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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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

```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();
}
```

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

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

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

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

    void threadTakeTakeTake() 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

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());
}

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();
}
```

Diagram:

- Thread 1
  - Tick 0: Lock
  - Tick 1: Wait for tick 1
  - Tick 2: Lock
- Thread 2
  - Tick 0: Wait for tick 1
  - Tick 1: Try lock
  - Tick 2: Locks (blocks)
  - Tick 2: 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*
    
    ```java
    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*
  
  ```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” under test
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 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 **ContTest**
  
  
  “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
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)
  - 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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