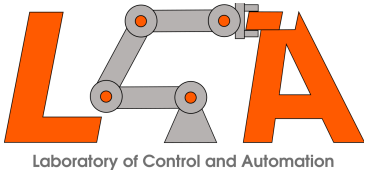
Robust Failure Diagnosis of Discrete Event Systems and Its Applications

João Carlos Basilio

Workshop on Analysis and Control for Resilience of Discrete Event Systems



Universidade Federal
do Rio de Janeiro

Talk outline

1. Fault Diagnosis and Robustness
2. Fault Diagnosis of Discrete-Event Systems
3. Online Diagnosis
4. Robust Fault Diagnosis of Discrete-Event Systems. Why?
5. Robust Diagnosis against intermittent loss of observation
6. Diagnosability of Networked DES
7. Conclusion

I. Fault Diagnosis and Robustness

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Fault occurrences must be diagnosed ASAP

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  - It is performed online
- Fault Diagnosability: is a system property that ensures that the fault can be diagnosed
  - It is performed offline
  - It requires the knowledge of a model of the system

Robustness

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How to bring robustness to Fault Diagnosis of Discrete-Event Systems?

II. Fault Diagnosis of Discrete-Event Systems

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- DES are event dependent $\Rightarrow$ Better described with languages
- Automaton is one of the modeling formalisms

$$G = (X, \Sigma, \delta, x_0)$$

  - Kleene-closure of Σ: Σ^*
  - Language generated by G:
    $L(G) = \{s \in \Sigma^* : (\exists x \in X)[\delta(x_0, s) = x]\}$

Language diagnosability

$$G = (X, \Sigma, \delta, x_0)$$

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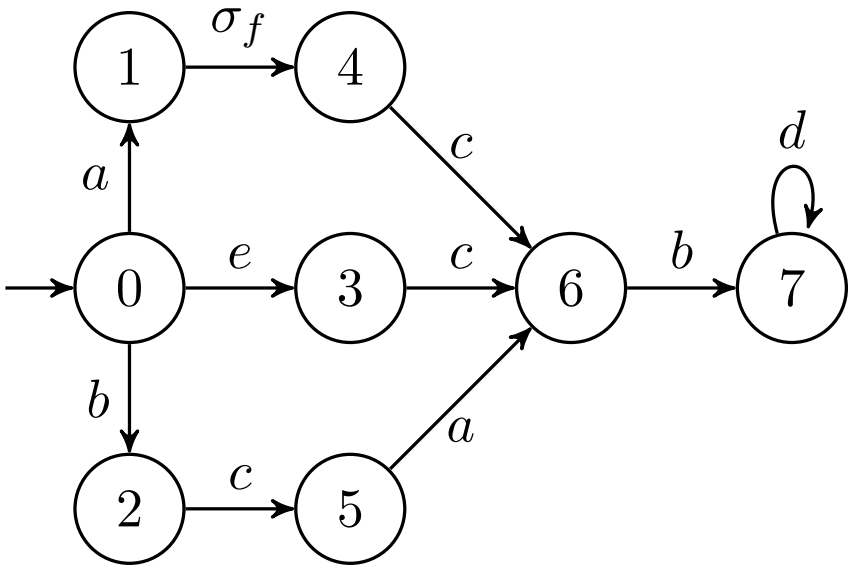

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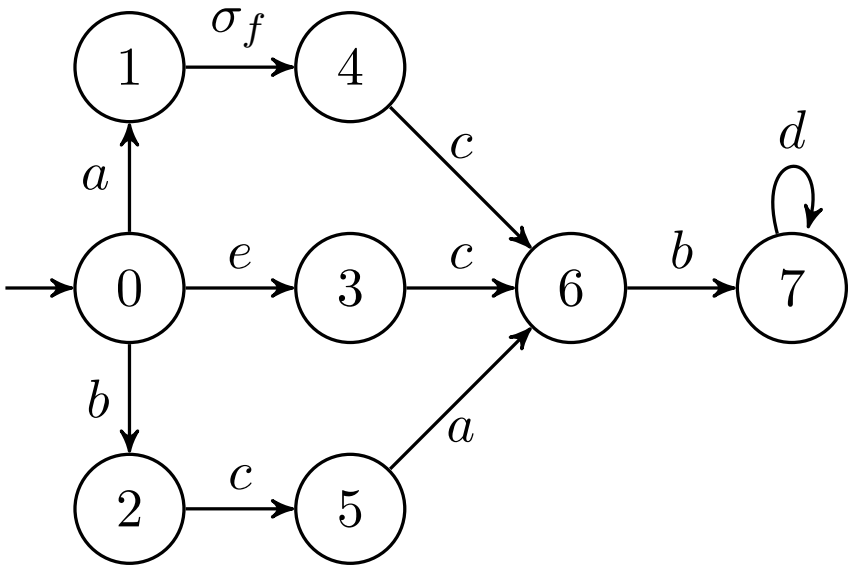

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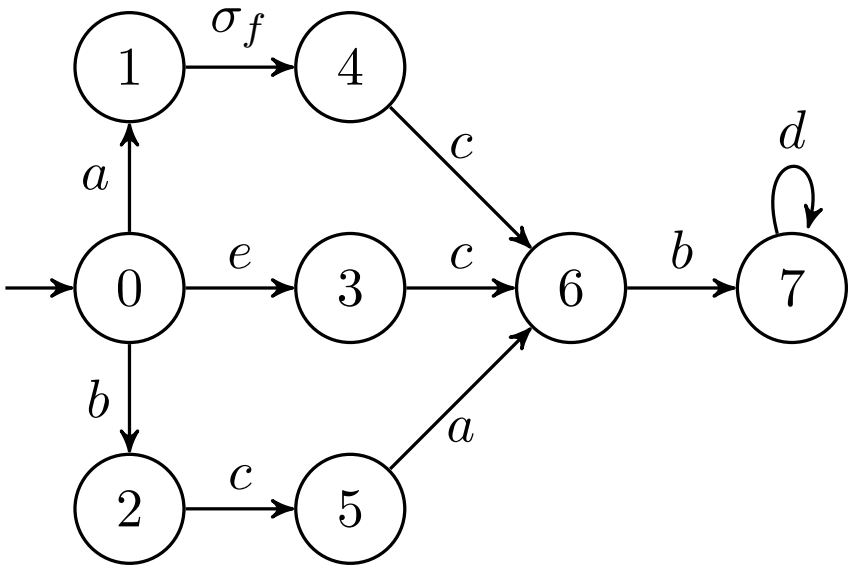

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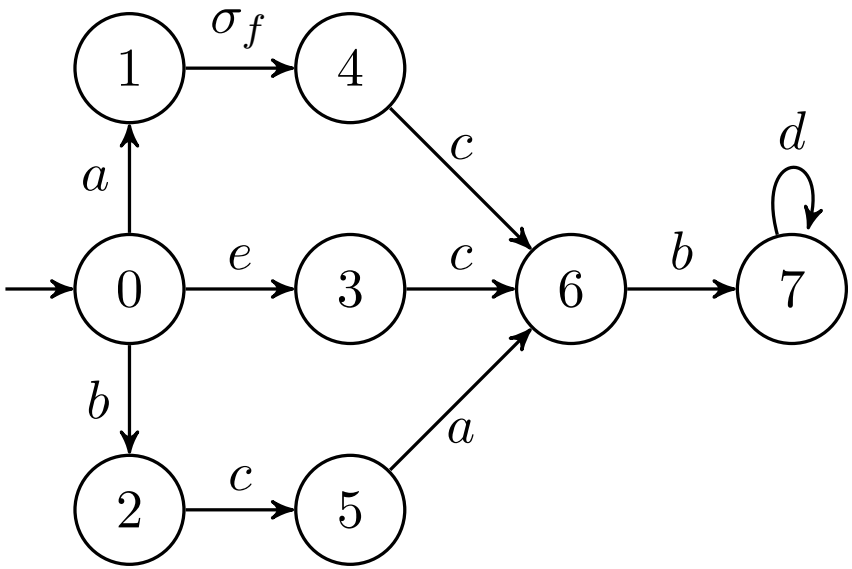

