CS5010: Lecture 10
More Concurrency

Fall 2022

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Lots of credit: Ian Gorton adapted by Abi Evans

Before we get started...

Pull the latest code from Code_from_Lectures (course Github org)

https://github.ccs.neu.edu/cs5010seaF22/Code_from_Lectures

Then, open Lecture10 project in the Evening_Lectures if you'd like to follow along.

Administrivia

- Homework #4 Code Walks
  - Everyone did a video Codewalk that was due last night
  - Half the class will present their code for hw4 next week
  - 2nd Half will present their code for hw5 after Thanksgiving week.
  - Presenters picked at random.
  - Code walks happen 2nd half of class
  - We'll use teams to present to the class
- Homework #5 out tomorrow
  - Due Monday, November 28th @ 11:59pm
  - Thanksgiving week just before
- No Lab next week.

Agenda

- Thread pools
- Executors
- Loops/recursion and threads
- Readers & Writers problem
- Scalability
- Testing

Recap from last week

- If threads share state → must use locks to achieve thread safety
    - Synchronized methods and objects
    - `java.util.concurrent` thread-safe collections, variables
- If threads need to coordinate actions (e.g. do something only if there is data) →
    - Guarded conditions (wait/notify)
    - Beware of deadlocks

Reflection on Assignment 5

- Threads don't necessarily make programs faster.
- In this case → use threads to reduce the amount of the file that must be stored in memory at any one time, maybe speed up some parts of processing

Thread pools & the Executor framework

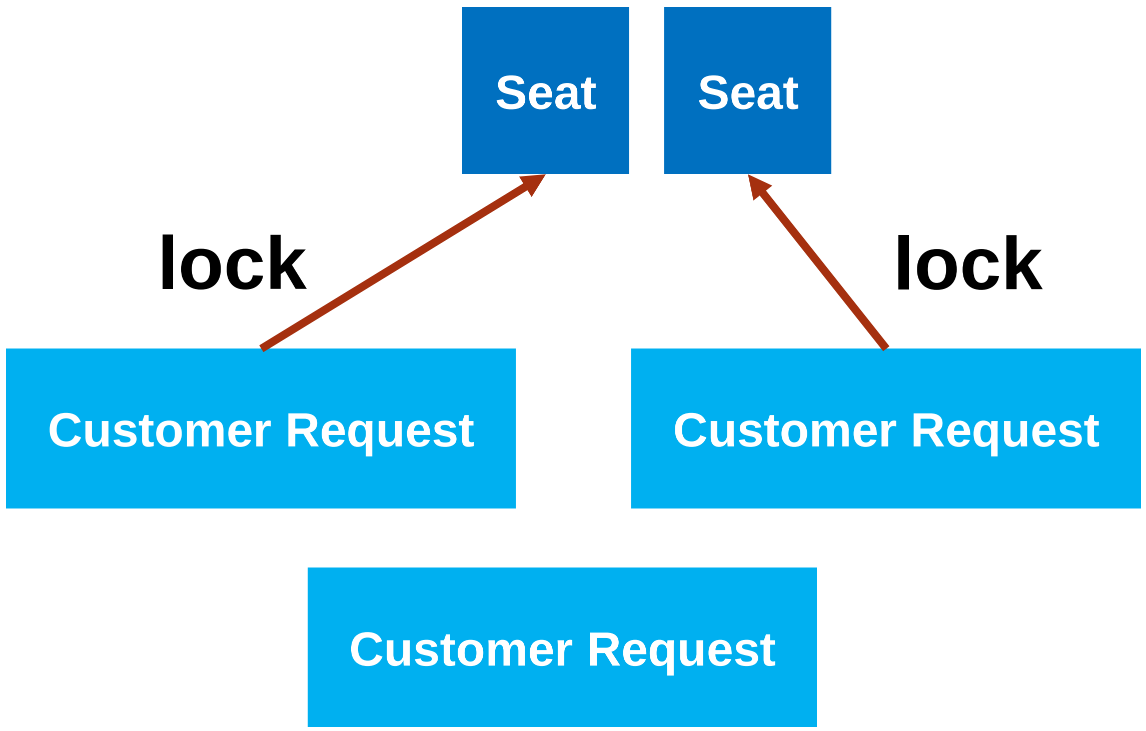
Scenario: ticketing system

- Seat availability stored in a database
- Must handle large volumes of concurrent read requests
  - Customer wants to see available tickets
- Must handle large volumes of concurrent write requests
  - Customer purchases tickets
- Can’t allow same seat to be sold multiple times

Scenario: ticketing system

Possible solution:

- Create a separate thread for each customer request
- Request holds lock on Seat until purchase completed (or customer changes their mind



must wait until lock available (or all seats taken → request denied)

Scenario: ticketing system

First attempt:

- Create a separate thread for each customer request
- Request holds lock on Seat until purchase completed (or customer changes their mind

Drawback?

- Threads use a lot of memory
- More time and resources spent on creating/destroying threads than processing

- > 70,000 seats
- Very high demand
- A lot to manage!

