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An Event/Non-Event Approach

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The Quaternality of Simulation: An Event/Non-Event Approach

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Abstract. Dualizing marked Petri nets results in *tokens for transitions (t-tokens).* A marked transition can strictly not be enabled, even if there are sufficient "enabling" tokens *(p-tokens)* on its input places. On the other hand, t-tokens can be moved by the *firing of places.* This permits flows of t-tokens which describe sequences of *non-events.* Their benefit to simulation is the possibility to model (and observe) causes and effects of non-events, e.g. if something is broken down.

1 Introduction

The first time I met the concept of "quaternality" was when I read a paper by Gottschalk [1], where quaternality is a logical concept that describes four variations of a logical formula. For example

$$\begin{aligned} f &= a \wedge b \wedge (\neg a \vee \neg b \vee c) \wedge \neg c \\ &\quad \text{is the original formula;} \\ f^C &= \neg a \wedge \neg b \wedge (a \vee b \vee \neg c) \wedge c \\ &\quad \text{is the "contradual" of } f; \\ f^D &= a \vee b \vee (\neg a \wedge \neg b \wedge c) \vee \neg c \\ &\quad \text{is the "dual" of } f; \\ f^N &= \neg a \vee \neg b \vee (a \wedge b \wedge \neg c) \vee c \\ &\quad \text{is the "negational" of } f; \end{aligned}$$

f^C is obtained from f by interchanging negated and non-negated variables,
f^D by interchanging $\wedge$ and $\vee$,
f^N by doing both: $f^N = f^{CD} = f^{DC}$.

In [1] one finds lots of rules like

$$\begin{gathered} f^{CC} = f^{DD} = f^{NN} = f \\ f^{DN} = f^{ND} = f^C \\ f^{NC} = f^{CN} = f^D \\ f^N = \neg f, f^C = \neg f^D, f^D = \neg f^C \qquad \text{etc.} \end{gathered}$$

Moreover, the quaternality is extended to first order logic and modal logic. So, without any doubt, [1] is a most interesting paper that inspired me to convey the concept of quaternality to Petri net theory.

In terms of simulation, one finds the following four variations for simulation processes. Let p be a usual simulation process that answers the question

something is the case; which are the consequences?

Then

p^C (answers the question)
something is the case; which are the reasons?

p^N (answers the question)
something is <u>not</u> the case; which are the consequences?

p^D (answers the question)
something is <u>not</u> the case; which are the reasons?

The aim of this paper is to analyze these four variations of simulational processes, to understand their interdependencies, and to give an impression of their practical significance.

The paper is organized as follows. Section 2 contains preliminaries of place/transition nets (2.1, 2.2) and the definition of the duality of structure and behavior (2.3, 2.4). Section 3 is a short introduction into the quaternality of place/transition nets. In section 4 the use of quaternality is shown by use of a small but informative example where emphasis is placed on describing cause and effect of events and non-events. Section 5 is a continuation to section 4 with examples on the basis of fault trees. Section 6, finally, is to summarize and to give an outlook on further work.

I am greatly indebted to Kerstin Susewind for valuable theoretical and practical assistance.

2 The Duality of Place/Transition Nets

In this section some basics of place/transition nets are introduced. After that the dual place/transition net is presented as the fundamental concept for defining the "quaternality".

2.1 Place/Transition Nets

Definition 1. *1. A* place/transition net (p/t-net) *is a quadruple* $\mathcal{N} = (P,T,F,W)$ *where*

- *(a) P and T are finite, non empty, and disjoint sets. P is the set of* places *(in the figures represented by circles). T is the set of* transitions *(in the figures represented by squares).*

   (b) $F \subseteq (P \times T) \cup (T \times P)$ *is the set of directed* arcs.
   (c) $W : F \to \mathbb{N}_0 \backslash \{0\}$ *assigns a* weight *to every arc.*
   In case of $W : F \to \{1\}$, *we will write* $\mathcal{N} = (P, T, F)$ *as an abridgement.*
2. *The* preset (postset) *of a node* $x \in P \cup T$ *is defined as* ${}^\bullet x = \{y \in P \cup T | (y, x) \in F\}$ $(x^\bullet = \{y \in P \cup T | (x, y) \in F\})$.
   The preset (postset) *of a set* $H \subseteq P \cup T$ *is* ${}^\bullet H = \bigcup_{x \in H} {}^\bullet x$ $(H^\bullet = \bigcup_{x \in H} x^\bullet)$.
   For all $x \in P \cup T$ *it is assumed that* $|{}^\bullet x| + |x^\bullet| \geqq 1$ *holds; i.e. there are* no isolated nodes.
3. *A place p (transition t) is* shared *iff* $|{}^\bullet p| \geqq 2$ or $|p^\bullet| \geqq 2$ $(|{}^\bullet t| \geqq 2$ or $|t^\bullet| \geqq 2)$.
4. *A place p is an* input (output) boundary place *iff* ${}^\bullet p = \emptyset$ $(p^\bullet = \emptyset)$.
5. *A transition t is an* input (output) boundary transition *iff* ${}^\bullet t = \emptyset$ $(t^\bullet = \emptyset)$.

□

Definition 2. *Let* $\mathcal{N} = (P, T, F, W)$ *be a p/t-net.*

1. *A* marking *of* $\mathcal{N}$ *is a mapping* $M : P \to \mathbb{N}_0$. $M(p)$ *indicates the number of* tokens *on p under M.* $p \in P$ *is* marked *by M iff* $M(p) \geqq 1$. $H \subseteq P$ *is* marked *by M iff at least one place* $p \in H$ *is marked by M. Otherwise p and H are* unmarked, *respectively.*
2. *A transition* $t \in T$ *is* enabled *by M, in symbols* $M[t\rangle$, *iff*
$$\forall p \in {}^\bullet t : M(p) \geqq W((p, t)).$$
3. *If* $M[t\rangle$, *the transition t may* fire *or* occur, *thus leading to a new marking* M', *in symbols* $M[t\rangle M'$, *with*
$$M'(p) := \begin{cases} M(p) - W((p,t)) & \text{if } p \in {}^\bullet t \backslash t^\bullet \\ M(p) + W((t,p)) & \text{if } p \in t^\bullet \backslash {}^\bullet t \\ M(p) - W((p,t)) + W((t,p)) & \text{if } p \in {}^\bullet t \cap t^\bullet \\ M(p) & \text{otherwise} \end{cases}$$
   for all $p \in P$.
4. *The set of all markings* reachable *from a marking* M_0, *in symbols* $[M_0\rangle$, *is the smallest set such that*
$$\begin{array}{l} M_0 \in [M_0\rangle \\ M \ \in [M_0\rangle \wedge M[t\rangle M' \Longrightarrow M' \in [M_0\rangle. \end{array}$$
   $[M_0\rangle$ *is also called the set of* follower markings *of* M_0.
5. $\sigma = t_1 \dots t_n$ *is a* firing sequence *or* occurence sequence *for transitions* $t_1, \dots, t_n \in T$ *iff there exist markings* $M_0, M_1, \dots, M_n$ *such that*
$$M_0[t_1\rangle M_1[t_2\rangle \dots [t_n\rangle M_n \text{ holds;}$$
   in short $M_0[\sigma\rangle M_n$. $M_0[\sigma\rangle$ *denotes that* σ starts from M_0. *The* firing count $\overline{\sigma}(t)$ *of t in* σ *indicates how often t occurs in* σ. *The (column) vector of firing counts is denoted by* $\overline{\sigma}$.
6. *The pair* $(\mathcal{N}, M_0)$ *for some marking* M_0 *of* $\mathcal{N}$ *is a p/t-system or a* marked *p/t-net.* M_0 *is the* initial marking.

7. *A marking* $M \in [M_0\rangle$ *is* reproducible *iff there exists a marking* $M' \in [M\rangle$, $M' \neq M$ *s.t.* $M \in [M'\rangle$. ☐

Definition 3. *Let* $\mathcal{N} = (P, T, F, W)$ *be a p/t-net and* M_0 *a marking of* $\mathcal{N}$.

