Model Checking Programs

http://d3s.mff.cuni.cz

Pavel Parízek
Model checking

Structure M

Formula f

LTL: $p \Rightarrow F q$

Verification task: $M, s \models f$ ?
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) $\rightarrow$ program state space

Property
- assertion, deadlock freedom, no data races, ...
Program state space

- Directed graph
  - States
  - Transitions
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)
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
Q: What types of choices there are?
Choices

- Thread scheduling

- Data
  - Unknown inputs
Program state space

- States
- Transitions
- Choices

PC: 3, i: 0
PC = PC+1, i++
PC: 4, i: 1
PC = PC+1, i = choose-int(2,3)
PC: 5, i: 2
PC: 5, i: 3
Example: producer – consumer

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

class 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
### Q: Divide properties into categories

<table>
<thead>
<tr>
<th>Properties</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>no deadlock</td>
<td>state</td>
</tr>
<tr>
<td>data race</td>
<td>path</td>
</tr>
<tr>
<td>assertion</td>
<td></td>
</tr>
<tr>
<td>LTL formula</td>
<td></td>
</tr>
</tbody>
</table>
Properties

no deadlock
assertion
LTL formula
data race

Category
state
path
multiple paths
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 $\Rightarrow$ 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

INIT

\[
\text{visited} := \{s_0\} \\
\text{push}(\text{stack}, s_0) \\
\text{DFS}(s_0) \\
\text{end INIT}
\]

DFS(s)

for each t in enabled(s) do

\[
s' := t(s) \\
\text{if not P}(s') \text{ then} \\
\text{counterexample} := \text{stack} \\
\text{exit} \\
\text{if } s' \text{ not in visited then} \\
\text{visited} := \text{visited} + \{s'\} \\
\text{push}(\text{stack}, s') \\
\text{DFS}(s') \\
\text{pop}(\text{stack})
\]

end for
end DFS()
Explicit state space traversal with DFS

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

DFS(s)
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            DFS(s')
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        end for
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      exit
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      visited := visited + \{s'\}
      push(stack, s')
      DFS(s')
      pop(stack)
  end for
end DFS()
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
  end if
  if s' not in visited then
    visited := visited + \{s'\}
    push(stack, s')
    DFS(s')
    pop(stack)
  end if
end for
end DFS()
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 \( \text{rnd} = \text{new Random()} \);
int \( i = 2 \);
int \( j = 0 \);

int \( c = \text{rnd.nextInt}(3) \);

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

int \( k = i / j \);

Stack: 1,2,7
Visited states: \( \{1,2,3,4,5,6,7\} \)

Division by zero!
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
Limitations

- Possibly infinite state systems

Q: What can make the state space infinite?
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
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

\[ M = \frac{(\sum_{i=1}^{N} n_i)!}{\prod_{i=1}^{N} (n_i!)} \]
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
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 $\rightarrow$ 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: \( s1 \neq s2 \)
  - Program execution: \( s1 == s2 \)

• Goal: avoid repeated processing of such states

• Approach
  - Divide state space into equivalence classes
  - Explore only \textit{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
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

• 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')
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')
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