True concurrency - from C.A. Petri to Telecom and Systems Biology

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France

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Nets and Concurrency

Carl Adam Petri, 12 July 1926 – 2 July 2010

K o m m u n i k a t i o n-
m i t
A u t o m a t e n

Von der Fakultät für Mathematik und Physik
der Technischen Hochschule Darmstadt

zur Erlangung des Grades eines
Doktors der Naturwissenschaften
(Dr. rer.nat.)

genehmigte
Dissertation

vorgelegt von
C a r l A d a m P e t r i
aus Leipzig

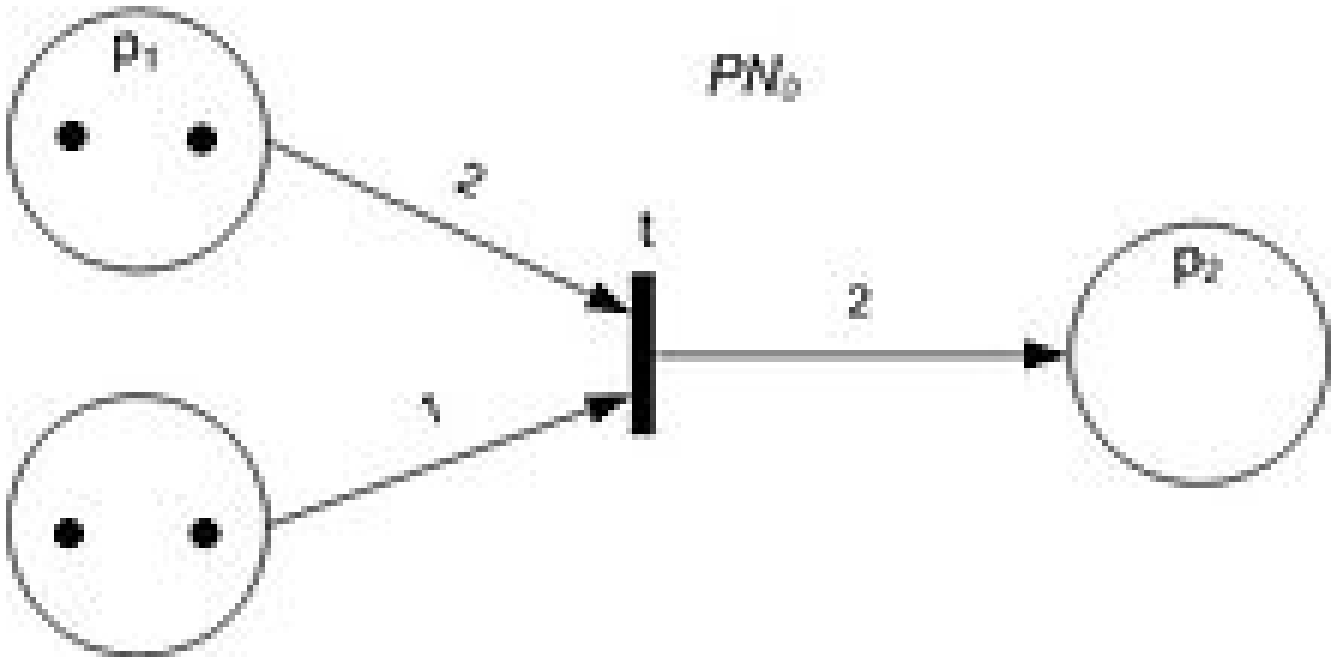
Referent: Prof.Dr.rer.techn.A.Walther
Korreferent: Prof.Dr.Ing.H.Unger

