Directed Explicit-State Model Checking

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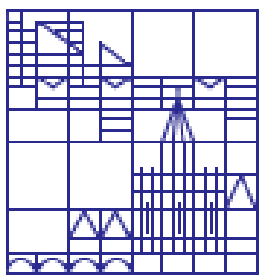

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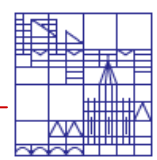
- **joint work with**
  - Stefan Edelkamp
    - Dortmund
  - Alberto Lluch-Lafuente
    - Pisa



Overview

1. Introduction

2. State Space Exploration Strategies

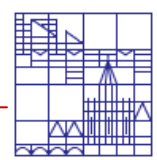
3. Directed Explicit-State Model Checking for Safety Properties

4. Directed Explicit-State Model Checking for Liveness Properties

5. Directed Explicit-State Model Checking and Partial-Order Reduction

6. Current and Future Research

7. Conclusion



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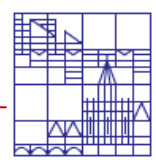


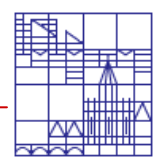
Motivation

- **Software Ubiquity**
  - software is a determining, if not the most determining, technology used in most technical systems used or developed

"*Our civilization runs on software*"

Bjarne Stroustrup

- **Software Complexity of Reactive, Embedded Systems**
  - ever growing complexity of services provided
    - bugs as ubiquitous as these systems are becoming

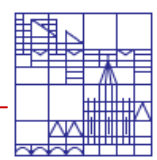


Motivation

- **Economical impact ...**
  - software failures cost huge amounts of money
    - according to NIST study (2002), software failures in the US cost about $59.5 billion annually (0.6% of US GDP)
    - esitmate that $22.2 billion could be saved by improved software quality assurance (including testing)

Quoted from *Software disasters are often people problems*, http://www.msnbc.msn.com/id/6174622/

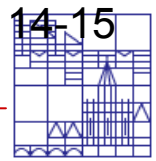
- **... but it's also an ehtics issue**
  - threat to human well-being and life
    - baby killed by front-seat airbag, even though airbag had been software disabled
    - re-use of a bit in the assembler code suspected as cause



Motivation

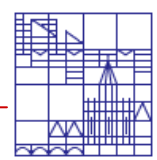
- **Faults are often due to unexpected interleavings**
  - AT&T Telephone Switch Failure, January 15, 1990
    - failure: new software release in 4ESS switches
      - a switch would no longer send messages to indicate it is no longer faulty, but other switches would notice this due to resumed activity
      - one switch signaled it went down, went through recovery cycle (reboot), and resumed sending traffic
      - second switch accepted down message and attempted to reset
      - due to software fault, when second switch received second message from first switch, it could not properly handle it and went itself through recovery / resume cycle
      - fault propagated through 114 different switches in AT&T network (all ran the same software!)
    - result: 9 hr. nationwide telephone traffic blockade

Source: Peter G. Neumann, *Computer Related Risks*, ACM Press, 1995, p. 14-15



Motivation

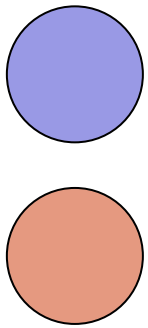
- **Model Checking**
  - automated, systematic state space exploration
  - provides error traces
  - a complementing technique
    - code reviews / inspections find most obvious faults
    - testing finds hidden, but unanticipated faults
    - model checking aims at unanticipated faults

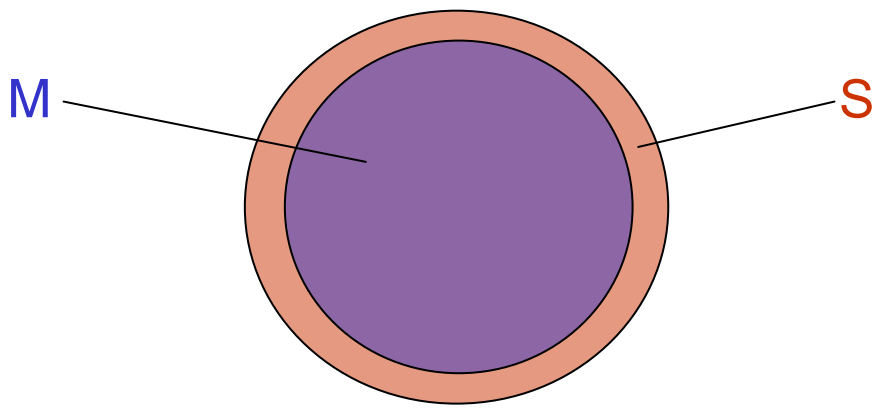


Model Checking

- **What is Model Checking?**
  - basic principle
    - given
      - (software-) model M
      - property specification S
    - does M satisfy S?

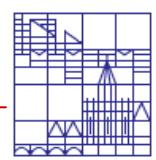
      M |= S
      - that is the case if every behaviour of M is also a behaviour of S
      - i.e., the model M does not reveal behaviour violating the specification S





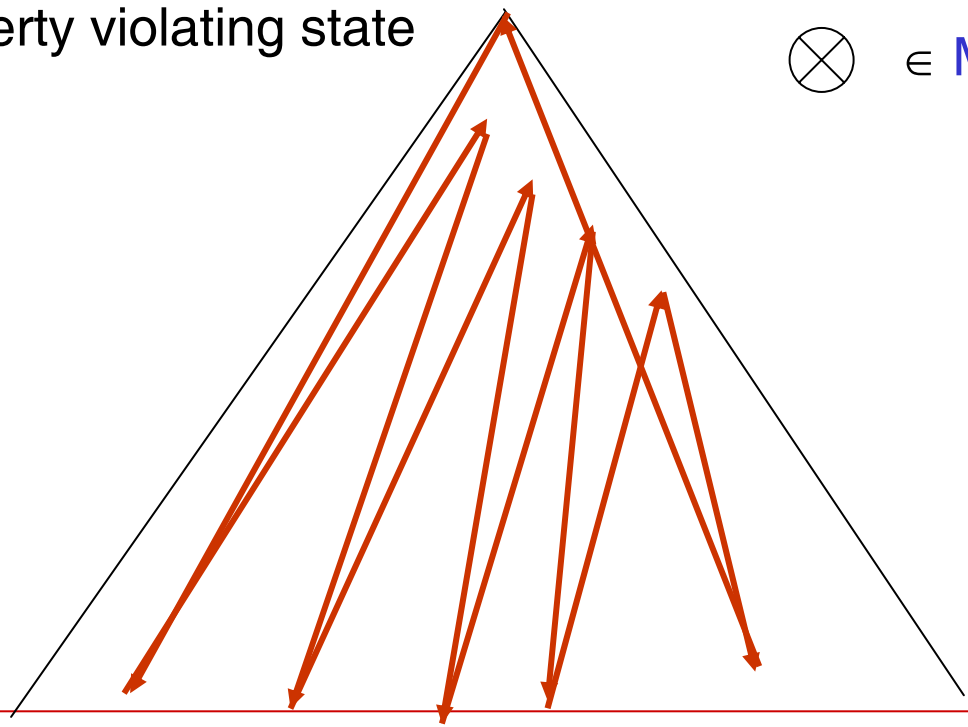
Model Checking

- **Explicit State Model Checking**
  - state space given by explicit state-transition function
  - successful in the verification of concurrent, asynchronous software systems
    - automatic, terminating procedure if M finite
    - error explanation by output of offending execution paths
      - "error trails"
      - "counterexamples"
    - partial order reduction, bit-state hashing to counter state space explosion
  - one prominent example
    - SPIN (G. Holzmann, formerly Bell Labs, now JPL)
      - ACM Software Systems Award



