Adding uncertainty: unobservable events and observers for finite state automata and PNs

From observability to privacy and security in discrete event systems

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DIETI. UNIVERSITA' DEGLI STUDI DI NAPOLI FEDERICO II
DIPARTIMENTO DI INGEGNERIA ELETTRICA E DELLE TECNOLOGIE DELL'INFORMAZIONE

Course syllabus

1. Discrete Event Systems (DES), Languages and Automata
2. Petri nets (PNs) and their twofold representation to model DES
3. MILP and ILP formulations: logical conditions, binary variables “do everything", and variable connecting
4. **Adding uncertainty: unobservable events and observers for finite state automata and PNs**
5. Augmenting the observers: diagnosability of prefix-closed languages, diagnosers and the fault detection for finite state automata
6. Diagnosability and fault detection in PNs - Part I: graph-based approaches
7. Diagnosability and fault detection in PNs - Part II: algebraic approaches for bounded systems
8. Security issues in DES: non-interference and opacity
9. Non-interference and opacity enforcement
10. Open issues

Outline

1. The automata case
   - Source of nondeterminism in DES modelled as logic automata
   - Nondeterministic automata
   - Observer automata

2. The Petri nets case
   - Source of nondeterminism in DES modelled as Petri nets
   - Observer coverability graph
   - State estimation in labeled net systems

Lack of sensors

- The primary source of nondeterminism is the limitations of the sensors attached to the system
- This results in unobservable events that causes a change in the state that cannot be directly *measured*
- From the point of view of an *external observer*, the occurrence of an unobservable event is equivalent to the occurrence of the silent event ε

Unknown initial state

- Another way to model uncertainty about the system behaviour can be the lack of knowledge about the initial state
- Sometime it is assumed that the initial state of a DES is one among a set of states

- There can be also uncertainty on the effects due to the occurrence of an event. . .
- . . . or uncertainty due to undistinguishable events
- Both sources of uncertainty can be modelled as an event that, from a given state x, can cause transitions to more than one state
- In this case the state transition function becomes nondeterministic

$$f : X \times E \mapsto 2^X$$

Unobservable events

- When unobservable events are used to model the uncertain system, we can assume that $E = E_o \cup E_{uo}$ with
  - E_o the set of observable events
  - E_{uo} the set of unobservable events
  - $E_o \cap E_{uo} = \emptyset$
- For an *external* observer the occurrence of and event $e \in E_{uo}$ is equivalent to the occurrence of ε
- The projection function can be used to *filter out* the unobservable events from the words generated by the system

Projection

$$Pr : E^* \mapsto E_o^*$$

$$\begin{cases} Pr(\varepsilon) := \varepsilon & \\ Pr(e) := e & \text{if } e \in E_o \\ Pr(e) := \varepsilon & \text{if } e \in E_{uo} \\ Pr(we) := Pr(w)Pr(e) & w \in E^*\,, e \in E \end{cases}$$

- Given a word $w \in E^*$ generated by the uncertain model, its protection $Pr(w) \in E_o^*$ represents what an *external* observer can measure

- **Nondeterministic automata** permit to take into account all the sources of uncertainty that have been introduced so far
- A nondeterministic automata (**NDA**) is defined a 6-ple

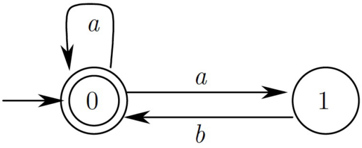
$$G_{nd} = (X\,, E \cup \{\varepsilon\}\,, f_{nd}\,, \Gamma\,, x_0\,, X_m)$$

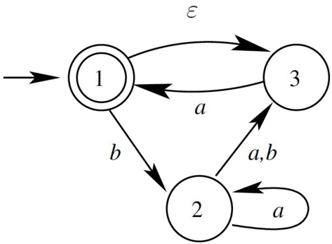
- The silent event ε is included in the set of events that drive the systems dynamic
- The transition function is defined as

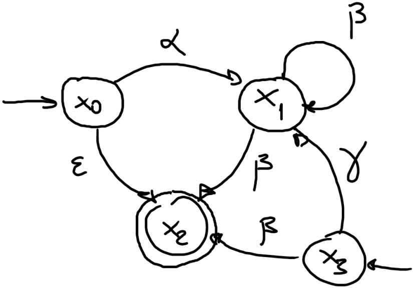
$$f_{nd} : X \times E \cup \{\varepsilon\} \mapsto 2^X$$

  that is $f_{nd}(x\,, e) \subseteq X$, when defined (uncertainty on the *conseguences* of a given event)
- The initial state may be itself a set of states, that is $x_0 \subseteq X$

