Model Checking with Abstract State Matching

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Introduction

- Abstraction in software model checking
  - Used to reduce data domains of a program
  - Described as abstract interpretation
  - Classic approach: over-approximation
    - SLAM, Blast, Magic; see also Bandera, Feaver
  - Preserves true results; abstract counter-examples may be infeasible
  - Counter-example based iterative abstraction refinement

Our approach

- Under-approximation based abstraction with refinement
  - Goal: error detection; explores only feasible system behaviors
  - Preserves errors of safety properties
  - Iterative refinement based on checking “exactness” of abstraction
- Framework for test input generation – built around Java PathFinder
  - Measure code coverage
  - Evaluate against other test input generation methods
  - Applied to Java container classes

Predicate Abstraction

- Maps a (possibly infinite state) concrete transition system into a finite state system
  - Via a set of predicates: Preds = $\{p_1, p_2 \ldots p_n\}$
- Abstraction function α: ConcreteStates → BitVectors

  $\alpha(s) = b_1 b_2 \ldots b_n$, $b_i = 1 \Leftrightarrow s \models p_i$

Traditional approaches:

- May abstract transitions:
  - Over-approximate concrete transitions
  - $a_1 \rightarrow_{may} a_2 : \exists\ s_1$ s.t. $\alpha(s_1) = a_1$ and $\exists\ s_2$ s.t. $\alpha(s_2) = a_2$, s.t. $s_1 \rightarrow s_2$
- Must abstract transitions:
  - Under-approximate concrete transitions
  - $a_1 \rightarrow_{must} a_2 : \forall\ s_1$ s.t. $\alpha(s_1) = a_1$, $\exists\ s_2$ s.t. $\alpha(s_2) = a_2$ and $s_1 \rightarrow s_2$

- Compute may/must transitions automatically:
  - Use a theorem prover/decision procedure: require $2^n \times n \times 2$ calls

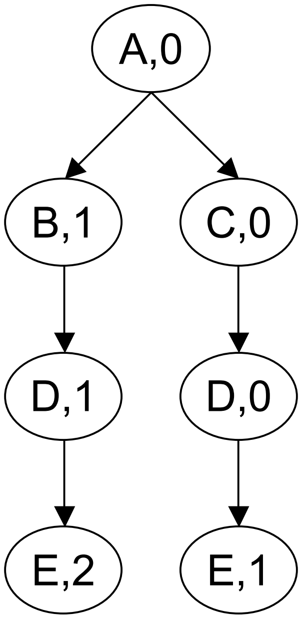
Our Approach

Concrete search with abstract matching:

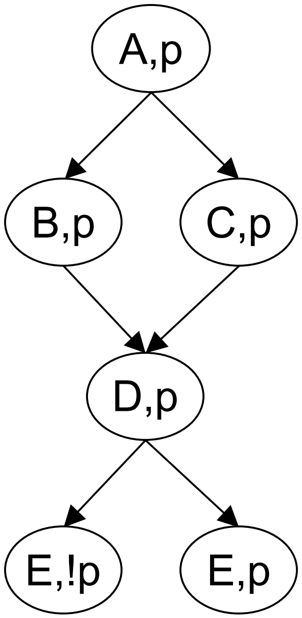
- Traverse the concrete system
- For each explored concrete state
  - Store abstract version of the state
  - Use predicate abstraction
- Abstract state used to determine if the search should continue or backtrack

- Does not build abstract transitions
  - It executes the concrete transitions directly
- Decision procedure invoked during refinement:
  - At most **2** calls for each explored transition

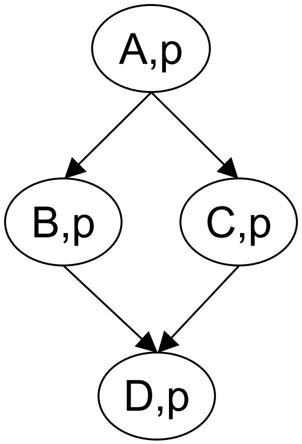
Example



Concrete system



May abstraction
p = (x < 2)
Over-approximation



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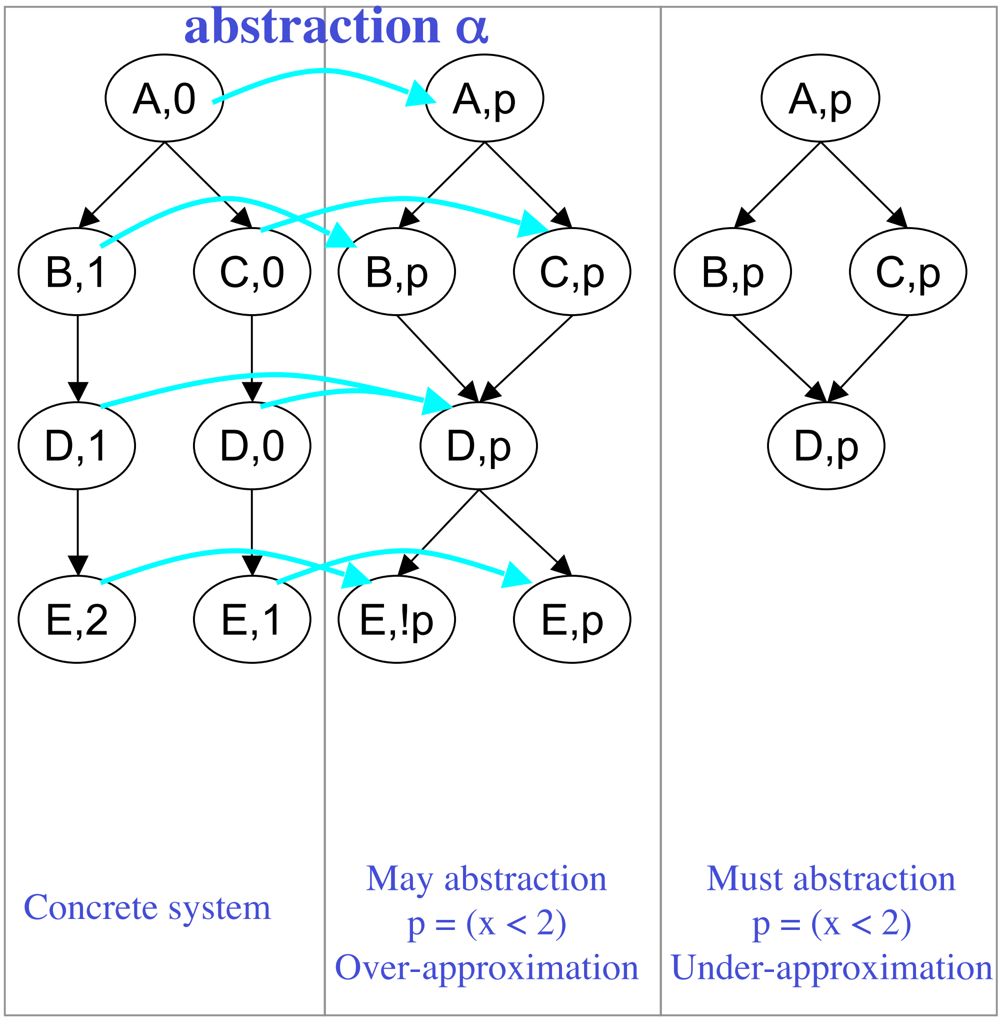
Example