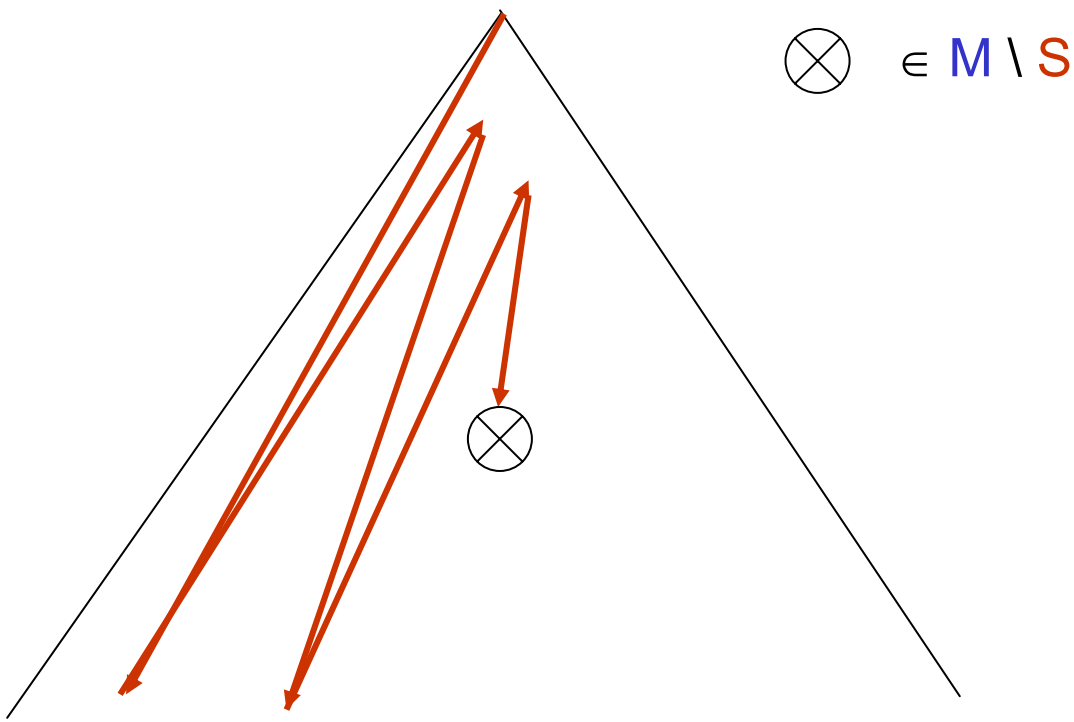
Model Checking of Safety Properties

- **Classical Use: Verification**
  - safety: invariants, absence of deadlock, reachability of states,...
  - DFS in the system's global state space
    - if no property violating state found
      - termination after complete state space exploration
    - if property violating state found
      - output counterexample
        - search stack contains path from initial system state into property violating state



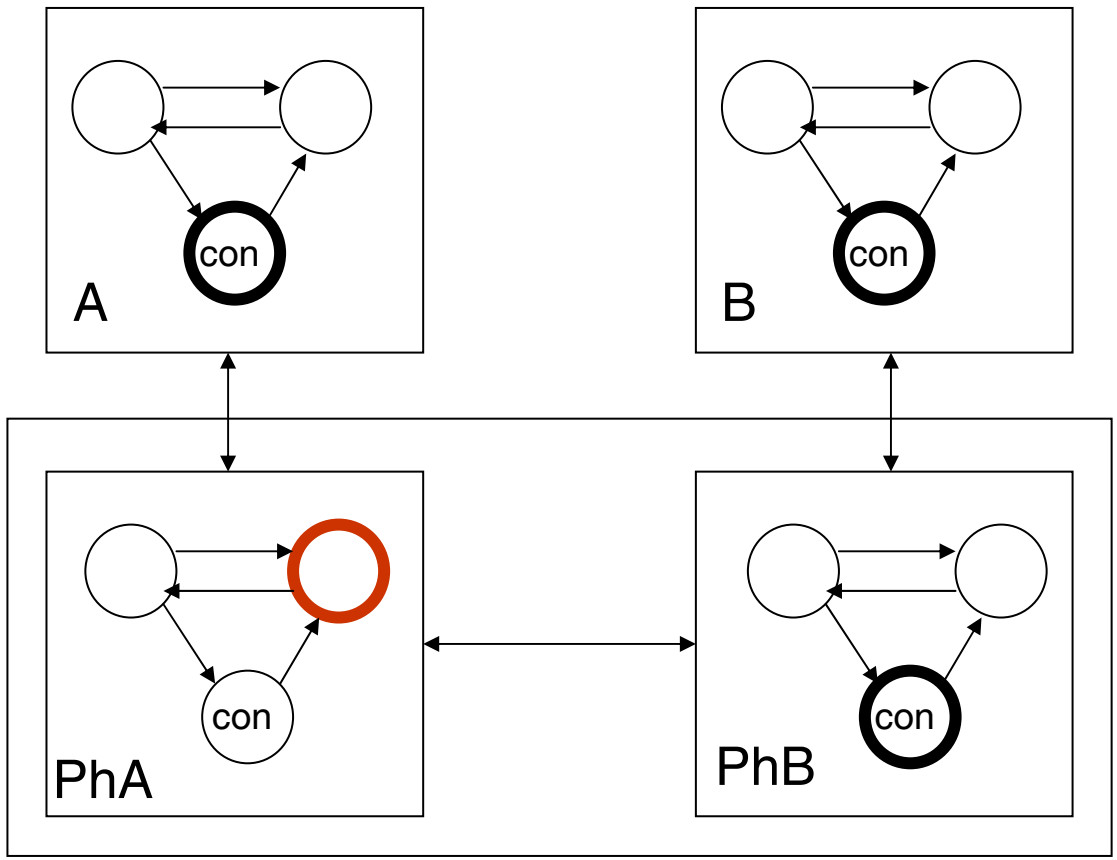
Model Checking of Safety Properties

- **More Recently: Use of Model Checker for Debugging Purposes**
  - let p an undesired state (safety) property
  - claim □¬p
    - model checker will try to disprove this claim and find a trail into a state satisfying the undesired property
  - error explanation



Model Checking of Safety Properties

- **Example: Debugging of POTS**

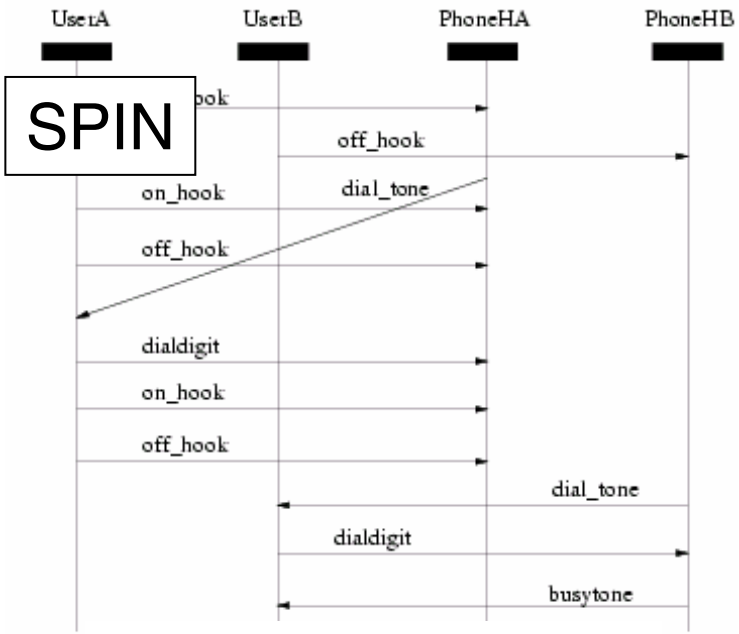


Invariant Property

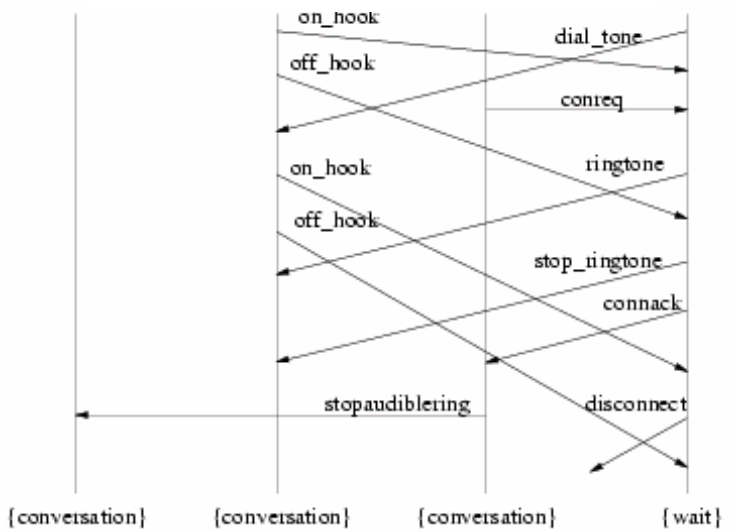
$$\neg(A@con \wedge \neg PhA@con \wedge B@con \wedge PhB@con)$$

