Testing Concurrent Software

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The Bottom Line
Some good news, some bad news

Testing concurrent software is difficult, but not impossible.

By a combination of multiple techniques (careful design, static analysis, code review, extensive testing), you can get the upper hand on concurrency bugs.
What This Talk Is, and Isn't

- Building correct concurrent software is a big topic
  - We can't teach you to do that in an hour (or a week)
- We'll discuss ways for effectively creating tests as part of a QA plan for concurrent software
- We assume you already have idea of what to do and what not to do
  - See also
    - Java Concurrency in Practice, Goetz et al.
    - Concurrent Programming in Java, Lea
    - TS-2388: Effective Concurrency for the Java Platform (Friday, 10:50am)
Agenda

Introduction
Creating a Test Plan
Unit Testing
Concurrent Failure Modes
Performance Testing
System Testing
Summary
Testing Concurrent Software
Like testing sequential code...

• Test cases for sequential code...
  • ...may test safety or performance (or both)
  • ...exercise code and assert invariants and postconditions
  • ...try to explore as much of the state space as possible
    • One rough measure of this is code coverage
  • ...try to find combinations of inputs and actions that are most likely to cause failure

• Test cases for concurrent code do the same
  • So we already know how to do it, right?
Testing Concurrent Software

Like testing sequential code... but different

• Concurrent programs have more failure modes than sequential ones
  • Liveness failures: deadlock, livelock, missed signals
  • Safety failures: synchronization errors, atomicity failures

• Failures in sequential programs are largely deterministic
  • Same input, same failure

• Many failures unique to concurrent programs are rare probabilistic events
  • Some bugs require exquisitely unlucky timing
Testing Concurrent Software
More extensive testing required

- State space is much larger due to thread interactions
- Need more intensive tests
  - Run for longer periods
  - Look for rare probabilistic failures
  - Account for impact of GC, JITing, etc
- Must test on multiple platforms
  - Different CPU architectures, JVMs, number of CPUs
  - Some tests don't happen on some architectures
- Tests must be written to avoid masking bugs
Design For Testability

Concurrent programming is hard enough

• Where possible, separate concurrency logic from business and functional logic
  • Concurrency is challenging enough
  • Even harder when mixed in with your business logic!

• Isolate concurrency by extracting concurrent abstractions
  • Such as bounded buffers, semaphores, thread pools
  • Use the ones from java.util.concurrent where possible
    • Implement your own only if the provided ones don't fit

• Testing a single concurrent abstraction is a lot easier than testing an entire application
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Building a QA Plan

Testing is only part of it

- The goal of QA is not to “find all the bugs”
  - Because this is impossible

- Goal of QA is really to *increase confidence*

- QA approaches include
  - Education, training, careful design
    - Understanding the concurrent design/implementation of what you have
  - Manual code review
  - Static analysis (automated code review)
  - Testing
    - Unit tests, load tests, performance tests, system tests
Building a QA Plan

Testing is only part of it

- Testing can never show the absence of errors, only their presence
  - Even more true with rare probabilistic failures
- Testing, code review, and reviewing analysis reports are all subject to *diminishing returns*
  - Luckily, also tend to find different types of problems
- By combining them, you buy more confidence for your QA budget than testing alone
Manual Code Review

Expensive, but effective

- Expert review is often the best way to find subtle concurrency bugs
  - Can spot bugs that occur extremely rarely in practice
  - Can find bugs that won't happen on specific hardware
  - Often improves general code and comment quality

- Doesn't scale well
  - Useful for small, isolated concurrent components
  - Really, really hard, even for experts, to manually review large or subtle components

- Expensive to do frequently
  - Typically done by senior developers or consultants
Static Analysis
Automated code review

- Analyzes a program without running it
- Can check rules/patterns
  - Such as “Hold a lock consistently when accessing a field”
- Annotations that document concurrency design are very helpful
  - For both humans and automatic tools
  - See *Java Concurrency in Practice*, FindBugs, and Fluid from SureLogic
- See TS-2007: Improving Software Quality with Static Analysis
Concurrent Testing Scenarios

Lots of reasons to test...