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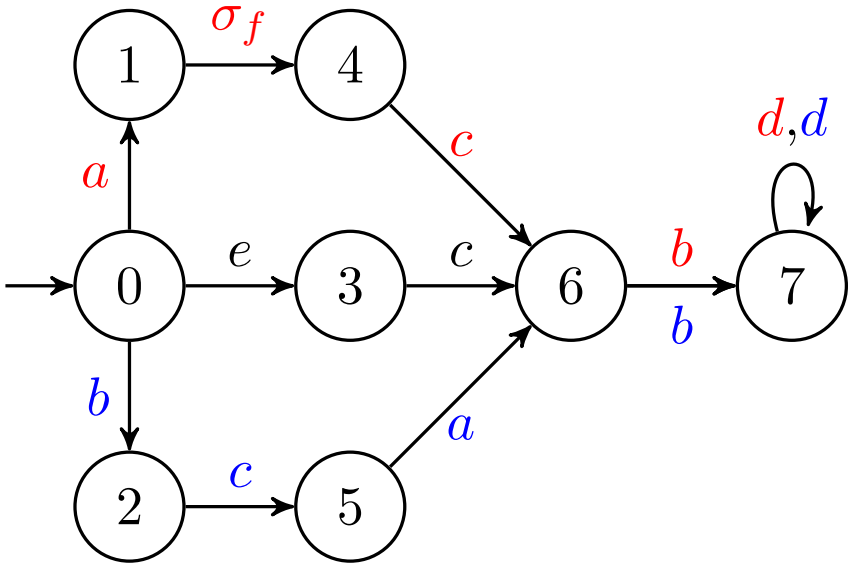

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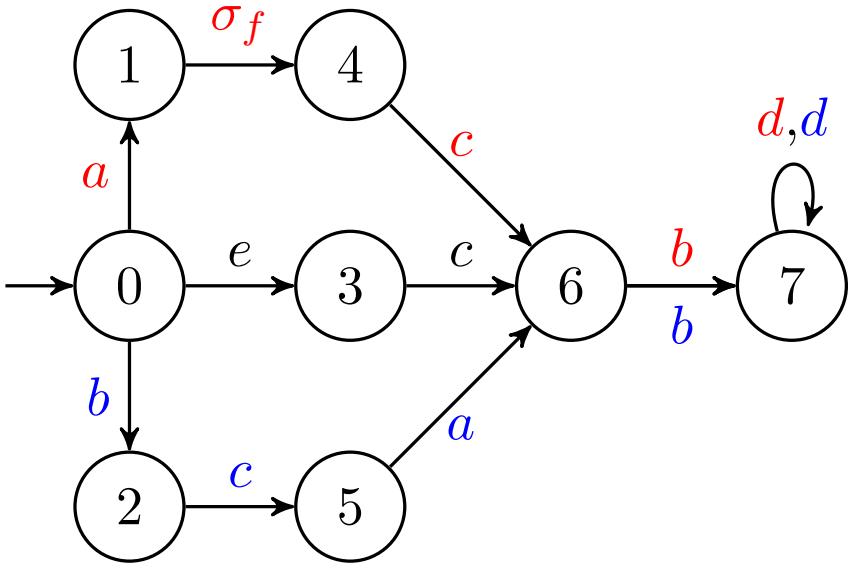

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- $L(G)$ **not diagnosable**

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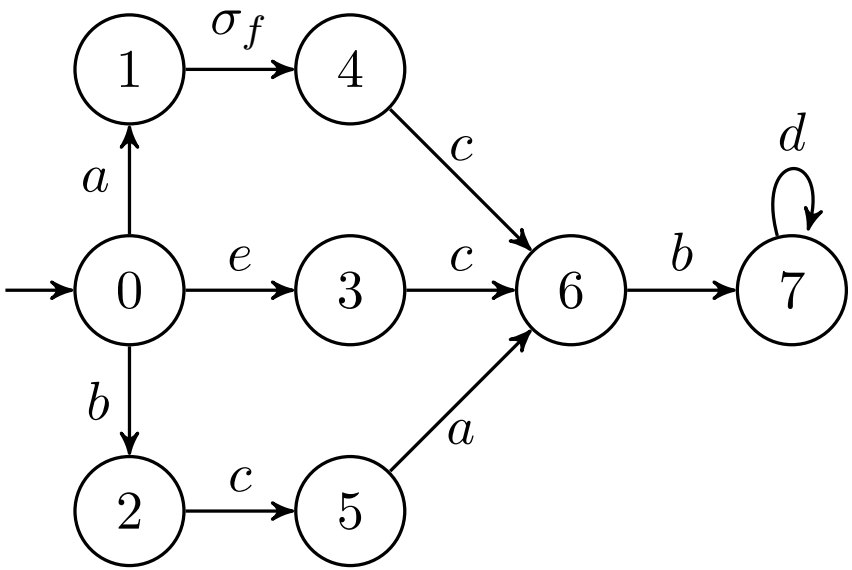

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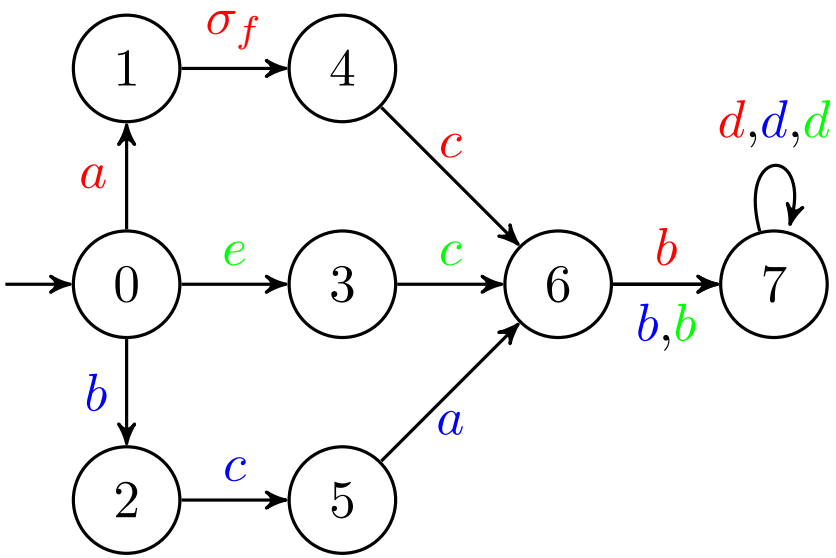

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- $s'_N = bcabd^n \Rightarrow P_{\Sigma,\Sigma_o}(s'_N) = bbd^n$
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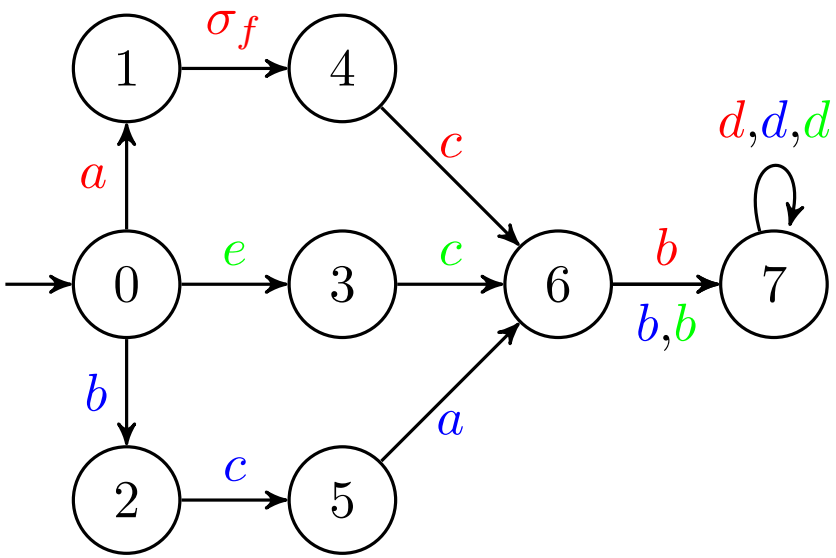

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- **$L(G)$ diagnosable**

Idea Behind Language Diagnosability

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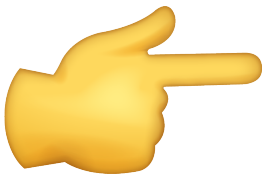

