25 Years (more or less . . .) of Net Unfoldings and True-Concurrency Analysis Tools

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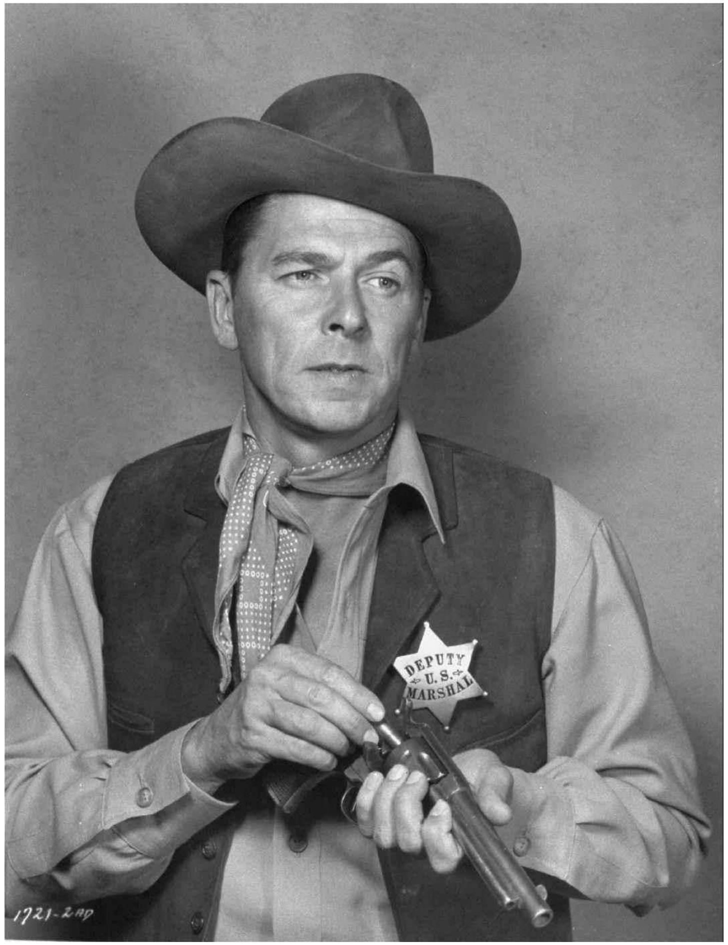
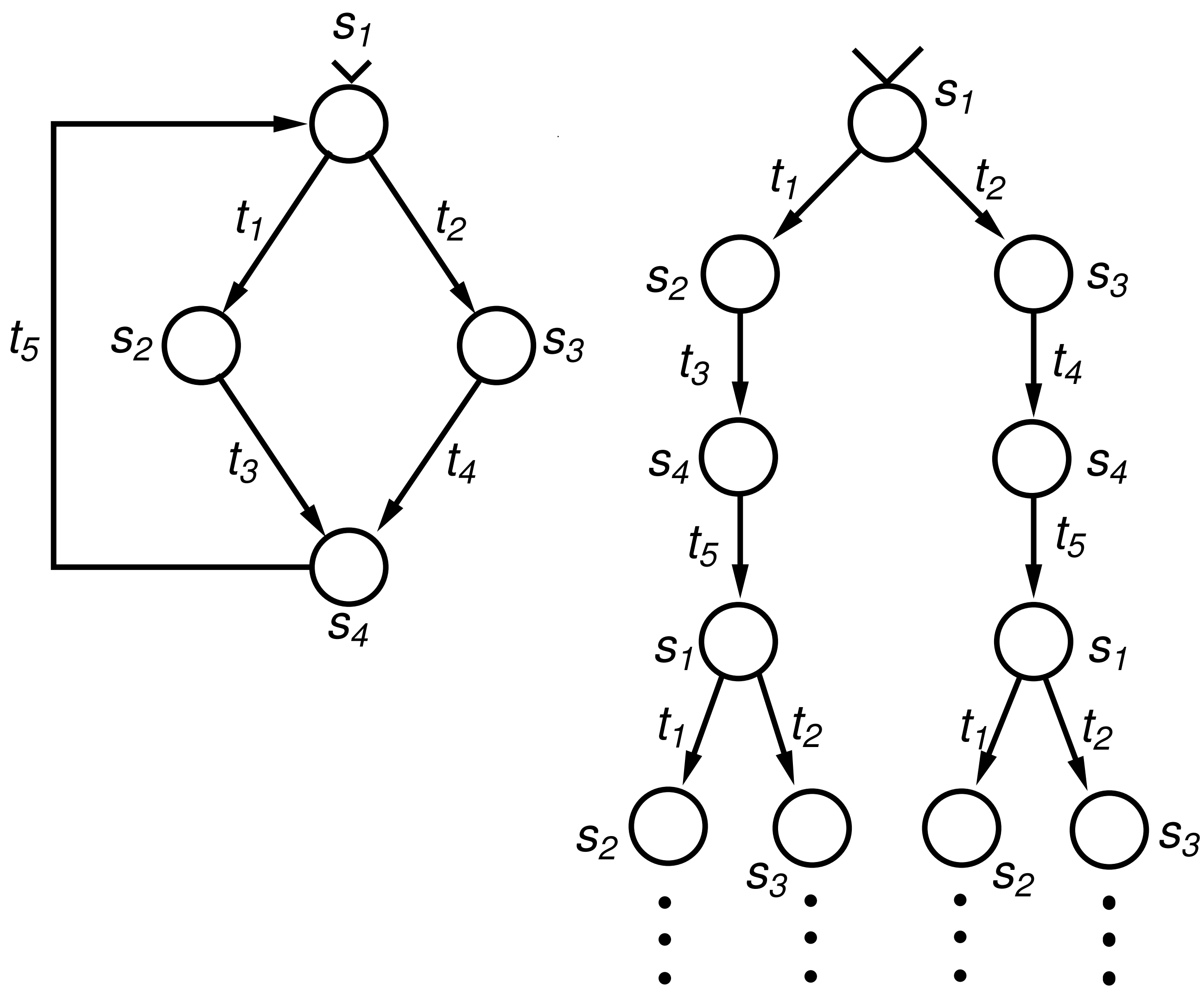
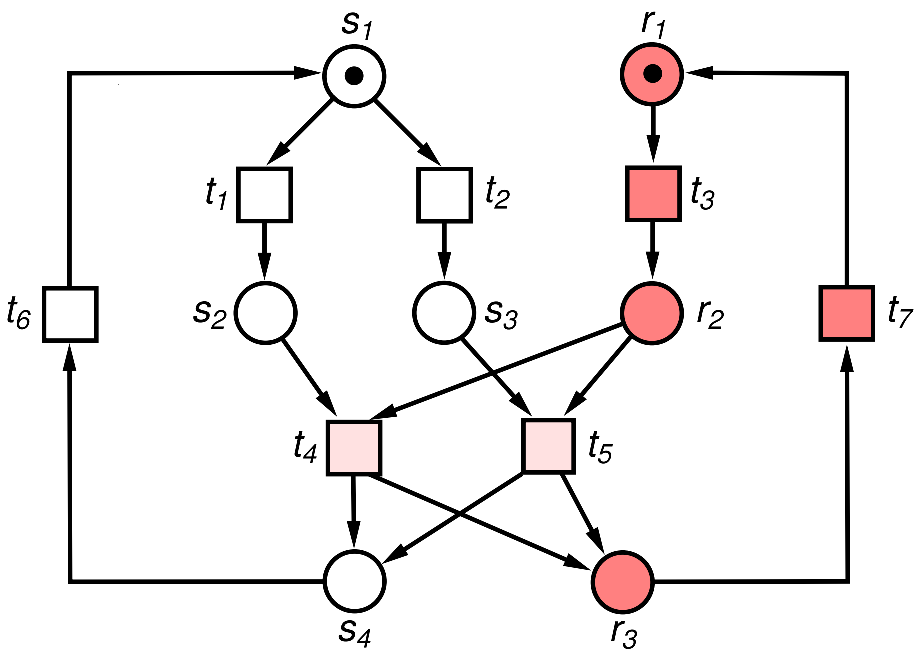
1981

