NuSMV

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Outline

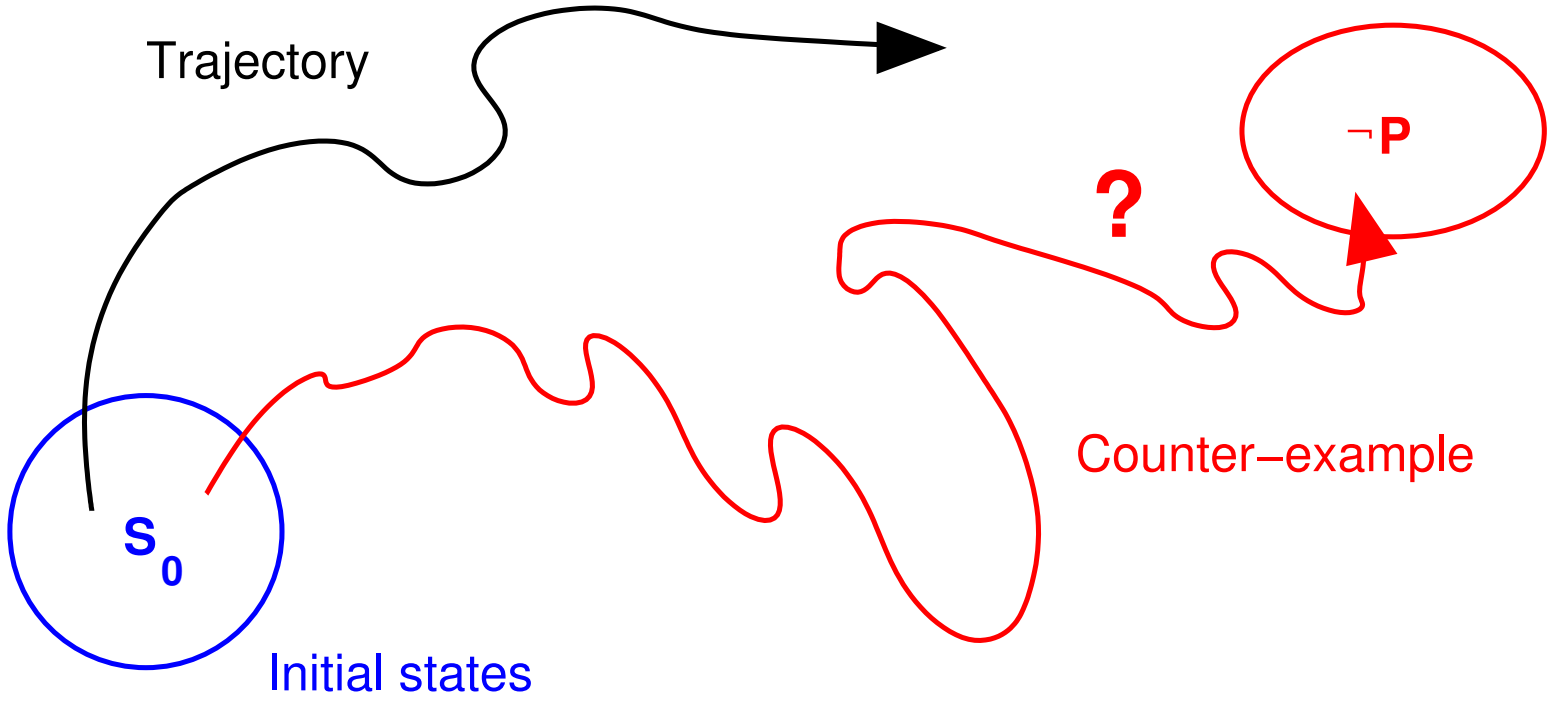
1. How to implement a model checker (key ideas):

   (a) Explicit-state model checking (SPIN).
   (b) Binary Decision Diagrams (BDDs).
   (c) Symbolic model checking/NuSMV.

2. Model validation.

3. Model checking for program analysis.

Model Checking = state space search



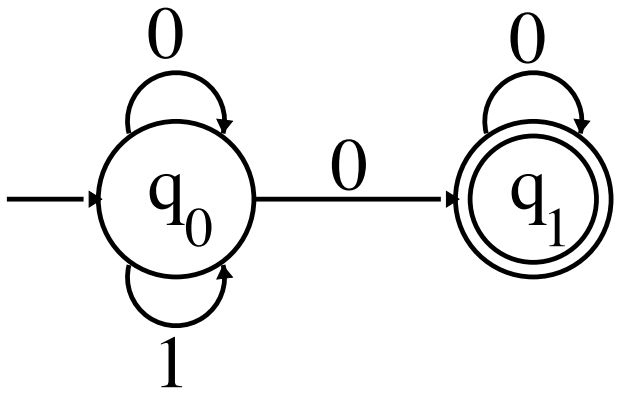
- Traditionally applied to specifications, protocols, algorithms.
- Certain types of software (embedded) can be mapped to such model checkers.

State space search

- How to analyze reachable states against the property?

How to check a model against a property

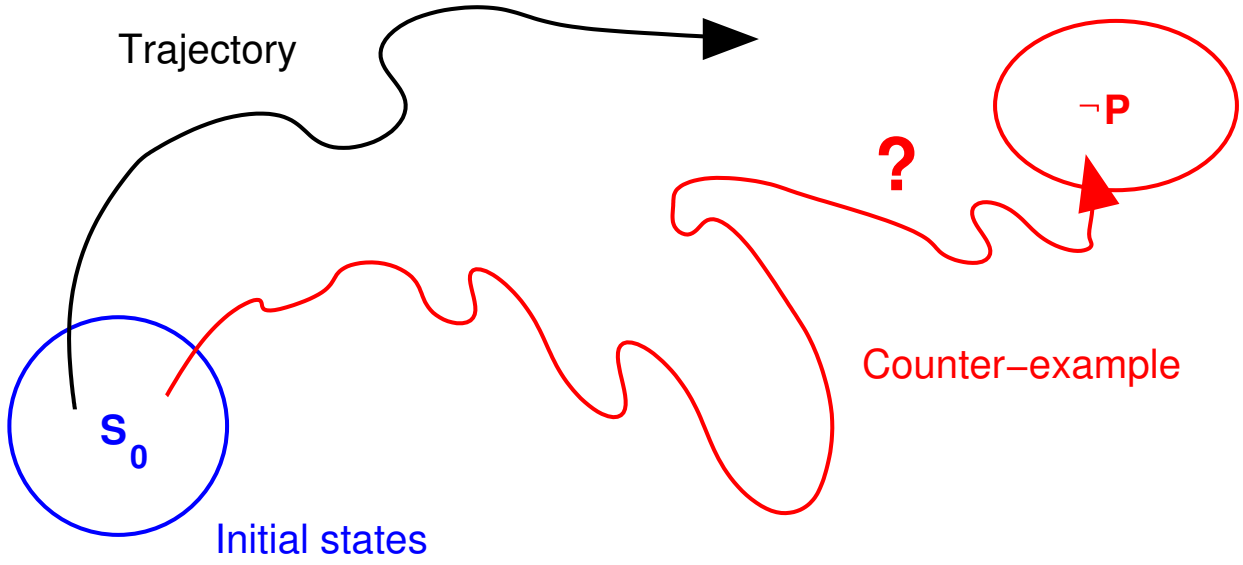
- Properties can be translated into so-called Büchi automata.
- These automata can be non-deterministic and accept infinite words.
- Automata can be determinized (at exponential cost).



- $0 \in L(A)$?
- 01?
- 00?
- 10?
- 100?
- 101?

How to implement a model checker

- **Negate** property $\neg p$: error state(s)
  (accepting states in Büchi automaton).
- Cross-product of model with that automaton encoding $\neg p$.
- All we need to do now is to check whether „bad” states are reachable
  (see beginning of this lecture).



Explicit-state model checking

- Enumerate all states one by one.
- Stop search when property violation found or no new states left.

```
def search(model: Model) = {
  currentStates = new Set(model.initialStates)
  visitedStates = new Set()
  var result = None
  // new search queue with init. state
  while (!currentStates.isEmpty && result == None) {
    currentState = currentStates.choose
    // choose removes returned state from currentStates
    result = explore(currentState.successors)
  }
  return result
}
```

State space exploration

```
def explore(states: List[State]) {
  // explore each successor of the current state
  // stop search at target
  for (s <- states) {
    if (s.isAccepting) {
      return Found
    }
    if (!visitedStates.contains(s)) {
      currentStates += s
    }
    visitedStates += s
  }
}
```

- This code shows the key concepts.
- Liveness properties require extra transformations or bookkeeping about loops.

SPIN

- Popular explicit-state open source model checker.
- Open source since 1991.
- Compiles transition system (in Promela) to C code.
- Uses optimizations such as state hashing to speed up search.
- Very fast if entire model fits in RAM.

What if model is too big to fit in memory?

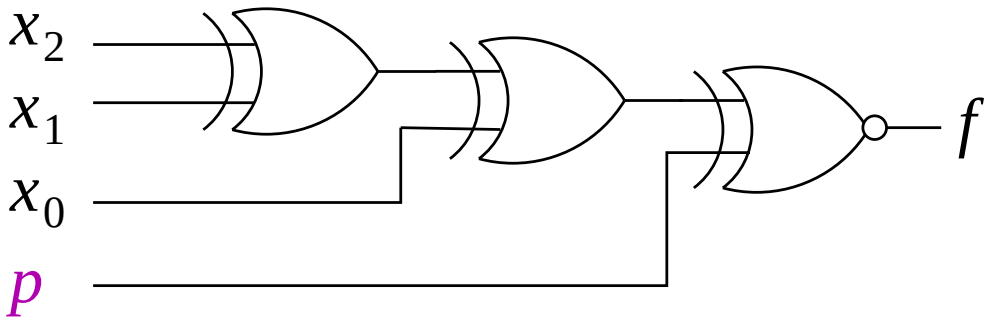
The answer will be given in the next lecture...

