Automated Construction of Reasonable Environment for Java Components

Pavel Parízek, Jiří Adámek, Tomáš Kalibera

DISTRIBUTED SYSTEMS RESEARCH GROUP
http://dsrg.mff.cuni.cz

CHARLES UNIVERSITY PRAGUE
Faculty of Mathematics and Physics

Software quality

- Key attribute of software quality
  - Absence of errors (bugs) in code
- How to discover errors in code
  - Software testing
  - Formal verification and analysis
    - model checking, theorem proving, static analysis

Model checking

- Automated verification technique
  - Good at detection of errors in concurrent and reactive systems
  - Used for a long-time in verification of both software and hardware systems

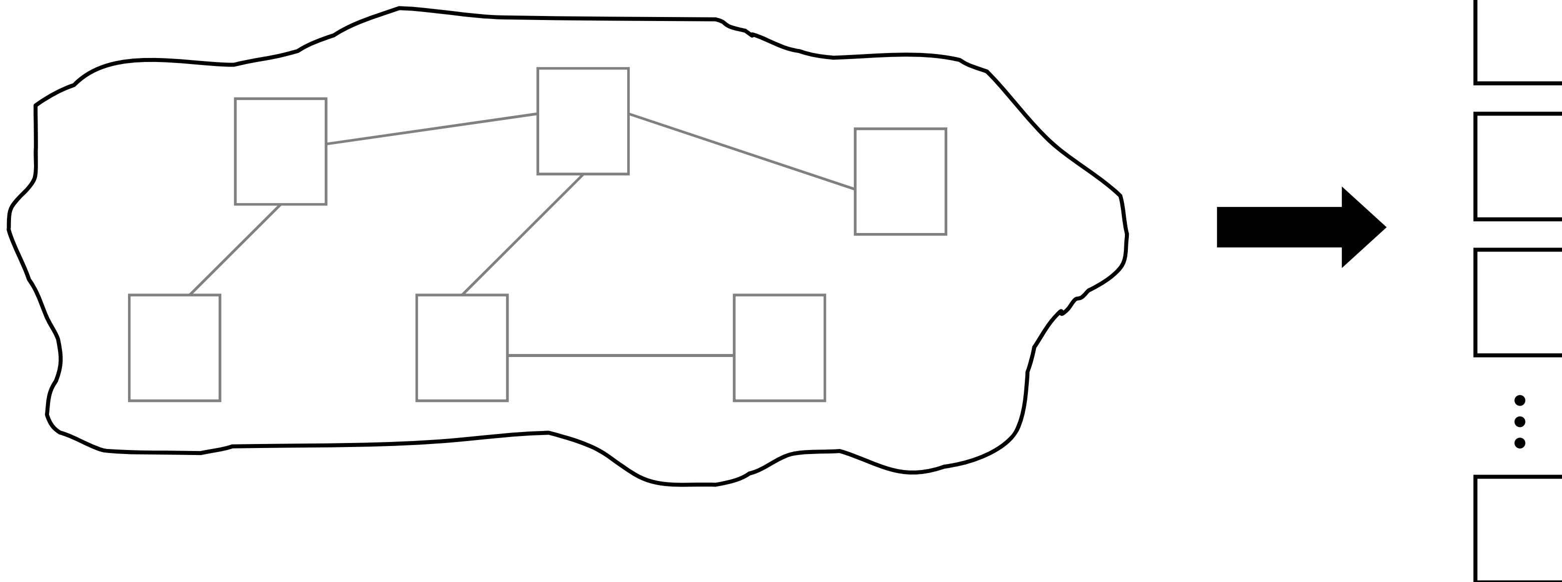
- Issue
  - Does not scale well to large systems
    - State explosion

Model checking of component systems

- Two aspects
  - Compositional approach to verification
  - Independent development of components

