Model Checking Programs

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Department of Distributed and Dependable Systems

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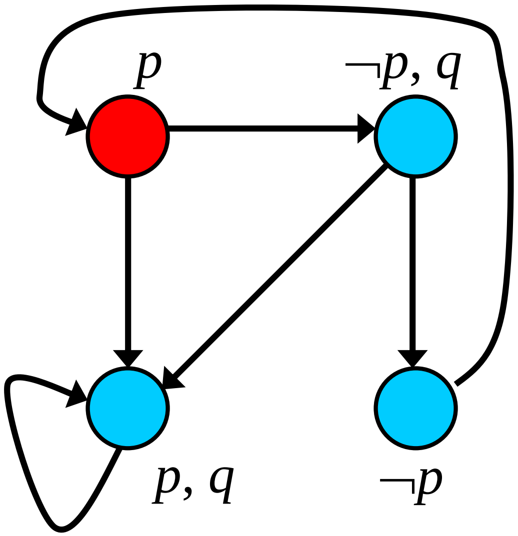
Model checking

Structure M



Formula f

$$\boxed{\text{LTL: } p \Rightarrow \mathrm{F}\ q}$$

Verification task: M, s $\models$ f ?

Model checking SW and HW

- Goals
  - Systematic exploration of all possible behaviors
    - Example: all possible interleavings of concurrent threads
  - Checking required properties in each state (path)

- Model
  - Source code (binary) → program state space
- Property
  - assertion, deadlock freedom, no data races, ...

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Program state space

- Directed graph
  - States
  - Transitions

States

Q: What does a program state contain ?

States

- Local state of each thread
  - Program counter (PC)
  - Call stack (parameters, local variables, operands)
- Global state shared between multiple threads
  - Heap objects (field values) and pointers
  - Status of each thread (runnable, waiting, ...)
  - Thread synchronization primitives (locks)

Transitions

Q: What about transitions ?

Transitions

- Statements (instructions)
  - Updating states (PC, variables)

Program state space

- Directed graph
  - States
  - Transitions
  - **what else ?**

Program state space

- Directed graph
  - States
  - Transitions
  - **Choices**

Choices

Q: What types of choices there are ?

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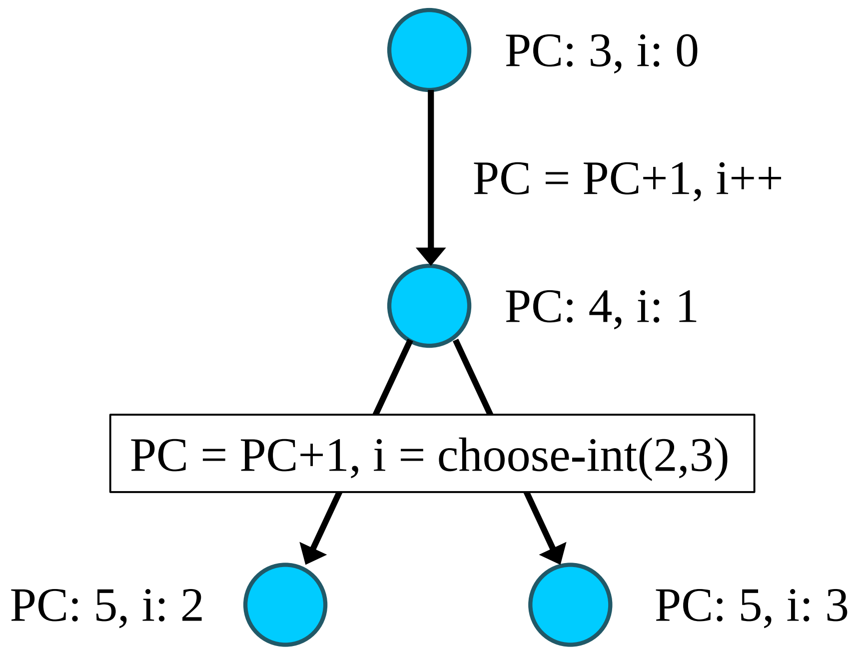
Choices