Examples







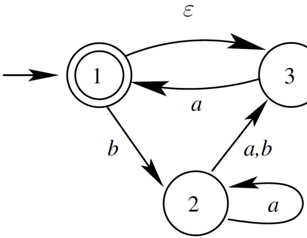
- For (logic) deterministic automata it is $f(x, \varepsilon) = x$ (in the deterministic case ε is used as *empty string*, rather than silent event)
- ε-reach of a state x

$\varepsilon R(x) = \{$all the states that can be reached from x following a silent transition$\}$

- **By definition it is** $x \in \varepsilon R(x)$
- If $B \in X$, then

$$\varepsilon R(B) = \bigcup_{x \in B} \varepsilon R(x)$$

- It is then possible to extend f_{nd} as
  - $f_{nd}^{ext}(x, \varepsilon) := \varepsilon R(x)$
  - $f_{nd}^{ext}(x, we) := \varepsilon R\left(\{z \in X \mid z \in f_{nd}(y, e) \text{ for some } y \in f_{nd}^{ext}(x, w)\}\right)$ with $w \in E^*$ and $e \in E$
- In general it is $f_{nd}(x, e) \subseteq f_{nd}^{ext}(x, e)$ with $e \in E \cup \{\varepsilon\}$



- $f_{nd}(1\,,\varepsilon) = \{3\}$; $f_{nd}^{ext}(1\,,\varepsilon) = \{1\,,3\}$
- $f_{nd}(3\,,a) = \{1\}$; $f_{nd}^{ext}(3\,,a) = \{1\,,3\}$
- $f_{nd}(3\,,a) = \{1\}$; $f_{nd}^{ext}(3\,,a) = \{1\,,3\}$
- $f_{nd}(2\,,a) = f_{nd}^{ext}(2\,,a) = \{2\,,3\}$
- $f_{nd}(2\,,b) = f_{nd}^{ext}(2\,,b) = \{3\}$
- $f_{nd}(1\,,bba) = \{1\}$; $f_{nd}^{ext}(1\,,bba) = \{1\,,3\}$

Languages of a NDA

Given the notion of extended transition function f_{nd}^{ext}, it is possible to define the languages generated and marked by a NDA

Language generated by G_{nd} – $\mathcal{L}(G_{nd})$

$$\mathcal{L}(G_{nd}) = \{w \in E^* \mid \exists\, x \in x_0 \text{ s.t. } f_{nd}^{ext}(x\,, w) \text{ is defined}\}$$

Language marked by G_nd – $\mathcal{L}_m(G_{nd})$

$$\mathcal{L}_m(G_{nd}) = \{w \in \mathcal{L}(G_{nd}) \mid \exists\, x \in x_0 \text{ s.t. } f_{nd}^{ext}(x\,, w) \cap X_m \neq \emptyset\}$$

Logic nondeterminism vs stochastic nondeterminism

- Here we are dealing with nondeterminism in the context of logic automata
- Nondeterminism can be associated also to the timing of event occurrences
- The inclusion of this further source of nondeterminism calls for the use of stochastic models. . .
  - Stochastic automata
  - Generalized Semi-Markov Process
  - Markov chains
  - . . .
- . . .which are out of the scope of these lectures :)

The observer

- The **observer** is a deterministic automaton that is equivalent to a given NDA
  - Equivalence in terms of languages
- If the NDA has finite state space, then also the observer will be a FSM
- The observer allows us to estimate the state of a NDA
- First results for fault detection have been obtained by extending the concept of observer
  - Be patient and wait for Lecture #5 by Prof. Basile

M. Sampath et al.
Diagnosability of Discrete-Event Systems
IEEE Transactions on Automatic Control, 1995

Let $G_{nd} = (X, E \cup \{\varepsilon\}, f_{nd}, x_0, X_m)$ be a NDA. Its observer is the deterministic automaton

$$Obs(G_{nd}) = \left(X_{obs}, E, f_{obs}, x_{0,obs}, X_{m,obs}\right)$$

where

- $x_{0,obs} := \varepsilon R(x_0)$
- For each $B \in X_{obs}$ and $e \in E$, the transition function of the observer is defined as