1. *A transition* $t \in T$ *is* live under M_0 *or in* $(\mathcal{N}, M_0)$ *iff* $\forall M \in [M_0\rangle\ \exists M' \in [M\rangle : M'[t\rangle$.
2. *A transition* t *is* dead *in* $(\mathcal{N}, M_0)$ *iff* $\forall M \in [M_0\rangle : t$ *is not enabled.*
   $(\mathcal{N}, M_0)$ *or* M_0 *is* dead *iff* $\nexists t \in T : M_0[t\rangle$.
3. $(\mathcal{N}, M_0)$ *or* M_0 *is* weakly live *(deadlock-free) iff* $\forall M \in [M_0\rangle\ \exists t \in T : M[t\rangle$.
4. $(\mathcal{N}, M_0)$ *or* M_0 *is* live *iff* $\forall t \in T : t$ *is live under* M_0.
5. *A place* $p \in P$ *is* bounded under M_0 *iff* $\exists k \in \mathbb{N}_0\ \forall M \in [M_0\rangle : M(p) \leqq k$.
   $(\mathcal{N}, M_0)$ *or* M_0 *is* bounded *iff* $\forall p \in P : p$ *is bounded under* M_0.
6. *A place* p *is* markable *in* $(\mathcal{N}, M_0)$ *iff* $\exists M \in [M_0\rangle : M(p) > 0$.
   A set $A \subseteq P$ *is* markable *in* $(\mathcal{N}, M_0)$ *iff* $\exists p \in A : p$ *is markable in* $(\mathcal{N}, M_0)$. ☐

2.2 Place Vectors and Transition Vectors

Definition 4. *Let* $\mathcal{N} = (P, T, F, W)$ *be a p/t-net.*

1. $\mathcal{N}$ *is* pure *iff* $\nexists (x, y) \in (P \times T) \cup (T \times P) : (x, y) \in F \wedge (y, x) \in F$.
2. *A* place vector *($|P|$-vector) is a column vector* $v : P \longrightarrow \mathbb{Z}$ *indexed by* P.
3. *A* transition vector *($|T|$-vector) is a column vector* $w : T \longrightarrow \mathbb{Z}$ *indexed by* T.
4. *The* incidence matrix *of* $\mathcal{N}$ *is a matrix* $[\mathcal{N}] : P \times T \longrightarrow \mathbb{Z}$ *indexed by* P *and* T *such that*

$$[\mathcal{N}](p, t) := \begin{cases} -\,W((p, t)) & \text{if } p \in {}^\bullet t \setminus t^\bullet \\ \,W((t, p)) & \text{if } p \in t^\bullet \setminus {}^\bullet t \\ -\,W((p, t)) + W((t, p)) & \text{if } p \in {}^\bullet t \cap t^\bullet \\ 0 & \text{otherwise} \end{cases}$$

Column vectors whose entries are all 0 (1) are denoted by $\mathbf{0}$ $(\mathbf{1})$. v^t *and* A^t *are the* transposes *of a vector* v *and a matrix* A*, respectively. The columns of* $[\mathcal{N}]$ *are* $|P|$*-vectors, the rows of* $[\mathcal{N}]$ *are transposes of* $|T|$*-vectors. Markings are representable as* $|P|$*-vectors, firing count vectors as* $|T|$*-vectors. The* $|P|$*-vector* $\mathbf{0}$ *denotes the empty marking* $\emptyset$. ☐

Definition 5. *Let* i *be a place vector and* j *a transition vector of* $\mathcal{N} = (P, T, F, W)$.

1. i *is a* place invariant (p-invariant) *iff* $i \neq \mathbf{0}$ *and* $i^t \cdot [\mathcal{N}] = \mathbf{0}^t$
2. j *is a* transition invariant (t-invariant) *iff* $j \neq \mathbf{0}$ *and* $[\mathcal{N}] \cdot j = \mathbf{0}$

3. $\|i\| = \{p \in P | i(p) \neq 0\}$ *and* $\|j\| = \{t \in T | j(t) \neq 0\}$ *are the* supports *of* i *and* j*, respectively.*
4. *A p-invariant* i *(t-invariant* j*) is*
   - non-negative *iff* $\forall p \in P : i(p) \geqq 0$ $(\forall t \in T : j(t) \geqq 0)$
   - positive *iff* $\forall p \in P : i(p) > 0$ $(\forall t \in T : j(t) > 0)$
   - minimal *iff* i (j) *is non-negative*
     and $\nexists$ *p-invariant* i'*:* $\|i'\| \subsetneqq \|i\|$ *(*$\nexists$ *t-invariant* j'*:* $\|j'\| \subsetneqq \|j\|$*)*
     and the greatest common divisor of all entries of i (j) *is 1*
5. *The* net representation $\mathcal{N}_i = (P_i, T_i, F_i, W_i)$ of a p-invariant i *is defined by*

$$\begin{aligned} &P_i := \|i\| \\ &T_i := {}^\bullet P_i \cup P_i^\bullet \\ &F_i := F \cap ((P_i \times T_i) \cup (T_i \times P_i)) \\ &W_i \textit{ is the restriction of } W \textit{ to } F_i. \end{aligned}$$

   The net representation $\mathcal{N}_j = (P_j, T_j, F_j, W_j)$ of a t-invariant j *is defined by*

$$\begin{aligned} &T_j := \|j\| \\ &P_j := {}^\bullet T_j \cup T_j^\bullet \\ &F_j := F \cap ((P_j \times T_j) \cup (T_j \times P_j)) \\ &W_j \textit{ is the restriction of } W \textit{ to } F_j. \end{aligned}$$

6. $\mathcal{N}$ *is* covered *by a p-invariant* i *(t-invariant* j*) iff* $\forall p \in P : i(p) \neq 0$ $(\forall t \in T : j(t) \neq 0)$ □

Proposition 1. *Let* $(\mathcal{N}, M_0)$ *be a p/t-system,* i *a p-invariant; then*

$$\forall M \in [M_0\rangle : i^t \cdot M = i^t \cdot M_0.$$ □

Proposition 2. *Let* $(\mathcal{N}, M_0)$ *be a p/t-system,* $M_1 \in [M_0\rangle$ *a follower marking of* M_0*, and* σ *a firing sequence that reproduces* $M_1 : M_1[\sigma\rangle M_1$*; then the firing count vector* $\overline{\sigma}$ *of* σ *is a t-invariant.* □

Definition 6. *Let* $\mathcal{N} = (P, T, F, W)$ *be a p/t-net,* M_0 *a marking of* $\mathcal{N}$*, and* $r \geqq \mathbf{0}$ *a* $|T|$*-vector;* r *is* realizable in $(\mathcal{N}, M_0)$ *iff there exists a firing sequence* σ *with* $M_0[\sigma\rangle$ *and* $\overline{\sigma} = r$*.* □

Proposition 3. *Let* $\mathcal{N} = (P, T, F, W)$ *be a p/t-net,* M_1 *and* M_2 *markings of* $\mathcal{N}$*, and* σ *a firing sequence s.t.* $M_1[\sigma\rangle M_2$*; then the linear relation*

$$M_1 + [\mathcal{N}]\overline{\sigma} = M_2 \text{ holds.}$$ □

2.3 Dualizing the Structure

Definition 7. (**Dual p/t-net**) *Let* $\mathcal{N} = (P, T, F, W)$ *be a p/t-net with*

- $P \neq \emptyset$ *(set of places)*
- $T \neq \emptyset$ *(set of transitions)*
- $P \cap T = \emptyset$
- $F \subseteq (P \times T) \cup (T \times P)$ *(Flow relation, set of arcs)*
- $W : F \rightarrow \mathbb{N}_0 \backslash \{0\}$ *(arc weight function)*;

the p/t-net $\mathcal{N}^d = (P^d, T^d, F^d, W^d)$ *is the* dual net *of* $\mathcal{N}$ *iff*

- $P^d = T$
- $T^d = P$
- $F^d = F^{-1} = \{(y, x) | (x, y) \in F\}$
- $W^d((y, x)) = W((x, y))$ *for all* $(x, y) \in F$

□

Roughly speaking, the dual net $\mathcal{N}^d$ of a p/t-net $\mathcal{N}$ is developed by transposing the incidence matrix $[\mathcal{N}]$ of $\mathcal{N}$. By that, places and transitions are exchanged and the direction of all arcs is changed. If $\mathcal{N}$ is marked, the tokens remain on their places and become transition tokens that way.

Proposition 4. (trivial)

(a) $[\mathcal{N}^d] = [\mathcal{N}]^t$
(b) p-invariants (t-invariants) of $\mathcal{N}^d$ *are*
t-invariants (p-invariants) of $\mathcal{N}$ □

Example 1. Figure 1 shows a p/t-net $\mathcal{N}$ and the dual net $\mathcal{N}^d$. Figure 2 shows the corresponding incidence matrices $[\mathcal{N}]$ and $[\mathcal{N}^d]$. □

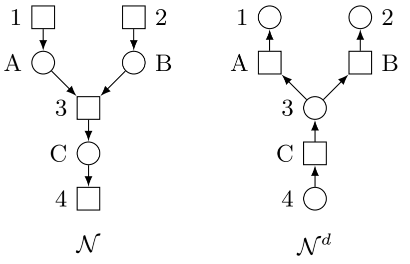


Fig. 1. P/t-nets $\mathcal{N}$ and $\mathcal{N}^d$

$[\mathcal{N}]$	1	2	3	4
A	1		−1	
B		1	−1	
C			1	−1

$[\mathcal{N}^d]$	A	B	C
1	1		
2		1	
3	−1	−1	1
4			−1

Fig. 2. Incidence matrices $[\mathcal{N}]$ and $[\mathcal{N}^d]$

2.4 Dualizing the Behavior

For dualizing the behavior, one needs an extension to nets with markings. The most obvious extension is to leave the tokens (place tokens, p-tokens) on their places. When the places are converted into transitions, the p-tokens are converted into transition tokens (t-tokens).

Remark 1. When marked nets are dualized, a second sort of tokens arises, namely t-tokens *as markings of transitions.*

Before defining all that formally, an introducing example might be advisable. In the figures, p-tokens are drawn as small circles (as usual) and t-tokens as small squares.