- **Unit testing functionality**
  - Basic tests of safety and liveness (can be sequential)
- **Unit testing functionality under concurrent stress**
  - Looking for rare, timing-related interactions
  - Attempting to explore more of the state space
- **Component performance testing**
  - Evaluate performance or scalability of a concurrent abstraction under varying load
- **System stress testing**
  - Test a large application to see if it works
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Unit Testing

Don't forget the basics

• Start with basic unit tests
  • Some tests can be sequential – goal is to establish that documented sequential functionality works at all
    • Easier to debug basic functionality in sequential environment
  • But many concurrent classes have behavior that cannot be tested with just one thread
    • Testing blocking behavior requires at least two threads
      • One thread that performs an operation that blocks
      • Another thread that then performs an action that unblocks the first thread

Don't forget the basics
Unit Testing
Some behaviors require multiple threads to test

- Exchanger
  - Inherently requires two threads to exchange
- CyclicBarrier
  - Inherently requires N threads to reach a barrier point
- Lock
  - If one thread holds it, does it actually block other threads?
  - When holding thread releases it, can another acquire it?
- BlockingQueue
  - Threads block if they try to add too many elements
  - Blocked threads unblock when room is made
  - Threads block if they try to remove nonexistent elements
Unit Testing
Framework support

- JUnit 4 and TestNG support timeouts
- TestNG supports concurrent testing
  - To allow tests to finish faster
  - For stress testing
- Addons to JUnit 4 also support concurrent testing
- But neither provides good support for single test cases that require coordination of multiple threads
Unit Testing
More framework support needed

```java
void testPutThenTake() throws InterruptedException {
    BoundedBlockingQueue<Integer> buf = new BoundedBlockingQueue<Integer>(1);
    buf.put(42);
    assertEquals(42, buf.take());
}

void testPutPutTakeTake() throws InterruptedException {
    BoundedBlockingQueue<Integer> buf = new BoundedBlockingQueue<Integer>(1);
    buf.put(42);
    buf.put(17);
    assertEquals(42, buf.take());
    assertEquals(17, buf.take());
}
```

This blocks and can't get unstuck
Unit Testing
More framework support needed

```java
void testPutPutTakeTake() throws InterruptedException {
    final BoundedBlockingQueue<Integer> buf
        = new BoundedBlockingQueue<Integer>(1);
    Thread t = new Thread() {
        public void run() {
            assertEquals(42, buf.take());
            assertEquals(17, buf.take());
        }
    };
    t.start();
    buf.put(42);
    buf.put(17);
    t.join();
}
```

Assertion failure won't be noticed by JUnit

Won't compile; `take()` throws `InterruptedException`
Unit Testing
More framework support needed

- Exception in second thread isn't seen by JUnit
  - Propagates up call stack of thread
    - Printed to console
  - Test always passes
    - JUnit unaware of exception

- Must ensure that exception in any thread is propagated back to the testing framework
  - Requires lots of messy boilerplate code
  - Runnables can't throw checked exceptions

- We need something better
Unit Testing

Necessity is the mother of invention

- At UMD, we teach writing concurrent abstractions
  - Blocking queue, etc.
- We have a fairly elaborate automated system for testing functional correctness of student work
  - The Marmoset project
- Need to have reliable, repeatable tests for concurrent functionality
  - And allow students to write such tests
- Developed new framework for concurrent tests
  - Which you can download and use

Necessity is the mother of invention
MultithreadedTestCase (aka MTC)

Adding support for multiple test threads

- Same test, rewritten with MTC
  - Framework infers test lifecycle from method names

```java
class TestPutPutTakeTake extends MTC {
    BoundedBlockingQueue<Integer> buf;

    void initialize() {
        buf = new BoundedBlockingQueue<Integer>(1);
    }

    void threadPutPut() throws InterruptedException {
        buf.put(42);
        buf.put(17);
    }

    void threadTakeTake() throws InterruptedException {
        assertEquals(42, buf.take());
        assertEquals(17, buf.take());
    }
}
```
Multithreaded Test Case
Adding support for multiple test threads

• Uses same ideas as JUnit
  • Run initialize() method (if it exists)
  • Run all threadXxx() methods concurrently
  • Run finish() method (if it exists)

• yeah, doing it with annotations would be cooler
  • But just needed something that worked

• Does this test case test what we wanted?
  • No, didn't check blocking behavior