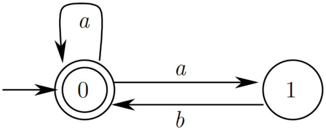
$$f_{obs}(B, e) := \varepsilon R\left(\{x \in X \mid \exists\, x_e \in B \text{ s.t. } x \in f(x_e, e)\}\right)$$

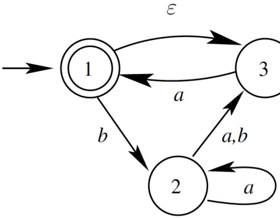
therefore the state $f_{obs}(B, e)$ is included in X_{obs}

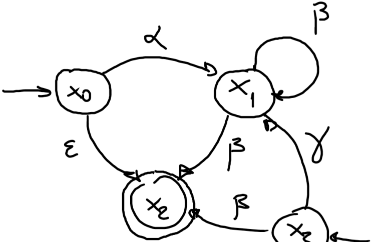
- $X_{m,obs} := \{B \in X_{obs} \mid B \cap X_m \neq \emptyset\}$

Examples

Let’s try to build the observer for these NDA!







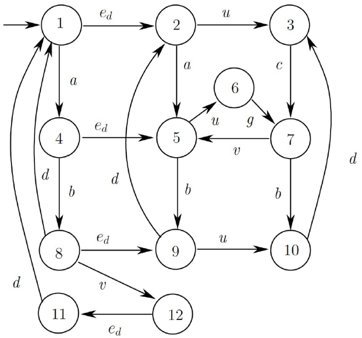
NDA and regular languages

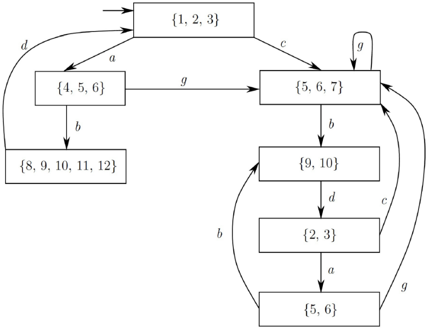
- Given a NDA G_{nd} with finite state space, its observer $Obs(G_{nd})$
  - has finite state space as well
  - is equivalent to G_{nd}
- Indeed, by definition it is
  - $\mathcal{L}(G_{nd}) = \mathcal{L}\left(Obs(G_{nd})\right)$
  - $\mathcal{L}_m(G_{nd}) = \mathcal{L}_m\left(Obs(G_{nd})\right)$
- **Finite-state NDA *speaks* regular languages as deterministic FSM**

Observer of deterministic automata with unobservable events

- The observer can be used to estimate the state of a partially observed **deterministic** automaton, i.e. a deterministic automaton with $E = E_o \cup E_{uo}$
- It is sufficient to *replace* the unobservable events with the silent transition $\rightarrow$ a NDA is derived from the deterministic automaton with unobservable events

Set of unobservable events $E_{uo} = e_d \, , u \, , v$





1. Unknown initial marking (state) – it applies also to unlabeled PNs
2. ε–free (λ–free) PNs $\rightarrow$ partial knowledge of the system dynamic or undistinguishable events
3. Unlabeled PNs with unobservable transitions $\rightarrow$ the unobservable transitions are mapped on the silent event ε $\rightarrow$ lack of sensors
4. Arbitrarily labeled PNs $\rightarrow$ both 2 and 3

Bounded PNs

- For bounded PNs with *relatively* small reachability set $R(N, \boldsymbol{m}_0)$, state estimation can be achieved by building the observer of the nondeterministic reachability graph
- However, specific approaches have been developed for PNs

The **observer coverability graph (OCG)** can be built to estimate the marking $\boldsymbol{m}$ of an unlabeled PNs under the following. . .

