imath)$	$D(\imath)$
$\{x_1, \dots, x_k\}$	$\left\{\begin{array}{c} \{(x_1^1, \tilde{x}_1^1), \dots, (x_{k_1}^1, \tilde{x}_{k_1}^1)\} \\ \vdots \\ \{(x_1^n, \tilde{x}_1^n), \dots, (x_{k_n}^n, \tilde{x}_{k_n}^n)\} \end{array}\right\}$

Current state

State at some previous instant

Information State Update

- **Update Rule: new observation $\sigma \in \Sigma_o$ & new control decision $\gamma \in \Gamma$**

$C(\imath)$

$\{x_1, \ldots, x_k\}$

$D(\imath)$

$$\begin{pmatrix} \{(x_1^1, \tilde{x}_1^1), \ldots, (x_{k_1}^1, \tilde{x}_{k_1}^1)\} \\ \vdots \\ \{(x_1^n, \tilde{x}_1^n), \ldots, (x_{k_n}^n, \tilde{x}_{k_n}^n)\} \end{pmatrix}$$

$$C(\imath_1) = UR_\gamma(NX_\sigma(C(\imath)))$$

- Update the CSE

$$D(\imath_1) = \{\widetilde{UR}_\gamma\left(\widetilde{NX}_\sigma(\rho)\right) \in 2^{X \times X} : \rho \in D(\imath)\} \cup \{\odot_\gamma(C(\imath'))\}$$

- Update all possible DSE
- Add CSE as DSE for the future

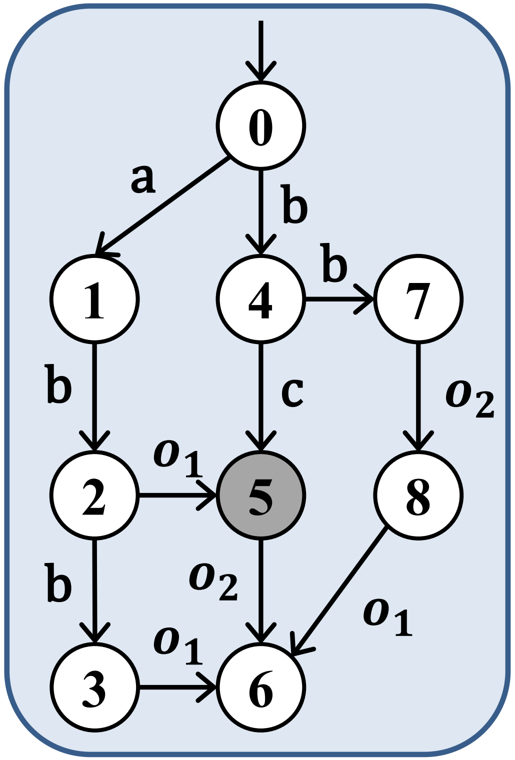
$C(\imath_1)$

$\{x_1, \ldots, x_k\}$

$D(\imath_1)$

$$\begin{pmatrix} \{(x_1^1, \tilde{x}_1^1), \ldots, (x_{k_1}^1, \tilde{x}_{k_1}^1)\} \\ \vdots \\ \{(x_1^n, \tilde{x}_1^n), \ldots, (x_{k_n}^n, \tilde{x}_{k_n}^n)\} \end{pmatrix}$$

