Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Distributed Computing

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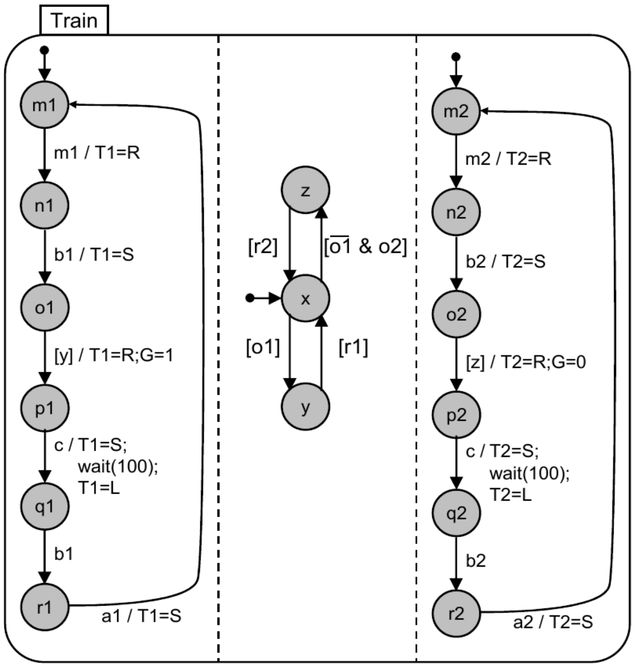
# Discrete Event Systems

## Solution to Exercise Sheet 6

## 1 The Winter Train Problem

We can model each train individually and combine the corresponding sub-states using an AND-super-state, see the figure below. Additionally, in order to "synchronize" the trains, a third sub-state is needed (shown in the middle) which implements a mutual exclusion: For instance, if there is no train between Stans and Engelberg and if train 1 is in state c1, T1 can enter the critical section and train 2 has to wait. (Notice that if both trains are in states c1 and c2 respectively, T1 has priority.)




- The trains start at their states m1 and m2. When m1 (m2) is pressed, then train 1 (2) moves to the right in n1 (n2), until it reaches the switch, where it stops in state o1 (o2).
- Now the "middle"-state can change its state to either y or z, depending on which train got there first. If train 1 (2) arrives first, then the state is changed to y (z) and train 1 (2) can move to state p1 (p2) while moving right.

- After arriving at the station Engelberg, the train waits for 100s, then moves to the left and switches to state q1 (q2) – until it hits the switch at b1 (b0), upon which the "middle"-state can change again – and the train continues to its original station, where it stops.

Positions of the trains (train 1 ; train 2):

- m1: Lucerne ; m2: Sarnen
- n1: Between Lucerne and the switch ; n2: Between Sarnen and the switch
- o1: At the left side of the switch ; o2: At the left side of the switch
- p1: Between the switch and Engelberg ; p2: Between the switch and Engelberg
- q1: Between Engelberg and the switch ; q2: Between Engelberg and the switch
- r1: Between the switch and Lucerne ; Between the switch and Sarnen

# 2 Structural Properties of Petri Nets and Token Game

**a)** The pre and post sets of a transition are defined as follows:

- pre set: $\bullet t := \{p \mid (p,t) \in C\}$
- post set: $t\bullet := \{p \mid (t,p) \in C\}$,

the pre and post sets of a place are defined analogously.

For the petri net $N_1$ we obtain the following sets:

$$\begin{aligned} \bullet t_5 &= \{p_5, p_9\}, \qquad & t_5\bullet &= \{p_6\} \\ \bullet t_8 &= \{p_8\}, & t_8\bullet &= \{p_{10}, p_5\} \\ \bullet p_3 &= \{t_2\}, & p_3\bullet &= \{t_3\} \end{aligned}$$

**b)** A transition is enabled if all places in its pre set contain enough tokens. In the case of $N_1$, which has only unweighted edges, one token per place suffices. When $t_2$ fires, it consumes one token out of each place in the pre set of $t_2$ and produces one token on each place in the post set of $t_2$. Hence, the firing of $t_2$ produces one token on place $p_3$ and $p_9$ each, the one on $p_2$ is consumed. After this, $t_5$ is enabled because both $p_9$ and $p_5$ hold one token. However, $t_3$ is not enabled because $p_3$ contains a token but $p_{10}$ does not.

**c)** Before $t_2$ fires there are two tokens in $N_1$, one on $p_2$ and $p_5$ each. Directly afterwards, there are tokens on places $p_3$, $p_9$ und $p_5$.

**d)** A token traverses the upper cycle until $t_2$ fires. Then one token remains on $p_3$ and waits, and another one is produced in $p_9$, which enables transition $t_5$. When $t_5$ consumes the tokens on $p_9$ and $p_5$ and produces a token on $p_6$, this one can traverse the lower cycle until $t_8$ is enabled. One token now remains on $p_5$ and waits, another one enables $t_3$, because there is still one token on $p_3$. Now one token traverses the upper cycle again until $t_2$ is enabled, and so on.

Hence, this petri net models two processes which always appear alternately.