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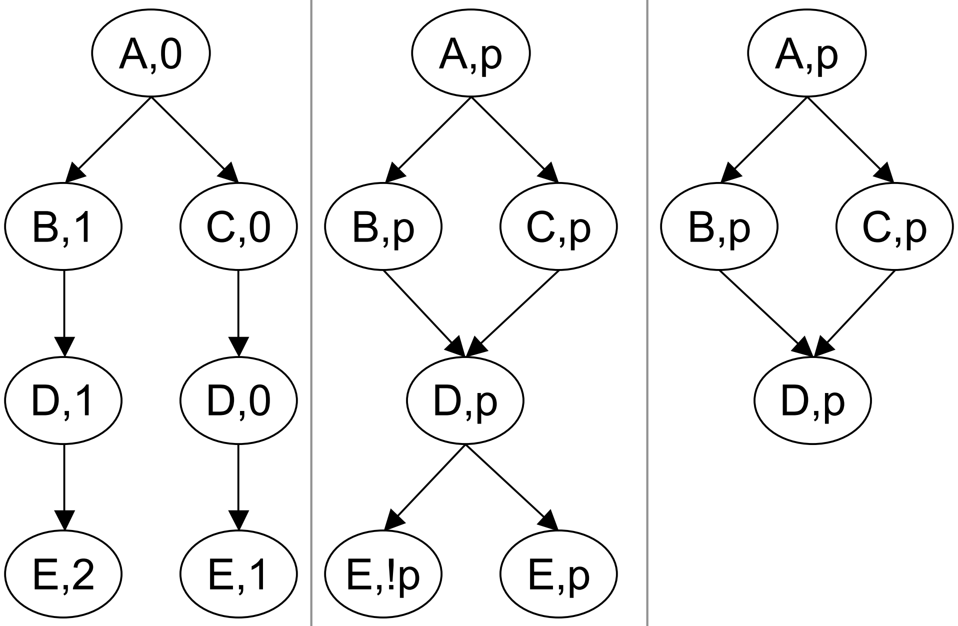

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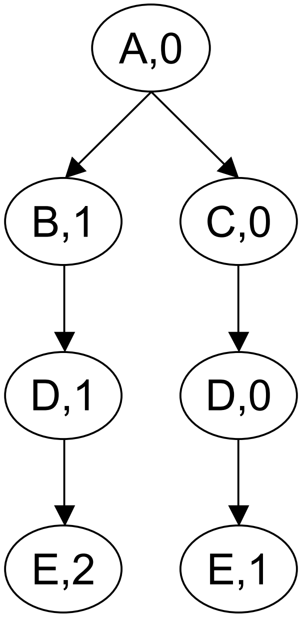
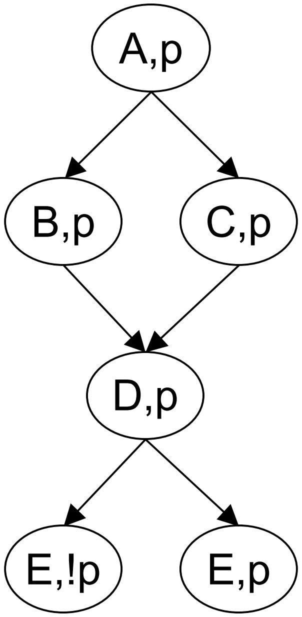


Concrete system



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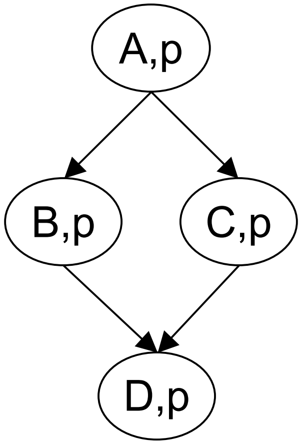

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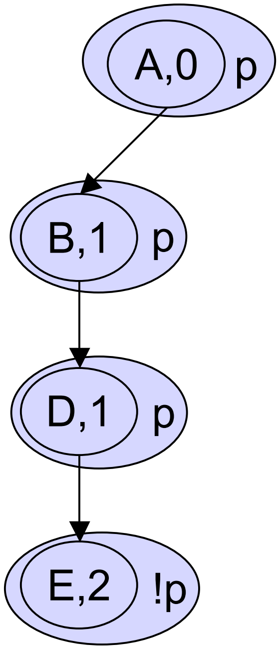
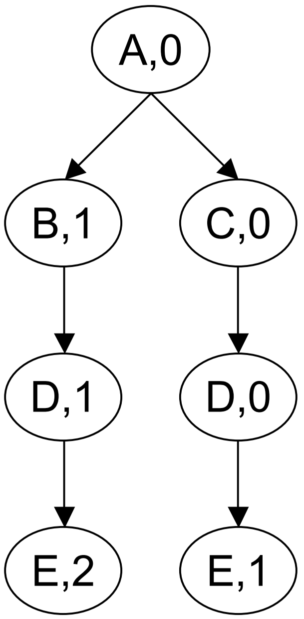
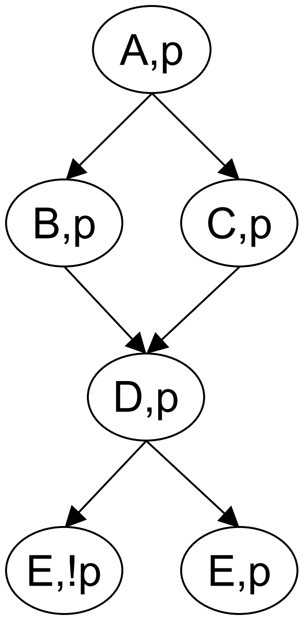