- Thread scheduling
- Data
  - Unknown inputs

Program state space

- States
- Transitions
- Choices



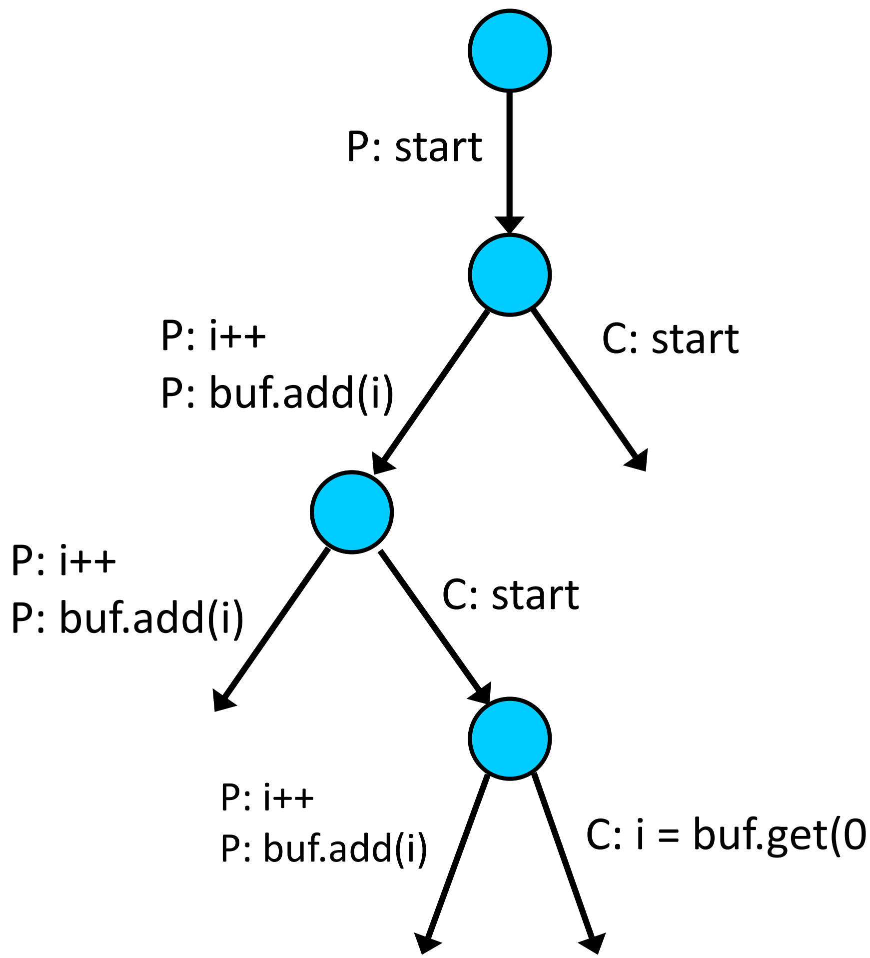
Example: producer – consumer

```
public Producer extends Thread {
  void run() {
    while (true) {
      buf.add(++i);
    }
  }
}

public Consumer extends Thread {
  void run() {
    while (true) {
      i = buf.get(0);
      print(i);
    }
  }
}

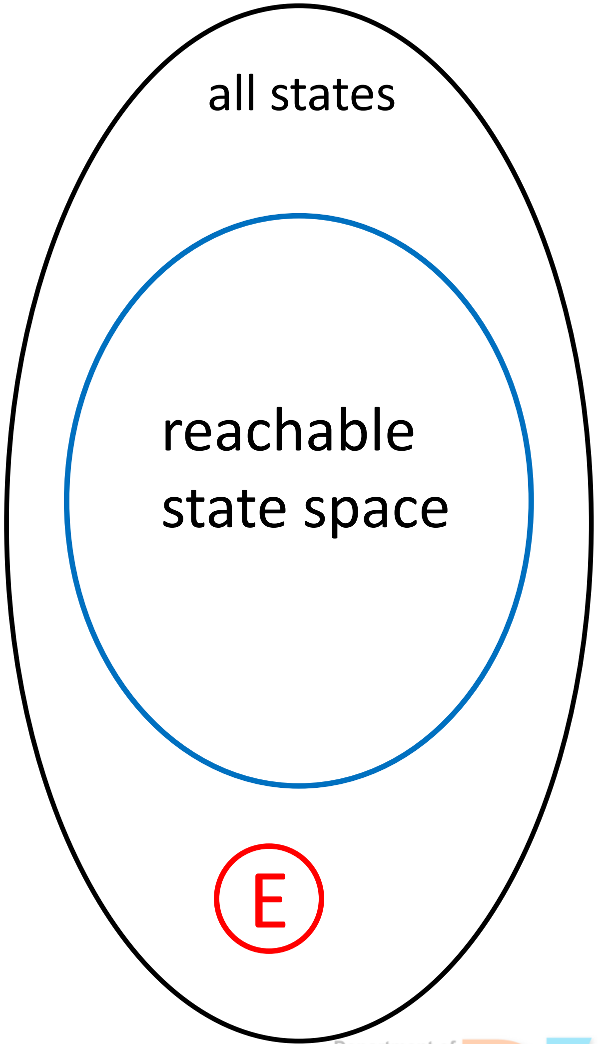
public static List buf;

(new Producer(var)).start();
(new Consumer(var)).start();
```