Counterexamples

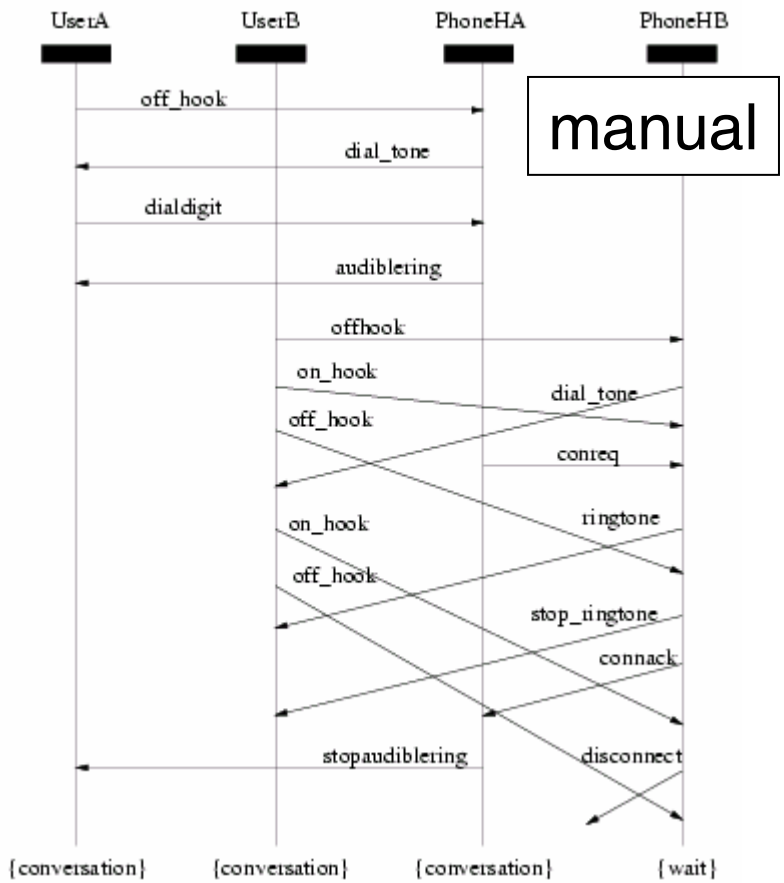
SPIN



… 440 messages …

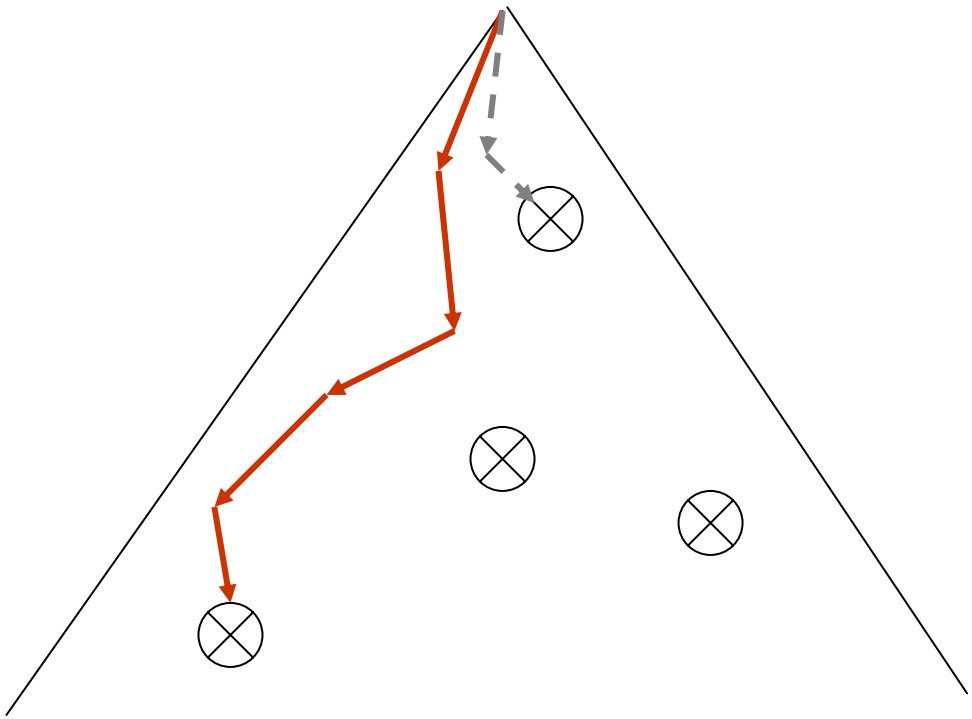


manual



total of 16 messages

Counterexample with Depth-First Search (DFS)



- **Shorter Counterexamples**
  - shorter path to **the same** property-violating state
  - shorter path to **some** property-violating state
- **State Space Exploration Strategies?**

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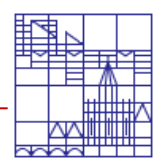
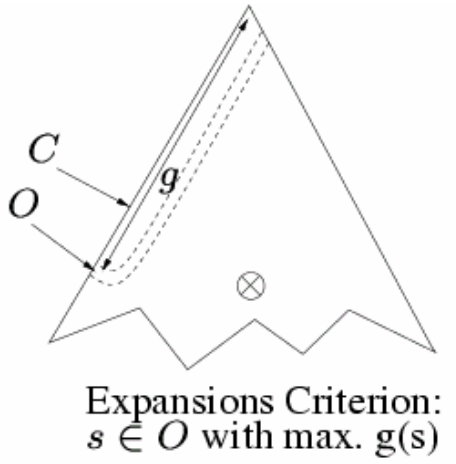


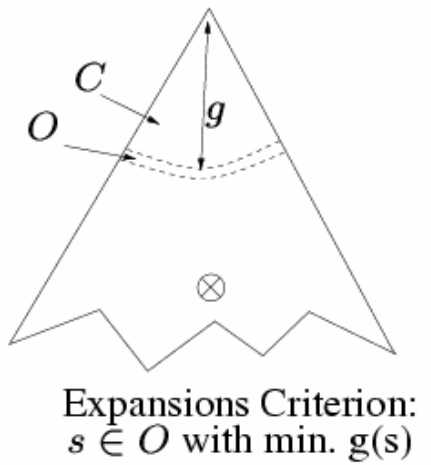
Uninformed Search

Depth-First Search (DFS)



- memory efficient
- potentially long error trails
- stack-based

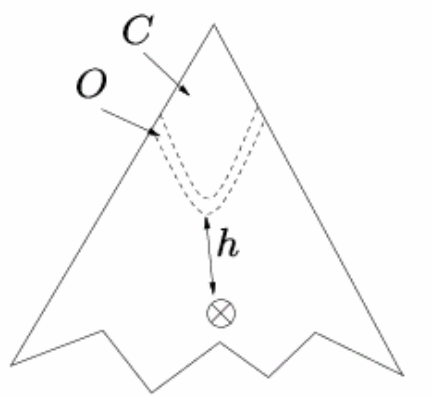
Breadth-First Search (BFS)



- memory inefficient
- shortest error trails
- no stack

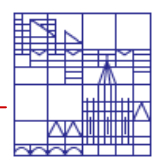
Informed Search

Best-First Search (BF)



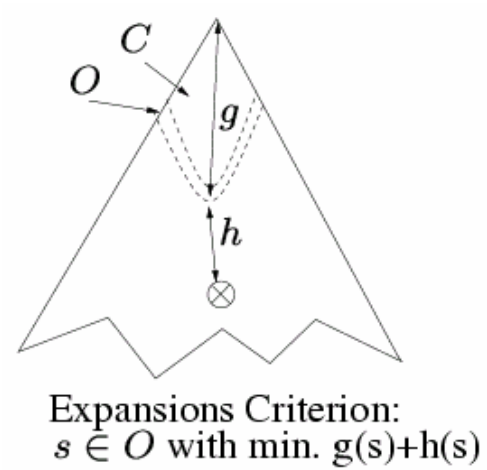
- informed search
  - heuristic estimate h(S): estimate of length of path to goal state S
- no guarantee for optimally short trails (sub-optimal solution)
- complete algorithm
  - goal state, if present, will be found
- often improved error trails

Graphiken von A. Lluch-Lafuente



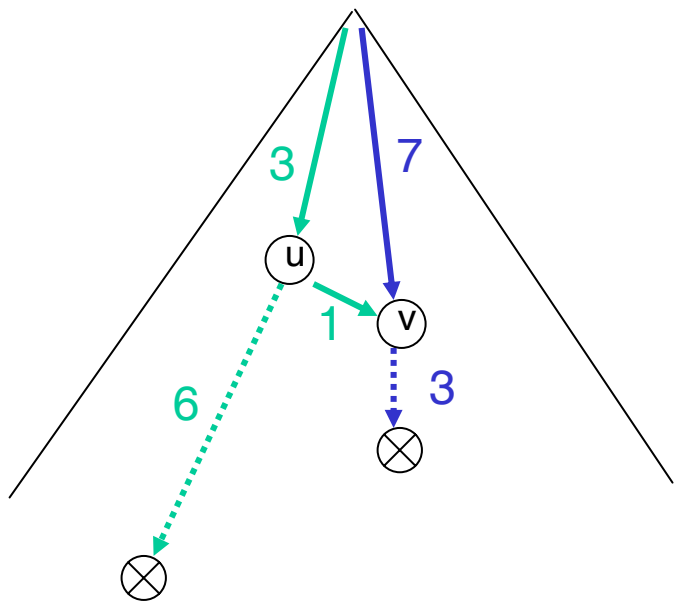
Informed Search

A*



- informed search
- optimally short error trails if h is a lower bound (admissible heuristics)
- complete
- no stack