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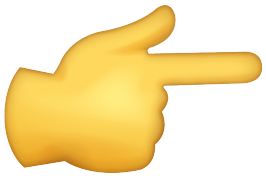

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III. Online Diagnosis

Diagnoser Automaton

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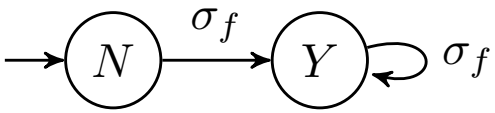

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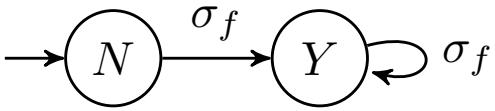

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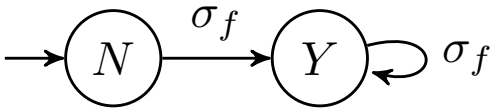
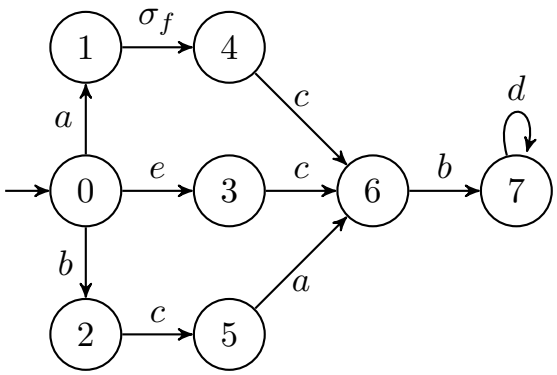


- Labeled automaton: $G_\ell = G \| A_\ell$
- Diagnoser: $G_d(\Sigma_o) = \text{Obs}(G_\ell, \Sigma_o) = (X_d, \Sigma_o, \delta_d, x_{0,d})$

Diagnoser Automaton - Example

- System Automaton G



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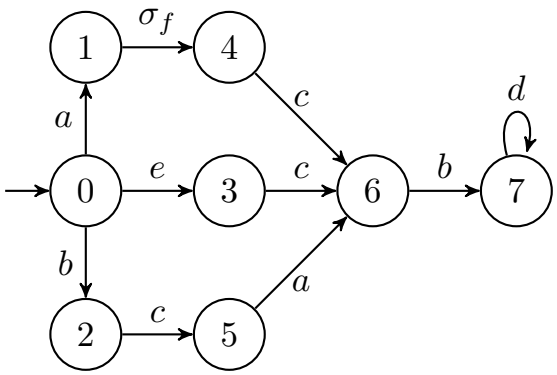

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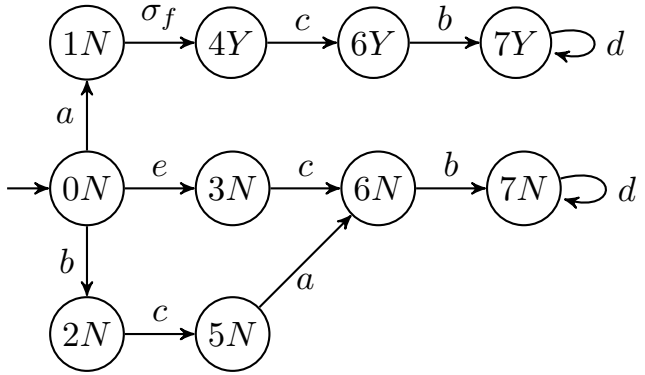

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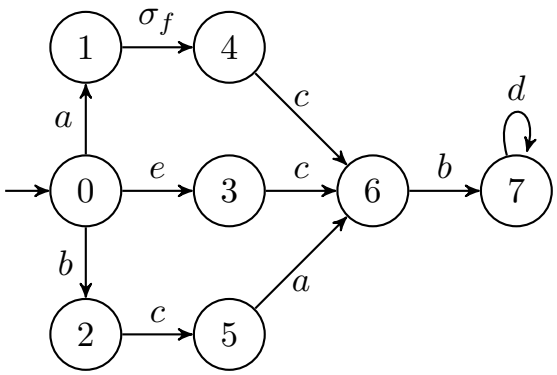

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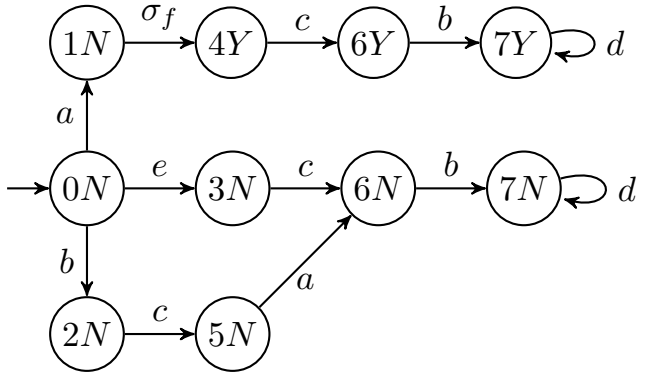
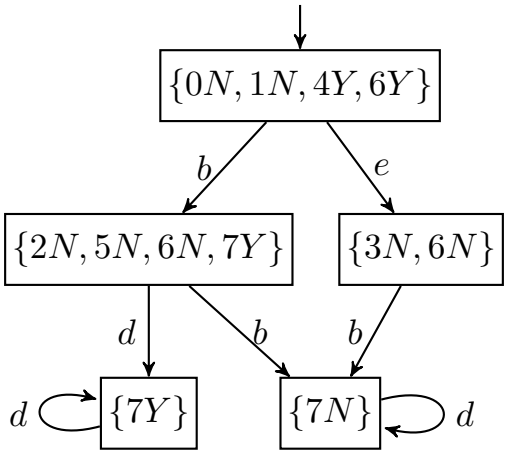


- Diagnoser Automaton G_d ($\Sigma_o = \{b, d, e\}$)



IV. Robust Fault Diagnosis of Discrete-Event Systems. Why?

Motivation Example: loss of event observation

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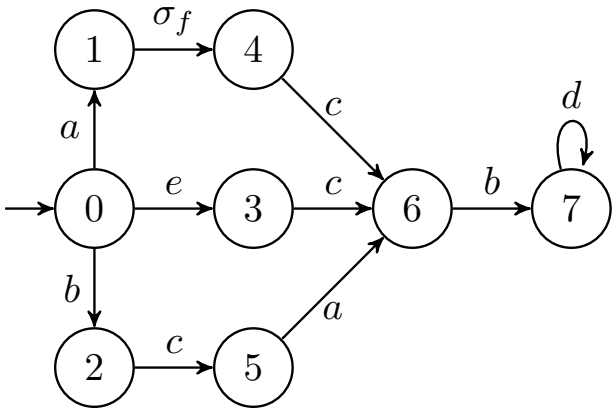

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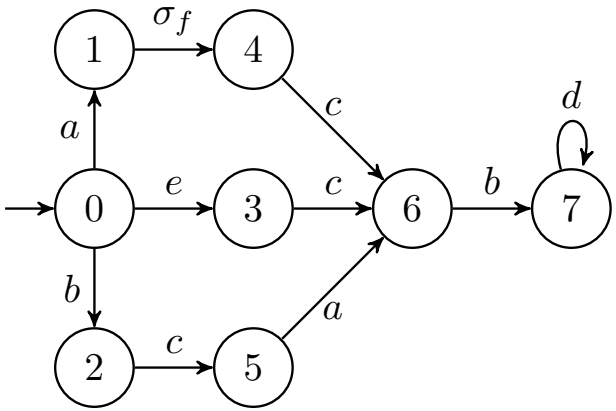

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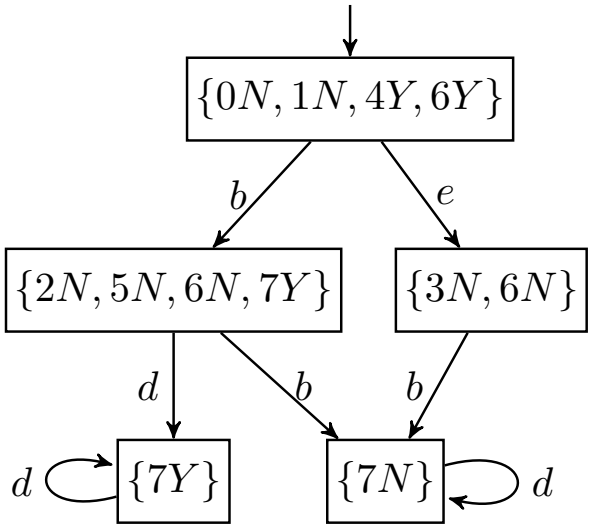

