Mutation Operators for Concurrent Java (J2SE 5.0)

(MUTATION 2006)

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Motivation and Background

- In the next few years applications will need to be concurrent to fully exploit CPU throughput gains [Sut05]
- It is difficult to develop correct concurrent code
  - *"...humans are quickly overwhelmed by concurrency and find it much more difficult to reason about concurrent than sequential code. Even careful people miss possible interleavings..."*

    - Herb Sutter & James Larus [SL05]
- Goal: use mutation to evaluate, compare and improve quality assurance techniques for concurrent Java.

[Sut05] H. Sutter. The free lunch is over: A fundamental turn toward concurrency in software. *Dr. Dobb's Journal*, 30(3), Mar. 2005.
[SL05] H. Sutter and J. Larus. Software and the concurrency revolution. Queue, 3(7):54–62, 2005.

Related Work

- Mutation with Java has been proposed in previous work
  - MuJava [MOK05]
- Method level mutation operators [MKO05]
  - statements (e.g., statement deletion)
  - operands and operators in expressions (e.g., operator insertion)
- Class level mutation operators [MKO02]
  - inheritance (e.g., super keyword deletion)
  - polymorphism (e.g., cast type change)
  - Java-specific features
- method and class level mutation operators do not directly mutate the source code in Java that handle concurrency.

[MOK05] Y.-S. Ma, J. Offutt, and Y.-R. Kwon. MuJava : An automated class mutation system. *J. of Software Testing, Verification and Reliability*, 15(2):97–133, Jun. 2005.
[MKO02] Y.-S. Ma, Y.-R. Kwon, and J. Offutt. Inter-class mutation operators for Java. In Proc. of *ISSRE 2002*, pages 352–363. Nov. 2002.

Our Approach

- Need a more comprehensive set of operators
- Additional operators are needed to reflect the types of bugs that often occur in concurrent programs.
- We present a set of concurrent operators for Java (J2SE 5.0)
- We believe our new set of concurrency mutation operators used in conjunction with existing operators is more comprehensive

Java Concurrency (Prior to J2SE 5.0)

- Java concurrency is built around the notion of **multi-threaded** programs
  - sleep(), yield(), join() can affect the status of a thread
- Concurrency supported primarily through **synchronized** methods and blocks
- Synchronization blocks can be used in combination with **implicit monitor locks**
  - Monitor methods: wait(), notify(), notifyAll()

Java Concurrency (J2SE 5.0)

- **Lock**
  - Same semantics as the implicit monitor locks
- **Semaphore**
  - Maintains a set of permits that restrict the number of threads accessing a resource
- **Latch**
  - Allows threads from a set to wait until other threads complete a set of operations
- **Barrier**
  - A point at which threads from a set wait until all other threads reach the point
- **Exchanger**
  - Allows for the exchange of objects between two threads at a given synchronization point

Java Concurrency (J2SE 5.0)

- **Built-in Concurrent Data Structures**
  - collection types including ConcurrentHashMap and five different BlockingQueues.
- **Built-in Thread Pools**
  - FixedThreadPool and an unbounded CachedThreadPool.
- **Atomic Variables**
  - can be used in place of synchronization
  - Each atomic variable type contains new methods to support concurrency.
    - e.g., AtomicInteger contains addAndGet(), getAndSet(), etc.

Bug Pattern Taxonomy for Java Concurrency [FNU03]

- Patterns based on common mistakes programmers make when developing concurrent code
- Used to classify bugs in an existing concurrency benchmark maintained by IBM Haifa
  - 40 programs (57 to 17000 loc)
  - student created programs, tool developer programs, open source programs, and a commercial product
- Developed prior to J2SE 5.0
  - We added additional patterns that occur in new concurrency constructs

[FNU03] E. Farchi, Y. Nir, and S. Ur. Concurrent bug patterns and how to test them. In *Proc. of IPDPS 2003*.

Bug Pattern Taxonomy for Java Concurrency

- Nonatomic operations assumed to be atomic
- Two-state access
- Wrong lock or no lock
- Double-checked lock
- The sleep() bug
- Losing a notify
- Other missing or nonexistent signals
- Notify instead of notify all
- A “blocking” critical section
- The orphaned thread
- Interference
- Deadlock (deadly embrace)
- Starvation
- Resource exhaustion
- Incorrect count initialization