Example 2. Figure 3 shows four marked p/t-nets (cf. Fig. 1). In $\mathcal{N}$ $M_0[3\rangle M_1$ holds, i.e. M_1 follows from M_0 by firing transition 3. Now, we *demand* $M_0^d[3\rangle M_1^d$ also in $\mathcal{N}^d$, i.e. M_1^d follows from M_0^d by firing place 3. So places *fire backwards (against the arc direction).* ☐

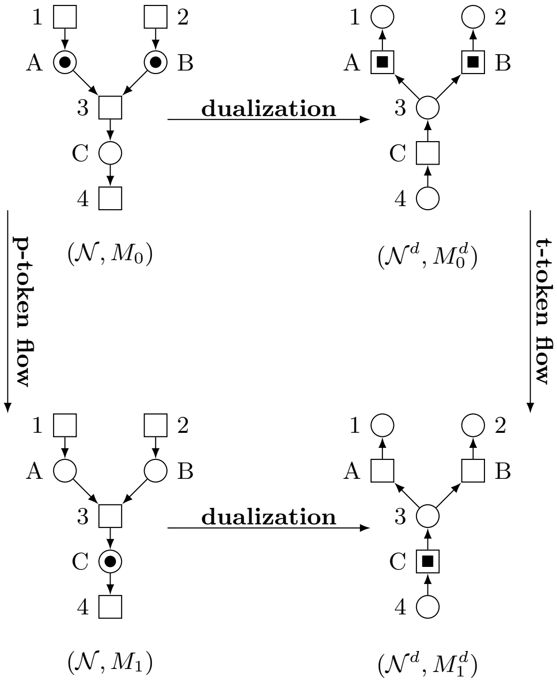


Fig. 3. Token flow in $\mathcal{N}$ and $\mathcal{N}^d$

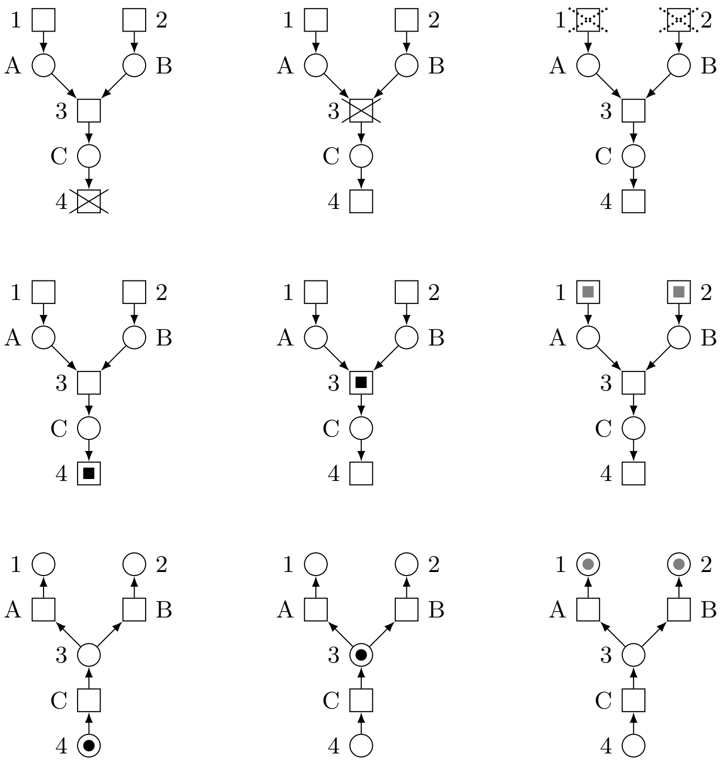


Fig. 4. Interpretation of t-tokens (1)

Remark 2. Dualizing marked p/t-nets induces the firing of enabled places. A place is enabled *if its output transitions are sufficiently marked by t-tokens.*

Of course, now the question of the meaning of t-tokens arises.

Example 3. Transition 4 of the first net of the first row in Fig. 4 is crossed out, what is assumed to mean that this transition was not able or not allowed to fire. The reason for it is that before (shown in the second net of the first row) transition 3 was not able or not allowed to fire. Here the reason is that transition 1 or 2 was not able or not allowed to fire. Comparing the first two rows shows that the crosses and the t-tokens behave without any difference because of the firing rule for t-tokens. ☐

Now an important question arises: What can be gained by duality? T-tokens and firing places yield only a *new interpretation* of the traditional net dynamics and nothing else because of $(\mathcal{N}^d, M_0^d)^d = (\mathcal{N}, M_0)$. But the dual should enrich the original net. That is to be achieved by permitting *nets with both sorts of tokens.*

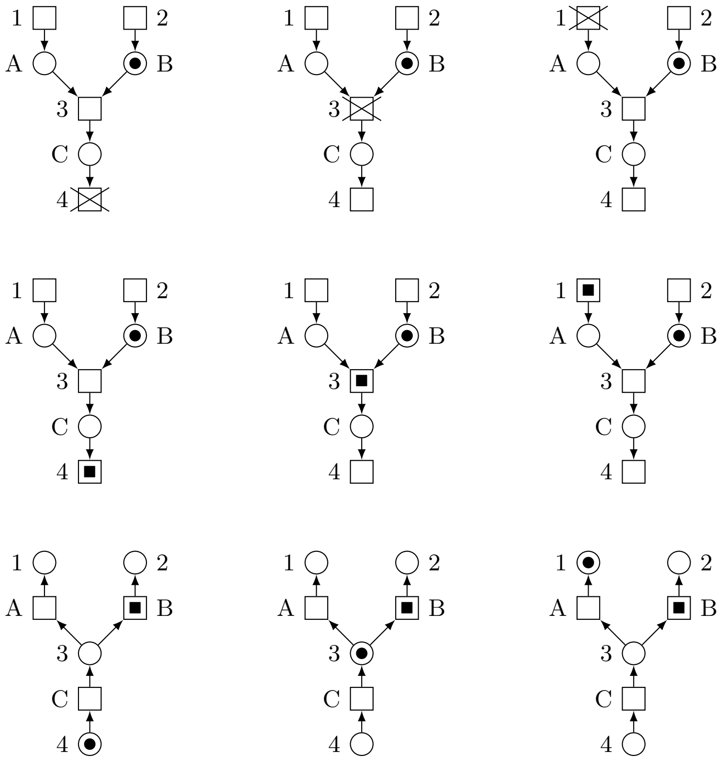


Fig. 5. Interpretation of t-tokens (2)

Example 4. This is a modification of example 3. In all nets of Fig. 5, node B is marked by one suitable token. In row one it is no longer sensible to assume that transition 2 was not able or not allowed to fire because the p-token on B might be the result of a firing of transition 2. Now we assume that a *marked* node (place and transition) cannot be enabled, regardless of the node being "enabled" in the usual way. Consequently, the t-tokens in the second row behave like the crosses. ☐

Remark 3. p- and t-tokens block each other*.*

Definition 8. **(p/t-marking)** *Let* $\mathcal{N} = (P, T, F, W)$ *be a p/t-net;*
M *is* a place/transition marking (p/t-marking) *iff* $M : P \cup T \to \mathbb{N}_0$*;*

$p \in P$ is p-marked (marked) *iff* $M(p) \geq 1$,
$t \in T$ is t-marked (marked) *iff* $M(t) \geq 1$;

the tokens on places are p-tokens*;*
the tokens on transitions are t-tokens*;*

$p \in P$ is enabled for M *iff* $M(p) = 0 \wedge \forall y \in p^{\bullet} : M(y) \geq W((p, y))$.

$t \in T$ is enabled for M *iff* $M(t) = 0 \ \wedge \forall x \in {}^{\bullet}t : M(x) \geq W((x,t))$.
So, marked nodes cannot be enabled.

Let p $\in P$ *be enabled for M;*
the follower marking M' of M after one firing of p *is given by*

$$M'(y) := \begin{cases} M(y) - W((p,y)) & \text{if } y \in p^{\bullet} \backslash {}^{\bullet}p \\ M(y) + W((y,p)) & \text{if } y \in {}^{\bullet}p \backslash p^{\bullet} \\ M(y) - W((p,y)) + W((y,p)) & \text{if } y \in {}^{\bullet}p \cap p^{\bullet} \\ M(y) & \text{if } y \notin {}^{\bullet}p \cup p^{\bullet} \end{cases}$$
$$\text{for all } y \in T$$
$$M'(x) := \quad M(x) \qquad \text{for all } x \in P;$$

let t $\in T$ *be enabled for M;*
the follower marking M'' of M after one firing of t *is given by*

$$M''(x) := \begin{cases} M(x) - W((x,t)) & \text{if } x \in {}^{\bullet}t \backslash t^{\bullet} \\ M(x) + W((t,x)) & \text{if } x \in t^{\bullet} \backslash {}^{\bullet}t \\ M(x) - W((x,t)) + W((t,x)) & \text{if } x \in {}^{\bullet}t \cap t^{\bullet} \\ M(x) & \text{if } x \notin {}^{\bullet}t \cup t^{\bullet} \end{cases}$$
$$\text{for all } x \in P$$
$$M''(y) := \quad M(y) \qquad \text{for all } y \in T; \qquad \square$$