Tag der Einreichung: 27.7.1961
Tag der mündlichen Prüfung: 20.6.1962

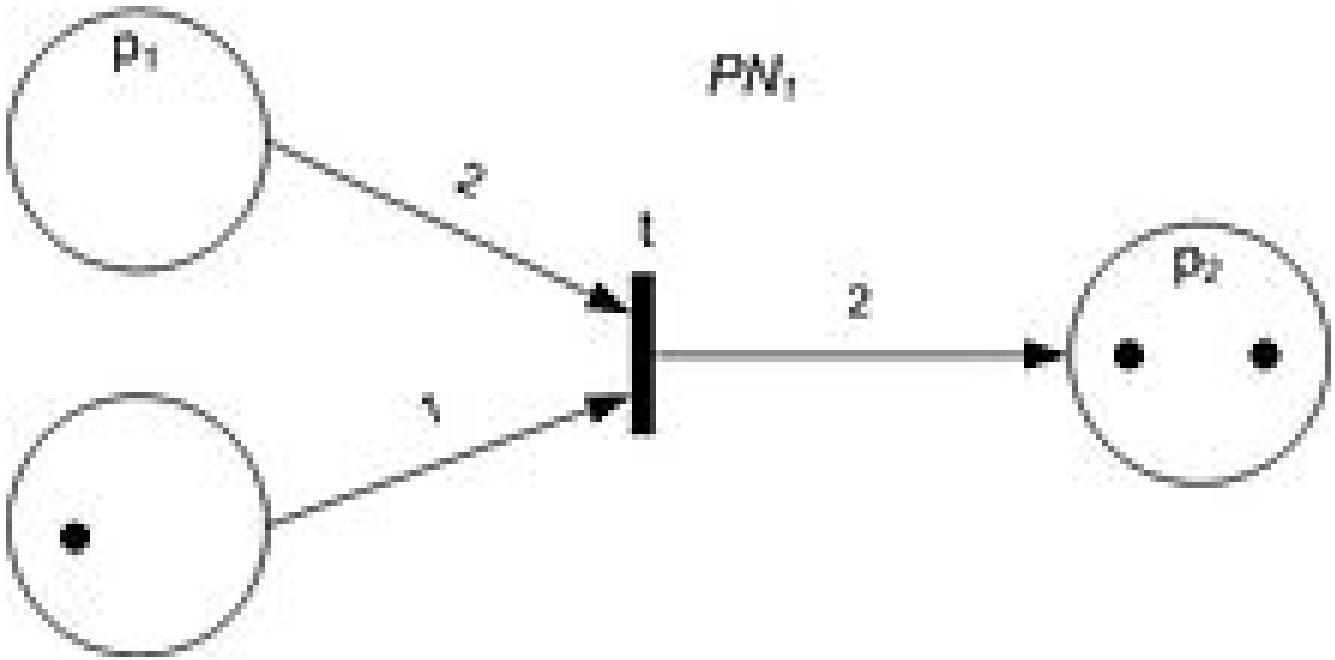
D 17

Bonn 1962

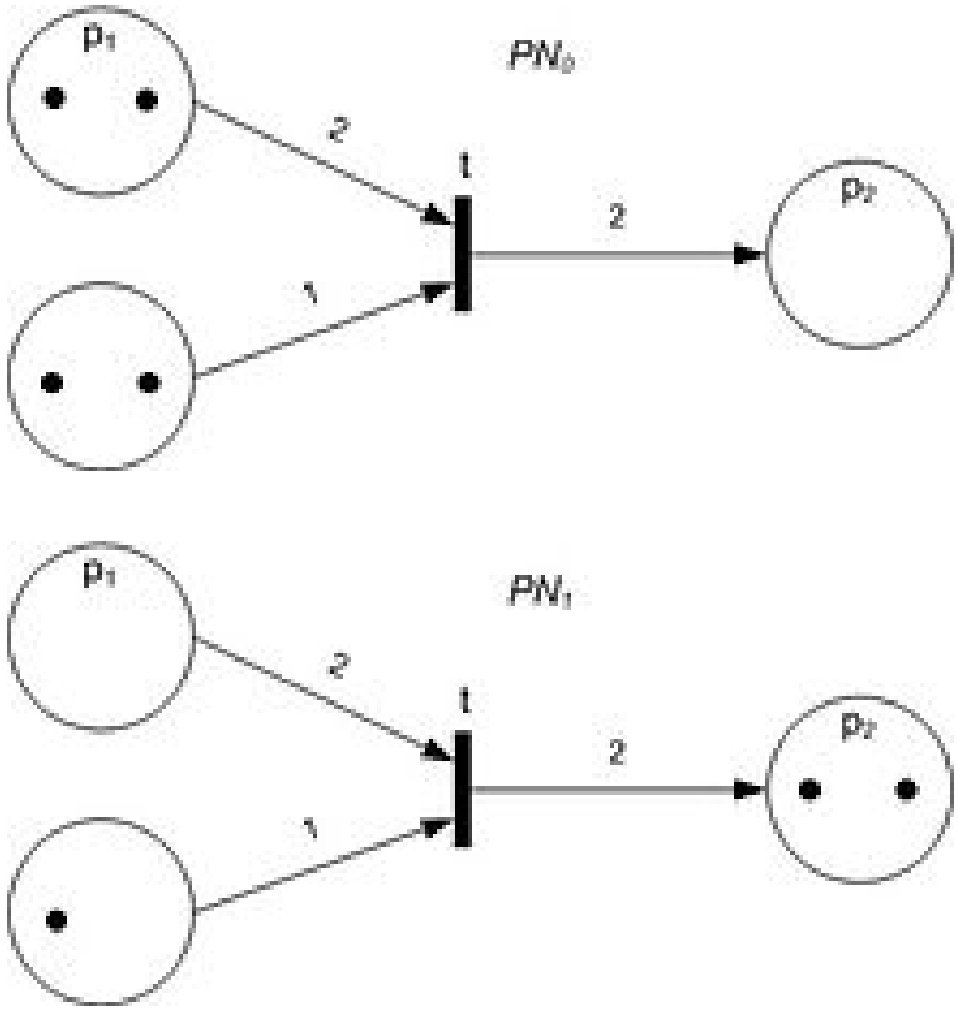
The Token Game



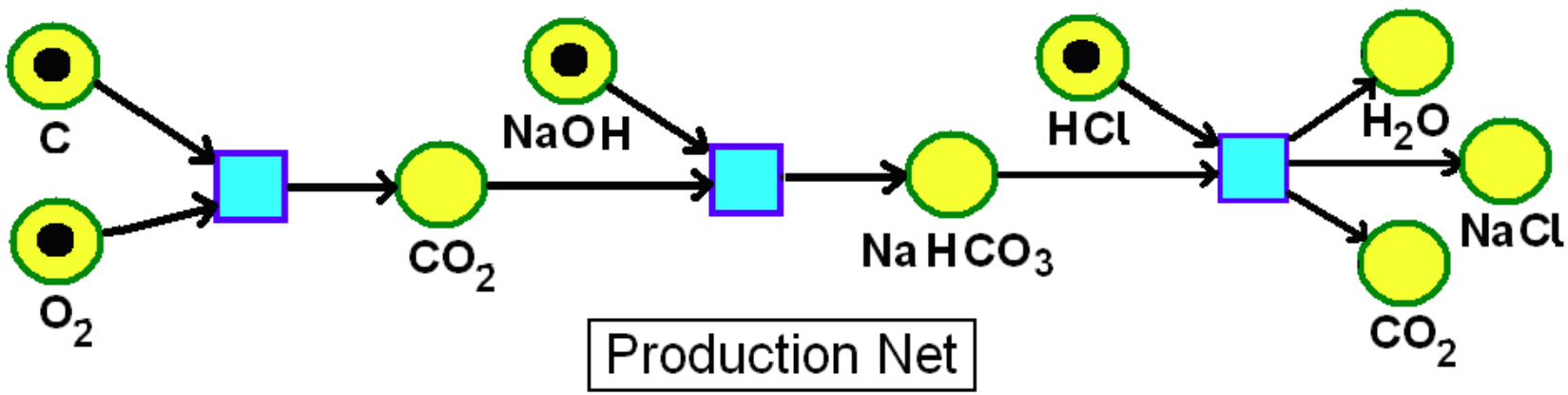
The Token Game



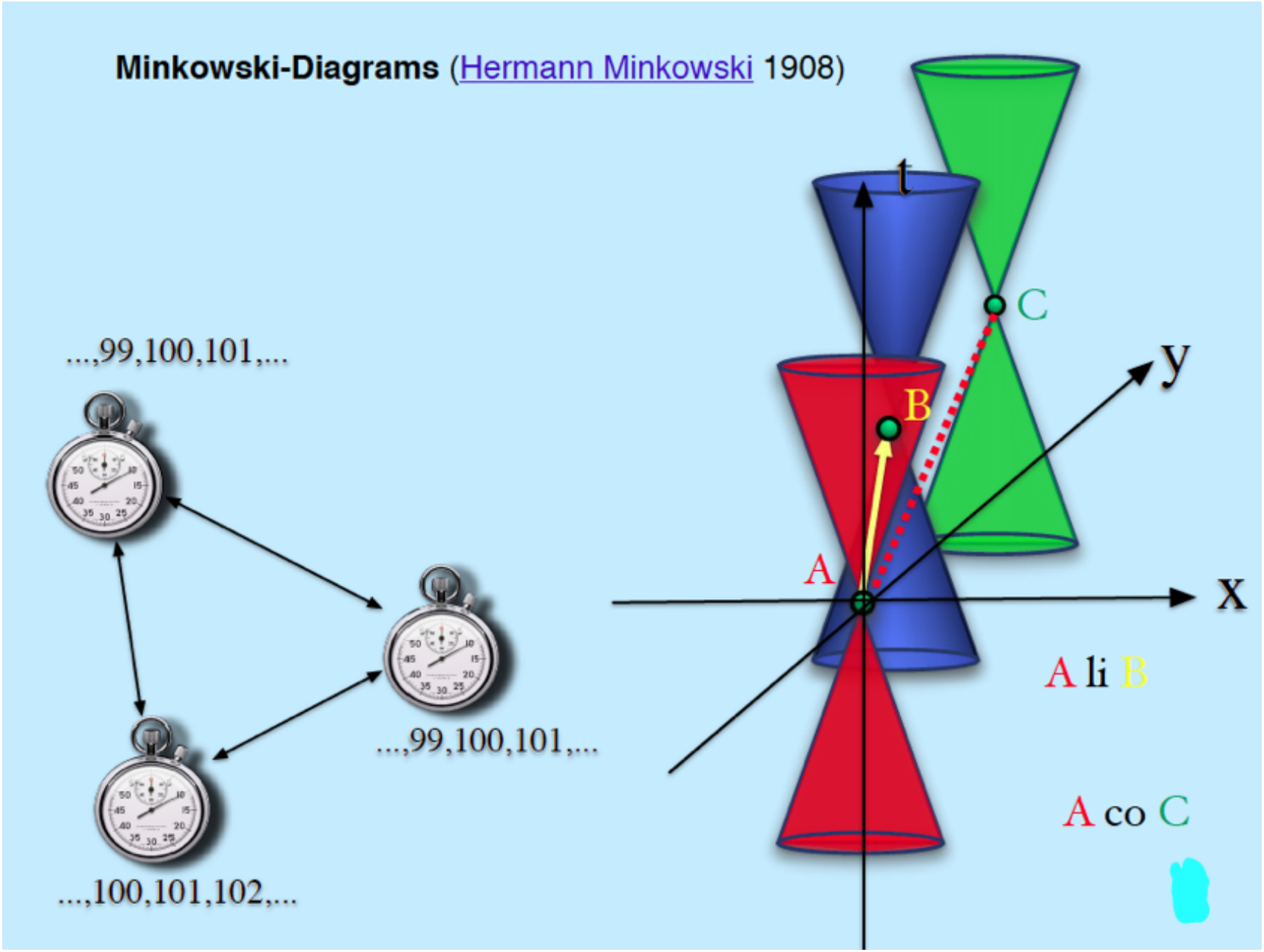
The Token Game



First Intended Use



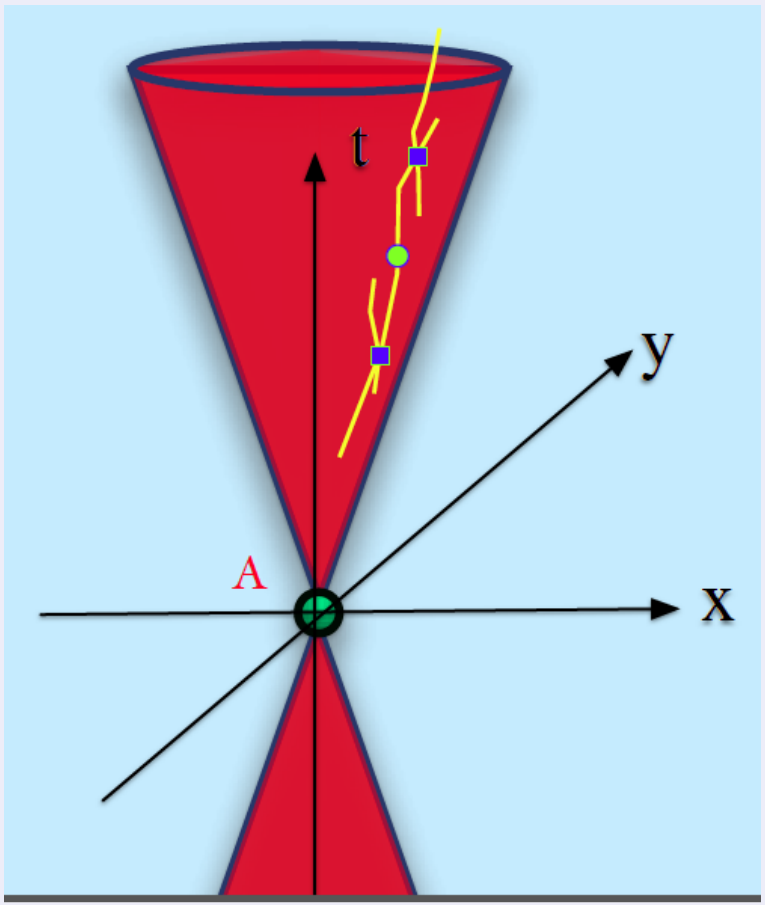
Nets and Concurrency



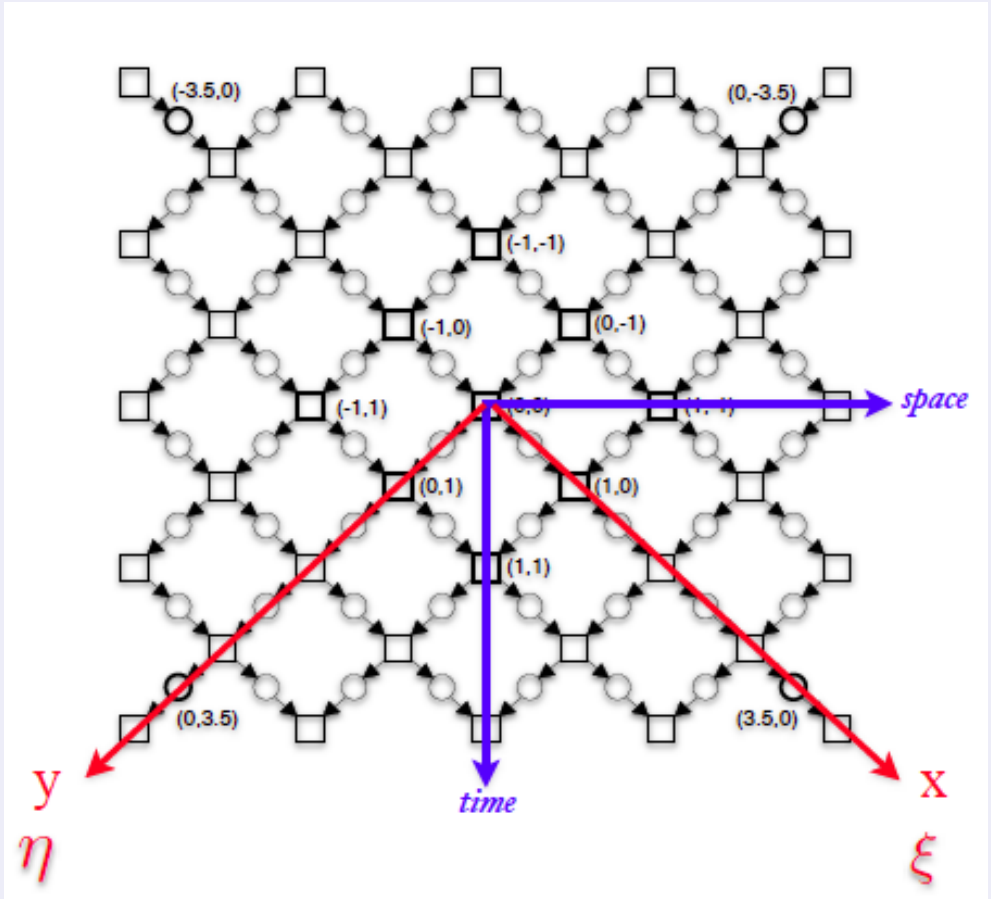
(Source: Petri and Valk 2008)

From Space-Time to Nets

Minkowski



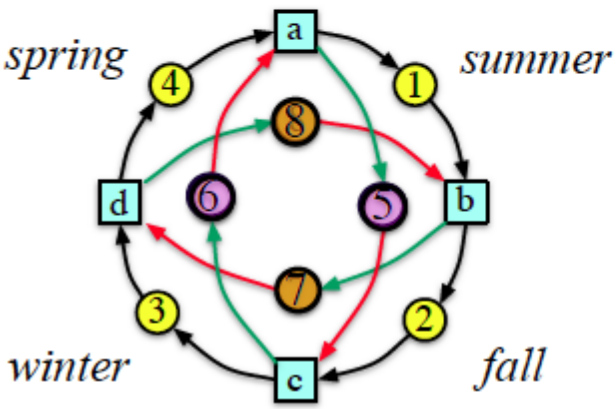
Petri Grid

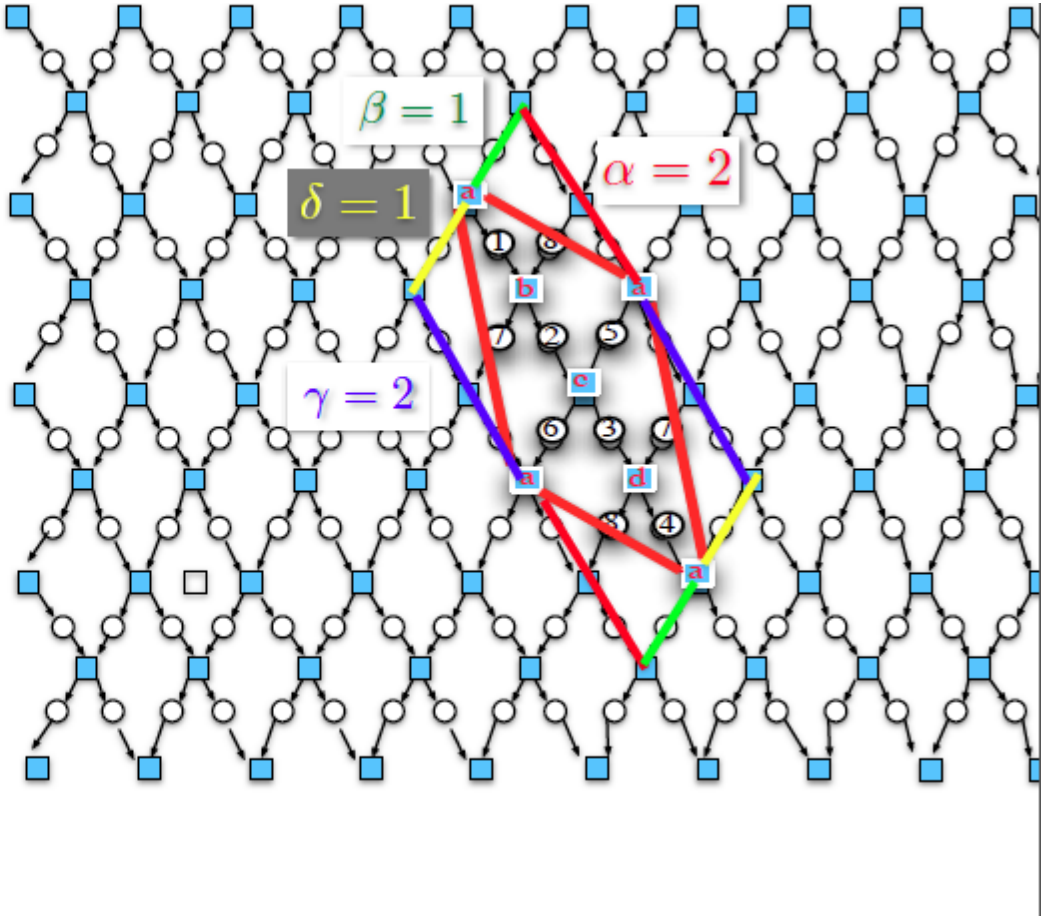


(Source: Petri/Valk 2008 and Valk 2013)

From Big to Small

(2,1,2,1)





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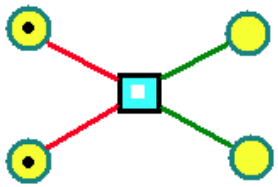
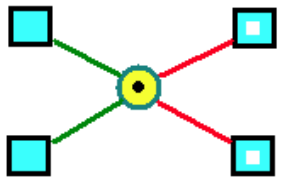
From Geometry to Topology



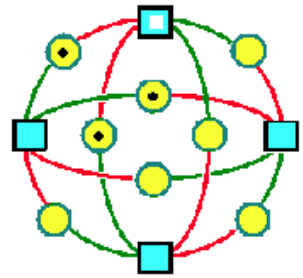
collection

GIVE

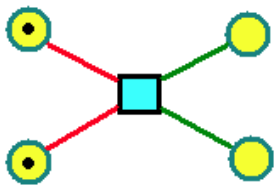


decision

TAKE

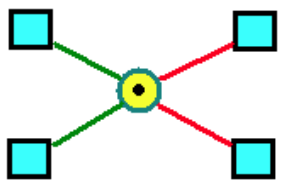


Oscillator



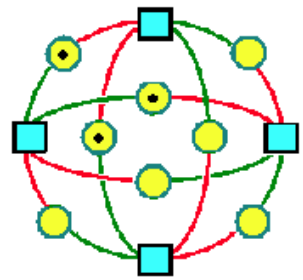
open subnet

The transition is completed by four states



closed subnet

The state is completed by four transitions



open subnet

The eight uncompleted states form the border

»Wir definieren: ein Raum ist eine Klasse von untereinander gleichzeitigen Weltpunkten, die mit jeder Weltlinie mindestens einen Weltpunkt gemein hat. …
Hieraus folgt, daß jeder Raum mit jeder Weltlinie genau einen Punkt gemein hat«
[Carnap-SL; 205]

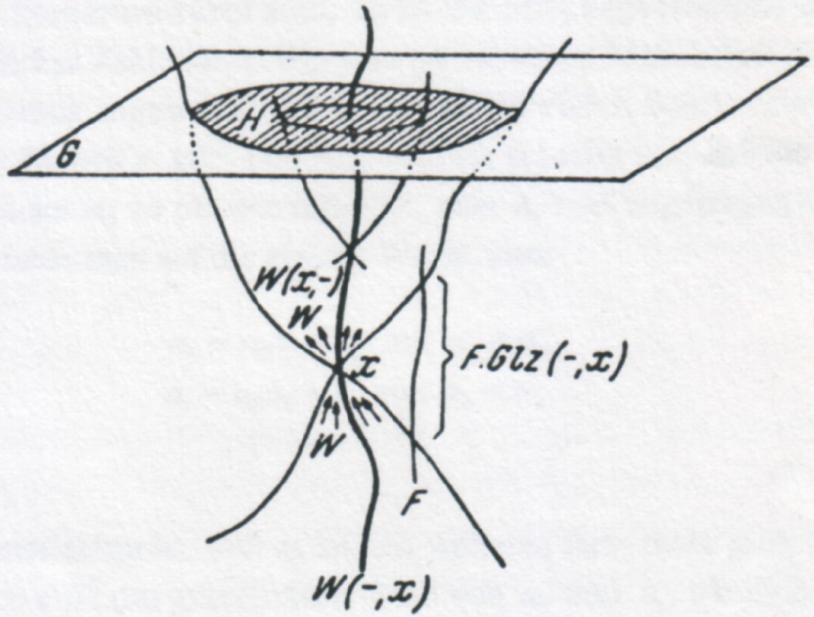


Abb. 1.4.2 Carnaps Orginaldarstellung des topologischen Raumes *G* als einer Art Zeitscheibe. Es läßt sich leicht der Vorkegel, der Nachkegel und das Wirkungsgebiet von *x* erkennen. »Ein Raum ist sozusagen ein dreidimensionaler Querschnitt durch die vierdimensionale Raum-Zeit-Welt, und zwar quer zur Zeitrichtung, also so, daß er alle Weltlinien schneidet.« [Carnap-SL; 205]

Physics and Concurrency

Concurrency

- Relativistic Space-Time:
  - You don't see what is going on at Alpha Centaury right now
- Quantum systems:
  - Uncertainty prevents you from obtaining a full global instantaneous snapshot

Some goals from Petri's program

- Axiomatic relational theory of concurrency (Carnap's spirit)
- Capture Lorentz transforms etc
- Build finitary but continuous mathematical picture of physics

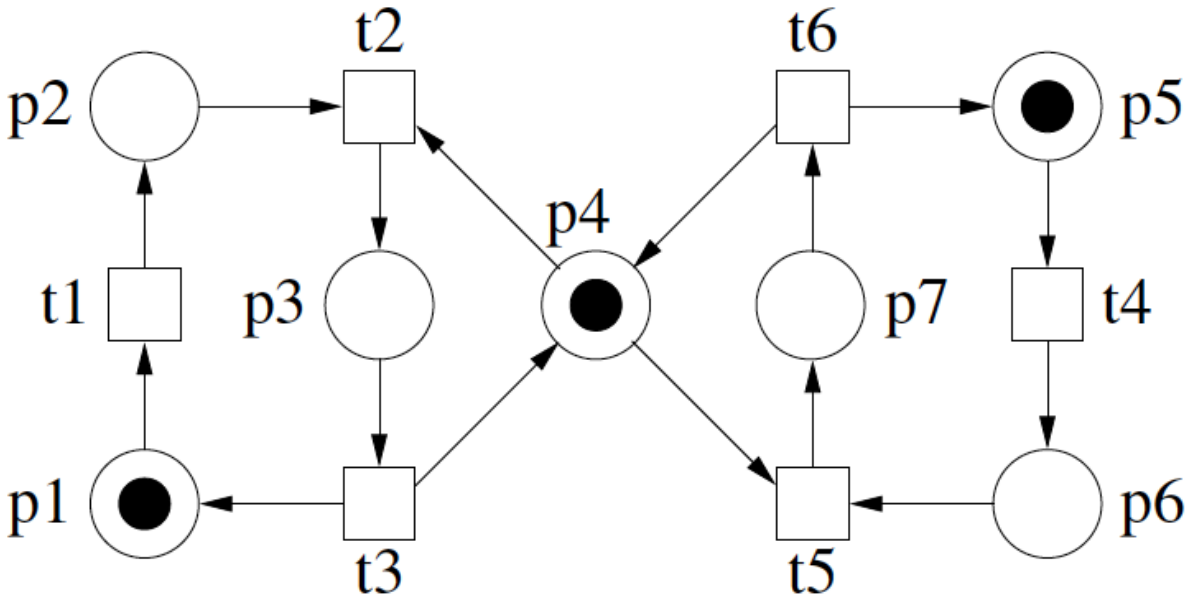
Here:

PN Techniques and Concurrency in

- Engineering
- Life Sciences

Nets and Concurrency

Formalize !



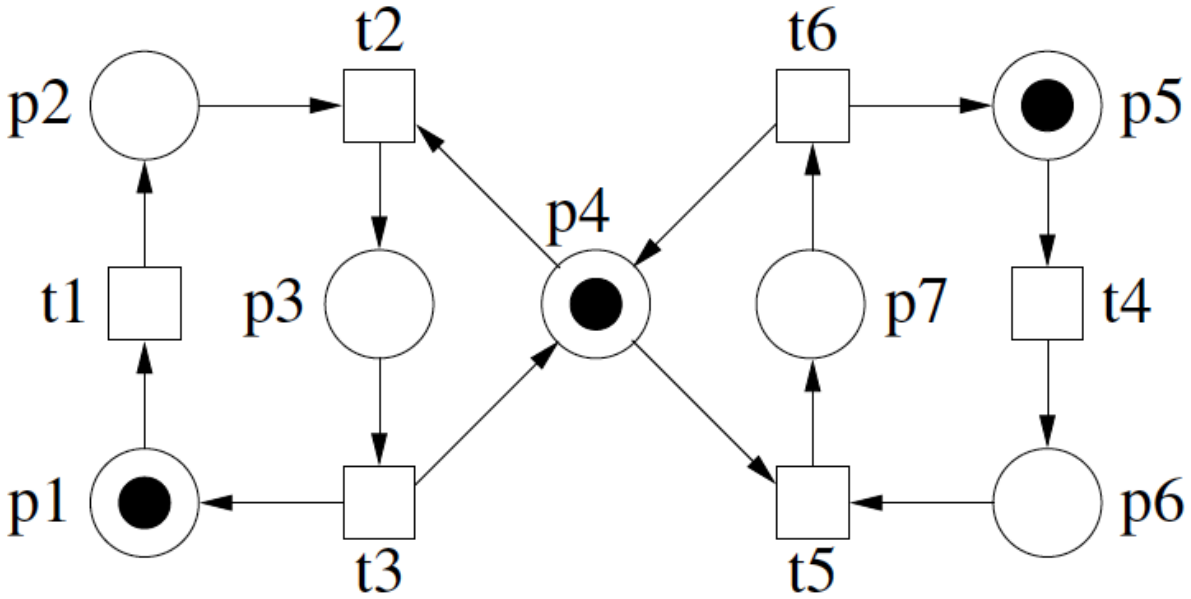
NET : $N = (P, T, F)$

- $P \cap T = \emptyset$, and
- $F \subseteq (P \times T \cup T \times P)$

$\mathcal{N} = (N, M_0)$ is a Petri net iff

- N is a net
- $M_0 : P \to \mathbb{N}_0$ a marking of N

Matrix Representation



Incidence Matrix

$$\begin{pmatrix} -1 & 0 & 1 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & -1 & 10 \\ 0 & 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \end{pmatrix} 0$$

Incidence Matrix and Invariants

Incidence Matrix $N \in \mathbb{Z}^{|P| \times |t|}$

$$N_{(p,t)} = \begin{cases} -1 & : \quad p \; F \; t \\ 1 & : \quad t \; F \; p \\ 0 & : \quad o/w \end{cases}$$

(note: we assume there are no loops)

State change equation

For $X, M, M' \in \mathbb{Z}^{|P|}$, $M \xrightarrow{t} M' \Leftrightarrow X^\top M' = X^\top M + X^\top W(t)$

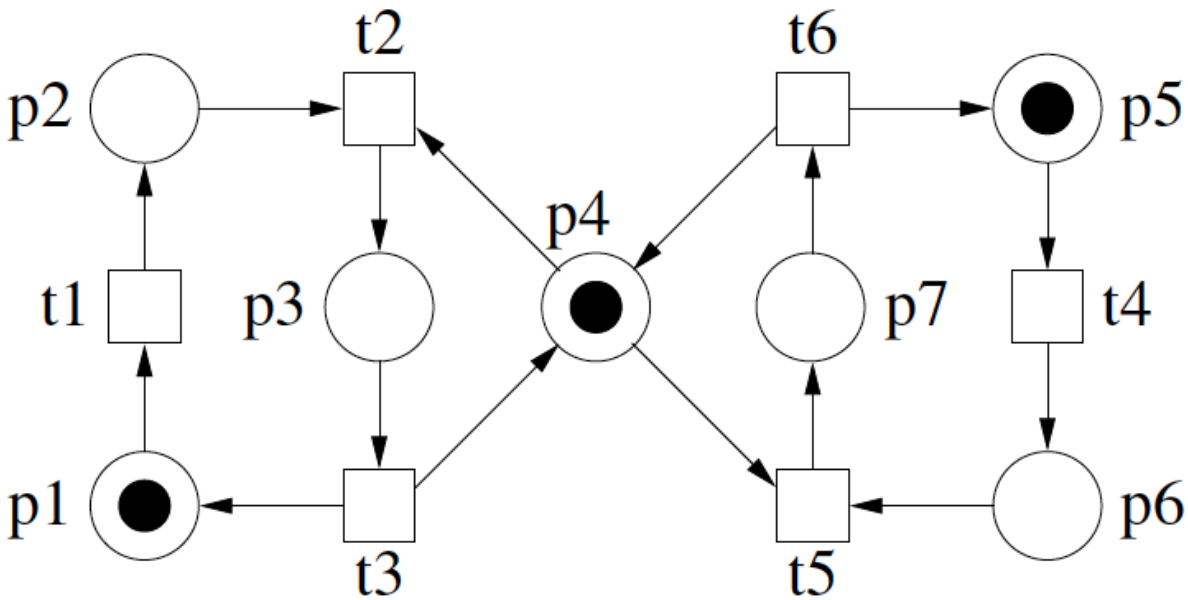
Definition

A non-negative and non-zero solution of

$$X^\top W(t) = 0$$

is a place invariant of N.