Example



$\Sigma_o = \{o_1, o_2\}$

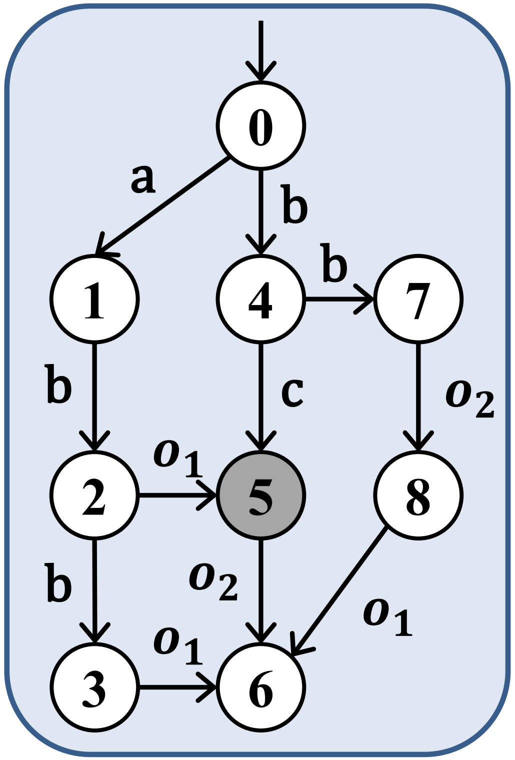
$\Sigma_c = \{a, b, c\}$

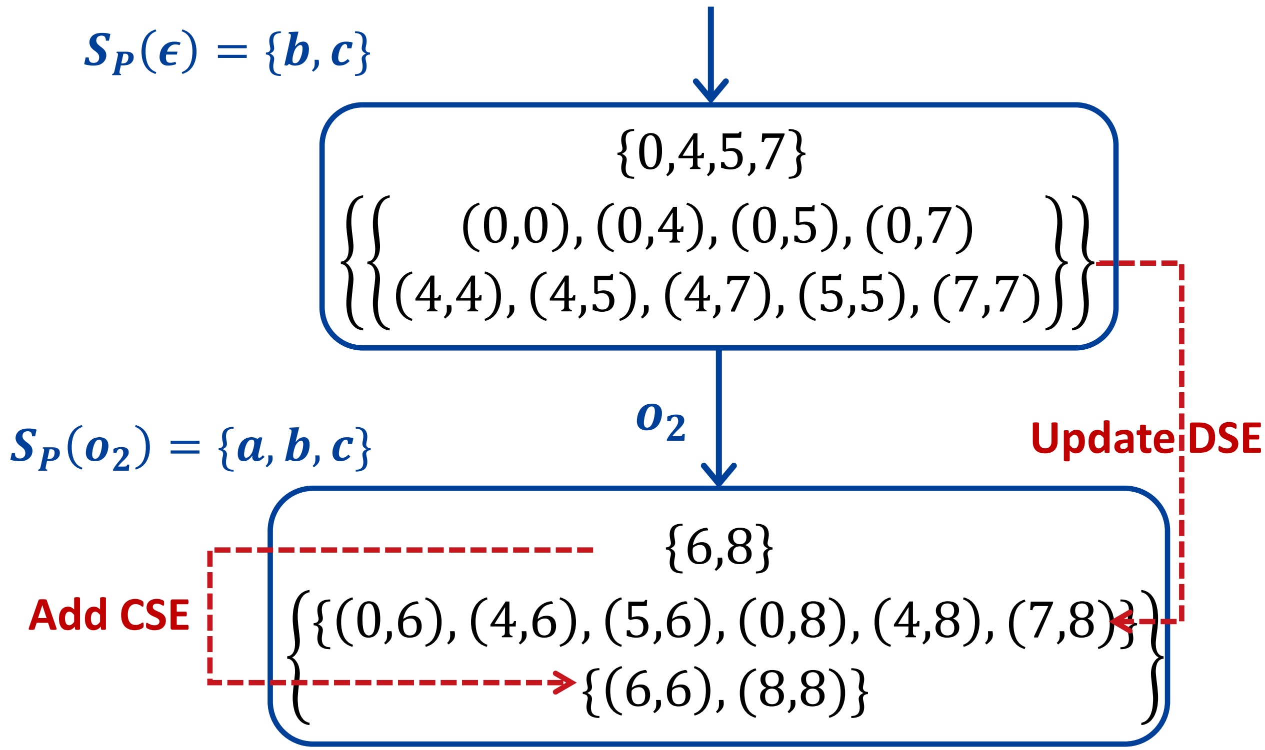
$S_P(\epsilon) = \{b, c\}$

$$\{0,4,5,7\}$$

$$\left\{\left\{\begin{matrix}(0,0),(0,4),(0,5),(0,7)\\(4,4),(4,5),(4,7),(5,5),(7,7)\end{matrix}\right\}\right\}$$

Example





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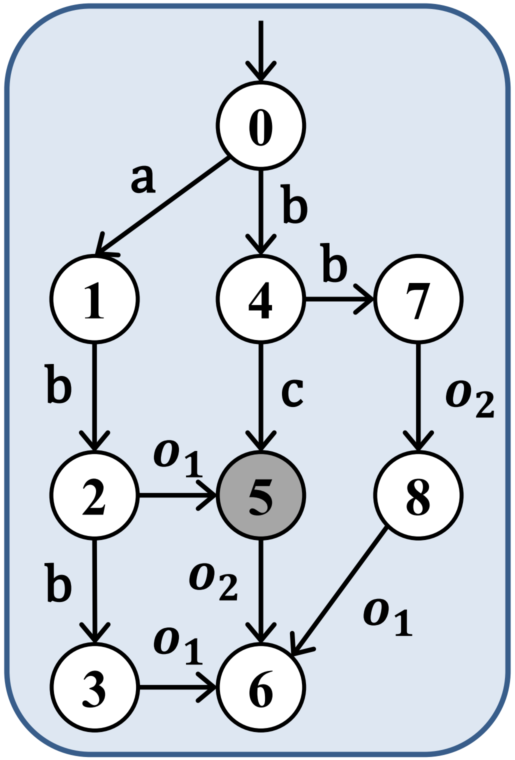