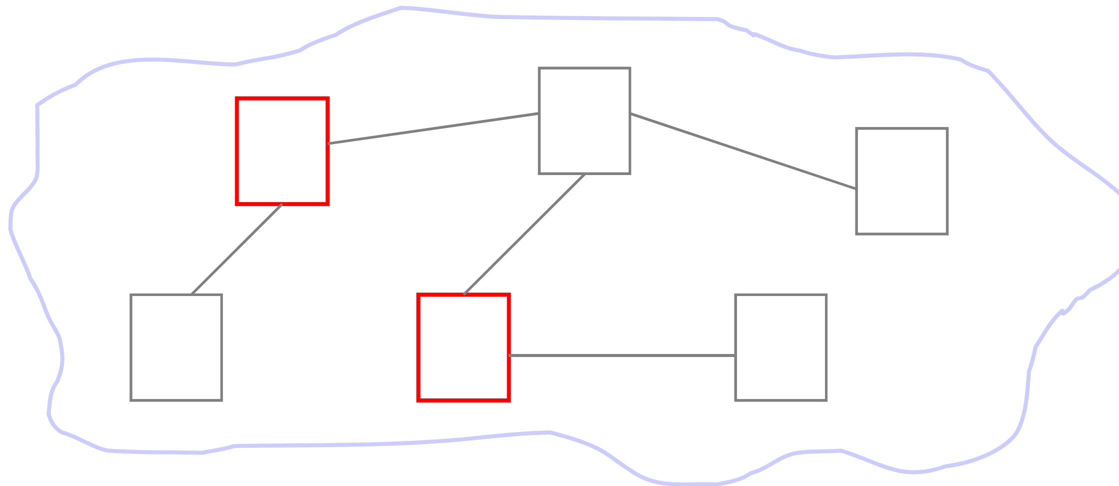
Compositional model checking

- Key idea
  - Components are checked separately (one at a time)
- Benefit
  - Model checking is less prone to state explosion



Independent development of components

- Each component may be developed by a different team (or at a different time)
  - Rest of a system may not be available upon completion of a component



Model checking of component systems

- Two aspects
  - Compositional approach to verification
  - Independent development of components
- Key requirement on techniques and tools
  - Ability to verify an isolated component

Our research

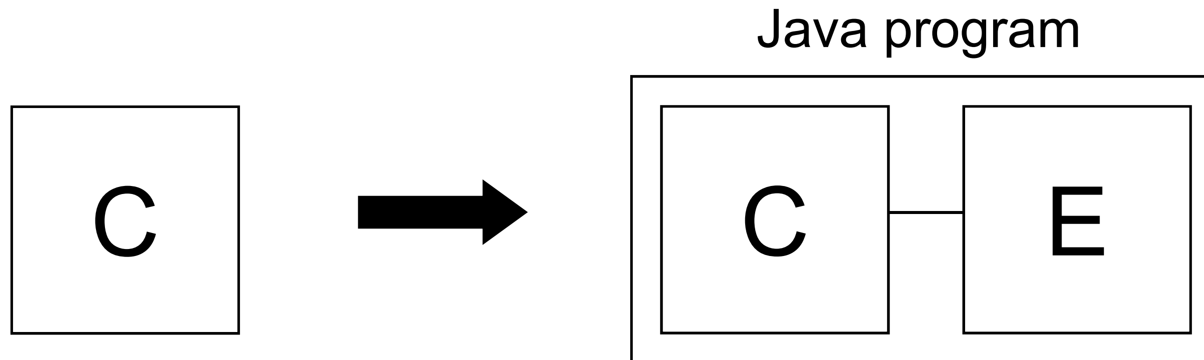
- Java component
  - Fragment of Java code with well-defined interface
  - Example: `HashMap` with interface `Map`

```
public interface Map<K,V> {
  V get(Object key);
  V put(K key, V value);
  V remove(Object key);
  ...
}
```

- Our goal: discovery of concurrency errors in isolated Java components
  - Using Java PathFinder model checker (JPF)

Model checking of isolated Java components

- General issue: problem of missing environment
  - JPF works only for complete Java programs (with `main`)
- Solution: construction of artificial environment
  - Fragment of Java code with `main`
    - Simulates behavior of a specific real environment for C
  - Artificial environment + component = complete program



Example of artificial environment

```
public static void main(String[])
{
  Map map = new HashMap();

  Thread th1 =
    new EnvThread(map).start();
  Thread th2 =
    new EnvThread(map).start();

  // wait for threads to finish
  th1.join();
  th2.join();
}
```

```
class EnvThread extends Thread
{
  public void run()
  {
    while (!done)
    {
      map.put(rndKey(), rndValue());
      Object o = map.get(rndKey());
      map.remove(rndKey());
    }
  }
}
```

Construction of artificial environment

- Code of the artificial environment
  - Written completely by the developer (by hand)
  - Generated from a high-level model
    - Model of environment’s behavior: sequences and parallel executions of methods
    - Values of method parameters

- High-level model
  - Again written by the developer
  - Constructed in an automated way