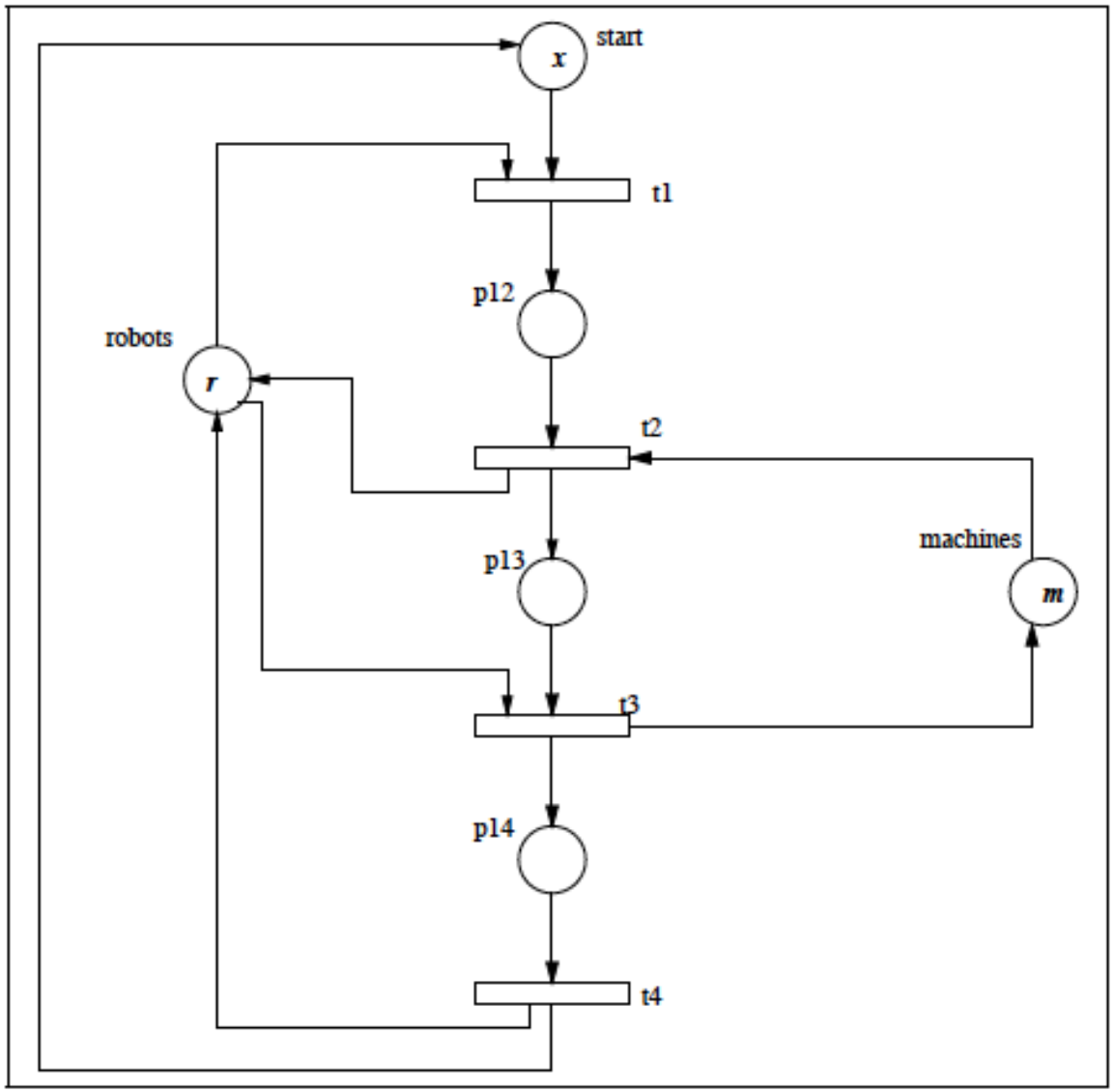
Running example



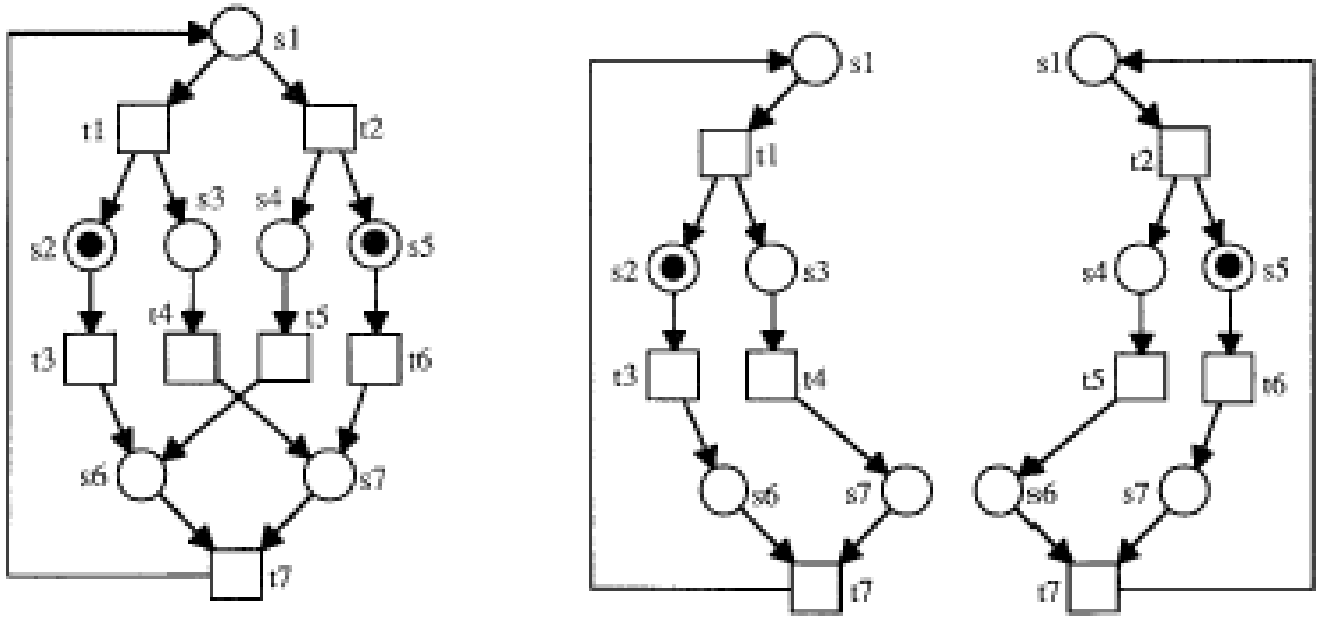
For all $M \in R(N, M_0)$,

$$\begin{aligned} M(p_1) + M(p2) + M(p3) &= 1 \\ M(p_5) + M(p6) + M(p7) &= 1 \\ M(p_3) + M(p4) + M(p7) &= 1 \end{aligned}$$

Production Systems



T - Invariants



$J \in \mathbb{N}_0^{|T|}$ is a *T-invariant* of N iff

$$A^t \cdot J \quad = \quad 0$$

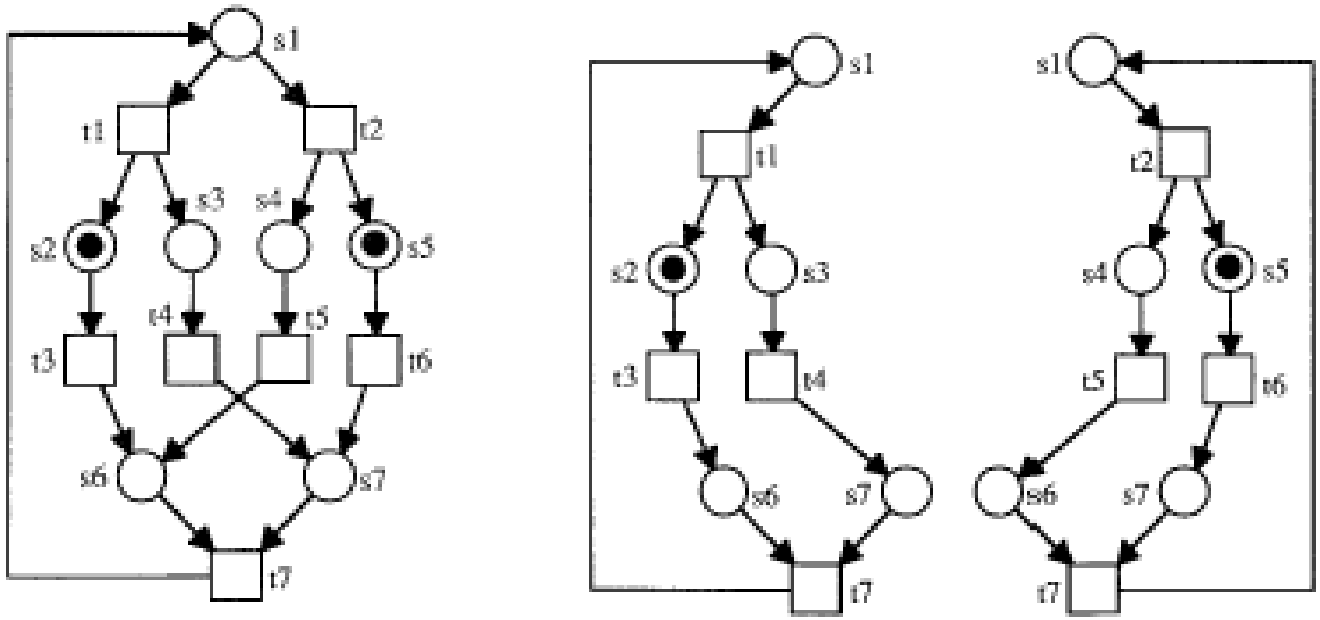
If $M_0 \xrightarrow{\sigma_J}$ for some $\sigma_J \in T^*$ such that

$$\forall\ t \in T:\ \ J\,(t) \quad = \quad |\sigma_J|_t,$$

then

$$A^t \cdot J = 0 \quad \Rightarrow \quad M_0 \xrightarrow{\sigma_J} M_0.$$

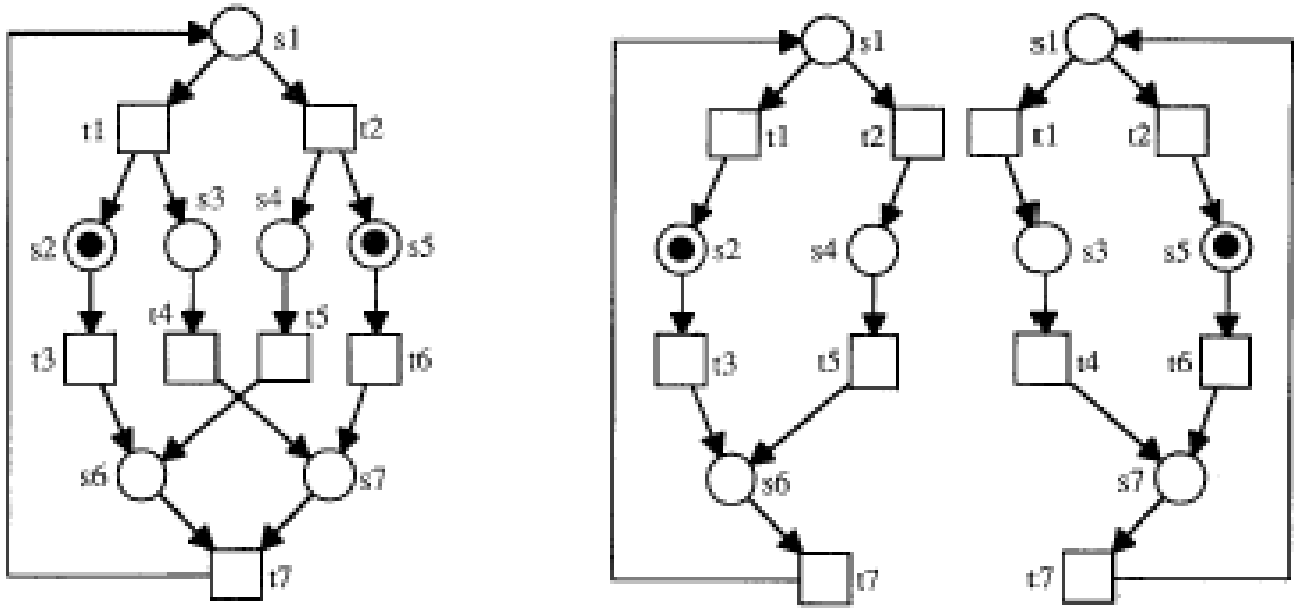
Comparison of Invariants



T-invariants

- Help find state-reproducing behaviors
- Exhibit "typical" processes
- Give hints on liveness

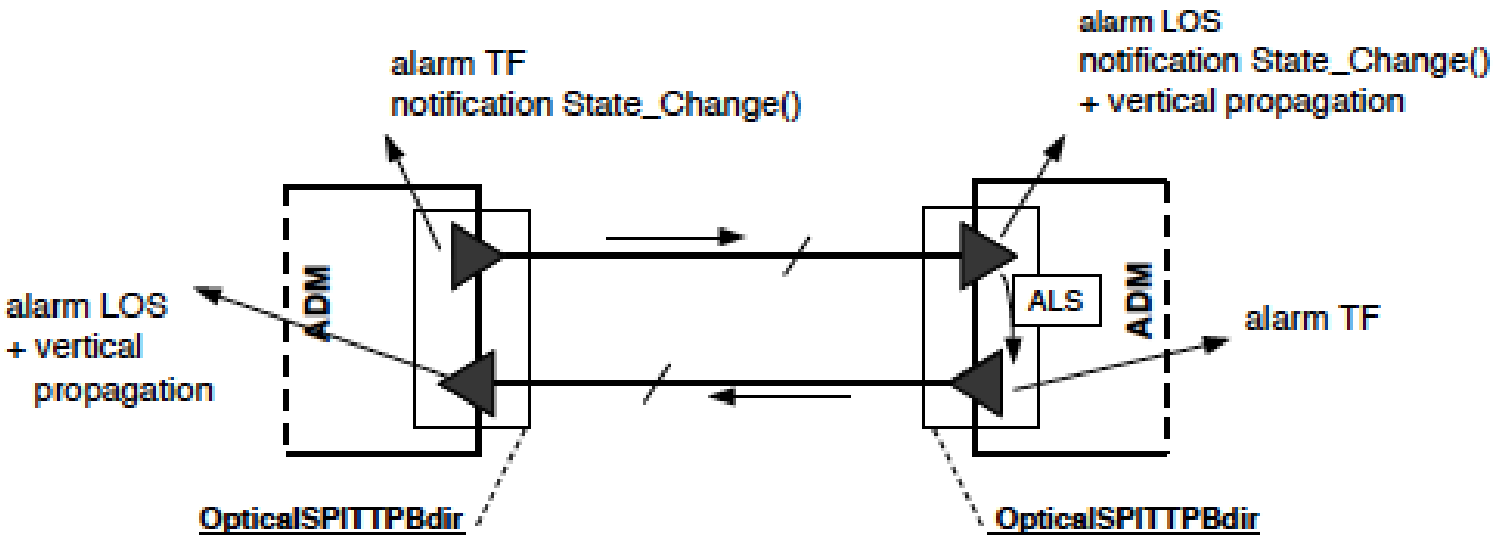
Comparison of Invariants



P-invariants

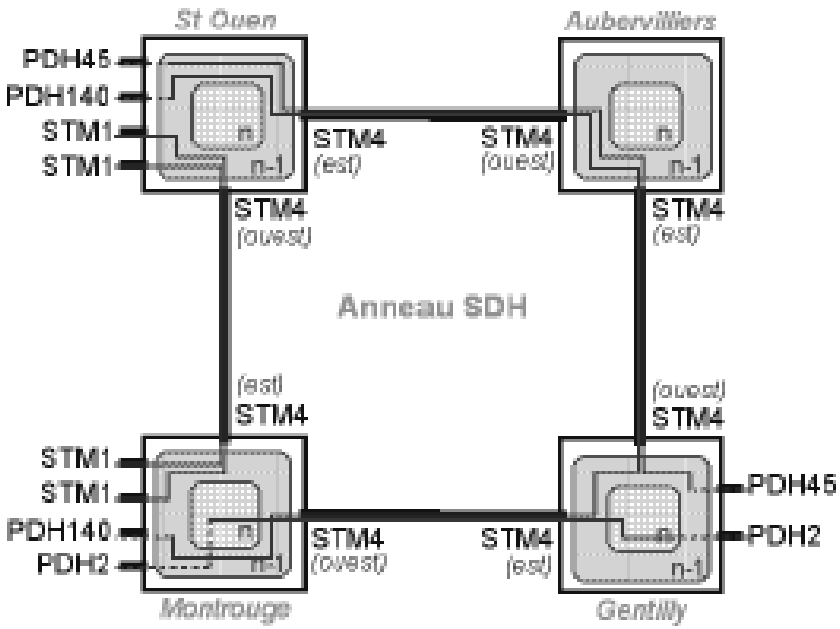
- Help express properties satisfied by all reachable markings
- Tell if the system is bounded $\rightarrow$ safety properties
- May allow decomposition
- Useful in control and supervision
- Next: Telecommunications , or: when one needs unfoldings