Thread pools

→ a **pool** (i.e. a group) of Threads that can be reused / queued

- Reduces overhead of thread management

In Java → Executor framework

`java.util.concurrent`

Utilities to simplify multithreaded programs:

- Atomic variables ☑
- Thread safe collections ☑
- **Executor framework**
- Lock objects

The Executor Framework

`public interface Executor`

- An object that executes submitted Runnable tasks
- Supports asynchronous task execution
- Decouples task submission from task executions
    - Supports different task execution policies
    - Provides task lifecycle support
    - Has hooks for statistics, management, monitoring
- Factory methods to create an Executor with desired policies

The Executor Framework

`public interface Executor`

- An object that executes submitted Runnable tasks

So far:

```
Thread t1
      = new Thread(new SomeRunnable());
Thread t2
      = new Thread(new SomeRunnable());
Thread t3
      = new Thread(new SomeRunnable());

t1.start();
t2.start();
t3.start();
```

With Executor:

```
Executor executor = anExecutor;

executor.execute(new SomeRunnable());
executor.execute(new SomeRunnable());
executor.execute(new SomeRunnable());
```

The Executor Framework

`public interface Executor`

- An object that executes submitted Runnable tasks

So far:

```
Thread t1
        = new Thread(new SomeRunnable());
Thread t2
        = new Thread(new SomeRunnable());
Thread t3
        = new Thread(new SomeRunnable());

t1.start();
t2.start();
t3.start();
```

With Executor:

```
Executor executor = anExecutor;

executor.execute(new SomeRunnable());
executor.execute(new SomeRunnable());
executor.execute(new SomeRunnable());
```

handles thread creation and start

Using the Executor framework

Step 1: declare an Executor

```
Executor mostSimple;
ExecutorService typical;
ScheduledExecutorService withTimer;
```

Using the Executor framework

Step 1: declare an Executor

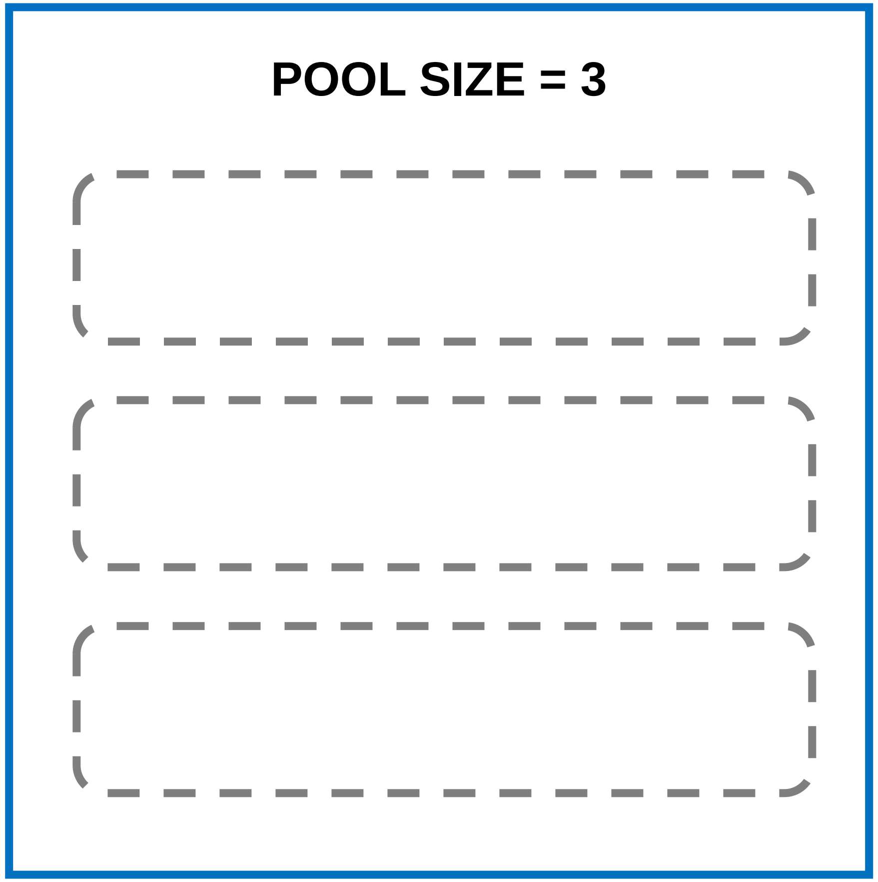
```
Executor mostSimple;
ExecutorService typical;
ScheduledExecutorService withTimer;
```

Step 2: create it with a factory method. Two possibilities among many:

```
ExecutorService e1
                = Executor.newFixedThreadPool(SIZE);
ExecutorService e2
                = Executor.newSingleThreadExecutor();
```

How thread pools work

When there are more threads to execute than the pool can hold, the extras are queued



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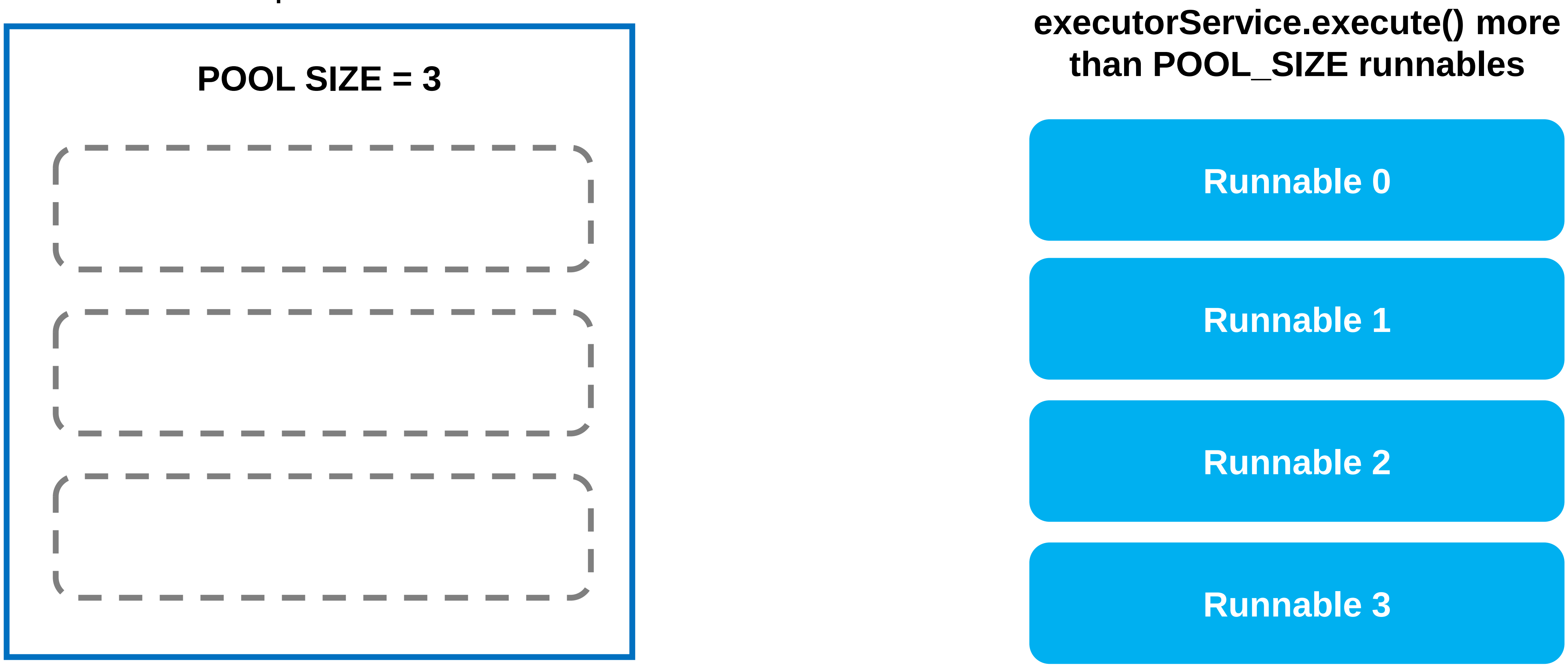