Assumptions

1. The initial marking $\boldsymbol{m}_0$ of the system is **completely unknown** (the only considered source of nondeterminism)
2. The structure of the net $N = (P, T, \mathbf{Pre}, \mathbf{Post})$ is known
3. All the transition occurrences can be observed $\rightarrow$ the system is unlabeled and $T_{uo} = \emptyset$

The OCG has been proposed in

A. Giua and C. Seatzu
Observability of Place/Transition Nets
IEEE Transactions on Automatic Control, 2002

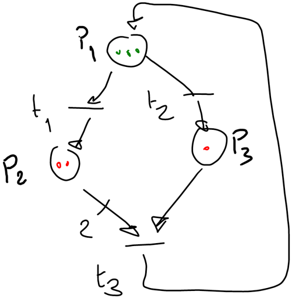
If $\sigma = t^1 t^2 \ldots$ is a sequence enabled under the (unknown) initial marking, i.e. $\boldsymbol{m}_0[\sigma\rangle$, then the following algorithm can be used to estimate the marking

Marking estimation by using the observation of the transition occurrences

1. Let the initial estimate be $\boldsymbol{\mu}_0 = \mathbf{0}$
2. Let $i = 1$
3. Wait until t^i fires
4. Set $\boldsymbol{\mu}_i'$ equal to

$$\boldsymbol{\mu}_i'(p) = \max\left(\boldsymbol{\mu}_{i-1}(p)\,, \mathbf{Pre}(p\,, t^i)\right)\,, \quad \forall\, p \in P$$

5. Let $\boldsymbol{\mu}_i = \boldsymbol{\mu}_i' + \boldsymbol{C}(\cdot\,, t^i)$
6. Let $i = i + 1$
7. Goto step 3



UNKNOWN INITIAL MARKING

$$m_0 = (3 \quad 2 \quad 1)^T$$

INITIAL ESTIMATION

$$\mu_0 = (0 \quad 0 \quad 0)^T$$

OBSERVED SEQUENCE

$$\sigma = t_3 t_2$$

$$\mu'_1 = (0 \quad 2 \quad 1)^T \Rightarrow \mu_1 = (1 \quad 0 \quad 0)^T$$

$$\mu'_2 = \mu_1 = (1 \quad 0 \quad 0)^T \Rightarrow \mu_2 = (0 \quad 1 \quad 0)^T$$

$m_0[\sigma > m$ WITH $m = (3 \quad 1 \quad 0)^T$

Marking complete sequences

Given a sequence $\sigma \in L(N, \boldsymbol{m}_0)$ with $\boldsymbol{m}_0 [\sigma\rangle \boldsymbol{m}$ and let $\boldsymbol{\mu}$ be the marking estimate built by means of the proposed algorithm after the occurrence of σ, then the following two definitions can be given

p-complete sequence

Given $p \in P$, the sequence σ is said to be p-complete if $\boldsymbol{\mu}(p) = \boldsymbol{m}(p)$

Marking complete sequence

The sequence σ is said to marking complete if it is p-complete for all $p \in P$

Observability of a net system

Marking observability

A system $\mathcal{S} = \langle N, \boldsymbol{m}_0 \rangle$ is said to be Marking Observable (MO) if there exists a marking complete sequence $\sigma \in L(N, \boldsymbol{m}_0)$

Strong marking observability

A system $\mathcal{S} = \langle N, \boldsymbol{m}_0 \rangle$ is said to be Strongly Marking Observable (SMO) in k steps, if

- $\forall\, \sigma \in L(N, \boldsymbol{m}_0)$ such that $|\sigma| \geq k$, σ is marking complete (every *sufficiently long* sequence is marking complete)
- $\forall\, \sigma \in L(N, \boldsymbol{m}_0)$ such that $|\sigma| < k$, either σ is marking complete or $\exists\, t \in T$ such that $\boldsymbol{m}_0 [\sigma t\rangle$ (*short* and non marking complete sequences can be always extended to marking complete ones)

Uniform observability of a net system

Uniform marking observability

A system $\mathcal{S} = \langle N, \boldsymbol{m}_0 \rangle$ is said to be Uniformly Marking Observable (uMO) if $\forall\, \boldsymbol{m} \in R(N, \boldsymbol{m}_0)$ the system $\langle N, \boldsymbol{m} \rangle$ is MO

Uniform strong marking observability

A system $\mathcal{S} = \langle N, \boldsymbol{m}_0 \rangle$ is said to be Uniformly Strongly Marking Observable (uSMO) in k steps, if $\forall\, \boldsymbol{m} \in R(N, \boldsymbol{m}_0)$ the system $\langle N, \boldsymbol{m} \rangle$ is SMO in k steps

Structural observability of a net

Structural marking observability

A **net** N is said to be Structurally Marking Observable (sMO) if $\langle N, \boldsymbol{m}_0 \rangle$ is MO $\forall\, \boldsymbol{m}_0 \in \mathbb{N}^m$