Definition 9. (**dual marking**) *Let* $\mathcal{N} = (P, T, F, W)$ *be a p/t-net and* $\mathcal{N}^d = (P^d, T^d, F^d, W^d)$ *its dual net, such that* $P^d = T$, $T^d = P$; *let* $M : P \cup T \to \mathbb{N}_0$ *be a p/t-marking of* $\mathcal{N}$. $M(P)$ *is a* $|P|$*-vector,* $M(T)$ *is a* $|T|$*-vector.*

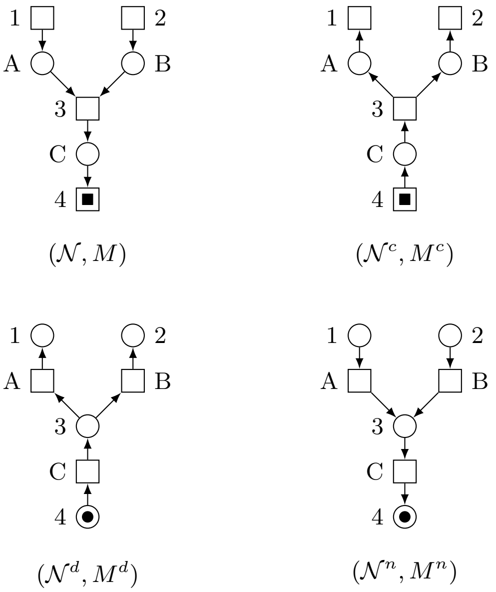
$M^d = P^d \cup T^d \to \mathbb{N}_0$ *is the* dual marking *of* M *iff* $M^d(P^d) = M(T)$ *and* $M^d(T^d) = M(P)$. ☐

Example 5. In the second net of the second row of Fig. 4, the places A and B are in a conflict (so, they are enabled!). In the corresponding net of Fig. 5, only place A is enabled. In the second row of both figures, transition 4 is only disabled in the first net. The corresponding statements hold for the dual nets in the third row. ☐

Although the concept of duality for marked nets was already introduced in [2], even for a class of higher level nets, it took quite a long time to ultimately get convinced that marked transitions and firing places might yet be useful concepts and no "net-theoretical sacrilege".

3 The Quaternality of Place/Transition Nets

In this section, we will expand the duality of place/transition nets to a quaternality.



$(\mathcal{N}, M)$ $(\mathcal{N}^c, M^c)$

$(\mathcal{N}^d, M^d)$ $(\mathcal{N}^n, M^n)$

Fig. 6. Quaternals

Definition 10. (quaternality) *Let* $\mathcal{N} = (P, T, F, W)$ *be a p/t-net,* $[\mathcal{N}]$ *its incidence matrix,* $M : P \cup T \to \mathbb{N}_0$ *its p/t-marking;*

$(\mathcal{N}, M)^d := (\mathcal{N}^d, M^d)$ *is the* dual system *of* $(\mathcal{N}, M)$ *(see Def. 7)*

$(\mathcal{N}, M)^c := (\mathcal{N}^c, M^c)$ *is the* contradual system *of* $(\mathcal{N}, M)$
iff $[\mathcal{N}^c] = -[\mathcal{N}]$ *and* $M^c = M$.

$(\mathcal{N}, M)^n := (\mathcal{N}^n, M^n)$ *is the* negational system *of* $(\mathcal{N}, M)$
iff $[\mathcal{N}^n] = -[\mathcal{N}^d]$ *and* $M^n = M^d$.

The systems $(\mathcal{N}, M)$, $(\mathcal{N}^d, M^d)$, $(\mathcal{N}^c, M^c)$, $(\mathcal{N}^n, M^n)$ *are* quaternals *of each other.* □

Proposition 5. (trivial) *Let* $\mathcal{N}^{xy}$ *be an abbreviation for* $(\mathcal{N}^x)^y$*;*

(a) $\mathcal{N}^{dd} = \mathcal{N}^{cc} = \mathcal{N}^{nn} = \mathcal{N}$
(b) $\mathcal{N}^{cd} = \mathcal{N}^{dc} = \mathcal{N}^n$
$\mathcal{N}^{dn} = \mathcal{N}^{nd} = \mathcal{N}^c$
$\mathcal{N}^{nc} = \mathcal{N}^{cn} = \mathcal{N}^d$ □

Example 6. Let $(\mathcal{N}, M)$ be the p/t-system given in Fig. 4 (first net, second row). Its quaternals are shown in Fig. 6. The corresponding incidence matrices and formal markings are given in Fig. 7. □

$$\begin{array}{c|cccc} [\mathcal{N}] & 1 & 2 & 3 & 4 \\ \hline A & 1 & & -1 & \\ B & & 1 & -1 & \\ C & & & 1 & -1 \end{array} \qquad \begin{array}{c|cccc} [\mathcal{N}^c] & 1 & 2 & 3 & 4 \\ \hline A & -1 & & 1 & \\ B & & -1 & 1 & \\ C & & & -1 & 1 \end{array}$$

$$\begin{array}{c|ccc} [\mathcal{N}^d] & A & B & C \\ \hline 1 & 1 & & \\ 2 & & 1 & \\ 3 & -1 & -1 & 1 \\ 4 & & & -1 \end{array} \qquad \begin{array}{c|ccc} [\mathcal{N}^n] & A & B & C \\ \hline 1 & -1 & & \\ 2 & & -1 & \\ 3 & 1 & 1 & -1 \\ 4 & & & 1 \end{array}$$

$$M : P \cup T = \{A, B, C\} \cup \{1, 2, 3, 4\} \to \mathbb{N}_0 \text{ s.t.}$$
$$M(p) = 0 \text{ for all } p \in \{A, B, C\},\ M(t) = \begin{cases} 1 & \text{if } t = 4 \\ 0 & \text{if } t \in \{1, 2, 3\} \end{cases}$$

$$M^d : P^d \cup T^d = \{1, 2, 3, 4\} \cup \{A, B, C\} \to \mathbb{N}_0 \text{ s.t.}$$
$$M^d(p^d) = \begin{cases} 1 & \text{if } p^d = 4 \\ 0 & \text{if } p^d \in \{1, 2, 3\} \end{cases},\ M^d(t^d) = 0 \text{ for all } t^d \in \{A, B, C\}$$

Fig. 7. Corresponding incidence matrices and markings

Every net of Fig. 6 might be the initial net, e.g. $\mathcal{N}_1 := \mathcal{N}^n$.

$$\text{Then}\quad \begin{aligned} \mathcal{N}_1^c &= \mathcal{N}_1^{nc} = \mathcal{N}_1^d \\ \mathcal{N}_1^d &= \mathcal{N}_1^{nd} = \mathcal{N}_1^c \\ \mathcal{N}_1^n &= \mathcal{N}_1^{nn} = \mathcal{N}. \end{aligned}$$

4 Using the Quaternality

In this section, we will show by means of examples how the quaternality approach can be applied. Even though the examples are rather small, there is no principle difference to real applications. It should be stressed that dual nets themselves are not needed in this section.

Example 7. This example is borrowed from [3]. Figure 8 shows two technical representations of an electrical circuit. The meaning of the symbols is

B:	battery
L1, L2:	bulbs
R1, R2:	leads to the bulbs
E:	energy
U1, U2:	voltages at the bulbs
H1, H2:	shining of the bulbs

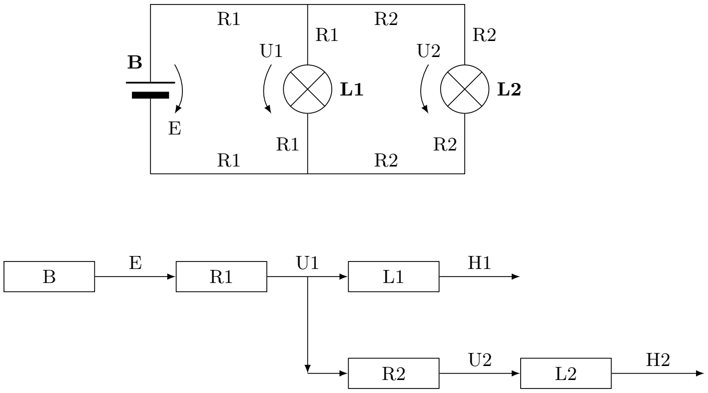


Fig. 8. Technical Representations

For constructing the net representation, we will use the following logical formulas (see [4]).

$$
\begin{array}{ll}
(1) & B \longrightarrow E \\
(2) & R1 \wedge E \longrightarrow U1 \\
(3) & L1 \wedge U1 \longrightarrow H1 \\
(4) & R2 \wedge U1 \longrightarrow U2 \\
(5) & L2 \wedge U2 \longrightarrow H2
\end{array}
$$

These formulas are nearly self-explanatory. The fourth one e.g. says that if the lead to bulb *L2* is ok and there is voltage at *L1* then there will also be voltage at *L2*. The transitions 1 to 5 of Fig. 9 originate from these formulas. Supposed now that *L2* is shining and that *L1* is not. This assumption is recorded in the initial marking M_0 (see Fig. 9) by a p-token on *H2* and a t-token on *okH1*:

$$M_0(\mathit{okH1}) = M_0(\mathit{H2}) = 1, \quad M_0(k) = 0 \quad \textit{for all other nodes } k.$$

Now, we are looking for the *reasons* that *L2* is shining and *L1* is not; i.e. transitions and places have to fire backwards.