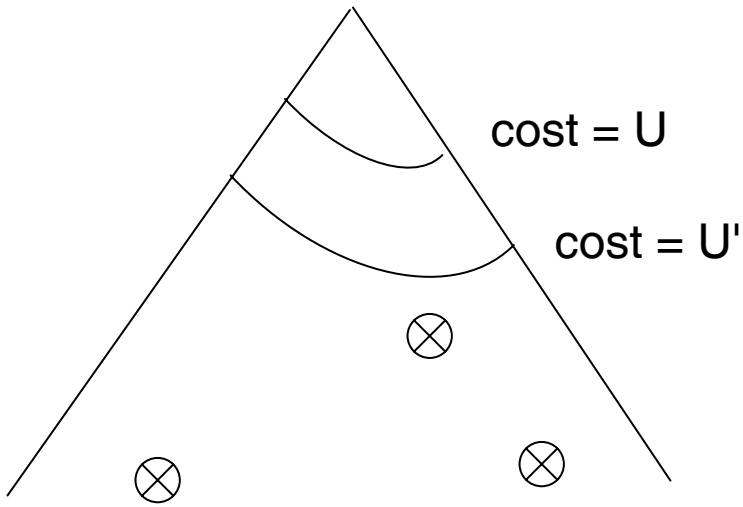
- re-opening of nodes
  - move states from *Closed* to *Open* if they can be reached on a shorter path
    - re-open v



Graphiken von A. Lluch-Lafuente

Informed Search

Iterative Deepening A* (IDA*)



- informed search
- iterate search depth according to increasing total cost bounds
- complete and optimal (simulates A*)
- stack-based DF search
  - bitstate hashing can be applied
    - avoid re-opening since generating path length information may be false due to duplicates
    - no problem for monotone heuristic estimates

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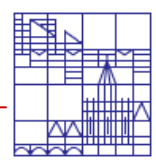
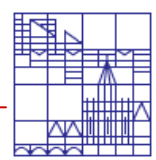


Directed Explicit-State Model Checking

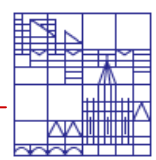
- **Statespace Exploration**
  - goal: locating errors
    - short error trails for easy error interpretation
  - exploration / search algorithms
    - BF
    - A*
      - A* does not maintain search stack
        - book-keeping to preserve predecessor information
    - IDA*
- **Tool**
  - implemented in HSF-SPIN (Lluch-Lafuente / Edelkamp, Freiburg)
    - based on SPIN version 3.4
    - handles a large fragment of Promela
    - http://www.informatik.uni-freiburg.de/~lafuente/hsf-spin/



Heuristic Estimator Functions

- **Formula based Heuristic H_f**
  - let f a state formula, S a global system state
    - H_f is a formula interpreted over S yielding a (lower bound) estimate for number of steps necessary to reach state satisfying f from S
  - for queue expressions and relational operators:

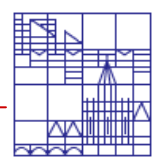
f	$H_f(S)$	$\overline{H}_f(S)$
$full(q)$	$capacity(q) - length(q)$	if $full(q)$ then 1, else 0
$empty(q)$	$length(q)$	if $empty(q)$ then 1, else 0
$q?[t]$	length of minimal prefix of q without t (+1 if q lacks message tagged with t)	if $head(q) \neq t$ then 0, else maximal prefix of t's
$a \otimes b$	if $a \otimes b$ then 0, else 1	if $a \otimes b$ then 1, else 0



Heuristic Estimator Functions

- **Formula based Heuristic H_f**
  - for predicates over control state locations
    - example for f: PhA@con
      - process i in control state s
    - lower bound for number of global state transitions is number of local state transitions
    - compute all-pairs-shortest path for local state transition matrix D_i

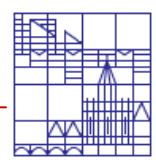
f	$H_f(S)$	$\overline{H}_f(S)$
$i@s$	$D_i(pc_i, s)$	if $pc_i = s$ 1, else 0



Heuristic Estimator Functions

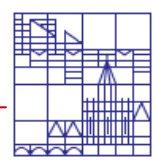
- **Formula based Heuristic H_f**
  - for boolean expressions

f	$H_f(S)$	$\overline{H}_f(S)$
$true$	0	∞
$false$	∞	0
a	**if** a **then** 0 **else** 1	**if** a **then** 1 **else** 0
$\neg g$	$\overline{H}_g(S)$	$H_g(S)$
$g \vee h$	$\min\{H_g(S), H_h(S)\}$	$\overline{H}_f(S) + \overline{H}_g(S)$
$g \wedge h$	$H_g(S) + H_h(S)$	$\min\{\overline{H}_g(S), \overline{H}_h(S)\}$



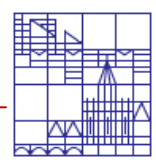
Heuristic Estimator Functions

- **Absence of Deadlock**
  - active processes heuristic: $H_{ap}(S)$
    - computes the number of currently active (=non-blocked) processes
    - relatively small range of heuristic function
  - H_U
    - based on *user* characterization of control states as "dangerous"
    - can be highly informative



Heuristic Estimator Functions

- **Assertions**
  - transition `(u, assert(a), v)` in process i
    - $f = i@u \wedge \neg a$
    - apply H_f
- **Partially or Completely Known State Vectors**
  - trail-guided model checking
    - characterize target state by given error trail
      - is there a shorter trail to same (or equivalent) state
    - directed search based on Hamming-distance heuristics
      - not always admissible but yields good results
        - admissible if each transition changes at most one bit in the state vector



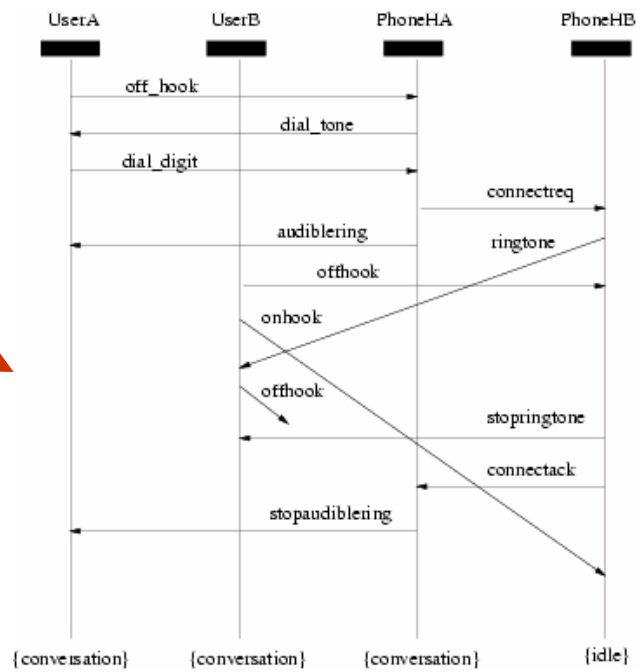
HSF-SPIN Experiments

- **Invariant Violation (H_f)**

Elevator	BFS	DFS	A*	BF	SPIN
s	38,662	279	38,598	2,753	292
e	38,564	279	38,506	2,297	292
t	160,364	356	160,208	5,960	348
l	203	510	203	421	510

states
exp.states
transitions
err. **l**ength

POTS	BFS	DFS	A*	BF	SPIN
s	24,546	-	6,654	781	148,049
e	17,632	-	3,657	209	148,049
t	99,125	-	18,742	1,067	425,597
l	81	-	81	83	2,765



12 messages

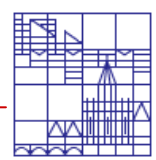
HSF-SPIN Experiments

- **Deadlock Detection with H_{ap}**

states
exp.states
transitions
err. **l**enght

GIOP	BFS	DFS	A*	BF	SPIN
s	40,847	218	31,066	117	326
e	37,266	218	27,061	65	326
t	151,671	327	108,971	126	364
l	58	134	58	65	134

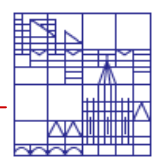
Philosophers	BFS	DFS	A*	BF	SPIN
s	3,678	1,341	67	493	1,341
e	2,875	1,341	17	225	1,341
t	15,775	1,772	73	622	1,772
l	34	1,362	34	66	1,362



HSF-SPIN Experiments

- **Dining Philosophers**
  - finding of errors where DFS fails
    - BFS up to p = 8,
    - DFS (SPIN) up to p = 15
    - for A*: p ≥ 255 (linear behavior dependent on p)
  - SPIN: DFS following lexical ordering of processes
  - A*: directed search avoids pitfalls of lexically ordered exploration