Structural strong marking observability

A net N is said to be Structurally Strongly Marking Observable (sSMO) in k steps, if $\langle N, \boldsymbol{m}_0 \rangle$ is SMO in k steps $\forall\, \boldsymbol{m}_0 \in \mathbb{N}^m$ (with k dependent on $\boldsymbol{m}_0$)

$$
\begin{array}{ccccc}
sSMO & \rightarrow & \underline{uSMO} & \rightarrow & SMO \\
\downarrow & & \downarrow & & \downarrow \\
sMO & \rightarrow & uMO & \rightarrow & MO
\end{array}
$$

uSMO guarantees that it is possible to estimate the current marking even if we start to observe the system not since the "beginning", i.e., since any $m \in R(N, m_0)$

The observer coverability graph

- The Observer coverability graph (OCG) permits to represent both the set of reachable markings of a net system (also unbounded), and an upper bound for the estimation error computed in accordance with the proposed algorithm
- Similarly to the coverability graph, the construction of the OCG is based the observer coverability **tree**

Observer coverability tree (taken from Giua & Seatzu, *IEEE TAC 2002*

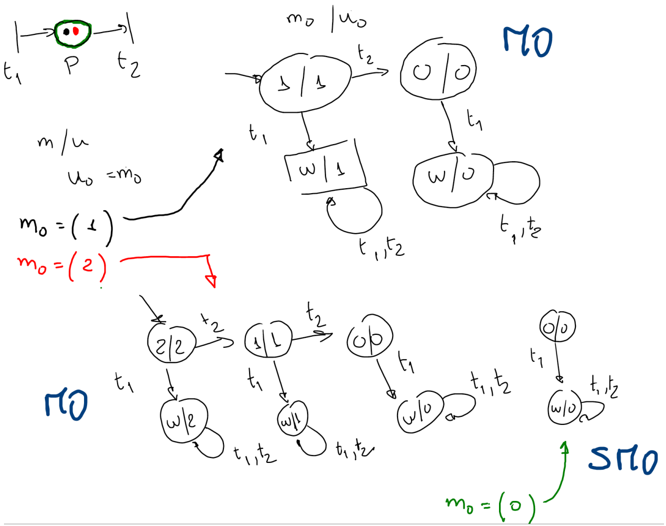
Algorithm 21 (Observer Coverability Tree)

1. Let $u_0 = M_0$. Label the initial node (M_0/u_0) as the root and tag it "new".
2. If "new" nodes exist, select a new node (M/u) and:
   - 2.1. If (M/u) is identical to a node labeled "old" then tag (M/u) "old" and go to step 2.
   - 2.2. If no transitions are enabled at M, tag (M/u) "dead" and go to step 2.
   - 2.3. For each transition t enabled at M do the following:
     - 2.3.1. $\forall p \in P$, if $M(p) = \omega$ then let $\tilde{M}(p) = M(p)$ and $\tilde{u}(p) = u(p)$, else let $\tilde{M}(p) = M(p) + C(p,t)$ and $\tilde{u}(p) = \min\{u(p), M(p) - Pre(p,t)\}$;
     - 2.3.2. on the path from the root to (M/u) if there exists a marking $\overline{M} \leq \tilde{M}$ and $\tilde{M} \neq \overline{M}$, i.e., $\overline{M}$ is covered by $\tilde{M}$, then let $\tilde{M}(p) = \omega$ for each p such that $\tilde{M}(p) > \overline{M}(p)$;
     - 2.3.3. introduce $(\tilde{M}/\tilde{u})$ as a node, draw an arc with label t from (M/u) to $(\tilde{M}/\tilde{u})$, and tag $(\tilde{M}/\tilde{u})$ "new".
   - 2.4 Tag (M/u) "old" and go to step 2. ■

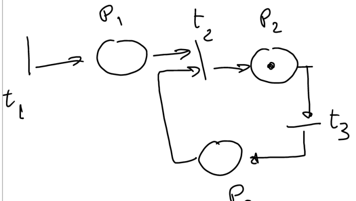
the u vector represents an upper bound for the estimation error $e = m - \mu$