The only *place firing sequence* to a *dead marking* is $M_0[\mathit{H1}, \mathit{L1}\rangle M_1$ with

$$M_1(\mathit{okL1}) = M_1(\mathit{H2}) = 1, \quad M_1(k) = 0 \quad \textit{for all other nodes } k.$$

Note that transition 4 cannot be marked. So place *U1* cannot be activated. That means that transition *okL1* is marked, thus representing the diagnosis:

The bulb L1 is damaged.

On the other hand, there is a backward *transition firing sequence*:
$M_0[5, 4, 2, 1, \mathit{okL2}, \mathit{okR2}, \mathit{okR1}, \mathit{okB}\rangle M_2$. That means that *L2, R2, R1,* and *B* are ok.

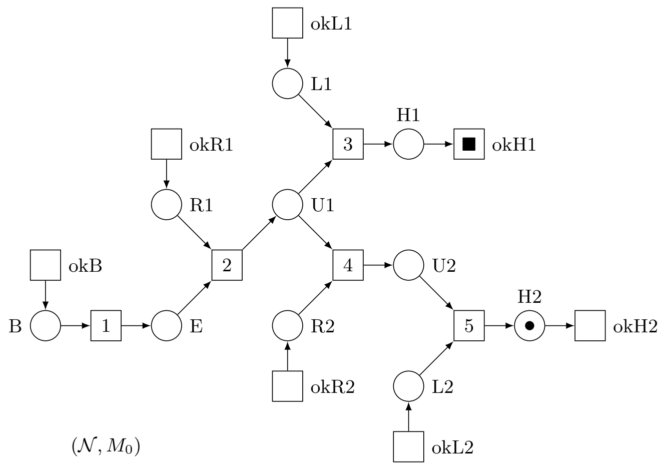


Fig. 9. Net representation of the circuit (1)

The situation is quite different in Fig. 10. The marking M'_0 with

$$M'_0(\mathit{okH1}) = 1, \quad M'_0(\mathit{okH2}) = 1, \quad M'_0(k) = 0 \quad \textit{for all other nodes } k$$

represents the non-shining of both bulbs. Then there are the following place firing sequences from M'_0 to *dead markings* which indicate mutually exclusive diagnoses:

$M'_0[\mathit{H1}, \mathit{L1}, \mathit{H2}, \mathit{L2}\rangle M'_1$ with
$M'_1(\mathit{okL1}) = M'_1(\mathit{okL2}) = 1$,
$M'_1(k) = 0$ otherwise;
L1 and *L2* are defective;

$M'_0[\mathit{H1}, \mathit{L1}, \mathit{H2}, \mathit{U2}, \mathit{R2}\rangle M'_2$ with
$M'_2(\mathit{okL1}) = M'_2(\mathit{okR2}) = 1$,
$M'_2(k) = 0$ otherwise;
L1 and *R2* are defective;

$M'_0[\mathit{H1}, \mathit{H2}, \mathit{U2}, \mathit{U1}, \mathit{R1}\rangle M'_3$ with
$M'_3(\mathit{okR1}) = 1$,
$M'_3(k) = 0$ otherwise;
R1 is defective;

$M'_0[\mathit{H1}, \mathit{H2}, \mathit{U2}, \mathit{U1}, E, B\rangle M'_4$ with
$M'_4(\mathit{okB}) = 1$,
$M'_4(k) = 0$ otherwise;
B is defective;

Yet another situation is shown in Fig. 11. The marking M''_0 with

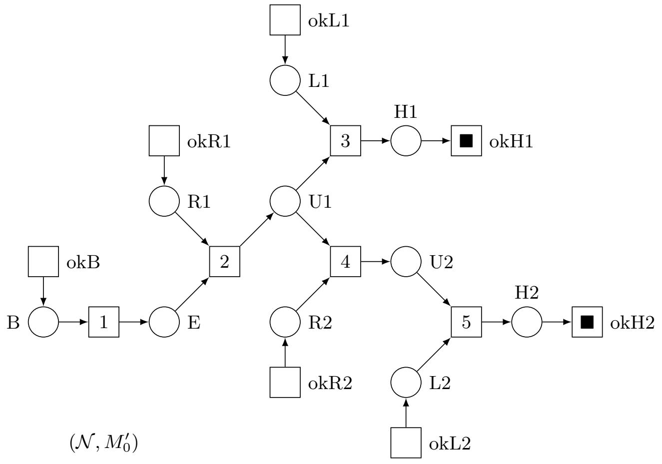


Fig. 10. Net representation of the circuit (2)

$$\begin{array}{llll} M_0''(okH1) = 1, & M_0''(okH2) = 1, & & \\ M_0''(L1) \quad = 1, & M_0''(L2) \quad = 1, & M_0''(k) = 0 & \textit{for all other nodes } k \end{array}$$

represents again the non-shining of both bulbs; but now we assume that both bulbs, *L1 and L2*, are ok. The place firing sequences from M_0'' to *dead markings* and the corresponding diagnoses are the following ones:

$M_0''[H1, H2, U2, R2\rangle M_1''$ with
$M_1''(3) = M_1''(okR2) = M_1''(L1) = M_1''(L2) = 1$,
$M_1''(k) = 0$ otherwise,
there is no voltage *U1*, whatever the reason –
moreover, *R2* is defective;

$M_0''[H1, H2, U2, U1, R1\rangle M_2''$ with
$M_2''(okR1) = M_2''(L1) = M_2''(L2) = 1$,
$M_2''(k) \quad = 0$ otherwise;
R1 is defective;

$M_0''[H1, H2, U2, U1, E, B\rangle M_3''$ with
$M_3''(okB) = M_3''(L1) = M_3''(L2) = 1$,
$M_3''(k) \quad = 0$ otherwise;
B is defective; ☐

Remark 4. Consequences of events occurring and reasons for events not occurring are dual to each other.

The commitment of backwards firing places was induced by dualizing a p-marked net before and after firing a transition. Of course, it is also justified to ask for an

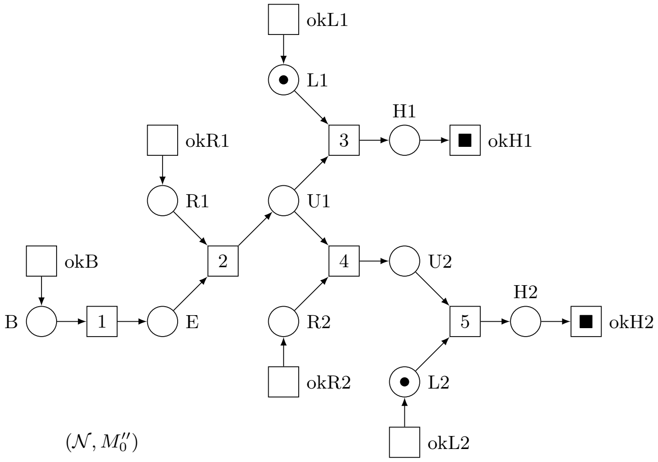


Fig. 11. Net representation of the circuit (3)

interpretation of *forwards firing places*, thus asking for consequences. The next example will show the practical use for that.

Example 8. The net $\mathcal{N} = (P, T, F, W)$ of Fig. 12 is marked by M_0 with

$$\begin{array}{llll} M_0(\mathit{L1}) &= 1, & M_0(\mathit{L2}) = 1, & \\ M_0(\mathit{okR2}) &= 1, & M_0(k) \;\; = 0 & \textit{for all other nodes } k; \end{array}$$

i.e. we assume that the lead *R2* is defective and that both bulbs are ok. Then the *forward place firing sequence* $M_0[\mathit{R2}, \mathit{U2}, \mathit{H2}\rangle M_1$ leads to the marking M_1 with

$$\begin{array}{llll} M_1(\mathit{L1}) &= 1, & M_1(\mathit{L2}) = 1, & \\ M_1(\mathit{okH2}) &= 1, & M_1(k) \;\; = 0 & \textit{for all other nodes } k. \end{array}$$

The above firing sequence $M_0[\mathit{R2}, \mathit{U2}, \mathit{H2}\rangle M_1$ says that if lead *R2* is broken, no voltage *U2* exists and, consequently, the bulb *L2* is not shining. Nothing else can be concluded. One easily recognizes that the p-tokens on *L1* and *L2* are of no influence, which is correct.