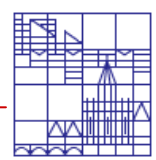
p		BFS	DFS	A*	BF	SPIN
2	s	9	6	6	6	6
	e	7	6	6	4	6
	t	10	7	4	6	7
	l	10	10	10	10	10
3	s	19	19	12	26	19
	e	14	10	7	23	10
	t	29	12	13	43	12
	l	14	18	14	14	18
4	s	56	45	19	70	45
	e	42	45	9	57	45
	t	116	62	21	142	116
	l	18	54	18	26	54
8	s	3,768	1,341	67	493	1,341
	e	2,875	1,341	17	225	1,341
	t	15,775	1,772	73	622	1,772
	l	34	1,362	34	66	1,362
14	s	-	-	199	1,660	2,164,280
	e	-	-	29	1,963	2,164,280
	t	-	-	211	684	27,050,400
	l	-	-	58	114	9,998
16	s	-	-	259	2,201	-
	e	-	-	33	893	-
	t	-	-	273	2,578	-
	l	-	-	66	130	-



HSF-SPIN Experiments

- **IDA* and Double-Bitstate Hashing**
  - deadlock detection in GIOP
  - memory bound: 256 MB, time limit 120 mins
  - IDA* and double bit-state hashing
    - number of expansions

Depth	A*	IDA*	IDA*+bitstate
58	150,344	146,625	146,625
59	168,191	164,982	164,982
60	184,872	184,383	184,383
61	-	206,145	206,145
62	exceeds memory limit	exceeds time limit	229,626
63	-	-	255,411
64	-	-	282,444
65	-	-	311,340
66	-	-	341,562
67	-	-	373,422
68	-	-	407,310
69	-	-	442,941
70	-	-	goal found



HSF-SPIN Experiments

- **Trail Improvement with Hamming (H^e_d) and FSM (H^e_m) Distance Metrics**

`marriers(4)`

	DFS	A*			
		f,H^e_d	f,H^e_m	f_e,H^e_d	f_e,H^e_m
s	407,009	26,545	225,404	126,479	1,754,408
l	121	99	66	121	121
m	58 MB	8 MB	26 MB	22 MB	248 MB
r	367 s	6 s	126 s	62 s	1,150 s

`pots`

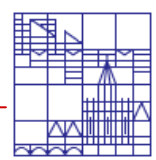
	DFS	A*			
		f,H^e_d	f,H^e_m	f_e,H^e_d	f_e,H^e_m
s	118,099	988	13,865	4,432	14,714
l	987	89	81	89	88
m	58 MB	7 MB	11 MB	7 MB	12 MB
r	81 s	5 s	5 s	5 s	5 s

`leader(8)`

	DFS	A*			
		f,H^e_d	f,H^e_m	f_e,H^e_d	f_e,H^e_m
s	36	10,733	3,161	10,773	3,173
l	71	71	69	71	71
m	3 MB	10 MB	6 MB	10 MB	6 MB
r	1 s	6 s	1 s	6 s	1 s

`giop(2,1)`

	DFS	A*			
		f,H^e_d	f,H^e_m	f_e,H^e_d	f_e,H^e_m
s	218	988	30,629	23,518	446,689
l	134	67	65	134	134
m	3 MB	5 MB	22 MB	18 MB	266 MB
r	1 s	1 s	8 s	21 s	128 s



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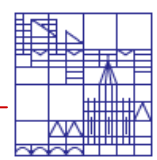
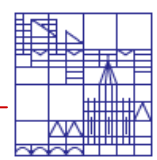


Directed Model Checking - Liveness

- **Liveness Properties**
  - satisfied along a path of infinite length
  - ”every sending is followed by a reception“ (response)
    - □(send ⇒ ◊receive)
      - contains liveness component
  - amounts to recognizing ω-regular expressions of the form uv^{ω}
    - => cycle detection

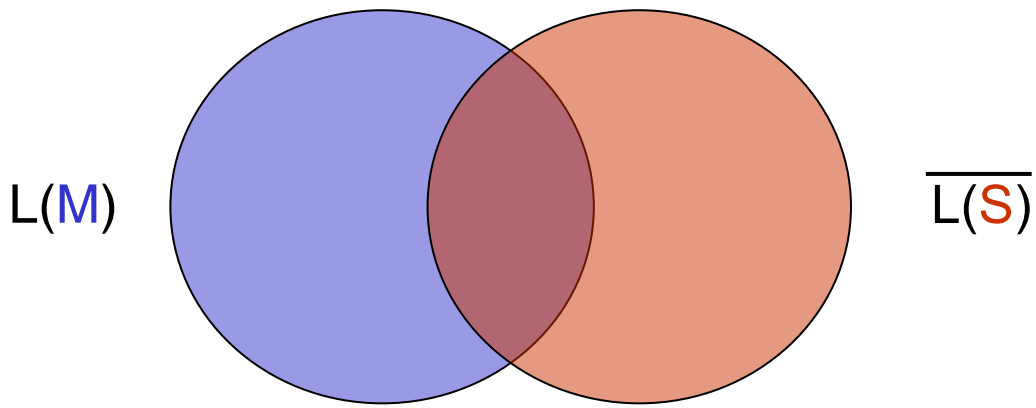


Directed Model Checking - Liveness

- **Automata-based Model Checking for Liveness Properties**
  - does model M satisfy the specification S

    $M \models S$
  - M satisfies S iff

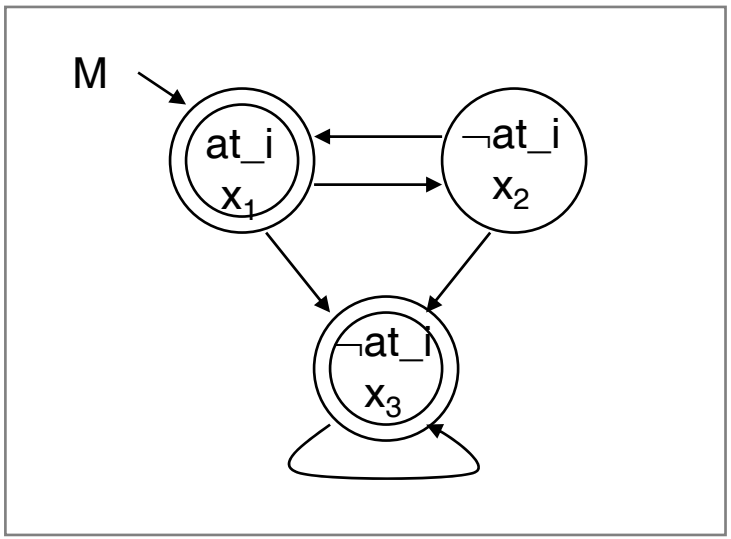
    $L(M) \subseteq L(S) \Leftrightarrow L(M) \cap (L(S) = \varnothing$

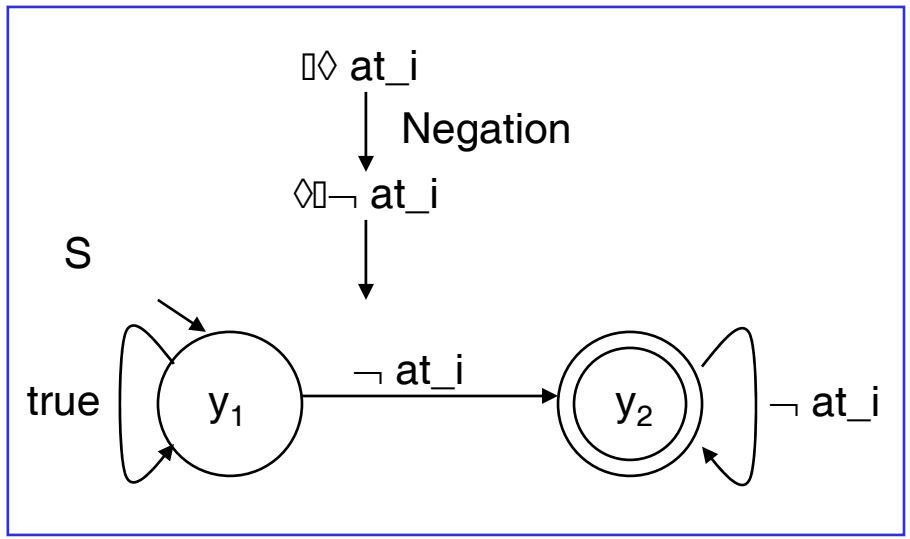


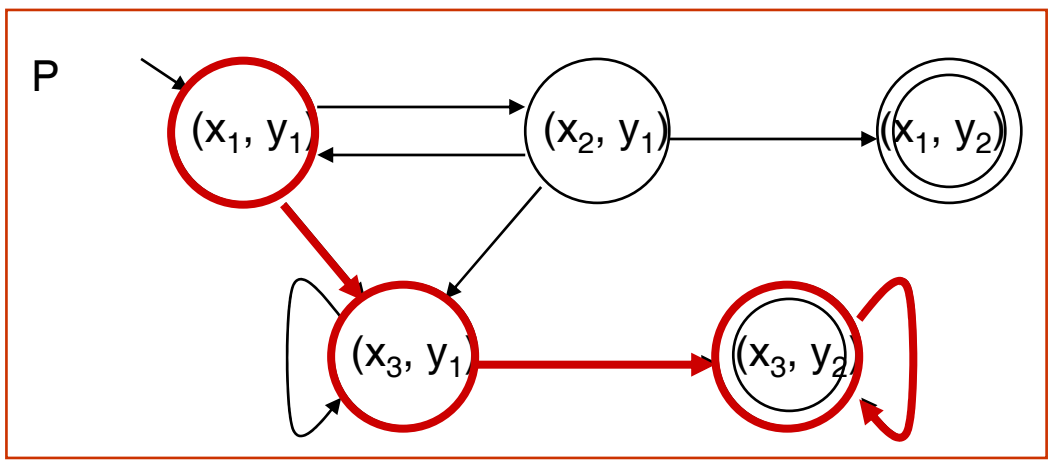
  - automata based emptyness test for $L(M) \cap \overline{L(S)}$ after Vardi and Wolper
    - detecting cycles in the synchronous product of M und $\overline{S}$