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o_2

$S_P(o_2) = \{a, b, c\}$

$$\{6,8\}$$
$$\left\{\begin{matrix}\{(0,6),(4,6),(5,6),(0,8),(4,8),(7,8)\}\\\{(6,6),(8,8)\}\end{matrix}\right\}$$

o_1

$S_P(o_2 o_1) = \{a, b, c\}$

Update DSE

$$\{6\}$$
$$\left\{\begin{matrix}\{(0,6),(4,6),(7,6)\}\\\{(8,6)\}\\\{(6,6)\}\end{matrix}\right\}$$

Add CSE

$D_1(\iota) = \{\{0, 4, 7\}, \{8\}, \{6\}\}$

Synthesis Procedure

- **Theorem**

Let $I(\alpha)$ be the information state reached by $\alpha \in P(\mathcal{L}(S_P/G))$. Then

$$D_1(I(\alpha)) = \{\hat{X}_{S_P/G}(\beta|\alpha) \in 2^X : \beta \in \overline{\{\alpha\}}\}$$

- **Synthesis for infinite-step opacity**
  - Construct the largest G-BTS
  - Avoid states $Q_{unsafe} = \{\imath \in I : \exists q \in D_1(\imath) \ s.t. \ q \subseteq X_S\}$
  - Delete all inconsistent states
  - Maximal decision at each instant