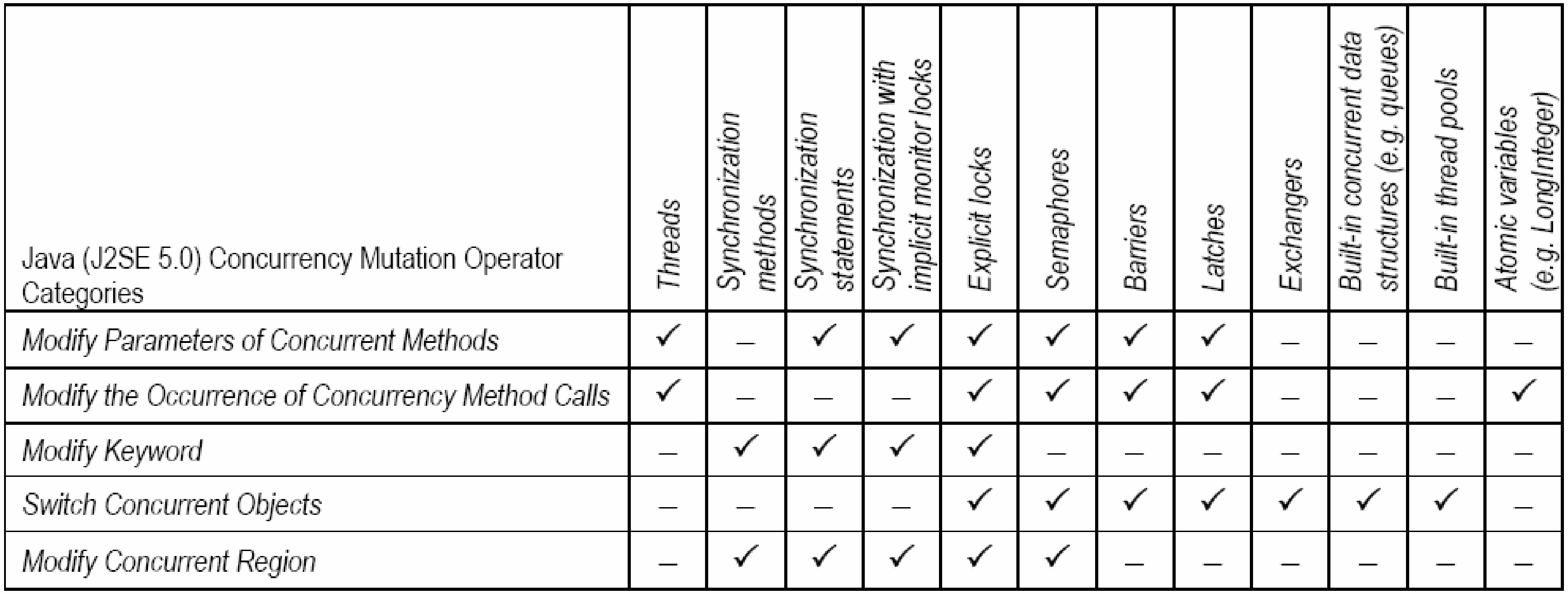
Bug Pattern Taxonomy for Java Concurrency

- Nonatomic operations assumed to be atomic
- Wrong lock or no lock
- Notify instead of notify all
- A “blocking” critical section
- Deadlock (deadly embrace)

Mutation Operators for Concurrent Java

- Five categories of mutation operators for concurrent Java:
    1. modify parameters of concurrent methods
    2. modify the occurrence of concurrency method calls (removing, replacing, exchanging)
    3. Modify concurrency keywords (addition and removal)
    4. switch concurrent objects
    5. modify critical regions (shift, expand, shrink, split)

Mutation Operators for Concurrent Java



Java (J2SE 5.0) Concurrency Mutation Operator Categories	*Threads*	*Synchronization methods*	*Synchronization statements*	*Synchronization with implicit monitor locks*	*Explicit locks*	*Semaphores*	*Barriers*	*Latches*	*Exchangers*	*Built-in concurrent data structures (e.g. queues)*	*Built-in thread pools*	*Atomic variables (e.g. LongInteger)*
Modify Parameters of Concurrent Methods	✓	–	✓	✓	✓	✓	✓	✓	–	–	–	–
Modify the Occurrence of Concurrency Method Calls	✓	–	–	–	✓	✓	✓	✓	–	–	–	✓
Modify Keyword	–	✓	✓	✓	✓	–	–	–	–	–	–	–
Switch Concurrent Objects	–	–	–	–	✓	✓	✓	✓	✓	✓	✓	–
Modify Concurrent Region	–	✓	✓	✓	✓	✓	–	–	–	–	–	–

The relationship between mutation operators for concurrency and the concurrency features provided by J2SE 5.0

Example Mutation: Modify Method Parameter

MSP – Modify Synchronized Block Parameter

```
//two lock objects created
private Object lock1 = new Object();
private Object lock2 = new Object();
....
//lock1 used in methodA
public void methodA() {
   synchronized (lock1) { ... }
}
...
```

Example Mutation: Modify Method Parameter

MSP – Modify Synchronized Block Parameter

```
//two lock objects created
private Object lock1 = new Object();
private Object lock2 = new Object();
....
//lock1 used in methodA
public void methodA() {
    synchronized (lock1) { ... }
}
...
```

```
//two lock objects created
private Object lock1 = new Object();
private Object lock2 = new Object();
....
//replace lock1 with lock2
public void methodA() {
    synchronized (lock2) { ... }
}
...
```