• Can use sleep and System.currentTimeMillis
  • imprecise, doesn't work with debuggers, ugly
class MyTest extends MultithreadedTestCase {
    OnePlaceBuffer<Integer> buf;
    public void initialize() {
        buf = new OnePlaceBuffer<Integer>();
    }
    public void thread1() {
        buf.put(42);
    }
    public void thread2() {
        Thread.sleep(1000);
        buf.put(17);
    }
    public void thread3() {
        Thread.sleep(2000);
        assertEquals(42, buf.get());
    }
    public void thread4() {
        Thread.sleep(3000);
        assertEquals(17, buf.get());
    }
}
Unit Testing Blocking Operations

Thread 1

Tick 0
- put 42

Tick 1
- put 17 (blocks)

Thread 2

- wait for tick 1
- take 42

This call to put should not return until after the call to take has started.
Unit Testing

Adding support for blocking operations

• System maintains a global *tick counter*
  • Starts at zero
  • Advanced only when all threads are waiting/blocked
  • Tests can wait until counter gets to a particular value
  • Tests can check the current value

• Plays well with debuggers
  • unlike using Thread.sleep()
Unit Testing
Using the tick counter to test blocking operations

- With tick counter support, we can now test blocking operations

```java
void threadPutPut() throws InterruptedException {
    buf.put(42);
    assertEquals(0, getTick());
    buf.put(17);
    assertEquals(1, getTick());
}
```

```java
void threadGetGet() throws InterruptedException {
    waitForTick(1);
    assertEquals(42, buf.take());
    assertEquals(17, buf.take());
}
```
Example: Unit Testing a Lock
Using the tick counter to test blocking operations

```java
void threadFirstLocker() {
    lock.lock();
    assertEqual(0, getTick());
    waitForTick(2);
    lock.unlock();
}

void threadSecondLocker() {
    waitForTick(1);
    assertFalse(lock.tryLock());
    assertEqual(1, getTick());
    lock.lock();
    assertEqual(2, getTick());
    lock.unlock();
}
```
MTC – History and Future

Try it – and contribute!

- We've been using this
  - In courses at Univ. of Maryland
  - To rewrite all of the TCK tests for JSR-166
    - Results are a lot simpler than the original 166 TCK tests!

- Once you've constructed a test case
  - Can run it once (for tests designed to be deterministic)
  - Can run it many times (for nondeterministic tests)

- Our implementation available from:
  - http://findbugs.cs.umd.edu/

- Hopefully, someone else will improve on it
Runtime tools

• You can use various tools to perform dynamic instrumentation and testing for concurrency:
  • data race detection
  • introduce additional thread interleaving
Preventing Data Races

- One programming technique to prevent races:
  - Ensure that for every shared field $x$, there is some lock $L$ such that no thread accesses $x$ without holding lock $L$

- Note: This is not the *only* way to avoid races
  - There are fancier, more complicated techniques
Detecting Races with checkSync

Algorithm

- Locks_held(t) = set of locks held by thread t
- For each shared field x, C(x) := { all locks }
- On each access to x by thread t,
  - C(x) := C(x) ∩ locks_held(t)
  - If C(x) = ∅ then issue a warning

- From Savage et al, “Eraser: A Dynamic Race Detector for Multithreaded Programs,” TOCS 1997
An Improvement

- Unsynchronized *reads* of a shared location are OK
  - As long as no one *writes* to the field after it becomes shared
- Track state of each field
  - Only enforce locking protocol when it becomes shared and written
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Concurrent Failure Modes
Things that can't go wrong in sequential programs

- Most features of the Java language are designed for repeatability across runs and platforms
  - e.g., floating point behavior
- ...except for *threads*
  - Even correct programs can vary their behavior
  - Some errors only manifested through very particular interleavings or timings
- Many failures in concurrent programs are rare, probabilistic events

* (and identity hash code)
Concurrent Failure Modes

Synchronization errors

- If a variable (field or array element):
  - Is accessed by two or more threads, and
  - At least one of those accesses is a write, and
  - The variable is not a `volatile` field

- Then the accesses must be ordered by synchronization
  - `synchronized`, `java.util.concurrent.locks.Lock`

- Otherwise, your code is bad
  - Code with synchronization errors has *exceptionally subtle semantics*
Concurrent Failure Modes

Atomicity failures

- Even without synchronization errors, can still have nasty, timing-dependent concurrency bugs
  - Occur when threads interact in an unexpected way
- These are usually *atomicity failures*
  - A sequence of actions thought of as an atomic unit, but not adequately protected from interference
- Volatiles cannot prevent atomicity failures!
  - Requires using locking or atomic variables
Concurrent Failure Modes