Concrete search w/
abstract matching
p = (x < 2)

Example



Concrete system



May abstraction
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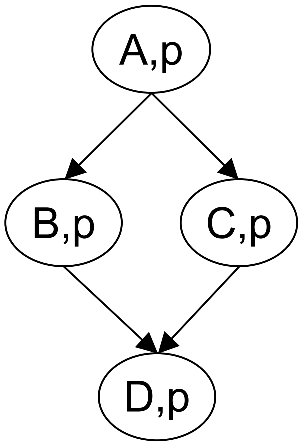
Over-approximation



Must abstraction
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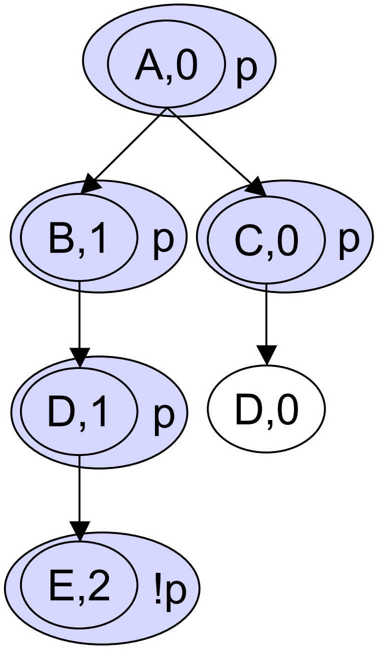
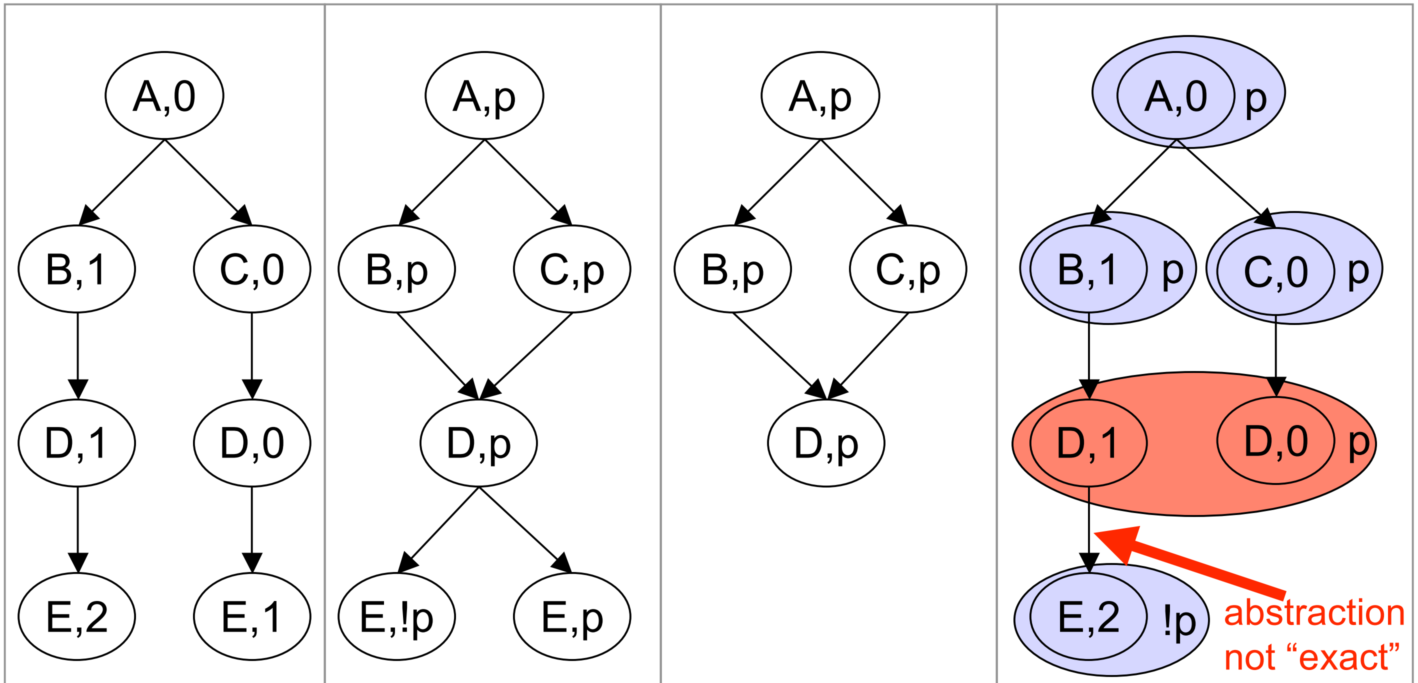
Under-approximation



Concrete search w/
abstract matching
$p = (x < 2)$

Example



Concrete system

May abstraction
$p = (x < 2)$
Over-approximation

Must abstraction
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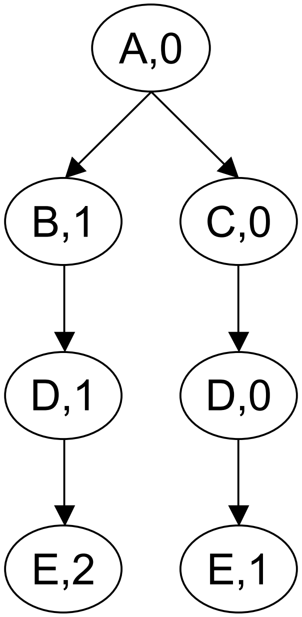
Under-approximation

Concrete search w/
abstract matching
$p = (x < 2)$

Example



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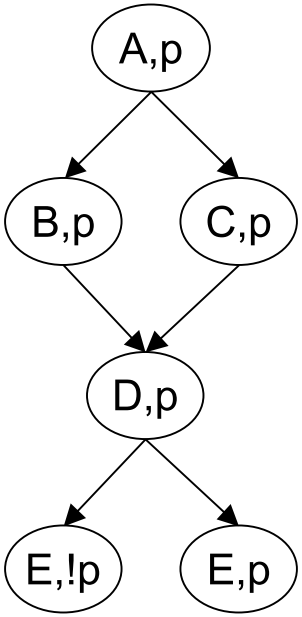