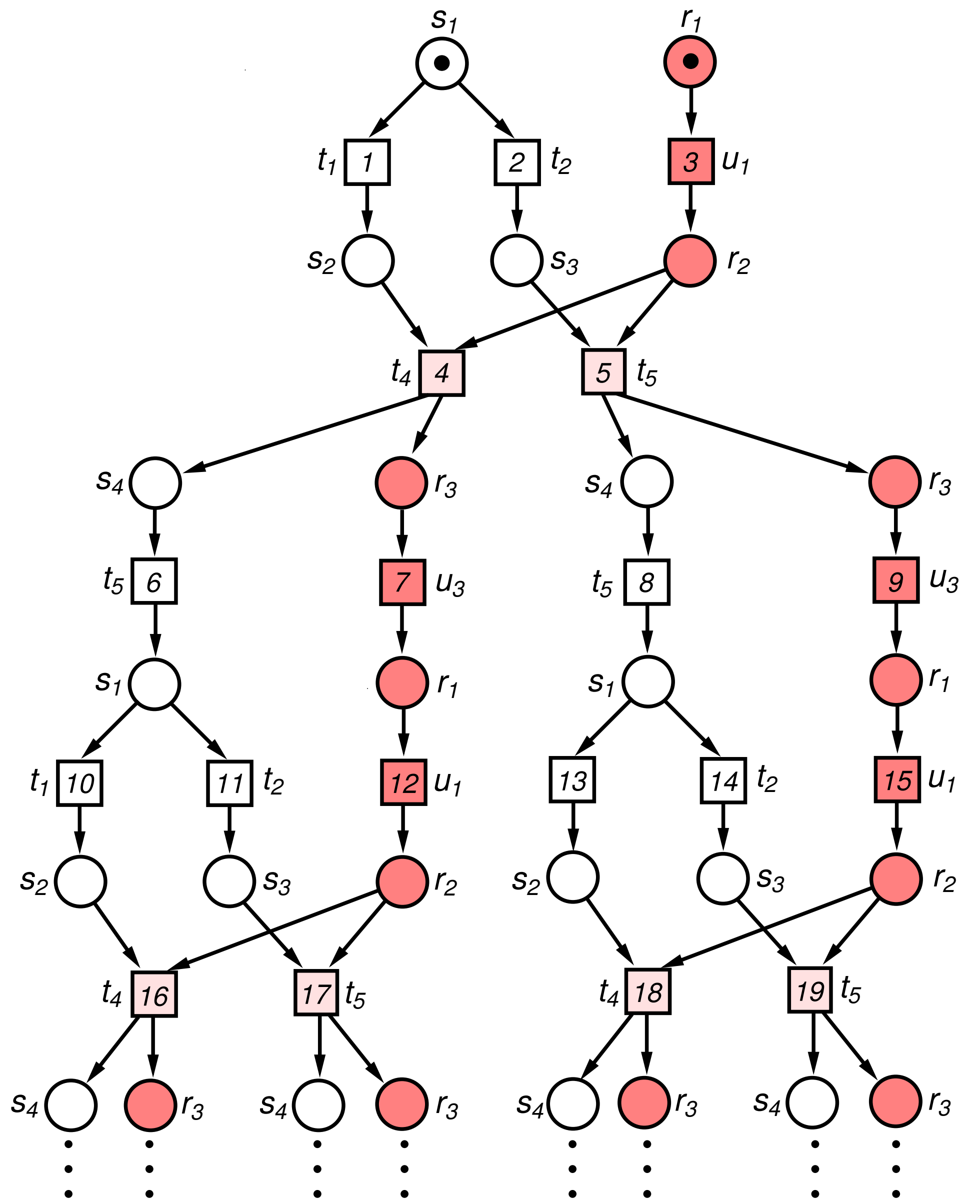


Unfolding of a transition system



Nielsen, Plotkin, Winskel ’81: Petri nets can also be unfolded





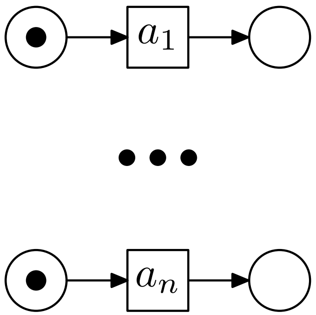
Nielsen, Plotkin, Winskel ’81: Petri nets can also be unfolded

- Motivation: Denotational semantics of concurrent behaviour (extension of Scott’s domain of computable functions to concurrent computation)
- During the 80s, theory of unfoldings further developed by
  - Winskel (synchronization trees ’84, event structures ’86)
  - Engelfriet (branching processes ’91)

1992

McMillan: Can unfoldings help to fight state-explosion ?

