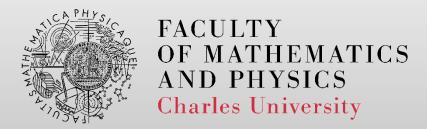
Model Checking Programs

http://d3s.mff.cuni.cz

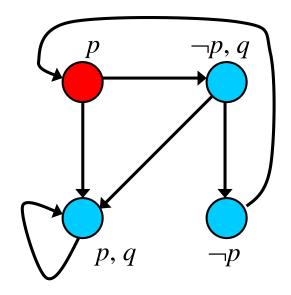


Pavel Parízek



Model checking

Structure M



Formula f

$$LTL: p \Rightarrow F q$$

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



Model checking SW and HW



- 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, ...



Program state space

- Directed graph
 - States
 - Transitions



States





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





Transitions



Updating states (PC, variables)



Program state space

- Directed graph
 - States
 - Transitions
 - what else?



Program state space

- Directed graph
 - States
 - Transitions
 - Choices



Choices





Choices

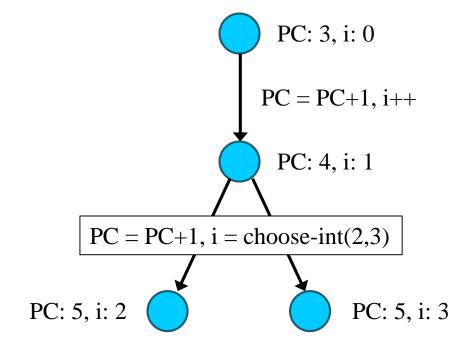


- Data
 - Unknown inputs



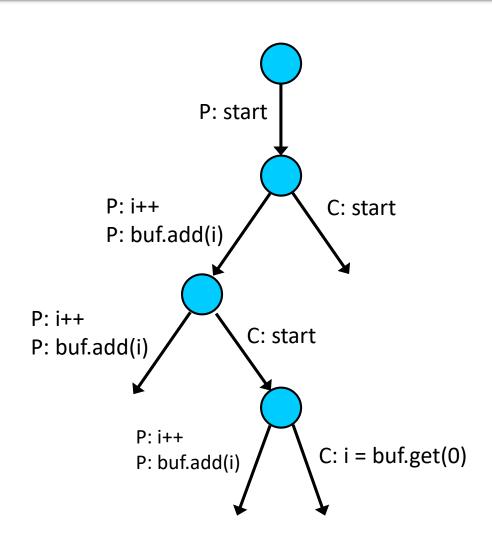
Program state space

- 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.qet(0);
      print(i);
public static List buf;
(new Producer(var)).start();
(new Consumer(var)).start();
```



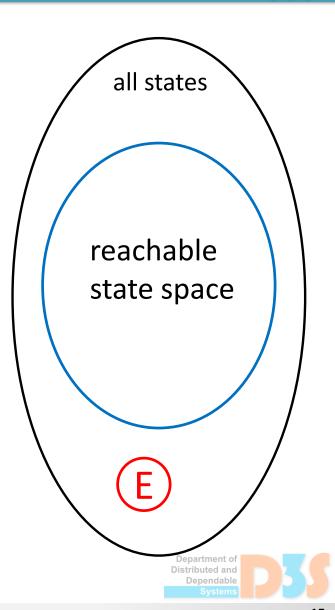


Terminology

- Reachable state space
 - From the initial program state

Error state

- Safety
 - Error state is not reachable



Properties

- Categories
 - State
 - Path



Properties

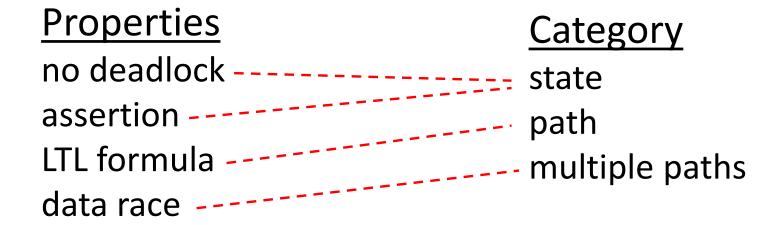


Properties
no deadlock
data race
assertion
LTL formula

Category state path



Properties





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



```
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()
```



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



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

Executing transitions

```
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()
```



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

Evaluating properties

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



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