Directed Model Checking - Liveness

- **Automata-based Model Checking (after Vardi/Wolper)**
  - synchronous product construction





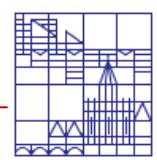


Directed Model Checking - Liveness

- **Exploration Algorithm**
  - nested DFS (NDFS)

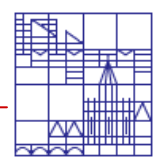
```
Nested-DFS(s)
    hash(s)
    for all successors s' of s do
      if s' not in the hash table then Nested-DFS(s')
    if accept(s) then Detect-Cycle(s)

Detect-Cycle(s)
    flag(s)
    for all successors s' of s do
      if s' on Nested-DFS-Stack then exit LTL-Property violated
      else if s' not flagged then Detect-Cycle(s')
```

  - note: second traversal in post-order
    - memory efficiency



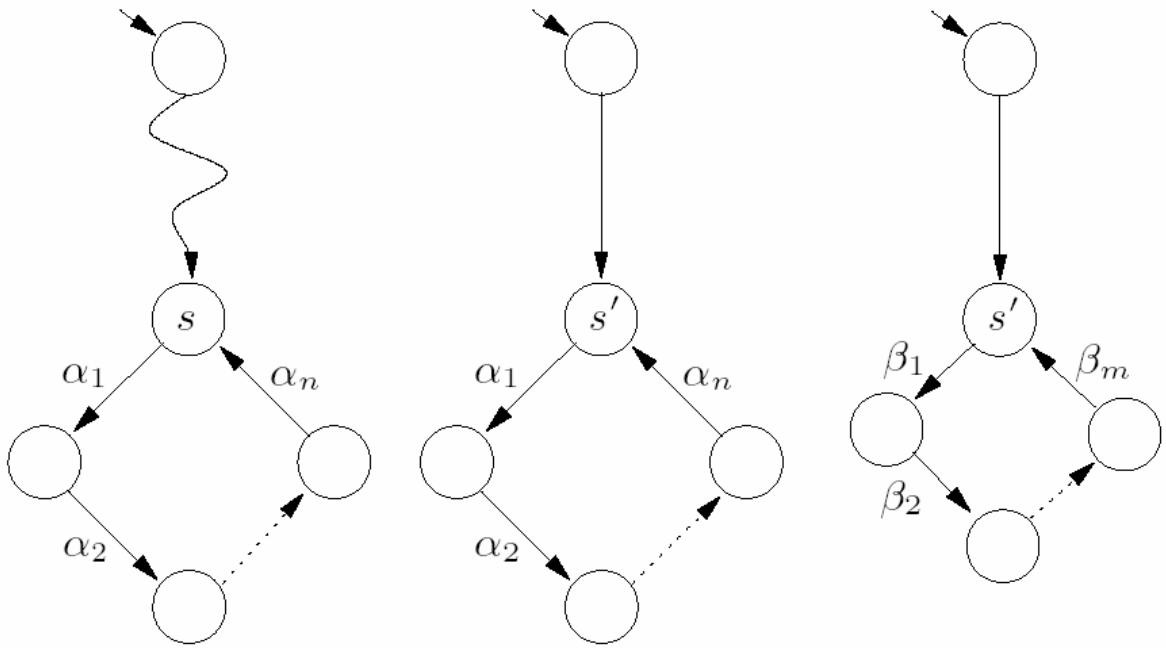
Directed Model Checking for Liveness

- **Potential of Improving Nested DFS**
  - improvement of second search (cycle finding) by directed search
    - not promising, since often only one cycle closing state on stack
  - alternative: pre-order traversal
    - quadratic time and linear memory overhead
  - improved nested DFS (I-NDFS)
    - results not as promising as for safety properties



Trail Improvement for Liveness

- **Trail Improvement**
  - given error trail
    - determine some state s starting a cycle
    - determine cycle of transitions α_1 .. α_n leading from s to s
  - improvement
    - path from root to s (or an equivalent s')
    - shorter cycle β_1 .. β_m equivalent to α_1 .. α_n



Trail Improvement für Liveness

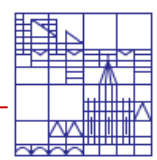
- **Trail Improvement**
  - m: Hamming distance
  - d: FSM distance
  - [s]: states equivalent to s
- **philo**
  - the existing cycle can be improved
- **GIOP**
  - search for equivalent state s' pays off

philo(8)

	NDFS	A*			
		s, H_d^s	s, H_m^s	$[s], H_d^{[s]}$	$[s], H_m^{[s]}$
s	57	18	11	18	11
l	71+68	31+4	31+4	31+4	31+4
m	3 MB	4 MB	4 MB	4 MB	4 MB
r	1 s	1 s	1 s	1 s	1 s

giop(2,1)

	NDFS	A*			
		s, H_d^s	s, H_m^s	$[s], H_d^{[s]}$	$[s], H_m^{[s]}$
s	7,331	355,249	931,901	1,730	1,929
l	288+2	288+2	288+2	52+2	52+2
m	8 MB	235 MB	609 MB	6 MB	6 MB
r	3 s	549 s	430 s	1 s	1 s



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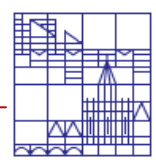
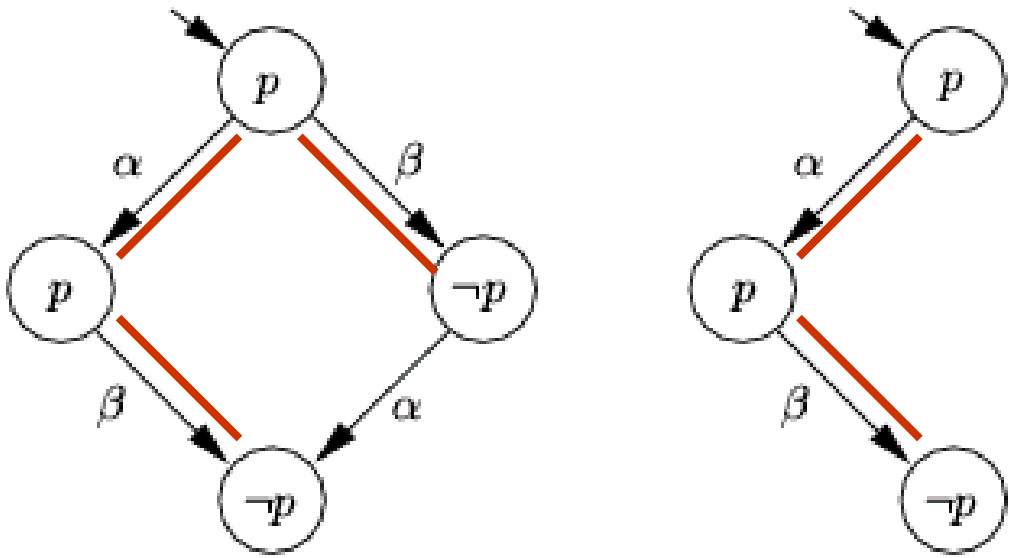


Partial Order Reduction

- **Partial Order Reduction**
  - exploit commutativity of concurrent transitions
    - exploration of only one representative of a class of equivalent paths in the state space
  - pre-processing: computing the "ample set" for a state
    - subset of the set of enabled transitions in a state that must be fully expanded
  - loss of solution length optimality



DMC and Partial Order Reduction

- **Conditions C0-C3 for the Construction of an Ample Set for Safety Protperties**

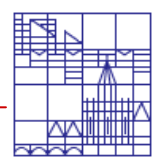
Condition C0: The ample set of s is void exactly when the enabled set of s is void.