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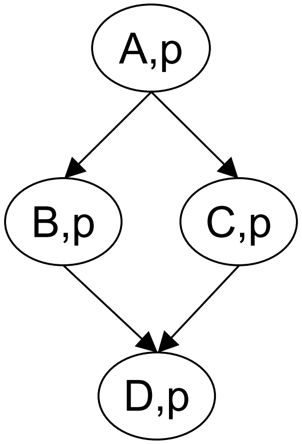

Must abstraction
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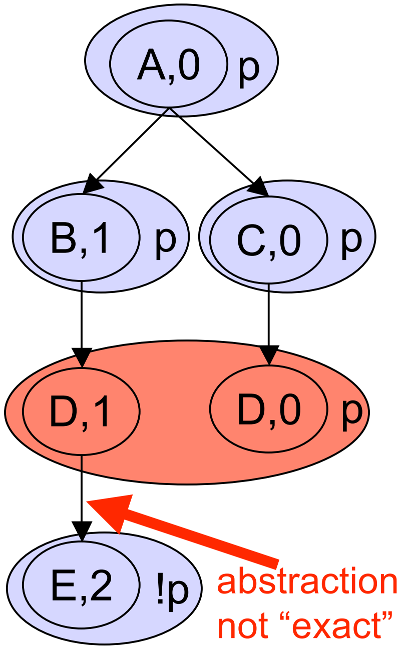
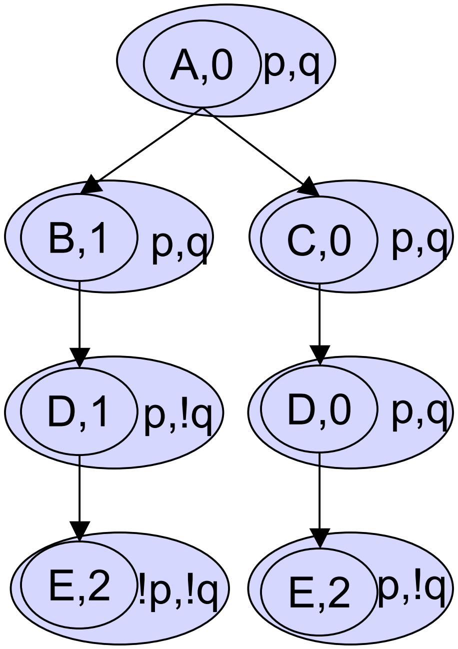


Concrete search w/
abstract matching
$p = (x < 2)$

refine



Concrete search w/
abstract matching
$p = (x < 2)$
$q = (x < 1)$

(Concrete) Search Algorithm

```
PROCEDURE dfs()

   BEGIN
      add($s_0$, VisitedStates);
      push($s_0$, Stack);
      WHILE ! empty(Stack) DO
         s = pop(Stack);
         FOR all transitions t enabled in s DO
                   s' = successor(s, t);
                   IF s' NOT IN VisitedStates THEN
                        add(s', VisitedStates);
                        push(s', Stack);
                   FI;
         OD;
      OD;
   END;
```

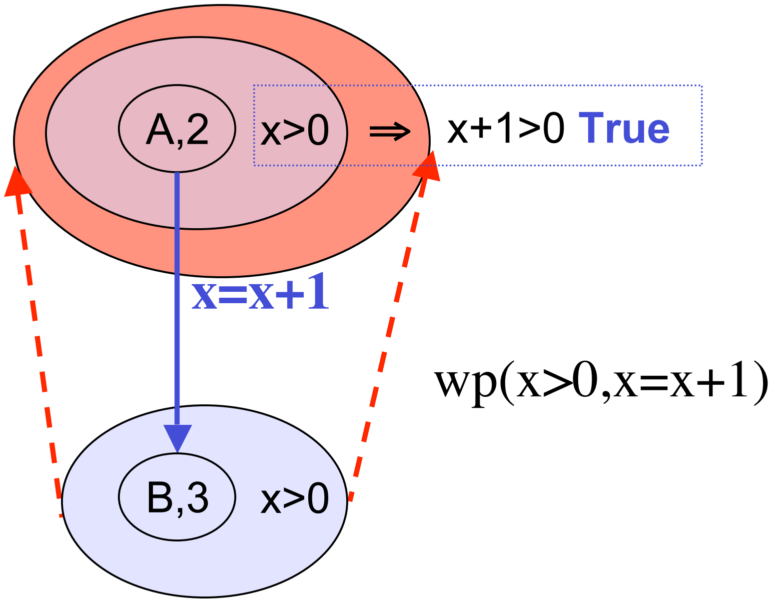
Search w/ Abstract Matching

```
PROCEDURE αSearch ( Preds )

    BEGIN
        add($\alpha_{Preds}(s_0)$, VisitedStates);
        push($s_0$, Stack);
        WHILE ! empty(Stack) DO
            s = pop(Stack);
            FOR all transitions t enabled in s DO
                s' = successor(s, t);
                IF $\alpha_{Preds}(s')$ NOT IN VisitedStates THEN
                    add($\alpha_{Preds}(s')$, VisitedStates);
                    push(s', Stack);
                FI;
            OD;
        OD;
    END;
```

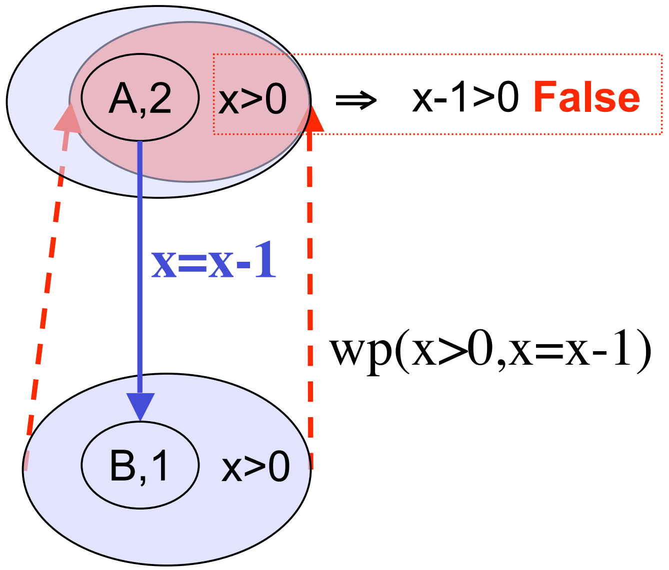
Abstraction Refinement

Check if abstraction is **exact** with respect to each transition t: s → s’