- A system composed of n independent components

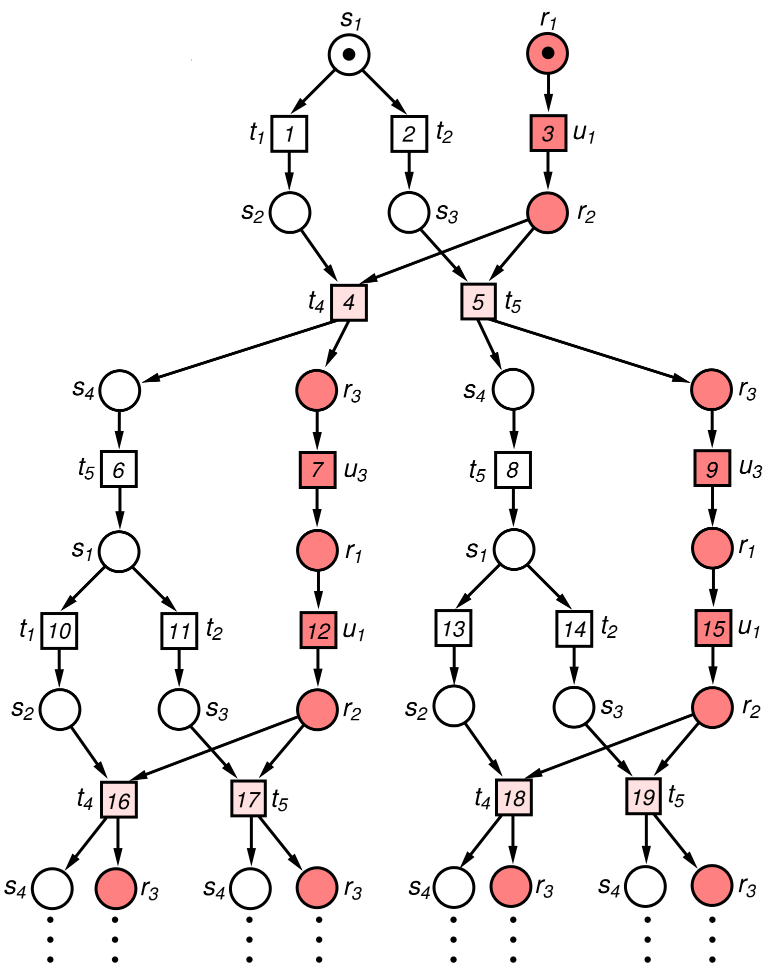


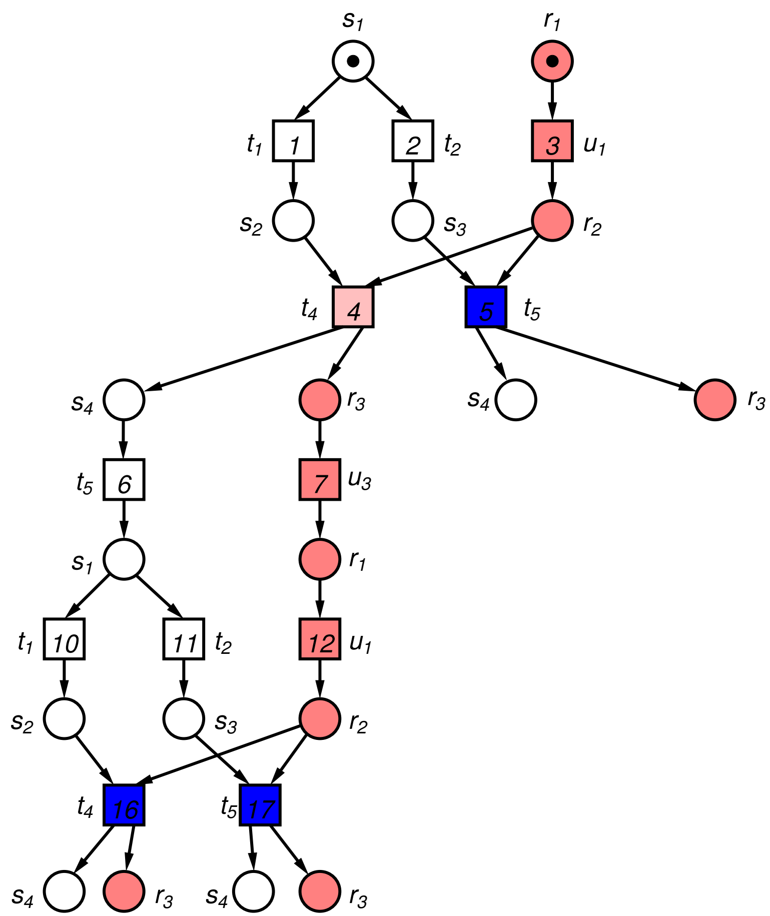
  - has 2^n reachable states, but
  - its unfolding is the system itself, and has size $O(n)$

- Question: Can we base verification on the unfolding?
- Obstacle: the unfolding is in most cases an infinite object!