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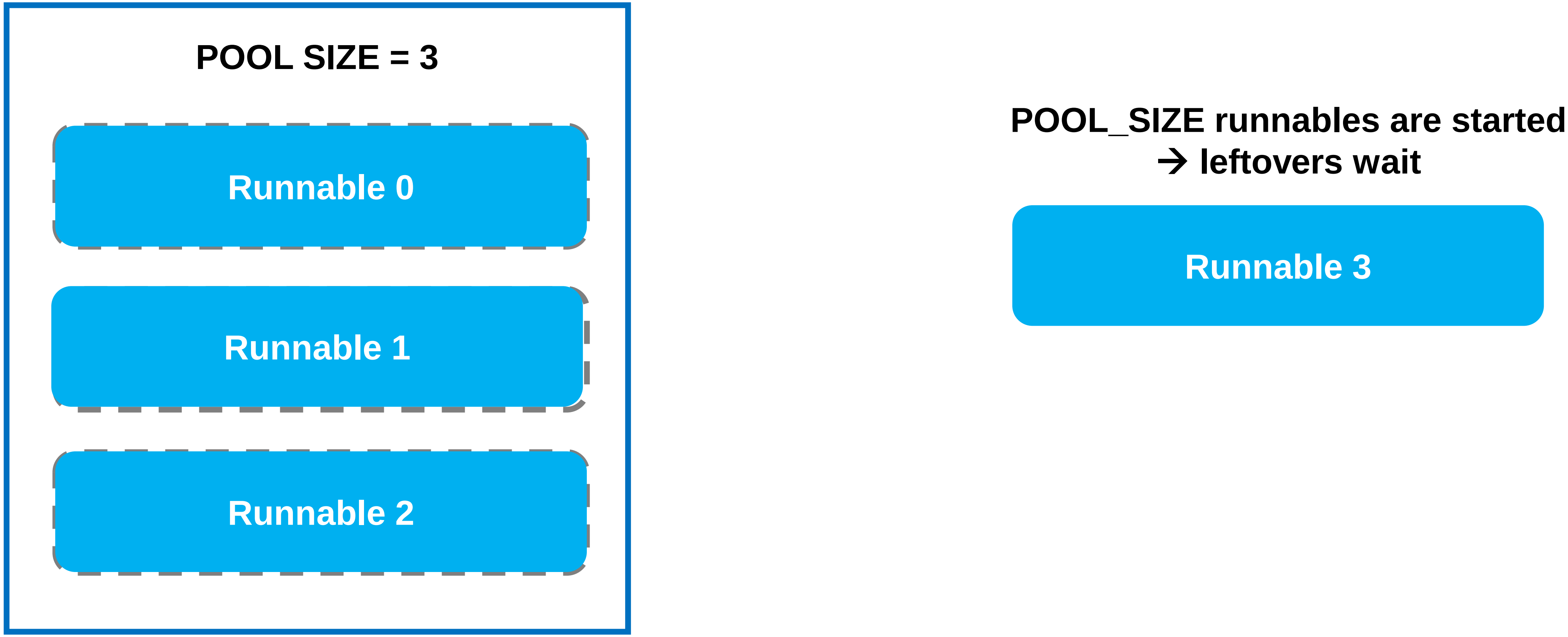
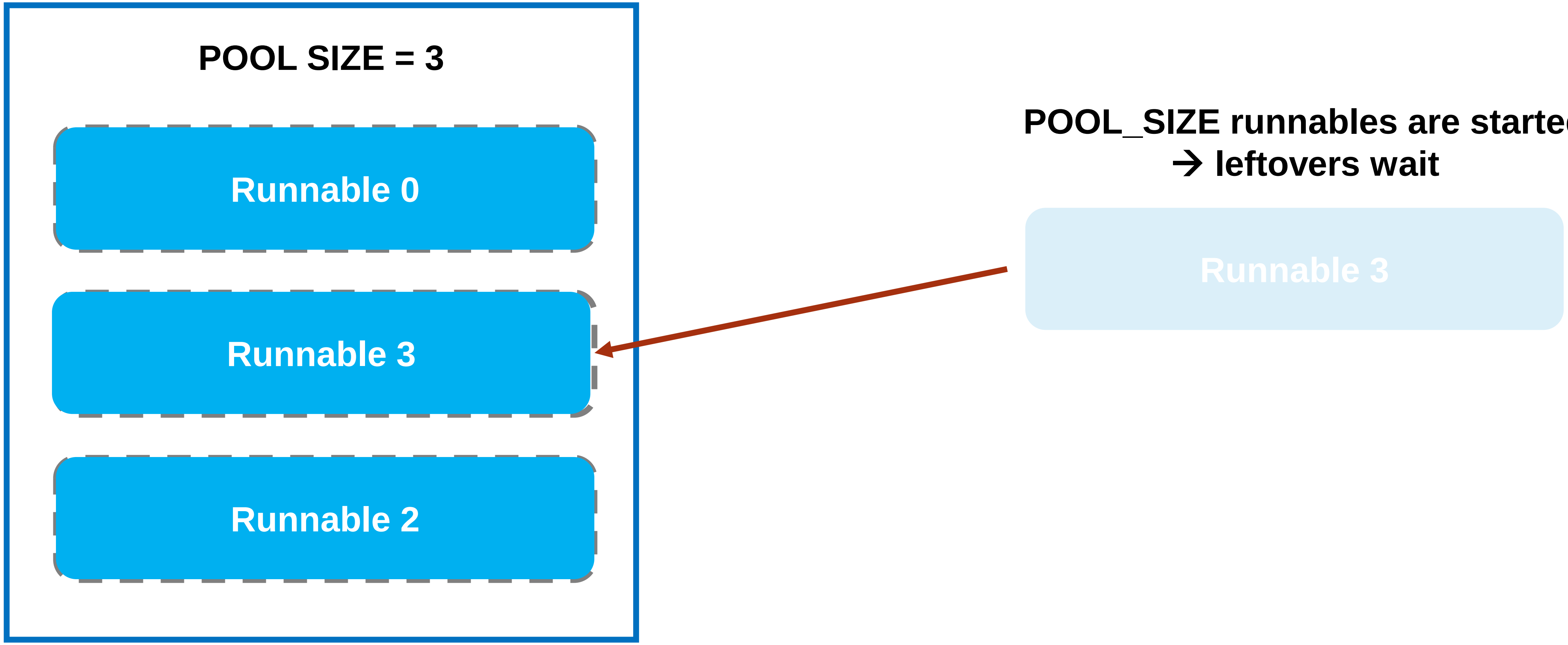