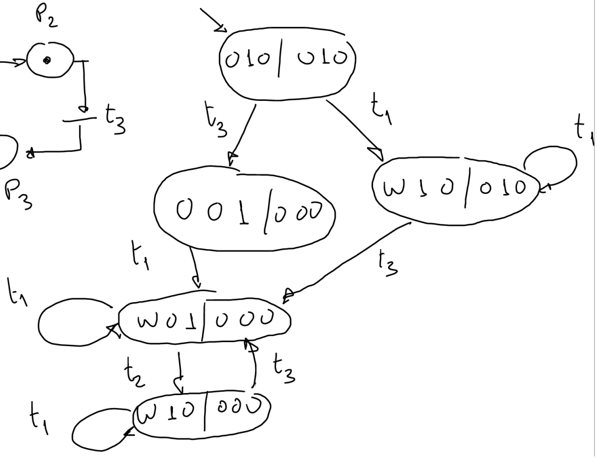
Use the OCG to check observability

1. A net system $\mathcal{S} = \langle N, \boldsymbol{m}_0 \rangle$ is **MO** if there exists a node in its OCG such that $\boldsymbol{u} = \mathbf{0}$
2. A net system $\mathcal{S} = \langle N, \boldsymbol{m}_o \rangle$ is **SMO** in k steps *iff* $\boldsymbol{u} = \mathbf{0}$ for each node $(\boldsymbol{m}, \boldsymbol{u})$ in the OCG such that
   - the node belongs to a cycle
   - the node is dead
3. Conditions to check uMO, uSMO, sMO and sSMO require additional *tools* (see Giua & Seatzu, *IEEE TAC*, 2002, for more details)


t1
P
t2
m0 | u0
m / u
u0 = m0
m0 = (1)
m0 = (2)
m0 = (0)
1 | 1
0 | 0
ω | 1
ω | 0
2 | 2
1 | 1
0 | 0
ω | 2
ω | 1
ω | 0
t1, t2
MO
SMO

$m_0 = (0 \ 1 \ 0)^T = v_0$



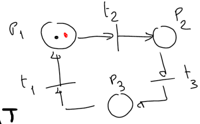


MO

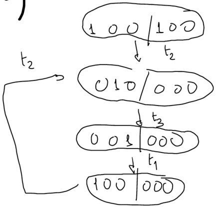
AND

SMO

OCG – Examples



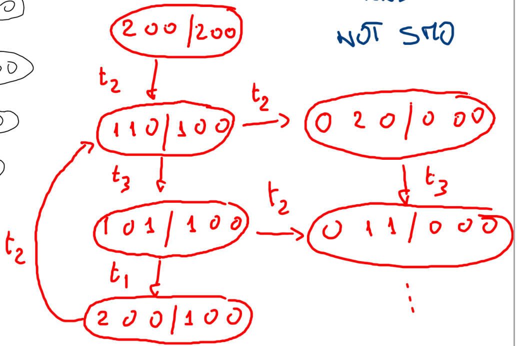
$m_0 = (1\ 0\ 0)^T$



SMO
AND
MO

$m_0 = (2\ 0\ 0)^T$

MO
AND
NOT SMO



- In ε-free labeled systems, an **event can map on more than one transition**, to model undistinguishable events or uncertain dynamic
- The concept of consistent markings with a given observer word $w \in E^*$ can be used to build a state observer that does not require the construction of the reachability graph, and thus works for both bounded and **unbounded** systems

Assumptions

1. The structure of the net $N = (P, N, \mathbf{Pre}, \mathbf{Post})$ is known
2. The initial marking $\boldsymbol{m}_0$ is known
3. The labeling function is ε-free and the events associated to transition firings can be observed

A. Giua, D. Corona, C. Seatzu
State estimation of λ-free labeled Petri nets with contact-free nondeterministic transitions
Discrete Event Dynamic Systems: Theory and Applications, 2005

Set of w-consistent markings $\mathcal{C}(w)$

Given an observed word w, the set of w-consistent markings $\mathcal{C}(w)$ is

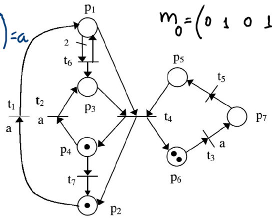
$$\mathcal{C}(w) = \left\{ \boldsymbol{m} \in \mathbb{N}^m \mid \exists \text{ a sequence } \sigma \in T^* \text{ such that } \boldsymbol{m}_0 \left[\sigma\right\rangle \text{ and } \ell(\sigma) = w \right\}$$