Cut-off events and complete prefixes

- Solution: Construct a complete prefix of the unfolding containing all reachable states by identifying cut-off events





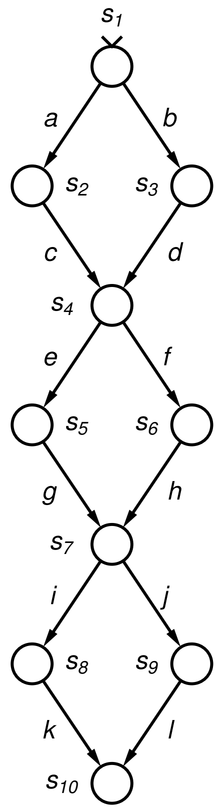
Cut-off events and complete prefixes

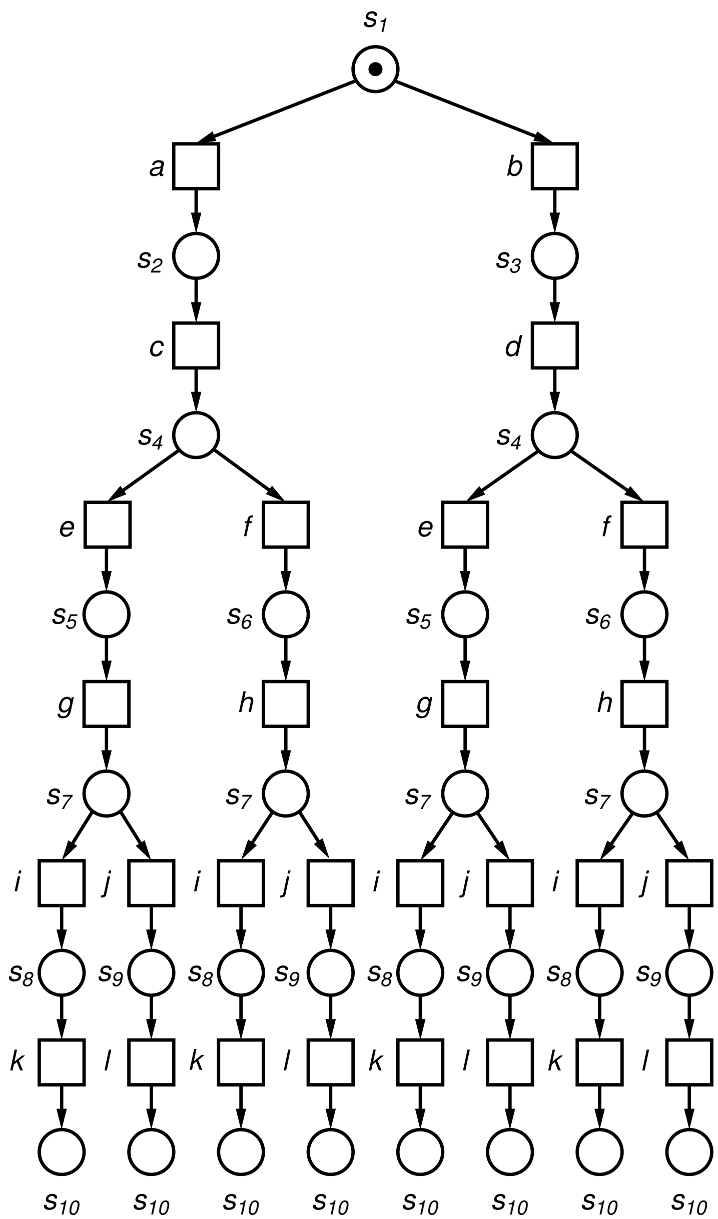
However, in the worst case McMillan's complete prefix could be