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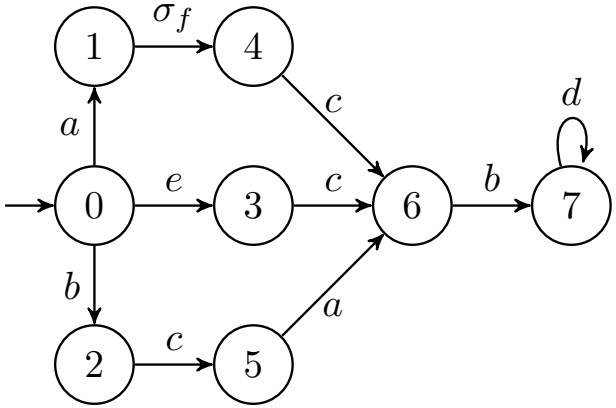
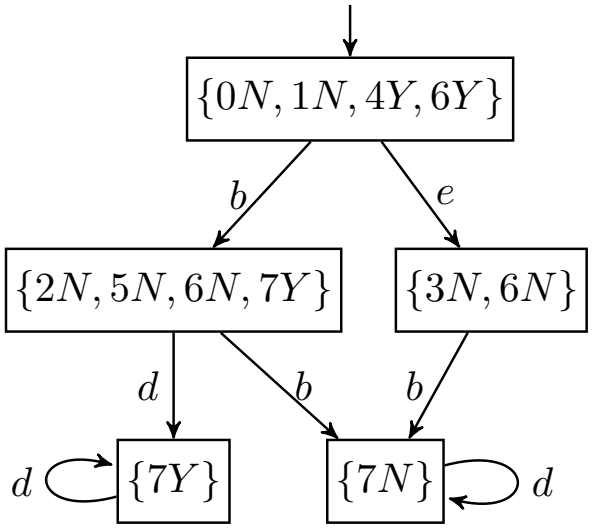
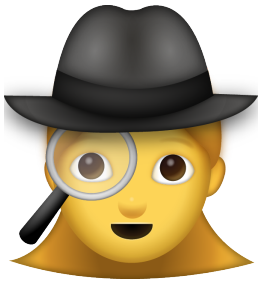


- Diagnoser G_d ($\Sigma_o = \{b, d, e\}$)

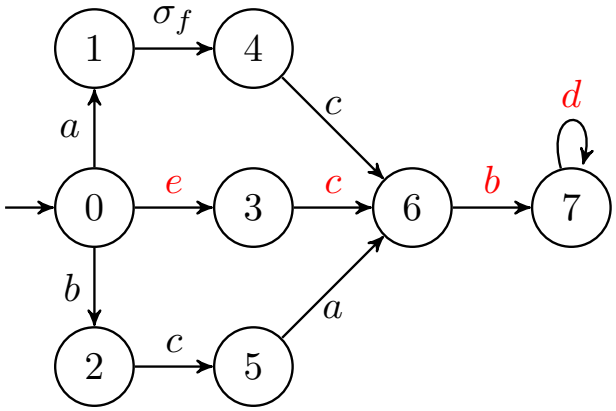




What would happen if, for some reason, the occurrence of event e did not reach G_d?

Motivation Example: loss of event observation

- System Automaton G



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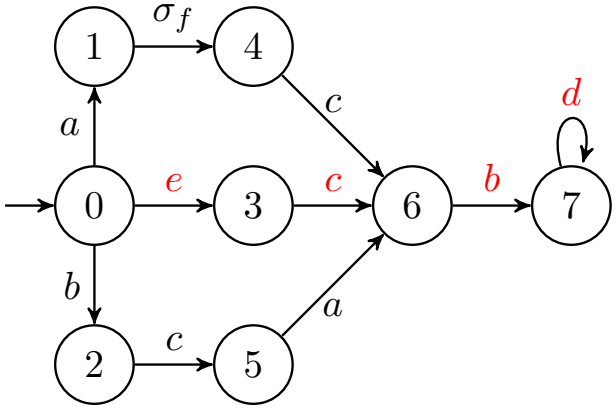
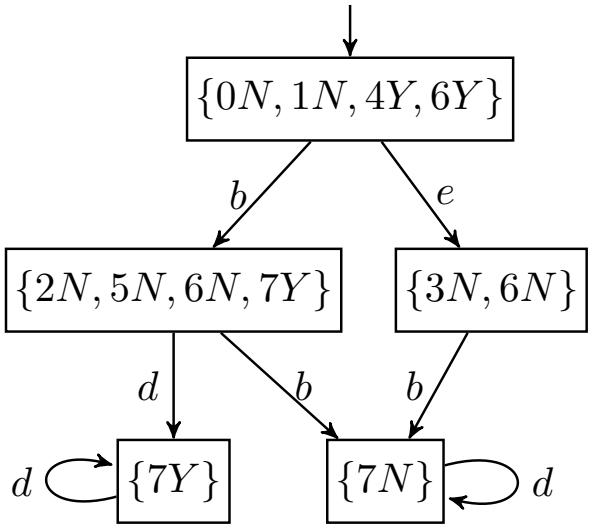


- Diagnoser G_d ($\Sigma_o = \{b, d, e\}$)



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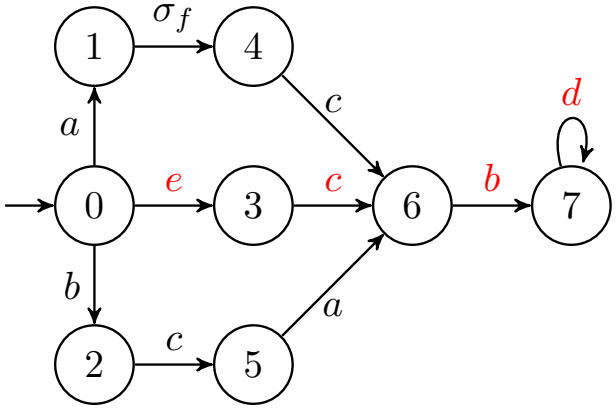

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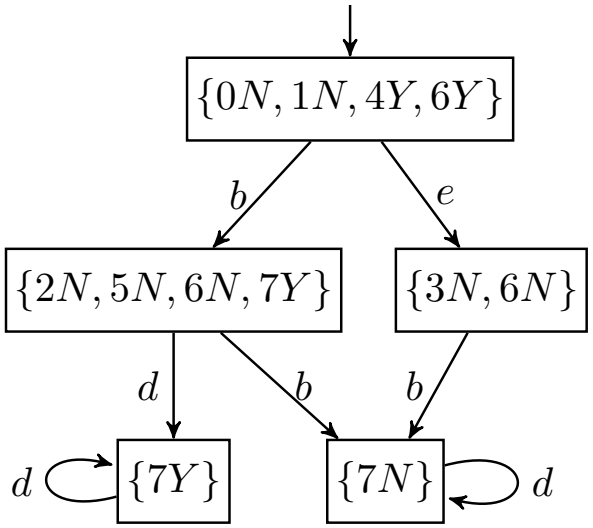
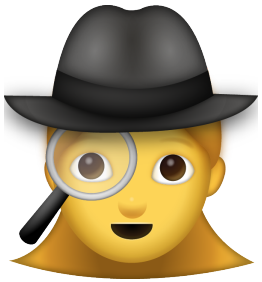
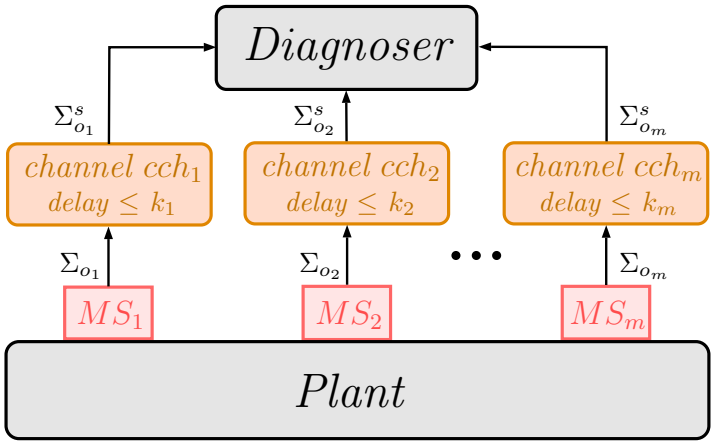