How thread pools work

When a thread completes → exits the pool → queued thread takes its place



Thread pool in code

```
ExecutorService executor
                    = Executors.newFixedThreadPool(2);

executor.execute(new SomeRunnable());
executor.execute(new SomeRunnable());
executor.execute(new SomeRunnable());
executor.execute(new SomeRunnable());
```

All 4 runnables added to the pool queue → 2 at a time will run

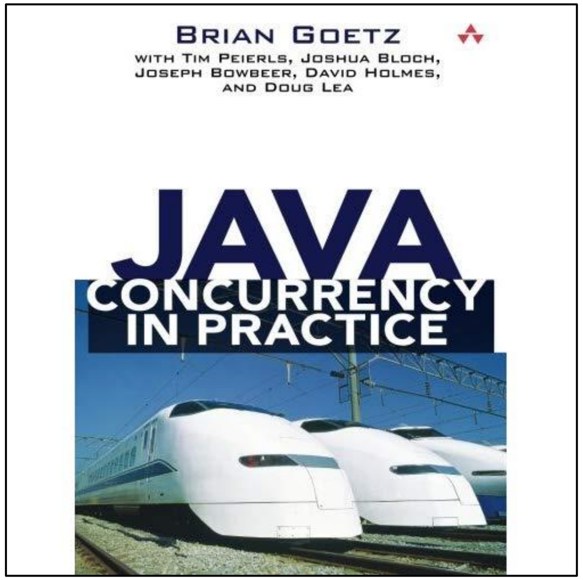
Why is a pool (often) better?

- Can restrict the number of threads created to the number that can meaningfully be used
- Reuses threads instead of creating new ones

→ less overhead

How big should the pool be?

It depends.



Brian Goetz’s formula:

```
available_cores * (1 + wait_time/service_time)
```

How many cores do you have?

```
Runtime.getRuntime().availableProcessors();
```

Wait time = time spent waiting for I/O (large files, HTTP requests)

Service time = time spent on tasks

Ticketing system with a thread pool

Original: start a new Thread for every incoming request

Revised: use a thread pool capped at some sensible size e.g. 5

Ticketing system with a thread pool

Original: start a new Thread for every incoming request

Revised: use a thread pool capped at some sensible size e.g. 5
→ **A LOT faster**

Some Executor limitations

- No way to obtain the result of a Runnable (e.g. was it successful?)
  - If necessary, often not
- Or find out when the Runnable has completed

To get results → Future and/or Callable

- Future: the future result of an asynchronous task
- Callable:
  - Like a Runnable but it *returns* something
  - Can only be used with an Executor

Using Future with a Runnable

`executorService.submit(runnable)`

```
Future future = executorService.submit(new Runnable()
{
  public void run() {...do stuff...}
});

future.get();
```

Using Future with a Runnable

`executorService.submit(runnable)`

```
Future future = executorService.submit(new Runnable()
{
  public void run() {...do stuff...}
});

future.get();
```

submit, not execute

Using Future with a Runnable

`executorService.submit(runnable)`

Stores the (eventual) result

```
Future future = executorService.submit(new Runnable()
{
   public void run() {...do stuff...}
});

future.get();
```

Using Future with a Runnable

`executorService.submit(runnable)`

```
Future future = executorService.submit(new Runnable()
{
  public void run() {...do stuff...}
});
```

```
future.get();
```

Blocks until the result is available

- Non-blocking: future.isDone()
- Result will be null

Using Future with a Callable

`executorService.submit(callable)`

```
Future future = executorService.submit(new Callable()
{
   public Object call() throws Exception {
      return “Result”;
   }
});

System.out.println(future.get());
```