exponentially larger

than the reachability graph!

Cut-off events and complete prefixes





1996

E., Römer, Vogler '96: Size-guarantee

- Adequate orders: orders on the events of the unfolding such that
  - if events added in this order, and
  - cut-offs identified as in McMillan's approach

  then the prefix so constructed is complete.

- Total adequate orders guarantee that number of events never exceeds number of reachable markings.

- Problem of McMillan's approach: His order was partial

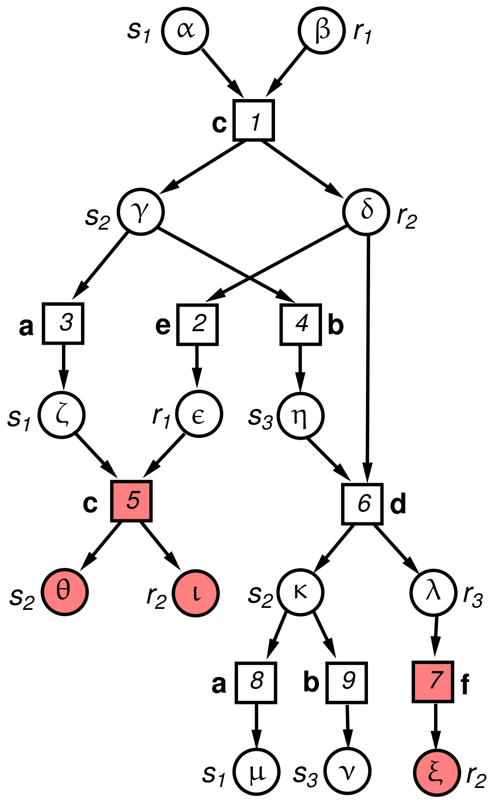
- ERV '96 found the first total adequate order; others followed (E., Römer '99; Niebert, Qu '06)

1999

Extracting information from complete prefixes

- Complete prefixes are a “compact encoding” of the state space, but reachability information must be “extracted” from them.
- Heljanko and Khomenko (PhD theses, several papers): Reachability queries can be solved very efficiently using SAT / ILP.

Extracting information from complete prefixes



place	clause
α	$\alpha \leftrightarrow \neg \mathbf{1}$
β	$\beta \leftrightarrow \neg \mathbf{1}$
γ	$((\mathbf{3} \vee \mathbf{4}) \rightarrow \mathbf{1}) \wedge \neg(\mathbf{3} \wedge \mathbf{4})$
	$\wedge(\gamma \leftrightarrow (\mathbf{1} \wedge \neg \mathbf{3} \wedge \neg \mathbf{4}))$
δ	$((\mathbf{2} \vee \mathbf{6}) \rightarrow \mathbf{1}) \wedge \neg(\mathbf{2} \wedge \mathbf{6})$
	$\wedge(\delta \leftrightarrow (\mathbf{1} \wedge \neg \mathbf{2} \wedge \neg \mathbf{6}))$
...	
ξ	$\xi \leftrightarrow \mathbf{9}$

- Further progress in SAT and SMT solving has turned the extraction problem into a non-issue.