Diagnoser would end up in state $\{7Y\}$
FALSE POSITIVE

Motivation Example: Networked DES

- Networked



Motivation Example: Networked DES

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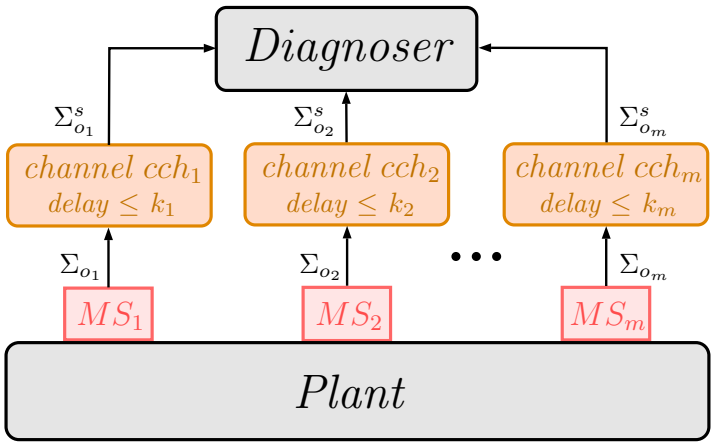
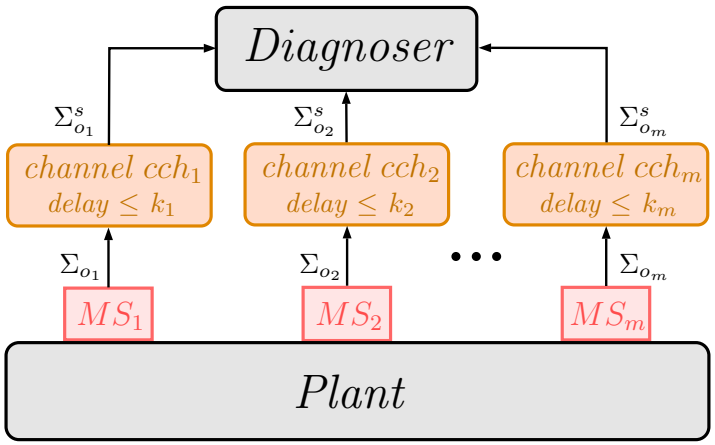


- Measurement sites: MS_i, $i = 1, 2, \ldots, m$
- Communication channels: cch_i, $i = 1, 2, \ldots, m$
- Communication channels delays: k_i, $i = 1, 2, \ldots, m$ Steps

Motivation Example: Networked DES

- Networked



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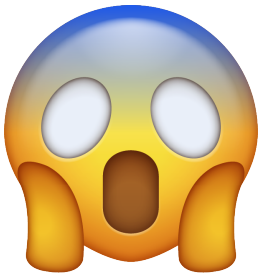
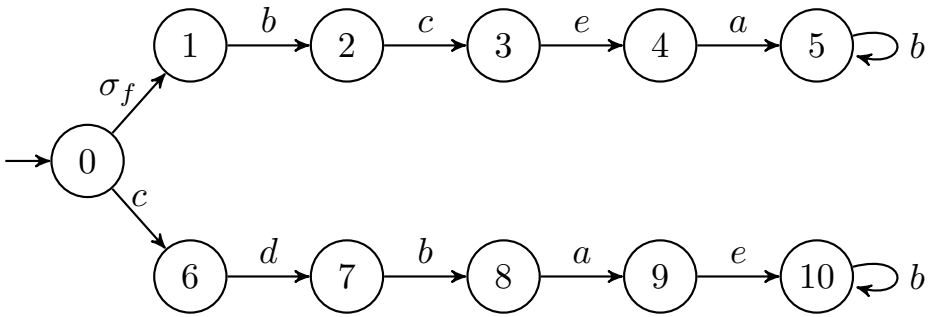


Event observation can be performed in an order different from the actual event occurrences due to different delays of the various communication channels employed.

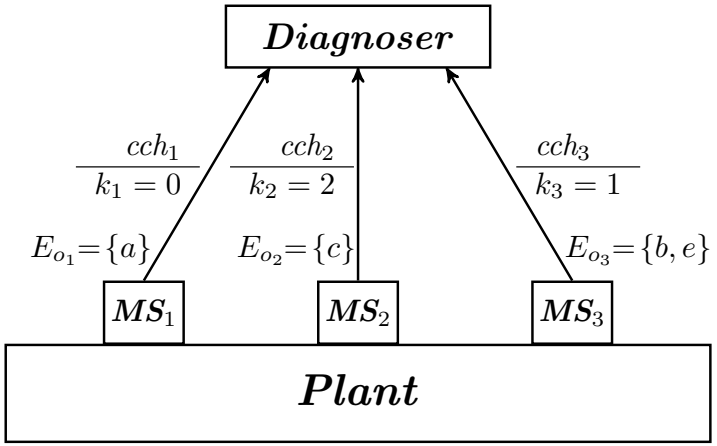
Motivation Example: Networked DES

- Automaton



- $\Sigma = \{a, b, c, d, e, \sigma_f\}$, $\Sigma_f = \{\sigma_f\}$

- Networked DES



Motivation Example: Networked DES

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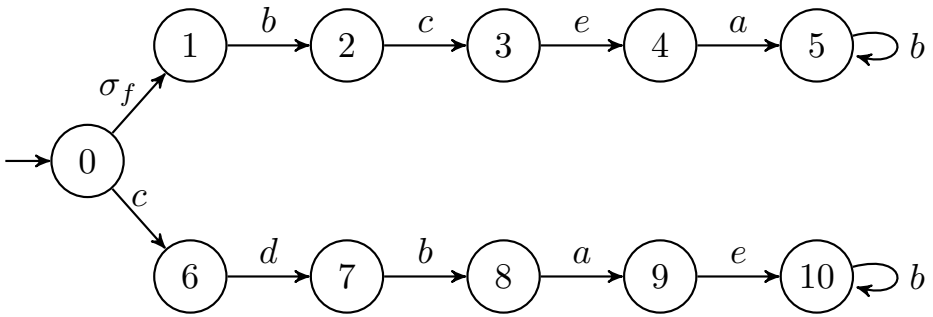
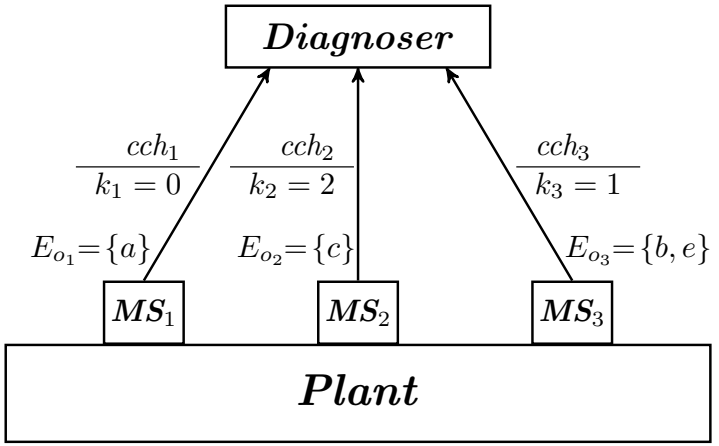


- $\Sigma = \{a, b, c, d, e, \sigma_f\}$, $\Sigma_f = \{\sigma_f\}$
  - Diagnosable if no delay exists