Synthesis Procedure

A generalized bipartite transition system (G-BTS) *T* w.r.t. G is a 7-tuple

$$T = (Q_Y^T, Q_Z^T, h_{YZ}^T, h_{ZY}^T, \Sigma_o, \Gamma, y_0^T)$$

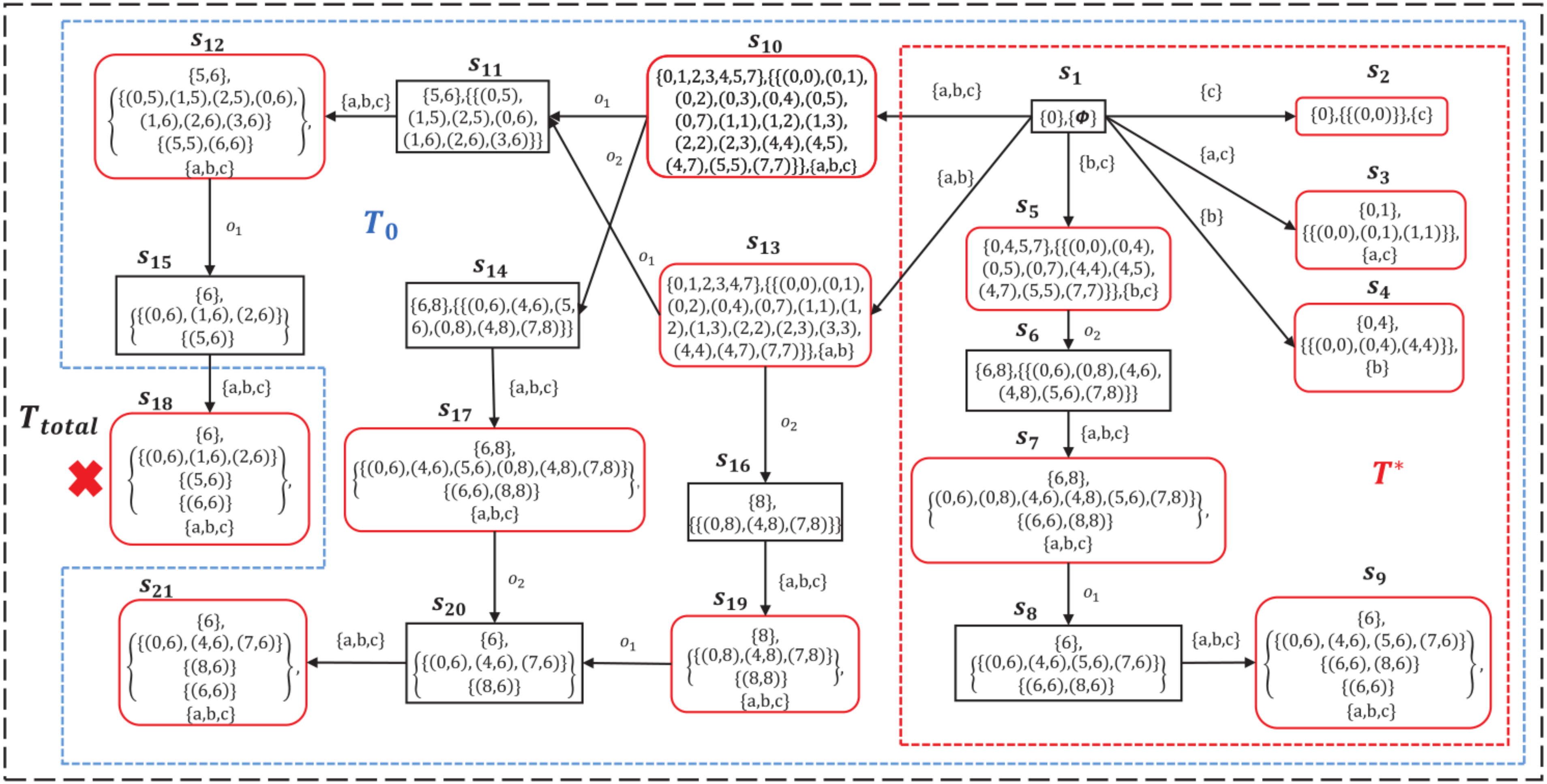
Unobservable reach   Observable reach

game structure between the controller and the environment

Inconsistent states

- A Y-state is consistent if at least one control decision is defined.
- A Z-state is consistent if all feasible events are defined.

Example



s_1
{0},{Φ}
s_2
{0},{{(0,0)}},{c}
s_3
{0,1},{{(0,0),(0,1),(1,1)}},{a,c}
s_4
{0,4},{{(0,0),(0,4),(4,4)}},{b}
s_5
{0,4,5,7},{{(0,0),(0,4),(0,5),(0,7),(4,4),(4,5),(4,7),(5,5),(7,7)}},{b,c}
s_6
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s_8
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s_9
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s_{10}
{0,1,2,3,4,5,7},{{(0,0),(0,1),(0,2),(0,3),(0,4),(0,5),(0,7),(1,1),(1,2),(1,3),(2,2),(2,3),(4,4),(4,5),(4,7),(5,5),(7,7)}},{a,b,c}
s_{11}
{5,6},{{(0,5),(1,5),(2,5),(0,6),(1,6),(2,6),(3,6)}}
s_{12}
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s_{13}
{0,1,2,3,4,7},{{(0,0),(0,1),(0,2),(0,4),(0,7),(1,1),(1,2),(1,3),(2,2),(2,3),(3,3),(4,4),(4,7),(7,7)}},{a,b}
s_{14}
{6,8},{{(0,6),(4,6),(5,6),(0,8),(4,8),(7,8)}}
s_{15}
{6},{{(0,6),(1,6),(2,6)} {(5,6)}}
s_{16}
{8},{{(0,8),(4,8),(7,8)}}
s_{17}
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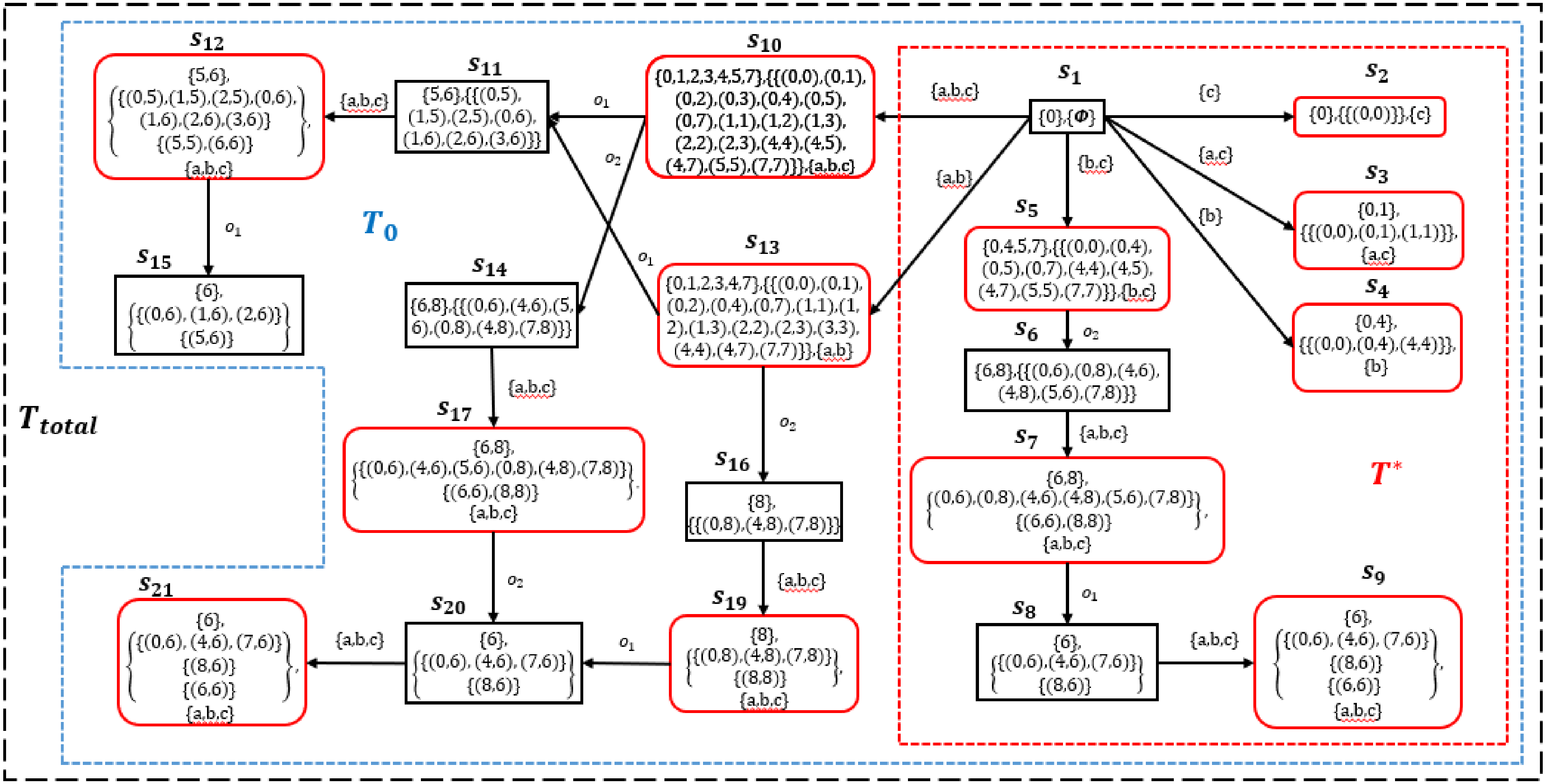
{a,b,c}
{c}
{a,c}
{b,c}
{b}
{a,b}
o_1
o_2
T_0
T_{total}
T^*