If, however, the initial marking is M_0' as in Fig. 13 with

$$\begin{array}{llll} M_0'(\mathit{L1}) &= 1, & M_0'(\mathit{L2}) = 1, & \\ M_0'(\mathit{okR1}) &= 1, & M_0'(k) \;\; = 0 & \textit{for all other nodes } k; \end{array}$$

i.e. if we now assume that the lead *R1* is defective, then the *forward place firing sequence* $M_0'[\mathit{R1}, \mathit{U1}, \mathit{H1}, \mathit{U2}, \mathit{H2}\rangle M_1'$ leads to the marking M_1' with

$$\begin{array}{lllll} M_1'(\mathit{L1}) &= 1, & M_1'(\mathit{L2}) = 1, & M_1'(\mathit{okH1}) = 1, & \\ M_1'(\mathit{okH2}) &= 1, & M_1'(k) \;\; = 0 & \textit{for all other nodes } k. & \end{array}$$

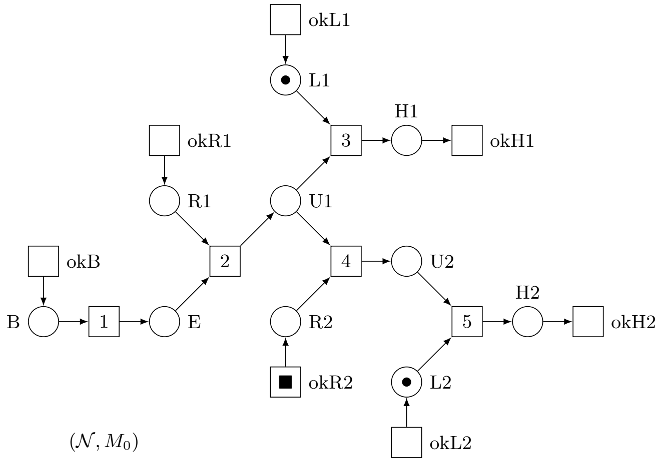


Fig. 12. Net representation of the circuit (4)

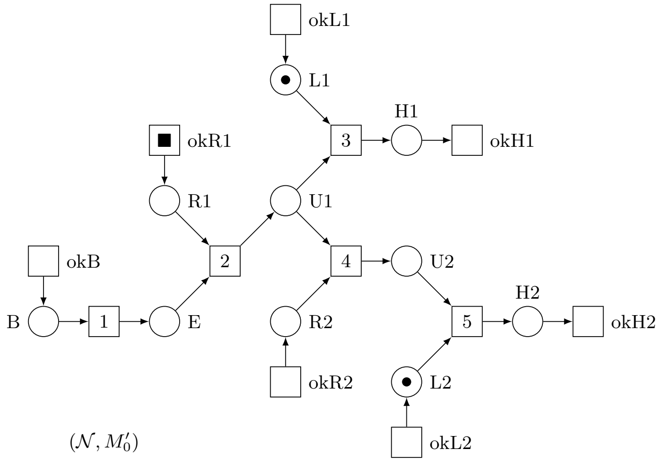


Fig. 13. Net representation of the circuit (5)

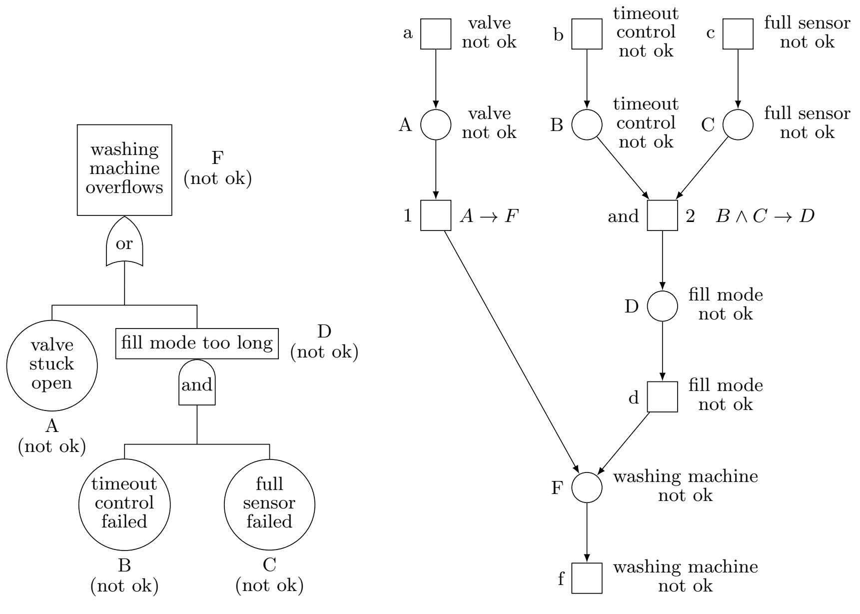
Now, we similarly come to the conclusion that both bulbs are not shining, even though they are ok. □

In forward direction, the t-token flow models what will happen if a component fails – what will fail next etc. So, it is possible to represent *cascading fails.*

Remark 5.
Diagnoses of non-occurrences are modelled by backwards flowing t-tokens.
Consequences of non-occurrences are modelled by forwards flowing t-tokens.
Diagnoses of occurrences are modelled by backwards flowing p-tokens.
Consequences of occurrences are modelled by forwards flowing p-tokens.

5 Further Examples

The focus of this section is to demonstrate how simple fault trees and simple fault tolerant systems are modeled by means of the event/non-event approach. Furthermore it will be shown how p/t-nets are folded into pr/t-nets. Thus the structure is condensed without losing any modeling power.



(a) **fault tree** (b) **Petri net**

Fig. 14. A fault tree and the corresponding upside down Petri net

Example 9. This example is borrowed from [5]. Figure 14 shows a fault tree for avoiding overflows in washing machines and an upside down p/t-net representation.

In order to demonstrate consequences and effects, we choose two suitable initial markings:

$$\begin{aligned} &M_0(A) = M_0(b) = M_0(C) = 1 \\ &M_0(k) \ = 0 \quad \textit{for all other nodes k.} \end{aligned}$$

M_0 represents the situation where the valve and the full sensor are not ok whereas the timeout control is ok. The firing sequence

$$M_0[B, D, 1\rangle M_1 \text{ where } \begin{aligned}[t] &M_1(F) = M_1(d) = M_1(C) = 1 \\ &M_1(k) \ = 0 \quad \textit{for all other nodes k} \end{aligned}$$

represents the consequence that the fill mode is ok ($M_1(d) = 1$) but the washing machine is not ($M_1(F) = 1$).

$$\begin{aligned} &M_0'(a) = M_0'(B) = M_0'(c) = 1 \\ &M_0'(k) = 0 \quad \textit{for all other nodes k} \end{aligned}$$

represents that the valve and the full sensor are ok but the timeout control is not.

$M_0'[C, D, A, F\rangle M_1'$ leads to M_1' where

$$\begin{aligned} &M_1'(B) = M_1'(f) = 1 \\ &M_1'(k) \ = 0 \quad \textit{for all other nodes k} \end{aligned}$$

shows that even though the timeout control is not ok the washing machine is (in the sense of not overflowing).

Two cases of looking for reasons are given by M_0'' with

$$\begin{aligned} &M_0''(f) = 1 \\ &M_0''(k) = 0 \quad \textit{for all other nodes k.} \end{aligned}$$

$M_0''[F, D, B, A\rangle M_1''$, $M_0''[F, D, C, A\rangle M_1^{('')}$ lead to

$$\begin{array}{llll} M_1''(a) \ = 1, & M_1''(b) \ = 1, & M_1''(c) \ = 0 & \text{and} \\ M_1^{('')}(a) = 1, & M_1^{('')}(b) = 0, & M_1^{('')}(c) = 1 & \text{respectively} \\ M_1''(k) \ = 0, & M_1^{('')}(k) = 0 & \textit{for all other nodes k} & \end{array}$$

and by M_0''' with

$$\begin{aligned} &M_0'''(F) = 1 \\ &M_0'''(k) \ = 0 \quad \textit{for all other nodes k.} \end{aligned}$$

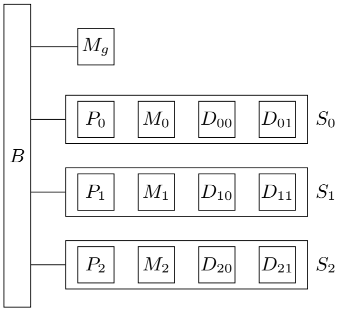


Fig. 15. Block diagram of S

$$\begin{aligned} &M_0'''[1\rangle M_1''' && \text{with } M_1'''(A) &&= 1, \\ & && \phantom{\text{with }} M_1'''(k) &&= 0 \quad \textit{for all other nodes k,} \\[1em] &M_0'''[d,2\rangle M_1^{('''')} && \text{with } M_1^{('''')}(B) = M_1^{('''')}(C) &&= 1, \\ & && \phantom{\text{with }} M_1^{('''')}(k) &&= 0 \quad \textit{for all other nodes k.} \end{aligned}$$

M_0'', by the way, works like the success tree belonging to the fault tree of Fig. 14. □

Example 10. This example is a simplified version of an example in [6]. The multiprocessor system S of Fig. 15 comprises 3 independent subsystems S_0, S_1, S_2. Each subsystem S_i $(i = 0, 1, 2)$ consists of a processor P_i, a local memory M_i, and 2 mirrored disc units D_{i0}, D_{i1}. Moreover, S contains a shared common memory M_g and a bus B which connects the 3 subsystems S_i and the shared memory M_g.

It is assumed that

the system S is down if
        the bus B is down
    or 2 of the 3 subsystems S_i are down;

a subsystem S_i $(i = 0, 1, 2)$ is down if
        the processor P_i is down
    or the local memory M_i and the global memory M_g are down
    or both discs D_{i0} and D_{i1} are down.