- Networked DES



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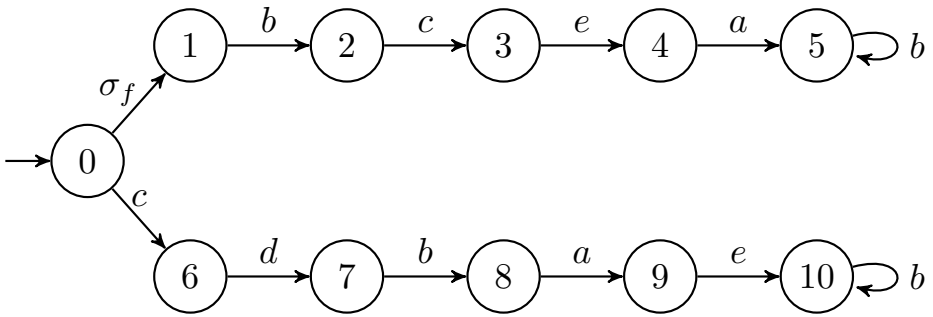
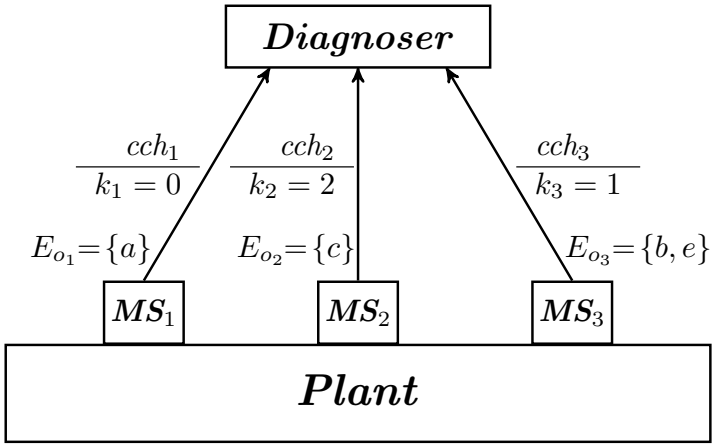
- Automaton



- Networked DES



- $\Sigma = \{a, b, c, d, e, \sigma_f\}$, $\Sigma_f = \{\sigma_f\}$
  - Diagnosable if no delay exists
  - Assuming there are communication channel delays:
    - $s_Y = \sigma_f bceab^n$ and $s_N = cdbaeb^n$, $n \in \mathbb{Z}_+$
    - $s_{Y_a} = \sigma_f bcc_s b_s eaa_s e_s (bb_s)^n$, $s_{N_a} = cc_s dbb_s aa_s ee_s (bb_s)^n$
    - $P_{\Sigma_a, \Sigma_o^s}(s_{Y_a}) = P_{\Sigma_a, \Sigma_o^s}(s_{N_a}) = c_s b_s a_s e_s (b_s)^n$
    - Non diagnosable

V. Robust Diagnosis against intermittent loss of observation

Key to the Solution: Language augmentation

- Dilation (Carvalho et al., 2014)
  - $\Sigma_o = \Sigma_{ilo} \dot{\cup} \Sigma_{nilo}$

    Σ_{ilo}: subset of Σ_o whose events are subject to intermittent loss of observations

    Σ_{nilo}: set of events whose observations are never lost.
  - $\Sigma'_{ilo} = \{\sigma' : \sigma \in \Sigma_{ilo}\}$
  - $\Sigma_{dil} = \Sigma \cup \Sigma'_{ilo}$

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  - $\Sigma_{dil} = \Sigma \cup \Sigma'_{ilo}$
  - The dilation D is the mapping

$$D : \Sigma \to 2^{\Sigma_{dil}}$$
$$\sigma \mapsto D(\sigma) = \begin{cases} \{\sigma\}, & \sigma \in \Sigma \setminus \Sigma_{ilo}, \\ \{\sigma, \sigma'\}, & \sigma \in \Sigma_{ilo}, \end{cases}$$

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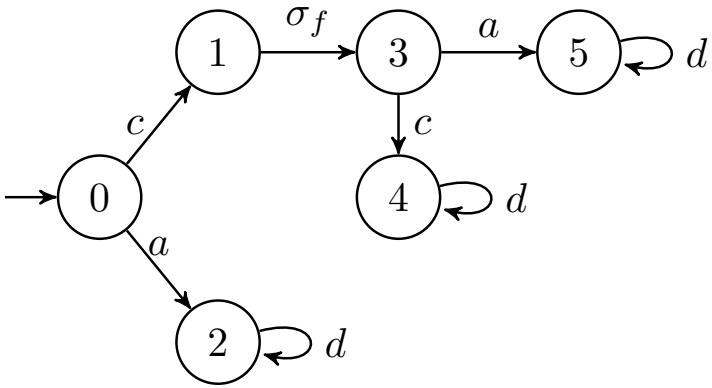
$$\begin{array}{rcccl} D & : & \Sigma & \to & 2^{\Sigma_{dil}} \\ & & \sigma & \mapsto & D(\sigma) = \left\{ \begin{array}{ll} \{\sigma\}, & \sigma \in \Sigma \setminus \Sigma_{ilo}, \\ \{\sigma, \sigma'\}, & \sigma \in \Sigma_{ilo}, \end{array} \right. \end{array}$$

  - Extension to languages:

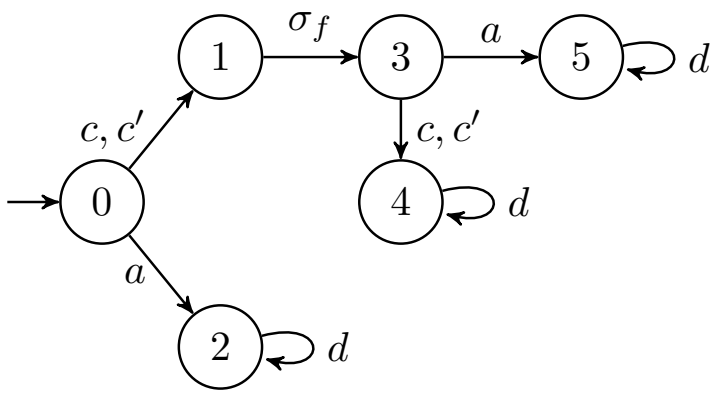
    $D(\varepsilon) = \varepsilon$, and $D(s\sigma) = D(s)D(\sigma)$, for $s \in \Sigma^*$ and $\sigma \in \Sigma$.

Dilation - Example

- Automaton G



- Dilated automaton G_{dil}



- $\Sigma = \{a, b, c, d, \sigma_f\}$, $\Sigma_o = \{a, b, c, d\}$, $\Sigma_f = \{\sigma_f\}$
- $L(G) = pre(c\sigma_f(a + c)d^* + ad^*)$
- $\Sigma_{ilo} = \{c\}$
- $L(G) = pre\big((c + c')\sigma_f(a + c + c')d^* + ad^*\big)$

Robust diagnosability

Diagnosability requires that there do NOT exist AMBIGUOUS SEQUENCES

Robust diagnosability

Diagnosability requires that there do NOT exist AMBIGUOUS SEQUENCES

- Definition: Language $L(G)$ is robustly diagnosable with respect to dilation D, projection $P_{\Sigma_{dil},\Sigma_o} : \Sigma^*_{dil} \to \Sigma^*_o$ and $\Sigma_f = \{\sigma_f\}$ if the following holds true:

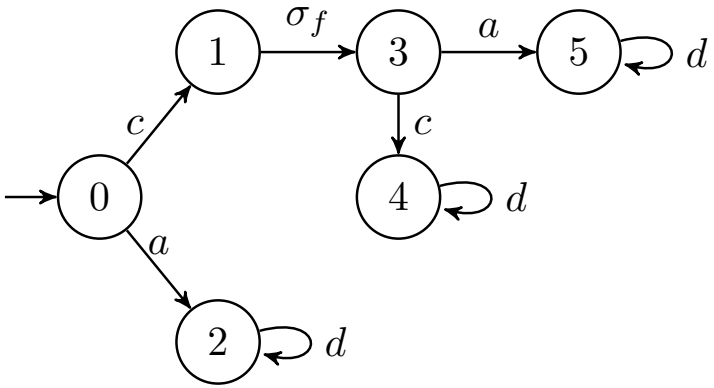
$$(\exists n \in \mathbb{N})(\forall s \in \Psi(\Sigma_f))(\forall t \in L/s)(\|t\| \geq n \Rightarrow R_D),$$

where the robust diagnosability condition R_D is

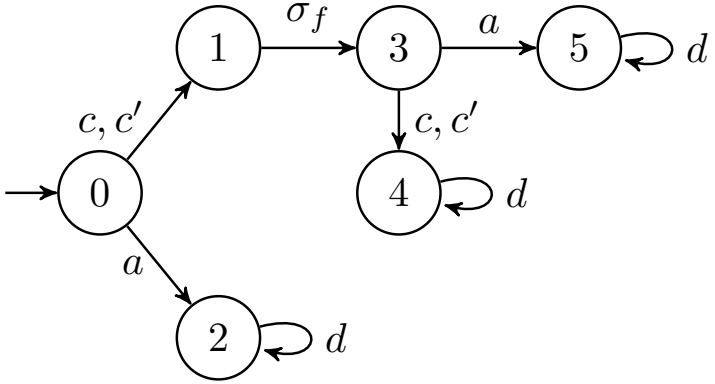
$$\left(\nexists \omega \in L \right) \left[P_{\Sigma_{dil},\Sigma_o}(D(st)) \cap P_{\Sigma_{dil},\Sigma_o}(D(\omega)) \neq \emptyset) \wedge (\Sigma_f \notin \omega) \right].$$