Example



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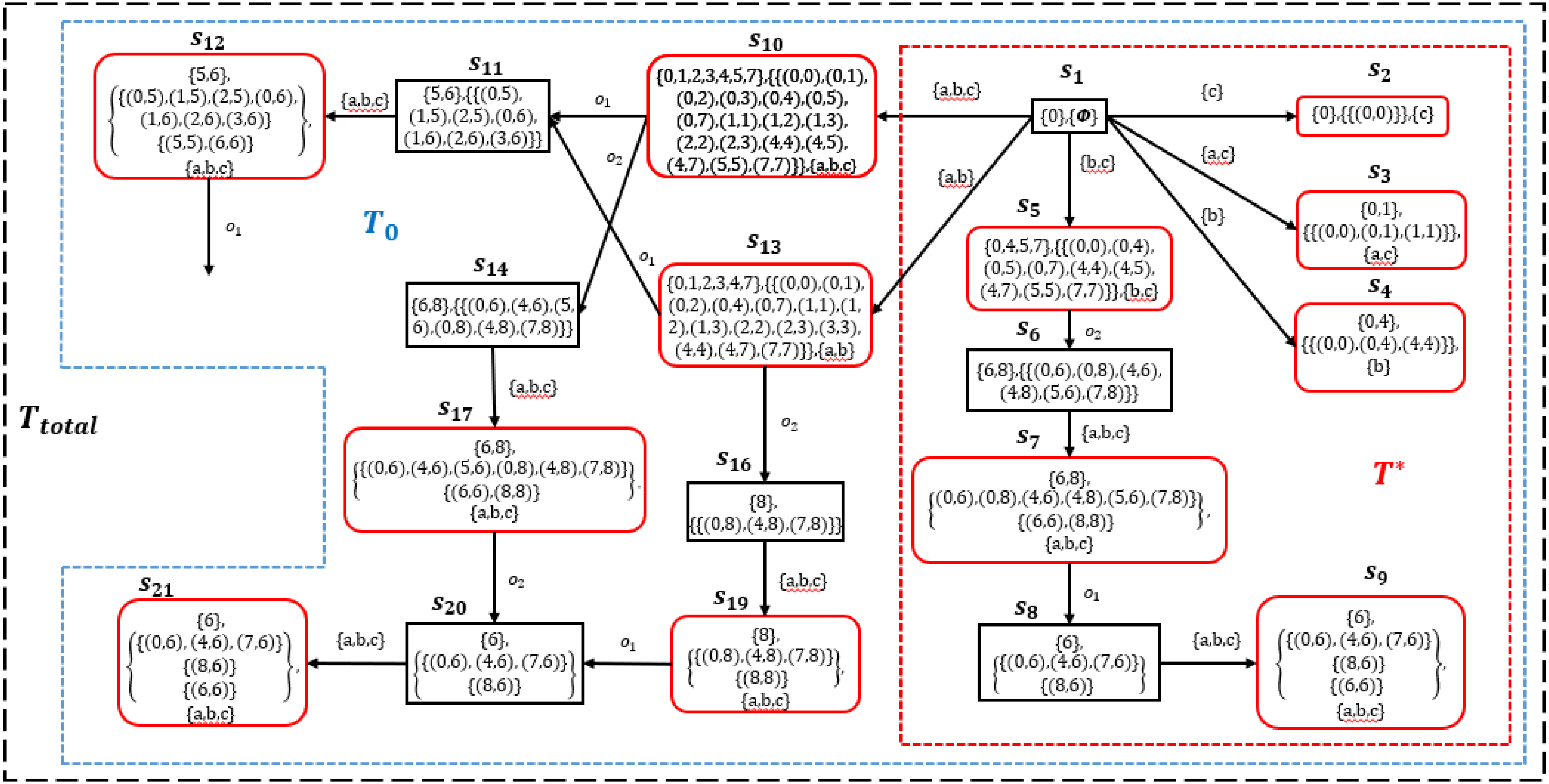