Supposed now that M_g, D_{00}, D_{11}, D_{20}, and D_{21} are down as given by the marking M_0 of the Petri net $\mathcal{N}$ in Fig. 16. We are interested in the question whether S is down or not. If the transition s can fire, S is not down.
s fires in the sequence

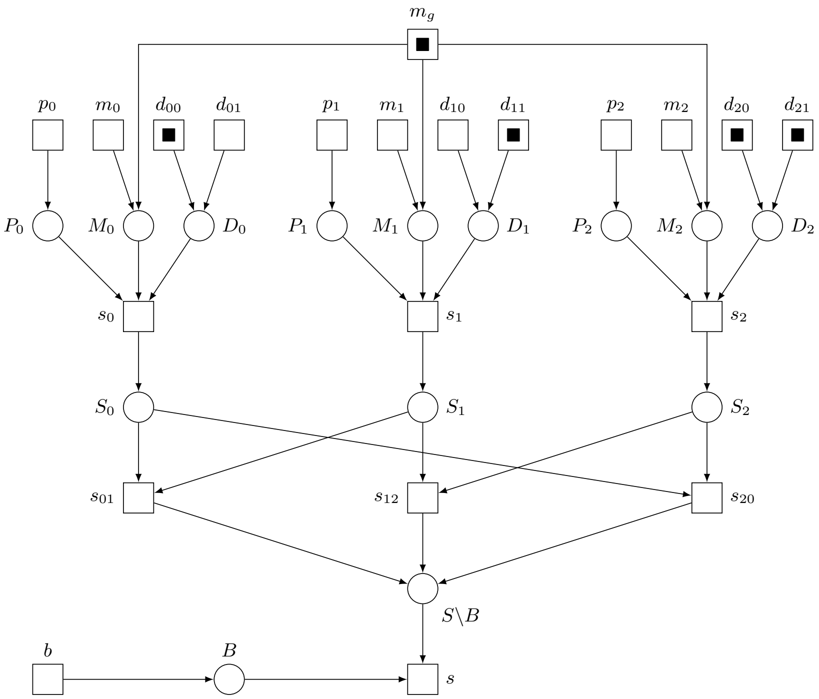


Fig. 16. $(\mathcal{N}, M_0)$

$$\begin{aligned}&M_0[p_0, m_0, d_{01}, p_1, m_1, d_{10}, b, s_0, s_1, s_{01}, s\rangle M_1\\ &\text{with } M_1(m_g) = M_1(d_{00}) = M_1(d_{11}) = M_1(d_{20}) = M_1(d_{21}) = 1\\ &\qquad M_1(k) = 0 \quad \textit{for all other nodes } k,\end{aligned}$$

so s is not down. But what about the t-tokens on d_{20}, d_{21}? In the firing sequence $M_1[D_2, S_2\rangle M_2$ where

$$\begin{aligned}&M_2(m_g) = M_2(d_{00}) = M_2(d_{11}) = M_2(s_{12}) = M_2(s_{20}) = 1\\ &M_2(k) = 0 \quad \textit{for all other nodes } k\end{aligned}$$

s_2 is marked after firing of D_2. That indicates that S_2 is down and S_0, S_1 is the only proper working pair of subsystems.

If in addition the local memory M_1 is down, i.e. if the initial marking is defined as shown in Fig. 17, then the firing sequence

$$\begin{aligned}&M_0'[M_1, S_1, D_2, S_2, S\backslash B\rangle M_1' \quad \text{with}\\ &M_1'(d_{00}) = M_1'(d_{11}) = M_1'(s_{12}) = M_1'(s) = 1\\ &M_1'(k) = 0 \quad \textit{for all other nodes } k\end{aligned}$$

leads to $M_1'(s) = 1$ indicating that the system S is down. No other firing sequence (triggered by firing of the unmarked boundary transitions) can inhibit that s will be marked.

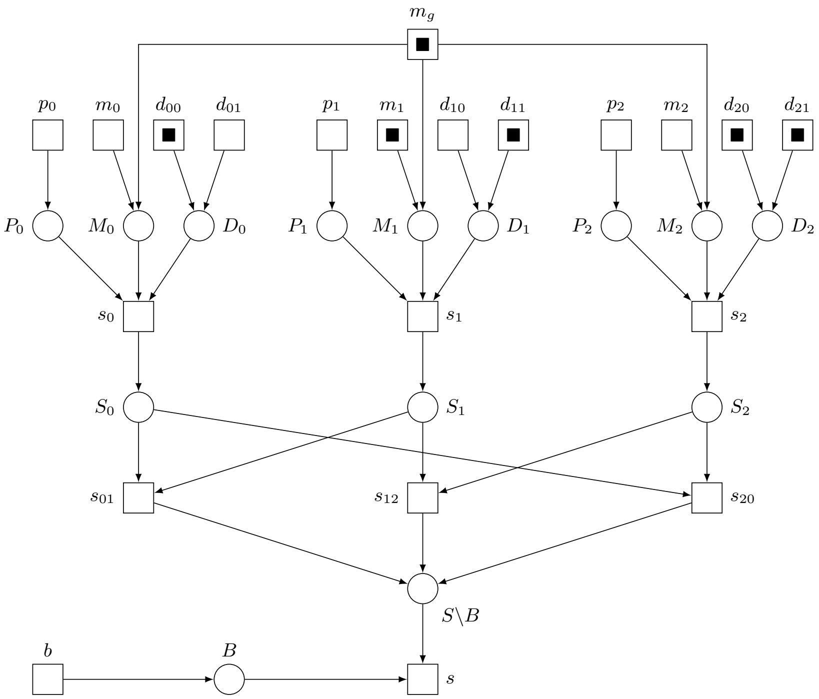


Fig. 17. $(\mathcal{N}, M'_0)$

Figure 18 shows a marking M''_0 of $\mathcal{N}$ which we will use to demonstrate how to look for the cause of the system S being down.

The firing sequence

$$
\begin{aligned}
&M''_0[S\backslash B, S_1, M_1\rangle M''_1 \quad \text{with}\\
&M''_1(d_{00}) = M''_1(s_{20}) = M''_1(S_0) = M''_1(P_1) = M''_1(D_1) = M''_1(P_2) =\\
&M''_1(M_2) = M''_1(B) = M''_1(m_1) = M''_1(m_g) = 1,\\
&M''_1(k) = 0 \quad \textit{for all other nodes } k
\end{aligned}
$$

shows that M_1 and M_g are down.

Moreover, the firing sequence $M''_0[S\backslash B, S_2, D_2\rangle M''_2$ shows that also D_{20} and D_{21} are down. Since S_0 is not down it cannot be detected that D_{00} is not intact. □

Example 11. This example is a continuation of example 10. There the three subsystems S_0, S_1, S_2 are folded on top of each other. Their indices $i = 0, 1, 2$ serve as identifiers which flow through the nets in the form of 1-tuples. The tuples on places and transitions are distinguished by their brackets: (i) and $[i]$, respectively. Since all tuples are 1-tuples the nets are unary predicate/transition nets. p- and t-tokens are represented as 0-tuples ( ) and [ ], respectively. This reflects the fact that p/t-nets are the "0-ary" special case of pr/t-nets. The

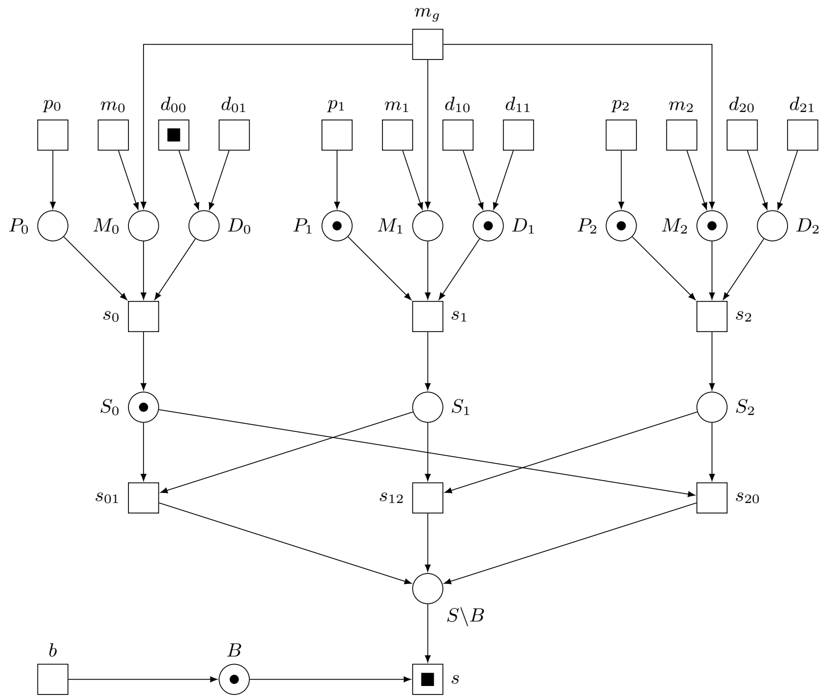


Fig. 18. $(\mathcal{N}, M_0'')$

marking M_0^* of Fig. 19 corresponds to the marking M_0 of Fig. 16:

M_0: ■ on m_g corresponds to M_0^*: [ ] on m_g
■ on d_{00} corresponds to [0] on d_0
■ on d_{11} corresponds to [1] on d_1
■ on d_{20} corresponds to [2] on d_0
■ on d_{21} corresponds to [2] on d_1

$M_0[p_0, m_0, d_{01}, p_1, m_1, d_{10}, b, s_0, s_1, s_{01}, s\rangle M_1$ corresponds to
$M_0^*[p(0), m(0), d_1(0), p(1), m(1), d_0(1), b(\;), s'(0), s'(1), s''(0), s(\;)\rangle M_1^*$.