Terminology

- Reachable state space
  - From the initial program state
- Error state E
- Safety
  - Error state is not reachable



Properties

- Categories
  - State
  - Path

Properties

Q: Divide properties into categories

Properties	Category
no deadlock	state
data race	path
assertion	
LTL formula	

Properties

Properties	Category
no deadlock	state
assertion	path
LTL formula	multiple paths
data race	

State space traversal

State space traversal

- Explicit traversal of the concrete state space
- SAT-based traversal of symbolic state space

Explicit state space traversal

- DFS: depth-first search
  - From the node corresponding to the initial state
- Properties checked in each state
  - Error state reached → counterexample
- Counterexample (error trace)
  - Path in the state space that violates given property

Explicit state space traversal with DFS

```
INIT
  visited : = {s0}
  push(stack, s0)
  DFS(s0)
end INIT
```

```
DFS(s)
  for each t in enabled(s) do
    s' := t(s)
    if not P(s') then
      counterexample := stack
      exit
    if s' not in visited then
      visited := visited + {s'}
      push(stack, s')
      DFS(s')
      pop(stack)
  end for
end DFS()
```

Explicit state space traversal with DFS

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INIT
  visited : = {s0}
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Explicit state space traversal with DFS

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      DFS(s')
      pop(stack)
  end for
end DFS()
```

Executing transitions

Explicit state space traversal with DFS

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  visited : = {s0}
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  DFS(s0)
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```

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DFS(s)
  for each t in enabled(s) do
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      exit
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      visited := visited + {s'}
      push(stack, s')
      DFS(s')
      pop(stack)
  end for
end DFS()
```

Evaluating properties

Explicit state space traversal with DFS

```
INIT
  visited : = {s0}
  push(stack, s0)
  DFS(s0)
end INIT
```

```
DFS(s)
  for each t in enabled(s) do
    s' := t(s)
    if not P(s') then
      counterexample := stack
      exit
    if s' not in visited then
      visited := visited + {s'}
      push(stack, s')
      DFS(s')
      pop(stack)
  end for
end DFS()
```

State matching

State space traversal with DFS – example

```
Random rnd = new Random();
int i = 2;
int j = 0;

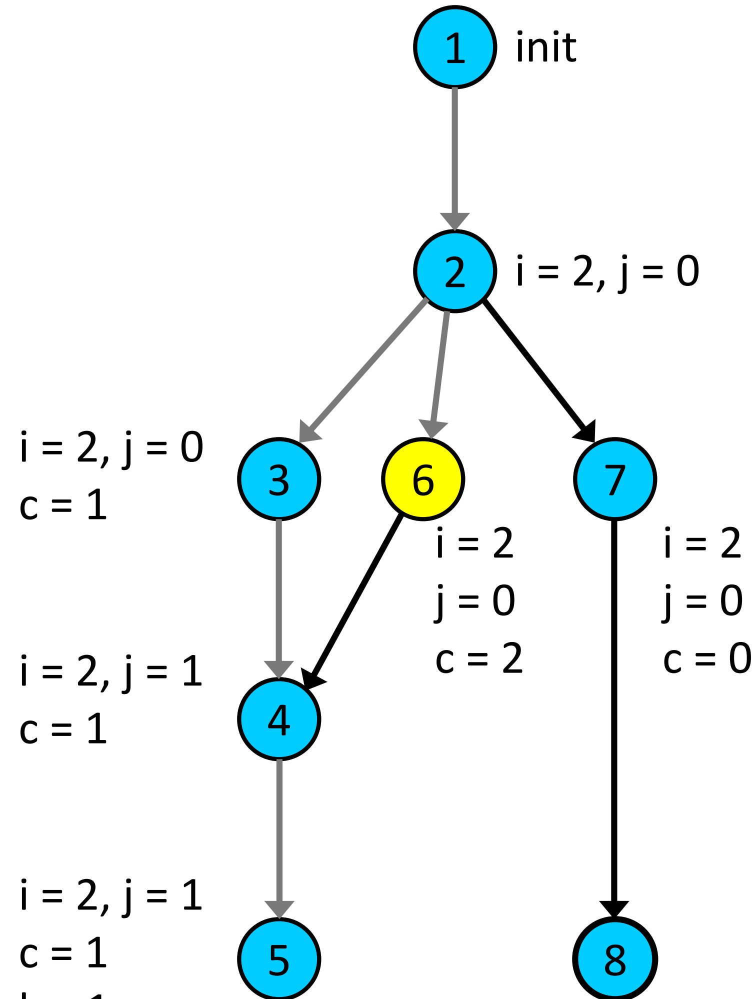
int c = rnd.nextInt(3);

if (c == 1)
  j++;
else if (c == 2) {
  j = 1;
  c = 1;
}

int k = i / j;
```