- Check if the induced abstract transition is a **must** transition w/ a decision procedure
- If not, add new predicates
- Use weakest precondition calculations $\alpha(s) \Rightarrow wp(\alpha(s'),t)$



Abstraction is exact



Abstraction is refined

Add **new predicate (x-1>0)** from failed check and repeat αSearch

Iterative Refinement

- Check if bad state φ_{err} is reachable

```
BEGIN
  Preds = $\emptyset$;
  WHILE true DO
      $\alpha$Search(Preds);
          /* during $\alpha$Search perform:
             • IF $\varphi_{err}$ is reachable THEN output counterexample FI;
             • check if abstraction is exact for each transition
             • NewPreds = newly generated predicates from failed checks
          */
      IF NewPreds = $\emptyset$ THEN output unreachable FI;
      Preds = Preds $\cup$ NewPreds;
  OD;
END;
```

Correctness and Termination

- In general
  - The iterative algorithm might not terminate
- If it terminates
  - It finds an error or
  - It computes a finite bisimilar structure
- If a finite (reachable) bisimulation quotient exists then
  - It will eventually compute a finite bisimilar structure
  - May still fail to terminate

Implementation

- Implementation for simple guarded command language
  - PERL, OCAML
  - Uses SIMPLIFY as a decision procedure

Applications

- Property verification for the Bakery mutual exclusion protocol
  - Search order matters

    5 iterations for breadth first search order

    4 iterations for depth first search order
- Error detection in RAX (Remote Agent Executive)
  - Component extracted from an embedded spacecraft-control application
  - Deadlocked in space
  - Error found faster than over-approximation based analysis

Related Work

- Refinement of under-approximations
  - For SAT based bounded model checking – Grumberg et al. [POPL'05]
- May and must abstractions
  - Branching time properties – Godefroid et al [Concur'01]
  - "Hyper" must transitions for monotonicity – Shoham and Grumberg [TACAS'04]
  - Dams and Namjoshi, de Alfaro et al [LICS'04], Ball et al [CAV'05]
  - Our previous work – choice free search [TACAS'01]
- Model driven software verification
  - Use abstraction mappings during concrete model checking – Holzmann and Joshi [SPIN'04]
- Over-approximation based predicate abstraction
- Online minimization of transition systems
  - Lee & Yannakakis [1992]

Conclusions (I)

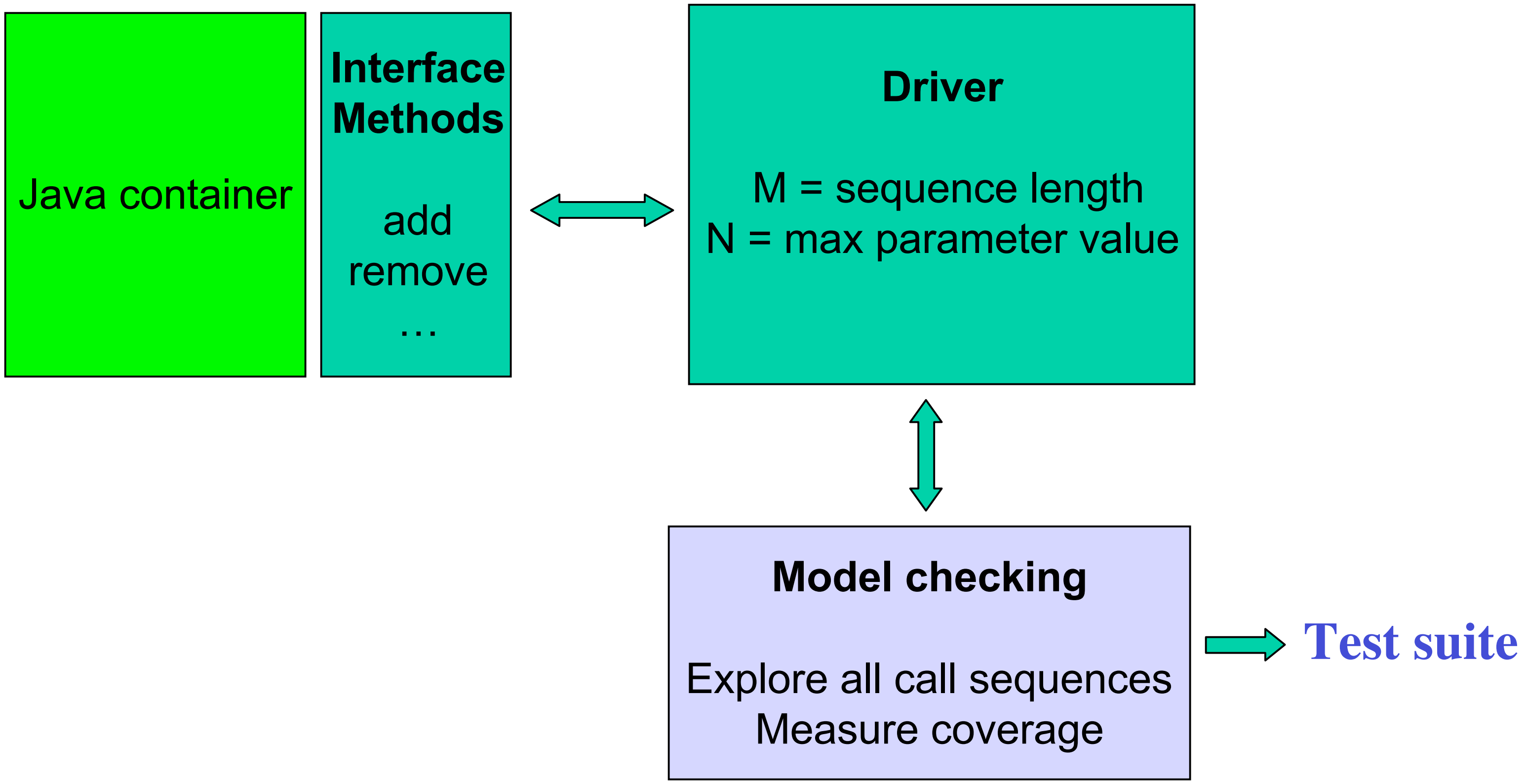
- Model checking algorithm
  - Under-approximation refinement
  - Integrates abstract analysis with concrete program execution
  - Uses decision procedure to detect incompleteness of abstraction and to refine the abstraction
- Comparison with standard over-approximation abstraction
  - Finds errors faster (potentially)
  - More efficient (in the number of theorem prover calls)
  - Complementary, should be **combined**
- Future work
  - Liveness properties
  - Backward vs. forward refinement, property driven refinement
  - Evaluation