Robust Diagnosability - Example

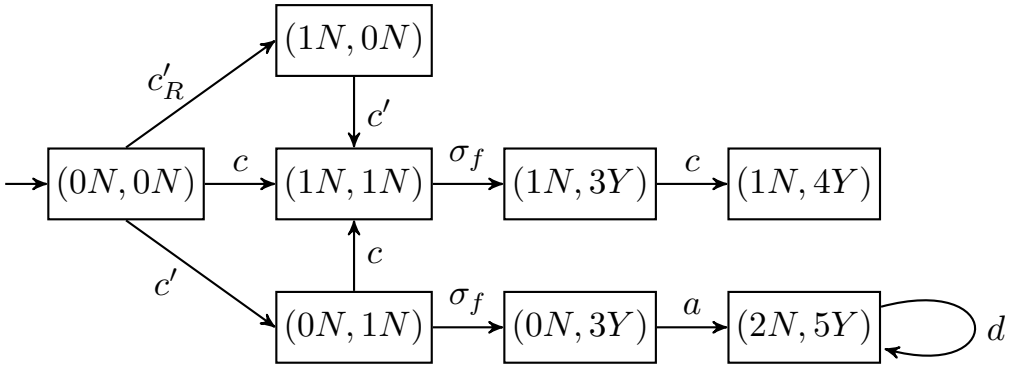
- Automaton G



- Dilated automaton G_{dil}

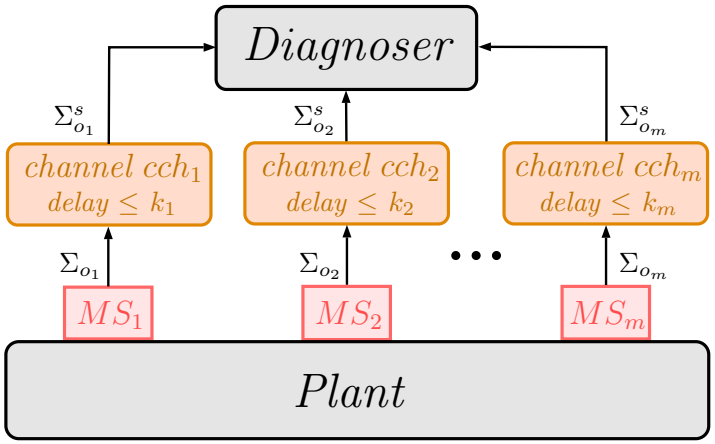


- Robust Diagnosability verification



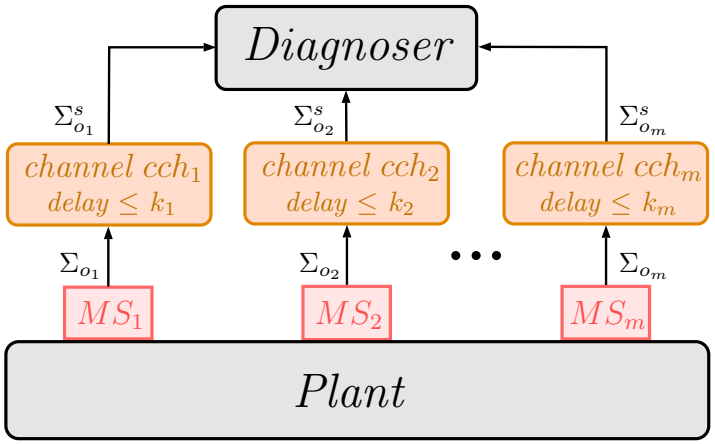
VI. Diagnosability of Networked DES

Networked DES



- Automaton:
  $G = (X, \Sigma, \delta, x_0)$
- Measurement sites:
  MS_i, $i = 1, \ldots, m$
- Channel delay structure:
  $\vec{k} = [\ k_1 \quad k_2 \quad \cdots \quad k_m\ ]$

Networked DES



- Automaton:
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- Measurement sites:
  MS_i, $i = 1, \ldots, m$
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- Event occurrences and observations must be distinguished
  $\Sigma^s_{o_i} = \{\sigma_s : \sigma \in \Sigma_{o_i}\} \rightarrow \Sigma^s_o = \cup_{i=1}^m \Sigma^s_{o_i}$
- Augmented event set
  $\Sigma_a = \Sigma \cup \Sigma^s_o$
- Observation of system evolution
  $P_{\Sigma_a, \Sigma^s_o} : \Sigma_a^* \rightarrow \Sigma_o^{s^*}$.

Language augmentation (Nunes et al, 2018)

$$\chi \quad : \quad \Sigma^* \to 2^{\Sigma_a^*}$$

$$s \mapsto \chi(s) = \{s_a \in \Sigma_a^* : (s_a \models \textbf{C1}) \wedge (s_a \models \textbf{C2}) \wedge (s_a \models \textbf{C3})\}$$

- C1. $P_{\Sigma_a,\Sigma}(s_a) = s$;
- C2. For all $\sigma \in \Sigma_{o,i}$, if $\sigma_s^{(p)} \in s_a$, then:

$$\|P_{\Sigma_a,\Sigma_{o_i}^s}(pre(s_a, \sigma_s^{(p)}))\| - \|P_{\Sigma,\Sigma_{o_i}}(pre(s, \sigma^{(p)}))\| \leq k_i,$$

- C3. For all $\sigma_s \in \Sigma_{o,i}^s$, if $\sigma_s^{(p)} \in s_a$ then

$$\left(\sigma^{(p)} \in pre(s_a, \sigma_s^{(p)})\right) \wedge$$

$$\left(\|P_{\Sigma_a,\Sigma_{o_i}^s}(pre(s_a, \sigma_s^{(p)}))\| = \|P_{\Sigma,\Sigma_{o_i}}(pre(s, \sigma^{(p)}))\|\right)$$

The extension of χ to the domain 2^{Σ^*} is $\chi(L) := \bigcup_{t \in L} \chi_i(t)$.