Atomicity failures

- Typical causes of atomicity failures
  - Check-then-act
    
    ```java
    if (foo != null)  // Another thread could set
        foo.doSomething(); // foo to null
    ```

    ```java
    Value v = map.get(k); // Even if Map is thread-safe,
    if (v == null) { // two threads might call get,
        v = new Value(k); // both see null, and both
        map.put(k, v); // add a new Value to map
    }
    ```

  - Read-modify-write
    ```java
    ++numRequests; // Really three separate actions
    // (even if volatile)
    ```
Concurrent Failure Modes

Rare interleavings

- Some interleavings are rare if interpreted
  - Compiler can aggressive reorder operations
    - Invisible to correctly synchronized code
- Some interleavings are rare on a 1-CPU system
  - OS context switches only happen at designated points
- More CPU's generate more interleavings; Want more threads than CPUs
  - About twice as many active threads as cores is generally good
Concurrent Failure Modes

Generating more interleavings

- Use a multicore or multiprocessor system
- Avoid synchronization in test harness or debugging code
  - e.g. `System.out.println()`
  - May cause bugs to disappear
- Or force “bad” interleavings
  - e.g. barrier sync before suspicious code
  - Sprinkling `Thread.yield()` or `Thread.sleep()`
  - Perhaps with a bytecode rewriting tool
Testing Components

Testing for races

- Generate as many interleavings as possible
- Main challenge: find testable properties that
  - Fail with high probability if something goes wrong
  - Don't artificially limit the concurrency of the test
  - Introduce no additional synchronization
- Errors may be masked by the test program
  - Test program messes with timings
  - Test program synchronization may mask data races
  - Delays in test program may mask race conditions
Testing Components

Testing for races

• Obvious test for bounded buffer: everything that goes in comes out (and no extras)
  • Without getting in the way...

• Checksum elements as they go in or out
  • Keep per-thread checksums, combine them at end
    • So no synchronization during test run!
  • Need an order-insensitive checksum (e.g., sum, xor)
  • Use deterministic termination criteria

• Don't share RNGs between threads
• Prevent compiler from “pruning” code you are testing
Testing Components
Testing under concurrent stress

```java
void testPutsAndTakes() {
    for (int i = 0; i < nPairs; i++) {
        pool.execute(new Producer);
        pool.execute(new Consumer);
    }
    barrier.await(); // wait for all threads to be ready
    barrier.await(); // wait for all threads to finish
    assertEquals(putSum.get(), takeSum.get);
}

class Consumer implements Runnable {
    public void run() {
        try {
            barrier.await();
            int sum = 0;
            for (int i = nTrials; i > 0; --i)
                sum += bb.take();
            takeSum.getAndAdd(sum);
            barrier.await();
        } catch (Exception e) {
            throw new RuntimeException(e);
        }
    }
}
```
Experience at Azul

The world is full of undiagnosed synchronization errors

- When customer's code fails
  - Azul's JVM has a switch enables a version of java.util that checks at runtime for concurrent access to non-thread-safe collections
    - And throws an exception when it finds it
    - On both threads

- Slight performance hit, but decent at finding bugs

- We've implemented our own that you can use
  - Added to JSR166 contributions
Lock Implementations for Debugging

Tools for building test cases

• UncontendableLock
  • Implements Lock, but throws an exception if contention is actually seen
  • Use when your design says you don't need a lock – but want to verify that at runtime
    • Use runtime flag choose this or NoOpLock
    • Also a ReadWriteLock version

• SlowReleasingLock
  • Delegates to ReentrantLock
  • But pauses after releasing a lock
    • Will cause atomicity failures to be more common
Lock Implementations for Debugging
Contributed to JSR166

- Look at contributions section of JSR166
  - http://gee.oswego.edu/dl/concurrency-interest/
- These and related locks for debugging
- Should Java 7 support runtime flags to check for bad concurrent access to standard non-thread-safe classes?
  - One extra field
  - Minimal overhead if not enabled
  - About half the cost of regular locks if enabled
Dynamic Tools For Debugging

• We've talked about just a few ideas for trying to identify probabilistic faults
• This is an active research area
  • Keep your eyes out for other tools that can help
• For example, IBM's ConTest
  • Systematically and transparently schedules execution to increase the likelihood that race conditions, deadlocks and other intermittent bugs will appear
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Performance Testing

Scalability vs. Performance

• How fast is it?
  • Without contention?
  • With expected contention?