Part II

Test Input Generation

- Model checking with abstract state matching
  - No automated refinement
  - User-provided abstractions
- Generate test input sequences for Java container classes
  - Use Java PathFinder (JPF)
    - Explicit state model checker for Java programs
  - (Abstract) state matching
    - To avoid generation of redundant test sequences
  - Measure coverage
    - Whenever coverage increased, output test sequence
- Test oracles
  - Method post-conditions, assertions
  - Absence of run-time errors

General Idea



Java container

Interface Methods

add
remove
…

Driver

M = sequence length
N = max parameter value

Model checking

Explore all call sequences
Measure coverage

Test suite

Test sequence: add(1); add(0); remove(0);

Driver Skeleton

M: sequence length
N: parameter values

```
Container c = new Container();
for (int i = 0; i < M; i++) {
    int v = Verify.random(N - 1);
    switch (Verify.random(1)) {
       case 0: c.add(v); break;
       case 1: c.remove(v); break;
    }
    Verify.ignoreIf(checkAbstractState(c));
}
```

Test Generation Techniques

- Explicit state model checking
  - "Classical" concrete state matching
  - Abstract state matching
- Model checking with symbolic execution
  - State matching using subsumption checking
  - Abstract matching
- Model checking with random selection

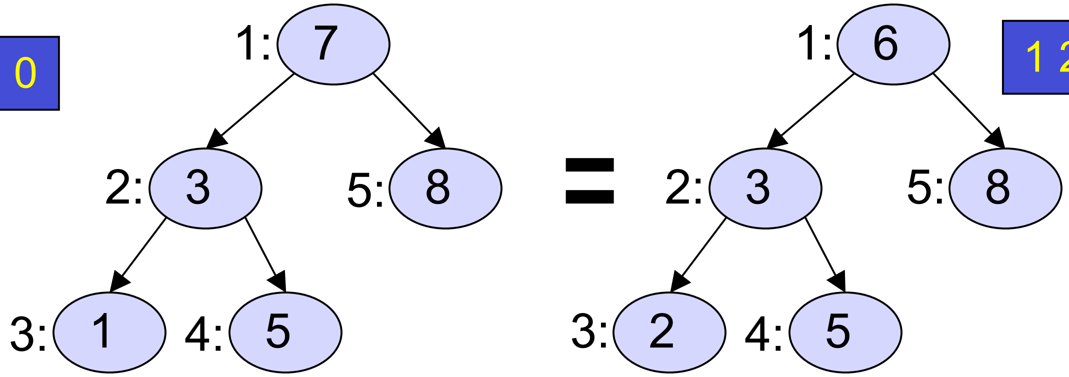
Explicit State Model Checking

Abstract Matching

- Perform state matching after each method call
  - Map container state to an abstract version
  - Backtrack if abstract state was seen before, i.e. discard test sequence
- Automated support for two abstractions:
  - Shape abstraction
    - Records (concrete) heap shape of container; discards numeric data
    - Obtained through heap “linearization”
    - Comparing shapes reduces to comparing sequences
  - “Complete” abstraction
    - Shape augmented with data
    - Similar to symmetry reduction in software model checking