Using Future with a Callable

`executorService.submit(callable)`

```
Future future = executorService.submit(new Callable()
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Using Future with a Callable

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Using Future with a Callable

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Future future = executorService.submit(new Callable()
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   public Object call() throws Exception {
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   }
});

System.out.println(future.get());
```

Key differences:

- call() not run()
- returns something

Using Future with a Callable

`executorService.submit(callable)`

```
Future future = executorService.submit(new Callable()
{
   public Object call() throws Exception {
      return “Result”;
   }
});

System.out.println(future.get());
```

Using Future with a Callable

Use Generics

```
Future<String> future = executorService.submit(new Callable<String>() {
  public String call() throws Exception {
    return “Result”;
  }
});

System.out.println(future.get());
```

Shutting an executor down

An executor must be shutdown

```
executorService.shutdown();
```

→ stops accepting new requests but does not shutdown immediately

To wait for all threads to complete after shutdown:

```
executorService.awaitTermination(time, unit);
```

Coordinating threads

CyclicBarrier

When a <u>known number</u> of threads have to execute before moving on

```
CyclicBarrier barrier
      = new CyclicBarrier(NUM, new OtherRunnable());
```

- After NUM threads have executed, run OtherRunnable()
  - 2nd parameter (action) is optional
- Cyclic – if there are more than NUM threads, OtherRunnable() will execute after every NUM threads

CyclicBarrier

When a known number of threads have to execute before moving on

```
CyclicBarrier barrier
    = new CyclicBarrier(NUM, new OtherRunnable());

for (int i = 0; i < NUM; i++) {
  Thread t = new Thread(new Runnable() {
    public void run() {
      barrier.await(); // Call at end
    }
  }).start();
}
```

The barrier counts the number of await() calls

Exercise: CyclicBarrier with a thread pool

Open cyclicbarrier > CyclicBarrierDeadlock.java

- Take a few minutes to make sure you understand the code

Then, try running the following conditions:

- barrier’s number of parties = POOL_SIZE; for loop: i < POOL_SIZE
- barrier’s number of parties = POOL_SIZE; for loop: i < POOL_SIZE * 2
- barrier’s number of parties = POOL_SIZE * 2; for loop as above

What do you observe?

Exercise: CyclicBarrier with a thread pool

Deadlock

- When barrier is waiting on await() calls > POOL_SIZE

Why?

barrier.await() blocks → runnable doesn't exit → pool space doesn't free up → next runnable in the queue can't take its place

Try printing something after await() to illustrate this

Loops / Recursion and Threads

Loops and threads

If we have a loop with completely independent iterations, can we use a thread to execute each iteration?

What are the effects on performance?

- Look at the drivers in looprunnables package
- (not in class) Try increasing the multiplying number of iterations by 10 and running → do this a few times
  - Few iterations → sequential (may be) faster
  - As iterations increase → concurrent becomes faster

Loops and threads

Parallelization of sequential loops works when:

- Each iteration **is completely independent** of others
- **Work done in each iteration is enough to offset cost** of thread management

Recursion and threads

Recursive algorithms often involve independent sequential loops → each iteration does not require results of recursive iterations it invokes.

Example:

- Depth-first tree traversal

Depth-First Tree Traversal: sequential

From https://jcip.net/listings.html (listing 8.11)

```
public <T> void sequentialRecursive(List<Node<T>> nodes,
                                    Collection<T> results) {
    for (Node<T> n : nodes) {
        results.add(n.compute());
        sequentialRecursive(n.getChildren(), results);
    }
}
```

Depth-First Tree Traversal: parallel

From https://jcip.net/listings.html (listing 8.11)

```
public <T> void parallelRecursive(final Executor exec,
                                  List<Node<T>> nodes,
                                  final Collection<T> results) {
    for (final Node<T> n : nodes) {
        exec.execute(new Runnable() {
            public void run() {
                results.add(n.compute());
            }
        });
        parallelRecursive(exec, n.getChildren(), results);
    }
}
```

Depth-First Tree Traversal: parallel results

From https://jcip.net/listings.html (listing 8.11)

```
public <T> Collection<T> getParallelResults(List<Node<T>> nodes)
        throws InterruptedException {

    ExecutorService exec = Executors.newCachedThreadPool();
    Queue<T> resultQueue = new ConcurrentLinkedQueue<T>();

    parallelRecursive(exec, nodes, resultQueue);

    exec.shutdown();
    exec.awaitTermination(Long.MAX_VALUE, TimeUnit.SECONDS);

    return resultQueue;
}
```

Readers & Writers Problem

Readers-writers problem

- Classic concurrency problem
- Multiple readers and writers to a shared database / file
- How to manage concurrent read/write requests?

Things to think about:

- Read/write requests could come in at any time and in any order
- Probably many more people looking at seat availability (readers) than making a purchase (writers)

Exercise: Readers & Writers

- **Spend a few minutes getting to know the code in ticketsystemdatabase**
- Run DatabaseDriver.java in each of the following conditions:
    - Readers: 1, writers: 1
    - Readers: 5, writers: 2
    - Readers: 10, writers: 3
- **What do you observe?**

ReadWriteLock

- Maintains a pair of associated locks
  - One for read-only operations
  - One for writing
- The read lock may be held simultaneously by multiple reader threads
  - If there are no writers
- The write lock is exclusive

Using a ReadWriteLock

```
private ReadWriteLock readWriteLock = new ReentrantReadWriteLock();

public Object get() {
  readWriteLock.readLock().lock();
  try { return someObject; }
  finally { readWriteLock.readLock().unlock(); }
}

public void set() {
  readWriteLock.writeLock().lock();
  try { ...write/change something... }
  finally { readWriteLock.writeLock().unlock(); }
}
```

Using a ReadWriteLock

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private ReadWriteLock readWriteLock = new ReentrantReadWriteLock();

public Object get() {
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}

public void set() {
  readWriteLock.writeLock().lock();
  try { ...write/change something... }
  finally { readWriteLock.writeLock().unlock(); }
}
```

Create a ReadWriteLock

- Will apply to instance of the current class

Using a ReadWriteLock