Condition C1: Along every path in the full state space that starts at s, a transition that is dependent on a transition in $ample(s)$ cannot be executed without a transition in $ample(s)$ occurring first.

Condition C2: If a state s is not fully expanded, then each transition α in the ample set must be invisible with regard to P.

Condition C3: If for each state of a cycle, a transition α is always enabled, then α must be selected in the ample set of some of the states of the cycle.

  - conditions C0-C2 are independent of the used search algorithm



DMC and Partial Order Reduction

- **Conditions C0-C3 for the Construction of an Ample Set for Safety Protperties**

> **Condition C3**: If for each state of a cycle, a transition α is always enabled, then α must be selected in the ample set of some of the states of the cycle.

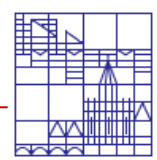
  - C3 can be over-approximated as $C3_{cycle}$:

    Every cycle in the reduced state space contains at least one state that is fully expanded.

    - expensive, since it requires cycle detection
  - C3 further over-approximated for safety properties as $C3_{stack}$ (for instance in SPIN):

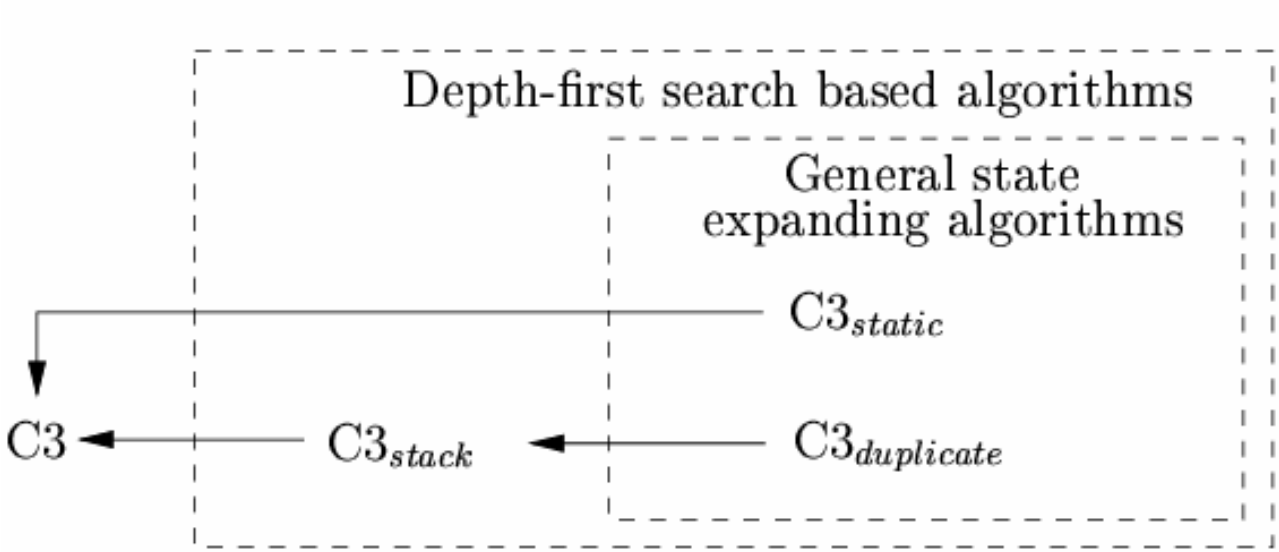
    If a state s is not fully expanded, then at least one transition in ample(s) does not lead to a state that is on the search stack

    - problem:
      - only applicable to stack-based DFS search
      - A* does not use a search stack



DMC and Partial Order Reduction

- **Overapproximations of C3 for non-DFS Algorithms**
  - $C3_{duplicate}$
    - *if a state is not entirely expanded then at least one transition in ample(s) does not lead into a **previously visited** state*
      - will not necessarily close a cycle
  - $C3_{static}$
    - *if a state is not fully expanded, then there is no transition in ample(s) which closes a cycle in the **control flow of a local process***

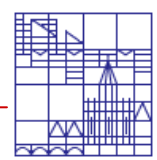


Experiments with HSF-SPIN

- **Safety Property Violation**
  - with po-reduction, with heuristic A* search

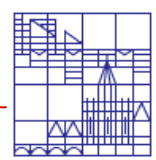
Model	Reduction	States	Transitions	Length
marriers	no	5,077	12,455	50
	$\mathbf{C3}_{duplicate}$	2,988	4,277	50
	$\mathbf{C3}_{static}$	1,604	1,860	50
pots	no	2,668	6,519	67
	$\mathbf{C3}_{duplicate}$	1,662	3,451	67
	$\mathbf{C3}_{static}$	1,662	3,451	67
leader	no	7,172	22,876	58
	$\mathbf{C3}_{duplicate}$	65	3,190	77
	$\mathbf{C3}_{static}$	399	3,593	66
giop	no	31,066	108,971	58
	$\mathbf{C3}_{duplicate}$	21,111	48,870	58
	$\mathbf{C3}_{static}$	12,361	24,493	58

  - further experiments with DMC + PO
    - no negative mutual influence
    - occasional synergetic effects were observed



Trail Reordering using PO Techniques

- **Trail Reordering**
  - loss of solution quality when process can immediately perform transition into error state but search algorithm postpones taking that transition
  - post-processing of error trail
    - ignore those transitions in the error trail that are *independent* from transition leading directly into error state
      - do not disable each other, are commutative
    - conditions to ignore *irrelevant* transition α
      - α is *invisible* wrt the property to be analyzed
      - α is *independent* from any later occurring transition
      - α *cannot enable* any later occurring transition
    - eliminate irrelevant transitions successively starting at the end of the trail
      - previously relevant transitions may become irrelevant, for instance, if they were only dependent on an eliminated transition



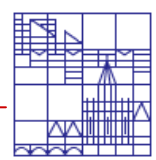
Trail Reordering using PO Techniques

- **Experimental Results**

leader(n)

n	$C3^{-}_{duplicate}$	reord.	$C3_{static}$	reord.	opt.
3	49	46	49	46	46
4	63	53	56	53	52
5	77	59	66	59	56
6	91	63	76	63	60
7	105	67	86	67	64
8	119	71	96	71	68

  - error states after reordering are very similar, differ only in transitions relevant to other processes than those which define the property (two processes assuming to be the leader)



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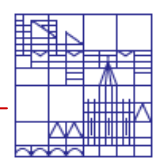
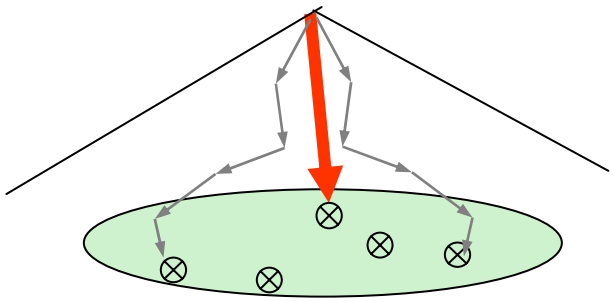


