tutorial: hardware and software model checking

gerard holzmann and *anuj puri*

{ gerard | anuj } @research.bell-labs.com

Bell Labs, USA

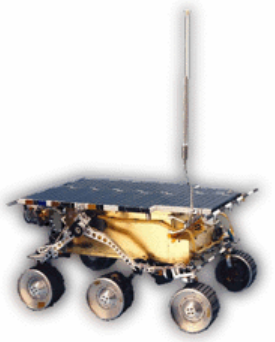
outline

- introduction (15 mins)
- theory and algorithms
  - system modeling and specifications (25 mins)
  - algorithms and data structures (25 mins)
- practice (25 minutes)
  - the role of abstraction
  - model checking tools
  - some applications

what is model checking ?

- a model of the hardware or software system
- a specification
- Question: does system satisfy specification?
- key is to build a model that is an appropriate abstraction of the system
- a model checking tool answers:
  - *yes* -- if the model definitely satisfies the specification
  - *no* -- in which case it provides the user a counter-example

the mars pathfinder

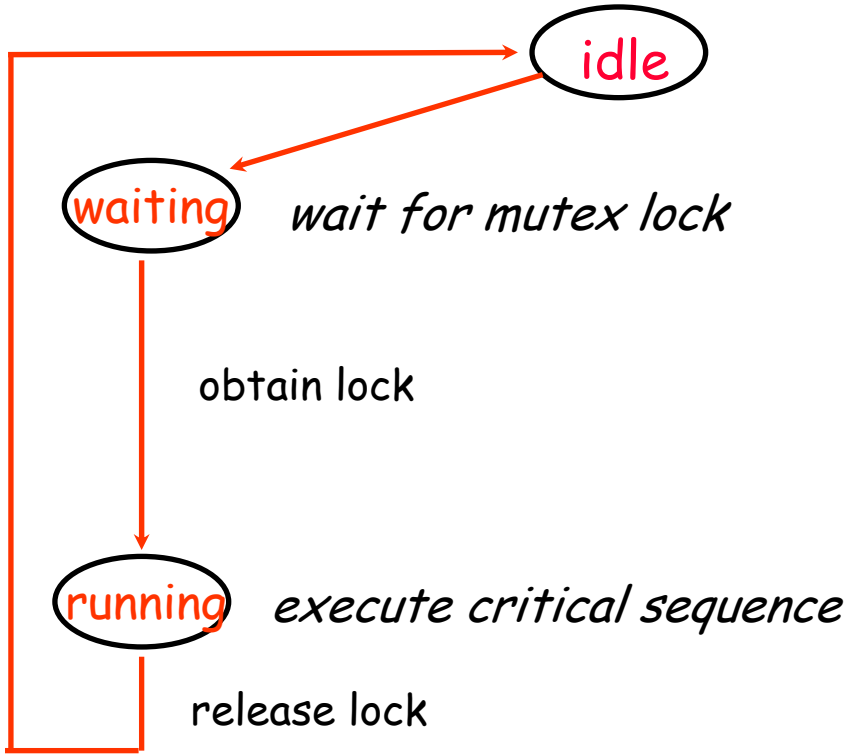


An Example:

The required properties for the Mars Pathfinder control software included:

- **mutual exclusion rules**
  - **a process cannot access the databus unless it owns a mutual exclusion lock**
- **scheduling priority rules**
  - **a lower priority process cannot execute when a higher priority process is ready to execute**
  - **saving data to memory, for instance, has higher priority than processing data**

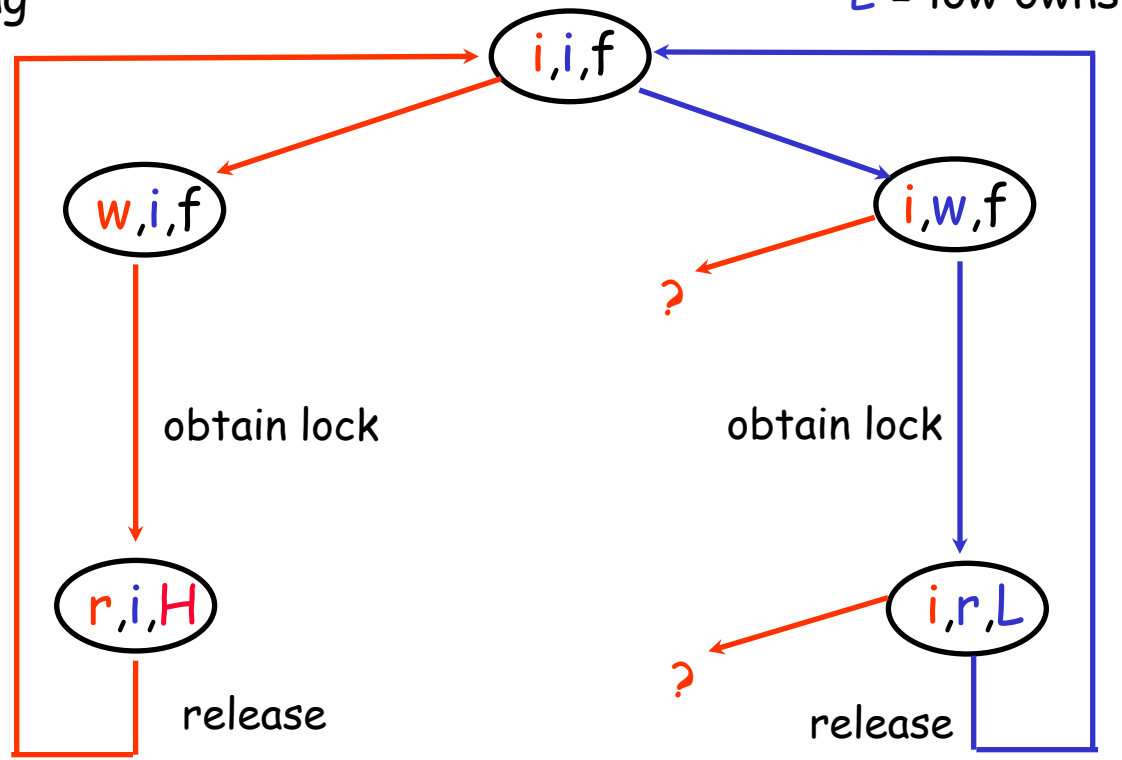
the basic sequence for access to the shared bus