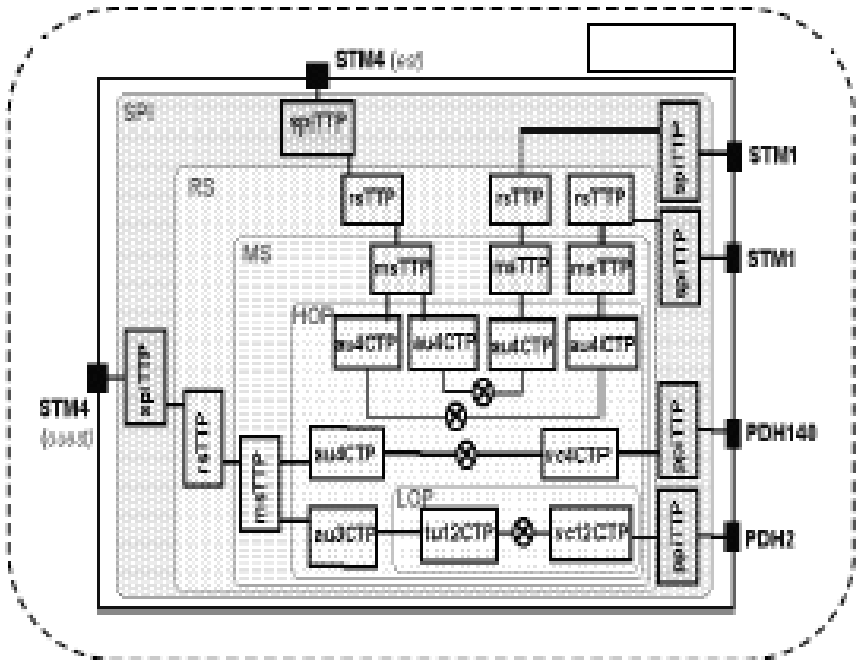
Telecommunications : need Fault Diagnosis



(Source: Benveniste et al, 2003)

Seeking a Needle in a Haystack





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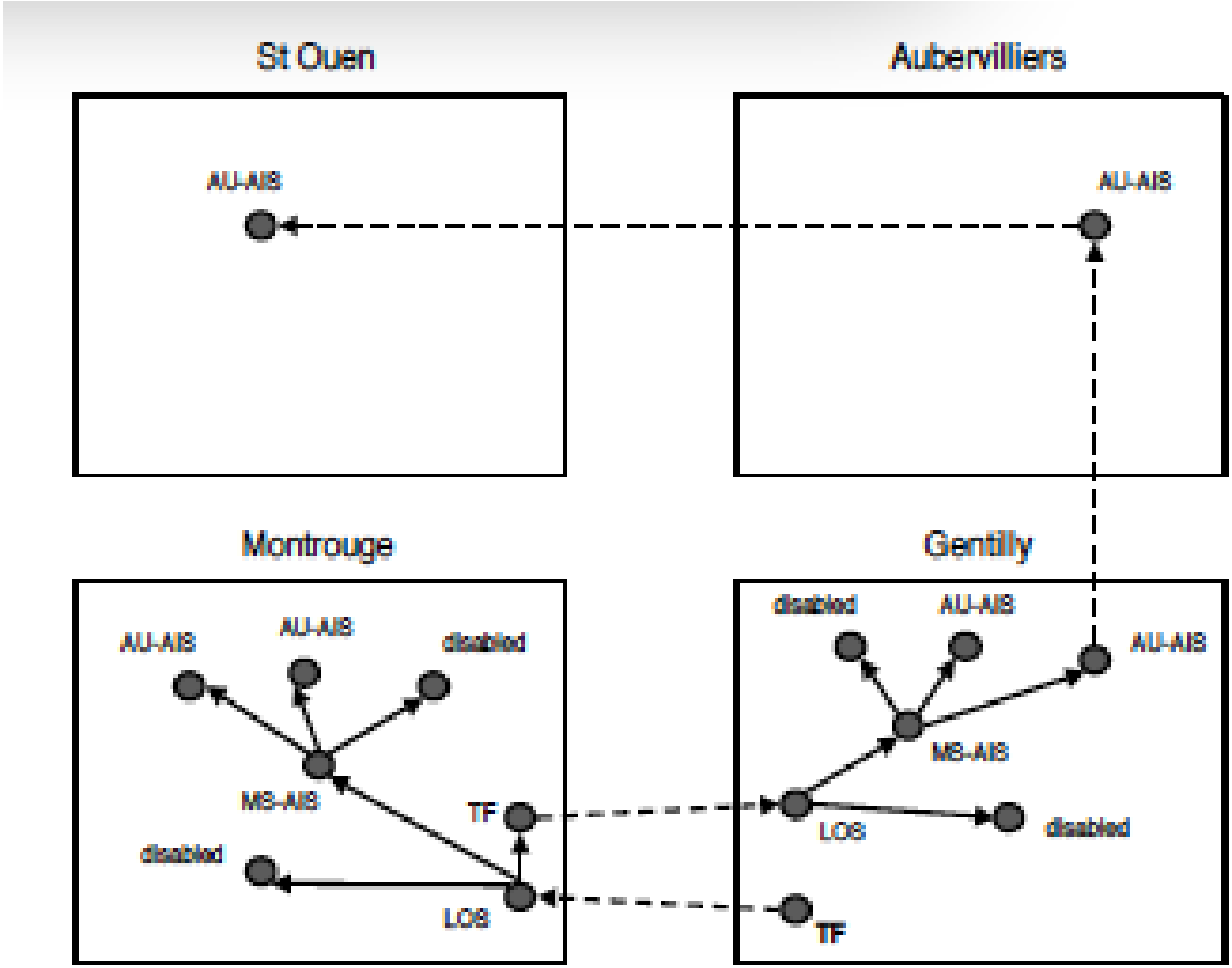

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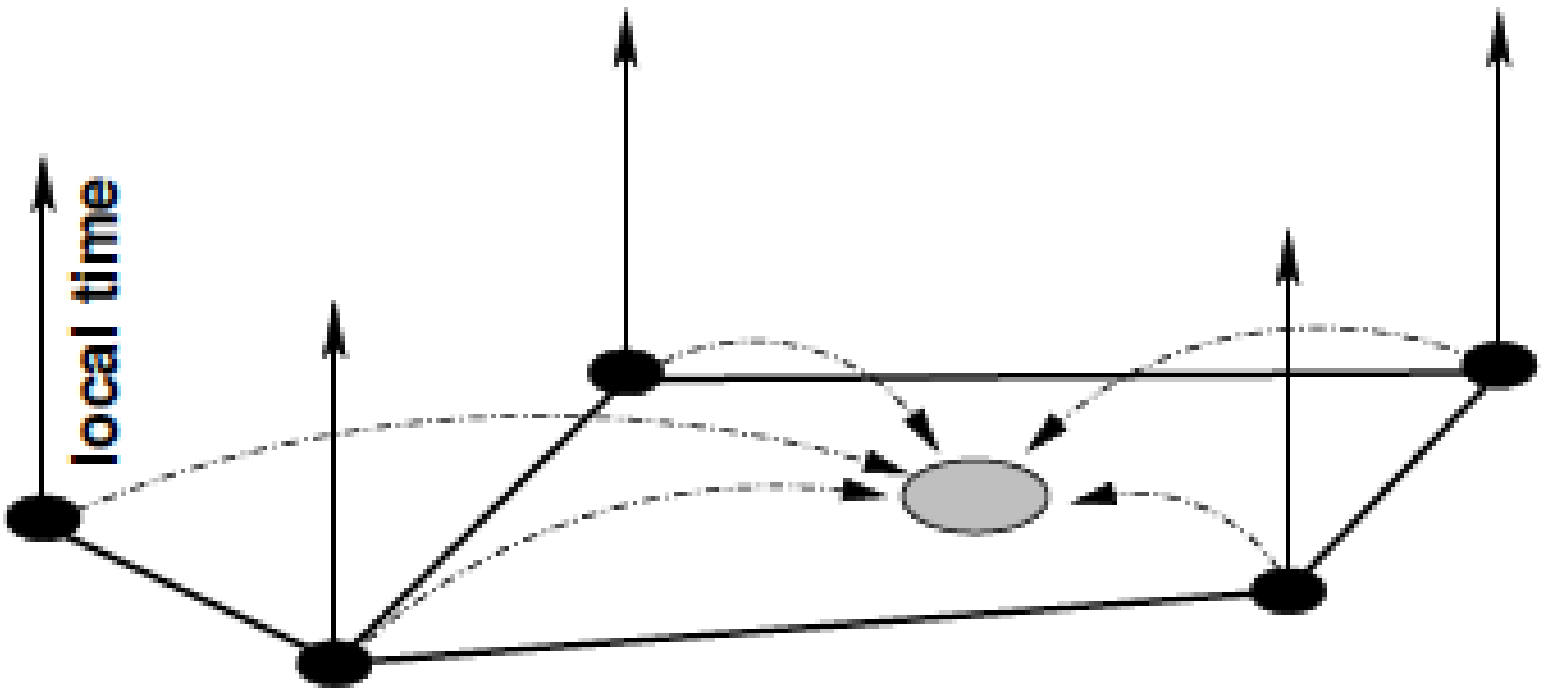

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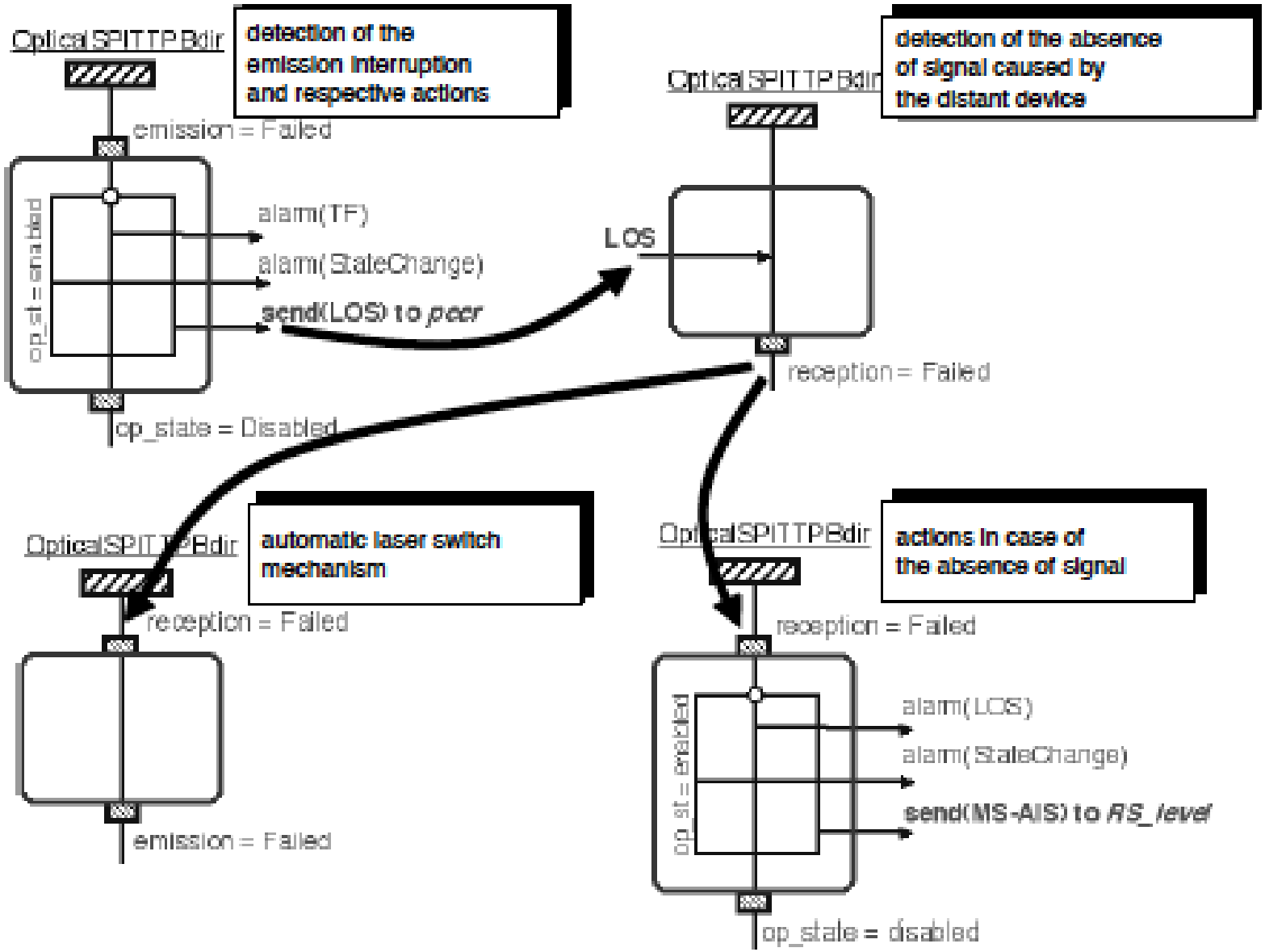
Reduce Complexity: Fault modeling