Binary Decision Diagrams (BDDs)

- Published by Randal Bryant in 1986.
- Compressed representation of Boolean functions.
- Eliminates redundancy in sub-expressions.
- For equal variable order, reduction is **canonical** (same result regardless of order in which subexpressions are added).
- Boolean **operations** can be implemented on **compressed** data (ROBDDs).

Example: Parity check for three-bit memory

1. Register $x_2x_1x_0$, Parity p
2. Formula f shows if parity is correct.



Example and illustrations by Armin Biere/JKU Austria.

$x_2x_1x_0\,p$	f
0 0 0 0	1
0 0 0 1	0
0 0 1 0	0
0 0 1 1	1
0 1 0 0	0
0 1 0 1	1
0 1 1 0	1
0 1 1 1	0
1 0 0 0	0
1 0 0 1	1
1 0 1 0	1
1 0 1 1	0
1 1 0 0	1
1 1 0 1	0
1 1 1 0	0
1 1 1 1	1

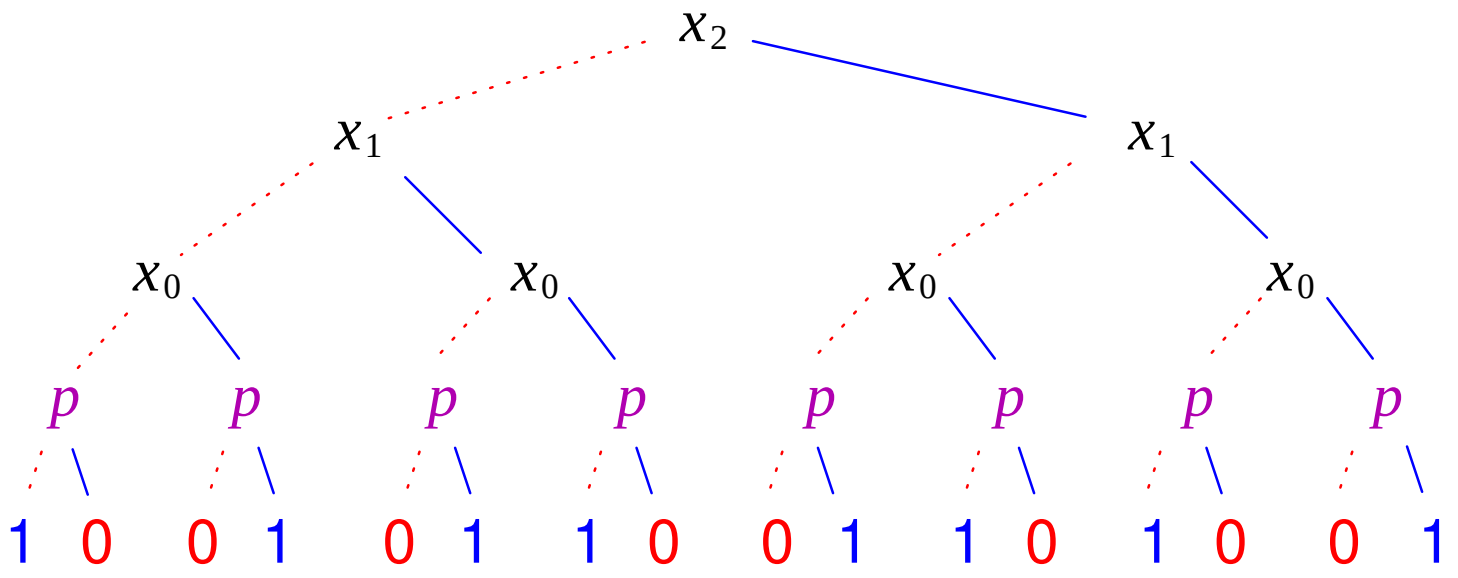
Transposed table

x_2	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
x_1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
x_0	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
p	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
f	1	0	0	1	0	1	1	0	0	1	1	0	1	0	0	1

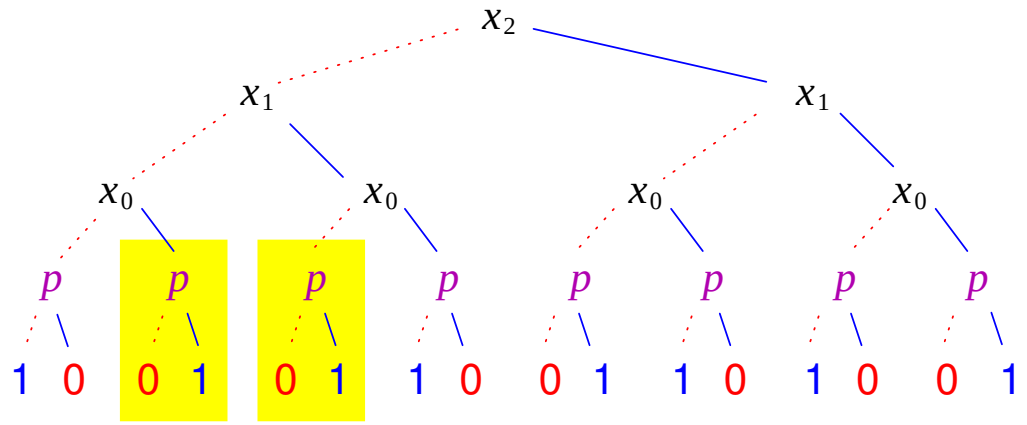
$\bar{x}_2$								x_2							
$\bar{x}_1$				x_1				$\bar{x}_1$				x_1			
$\bar{x}_0$		x_0		$\bar{x}_0$		$\bar{x}_0$		$\bar{x}_0$		$\bar{x}_0$		$\bar{x}_0$		$\bar{x}_0$	
$\bar{p}$	p	$\bar{p}$	p	$\bar{p}$	p	$\bar{p}$	p	$\bar{p}$	p	$\bar{p}$	p	$\bar{p}$	p	$\bar{p}$	p
1	0	0	1	0	1	1	0	0	1	1	0	1	0	0	1

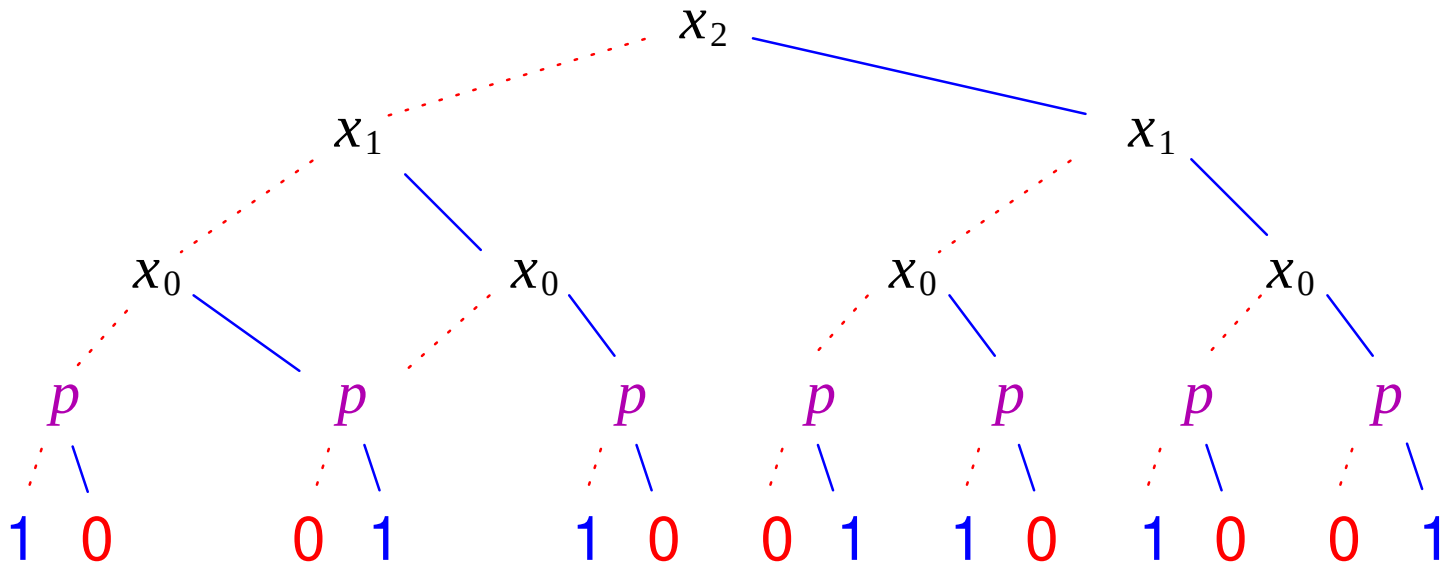
Graphical representation

$\bar{x}_2$								x_2							
$\bar{x}_1$				x_1				$\bar{x}_1$				x_1			
$\bar{x}_0$		x_0		$\bar{x}_0$		$\bar{x}_0$		$\bar{x}_0$		$\bar{x}_0$		$\bar{x}_0$		$\bar{x}_0$	
$\bar{p}$	p	$\bar{p}$	p	$\bar{p}$	p	$\bar{p}$	p	$\bar{p}$	p	$\bar{p}$	p	$\bar{p}$	p	$\bar{p}$	p
1	0	0	1	0	1	1	0	0	1	1	0	1	0	0	1

