Testing Concurrent Software

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The Bottom Line

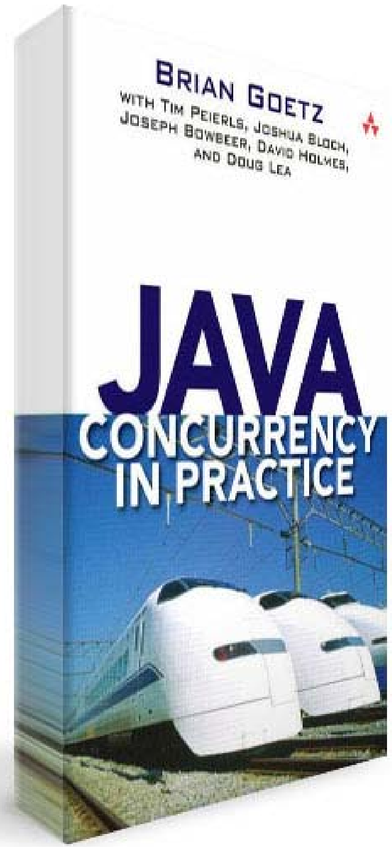
Some good news, some bad news

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 some 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, Virtual Machine for the Java platform (JVM™ machines), number of CPUs
  - Some tests don't happen on some architectures
- Tests must be written to avoid masking bugs

The terms “Java Virtual Machine” and “JVM” mean a Virtual Machine for the Java™ platform.

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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Concurrent Failure Modes

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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

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

```
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

```
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();
}
```

Won't compile; `take()` throws InterruptedException

Assertion failure won't be noticed by JUnit

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

MultithreadedTestCase (a.k.a. MTC)

Adding support for multiple test threads

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

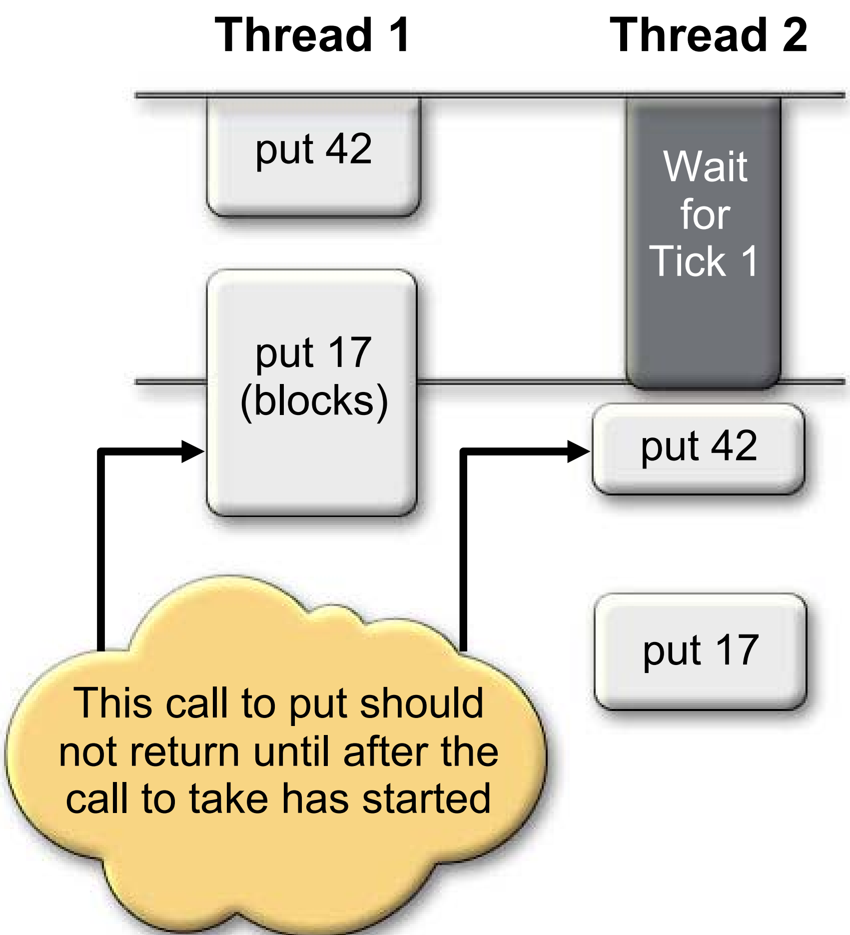
```
class TestPutPutTakeTake extends MTC {
      BoundedBlockingQueue<Integer> buf;