```
private ReadWriteLock readWriteLock = new ReentrantReadWriteLock();
```

```
public Object get() {
  readWriteLock.readLock().lock();
  try { return someObject; }
  finally { readWriteLock.readLock().unlock(); }
}
```

Handles read operations

Needs to lock/unlock

`readWriteLock.readLock()`

```
public void set() {
  readWriteLock.writeLock().lock();
  try { ...write/change something... }
  finally { readWriteLock.writeLock().unlock(); }
}
```

Handles write operations

Needs to lock/unlock

`readWriteLock.writeLock()`

Using a ReadWriteLock

```
private ReadWriteLock readWriteLock = new ReentrantReadWriteLock();

public Object get() {
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}
```

1. Lock...

`readWriteLock.readLock()`

1. Lock...

`readWriteLock.writeLock()`

Using a ReadWriteLock

```
private ReadWriteLock readWriteLock = new ReentrantReadWriteLock();

public Object get() {
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public void set() {
  readWriteLock.writeLock().lock();
  try { ...write/change something... }
  finally { readWriteLock.writeLock().unlock(); }
}
```

2. Perform the read & return

`try { }`

2. Perform the write

`try { }`

Using a ReadWriteLock

```
private ReadWriteLock readWriteLock = new ReentrantReadWriteLock();

public Object get() {
  readWriteLock.readLock().lock();
  try { return someObject; }
  finally { readWriteLock.readLock().unlock(); }
}

public void set() {
  readWriteLock.writeLock().lock();
  try { ...write/change something... }
  finally { readWriteLock.writeLock().unlock(); }
}
```

3. Unlock the read lock

`finally { }`

3. Unlock the write lock

`finally { }`

Exercise: Using a ReadWriteLock

```
private ReadWriteLock readWriteLock = new ReentrantReadWriteLock();

public Object get() {
  readWriteLock.readLock().lock();
  try { return someObject; }
  finally { readWriteLock.readLock().unlock(); }
}