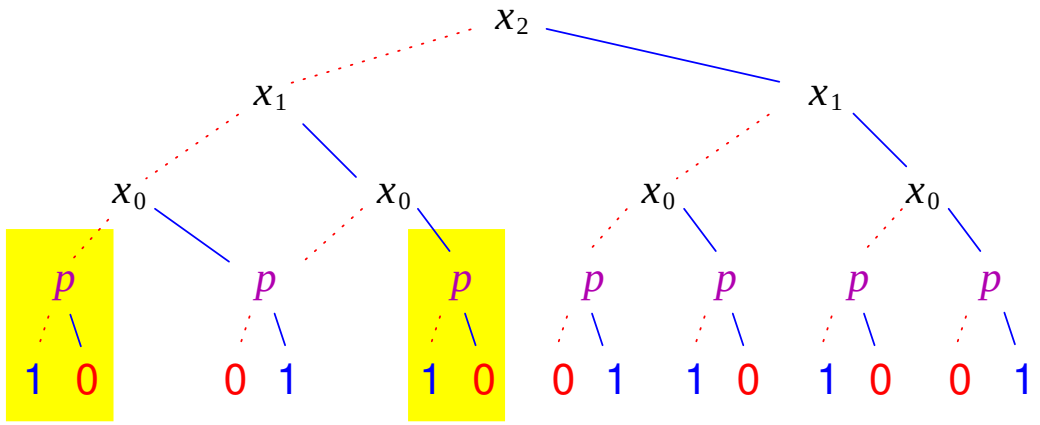


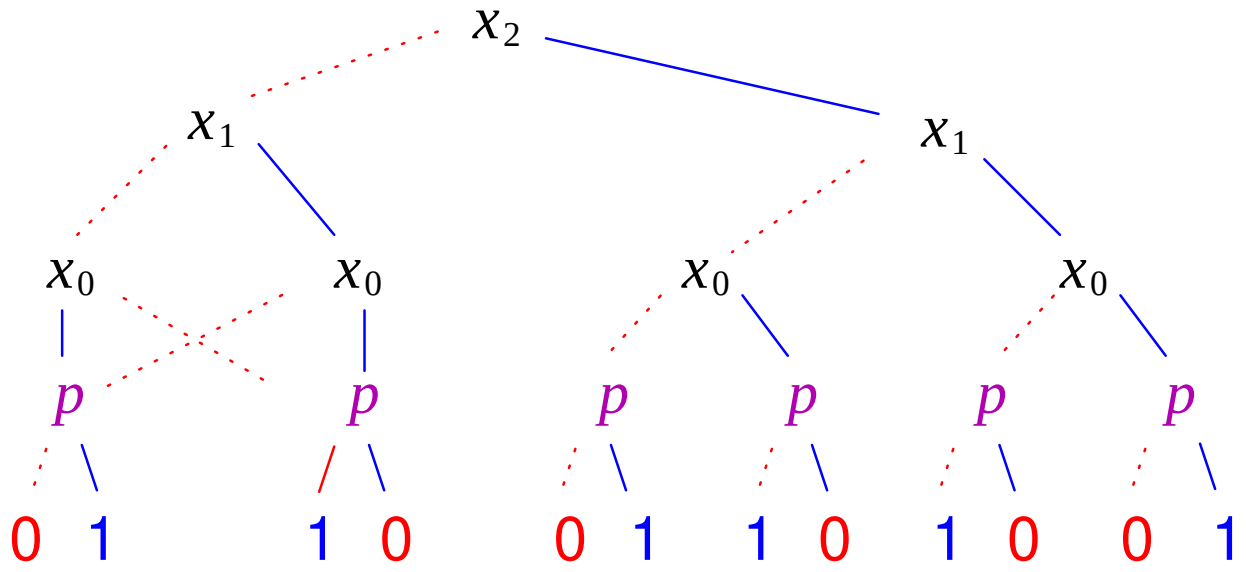
Combining identical subtrees



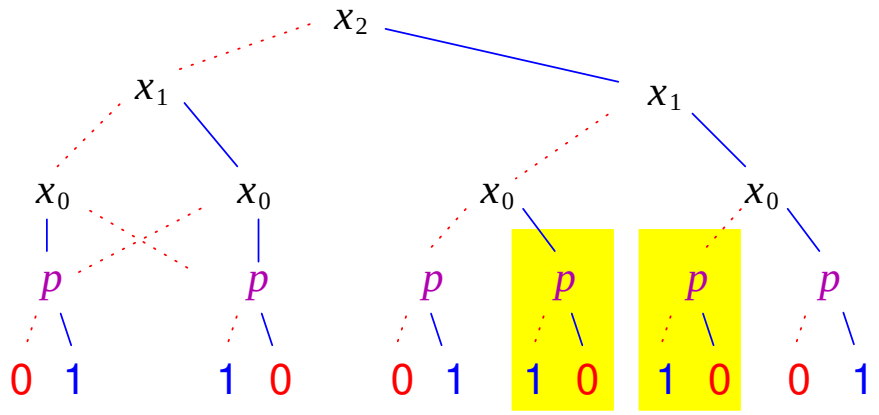


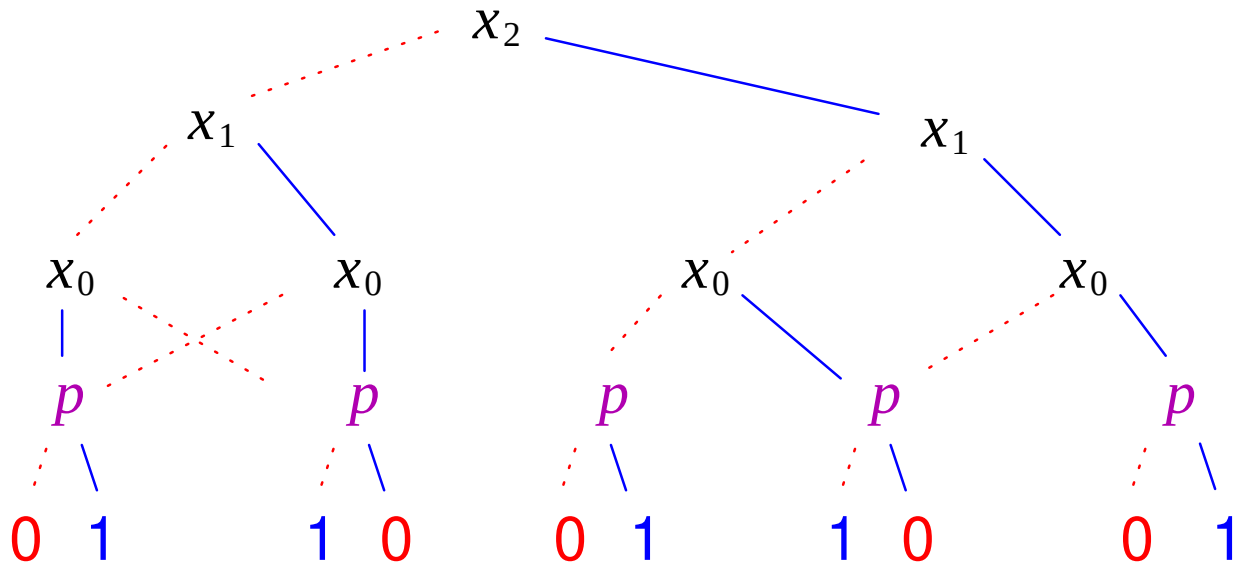
Combining identical subtrees — 2



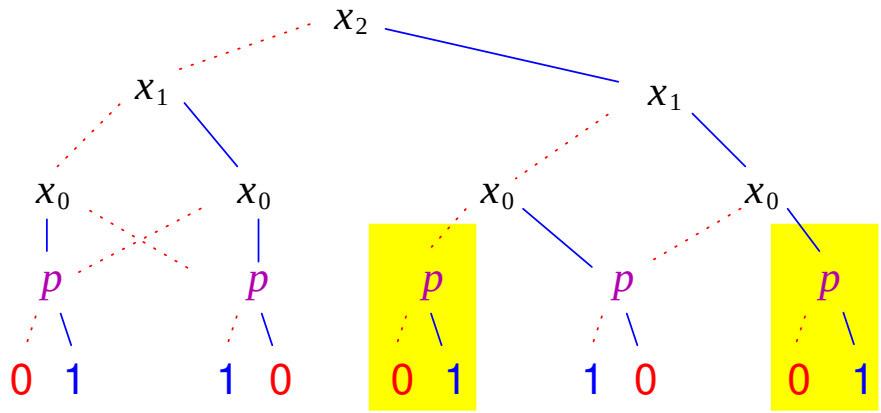


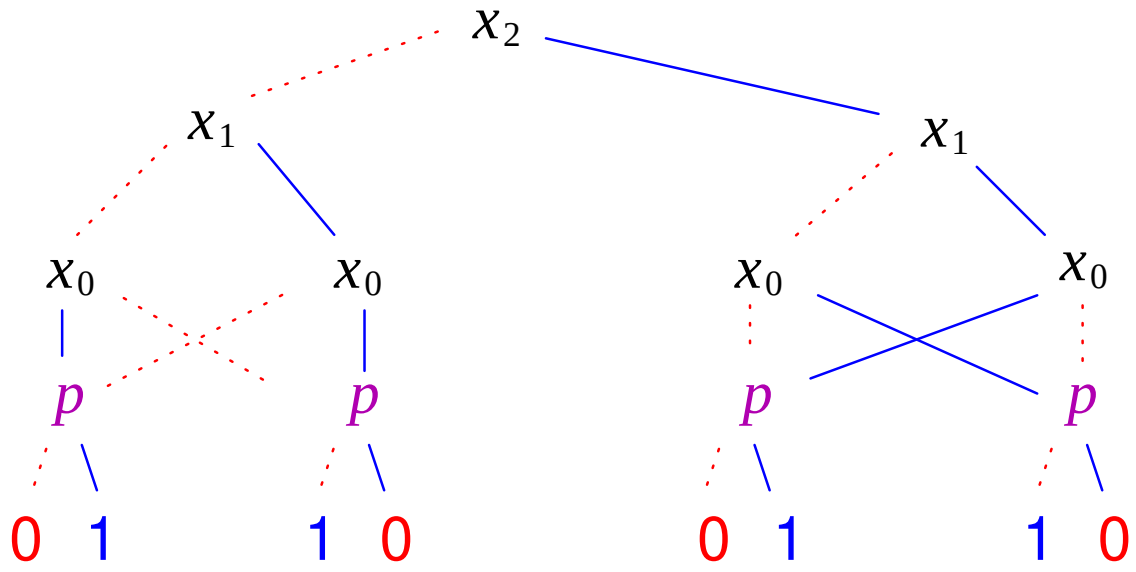
Combining identical subtrees — 3



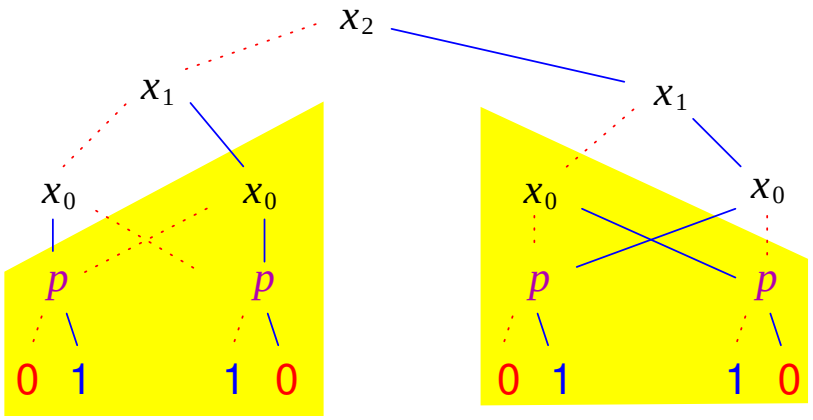


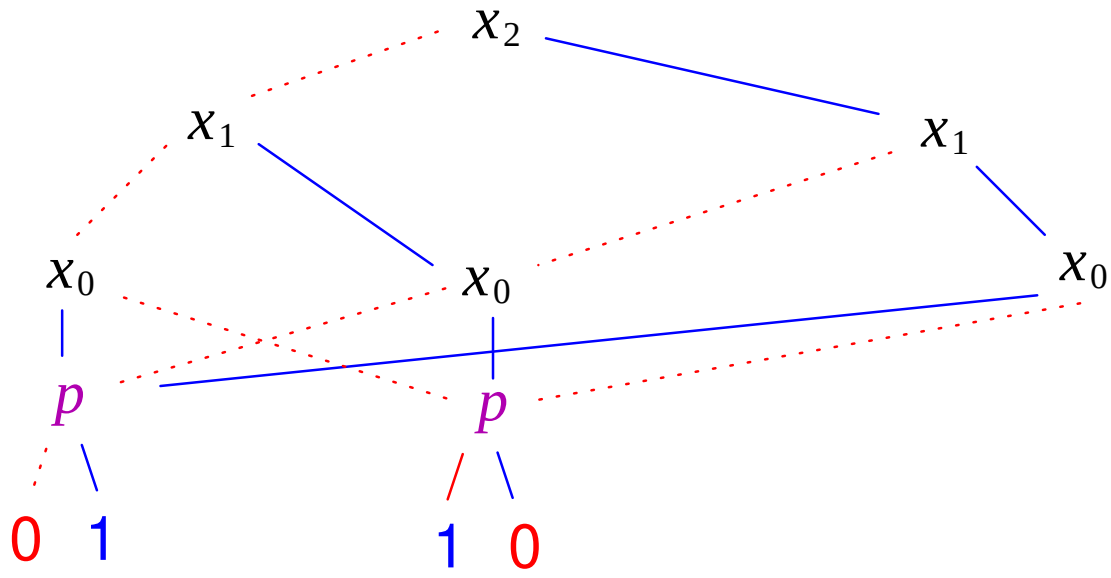
Combining identical subtrees — 4



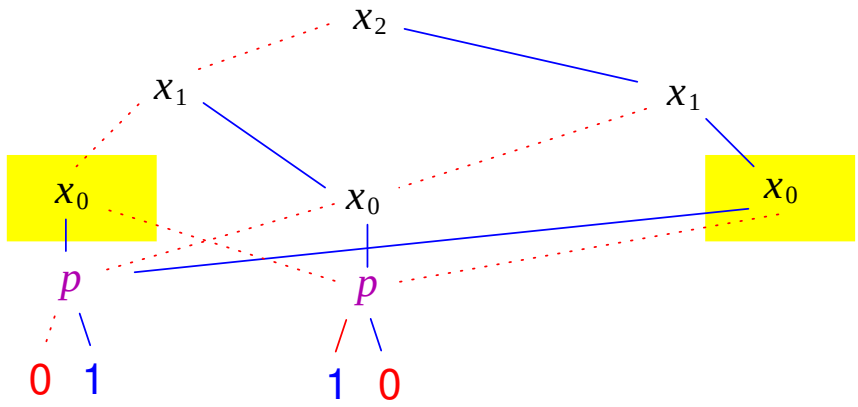