DMC and Probabilistic Model Checking



Set of "Goal" States

• satisfying reachability condition

• jointly contributing to required probability measure

CSL Model Checking

• establishes reachability and satisfaction of probability measure

• no counterexample

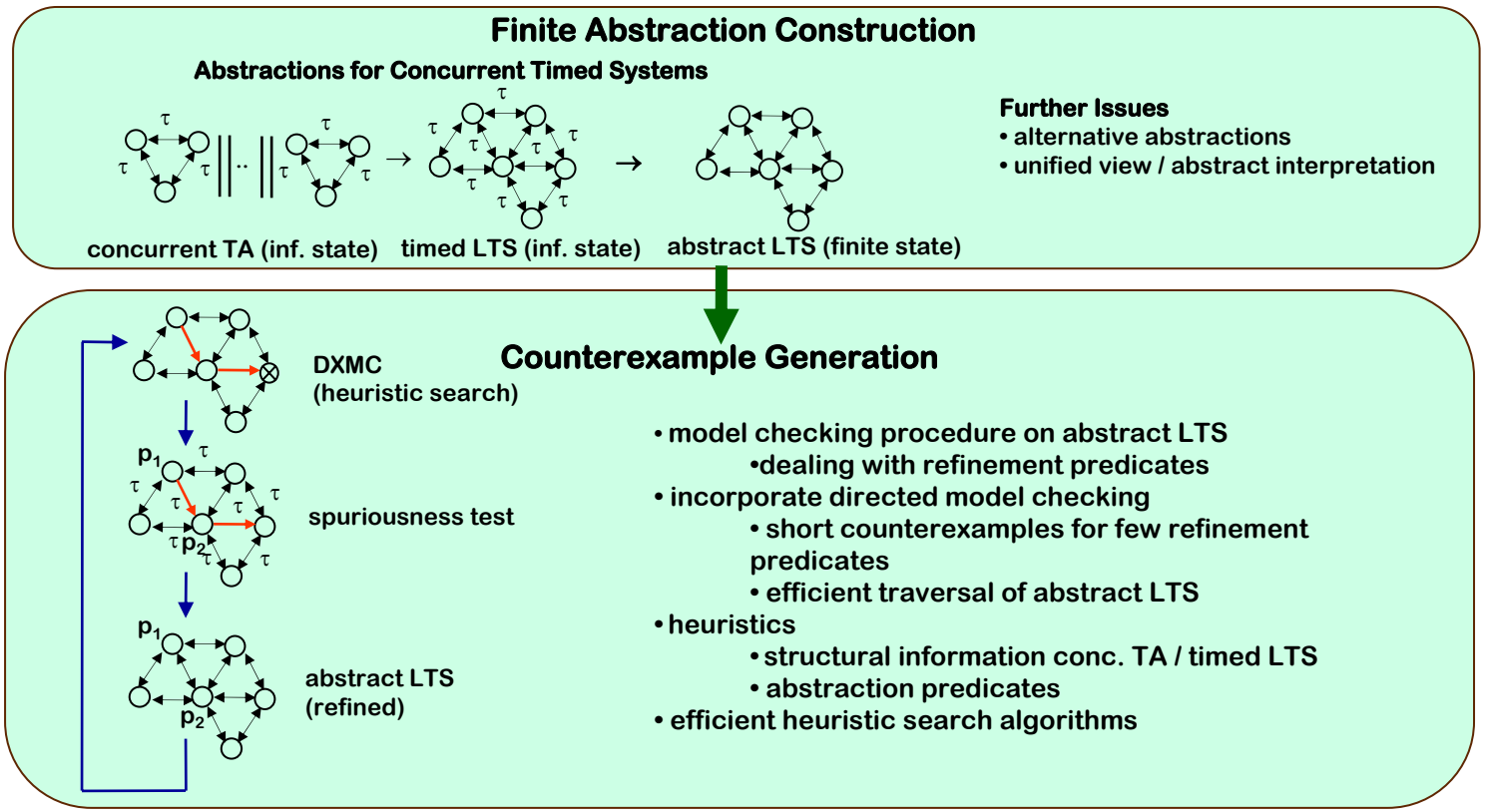
Directed Model Checking on LTS

• short, partial counterexample

  • large amount of probability mass

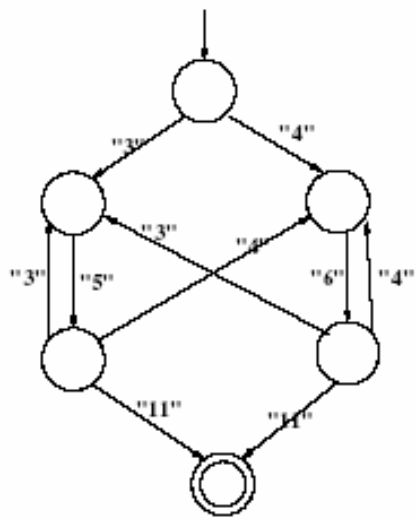
• efficient search in large state spaces

DMC and Abstraction Refinement



Guided Search in FLAVERS

- **Structural Heuristics**
  - e.g., in Java PathFinder (NASA Ames)
    - maximize number of thread switches to detect concurrency related bugs more easily
- **FLAVERS (UMass Amherst)**
  - finite-state verification based on data-flow abstracted model of Ada/Java programs
    - heuristics: minimal distance in task automaton to reach an accepting (= property violating state) [FSE 2004]



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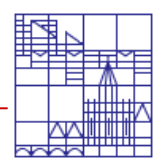
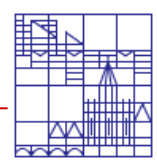


Conclusion

- **Directed Model Checking with A* and BF Searches for Safety Properties**
  - BF for fast error finding, A* for later improvement
  - shorter counterexamples than with DFS, often optimal
  - often less exploration effort than with BFS
  - even crude heuristic estimates improve error trail length
  - for dining philosophers, DMC with A* permits the solution of problems for which DFS fails
- **Liveness Properties**
  - certain improvements through A*+INDFS
  - good results with trail improvement based on Hamming and FSM distance metrics
- **Partial Order Reduction and DMC**
  - approximations $C3_{static}$ and $C3_{duplicate}$
  - occasional loss of optimality
  - good overall co-existence



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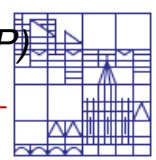
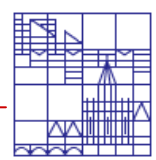


HSF-SPIN Experiments

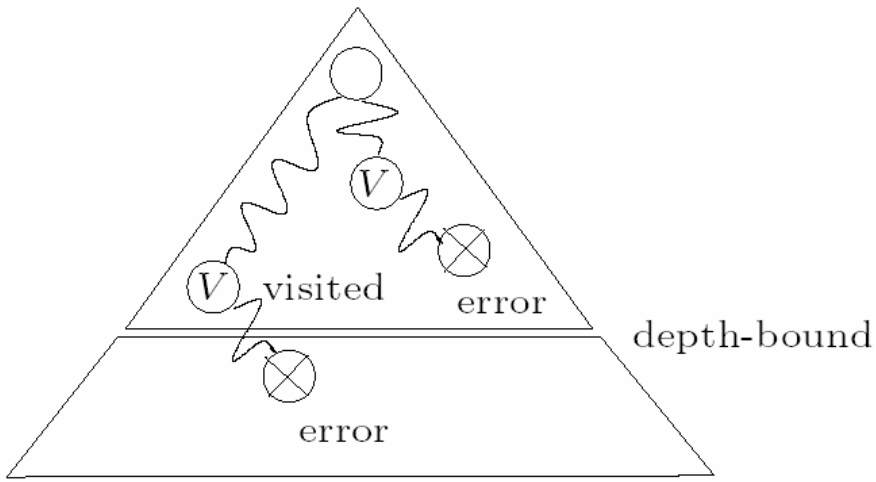
- **Impact of Range of Heuristic Functions**
  - deadlock detection, # of expanded states

Philosophers	no	H_{ap}	H_f	$H_f + U$
e	2,875	17	17	10
r	0..0	0..8	0..10	0..16
Optical	**no**	H_{ap}	H_f	$H_f + U$
e	110,722	14	342	342
r	0..0	0..12	0..14	0..12
Marriers	**no**	H_{ap}	H_f	$H_f + U$
e	493,840	432,483	462,235	192,902
r	0..0	0..4	0..25	0..25
GIOP	**no**	H_{ap}	H_f	$H_f + U$
e	37,266	27,061	28,067	24,859
r	0..0	0..6	0..12	0..25



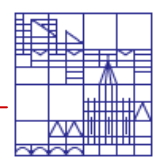
Depth-Bounded DFS

- **Finding Shortest Error Paths**
  - continue to explore when property-violating state found
    - bound search depth to shallowest error found
  - anomaly in depth-bounded search



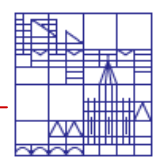
    - the fact that V has already been visited at higher depth means that the shallower V will not be re-explored, i.e., error not found
    - solution: enforce re-exploring of states reached along another, shorter path (-DREACH in SPIN)
      - worst-case exponential time penalty

Graphiken von A. Lluch-Lafuente



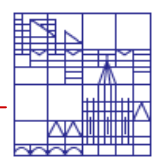
- **Monotonicity of Heuristics**
  - monotonicity
    - for each state u and each successor v of u:

      $h(u) - h(v) \leq cost(u \rightarrow v)$
  - impact
    - non-monotone heuristics may lead to exponential blow-up of reopenings in A*
    - in practice: reopening rarely observed for non-monotone heuristics



IDA* for Safety Properties

```
IDA*(s)
  Push(S, s, h(s)); U ← U' ← h(s)
  while (U' ≠ ∞)
    U ← U'; U' ← ∞
    while (S ≠ ∅)
      (u, f(u)) ← Pop(S)
      if (failure(u)) exit Safety Property Violated
      for all v in Γ(u)
          if (f(u) + 1 − h(u) + h(v) > U)
            if (f(u) + 1 − h(u) + h(v) < U')
              U' ← f(u) + 1 − h(u) + h(v)
          else
            Push(S, v, f(u) + 1 − h(u) + h(v))
```

Complexity Issues

- **Model Checking**
  - Translation LTL -> Büchi automata: exponential in the length of the formula
  - DFS: O(n+e)
- **A***
  - maintaining the nodes
    - open_list: priority queue
      - as heap: O((n+e) log n)
      - as Fibonacci-heaps: O(e + n log n)
  - additional effort for the state exploration (current research)
    - h admissible, h not monotone: exploration of exponentially many nodes
    - h inadmissible (no search for an optimal solution): avoidance of re-opening
      - H_{ap}: monotone, admissible
      - H_D without rendez-vous: monotone, admissible