• Does performance fall off a cliff under higher than expected contention?

• Performance tests must reflect realistic use cases
  • Selecting these is often the hardest part
  • Usually extensions of safety tests

• Secondary goal: empirically select parameters
  • Buffer sizes, queue sizes, pool sizes
Performance Testing

Parallel bottlenecks

- Need to watch out for contention points
  - Bottlenecks that don't scale with your application
- One bottleneck can prevent the entire application from scaling
- If it isn't a bottleneck, keep it simple
  - A simple, blocking, thread-safe class is going to be easier to get right than one designed for concurrent access
Some commercial and vendor specific tools
Azul has some nice ones
Tools that visually display CPU usage are helpful
Perfbar for Solaris and gtk
Are you pegging your CPU utilization?
Are you spending too much time in the kernel?
Can use JMX and JVMTI to get some information
ThreadMXBean provides information:
- Cpu time per thread
- # of times blocked
- # of times waited for notification

Performance Testing
Tool support
Performance Testing
Using JMX and jconsole to measure contention

• Can access JMX through jconsole
  
  ```java
  setThreadContentionMonitoringEnabled(true)
  ```

  • Allows you to get total time spent waiting for contended locks
  • Can also set this through jconsole

• Won't tell you which lock is contended
  • But will tell you if you have an issue
Performance Testing

GC bottlenecks

- Never call `System.gc()`
  - Forces a horrible, slow, stop the world collection

- If you use any RMI or EJB, Sun's JVM calls `System.gc()` every 60 seconds
  - Bug # 4403367
  - Totally kills scalability, particularly with large heap

- Workaround for Sun's bug
  - Set `-Dsun.rmi.dgc.server.gcInterval=2000000000`
Performance Testing

Document concurrency requirements

- Document whether a class is supposed to handle concurrent requests
  - Concurrent classes are not just thread-safe – they are designed to perform well under concurrent access

- Document how many concurrent operations it can handle
  - With default parameters, ConcurrentHashMap tops out at about 16 concurrent updates
    - But effectively no limit on concurrent reads

- Test to see if your expectations are being met
Performance Testing

What are we testing for?

- Performance tests often derived from safety tests
  - With some timing added
- Can learn many things from performance tests
  - Throughput under specific parameters
  - Sensitivity to varying parameters
  - Scalability with increasing thread count
- Exercise care applying results of component tests
  - Most tests are unrealistic simulations of the *application*
  - Component tests usually focus on extreme contention
Performance Testing

Common pitfalls

- Watch out for these when writing performance tests!
  - Introducing timing or synchronization artifacts
  - Not accounting for compilation or GC
  - Unrealistic sampling of code paths
  - Unrealistic degrees of contention
  - Dead code elimination
    - Make sure every result is used and unguessable

- Avoiding these often requires “tricking” the compiler – which is hard!
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System Testing

Touchpoints

• Get a machine with as many cores as possible
  • At least as many as will be used in production

• Log every error
  • If an probabilistic error occurs only once every 4 hours, you need to have good logging

• Verify concurrent expectations
  • Use UncontendableLocks where appropriate
  • If a method is only supposed to be invoked in the event thread, check it
System Testing

Using aspects

- You can use Aspect Oriented Programming (AOP) to inject runtime assertions
  - That System.gc isn't called
  - That Swing methods are called from the event thread
- Or to swap in debugging versions of classes
  - Substitute versions of HashMap that check for improper concurrent access
  - Substitute version of Lock that looks for deadlock risks
- See “Testing with Leverage, part III” (Goetz)
  - Contains precooked code, ready to use
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Summary...

- Testing concurrent software is hard!
  - Keep your expectations appropriate
  - Testing is not going to give high confidence you don't have rare probabilistic bugs

- Separate business logic from concurrency logic
  - Easier to get each right
  - Easier to test

- Use precooked code, already picked over by experts, when possible
  - `java.util.concurrent` is pretty darn good
  - But only because they've done everything recommended here, fixing bugs in the process
For More Information

- Other sessions and BOFs
  - TS-2388: Effective Concurrency for the Java Platform (Friday, 10:50am)
  - TS-2007: Improving Software Quality with Static Analysis
  - BOF-2864: Experiences with Debugging Data Races

- Books
  - *Java Concurrency in Practice*, Goetz et. al.
  - *Concurrent Programming in Java*, Doug Lea
Q&A

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