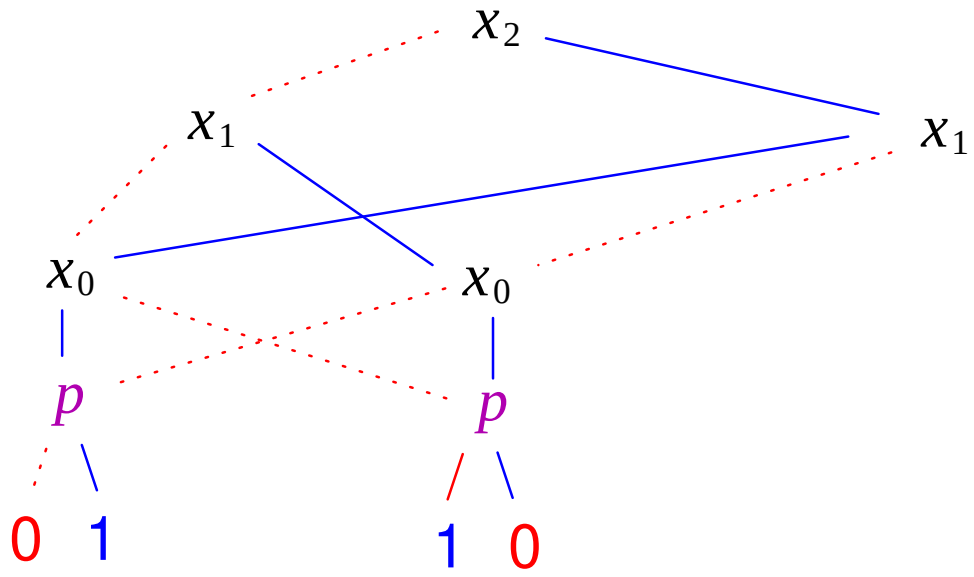
Combining identical subtrees — 5



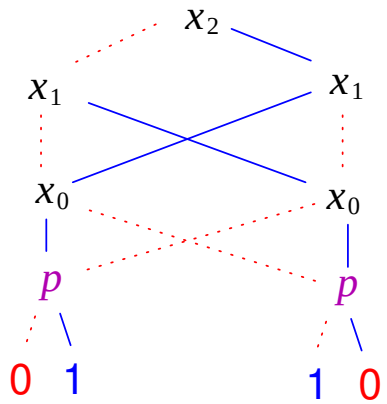


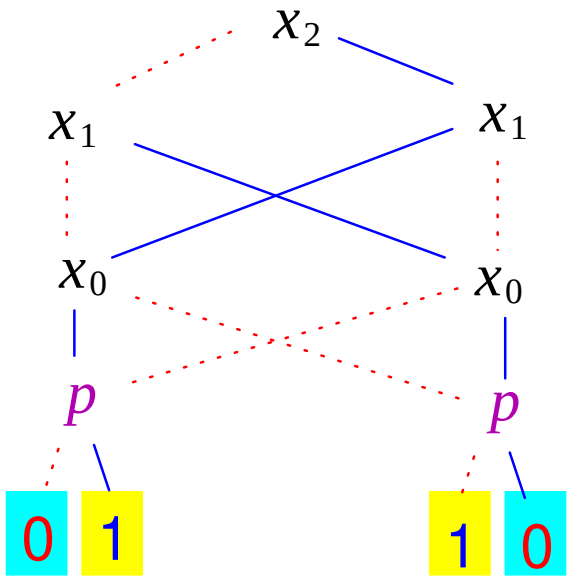
Combining identical subtrees — 6



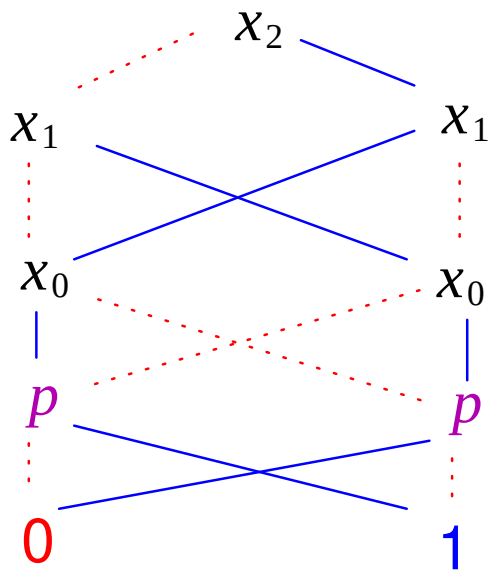


Combining identical subtrees — 7





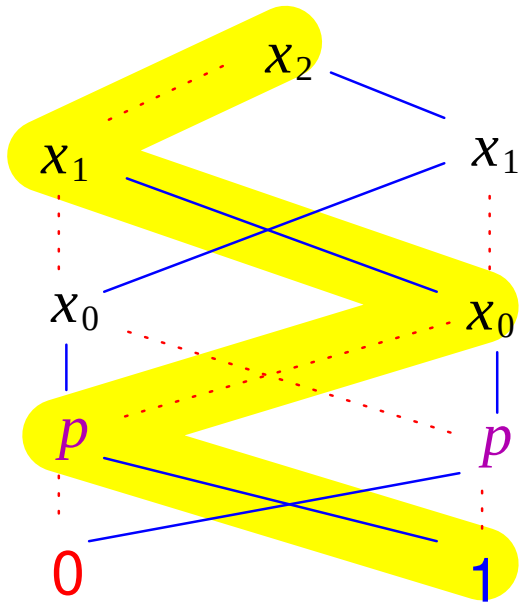
Final result: A Reduced, Ordered Binary Decision Diagram (ROBDD)



- All redundant subtrees are shared.
- Memory-efficient data structure.
- Usually „BDD” is used to denote ROBDD.