public void set() {
  readWriteLock.writeLock().lock();
  try { ...write/change something... }
  finally { readWriteLock.writeLock().unlock(); }
}
```

Add a ReadWriteLock to SeatDatabase.java

Run with 10 readers and 3 writers

Scalability

Scalability

The ability to improve performance / capacity with additional resources:

- CPUs
- Memory
- Storage
- Bandwidth
- etc.

Engineering concerns

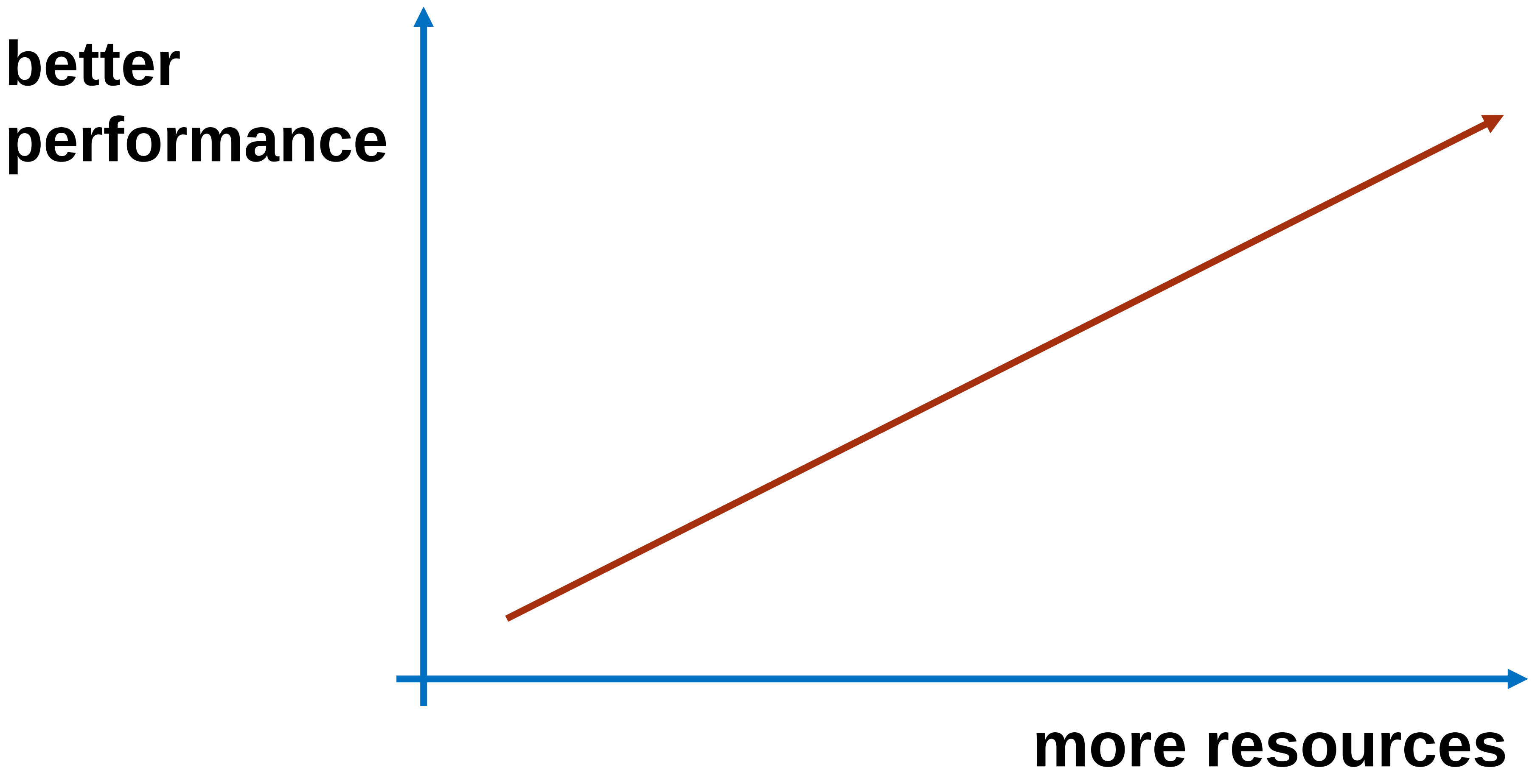
- Threads make it possible to better utilize resources
- But also introduce overheads:
  - creation, context switching, management, coordination

Terminology:

- Service time / latency / response time → how fast a piece of work happens
- Capacity / throughput → how much work can be performed with a given quantity of computing resources

More resources = better performance?

What we would like to happen:

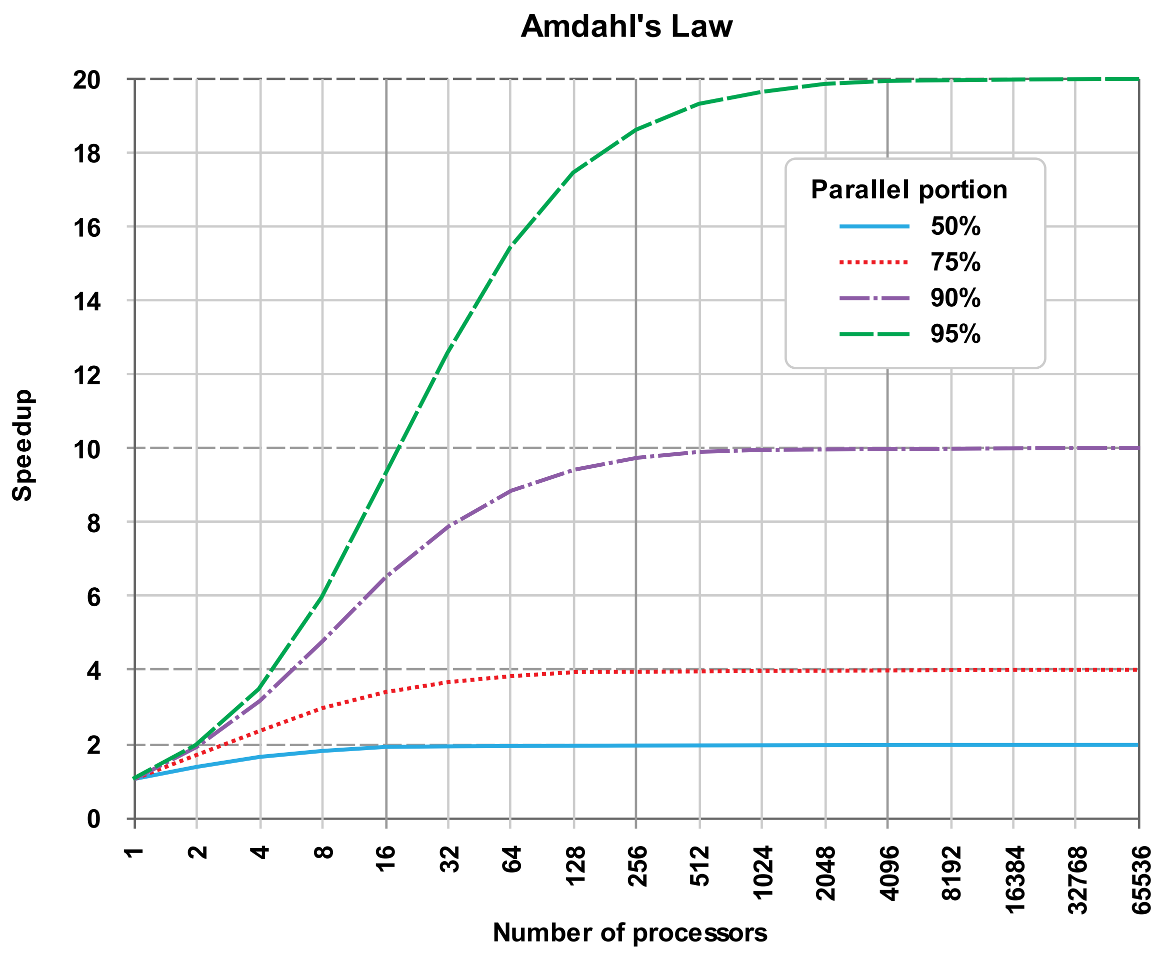


Amdahl’s Law

Formula for theoretical speedup with more processors

Speedup limited by serial part of program:

- e.g. if 95% of program can be parallelized, can be sped up 20 times with enough processors



Thread overheads

- Context switching has costs
- Every time a thread blocks it gets switched:
  - Blocking I/O
  - Contention over locks
  - Condition variables
- Frequently blocking threads reduce throughput

Reducing lock contention

- Serialization hurts scalability
- Context switching hurts performance
- Lock contention hurts both! e.g.:
  - Operation holds a lock for 2 mins
  - All threads must acquire this lock
  - What is the *maximum* throughput we can attain?
    - After a point, more processors make no difference!

Don’t lock for longer than necessary

all this has to be done

```
public class AttributeStore {
    private final Map<String, String>
    attributes = new HashMap<String, String>();

   public synchronized boolean userLocationMatches(String name,
                                                   String regexp) {
      String key = "users." + name + ".location";  // construct key
      String location = attributes.get(key);        // search hashmap
      if (location == null)
         return false;
      else
         return Pattern.matches(regexp, location);  // process results
   }
}
```

From Java Concurrency in Practice, p. 145 (classic book!)

Don't lock for longer than necessary

a lot less to do...