Example Mutation: Modify Method Call

RNA – Replace NotifyAll with Notify

```
//notifyAll is used to wake up all waiting
//threads

...notifyAll();...
```

Example Mutation: Modify Method Call

RNA – Replace NotifyAll with Notify

```
//notifyAll is used to wake up all waiting
//threads

...notifyAll();...
```

```
//notify will wake up only one waiting
//threads

...notify();...
```

Example Mutation: Modify Keyword

RFU – Remove Finally around Unlock

```
. . .
private Lock lock1
    = new ReentrantLock ( ) ;
. . .
lock1.lock( ) ;
try {
                //critical region
                . . .
} finally {
                lock1.unlock ( ) ;
}
. . .
```

Example Mutation: Modify Keyword

RFU – Remove Finally around Unlock

```
. . .
private Lock lock1
    = new ReentrantLock ( ) ;
. . .
lock1.lock( ) ;
try {
                //critical region
                . . .
} finally {
                lock1.unlock ( ) ;
}
. . .
```

```
. . .
private Lock lock1
    = new ReentrantLock ( ) ;
. . .
lock1.lock( ) ;
try {
                //critical region
                . . .
} //finally removed
lock1.unlock ( ) ;
. . .
```

Example Mutation: Switch Concurrent Objects

EELO – Exchange Explicit Lock Objects

```
private Lock lock1
  = new ReentrantLock();
private Lock lock2
  = new ReentrantLock();
...
lock1.lock();
...
lock2.lock();
...
finally {
   lock2.unlock();
}
...
finally {
   lock1.unlock();
}
...
```

Example Mutation: Switch Concurrent Objects

EELO – Exchange Explicit Lock Objects

```
private Lock lock1
  = new ReentrantLock();
private Lock lock2
  = new ReentrantLock();
...
lock1.lock();
...
lock2.lock();
...
finally {
   lock2.unlock();
}
...
finally {
   lock1.unlock();
}
...
```

```
private Lock lock1
  = new ReentrantLock();
private Lock lock2
  = new ReentrantLock();
...
lock2.lock(); //should be lock1
...
lock1.lock(); //should be lock2
...
finally {
   lock2.unlock();
}
...
finally {
   lock1.unlock();
}
...
```

Example Mutation: Modify Critical Region

SKCR – Shrink Critical Region

```
private Lock lock1
    = new ReentrantLock();
...
public void m1 () {
   <statement n1>
   lock1.lock();
   try {
       //critical region
       <statement c1>
       <statement c2>
       <statement c3>
   } finally {
       lock1.unlock();
   }
<statement n2>
...
```

Example Mutation: Modify Critical Region

SKCR – Shrink Critical Region

```
private Lock lock1
    = new ReentrantLock();
...
public void m1 () {
   <statement n1>
   lock1.lock();
   try {
       //critical region
       <statement c1>
       <statement c2>
       <statement c3>
   } finally {
       lock1.unlock();
   }
<statement n2>
...
```

```
private Lock lock1
    = new ReentrantLock();
...
public void m1 () {
   <statement n1>
   //critical region
   <statement c1>
   lock1.lock();
   try {
       <statement c2>
   } finally {
       lock1.unlock();
   }
   <statement c3>
   <statement n2>
...
```

Mutation Operators vs. Bug Patterns

Concurrency Bug Pattern	Mutation Operators
Nonatomic operations assumed to be atomic bug pattern	RVK, EAN
Two-stage access bug pattern	SPCR
Wrong lock or no lock bug pattern	MSP, ESP, EELO, SHCR, SKCR, EXCR, RSB, RSK, ASTK, RSTK, RCXC, RXO
Double-checked locking bug pattern	–
The sleep() bug pattern	MXT, RJS, RTXC
Losing a notify bug pattern	RTXC, RCXC
Notify instead of notify all bug pattern	RNA
Other missing or nonexistent signals bug pattern	MXC, MBR, RCXC
A "blocking" critical section bug pattern	RFU, RCXC
The orphaned thread bug pattern	–
The interference bug pattern	MXT, RTXC, RCXC
The deadlock (deadly embrace) bug pattern	ESP, EXCR, EELO, RXO
Starvation bug pattern	MSF, ELPA
Resource exhaustion bug pattern	MXC
Incorrect count initialization bug pattern	MXC

Conclusions and Future Work

- Presented a set of 24 concurrency mutation operators
  - Can be used as both a comparative metric and coverage criteria
- Our operators are comprehensive and representative of bugs in an existing bug pattern taxonomy
- Concurrency operators are a complement not a replacement for existing operators
  - e.g., the concurrency operators can cause direct concurrency bugs while method and class operators can cause indirect concurrency bugs
- Currently we have implemented almost all of the operators.
- We are currently conducting empirical evaluations.

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