How to read a BDD

x_2	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
x_1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
x_0	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
p	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1



Binary Decision Diagrams: Definition

- Given: Set of variables $V = \{x_0, x_1, x_2, \ldots\}$.
- BDD on V is a directed, acyclic graph (DAG)

$$G = (N, \rightarrow, \ell)$$

- DAG contains set of nodes N,
  one root $r \in N$ (only nodes without predecessor),
  one or two sinks in N (only nodes without sucessor), written $0, 1$;
- edges $\rightarrow \subseteq N \times N$, $\rightarrow^+$ is acyclic;
  exactly two successors n_0 and n_1 for all $n \in N \backslash \{0, 1\}$;
- labels $\ell : N \backslash \{0, 1\} \rightarrow V$ of nodes with variables ($\ell() = 0, \ell(1) = 1$).

Semantics of BDDs

$$[\![\cdot]\!] : N \to \text{BooleExpr}$$

Projection $[\![\cdot]\!]$ of nodes N on Boolean expressions/functions over V.

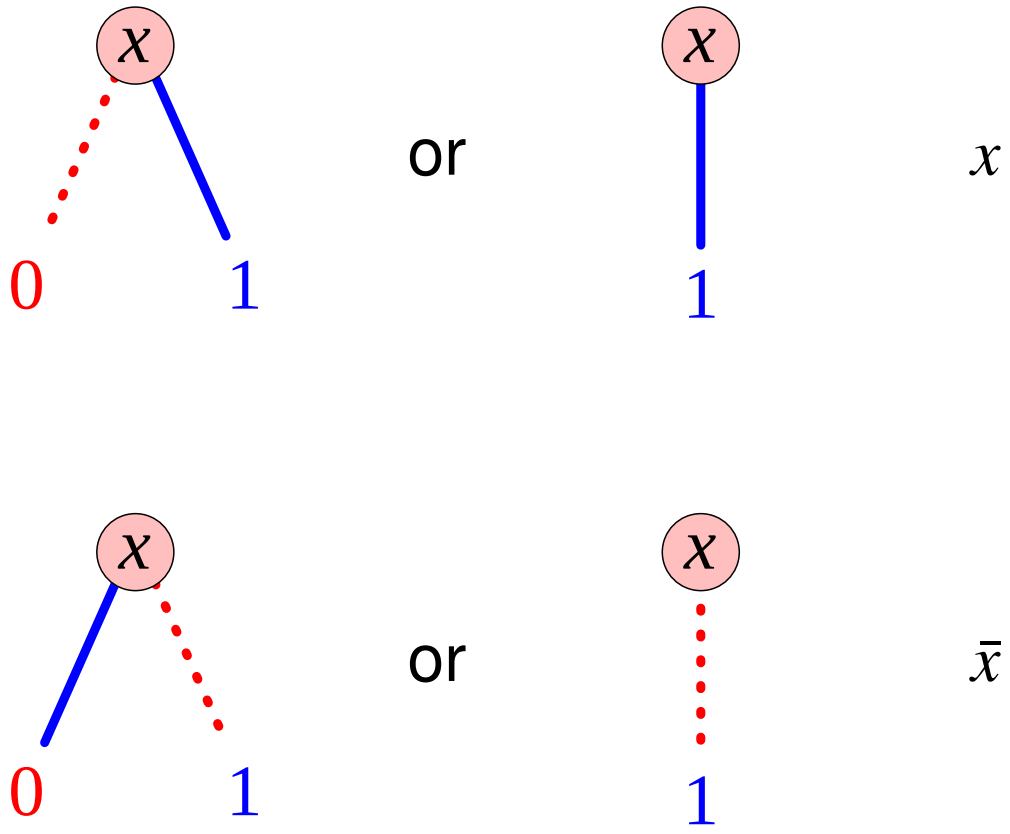
$$[\![n]\!] = \bar{x}_i \wedge [\![n_0]\!] \vee x_i \wedge [\![n_1]\!]$$

$$[\![0]\!] = 0$$

$$[\![1]\!] = 1$$

for $n = \text{node}(\text{x}_\text{i}, \text{n}_1, \text{n}_0)$

Reading BDDs

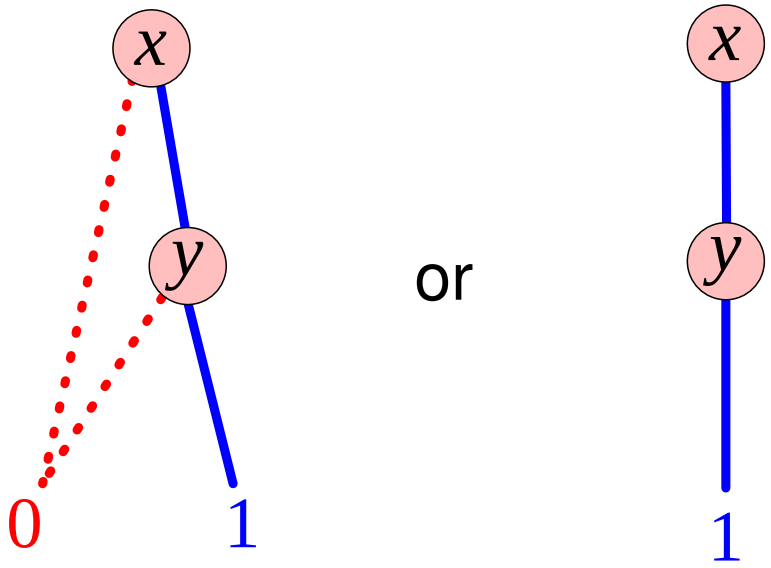


x

$\bar{x}$

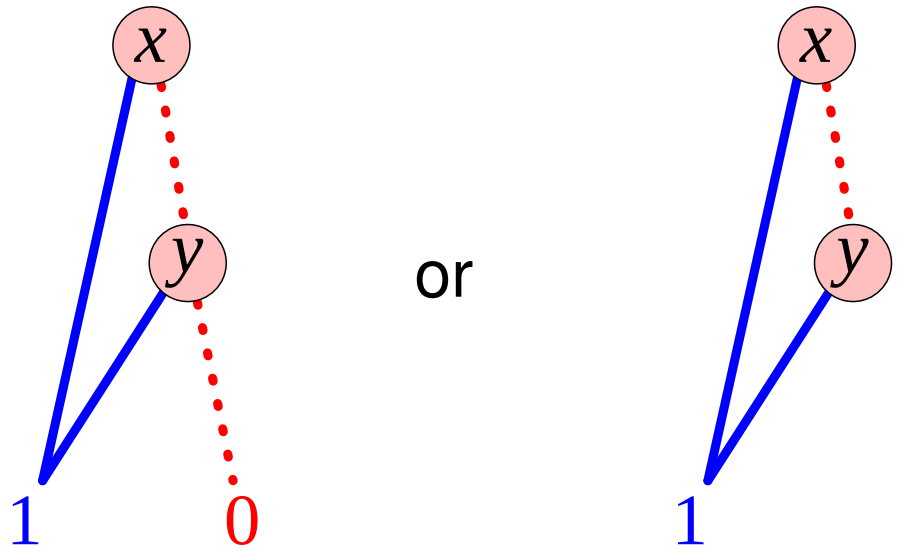
Examples and illustrations by Armin Biere/JKU Austria.

More examples



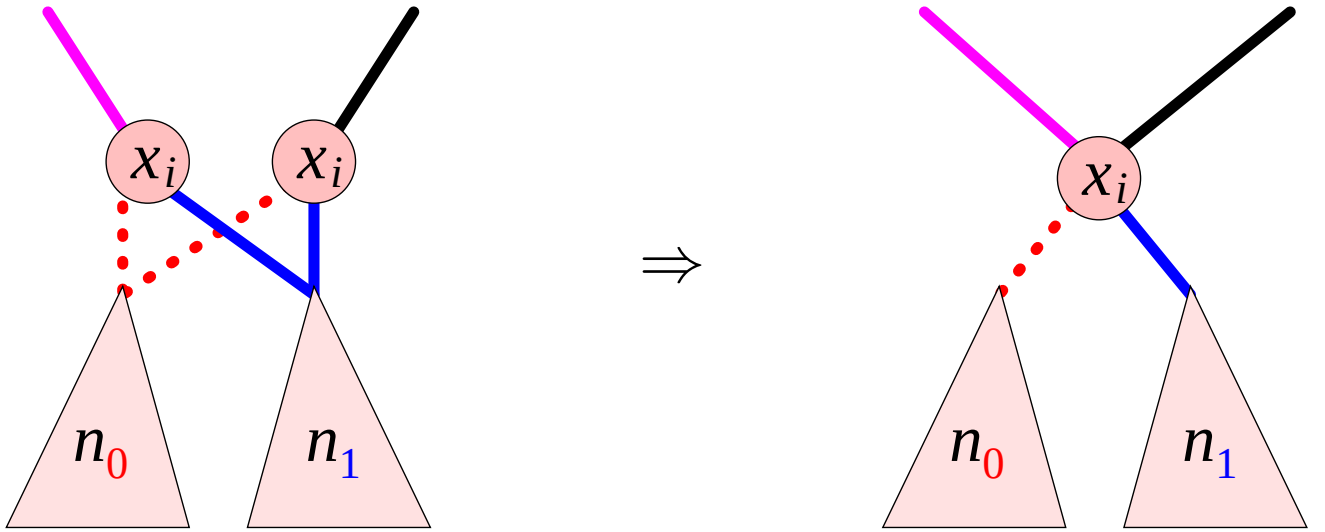
What does this BDD express?