Stack: 1,2,6

Visited states: {1,2,3,4,5,6}



State space traversal with DFS – example

```
Random rnd = new Random();
int i = 2;
int j = 0;

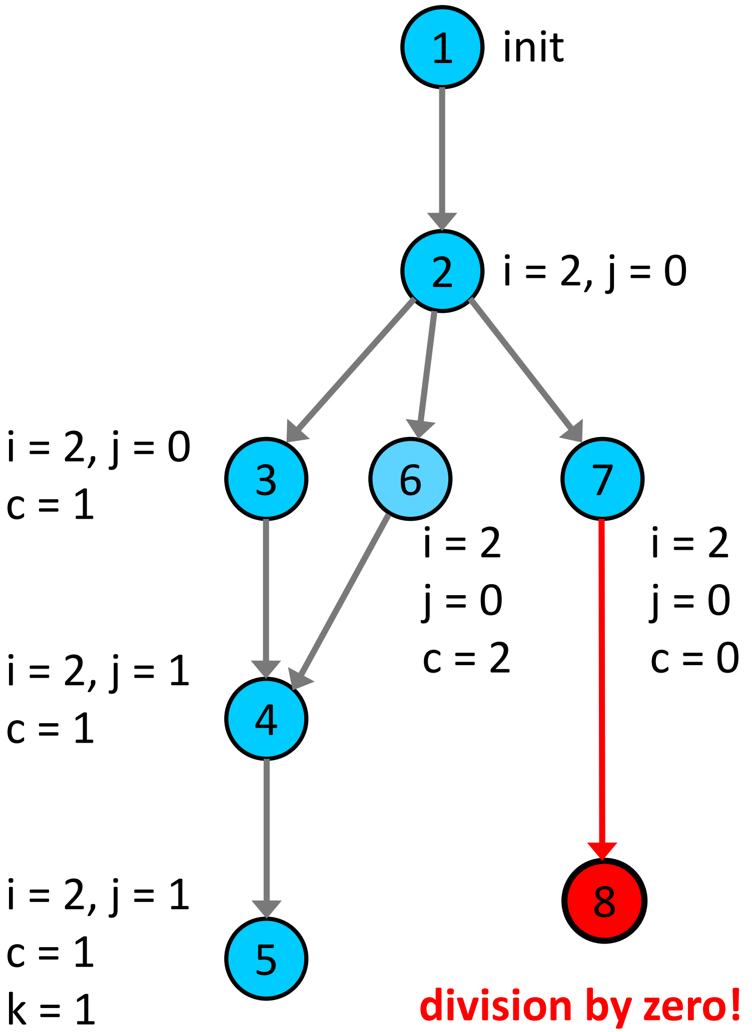
int c = rnd.nextInt(3);

if (c == 1)
  j++;
else if (c == 2) {
  j = 1;
  c = 1;
}

int k = i / j;
```

Stack: 1,2,7

Visited states: {1,2,3,4,5,6,7}



Model checking programs: limitations

Limitations

- Decidability
  - For many interesting programs and interesting properties, model checking is undecidable
  - Example: **assertion checking**
    - Undecidable for multi-threaded programs with procedures
    - Decidable for single-threaded boolean programs

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Limitations

- Possibly infinite state systems

Q: What can make the state space infinite ?