Algorithm to compute $\mathcal{C}(w)$

1. Let $w_0 = \varepsilon$ and $\mathcal{C}(w_0) = \boldsymbol{m}_0$
2. Let $i = 0$
3. Wait until a new event e is observed
4. Let $i = i + 1$
5. Let $w_i = w_{i-1}e$ and $\mathcal{C}(w_i) = \emptyset$
6. For all $\boldsymbol{m} \in \mathcal{C}(w_{i-1})$ do
   - For all t such that $\boldsymbol{m}\left[t\right\rangle$ and $\ell(t) = e$
     compute $\boldsymbol{m}' = \boldsymbol{m} + \boldsymbol{C}(\cdot\,, t)$ and let $\mathcal{C}(w_i) = \mathcal{C}(w_i) \cup \boldsymbol{m}'$
7. Goto step 3

- To compute the set of markings that are consistent with an observed word w with $|w| = k$, requires to compute the set of markings that are consistent with all prefixes of w
- Therefore, given a word w, each set $\mathcal{C}(\tilde{w})$ with $\tilde{w} \in \overline{\{w\}}$ must be explicitly enumerated
- However, note that the cardinality of the set of consistent markings may either increase or decrease as the length of the observed word increases

$\ell(t_1) = \ell(t_2) = \ell(t_3) = a$



$m_0 = (0\ 1\ 0\ 1\ 0\ 2\ 0)^T$

t_4, t_5, t_6, t_7 map on different events

$\Downarrow$

$E = \{a, t_4, t_5, t_6, t_7\}$

$C(\varepsilon) = \{m_0\}$

"a is observed" $(\Rightarrow w = a)$

$C(a) = \{(1\ 0\ 0\ 1\ 0\ 2\ 0)^T, (0\ 1\ 1\ 0\ 0\ 2\ 0)^T, (0\ 1\ 0\ 1\ 0\ 1\ 1)^T\}$

"a is observed again" $(\Rightarrow w = aa)$

$C(aa) = \{(1\ 0\ 1\ 0\ 0\ 2\ 0)^T, (0\ 1\ 1\ 0\ 0\ 1\ 1)^T, (0\ 1\ 0\ 1\ 0\ 0\ 2)^T, (1\ 0\ 0\ 1\ 0\ 1\ 1)^T\}$

"t_7 is observed" $(\Rightarrow w = aat_7)$

t_7 requires a token in p_4 to fire

$C(aat_7) = \{(0\ 2\ 0\ 0\ 0\ 0\ 2)^T, (1\ 1\ 0\ 0\ 0\ 1\ 1)^T\}$

Linear algebraic characterization of $\mathcal{C}(w)$

A **linear algebraic characterization of $\mathcal{C}(w)$** can be given, with a fixed number of constraints, when the following additional assumption is made

- *Nondeterministic* transitions are *contact*-free, i.e., being t_i and t_j non deterministic, it is

$$^\bullet t_i^\bullet \cap {}^\bullet t_j^\bullet = \emptyset \quad \text{and} \quad {}^\bullet t_i \cap t_i^\bullet = \emptyset$$

- The nondeterministic transition are those ones that share the event with other transitions
- **A linear characterization permits to avoid the enumeration of elements in $\mathcal{C}(w)$**
- **In some applications enumeration is not needed, while an algebraic characterization is sufficient (see also the diagnosability case in Lecture #7)**
- The details can be found in A. Giua, D. Corona, C. Seatzu, *Discrete Event Dynamic Systems: Theory and Applications*, 2005

A **linear algebraic characterization of $\mathcal{C}(w)$** has been given also in the case of labeled system whose transitions map on the silent event ε

Assumptions

1. The structure of the net $N = (P, N, \mathbf{Pre}, \mathbf{Post})$ is known
2. The initial marking $\boldsymbol{m}_0$ is known
3. The labels associated to the firing of transitions that do not map on ε can be observed, and a different label is associated to each of these transitions
4. The subnet induced by the *silent* transitions is *acyclic*
5. The subnet induced by the *silent* transitions is *backward conflict-free*, i.e., any two distinct silent transitions have no common output place

- Assumption 3 prevent to model undistinguishable events and some uncertainty on the dynamic
- The details can be found in

A. Giua, C. Seatzu, D. Corona
Marking Estimation of Petri Nets With Silent Transitions
IEEE Transactions on Automatic Control, 2007

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Adding uncertainty: unobservable events and observers for finite state automata and PNs

From observability to privacy and security in discrete event systems

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