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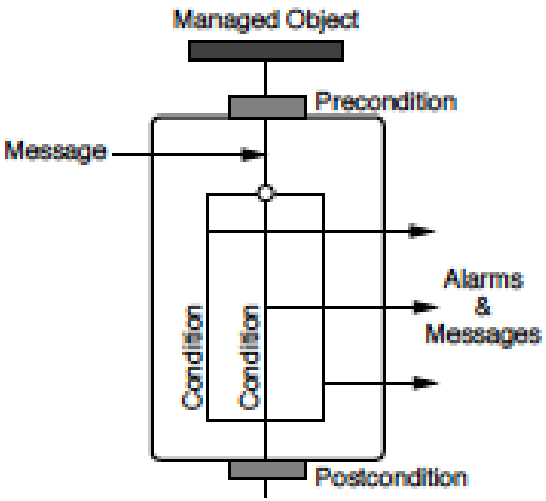
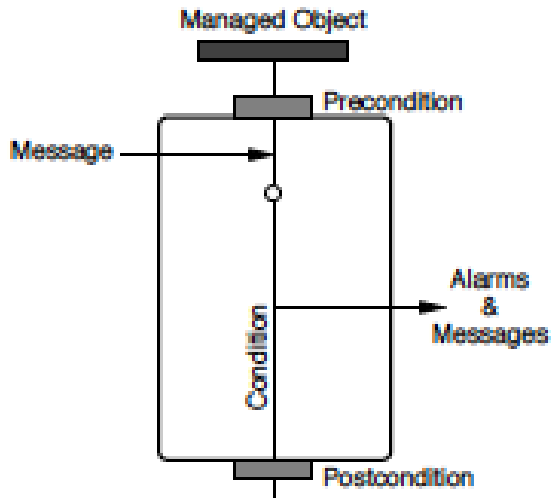
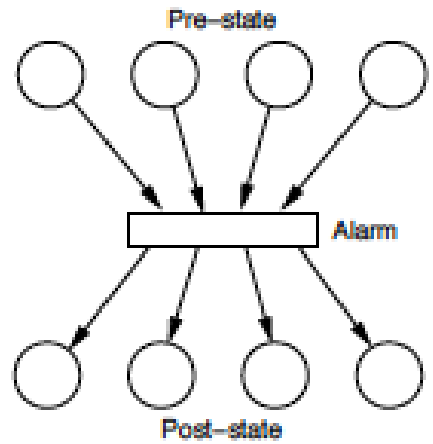
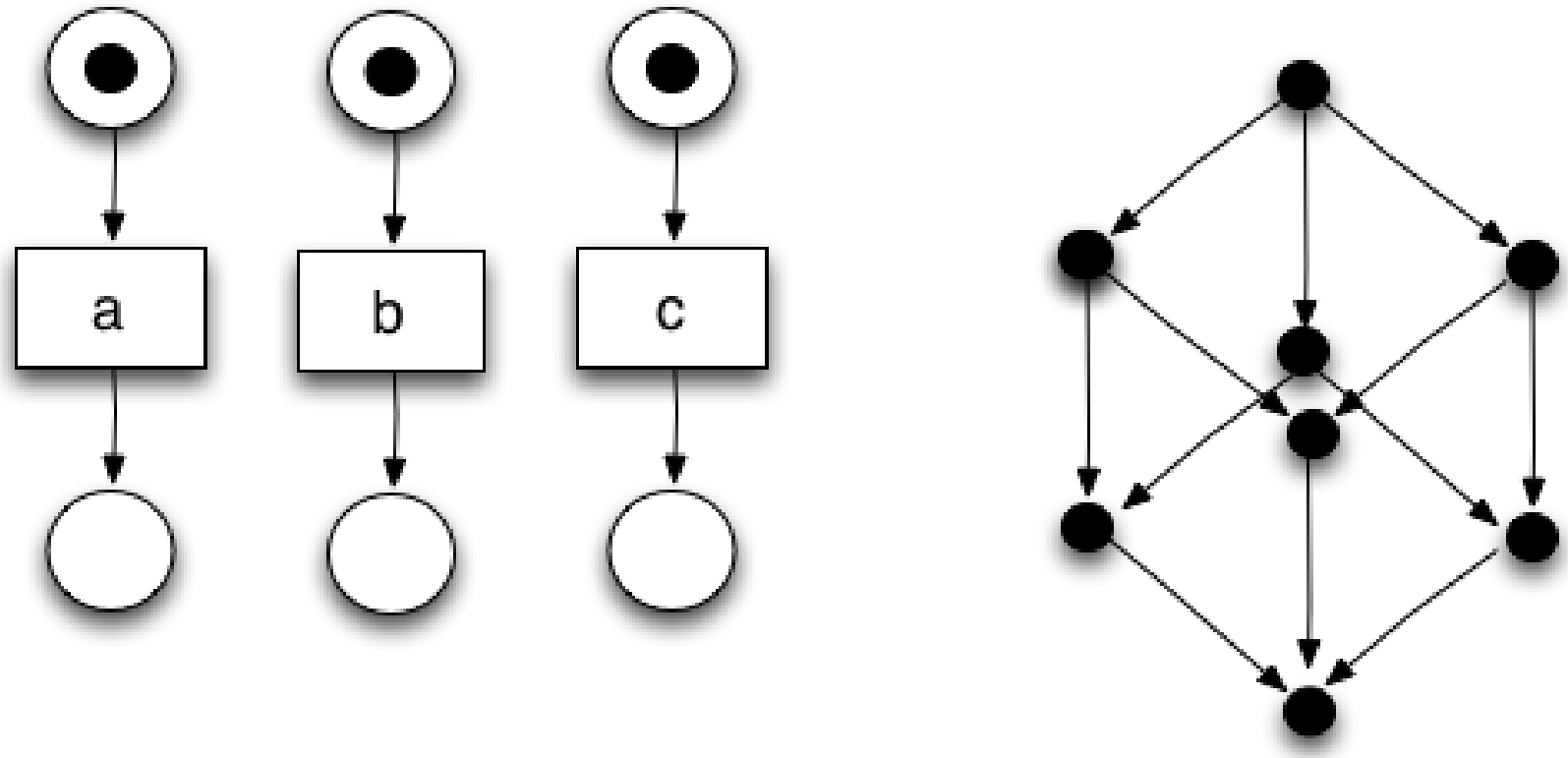






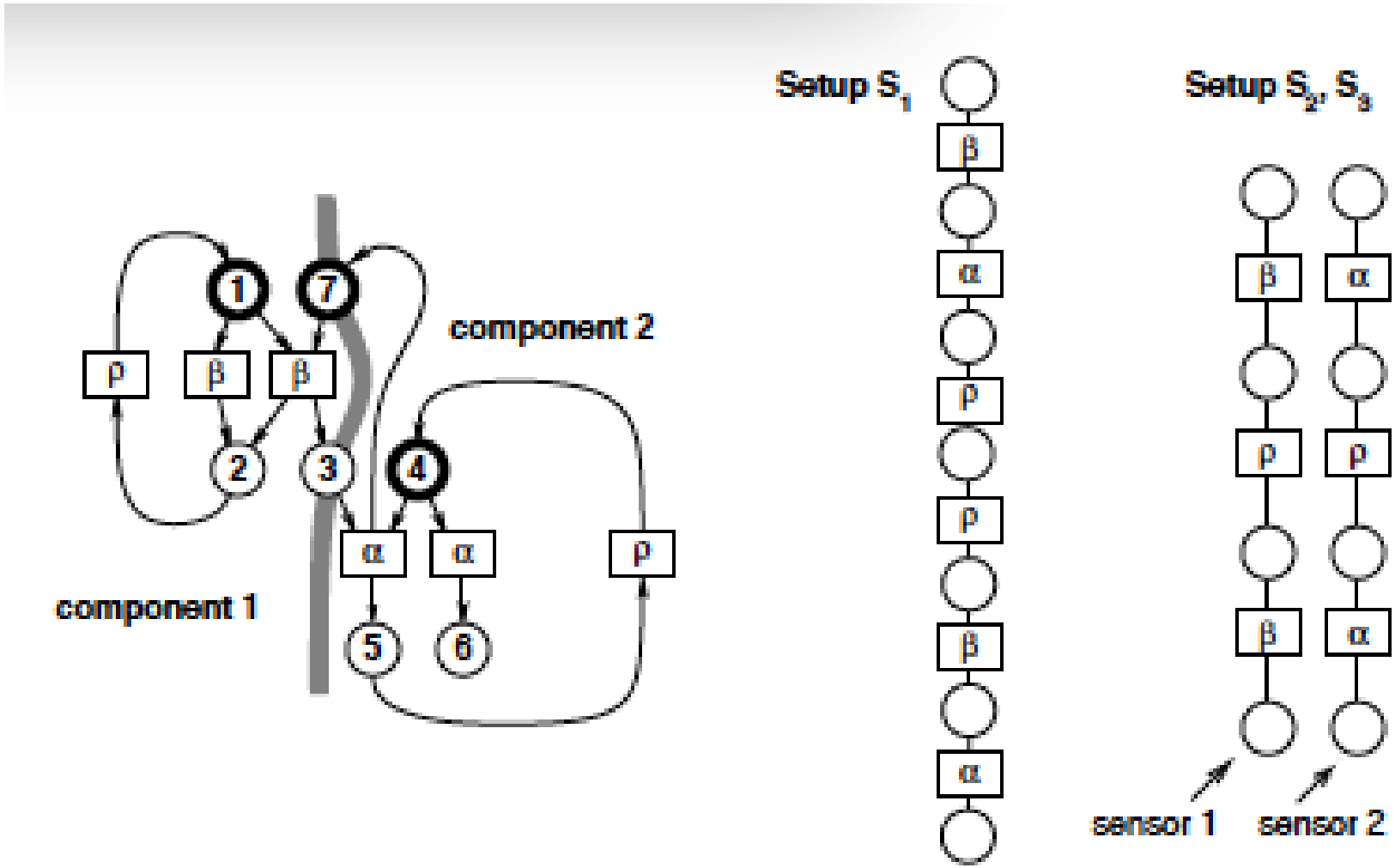
(Source: Benveniste et al, 2003)

Reduce Size: True Concurrency



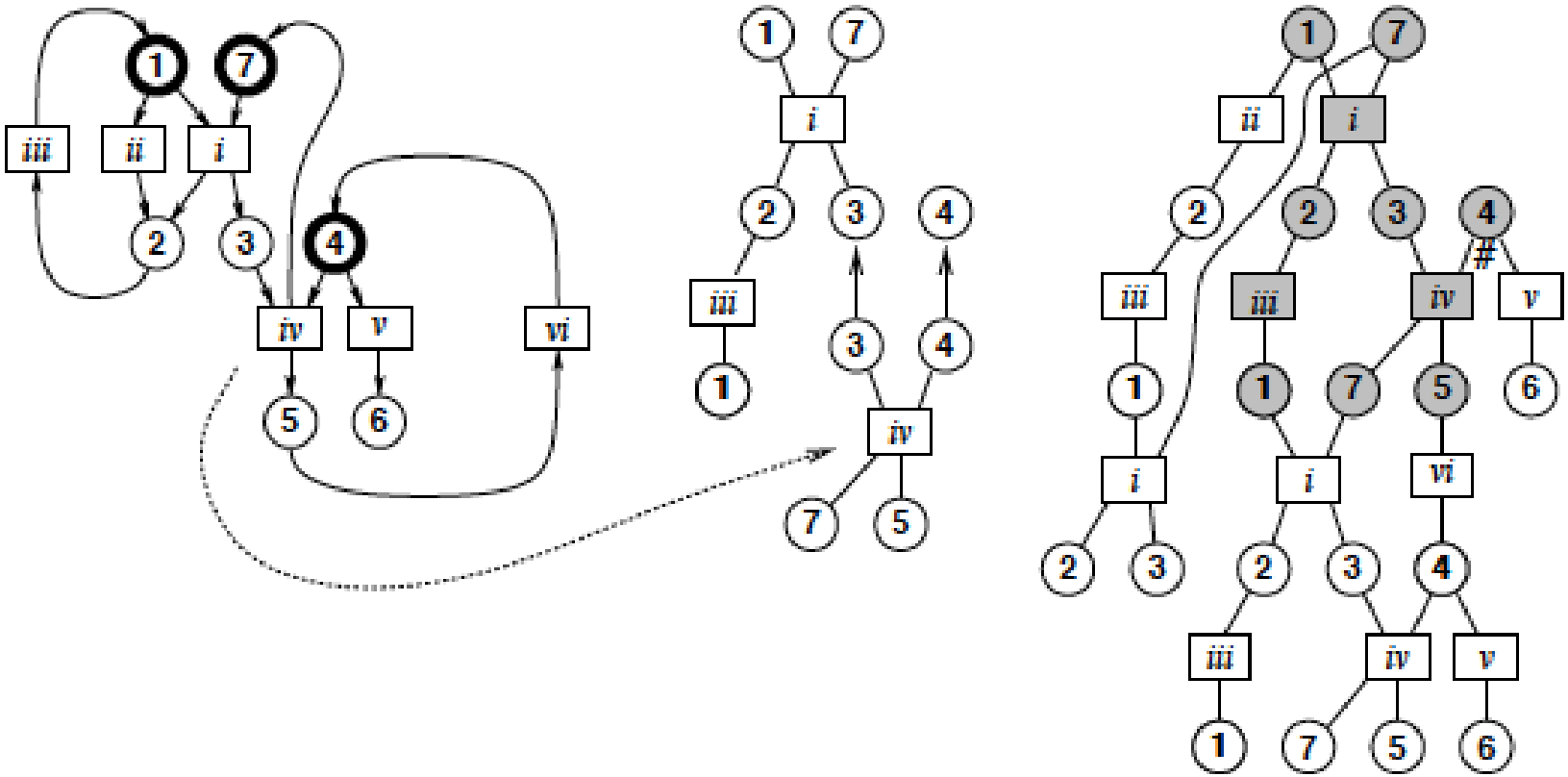
(Source: Benveniste et al, 2003)

PN as Propagation + Observation Model



(Source: Benveniste et al, 2003)

Finding behaviors: unfold



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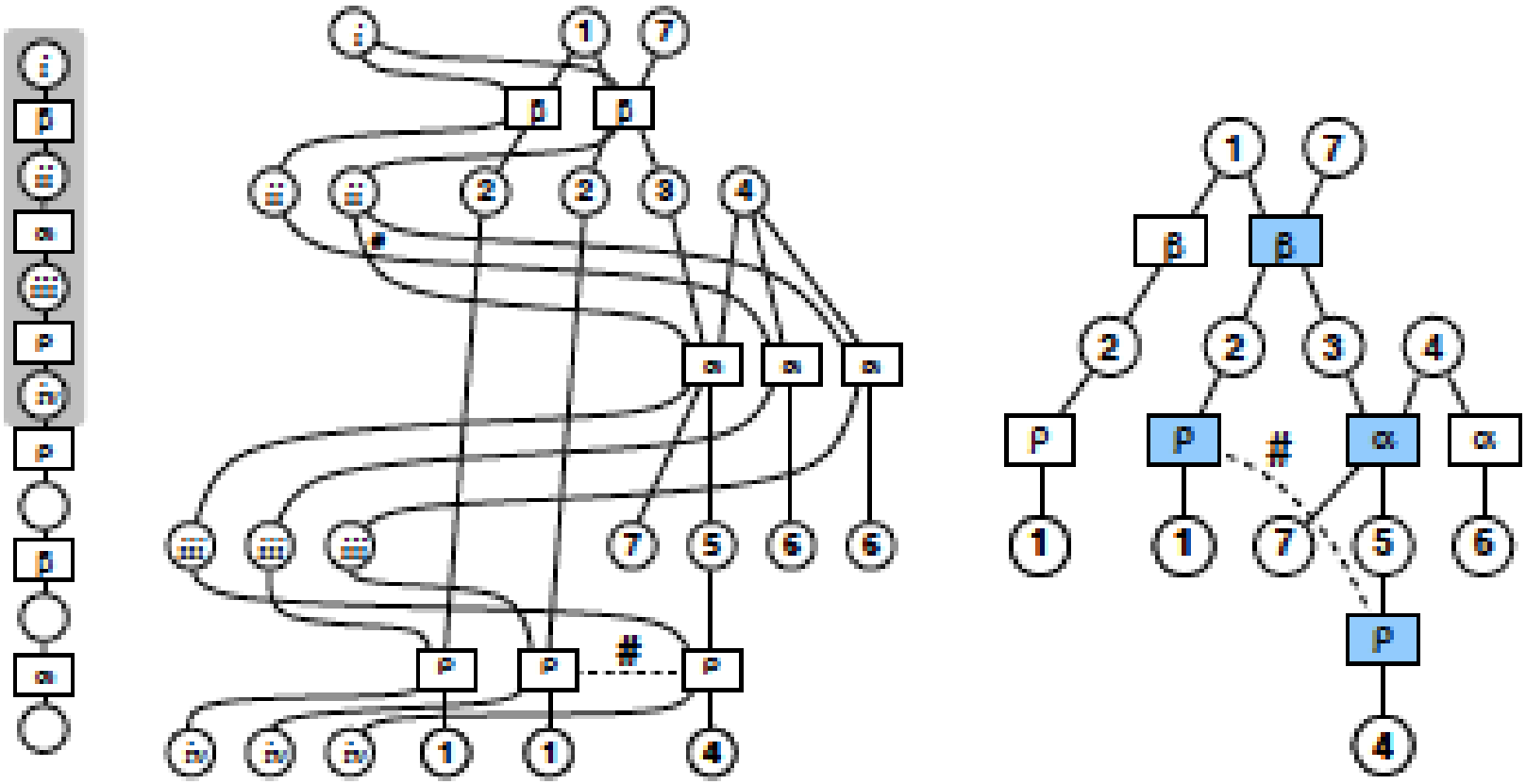
Finding explanations: Correlate and unfold



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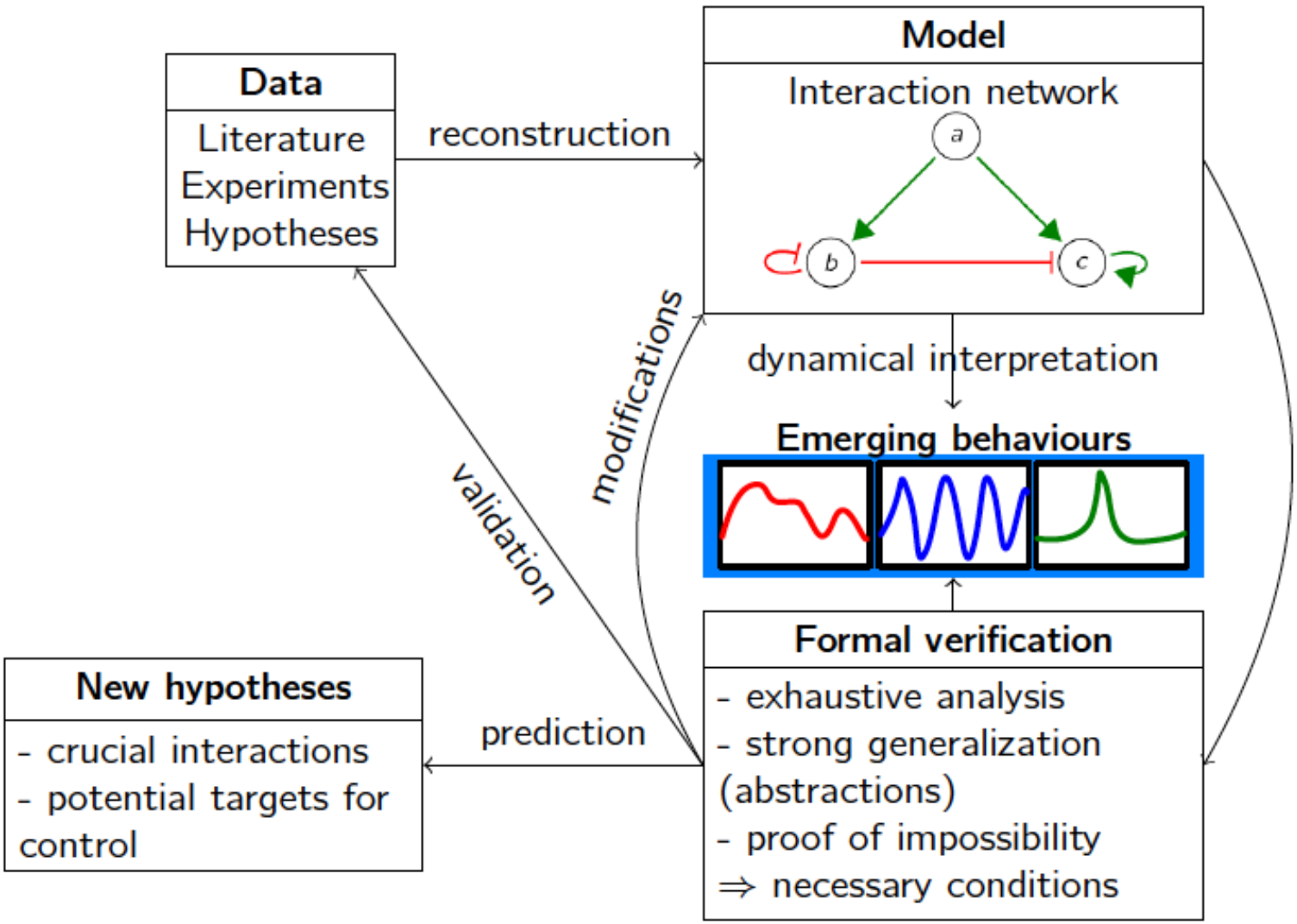
Nets and Concurrency