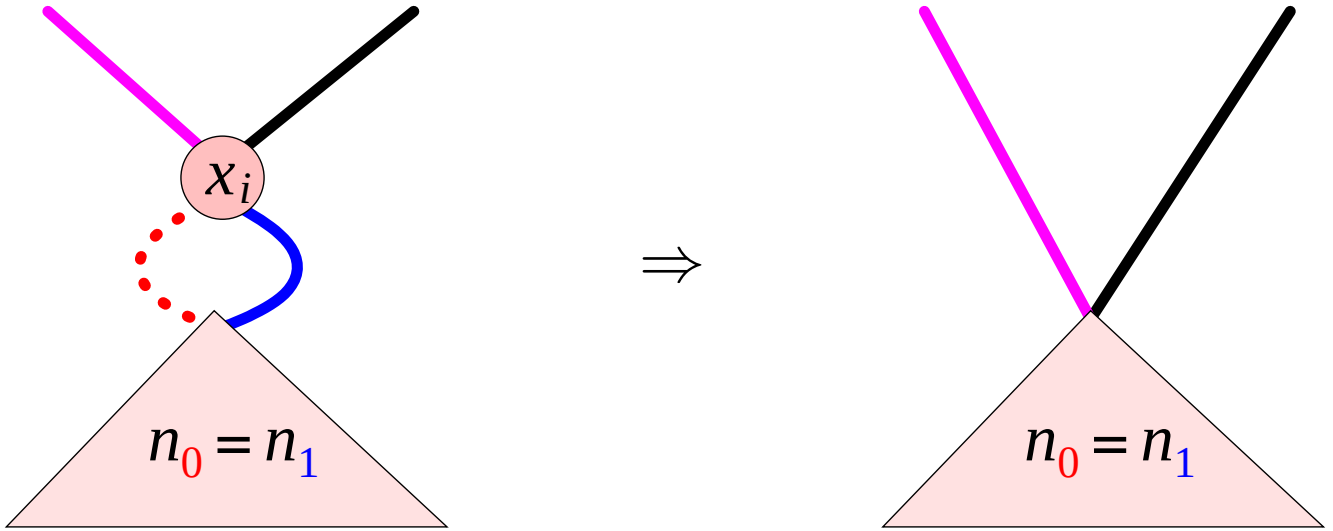
More examples — 2



What does this BDD express?

Reduction





Reduction algorithm

1. Traverse BDD from bottom to top

2. For each layer of variables,

   (a) eliminate nodes with two equal successors,
   (b) sort nodes lexicographically,
   (c) unite nodes with pairwise equal successors.

   Alternative to (b): hashing.

   Hashing: nodes are unified as they are created!

ROBDDs [Bryant86]

Assumption 1: Variables $V \cup \{0, 1\}$ are (linearly) ordered:

$$0 < 1 < x_0 < x_1 < x_2 < \ldots$$

Induced order on nodes N:

$n < n'$ iff (if and only if) $\ell(n) < \ell(n')$

Assumption 2: Edge relation is compatible with order:

$n > n_0$ and $n > n_1$

Each function has exactly one BDD!

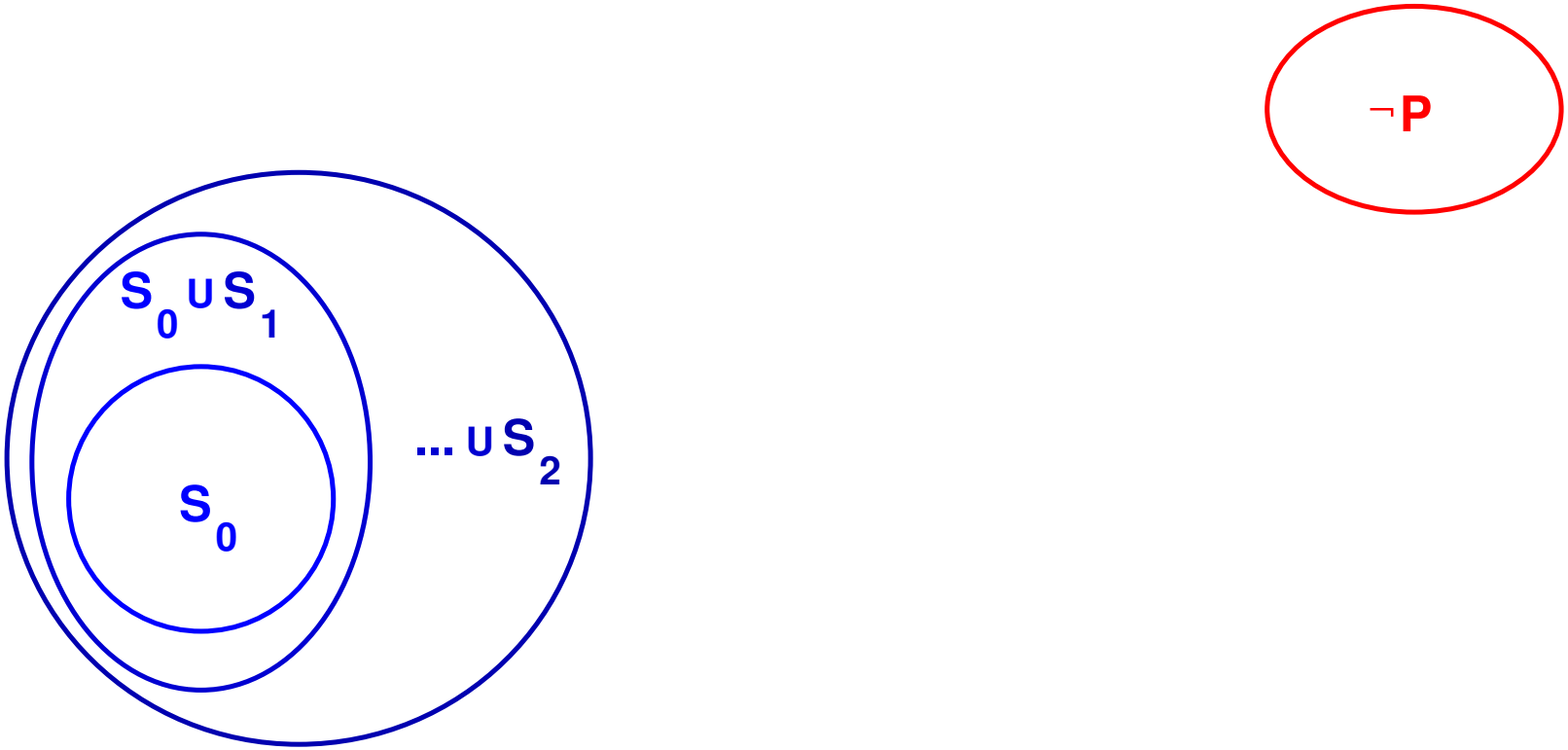
(for a given variable order)

Usage of BDDs in model checking

- Equivalence checking.
- Efficient representation of formulas, sets.
- „Good” variable order crucial for small size and performance.
  - → Heuristics determine variable order.
  - → Computations on BDDs use hashing, caching to avoid redundant computations.
  - → Some BDDs (e. g., multiplication) always exponentially large.
- Free efficient implementations (e. g.„ CUDD).

Key data structure for symbolic model checking.

Symbolic model checking



$$New := \mathrm{Image}(Old) \cup Old$$

Basic algorithm

S = states; R = transition relation; I= initial states

$\mathrm{CalculateReachable}(S,R,I)$

$New := I$

do

$Old := New$

$New := \mathrm{Image}(S,R,Old) \cup Old$

while $Old \neq New$

return New

$\mathrm{Image}(S,R,Old)$

return $\{t \in S | \exists s \in Old \text{ with } R(s,t)\}$

Representing sets and formulas as binary vectors (BDDs)

1. Encode systems as Booleans:
   encode S in 2^n, interpret states $s \in S$ as n-ary Boolean vectors.

2. Interpret initial states I as characteristic function $I : 2^n \to \{0, 1\}$.

3. Interpret transitions R as characteristic function $R : 2^n \times 2^n \to \{0, 1\}$.

4. Represent Boolean functions as BDDs.

5. Use BDD operations instead of set operations.

Inventors: McMillan and Coudert/Madre.

Quizzes

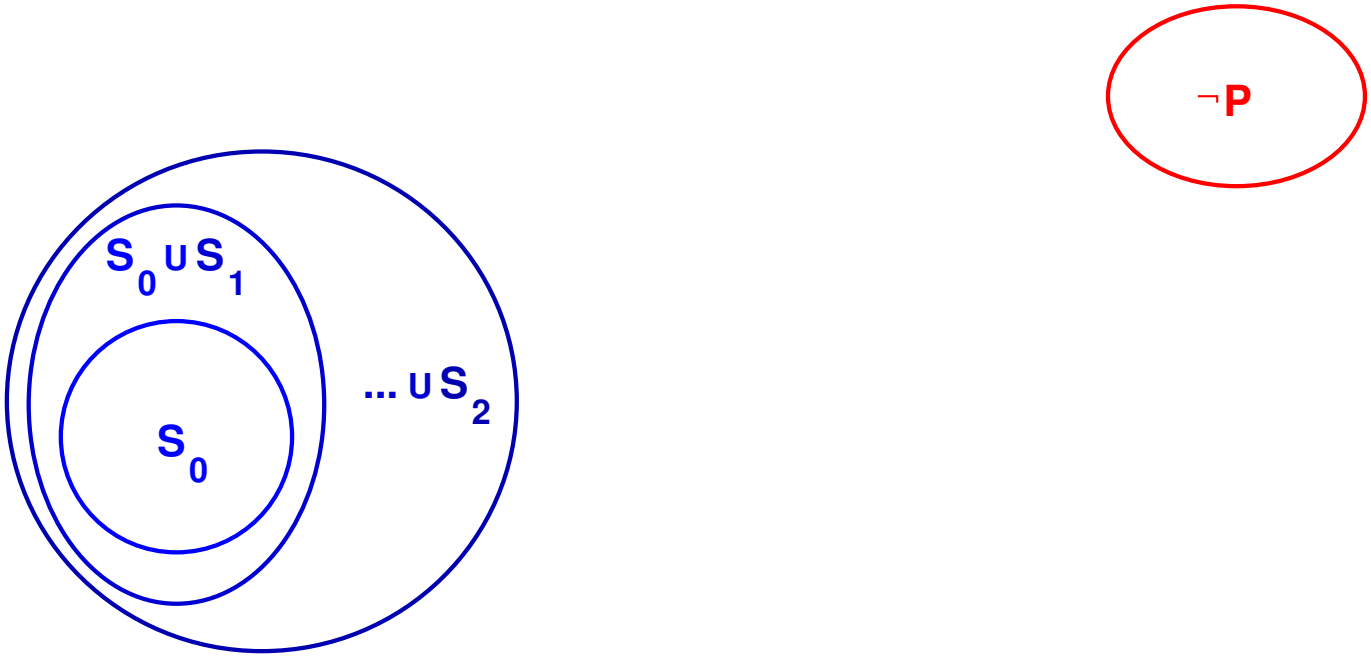
- Available after this lecture.