The reachability graph $RG(P, \vec{s}_0)$ of a petri net $P$ is a quadruple $(\mathbb{S}, \mathbb{S}_0, Act, \mathbb{E})$ such that

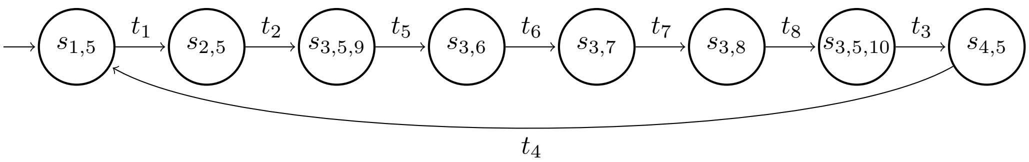
- $\mathbb{S}$ is the set of reachable states of $P$ starting from $\vec{s}_0$
- $\mathbb{S}_0 := \{\vec{s}_0\}$ is the start state of $P$
- $Act$ is the set of transition labels
- $\mathbb{E} \subseteq \mathbb{S} \times Act \times \mathbb{S}$ is the set of edges such that $\mathbb{E} = \{\big(\vec{s}, t, \delta(\vec{s}, t)\big) \mid \vec{s} \in \mathbb{S} \wedge t \in T \wedge \vec{s} \triangleright t\}$

Usually the states of the petri net are denoted by vectors such that the $i$-th position in the vector indicates the number of tokens on place $p_i$ of the petri net. So, for example, the starting state $\vec{s}_0$ of $N_1$, in which the places $p_1$ and $p_5$ hold one token each, is denoted by $\vec{s}_0 = (1,0,0,0,1,0,0,0,0,0)$. Hence, the reachability graph looks as follows:

$$\begin{aligned}
\mathbb{S} = \{ \quad & (1,0,0,0,1,0,0,0,0,0), (0,1,0,0,1,0,0,0,0,0), (0,0,1,0,1,0,0,0,1,0),\\
& (0,0,1,0,0,1,0,0,0,0), (0,0,1,0,0,0,1,0,0,0), (0,0,1,0,0,0,0,1,0,0),\\
& (0,0,1,0,1,0,0,0,0,1), (0,0,0,1,1,0,0,0,0,0) \quad \},\\[1em]
\mathbb{S}_0 = \{ \quad & (1,0,0,0,1,0,0,0,0,0) \quad \},\\[1em]
Act = \{ \quad & t_1, t_2, t_3, t_4, t_5, t_6, t_7, t_8, t_9, t_{10} \quad \},\\[1em]
\mathbb{E} = \{ \quad & \big((1,0,0,0,1,0,0,0,0,0), t_1, (0,1,0,0,1,0,0,0,0,0)\big),\\
& \big((0,1,0,0,1,0,0,0,0,0), t_2, (0,0,1,0,1,0,0,0,1,0)\big),\\
& \big((0,0,1,0,1,0,0,0,1,0), t_5, (0,0,1,0,0,1,0,0,0,0)\big),\\
& \big((0,0,1,0,0,1,0,0,0,0), t_6, (0,0,1,0,0,0,1,0,0,0)\big),\\
& \big((0,0,1,0,0,0,1,0,0,0), t_7, (0,0,1,0,0,0,0,1,0,0)\big),\\
& \big((0,0,1,0,0,0,0,1,0,0), t_8, (0,0,1,0,1,0,0,0,0,1)\big),\\
& \big((0,0,1,0,1,0,0,0,0,1), t_3, (0,0,0,1,1,0,0,0,0,0)\big),\\
& \big((0,0,0,1,1,0,0,0,0,0), t_4, (1,0,0,0,1,0,0,0,0,0)\big) \quad \}.
\end{aligned}$$

For better legibility we denote the states in such a way that the index contains the places that hold a token in this state, for example $\vec{s}_0 = (1,0,0,0,1,0,0,0,0,0) = s_{1,5}$.

Then the reachability graph can also be specified as follows:



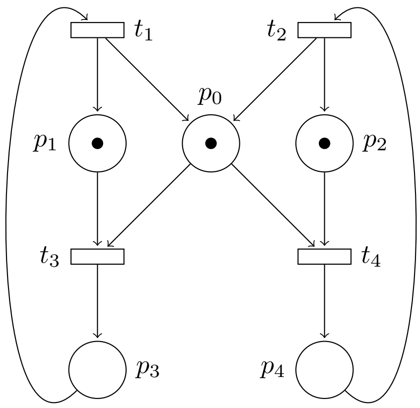

## 3 Basic Properties of Petri Nets

A petri net is $k$-bounded, if there is no fire sequence that makes the number of tokens in one place grow larger than $k$. It is obvious that petri net $N_2$ is 1-bounded if $k \leq 1$. This holds because in the initial state there is only one token in the net, and in the case $k \leq 1$ no transition increases the number of tokens in $N_2$. If $k \geq 2$, the number of tokens in $p_1$ can grow infinitely large by repeatedly firing $t_1$, $t_3$ and $t_4$. So, the petri net $N_2$ is unbounded for $k \geq 2$.

A petri net is deadlock free if no fire sequence leads to a state in which no transition is enabled. If $k = 0$, $N_2$ is not deadlock-free. The fire sequence $t_1, t_3, t_4$ causes the only existing token to be consumed and hence, there is no enabled transition any more. For $k \geq 1$, however, no deadlock can occur.

## 4 Mutual Exclusion

For each process we introduce two places ($p_1$, $p_2$, $p_3$ und $p_4$) representing the process within the normal program execution ($p_1, p_2$) as well as in the critical section ($p_3, p_4$). For each process, we have a token indicating which section of the program currently is executed. Additionally, we introduce a place $p_0$ representing the mutex variable. If the mutex variable is 0, then we have a token at $p_0$. We have to make sure that a process can only enter its critical section if there is a token at the mutex place. The resulting petri net looks as follows.




Assume that initially, both processes are in an uncritical section (in the petri net, this is denoted by a token in place $p_1$ and $p_2$ respectively). A process can only enter its critical section ($p_3/p_4$) if there is a token at $p_0$. In this case, the token is consumed when entering the critical section. A new mutex token at $p_0$ is not created until the process leaves its critical section. Hence, both processes exclude each other mutually from the concurrent access to the critical section.