Criteria for definition of environment's model

- Coverage of component's code
  - Artificial environment should trigger most errors in code
- Performance and scalability of checking
  - Model checker should find at least some errors
    - Before running out of memory because of state explosion

- Goal of application of a model checker
  - Verify that the component is free of errors
    - High coverage, low performance and scalability
  - Discover at least some errors in code
    - Low coverage, better performance and scalability

Model of environment's behavior

- Typical options
  - Universal environment

    `get* | .. | get* | put* | .. | remove* | ..`
  - Context-specific environment
  - Environment optimized for discovery of specific errors in code

Environment for discovery of concurrency errors

- Options
  - Randomly ordered sequence of method pairs

    `(put | put) ; (get | remove) ; (get | put) ; ...`
  - List of method pairs selected via error patterns

    `(remove | put) ; (remove | remove) ; (remove | get) ; ...`

Assumption: access to an important variable is not synchronized in the `remove` method

- Key idea
  - Selection of method pairs to be executed in parallel
  - Rationale
    - Most concurrency errors can be triggered by two threads

Our approach

- Goal
  - Efficient discovery of concurrency errors in Java code of isolated components
  - Addressing drawbacks of existing techniques
    - Including our earlier work (error patterns)
- Model of environment's behavior
  - Automatically constructed on the basis of static analysis and a software metric
- Values of method parameters
  - Defined manually by the user

Key ideas

- Concurrency error can be triggered only if
  - Methods are executed in parallel (in different threads)
  - Methods interact via concurrency constructs of Java
    - Accesses to shared variables (fields, objects, …)
    - Synchronization (locks, calls of `wait` and `notify`)

- High degree of interaction between methods implies higher chance of an error
  - Assessment of the interaction ➔ **interaction metric**

Interaction between Java methods – example

```
public V put(K key, V value)
{
  int h = hash(key);
  V old = data[h];
  data[h] = value;
  size++;
  return old;
}
```

```
public V remove(Object key)
{
  int h = hash(key);
  V value = data[h];
  data[h] = null;
  size--;
  return value;
}
```

```
public V put(K key, V value)
{
  int h = hash(key);
  V old = data[h];
  data[h] = value;
  size++;
  return old;
}
```

```
public V get(Object key)
{
  int h = hash(key);
  V value = data[h];
  return value;
}
```

Our approach – algorithm

- Input
  - List of all possible sets of component's methods
  - Example: `{put, get}, {put, put}, {put, remove}, ...`

- Two steps are performed for each method set
  1) Static analysis of methods' code
     - Identifies accesses to shared variables in methods in each set
  2) Application of interaction metric
     - Computes the degree of mutual interaction among methods on the basis of numbers of accesses to shared variables

- Output
  - Sequence of method sets that is ordered according to the metric
  - Example: `{put, remove}, ..., {put, get}, ...`

Whole picture – verification process

Isolated component
(Java code)

Static
analysis

Information on
concurrent
method interaction

Interaction
metric
computation

Interaction
metric

JPF

Reasonable
artificial
environment
(Java code)

Environment
generator

Reasonable
behavior model
of artificial
environment

Artificial
environment
construction

Verification results

Specification of
method parameter values
(Java class)

Experiments

- Interaction metric is configurable
  - Different configurations may work better in different cases
- Non-trivial components
  - `ConcurrentHashMap` from `java.util.concurrent`
  - Daisy file system
    - Used as an assignment for challenge problem at CAV/ISSTA 2004

	Daisy file system		ConcurrentHashMap	
	Time	Memory	Time	Memory
Metric cfg 1 (EEN)	1 s	52 MB	411 s	369 MB
Metric cfg 2 (UUS)	9782 s	1023 MB	64 s	229 MB
Random pairs	1715 s	310 MB	65 s	169 MB

Evaluation

- Results of experiments show that our approach
  - Significantly reduces time and memory needed for discovery of errors in some components
  - Does not help for some other components

- Different configurations of the interaction metric yield very different results
  - Results depend on the metric's configuration

Future work

- Use of more precise static analysis of Java code
  - Goal: more precise assessment of the degree of interaction among Java methods
    - Values of variables (data-flow) should be taken into account
  - Options: points-to analysis, shape analysis
- Design of several metrics and their comparison
  - Several different metric functions
- Extensive evaluation on many components
  - Problem: how to get complex Java components with concurrency errors
    - We plan to use fault injection (seeding) techniques