priority rule

i = idle
w = waiting
r = running

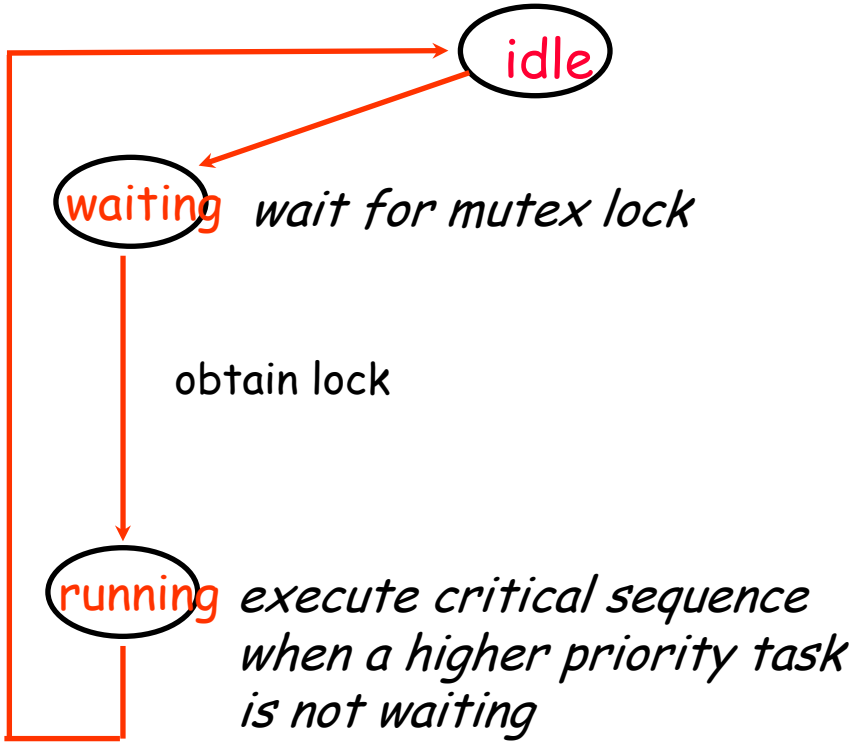
f = mutex lock free
H = high owns lock
L = low owns lock