Shape Abstraction: Linearization

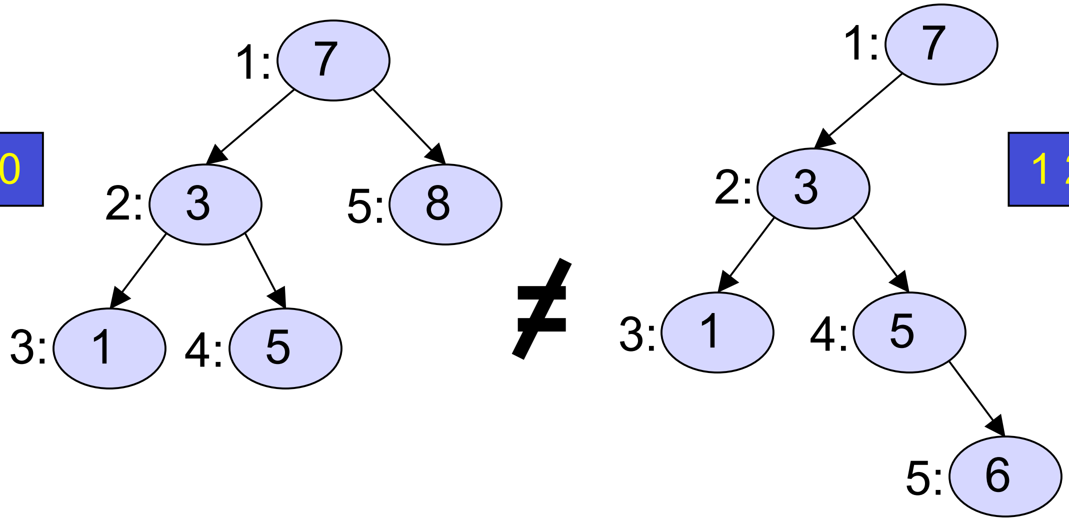
1 2 3 0 0 4 0 0 5 0 0



1 2 3 0 0 4 0 0 5 0 0

---

1 2 3 0 0 4 0 0 5 0 0

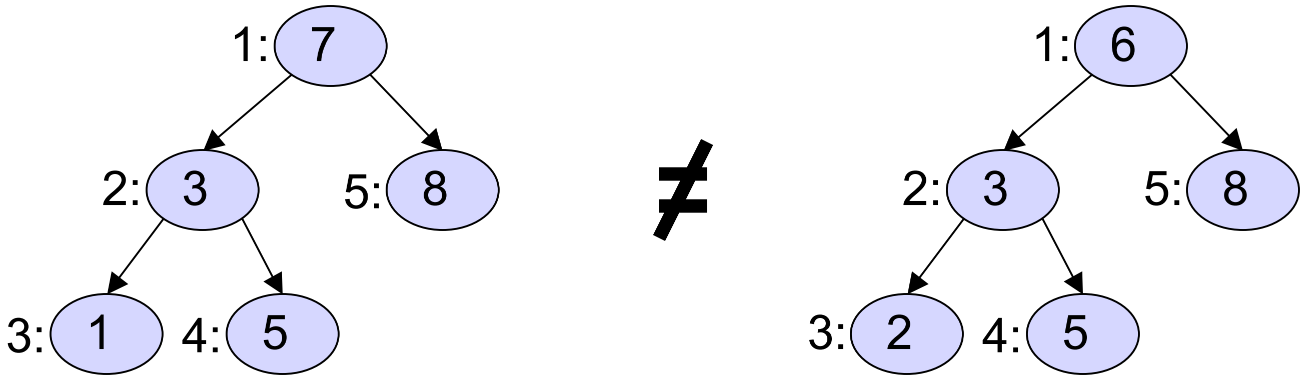


1 2 3 0 0 4 0 5 0 0 0

Complete Abstraction: Shape + Data

17 23 31 0 0 45 0 0 58 0 0

16 23 32 0 0 45 0 0 58 0 0



Symbolic Execution

- Execute methods on symbolic input values
- Symbolic states represent sets of concrete states
  - Can yield significant improvement over explicit execution
- For each path, build a path condition
  - Condition on inputs – for the execution to follow that path
  - Check satisfiability

Example – Explicit Execution

Code that swaps 2 integers:

```
int x, y;

if (x > y) {

  x = x + y;

  y = x – y;

  x = x – y;

  if (x > y)

    assert false;

}
```

Concrete Execution Path:

x = 1, y = 0

1 > 0 ? true

x = 1 + 0 = 1

y = 1 – 0 = 1

x = 1 – 1 = 0

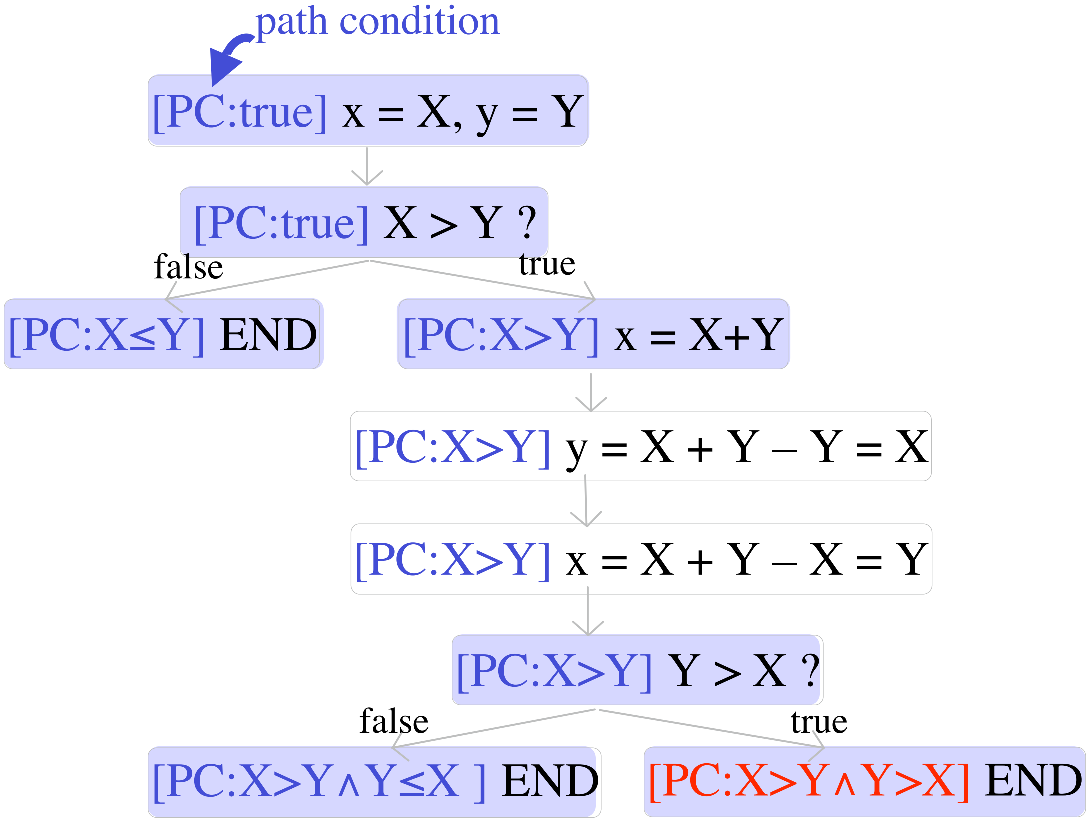
0 > 1 ? false

Example – Symbolic Execution

Code that swaps 2 integers:

```
int x, y;

if (x > y) {

  x = x + y;

  y = x – y;

  x = x – y;

  if (x > y)

    assert false;

}
```

Symbolic Execution Tree:



path condition

[PC:true] x = X, y = Y

[PC:true] X > Y ?

false

true

[PC:X≤Y] END

[PC:X>Y] x = X+Y

[PC:X>Y] y = X + Y – Y = X

[PC:X>Y] x = X + Y – X = Y

[PC:X>Y] Y > X ?

false

true

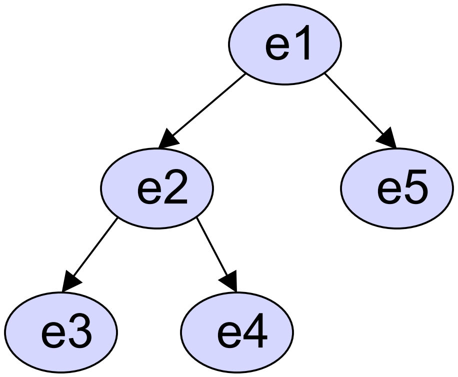
[PC:X>Y∧Y≤X] END

[PC:X>Y∧Y>X] END

Symbolic Execution in JPF

- Handles dynamically allocated data, arrays, concurrency
- Uses Omega library for linear integer constraints
- State matching
  - Subsumption between symbolic states