2000

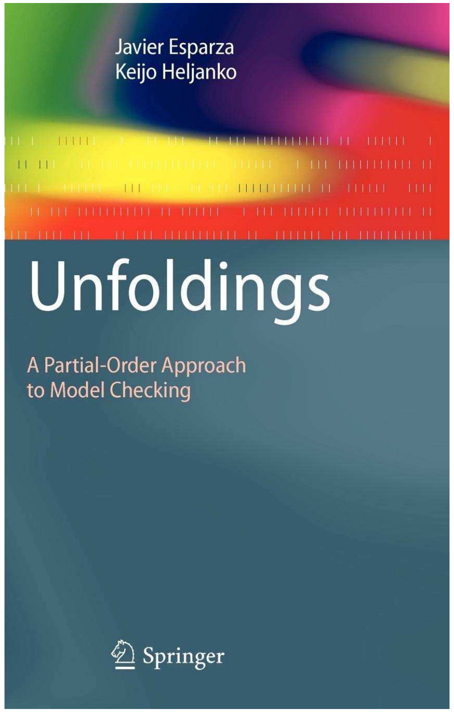

Newsweek
June 2, 1997
THE DAY THE WORLD CRASHES
Can We Fix the 2000 Computer Bug Before It's Too Late?

From reachability to model-checking LTL

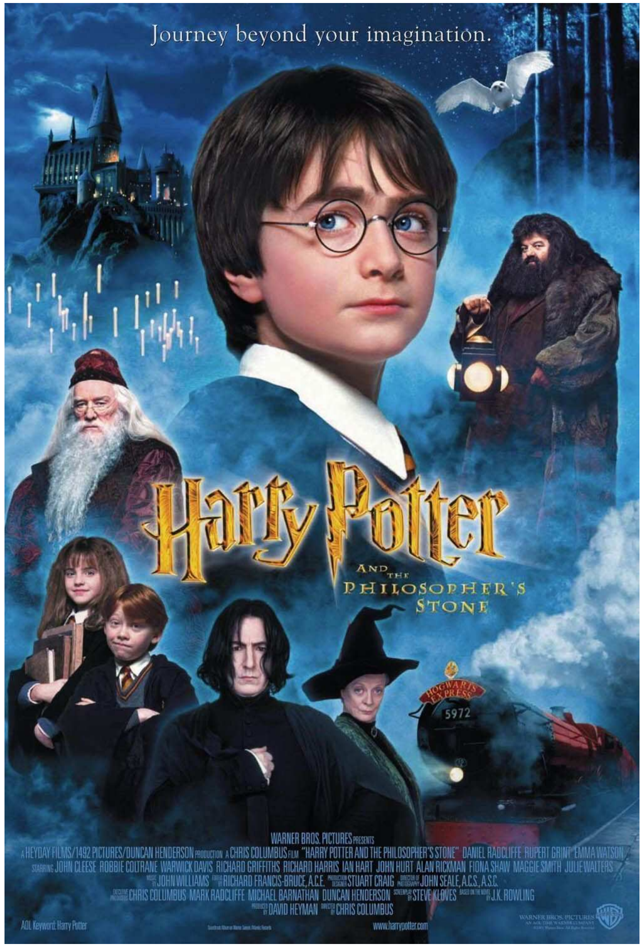
- Two unfolding-based algorithms to model-check arbitrary (next-free) LTL properties presented at ICALP '00 (Couvreur, Grivet, Poitrenaud; E., Heljanko)

- The algorithm by E. and Heljanko is described in

E., Heljanko:
Unfoldings
A Partial Order Approach
to Model Checking
Springer, 2008