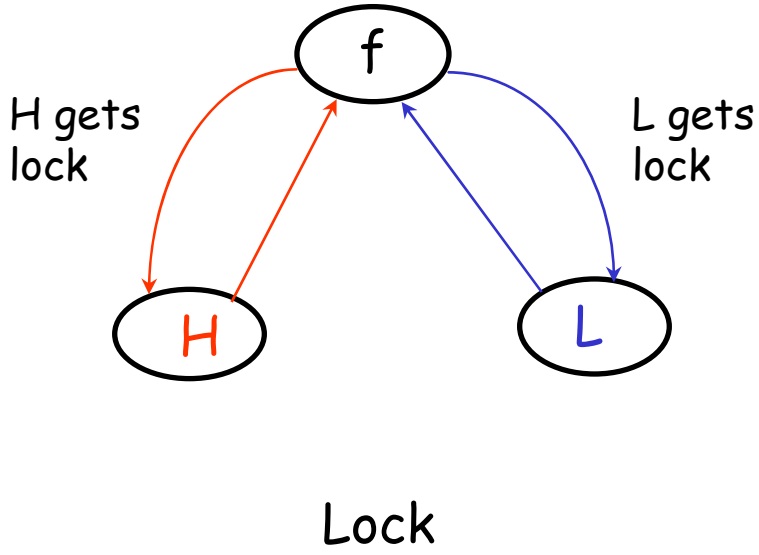


High priority process
(dumping measurements)
restricted by lock

Low priority process
(processing data)
cannot run unless: i,-,-

system model



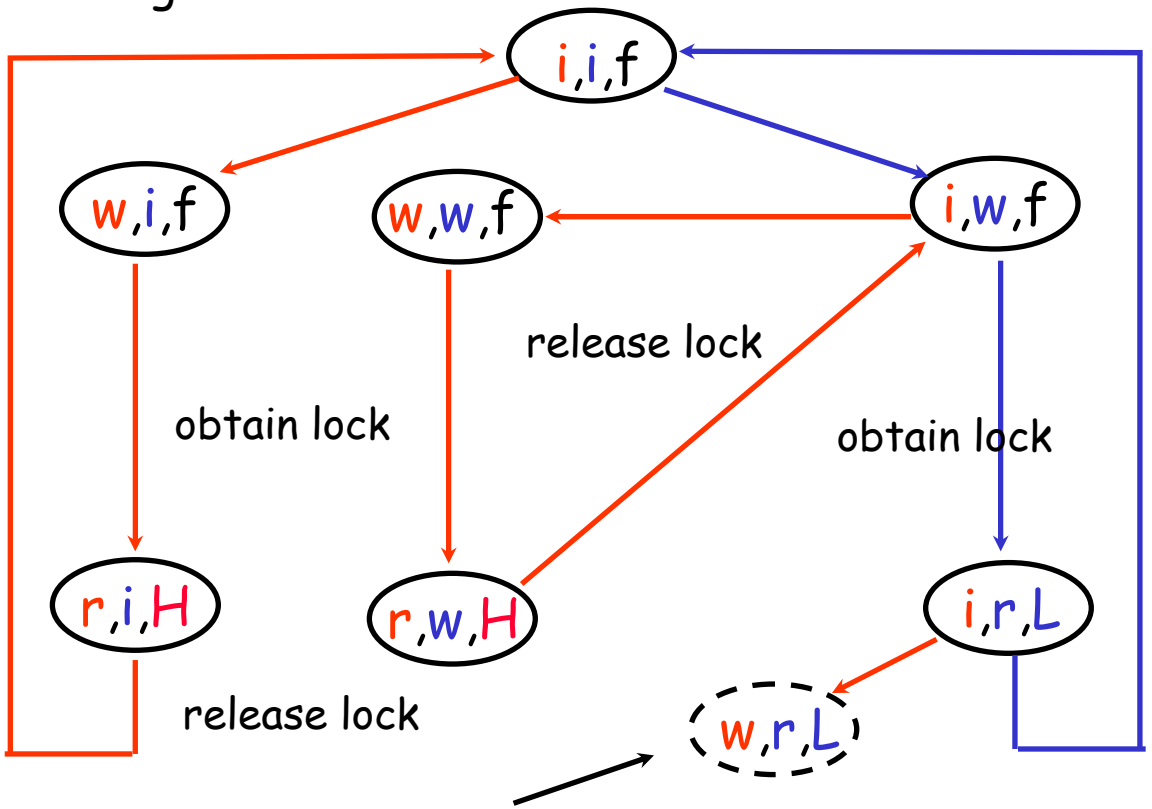


high priority and low priority tasks

model checking run

i = idle
w = waiting
r = running

f = mutex lock free
H = high owns lock
L = low owns lock



the hangup problem
from July 1997

model checking procedure

- **build a model of the system abstracting out irrelevant details**
- **write a specification**
  - **deadlocks, reachability issues, system invariants etc.**
- **run the model checker**
  - **performs some variation of reachability analysis on the *finite state* model**
- **the possible answers are:**
  - **yes -- specification satisfied**
  - **no -- a counter-example provided**

defining issues

- how do you formalize
  - modeling issues
  - specification
- how do you search for counter-examples
  - explicit state model checking
  - symbolic model checking
- how do you control complexity
  - avoiding or containing state space explosion
  - abstraction and reduction techniques

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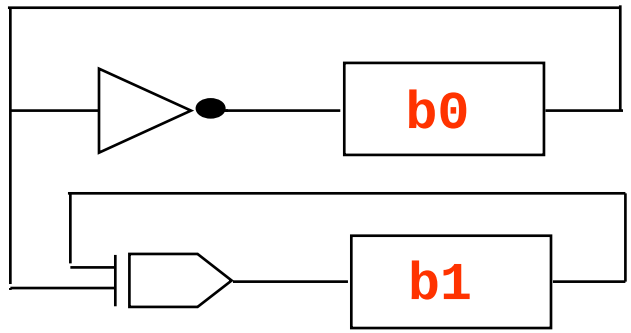
system modeling

hardware:

- **typically synchronous, clock-driven**
- **bit-registers, signal wires, gates**
- **modeled with hardware description language**

2 bit counter:



b1 b0 : 00 -> 01 -> 10 -> 11 -> 00

system modeling (cont.)

software:

- **asynchronous, distributed processes**
- **message passing, shared variables, higher level data structures, semaphores, rv-ports**

SPIN model for the Pathfinder:

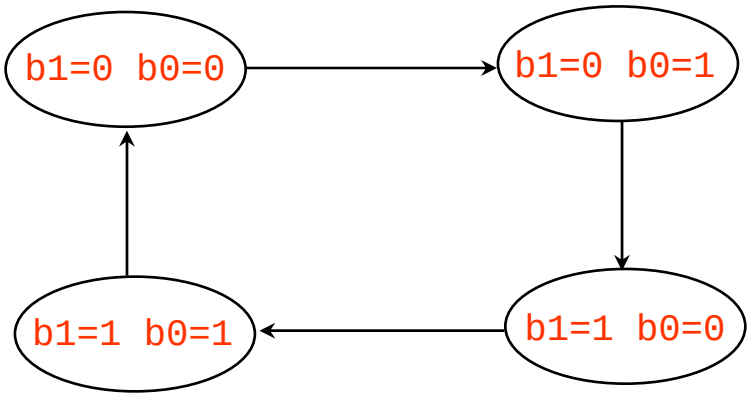
```
active proctype low_priority()
   provided (h_state == idle) {
end: do
    :: l_state = waiting;
       atomic { mutex == free ->
                mutex = busy };
       l_state = running;
     /* consumes data */
       atomic { l_state = idle;
                mutex = free };
    od }
```

```
active proctype high_priority (){
end: do
     :: h_state = waiting;
        atomic { mutex == free ->
                 mutex = busy };
        h_state = running;
      /* produces data */
        atomic { h_state = idle;
                 mutex = free };
     od }
```

system modeling (cont.)

- underlying model is finite automata
- models (hardware description language models or promela models) can be translated to finite automata

2-bit counter:



formalizing specifications

- **PLTL (temporal logic)**
  - **propositional linear time logic**
  - **first suggested by Amir Pnueli in late 70s**
- **ω-automata**
  - **finite automata accepting infinite sequences**
- **many other logics**
  - **CTL, u-calculus, many variations**

Syntax of PLTL

- formula ::=
  - true, false
  - propositional symbols p, q, r, …
  - (f)
  - unary_operator f
  - f binary_operator f
- unary_operator ::=

```
[]      --- always, henceforth
<>      --- eventually
!       --- logical negation
```

- binary_operator ::=

```
U     --- strong until
&&     --- logical and
||     --- logical or
->     --- implication
<->    --- equivalence
```

semantics of PLTL

Model: s = s[0] s[1] s[2] s[3] ....

for each proposition p,
s[i] |= p is defined

temporal formulas:
s[i] |= []f provided $\forall$j >= i s[j] |= f
s[i] |= <>f provided $\exists$j, j >= i s[j] |= f
s[i] |= f U g

s |= f provided s[0] |= f

typical PLTL formulae

- **frequently used properties:**
  - **[] p --- invariance**
  - **<> p --- guarantee**
  - **p -> (<> q) --- response**
  - **p -> (q U r) --- precedence**
  - **[]<> p --- recurrence (progress)**
  - **<>[] p --- stability (non-progress)**
  - **<> p -> <> q --- correlation**
- **two useful equivalences:**