Systems Biology needs Formal Methods

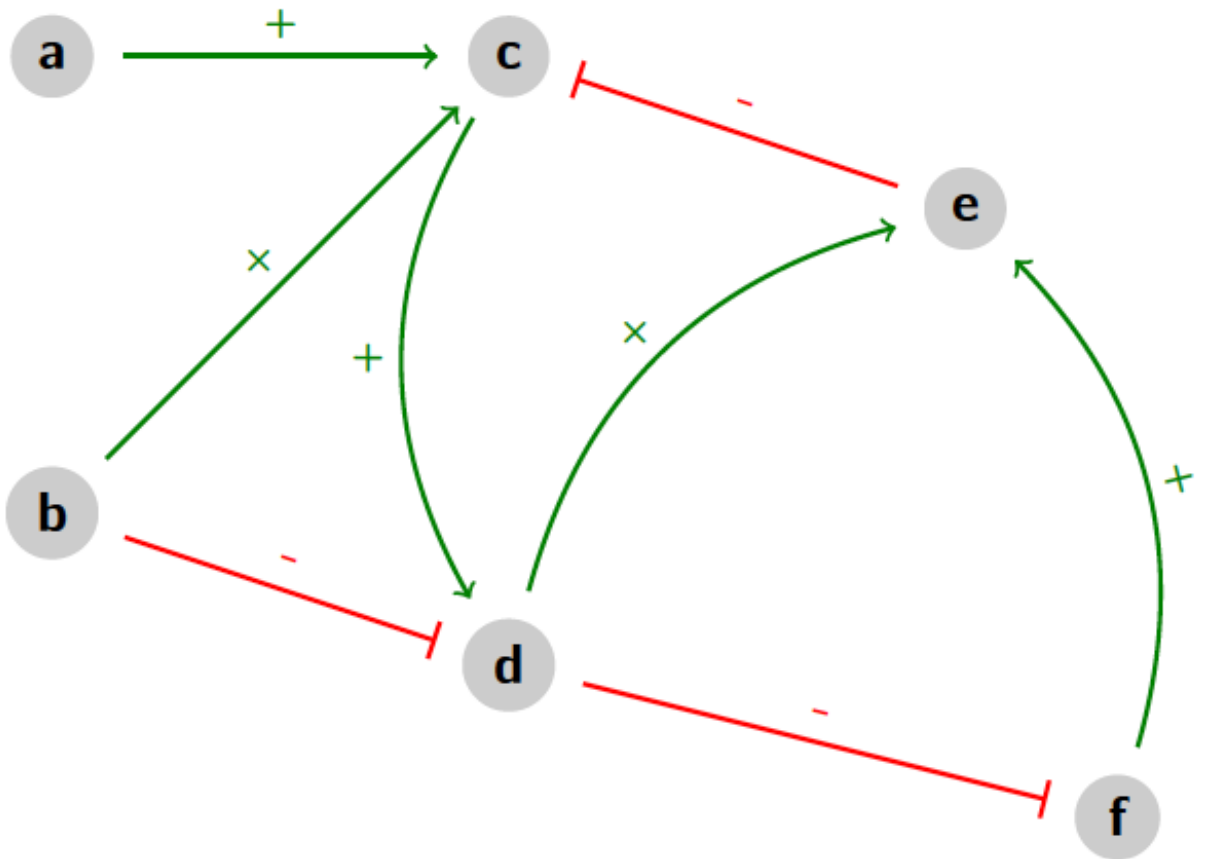
Aim: **understand, analyse, control** emerging dynamics.



Source : L. Paulevé

Biological Networks

E.g., Gene Regulatory Networks, Signalling Networks



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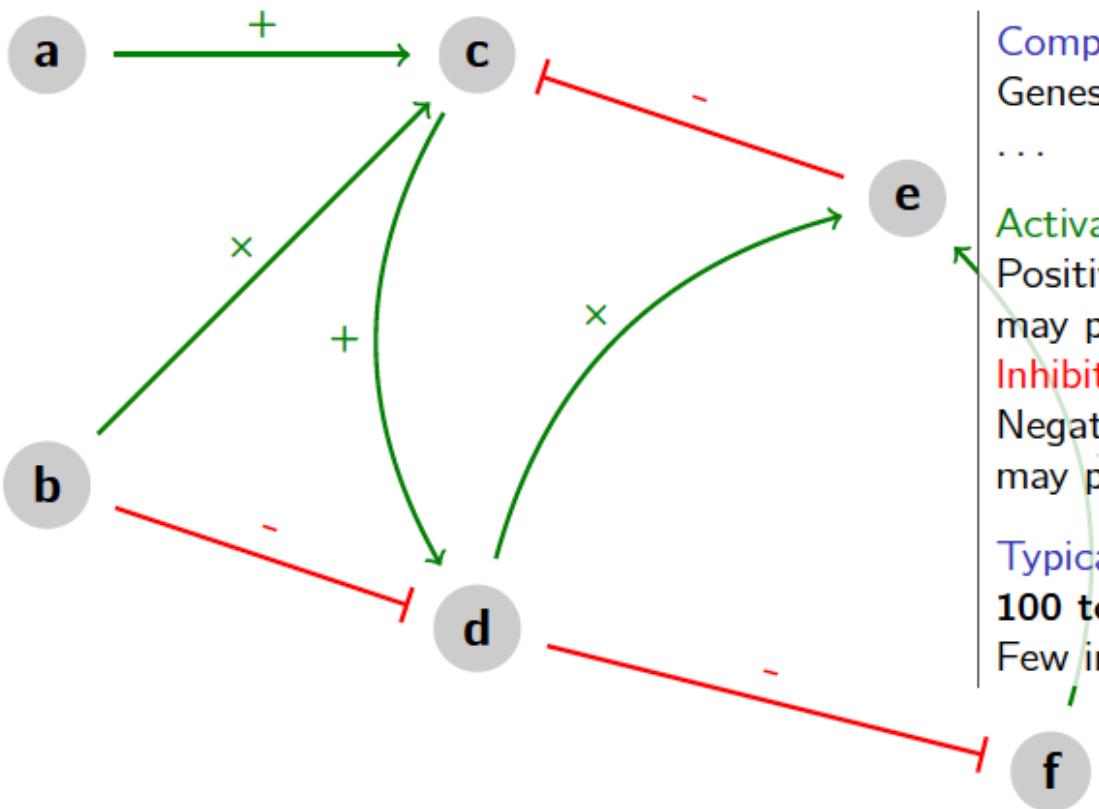


Components
Genes, proteins, complexes, ...

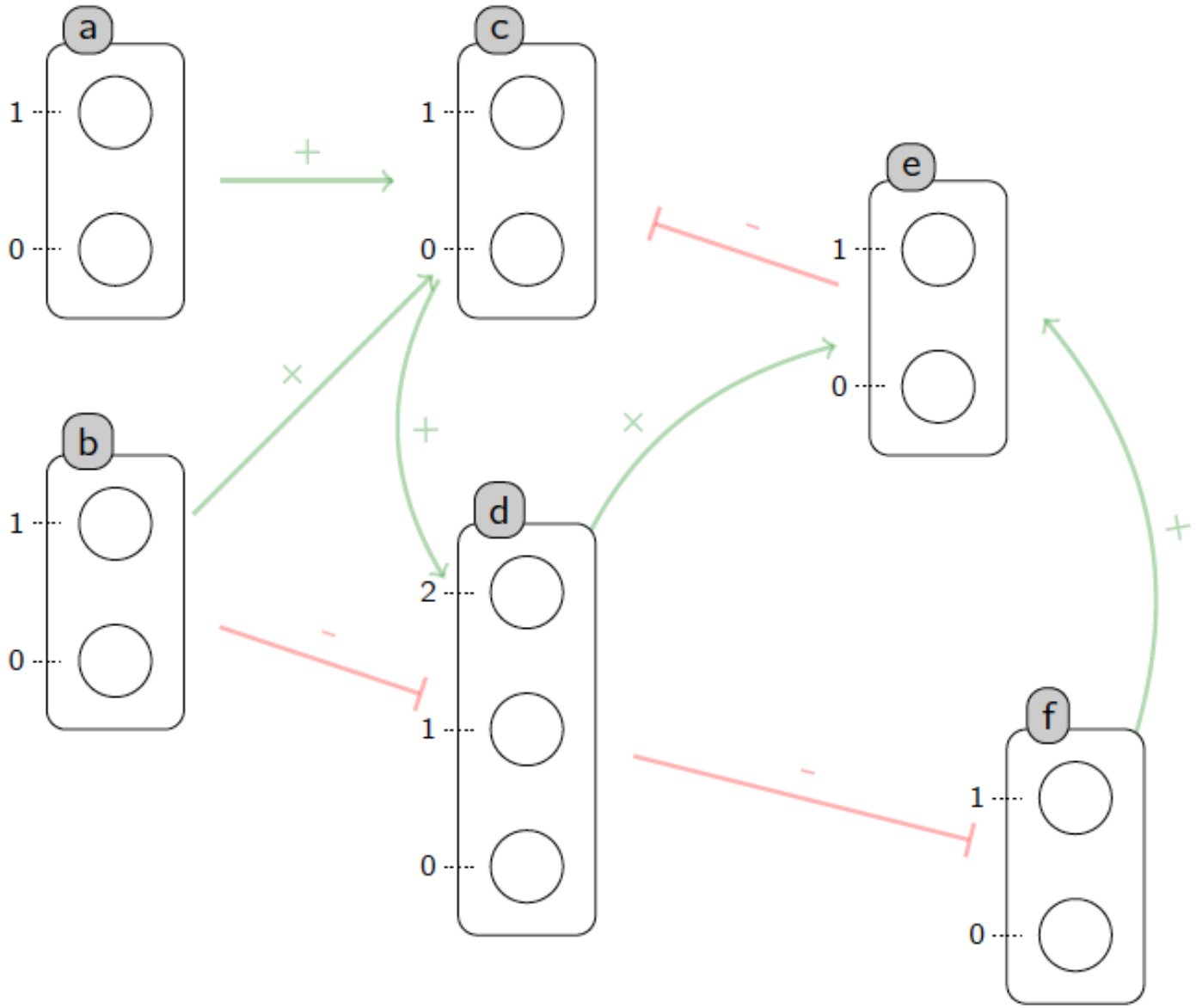
Activations
Positive influence (*a* increase may promote *c* increase).

Inhibitions
Negative influence (*b* increase may promote *d* decrease).

Typical settings
100 to +10,000 components
Few information on kinetics

Source : L. Paulevé

Qualitative Models for Biological Networks



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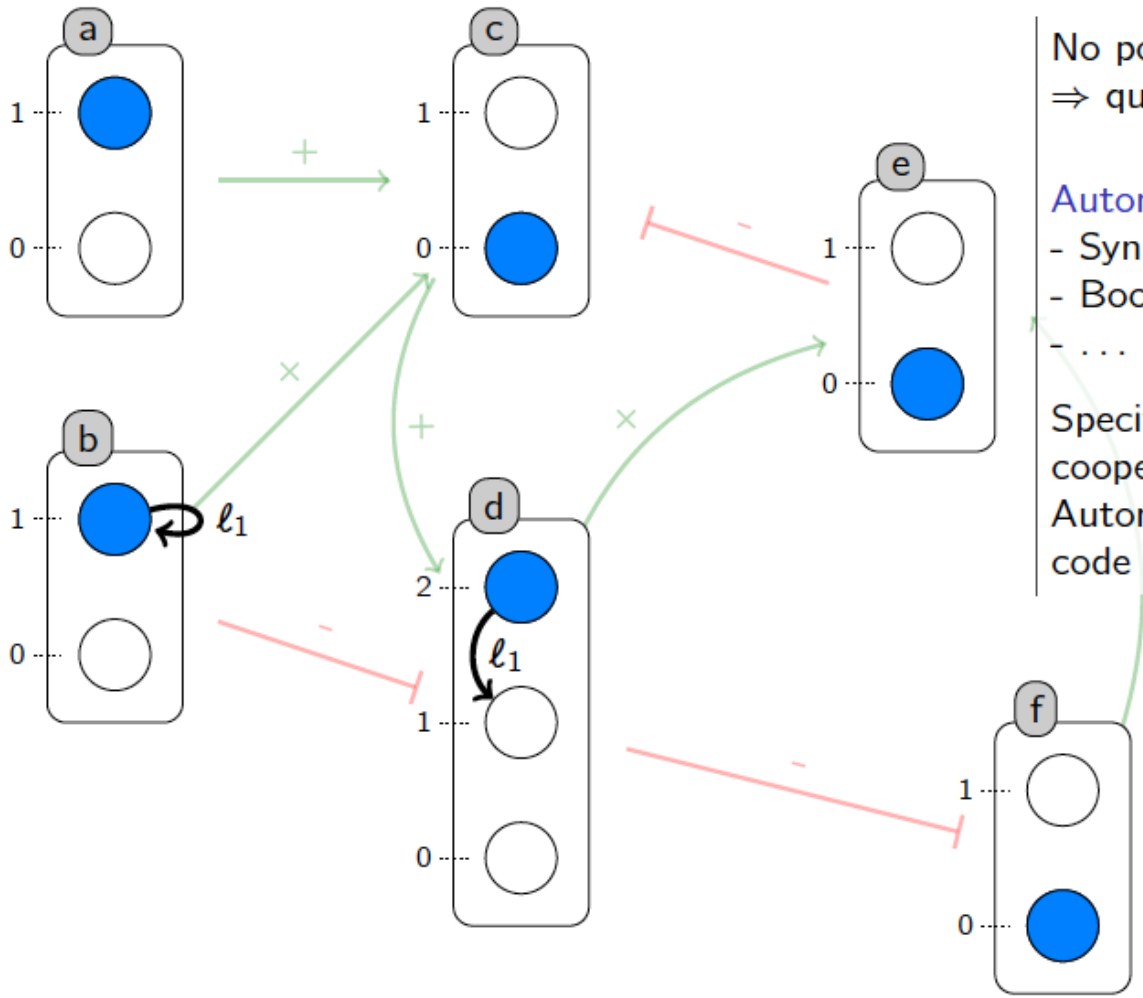


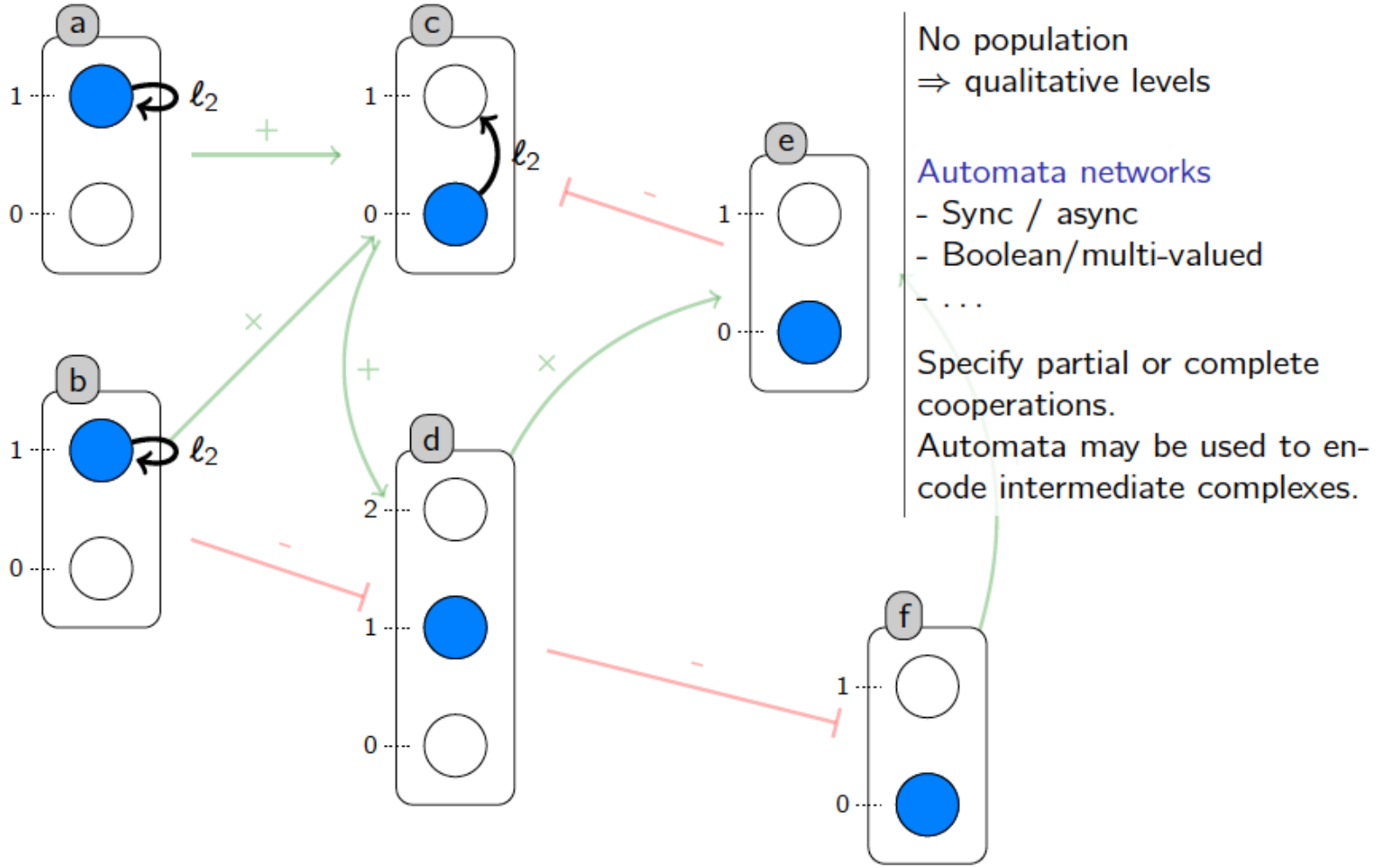
No population
⇒ qualitative levels

Automata networks
- Sync / async
- Boolean/multi-valued
- ...