1. BDDs: Link to interactive web page where you can practice.
2. Temporal logics: Three examples for practice.

- Quizzes are not graded but highly recommended as exam preparation.

Bounded model checking

- Symbolic model checking is efficient if formula can be compressed.
- Good variable order is not always possible.
- Another approach: Expand the state transition system for k steps:



Use solver to check system states after k steps.

SAT solving

- Satisfiability (SAT) problem is NP-complete.
- SAT solvers are efficient solvers for logical formulas.
- Intelligent pre-processing and state space search take advantage of structure in formula.
- Does not work against worst case, but real formulas have internal structure.
- Expanded state transition system can be expressed in propositional logic and solved by SAT solver.

Bounded model checking in NuSMV

```
MODULE main -- from the NuSMV tutorial
VAR
  y : 0..15;
ASSIGN
  init(y) := 0;
TRANS
case
  y=7: next(y)=0;
  TRUE : next(y) = ((y + 1) mod 16);
esac
LTLSPEC G (y=4 -> X y=6)
```

Running NuSMV in BMC mode

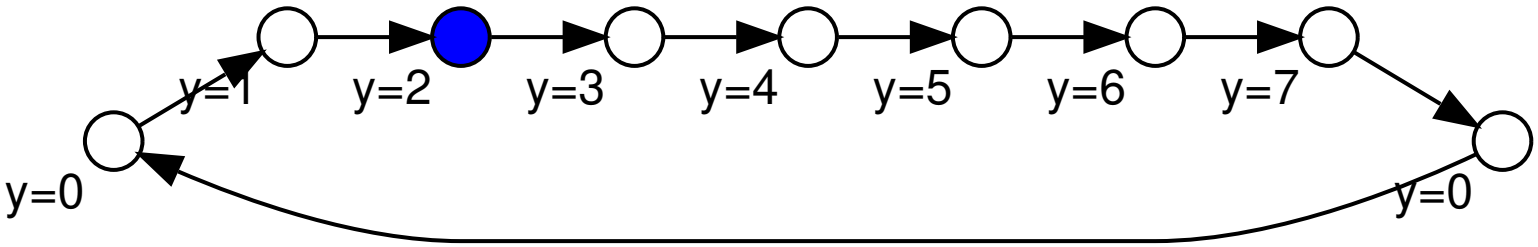
```
NuSMV -bmc bmc_tutorial.smv
-- no counterexample found with bound 0
-- no counterexample found with bound 1
-- no counterexample found with bound 2
-- no counterexample found with bound 3
-- no counterexample found with bound 4
-- specification  G (y = 4 ->  X y = 6) is false
-- as demonstrated by the following execution sequence
Trace Description: BMC Counterexample
Trace Type: Counterexample
  -> State: 1.1 <-
    y = 0
  -> State: 1.2 <-
    y = 1
...
  -> State: 1.6 <-
    y = 5
```

Liveness properties with BMC

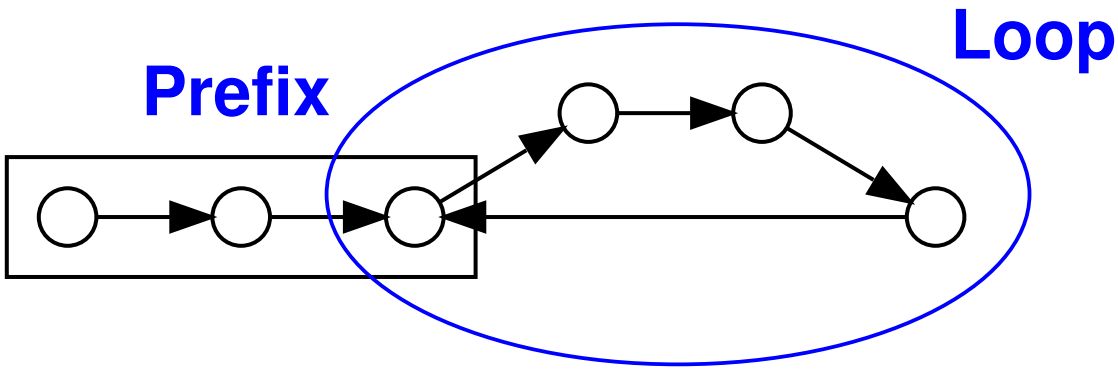
```
LTLSPEC !G F(y = 2)
NuSMV -bmc bmc_tutorial.smv
-- no counterexample found with bound 0
...
-- no counterexample found with bound 7
-- specification !( G ( F y = 2)) is false
-- as demonstrated by the following execution sequence
Trace Description: BMC Counterexample
Trace Type: Counterexample
-- Loop starts here
-> State: 1.1 <-
y = 0
-> State: 1.2 <-
y = 1
...
-> State: 1.9 <-
y = 0
```

Counterexamples for liveness properties

Previous example:



General case:



How large does the bound k have to be for BMC?

Model validation

Model

Real system

Is the model adequate?

Correct but flawed models

Vacuity: $a \rightarrow b$ holds, but a is never true.
Entire property holds for the wrong reason („antecedent failure”)!

Solution: Check that a holds in at least some states.

Zeno-timelocks: Model executes infinitely fast.
No way for real system to fulfill property!

Solution: Use simulation mode to get example traces,
study how model reacts.

Model validation

1. Check the reachability of desired states.
   Use simulation mode or define additional liveness properties.

2. Negate the specification.
   Now there should be paths that fulfill the desired property.
   Study the result and see if it makes sense.

3. Add additional simple properties as sanity checks.

From: Artho, Hayamizu, Ramler, Yamagata: With an Open Mind: How to Write Good Models.

Simulating models with NuSMV

Key simulation commands:

`NuSMV > go`	Load and prepare model
`NuSMV > pick_state -i`	Pick initial state interactively
`NuSMV > simulate -p -i`	Simulate (interactively), print progress; control-C exits
`NuSMV > show_trace -v`	Show trace
`NuSMV > quit`	Exit

Back to vending machine

```
-> State: 1.1 <-
   choice = TRUE
   payment = TRUE
   acc_payment = FALSE
   state = ready
   release_item = FALSE
-> State: 1.2 <-
   state = expect_payment
-> State: 1.3 <-
   acc_payment = TRUE
-> State: 1.4 <-
   state = dispense_item
   release_item = TRUE
```

```
-> State: 1.5 <-
   acc_payment = FALSE
   state = ready
   release_item = FALSE
-> State: 1.6 <-
   state = expect_payment
-> State: 1.7 <-
   acc_payment = TRUE
-> State: 1.8 <-
   state = dispense_item
   release_item = TRUE
```

Usage of NuSMV in the real world

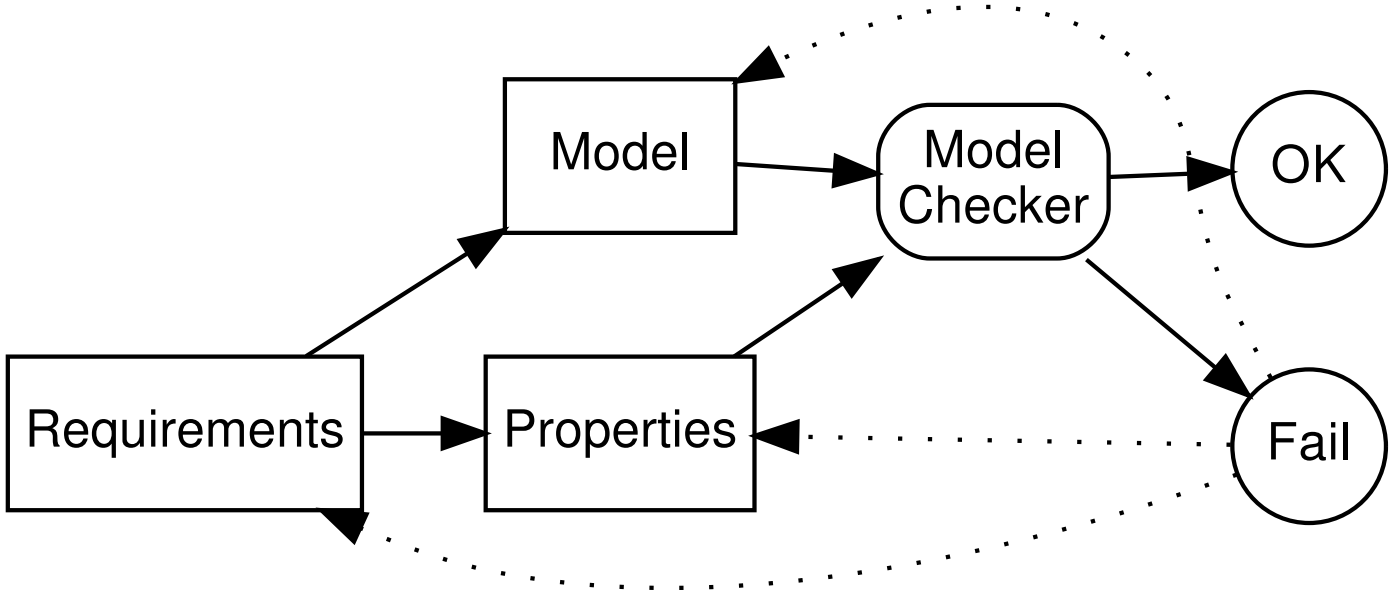
- As a back-end to other tools:
  - → NuSMV-PA: Safety analysis platform
  - → Back-end for Petri net model checking (another modeling approach).
  - → Test case generation.
- Case studies:
  - → Kerberos protocol.
  - → Web service composition.
  - → Railway interlocking control tables.