  ![] p <=> <> !p

  !<> p <=> [] !p

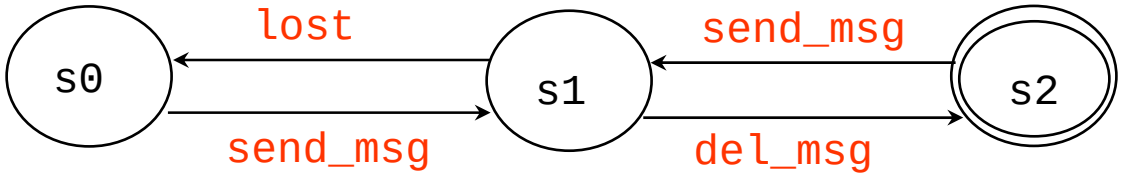
model checking PLTL formulae

System model: S
Specification: PLTL formula *f*

How do we model check ?

we need to learn about ω-automata ....

automata theoretic approach



standard finite automata

σ = send_msg lost send_msg del_msg
run = s0 s1 s0 s1 s2
σ is accepted when s2 is final

ω–automata (buchi automata)

σ = send_msg lost send_msg del_msg ....
run = s0 s1 s0 s1 s2 ....
σ is accepted when s2 is visited infinitely often

language: set of accepted strings or sequences

automata theoretic approach(cont.)

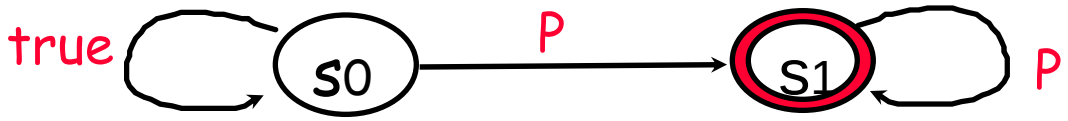
- deterministic vs. non-deterministic
- ω-automata are closed under all boolean operations
  - automata A with language Lang(A)
  - there exists C with Lang(C) = $\Sigma^{\omega} \setminus$ Lang(A)
  - for A and B, there exists C with Lang(C) = Lang(A) $\cap$ Lang(B)
- checking non-emptiness: is there a reachable strongly connected component which contains a final state ?

automata theoretic approach (cont.)

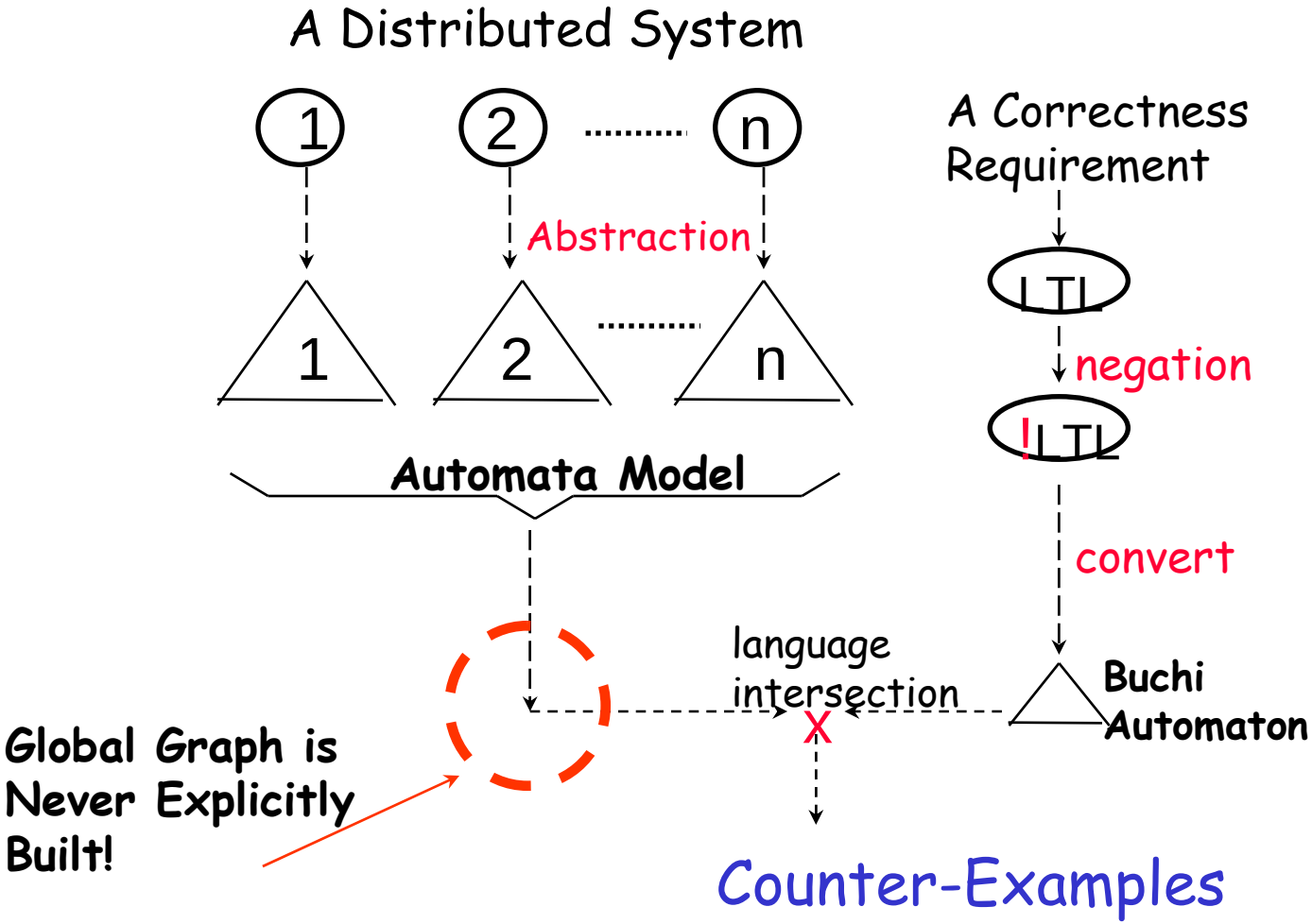
- Model: Lang(Model)
- Specification - another automaton - Lang(Spec)
- Model Checking Question:
  - Lang(Model) $\subset$ Lang(Spec)
- Algorithm:
  - Lang(Model) $\subset$ Lang(Spec) iff
    Lang(Model) $\cap$ (Σ^{ω} \ Lang(Spec)) = $\varnothing$
  - Yes/No(counter-example)