```
State matching
```

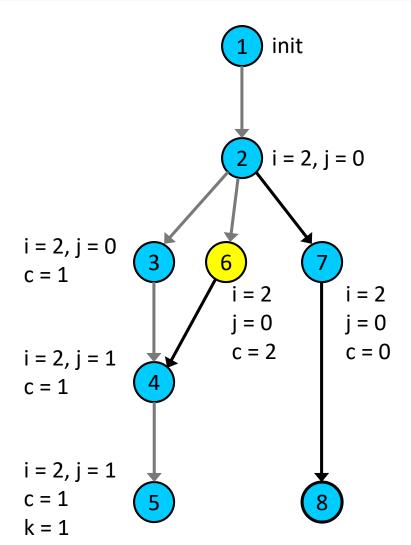
```
DFS(s)
  for each t in enabled(s) do
    s' := t(s)
    if not P(s') then
      counterexample := stack
      exit
    if s' not in visited then
      visited := visited + {s'}
      push(stack, s')
      DFS(s')
      pop(stack)
  end for
end DFS()
```

State 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}

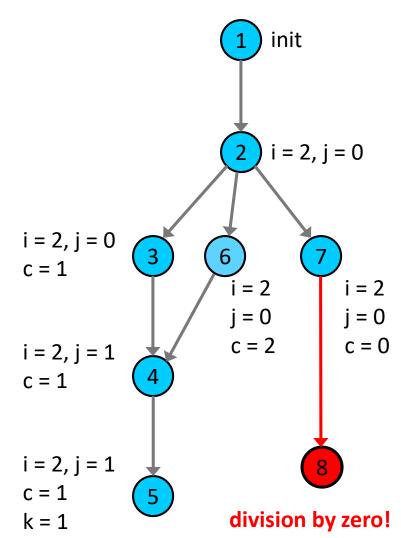


State space traversal with DFS – example

```
Random rnd = new Random();
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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





- 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



Possibly infinite state systems

Q: What can make the state space infinite?



- 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



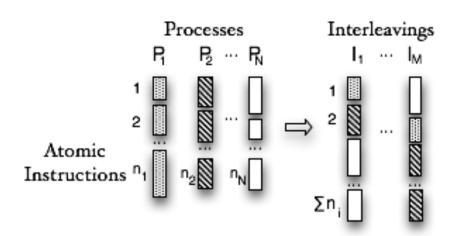
- State explosion
 - a non-trivial program has too many states
 - the state space contains too many choices

- 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



$$M = \frac{(\sum_{i=1}^{N} n_{i})!}{\prod_{i=1}^{N} (n_{i}!)}$$



State explosion

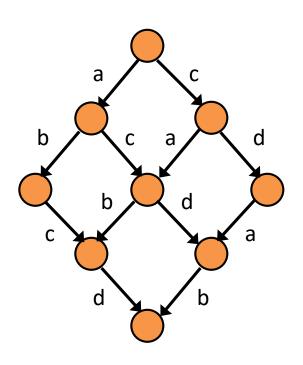
- Consequences
 - Exploring too many choices, states, and transitions
 - Storing too many states in memory
 - model checker runs out of memory and time

- 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

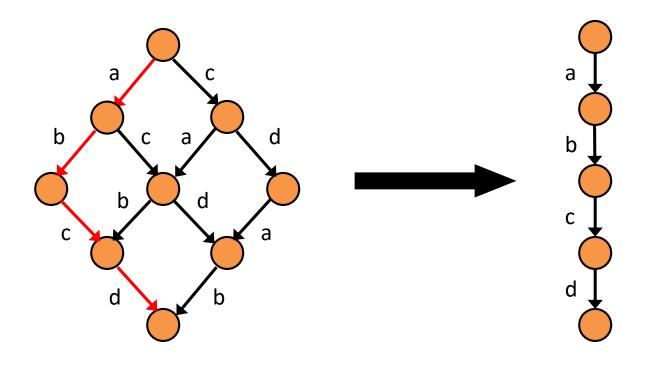


- Most transitions perform operations local to a given thread
 - Examples: arithmetic over stack operands (in Java), updating local variables

- Global operations (statements)
 - Field access on a shared heap object
 - Thread synchronization (lock, wait)



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



- 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





- 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



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



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



Heuristics



- "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



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

- C. Baier, J.-P. Katoen, and K.G. Larsen. Principles of Model Checking. MIT Press, 2008
- P. Godefroid. Partial-Order Methods for the Verification of Concurrent Systems. LNCS 1032, 1996
- C. Flanagan and P. Godefroid. Dynamic Partial Order Reduction for Model Checking Software. POPL 2005
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