    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

Unit Testing Blocking Operations



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

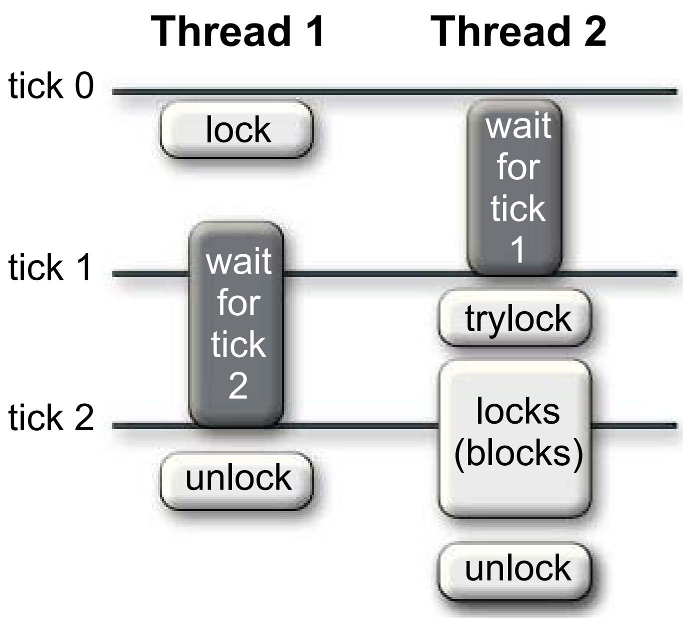
- With tick counter support, we can now test blocking operations

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

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

```
  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 Java Specification Request (JSR) 166
    - Results are a lot simpler than the original JSR 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)
- Open source, pointer to implementation at:
  - http://findbugs.sourceforge.net/
- Hopefully, someone else will improve on it

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Concurrent Failure Modes

Things that can't go wrong in sequential programs

- Most features of the Java programming 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 (“happens-before”)
  - **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*

```
if (foo != null)          // Another thread could set
    foo.doSomething();    // foo to null

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

```
++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" under test*

Testing Components

Testing under concurrent stress

```
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 VM can check 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

Lock Implementations for Debugging

Tools for building test cases

- UncontendedLock
  - 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

Open source

- Pointer to implementation at:
  - http://findbugs.sourceforge.net/
- These and related locks for debugging
- Should Java Platform v.7 assert against concurrent access to 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***

  http://www.haifa.ibm.com/projects/verification/contest/index.html
  - *" Systematically and transparently schedules execution to increase the likelihood that race conditions, deadlocks and other intermittent bugs will appear"*

Agenda

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Summary

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

Performance Testing

Tool support

- 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 Java Management Extensions (JMX™) API and JVM tool interface to get some information
  - ThreadMXBean provides information:
    - Cpu time per thread
    - Number of times blocked
    - Number of times waited for notification

Performance Testing

Using JMX API and jconsole to measure contention

- Can access JMX API through jconsole
- **`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 Java RMI or EJB™ architecture, Sun's JVM machine 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 UncontendedLocks 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)
  - http://www.ibm.com/developerworks/java/library/j-jtp08226.html
  - Contains precooked code, ready-to-use

Agenda

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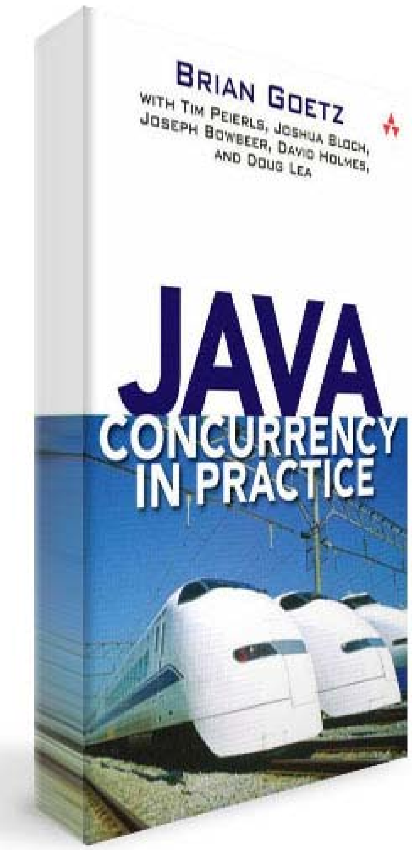
Summary…

- 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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