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Limitations

- Possibly infinite state systems
  - Data types with large or infinite domains (int, float)
  - Unbounded heap and number of threads
  - Unbounded recursion of procedure calls (stack)

- Remedy: **abstraction**

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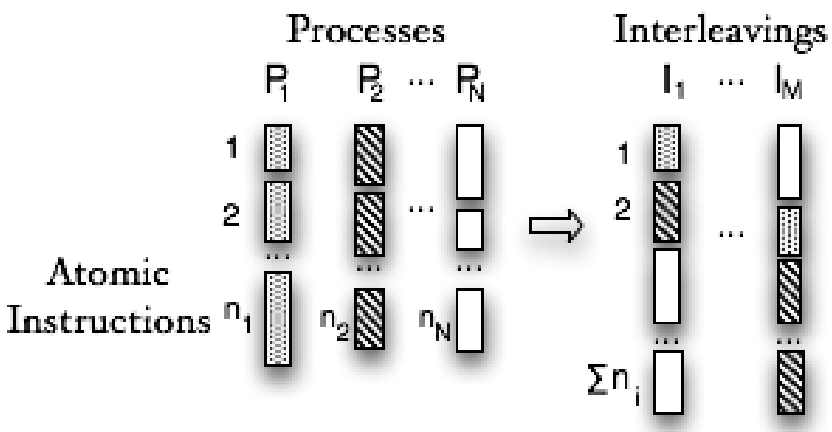
Limitations

- State explosion
  - a non-trivial program has too many states
  - the state space contains too many choices

- State space size exponential with respect to
  - Number of threads
  - Size of data domains

State explosion

- High number of concurrent program threads
- Many instructions executed by each thread



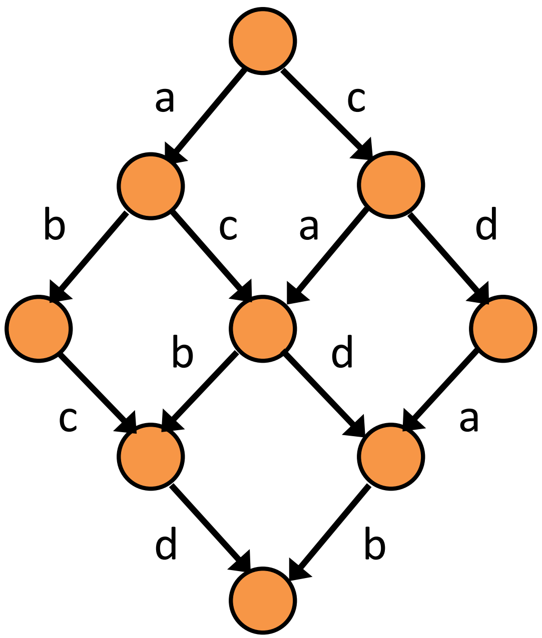
$$M = \frac{(\Sigma_{i=1}^{N} n_i)!}{\Pi_{i=1}^{N}(n_i!)}$$

State explosion

- Consequences
  - Exploring too many choices, states, and transitions
  - Storing too many states in memory
  - ➔ **model checker runs out of memory and time**
- Model checking of large and complex programs is not practically feasible
  - ... **but many research teams are working on this**

State explosion

Q: So what can we do with state explosion ?