Specify partial or complete cooperations.
Automata may be used to encode intermediate complexes.

Source : L. Paulevé

Qualitative Models for Biological Networks



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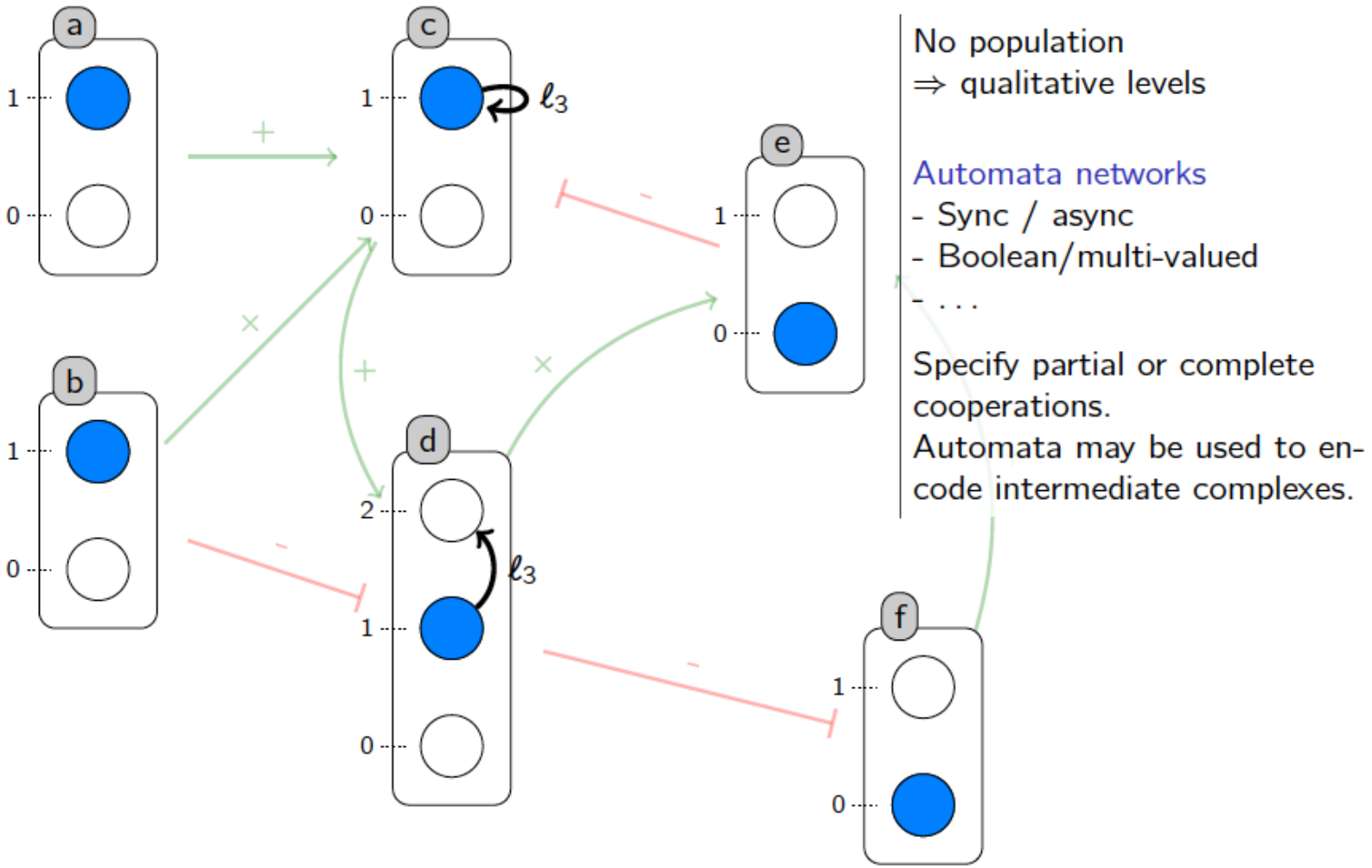

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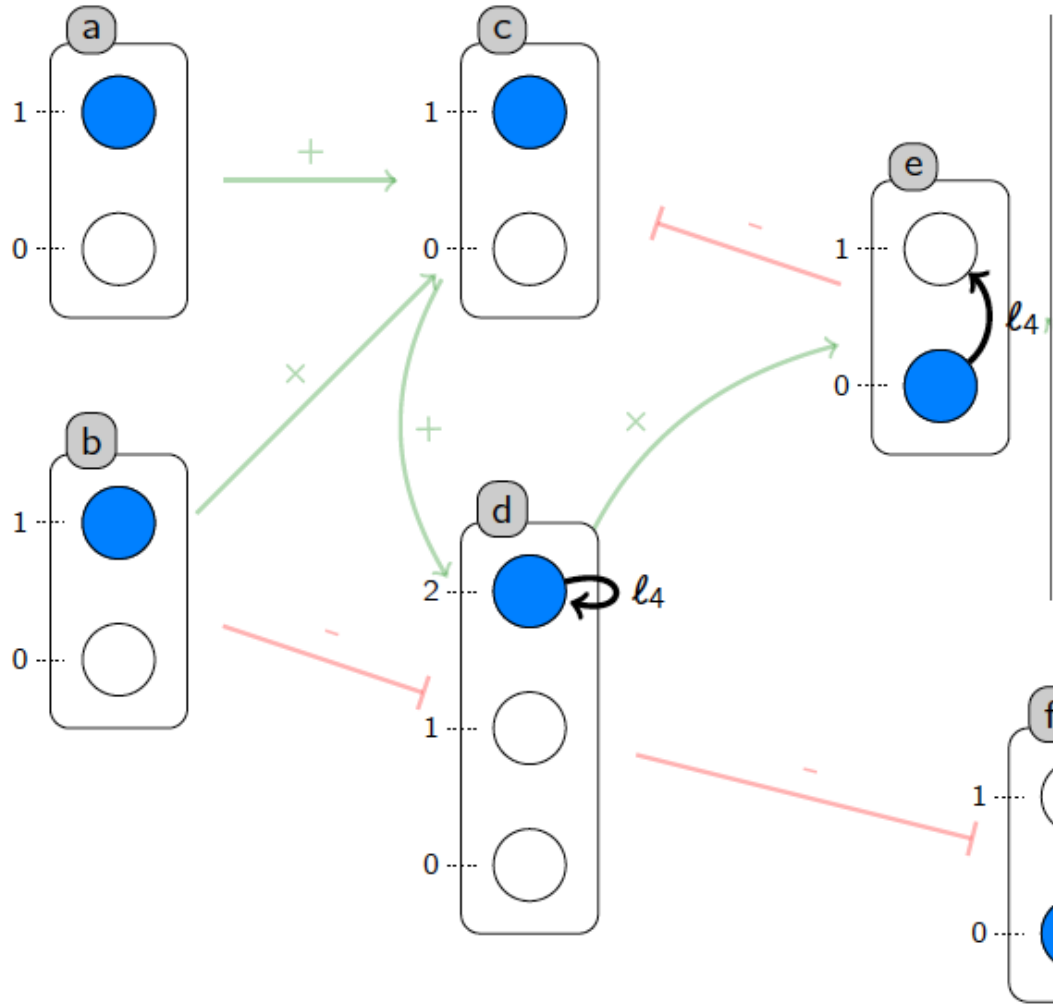

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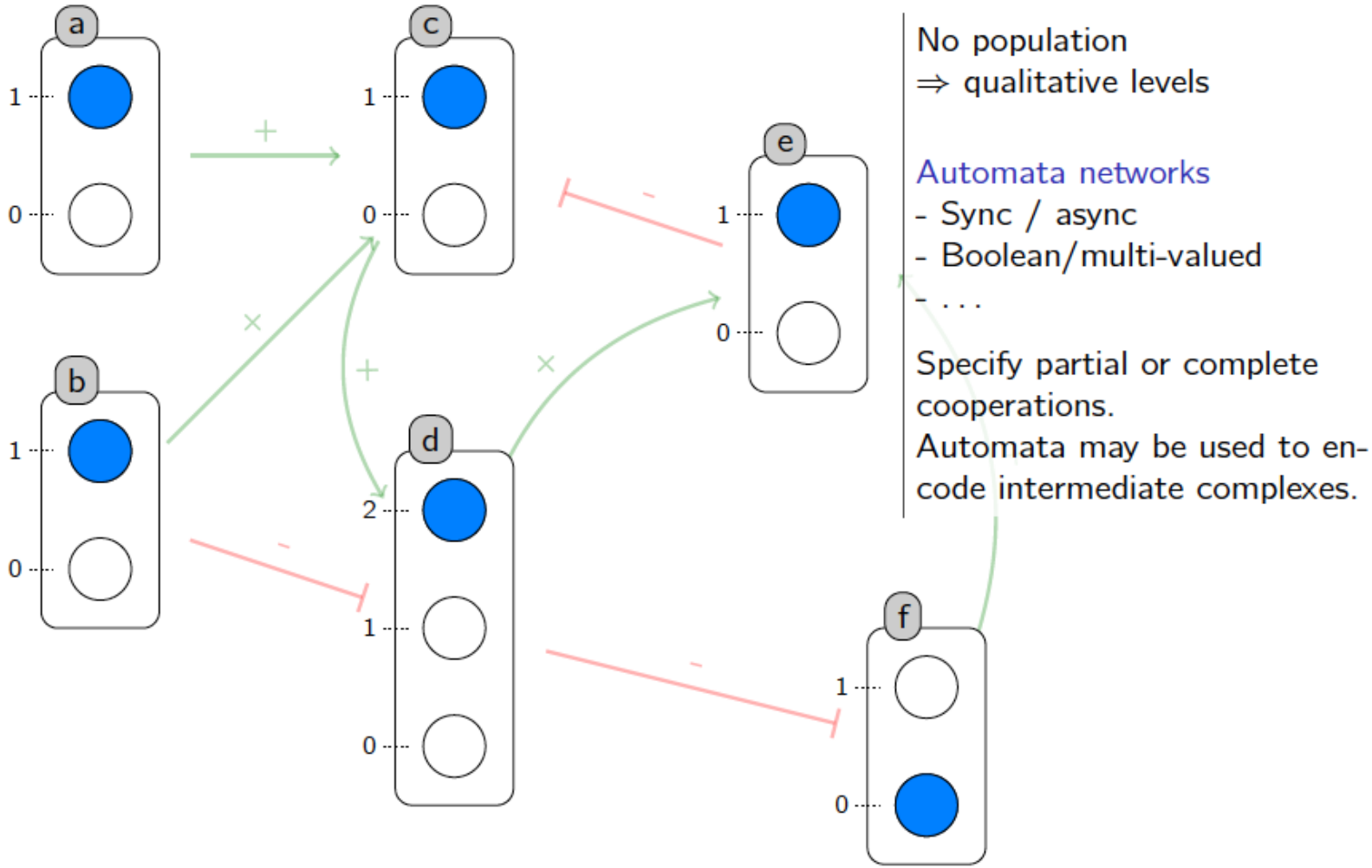

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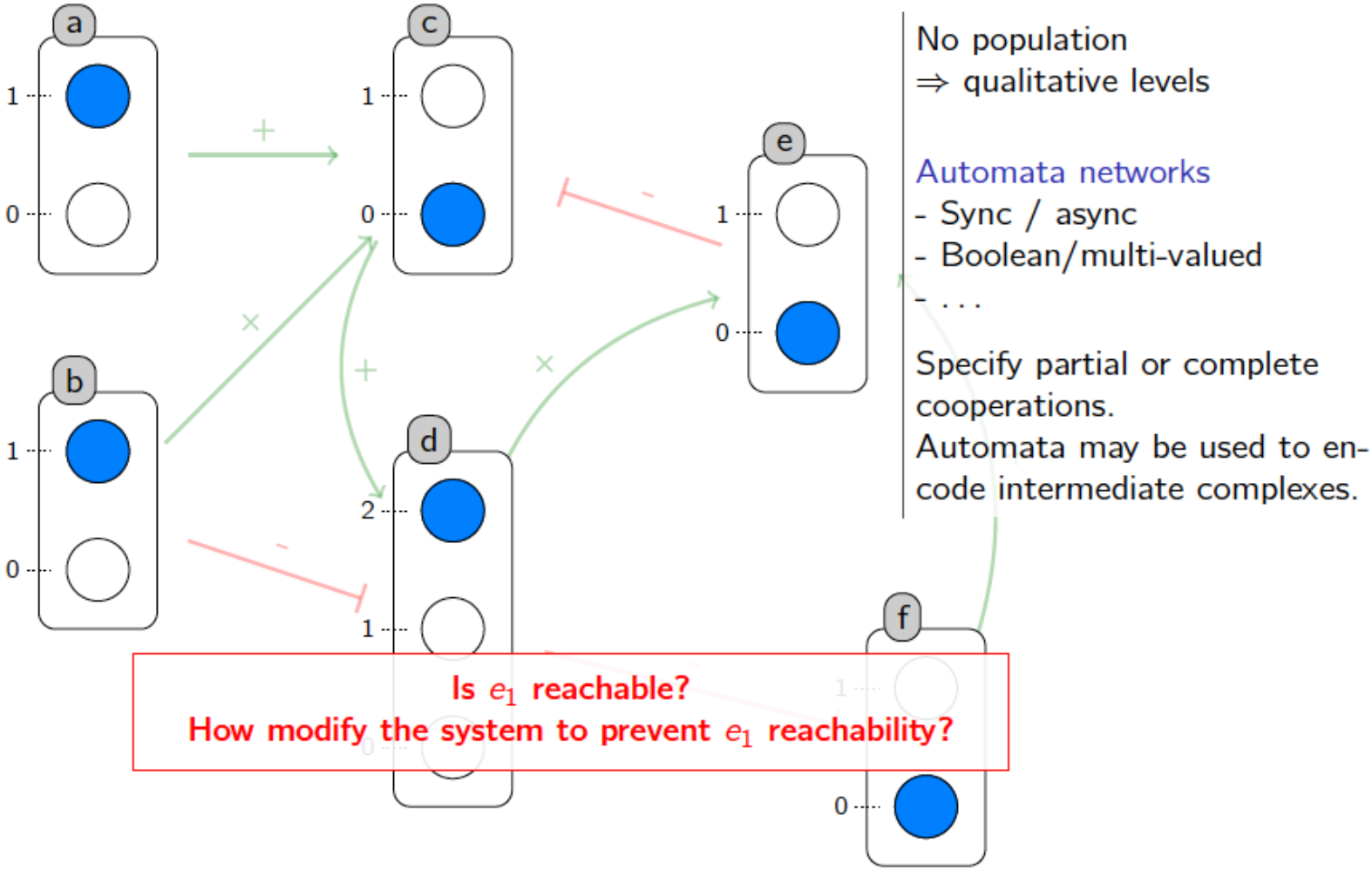
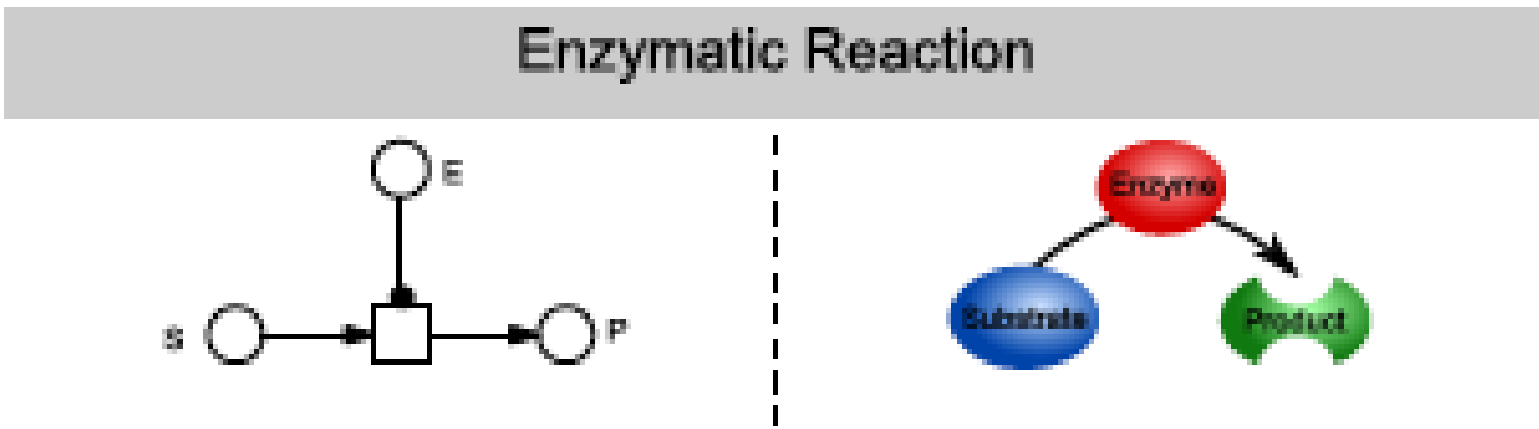