from logic to automata

- The truth of an PLTL formula is defined over execution sequences where □□□□
- For any LTL formula f there exists a buchi automaton that accepts precisely those executions for which f is true
- Example: the LTL formula <>[] P corresponds to the Buchi automaton:



spin's on-the-fly verification procedure



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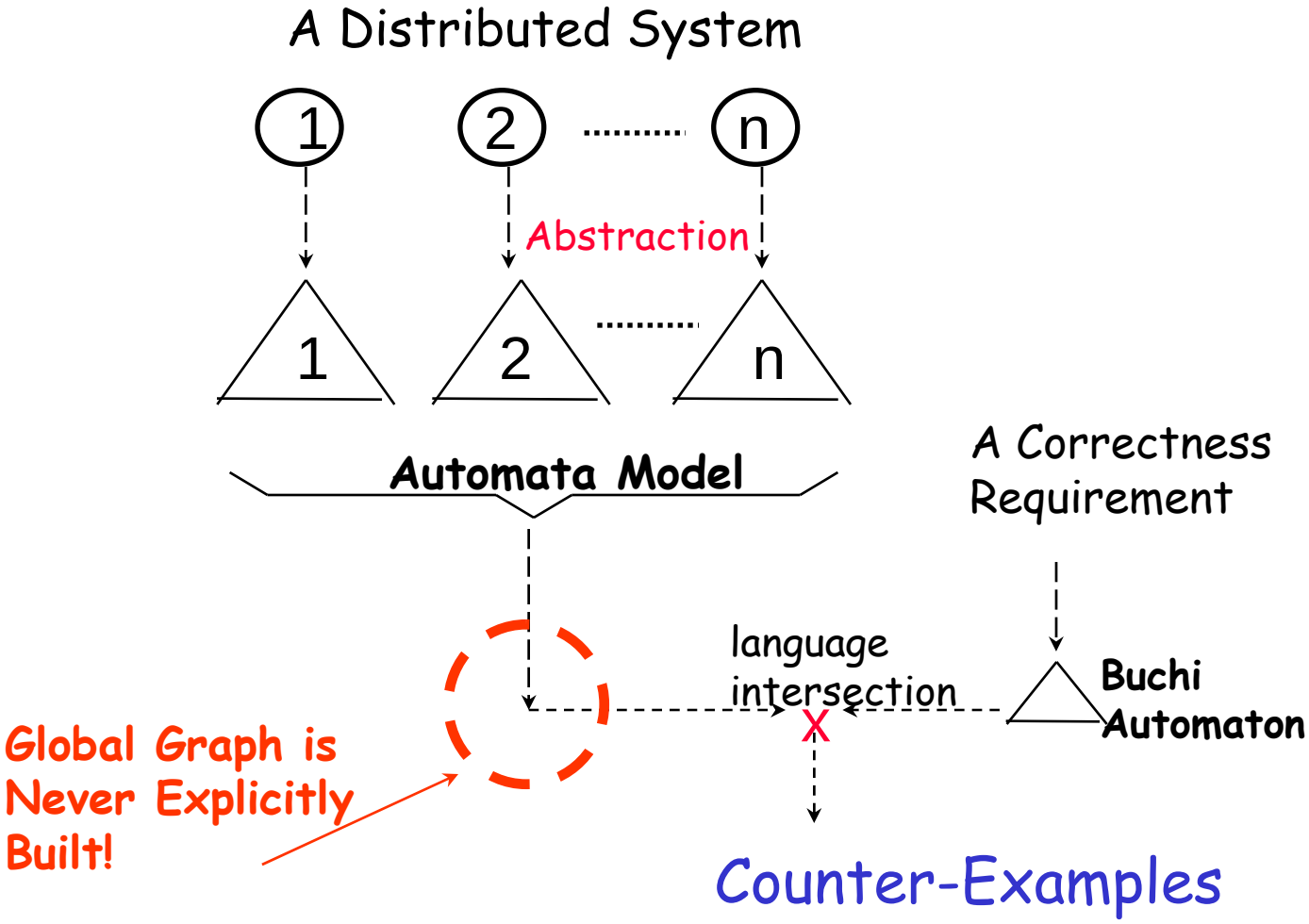
algorithms and data structures

- basic issues
  - reachability
  - cycle detection
- explicit state enumeration
  - dfs
- implicit state enumeration
  - bfs
- data structures for storing states

explicit state enumeration

- **problem:** is there a cycle containing a final state ?
- depth first search (dfs)
  - compute strongly connected components
- nested depth first search (used in Spin)
- state storage
  - compression techniques

spin's on-the-fly verification procedure (language intersection)



depth first search

dfs algorithm:

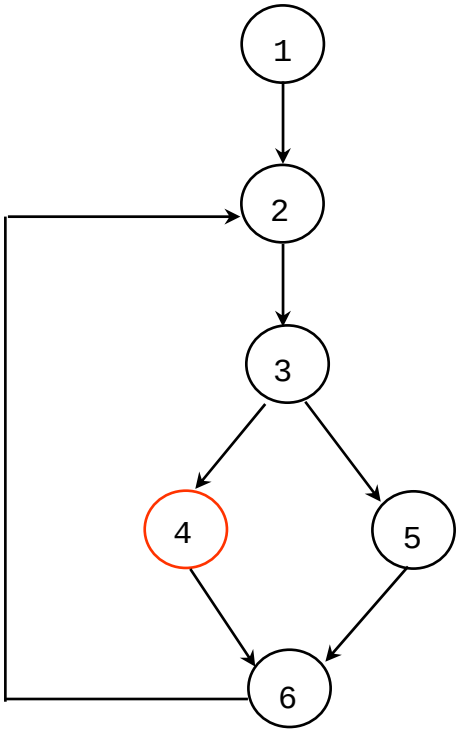
```
store = ∅

dfs(q)
{
  if q ∈ store
    return;
  else
    store = store ∪ {q};

  for each successor s of q
    dfs(s);
}
```