2000-2010


Journey beyond your imagination.
Harry Potter
AND THE
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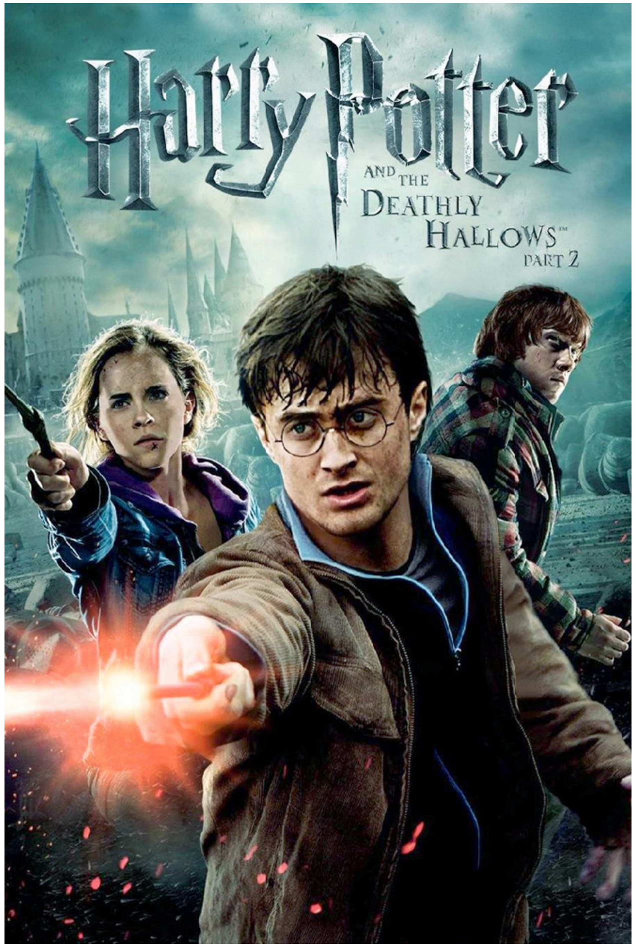
WARNER BROS. PICTURES PRESENTS
www.harrypotter.com


Harry Potter
AND THE
DEATHLY
HALLOWS
PART 2

Theory

- Parallel and distributed generation of the unfolding
  (Baldan, Haar, Heljanko, Khomenko, König, Koutny . . .)
- Even more compact representations: Merged processes
  (Khomenko, Koutny, Rodriguez, Schwoon, Vogler . . .)
- Extensions to more general models
  - Contextual nets (Baldan, Rodriguez, Schwoon, Vogler, Yakovlev . . .)
  - High-level nets (Khomenko, Koutny, Schöter . . .)
  - Timed models (Bouyer, Cassez, Chatain, Haddad, Jard . . .)

Tools

- PEP (Oldenburg, Best, Stehno, . . .)
- Mole (Schwoon)
- Unfolding Tools (Khomenko)
- unfsmodels, mcsmodels (Heljanko)

Applications

- Analysis of asynchronous circuits
  - Circuits specified as interpreted Petri nets
  - Concurrent Asynchronous Systems Group, University of Newcastle: tool-chain for verification and fault-fixing of STGs based on unfoldings (Khomenko, Koutny, Vogler, Yakovlev . . .)
- Monitoring and diagnosis
  - Distributed systems with alarms attached to some nodes
  - Problem: find cause of the alarms $\longrightarrow$ true-concurrency approach
  - IRISA group in Rennes, MEXICO project at ENS Cachan: diagnosis tools (Benveniste, Chatain, Haar, Jard, Schwoon . . .)

Applications

- Verification of graph transformation systems
  - Unfolding used to overapproximate the set of reachable graphs

    (Baldan, Corradini, König, Kozioura . . .)
- AI Planning (Bonet, Haslum, Hickmott, Khomenko, Vogler, . . .)

2010-today

Applications (2010-today)

- Systems Biology
  - Boolean networks used to model cellular regulatory processes
  - Unfoldings give compact representation of the reachable transitions (Pauleve, Chatain, Haar, Schwoon, . . .)
- Testing and verification of multithreaded programs
  - Unfolding used to generate small set of test cases with high coverage (Heljanko, Kähkönen, Ponce de Leon, Saarikivi . . .)
  - Unfolding used to guide partial-order reduction (Rodriguez, Sousa, Petrucci, Kröning . . .)
- Process discovery (Carmona, Ponce de Leon, Rodriguez . . .)

Conclusions

- Straight line from Petri's nonsequential processes to concrete algorithms, tools, and application domains
- (Most?) successful spin-off of true-concurrency semantics
- Turning point: verification through algorithmic construction of semantic objects
- True-concurrency useful in two ways:
  - Compact representation of state spaces
  - Information about causality and independence
- Blockchain ?