Symbolic State



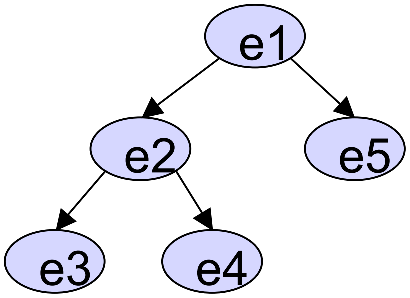
$e1 > e2 \wedge$
$e2 > e3 \wedge$
$e2 < e4 \wedge$
$e5 > e1$

Shape

Symbolic Constraints

Subsumption Checking

Stored state:



$e1 > e2 \wedge$
$e2 > e3 \wedge$
$e2 < e4 \wedge$
$e5 \geq e1$

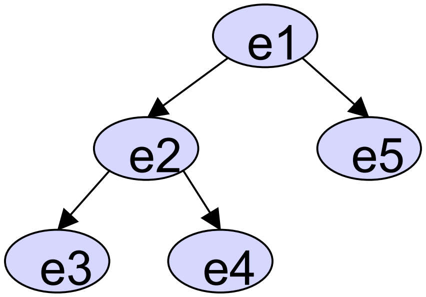
Set of concrete states represented by stored state

Same shape

$\Uparrow$ Matched

$\supseteq$

New state:

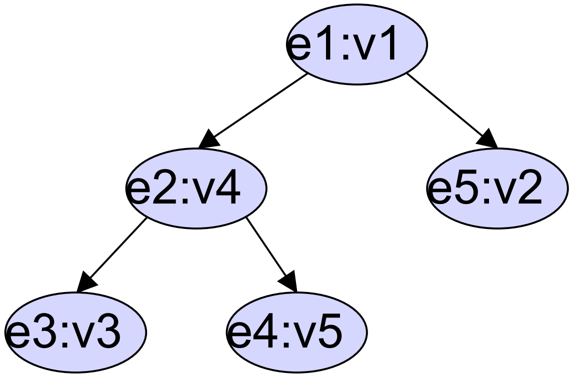


$e1 > e2 \wedge$
$e2 > e3 \wedge$
$e2 < e4 \wedge$
$e5 > e1$

Set of concrete states represented by new state

Subsumption Checking

Existential Quantifier Elimination



$e1 = V1 \land e2 = V4 \land e3 = V3 \land$
$e4 = V5 \land e5 = V2$

<u>PC:</u>

$V1 < V2 \land V4 > V3 \land V4 < V1 \land$
$V4 < V5 \land V7 < V2 \land V7 > V1$

$\exists$ V1,V2,V3,V4,V5,V7:

$e1 = V1 \land e2 = V4 \land e3 = V3 \land e4 = V5 \land e5 = V2 \land PC$

simplifies to

$e1 > e2 \land e2 > e3 \land e2 < e4 \land e5 > e1$

Evaluation

- Four container classes
  - BinaryTree, BinomialHeap, FibonacciHeap, TreeMap
- Measured coverage
  - Number of basic blocks covered by the generated tests
- Measured predicate coverage – at each basic block
  - Combinations of predicates chosen from conditions in the code
  - More difficult to achieve

- Breadth first search order
- Sequence Length = Number of Values (M=N)
  - Tried other values
- Dell Pentium 4, 2.2 GHz, Windows 2000, 1GB memory
- Out of Memory runs not considered

TreeMap – Basic Block Coverage

Exhaustive Techniques

Technique	Coverage	Seq Length	Time (s)	Memory (MB)
Model Checking	37	6	38	243
Complete Abstraction	39	7	9	34
SymEx w/ Subsumption	39	7	15	22

Lossy Techniques

Technique	Coverage	Seq Length	Time (s)	Memory (MB)
Shape Abstraction	39	10	2	6
SymEx w/ Shape Abstraction	39	7	7	22
Random Selection	39	10	18	5

TreeMap – Predicate Coverage

Exhaustive Techniques

Technique	Coverage	Seq Length	Time (s)	Memory (MB)
Model Checking	55	6	38	229
Complete Abstraction	95	10	271	844
SymEx w/ Subsumption	104	12	594	896

Lossy Techniques

Technique	Coverage	Seq Length	Time (s)	Memory (MB)
Shape Abstraction	106	20	281	1016
SymEx w/ Shape Abstraction	102	13	1309	1016
Random Selection	106	39	78	17

Observations

Coverage

- Basic block coverage – easily achieved with all techniques
- Predicate coverage
  - Difficult to achieve with “classical” model checking
  - Its close “cousin” (complete abstraction) scales better
  - Lossy techniques better than exhaustive ones

Symbolic vs. explicit execution

- Exhaustive – subsumption checking
  - Better than exhaustive concrete execution
- Lossy – abstract matching
  - Worse than concrete search with abstract matching

Random selection

- Requires longer sequences to achieve good coverage
- Could not obtain “best” coverage for FibonacciHeap and BinomialHeap (more interface methods with more parameters)
  - Concrete search with abstract matching performed better

Conclusions (II)

- Test input generation techniques for Java containers
  - State matching to avoid generation of redundant tests
  - Concrete/abstract matching, explicit/symbolic execution
  - Compared to random selection
- Model checking with shape abstraction
  - Good coverage with short sequences
  - Shape abstraction provides an accurate representation of containers

- Future work
  - Coverage highly dependent on abstraction – automatic refinement
  - Complex data structures, arrays as input parameters
  - Abstractions used in shape analysis [SPIN’06]
  - More experiments
  - Measure techniques in terms of defect detection, rather than coverage

Explanation

- Bisimulation: symmetric relation ~
  - $s \sim s'$ iff for every $s \rightarrow s_1$ there exists $s' \rightarrow s_1'$ s.t. $s_1 \sim s_1'$
- Two transition systems are bisimilar if
  - Their initial states are bisimilar
- ~ induces a quotient transition system
  - States are equivalence classes
  - $A \rightarrow B$ if there exist s in A and s' in B s.t. $s \rightarrow s'$

Non-monotonic Refinement

State space explored