Memory Bottleneck ←

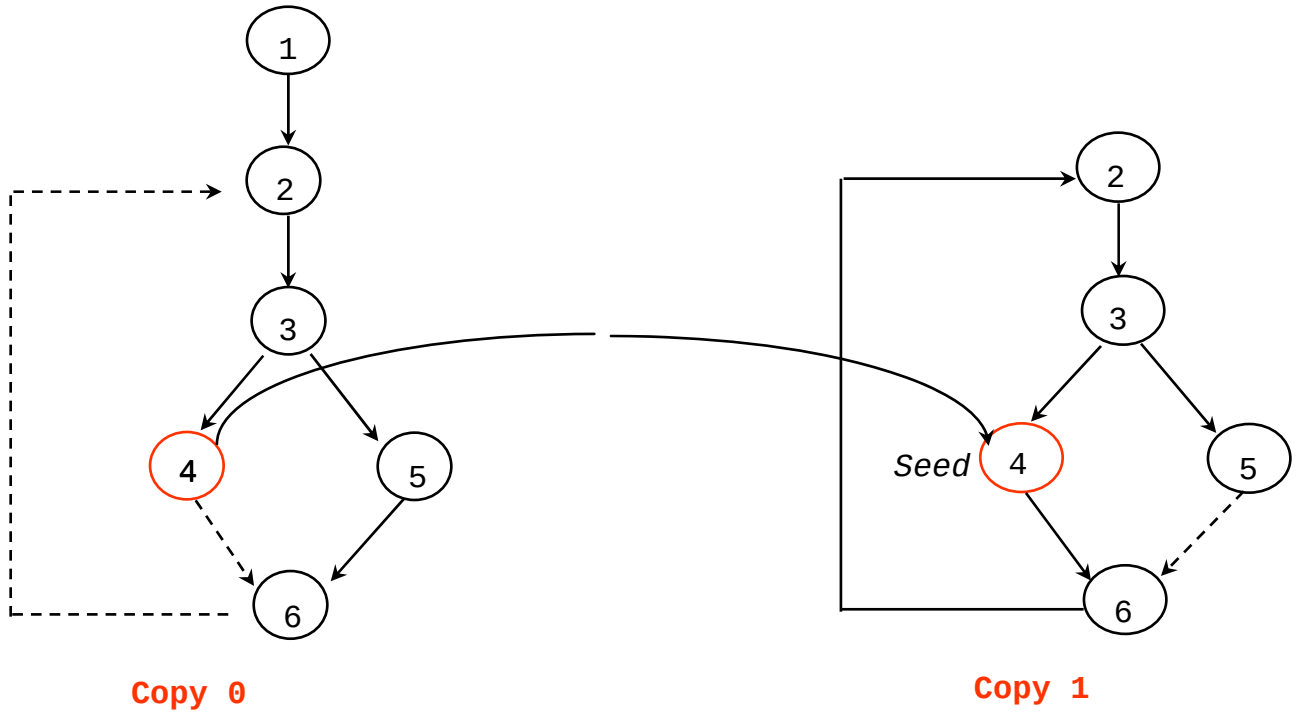
- **recursively explore state graph**
- **store as little data as possible about previously visited states**
- **no need to store transitions**

Example

Problem: **Is there a cycle through the final state ?**



Nested Depth-First Search



- Memory Overhead: 2 bits per state
  - Tarjan's dfs requires 2 x 32 bits per state
- Worst case time overhead: 2 x dfs

computational cost

Number of States: R

Size of each state: S

R x S dominates all costs

1) try to reduce R

- **model reduction (abstraction)**
- **partial order reduction**

2) try to reduce S

- **store each state explicitly (fast - default)**
- **compress states (-DCOLLAPSE)**
  - **lossy compression (ie, using hash function)**
- **compute minimized DFA recognizer for the states (-DMA=N)**

implicit state enumeration

- **boolean functions**
  - **canonical representation using minimized dfa (obdds)**
- **basic boolean operations**
- **symbolic representation of transition relation**
- **symbolic breadth first search (bfs)**

Boolean Functions

Example:

Boolean Variables: a, b, c

f = ab + bc + ac

n-variable boolean function:

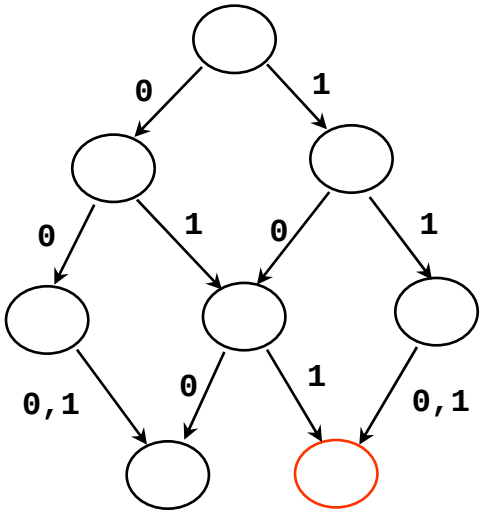
$f : \{0,1\}^n \rightarrow \{0,1\}$

Truth Table:

a	b	c	f
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

Minimized DFA representation of Boolean Functions

f = ab + bc + ac



- Almost same as OBDDs

Basic Boolean Operations

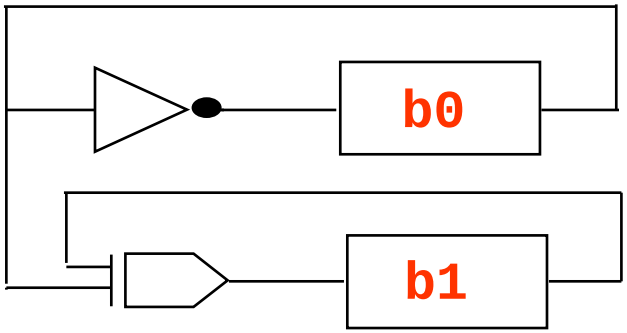
- All boolean operations can be performed efficiently using the minimized DFA representation
- Disjunction: h = f + g
- Negation: h = ~ f
- Existential quantification:
  - h(y) = $\exists$x f(x,y) = f(0,y) + f(1,y)
- Canonical form
  - equivalence of two boolean functions