Network diagnosability

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Network diagnosability

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Definition: Language $L(G)$ is network diagnosable with respect to augmentation $\chi : 2^{\Sigma^*} \to 2^{\Sigma_a^*}$, projection $P_{\Sigma_a,\Sigma_o^s} : \Sigma_a^* \to \Sigma_o^{s^*}$ and $\Sigma_f = \{\sigma_f\}$ if the following holds true:

$$(\exists n \in \mathbb{N})(\forall s \in \Psi(\Sigma_f))(\forall t \in L/s)(||t|| \geq n \Rightarrow N_D)$$

where the network diagnosability condition N_D is

$$(\nexists w \in L)\left[P_{\Sigma_a,\Sigma_o^s}(\chi(st)) \cap P_{\Sigma_a,\Sigma_o^s}(\chi(w)) \neq \emptyset) \wedge (\Sigma_f \notin w)\right].$$

Verification of Network diagnosability

- Basic idea: construct an augmented automaton G_a such that $L(G_a) = \chi(L(G))$

Verification of Network diagnosability

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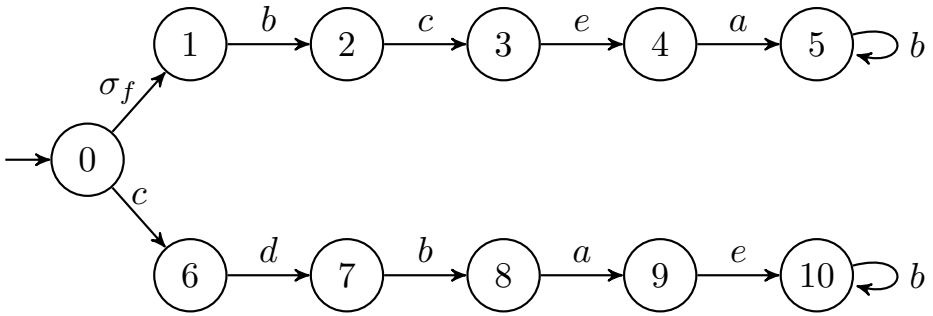
- Alves et al., (2021) proposes a construction for $G_a = (X_a, \Sigma_a, \delta_a, x_{a_0})$, whose general idea is as follows:
  - $x_a = (x, q)$
    ✓ x is the current state of G
    ✓ $q = \sigma_1 n_1 \sigma_1 n_2 \ldots \sigma_p n_p$
    where
    ✓ $\sigma_i \in \Sigma_o$: event occurrence
    ✓ n_i : counts the number of event occurrences (observable or unobservable) after the occurrence of σ_i
  - $x_a = (5, c2a0)$
    ✓ G is currently at 5 and ✓ either one unobservable event has occurred between the occurrences of c and a, ✓ or one observable event has occurred and its transmission has been successfully received at the diagnoser.

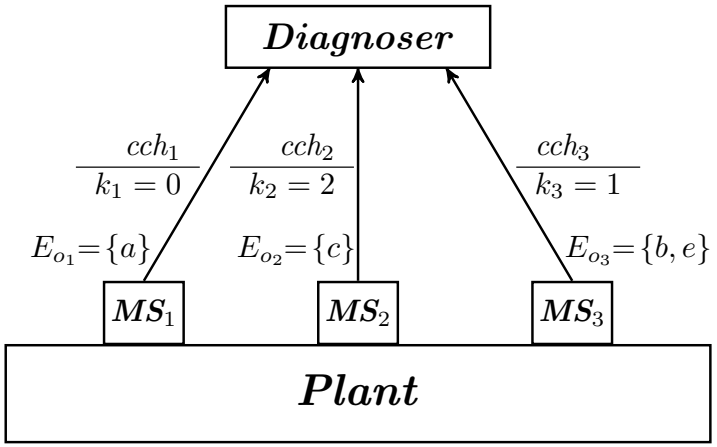
Back to the Motivation Example of Networked DES

- Automaton

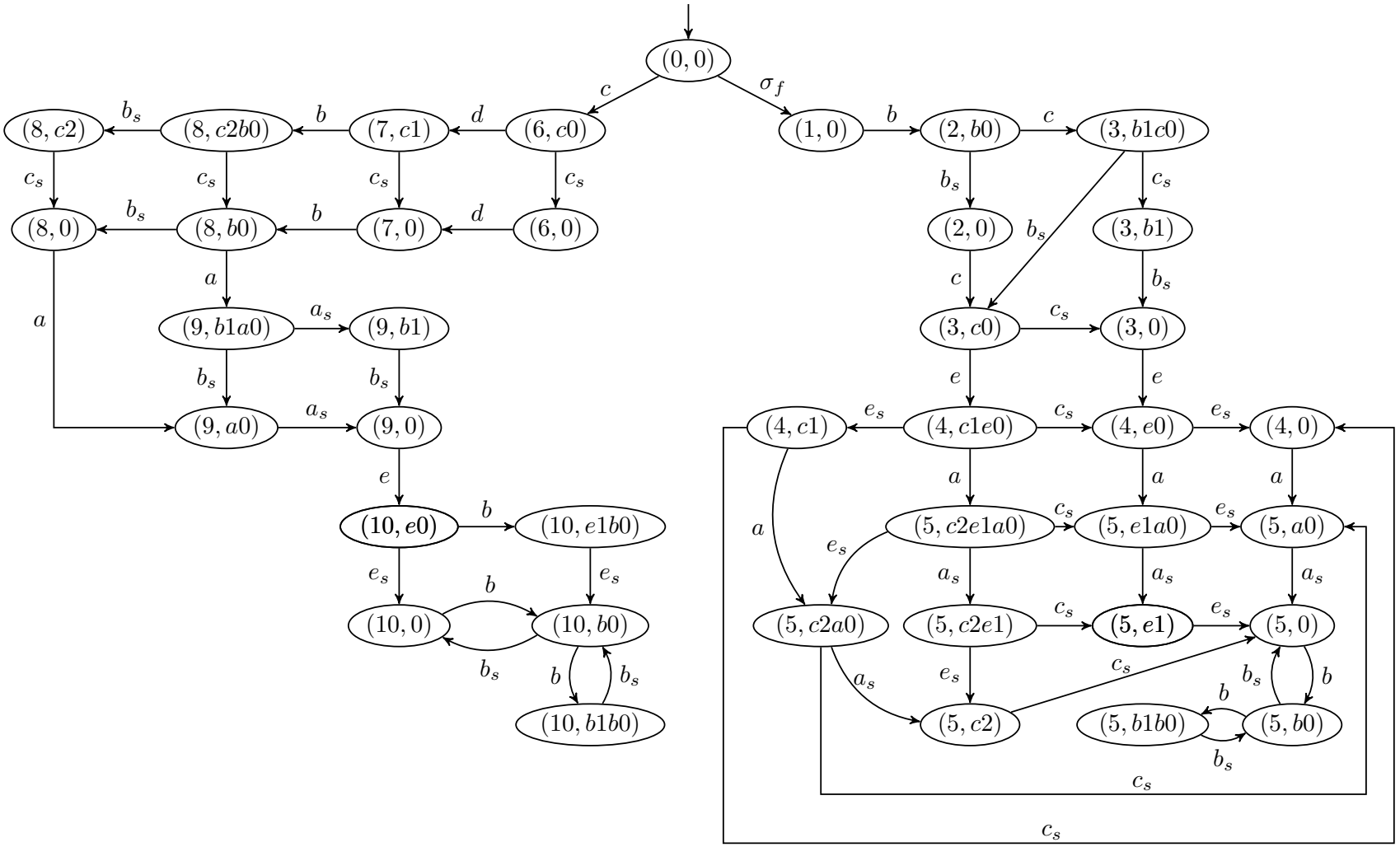


- $\Sigma = \{a, b, c, d, e, \sigma_f\}$, $\Sigma_f = \{\sigma_f\}$
- $\Sigma_o^s = \{a_s, b_s, c_s, e_s\}$
- $\vec{k} = [\ 0 \quad 2 \quad 1\ ]$

- Networked DES



Augmented automaton G_a



Verification of network diagnosability

- It can be performed with any verification algorithm applied on G_a assuming Σ_o^s as the set of observable events (Moreira et al., 2012, Viana & Basilio, 2019)

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- Loss of observation can also be taken into account by applying dilation to events $\sigma_s \in \Sigma_o^s$ that are subject to intermittent loss of observation
- $L(G)$ is not network diagnosable with respect to χ, P_{Σ_a,Σ_o^s} and σ_f.

VII. Conclusion

Concluding remarks

- We have restricted ourselves to the problem of diagnosability and diagnosis of monolithic DES

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- The augmentation approach adopted in the diagnosability of networked DES can be leveraged so as to allow other problems of networked DES, such as networked supervisory control or opacity enforcement, to be converted in standard problems, which can be solved with existing tools.

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- Robust diagnosis of DES is a lively research topic. There is still much to be done!

Acknowledgments

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- My son Renan Basilio, for helping me in the production of this presentation

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Robust Failure Diagnosis of Discrete Event Systems and Its Applications

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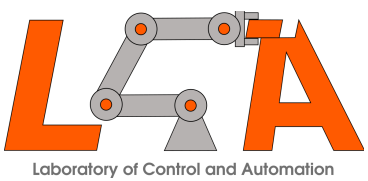
Workshop on Analysis and Control for Resilience of Discrete Event Systems



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