T_{total}
T_0
T^*
s_1 {0},{Φ}
s_2 {0},{{(0,0)}},{c}
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o_1
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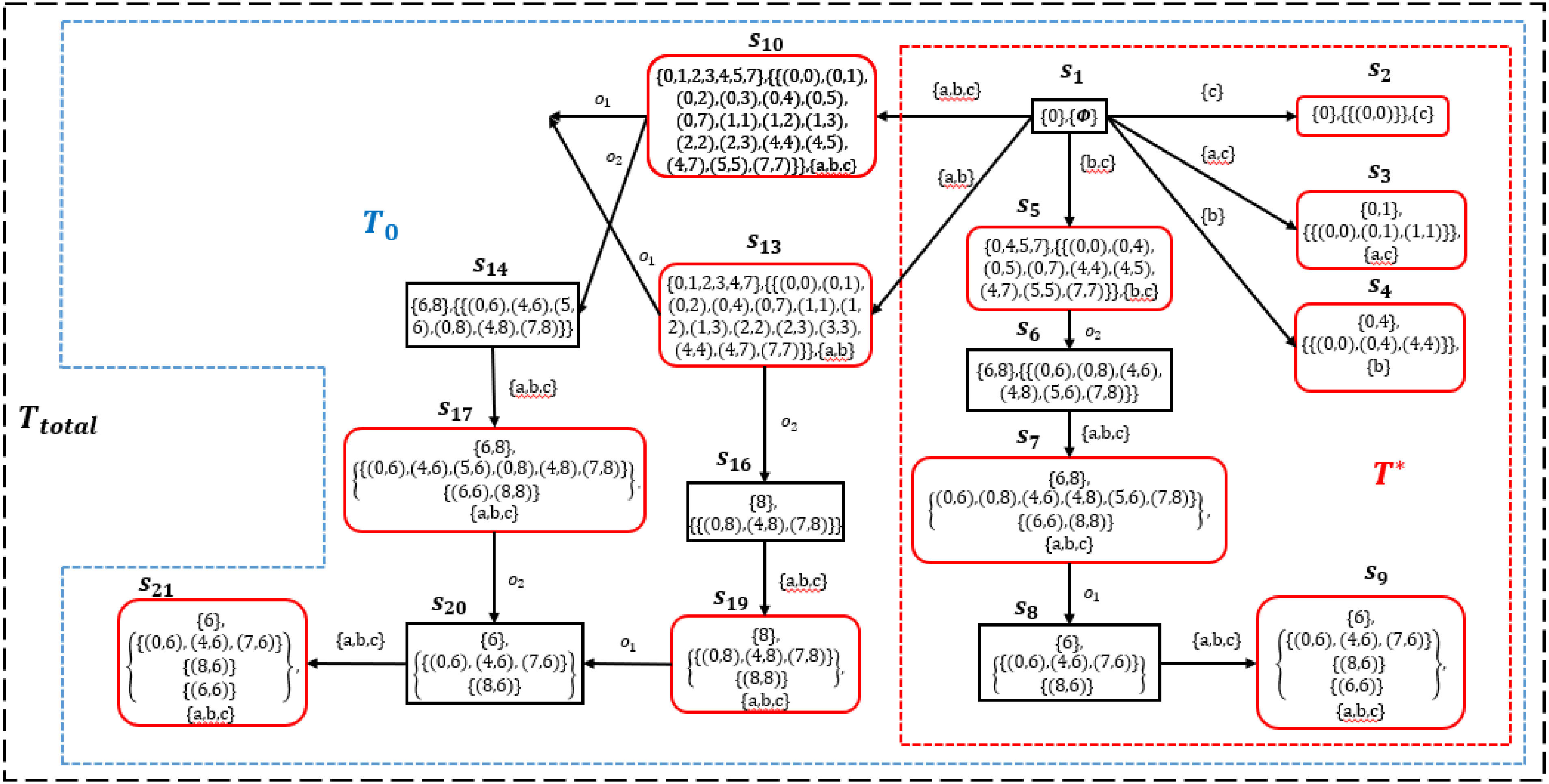
Example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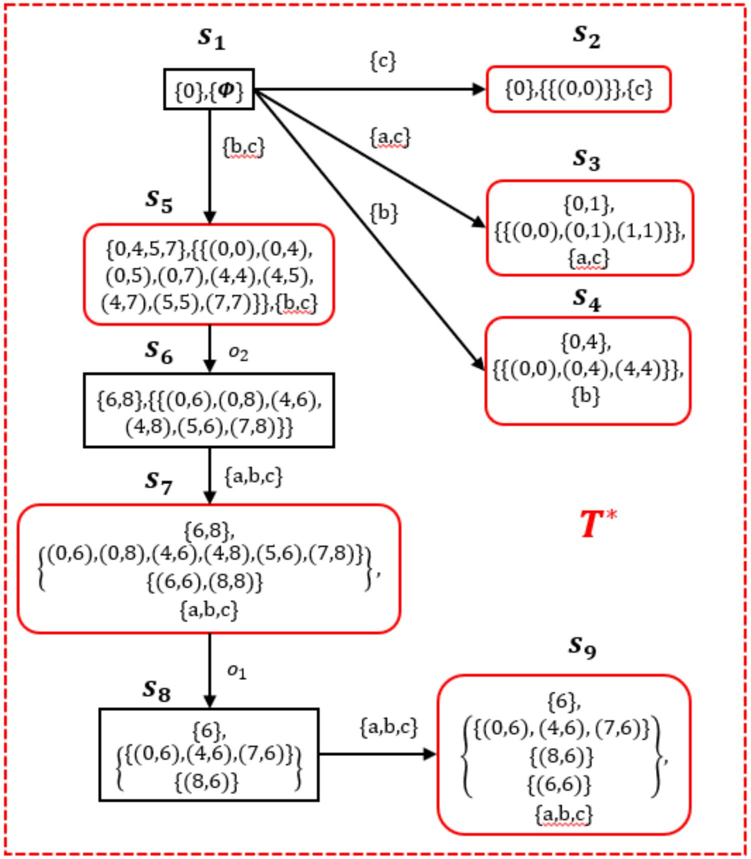