Symbolic Transition Relation

Transition Relation:

$R \subset Q \times Q$

$(q,r) \in R$ iff there is an edge from q to r



symbolic transition relation:

$(b0' = \sim b0) \wedge (b1' = b1 \oplus b0)$

boolean function representation:

$R : \{0,1\}^2 \times \{0,1\}^2 \rightarrow \{0,1\}$

symbolic breadth first search

symbolic transition relation: $R(q,q')$

initial state: $s0(q)$

symbolic breadth first search:

$$states0(q) = s0(q)$$

$$s1(q') = \exists q \; (\; s0(q) \wedge R(q,q') \;)$$

$$states1(q) = states0(q) + s1(q)$$

$$s2(q') = \exists q \; (\; s1(q) \wedge R(q,q') \;)$$

$$states2(q) = state1(q) + s2(q)$$

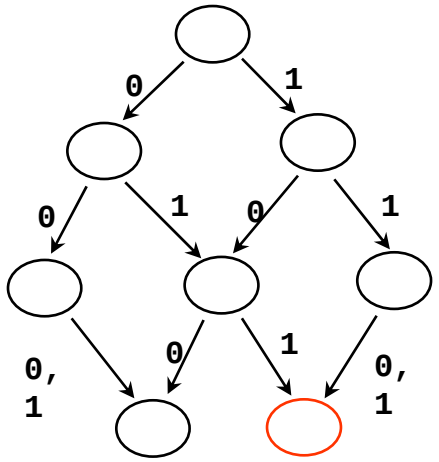
⋮

stop when states $i(q) = states\ i\text{-}1(q)$

minimized dfa storage in spin

explicit state enumeration --- states stored as minimized dfa

example:



store = { 011, 101, 110, 111 }

Add state s in time O(|s|)

time/memory tradeoff

- reduces memory use by 10x-100x
- but adds a time penalty of 10x-100x

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exponential effects in the state space

- **Example:**
  - **k integers, each taking values from -N to N**
  - **number of states ~ $(2N)^k$**
- **Example:**
  - **k buffers, s slots per buffer, m different items**
  - **number of states ~ m^{sk}**

importance of abstraction

- model checkers are intended to be applied to models of systems, not directly to implementations
  - a model is a design abstraction
- find the appropriate abstraction
  - modeling the interfaces between modules without modeling the internal details of modules
- without abstractions, simple problems can become intractable
- and with abstractions, even hard problems can be solved if you know which parameters to tune

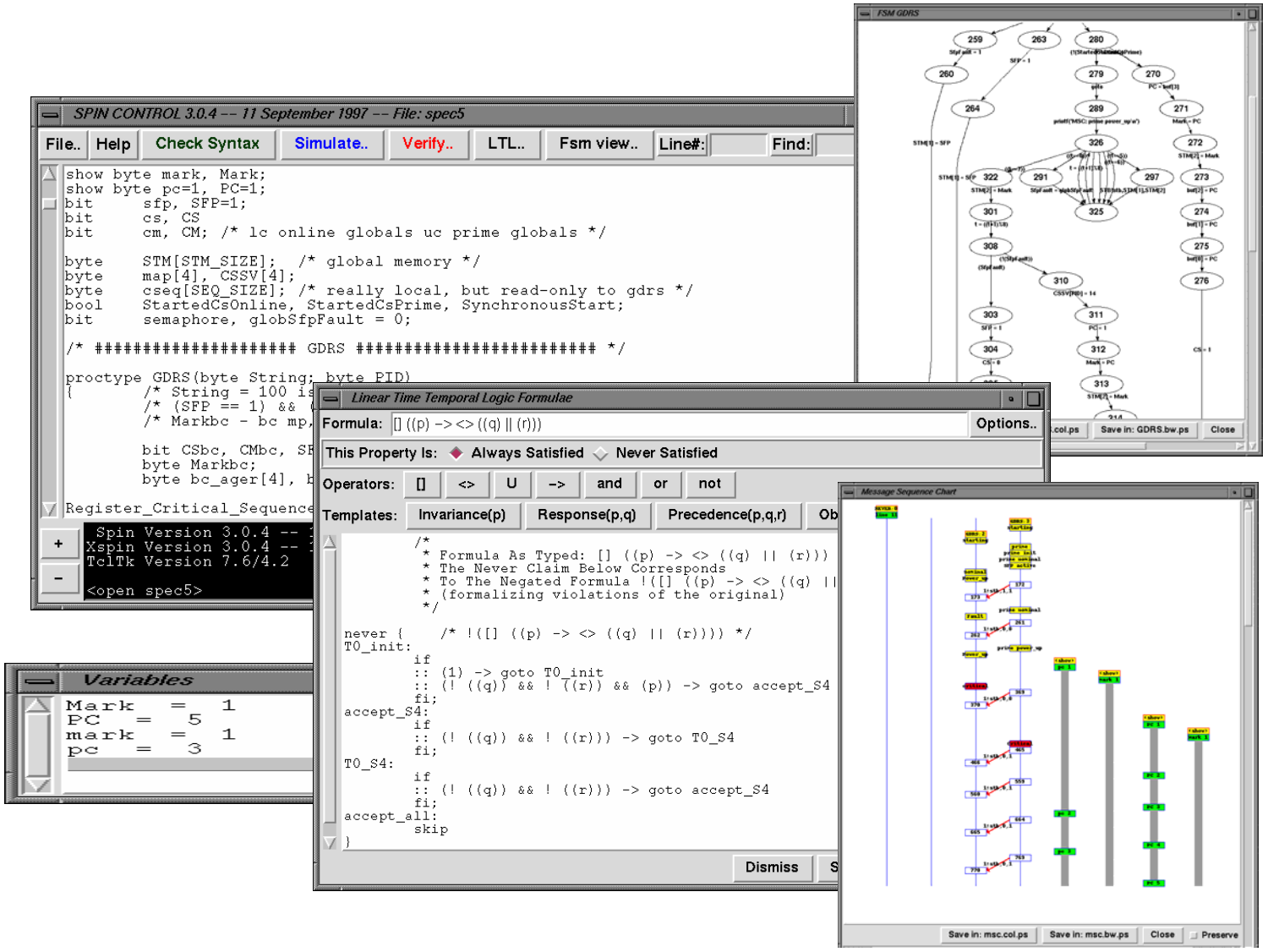
importance of abstractions (cont.)