A critique of NuSMV

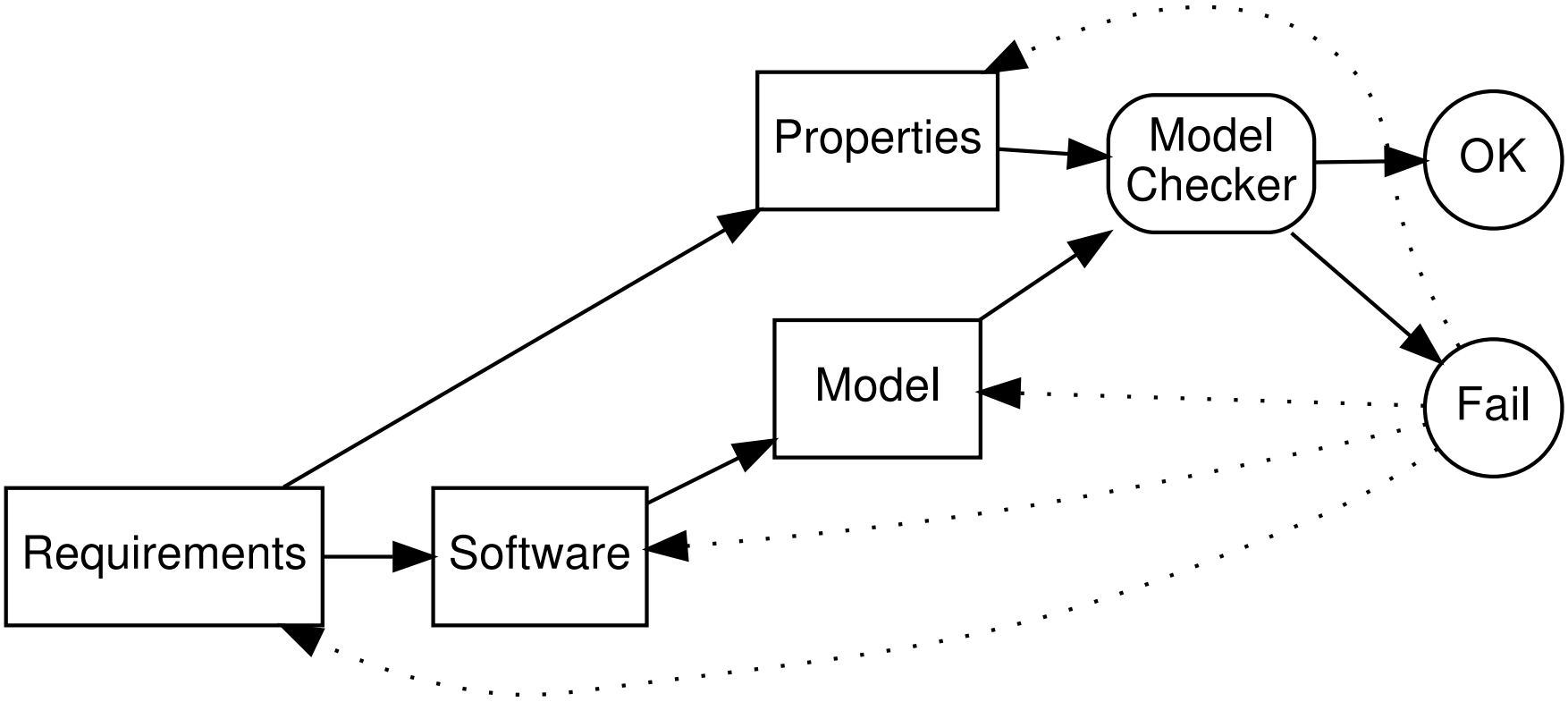
Pro	**Con**
open source	limited open tool set
mature	limited syntax
fast	no arrays of modules
well-defined semantics	focus on synchronous systems

Protocol/algorithm verification

- Knowledge on security/safety/reliability concerns.
- Logics to express temporal properties.
- Tools to verify transition systems.

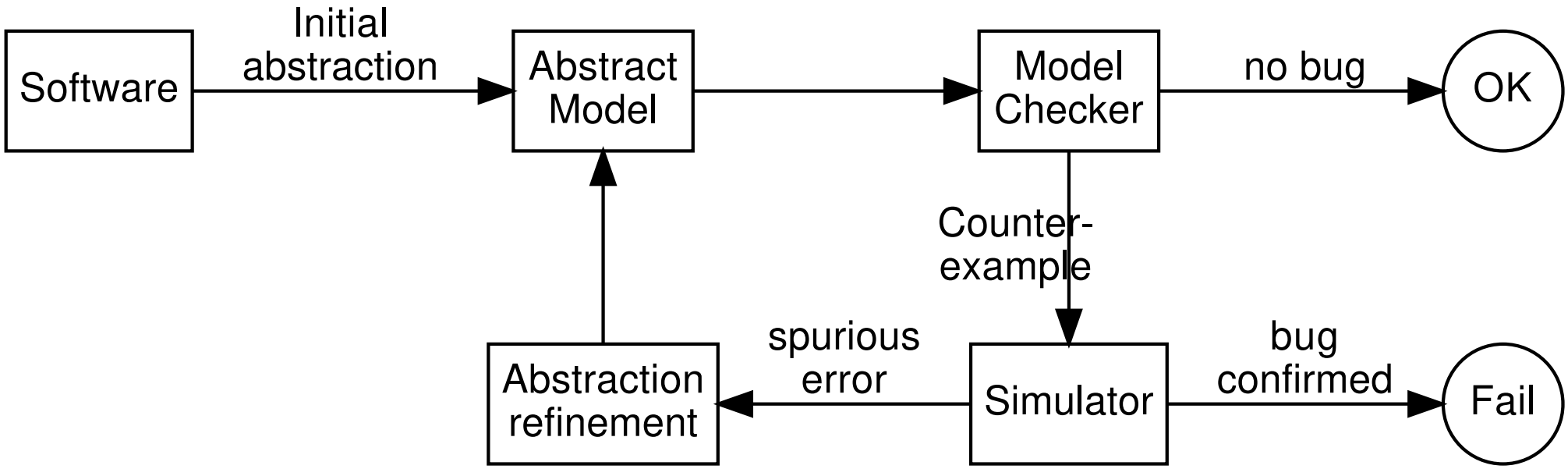


Software verification



Challenging to maintain model by hand.

Counter-Example Guided Abstraction Refinement (CEGAR)



Practical program verification for small systems.

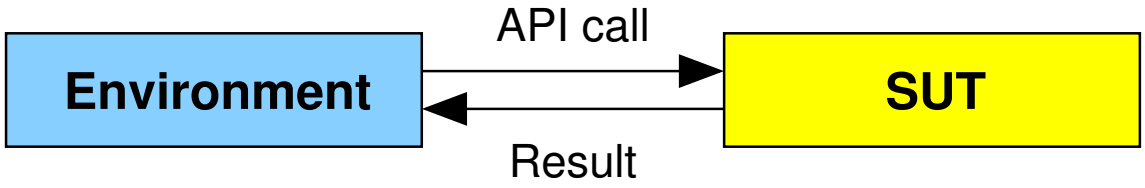
The SLAM Toolkit

- Goal: Verify Windows NT device drivers by model checking.
- System calls approximated by model.

  $\rightarrow$ Model includes state changes in kernel.
- Model used to check dozens of device drivers.
- Continuous effort (over 5 man-years for kernel model alone!)
- For MC a single application, manual abstraction more economical.

Assignment: Read paper on SLAM, answer quiz.

Model-based Testing vs. Model Checking



SUT = System under test; API = Application programming interface

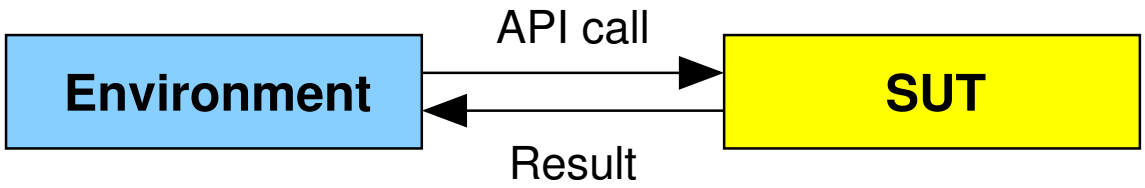
Test model

What

System model

How

Test Model vs. System Model



SUT = System under test; API = Application programming interface

Test model

- Represents **environment**.
- Models system **behavior**.
- Used to generate **test** cases.
- Model, test one module at a time; SUT itself provides counterpart.
- Model-based testing.

System model

- Represents **system** itself.
- Models system **implementation**.
- Used to **verify** system.
- Need model of most components to analyze system behavior.
- Model checking, theorem proving.

Summary

Model checking

Symbolic checking (last week).

- Everything is a bit vector.
- Efficient representation: BDDs.

Bounded model checking.

- Expand k trans. $\rightarrow$ 0-order formula.
- Efficient solution: SAT solver.

Model validation

- Negate properties.
- Check if antecedent (a in $a \rightarrow b$) is ever true.
- Ensure „interesting” states are actually reachable.