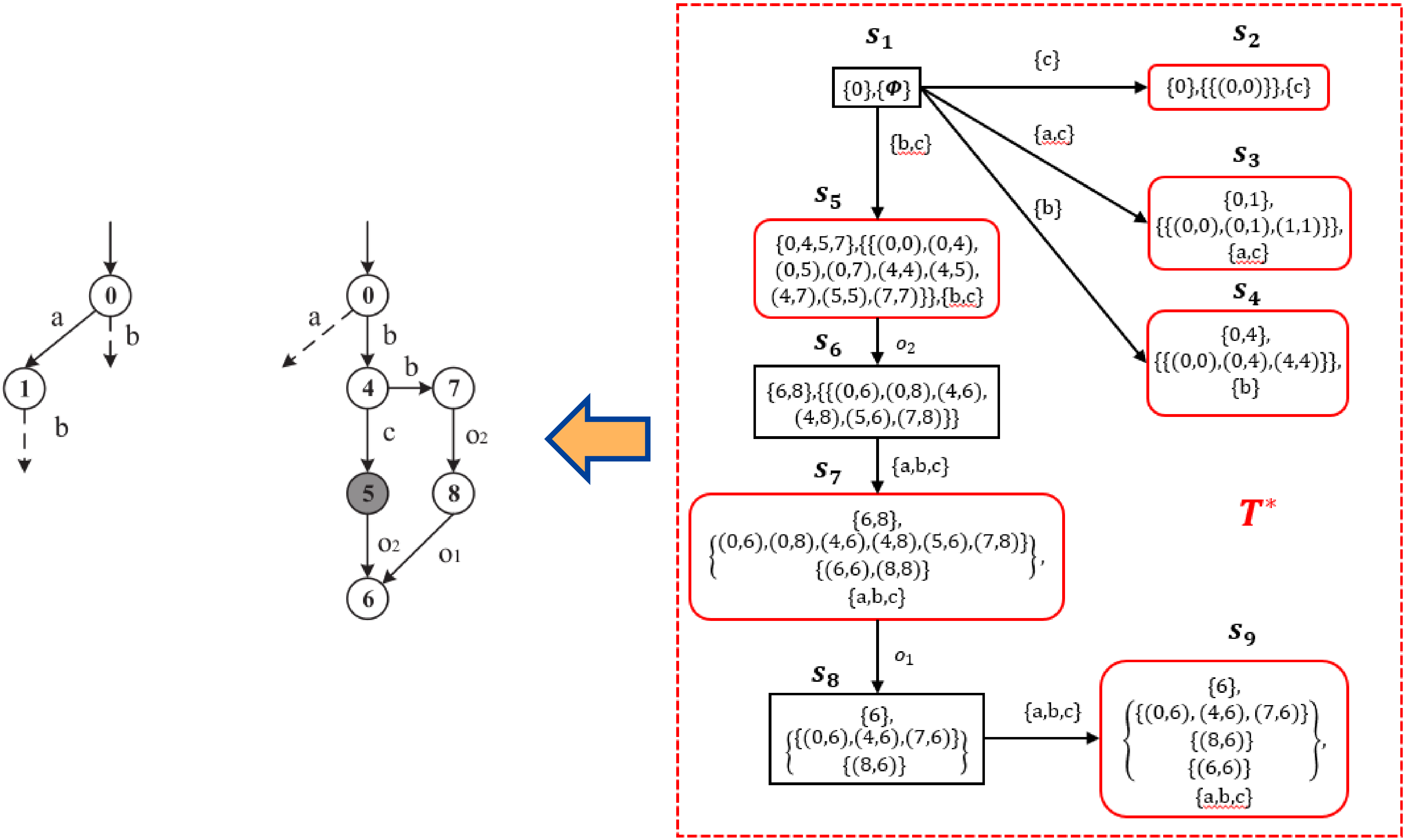
s_{19}
{8},{(0,8),(4,8),(7,8)} {(8,8)},{a,b,c}
s_{20}
{6},{(0,6), (4,6), (7,6)} {(8,6)}
s_{21}
{6},{(0,6), (4,6), (7,6)} {(8,6)} {(6,6)},{a,b,c}
{a,b,c}
{c}
{a,c}
{b,c}
{a,b}
{b}
o_1
o_2
T_0
T_{total}
T^*