- if the problem is complex:
  - there is no free lunch: you have to find the right design abstraction
  - be suspicious of variables, counters, integer data items
  - think of how you would explain the principles of the design on a blackboard to a friend
  - model only the relevant aspects

tools

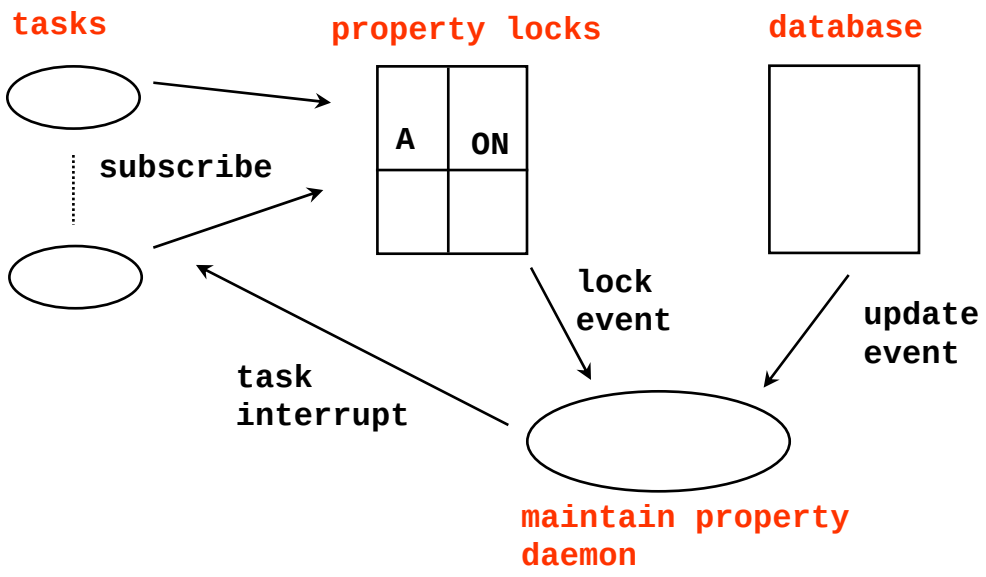
- implicit state enumeration
  - oriented towards hardware verification
  - smv (CTL), vis, cospan, ...
- explicit state enumeration
  - oriented towards software verification
  - spin (LTL), murphi, ...
- commercial model checking tools

design verification: spin



deep space 1 mission to mars

remote agent executive resource manager
- verification of a new experimental distributed controller design using SPIN



[Havelund, Lowry, Penix, 1998]

deep space 1 - results

- modeling effort - 2 people from NASA/Ames Research center about 6-8 weeks (354 lines in SPIN)
- 1 week to run and document verification (approx. 300K states, 10 seconds/run)
- 2 properties checked, both failed
- 4 serious errors found
- developer's reaction
  - "you've found a number of bugs that i am sure would not have been found otherwise. One of the bugs revealed a major design flaw. So I'd say you have had a substantial impact."

processor verification

- pentium floating-point division bug cost Intel $475 million
- plenty of dollars to do a lot of formal verification
- specialized techniques
  - ALU verification
  - pipelines etc.
- much commercial activity by EDA tool vendors and chip design companies

intel looking to hire ...

although formal verification methods have been in widespread use at Intel for several years, sequential formal verification (using model checking) has seen its first wide deployment on the Merced project in the Santa Clara Processor Division

we have trained a large number of engineers in the techniques of formal specification and proof, made great strides in mastering the technology, improving the tools and developing methodologies of usage; but most importantly, we have found numerous bugs, some of them very sneaky, and established FV as a valuable contributior to the quality of logic design.

we are looking for a small number of exceptional candidates to own the formal verification of blocks of Merced logic design.
The work involves defining a comprehensive set of assertions which describe the behavior of the blocks, formulating them in a formal language, and proving these properties using our automated proof tools. Our current focus is on model checking as the primary proof mechanism, but we have access to and will make use of other tools as appropriate.

summary

- real problem: find bugs in design
- model checking: build a model of the system, then the model checking tool will automatically check whether the specification is satisfied
- abstractions are key in building tractable models
- theory of model checking
- good tool support
- both software and hardware model checking are becoming mainstream, after having proven their value in academic and industrial use

some references

- **Gerard Holzmann,** *Design and Validation of Computer Protocols, Prentice-Hall, 1991.*
  - **good introduction on spin and protocol verification**
- **Ken McMillan,** *Symbolic Model Checking, Kluwer Academic Publishers, 1993.*
  - **good introduction to SMV, hardware and symbolic verification**
- **K.Havelund, M.Lowry, J.Penix,** *Formal Analysis of a Space Craft Controller using SPIN, 1998.*
  - **nice application of model checking**