T1: a ; b

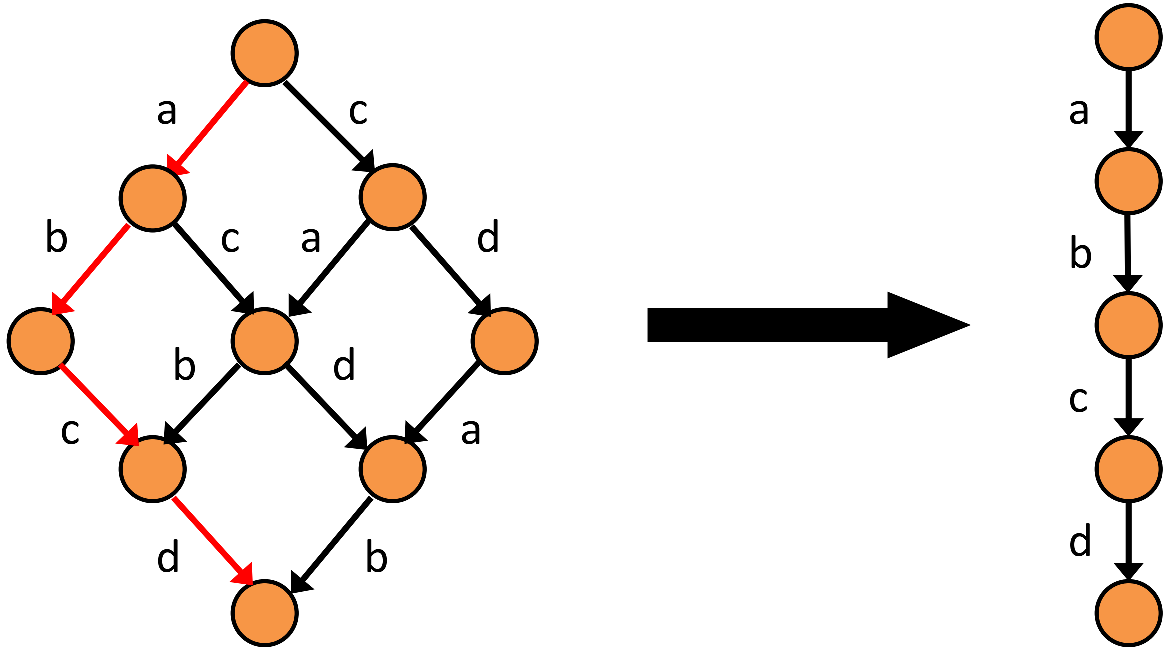
T2: c ; d

Partial order reduction

- Most transitions perform operations local to a given thread
  - Examples: arithmetic over stack operands (in Java), updating local variables
- Global operations (statements)
  - Field access on a shared heap object
  - Thread synchronization (lock, wait)

Partial order reduction

- Independent transitions
  - Performing only thread-local statements
  - All their interleavings give the same result



Partial order reduction

- Independent transitions
  - Commutative → any ordering is valid
  - Execution of one does not disable others

- All the possible interleavings of independent transitions from a given state are equivalent

Partial order reduction

- Practical approach
  - Scheduling choices only at statements that represent communication among threads (conflicts)
- Communication statement
  - may have effects visible to other concurrent threads
  - may depend on other threads by reading shared data
- Why thread choice
  - Let other threads react or modify shared data

Addressing state explosion

- Symmetry reductions
- Heuristics

Symmetry reductions

- Two states: *s1*, *s2*
  - State matching: *s1* != *s2*
  - Program execution: *s1* == *s2*
- Goal: avoid repeated processing of such states
- Approach
  - Divide state space into equivalence classes
  - Explore only **canonical representation**

Symmetry reductions

- Class loading order
- Heap addresses

- Partial order reduction

Class loading symmetry

- Program execution
  - Actual position of class data in the static area does not influence observable behavior
- Model checkers
  - Internal representation of program states
  - Class loading order matters in some cases

- Solution
  - Canonical representation of the static area
    - Fixed order of class loading over all state space paths

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Heap symmetry

- Program execution
  - Exact address of a heap object does not influence observable behavior
- Model checkers
  - Internal representation of program states
  - Heap shape and layout matters in some cases
- Solution: heap canonicalization
  - Canonical addresses of heap objects
  - Issues: garbage collection, deallocation

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Heuristics

- Motto
  - "find an error before the model checker runs out of memory and time (resources)"
  - Better testing: find many errors in reasonable time

- Approach
  - Focus on state space fragments with errors
    - Guide model checker towards possible error states
    - Identify and drop error-free parts of the state space

State space traversal with heuristics

“standard” DFS

```
INIT
 visited := {s0}
 push(stack, s0)
 DFS(s0)
end INIT

DFS(s)
 workSet := enabled(s)
 for each t in workSet do
   s' := t(s)
   if not P(s') then
     counterexample := stack
     exit
   if s' not in visited then
     visited := visited + {s'}
     push(stack, s')
     DFS(s')
     pop(stack)
 end for
end DFS()
```

BeFS + heuristics

```
INIT
 visited := {s0}
 push(stack, s0)
 BeFS(s0)
end INIT

BeFS(s)
 workList := order(enabled(s), h)
 for each t in workList do
   s' := t(s)
   if not P(s') then
     counterexample := stack
     exit
   if s' not in visited then
     visited := visited + {s'}
     push(stack, s')
     BeFS(s')
     pop(stack)
 end for
end BeFS()
```

Heuristic functions

- Random walk (search)
- Branch coverage
  - Preferring unexplored paths at branching point
- Maximize thread switching
- Prioritize selected threads
- Prefer most blocked threads
- ... and many others

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Heuristics functions

- Problem: may not give the best/correct answer
  - Error states usually identified on-the-fly during state space traversal

- Consequences
  - Dropped state space fragments with errors inside
  - Misguided search towards error-free state space

Success not guaranteed !!

Practical issues

- Relaxed memory models (e.g., JMM for Java)
- Mapping counterexamples to source code
- Efficient management of program states
  - Operations: storage, state matching, backtracking
  - Transitions modify a small part of program state
    - Keep only “diffs” from the previous state on the path
  - Comparing hash values ➔ possible collisions

Further reading

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