Example



s_1
{0},{Φ}
{c}
s_2
{0},{{(0,0)}},{c}
{a,c}
s_3
{0,1}, {{(0,0),(0,1),(1,1)}}, {a,c}
{b}
s_4
{0,4}, {{(0,0),(0,4),(4,4)}}, {b}
{b,c}
s_5
{0,4,5,7},{{(0,0),(0,4),(0,5),(0,7),(4,4),(4,5),(4,7),(5,5),(7,7)}},{b,c}
o_2
s_6
{6,8},{{(0,6),(0,8),(4,6),(4,8),(5,6),(7,8)}}
{a,b,c}
s_7
{6,8}, {{(0,6),(0,8),(4,6),(4,8),(5,6),(7,8)}, {(6,6),(8,8)}}, {a,b,c}
T^*
o_1
s_8
{6}, {{(0,6),(4,6),(7,6)}, {(8,6)}}
{a,b,c}
s_9
{6}, {{(0,6), (4,6), (7,6)}, {(8,6)}, {(6,6)}}, {a,b,c}

Example



0
a
b
1
b
0
a
b
4
b
7
c
o2
5
8
o2
o1
6
s1
{0},{Φ}
{c}
s2
{0},{{(0,0)}},{c}
{a,c}
{b,c}
s3
{0,1},
{{(0,0),(0,1),(1,1)}},
{a,c}
{b}
s5
{0,4,5,7},{{(0,0),(0,4),
(0,5),(0,7),(4,4),(4,5),
(4,7),(5,5),(7,7)}},{b,c}
s4
{0,4},
{{(0,0),(0,4),(4,4)}},
{b}
s6
o2
{6,8},{{(0,6),(0,8),(4,6),
(4,8),(5,6),(7,8)}}
s7
{a,b,c}
{6,8},
{(0,6),(0,8),(4,6),(4,8),(5,6),(7,8)}
{(6,6),(8,8)}
{a,b,c}
T*
o1
s8
s9
{6},
{(0,6),(4,6),(7,6)}
{(8,6)}
{a,b,c}
{6},
{(0,6), (4,6), (7,6)}
{(8,6)}
{(6,6)}
{a,b,c}

Conclusion

- Synthesis of supervisor for infinite-step opacity
- New type of information state for delayed information
- Effective synthesis procedure based on the proposed new IS

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Thank You!