$\mathcal{N}$: p_0 puts $\bullet$ on P_0	$\mathcal{N}^*$: p puts (0) on P
m_0 puts $\bullet$ on M_0	m puts (0) on M
d_{01} puts $\bullet$ on D_0	d_1 puts (0) on D
p_1 puts $\bullet$ on P_1	p puts (1) on P
m_1 puts $\bullet$ on M_1	m puts (1) on M
d_{10} puts $\bullet$ on D_1	d_0 puts (1) on D
b puts $\bullet$ on B	b puts ( ) on B
s_0 takes $\bullet$ from P_0, M_0, D_0	s' takes (0) from P, M, D
puts $\bullet$ on S_0	puts (0) on S

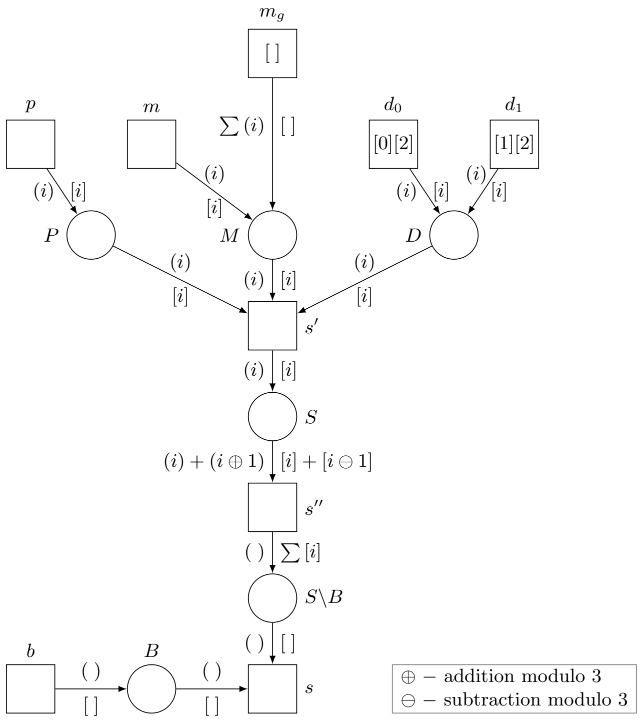


Fig. 19. $(\mathcal{N}^*, M_0^*)$

s_1	takes • from P_1, M_1, D_1	s'	takes (1) from P, M, D
	puts • on S_1		puts (1) on S
s_{01}	takes • from S_0, S_1	s''	takes (0) and (1) from S
	puts • on $S\backslash B$		puts ( ) on $S\backslash B$
s	takes • from $B, S\backslash B$	s	takes ( ) from $B, S\backslash B$

Note that the t-markings on transitions work as blockings. For example in Fig. 19, the tuples [0] and [2] on d_0 make it impossible that d_0 puts (0) and (2) on D. Correspondingly, the p-markings block firings of places. $(\mathcal{N}^*, M_0''^*)$ in Fig. 20 is the pr/t-net version of $(\mathcal{N}, M_0'')$ in Fig. 18. Again, we list corresponding markings and firings face to face:

M_0'':	■ on d_{00}	corresponds to	$M_0''^*$:	[0] on d_0
	■ on s	corresponds to		[ ] on s
	• on P_1	corresponds to		(1) on P
	• on P_2	corresponds to		(2) on P
	• on D_1	corresponds to		(1) on D
	• on M_2	corresponds to		(2) on M
	• on S_0	corresponds to		(0) on S
	• on B	corresponds to		( ) on B

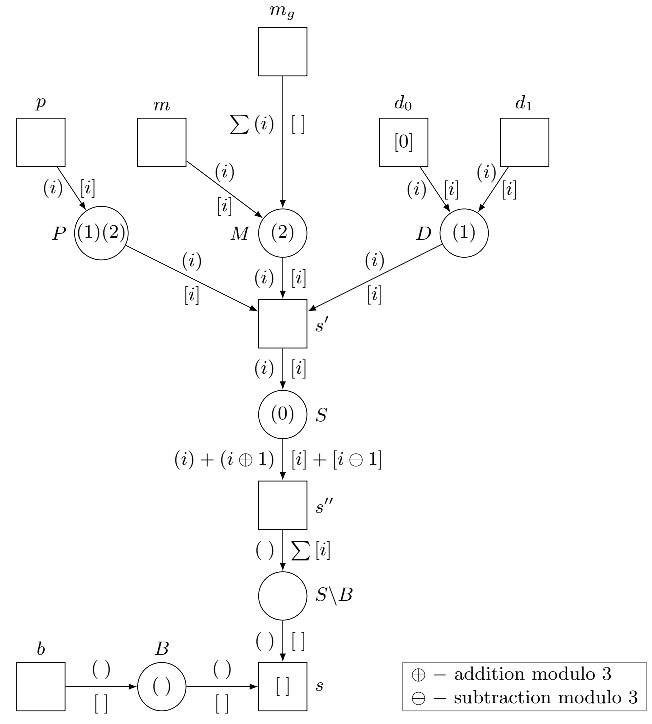


Fig. 20. $(\mathcal{N}^*, M_0''^*)$

The backward firing sequence

$M_0''[S\backslash B, S_1, M_1\rangle M_1''$ corresponds to $M_0''^*[S\backslash B[\ ], S[1], M[1]\rangle M_1''^*$.

$\mathcal{N}$: $S\backslash B$ takes ■ from s	$\mathcal{N}^*$: $S\backslash B$ takes [ ] from s
puts ■ on s_{01}, s_{12}, s_{20}	puts [0],[1],[2] on s''
S_1 takes ■ from s_{01}, s_{12}	S takes [1],[0] from s''
puts ■ on s_1	puts [1] on s'
M_1 takes ■ from s_1	M takes [1] from s'
puts ■ on m_1, m_g	puts [1] on m,[ ] on m_g

Note that S fired for $i = 1$, thus taking $[i] + [i \ominus 1] = \{[1], [0]\}$ from s''. Because of the (0) on S a firing for $i = 0$ was not possible.

The backward firing sequence $M_0''[S\backslash B, S_2, D_2\rangle M_2''$ can be "translated" in the same way. The larger i is the more effective is $\mathcal{N}^*$ in contrast to $\mathcal{N}$ because the structure of $\mathcal{N}^*$ remains unchanged whereas the structure of $\mathcal{N}$ would explode. Only the modulus (which is 3 in our example) should be increased. ☐

6 Summary and Outlook

Based on the idea of a *dual marked p/t-net*, in this paper *t-tokens* are introduced as markings for transitions. T-marked transitions cannot be enabled and are thus excluded from firing. T-tokens are subjected to a dynamics caused by the *firing of places* which is dual to the "normal" firing of transitions.

Whereas p/t-nets usually are dynamic models of events, the dynamics and causality of *non-events* become visible by means of the dual approach. If a system component breaks down, one can point to the components which are the next ones that cannot work any more, the next but ones etc. Also, the diagnoses for the non-working of components can be found.

So, there exist four kinds of moves in p/t-nets: p-tokens and t-tokens in forward and backward direction. These moves can be embedded into the quaternality concept as a theoretical background with close connections to logic.

Even the small examples clearly show that the duality of marked nets supplements the modelling power of p/t-nets, because the *non-occurring* of events becomes an integral and actively representable part of the theory. Thus, the approach might help to apply Petri net theory more intensively.

The next step should be the development of a mathematical fundament for "quaternalizing" higher level marked nets, in particular nets featuring time and probability.

References

1. Gottschalk, W.H.: The Theory of Quaternality. The Journal of Symbolic Logic **18**(3) (1953) 193–196
2. Lautenbach, K.: Simple Marked-graph-like Predicate/Transition Nets. Arbeitspapiere der GMD Nr. 41, Informatik Fachberichte 66, Bonn (1983)
3. Lunze, J.: Künstliche Intelligenz für Ingenieure. Volume 2 (in German). Oldenburg-Verlag München / Wien (1995)
4. Lautenbach, K.: Logical Reasoning and Petri Nets. In van der Aalst, W., Best, E., eds.: Applications and Theory of Petri Nets 2003. Volume 2679 of Lecture Notes in Computer Science. Springer Berlin / Heidelberg (2003) 276–295
5. Dugan, J.B.: Fault Tree Analysis of Computer-Based Systems. University of Virginia, RELIABILITY and MAINTAINABILITY Symposium, http://www.fault-tree.net/papers/dugan-comp-sys-fta-tutor.pdf (2002)
6. Bobbio, A., Franceschinis, G., Gaeta, R., Portinale, L.: Parametric Fault Tree for the Dependability Analysis of Redundant Systems and Its High-Level Petri Net Semantics. IEEE Transactions on Software Engineering **29** (March 2003) 270–287

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