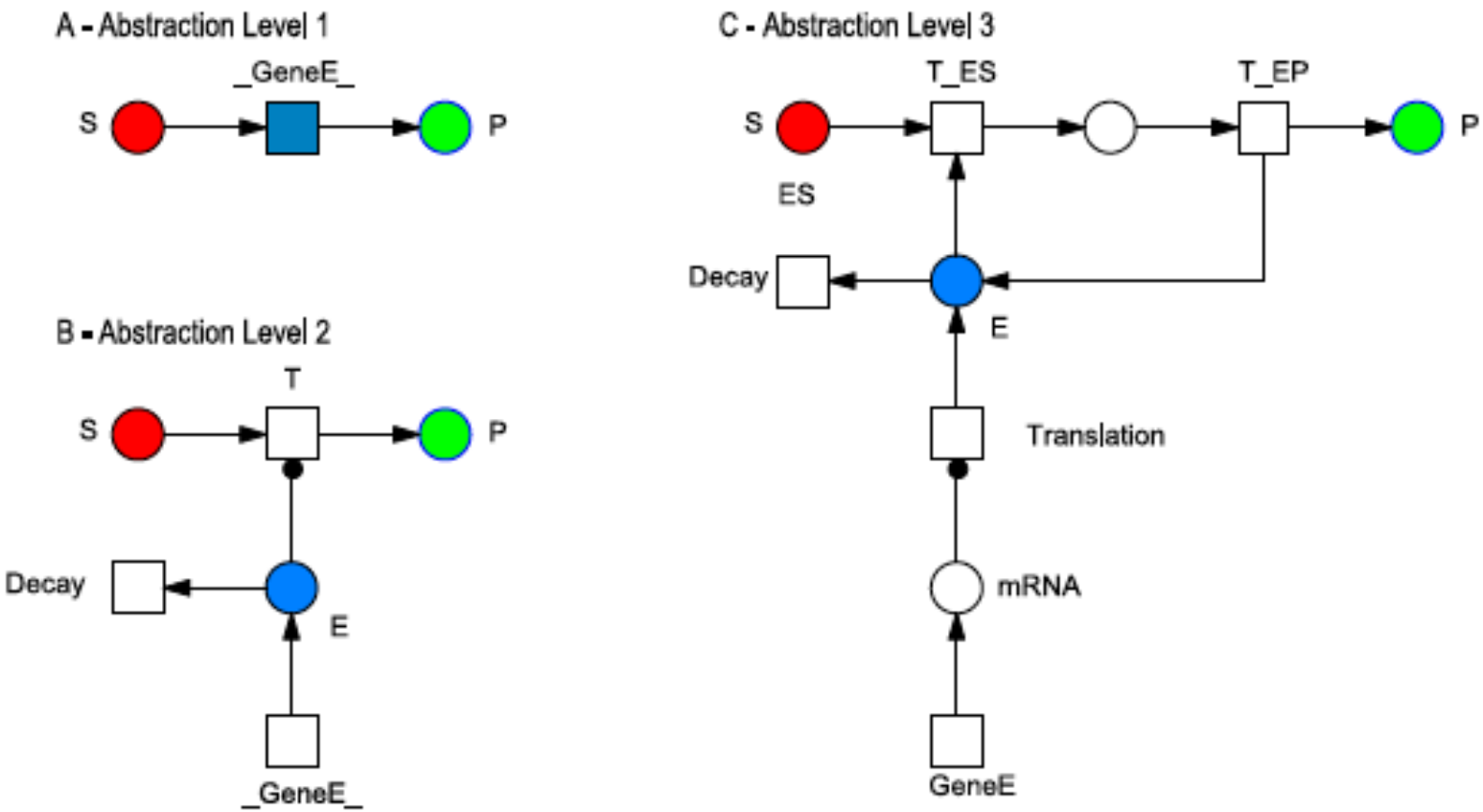
Source : L. Paulevé

Petri Nets are a Natural Choice !



Building complex networks

Enzymatic Reaction Coupled with Gene Expression



What For ?

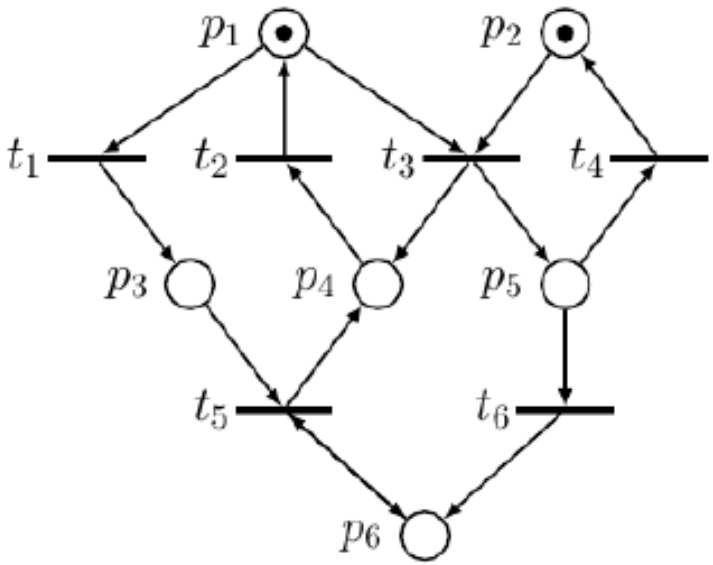
Compute Attractors

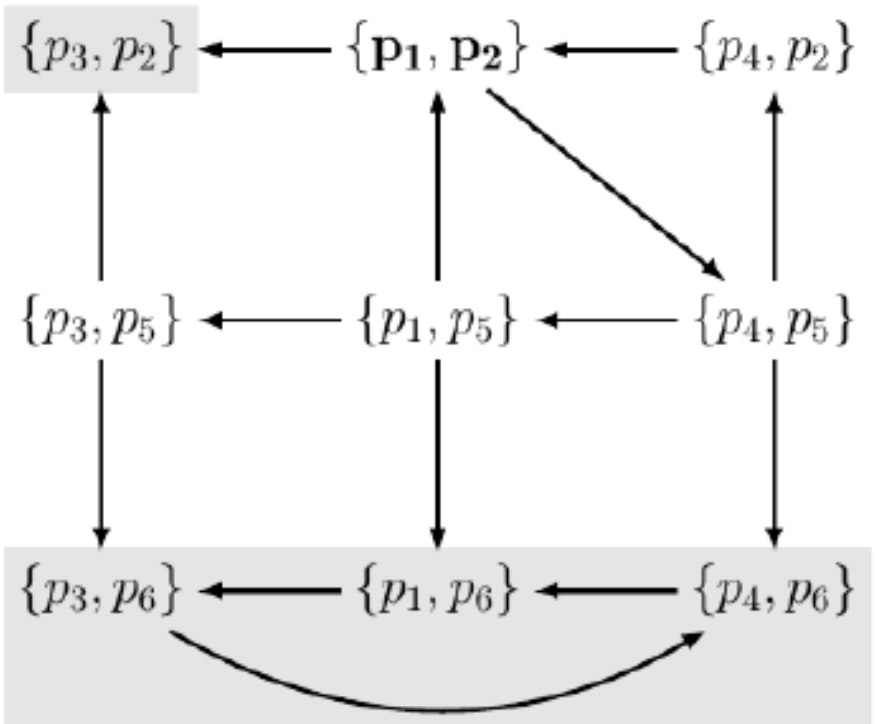
- Terminal strongly connected components of State graph
- E.g.:
  - Stable state of a cell after de-differentiation
  - Reachable mutations

Identify Cut Sets

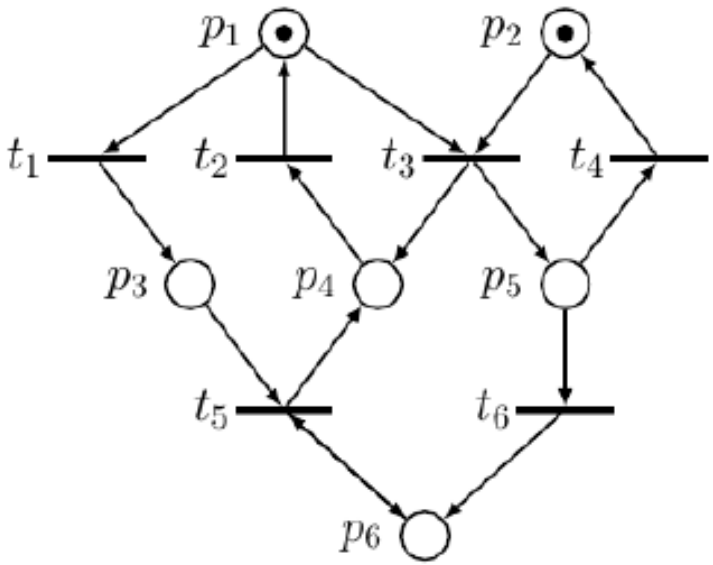
- Sets of factors/actions/ ... that are necessary to reach some attractor
- E.g.:
  - Interventions to prevent a mutation
  - Medication to enforce a certain "healthy" attractor
  - Cell re-programming: move from one attractor to another

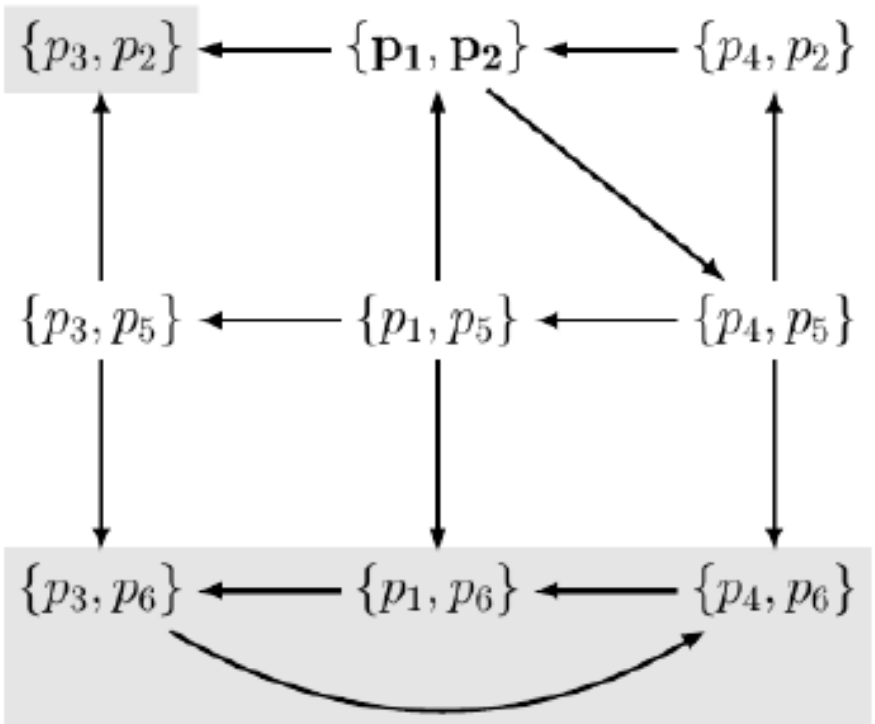
The Petri View: State Graph ...



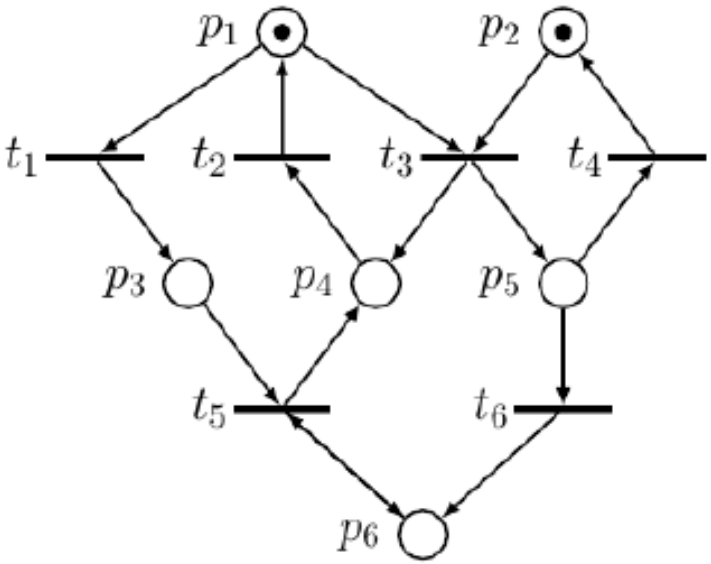


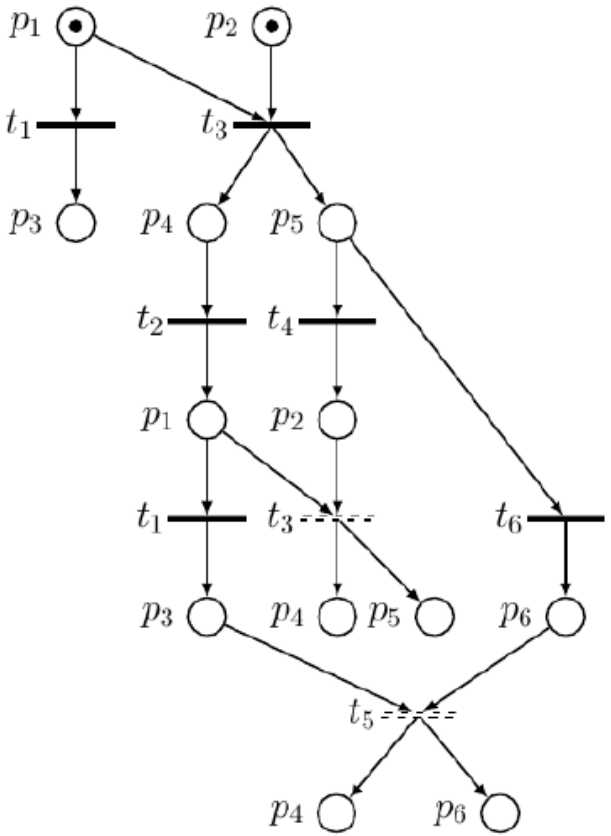
The Petri View: State Graph ...

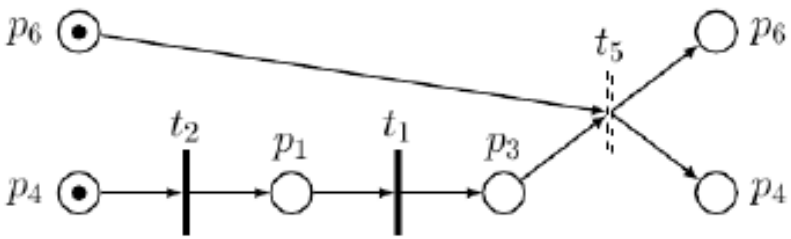




... vs Unfolding







Some More Leads for PNs in Biology

Unfoldings

- Accelerate search of attractors
- Find cut sets for control
- Understand cell reprogramming
- ...

Compositionality, Invariants

- Synthetic genetic circuits
- Regulatory networks analysis
- Control
- Monitoring
- ...

Nets and Concurrency

Conclusion: What was mentioned ...

PNs and concurrency are

meaningful in

- Physics
- Engineering
- (Chemistry)
- Biology

Concurrency

- is inherent
- is intuitive
- is helpful to save time

... and what wasn't mentioned

More models and mathematics

- Contextual nets, time(d) nets, stochastic nets, fluid nets ...
- High-level nets, nested nets
- Max-Plus analysis

More applications

- Verification of protocols, distributed algorithms, ...
- Workflows
- Railway Networks
- ... and everything I forgot

References

... follow on next slides

What Remains to be Said

BIG THANKS !!

References I : Papers

On the subjects here:

- T. Murata. *Petri Nets: Properties, Analysis and Applications*. Proceedings of the IEEE, Vol. 77, No 4, April, 1989, pp. 541-580.
- J. L. Peterson. *Petri Net Theory and the Modeling of Systems*. Prentice-Hall, N.J., 1981, ISBN: 0-13-661983-5.
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- C.A. Petri. *Nets, time and space*. Theor. Computer Science Vol. 153, 199 pp 3-48
- E. Fabre, A. Benveniste, S. Haar and C. Jard. *Distributed monitoring of concurrent and asynchronous systems*. Discrete Event Dynamic Systems: Theory and Applications 15(1), pages 33-84, 2005.
- Th. Chatain, S. Haar, L. Jezequel, L. Paulevé and S. Schwoon. Characterization of Reachable Attractors Using Petri Net Unfoldings. In CMSB'14.

References II : Online

- Online tutorial:
  http://www.informatik.uni-hamburg.de/TGI/PetriNets/introductions/aalst/
- C.A.Petri and R. Valk. *On the Physical Basics of Information Flow*. Talk at ICATPN 2008, Xi'An;
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