```
public class BetterAttributeStore {
        private final Map<String, String>
        attributes = new HashMap<String, String>();

    public boolean userLocationMatches(String name, String regexp) {
        String key = "users." + name + ".location";
        String location;
        synchronized (this) {
            location = attributes.get(key);
        }
        if (location == null)
            return false;
        else
            return Pattern.matches(regexp, location);
    }
}
```

From Java Concurrency in Practice, p. 145 (classic book!)

Easier—use thread safe collections

```
public class BetterAttributeStore {
        private final ConcurrentHashMap<String, String>
        attributes = new ConcurrentHashMap<String, String>();

    public boolean userLocationMatches(String name, String regexp) {
        String key = "users." + name + ".location";
        String location;

        location = attributes.get(key);

        if (location == null)
            return false;
        else
            return Pattern.matches(regexp, location);
    }
}
```

From Java Concurrency in Practice, p. 145 (classic book!)

Lock splitting & striping

Splitting:

- Using different locks for different functionality within a class
  - e.g. locking methods, individual operations

Striping:

- Using different locks for different parts of the data
  - e.g. breaking a large data structure into smaller parts, use different locks for each part (remember ConcurrentHashMap?)

Lock striping example

```
public class StripedMap {
    // Synchronization policy: buckets[n] guarded by locks[n%N_LOCKS]
    private static final int N_LOCKS = 16;
    private final Node[] buckets;
    private final Object[] locks;

    private static class Node { ….} // stuff missing

    public StripedMap(int numBuckets) {
        buckets = new Node[numBuckets];
        locks = new Object[N_LOCKS];
        for (int i = 0; i < N_LOCKS; i++)
            locks[i] = new Object();
    }
```

each lock guards a portion of the map

From Java Concurrency in Practice, p. 148

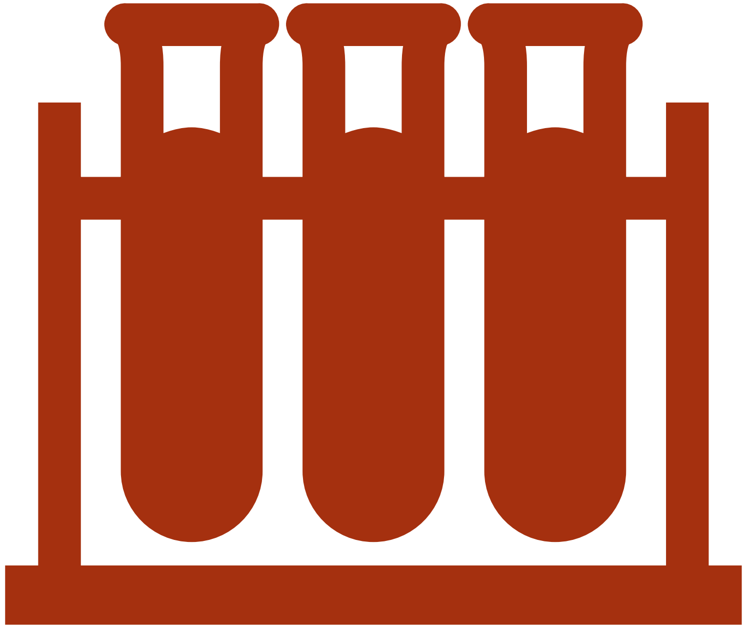
Lock striping example continued

operations can take advantage of locks

```
private final int hash(Object key) {
        return Math.abs(key.hashCode() % buckets.length);
    }
    public Object get(Object key) {
        int hash = hash(key);
        synchronized (locks[hash % N_LOCKS]) {
            for (Node m = buckets[hash]; m != null; m = m.next)
                if (m.key.equals(key))
                    return m.value;
        }
        return null;
    }
    public void clear() { // non atomic clear
        for (int i = 0; i < buckets.length; i++) {
            synchronized (locks[i % N_LOCKS]) {
                buckets[i] = null;
            }
        }
    } }
```

From Java Concurrency in Practice, p. 148

Testing



Testing concurrent programs

- Tricky in the face of non-determinism
- Larger number of potential interactions and failure cases
- Test suites have to be more extensive and run for longer

Testing concurrent programs

Most tests are testing for

- Safety:
  - Nothing bad ever happens
  - Test invariants usually hold
- Liveness:
  - Something good eventually happens
  - Trickier – e.g. testing for deadlocks, race conditions
  - Also throughput, response times, scalability

Testing for correctness

- Similar to testing sequential code
- Identify post conditions and invariants
  - **Post conditions**: state of system after an action has happened
  - **Invariants**: rules that must hold true for the life cycle of an object e.g. you have two boolean fields but only one of them should be true at a time

Example: testing a shared buffer

If buffer has methods for:

- adding and removing items
- checking if it's full /empty

Test:

- New buffer identifies itself as empty
- New buffer identifies itself as not full
- Insert N items into a buffer with capacity N → buffer should be full
- Insert N items into a buffer with capacity N → buffer should be not empty

Bounded buffer tests

```
public class TestBoundedBuffer extends TestCase {

    void testIsEmptyWhenConstructed() {
        SemaphoreBoundedBuffer<Integer> bb = new SemaphoreBoundedBuffer<Integer>(10);
        assertTrue(bb.isEmpty());
        assertFalse(bb.isFull());
    }

    void testIsFullAfterPuts() throws InterruptedException {
        SemaphoreBoundedBuffer<Integer> bb = new SemaphoreBoundedBuffer<Integer>(10);
        for (int i = 0; i < 10; i++)
            bb.put(i);
        assertTrue(bb.isFull());
        assertFalse(bb.isEmpty());
    }
```

From https://jcip.net/listings.html, (listing 12.2)

Testing blocking operations

E.g. a consumer thread tries to take from an empty buffer → should be blocked until the buffer is no longer empty

- Test outcome: thread should not succeed in taking while empty

Testing steps:

1. Try to take an element from an empty buffer
2. Thread should be blocked → put it to sleep for a bit
3. After sleep, if still blocked → interrupt the taker thread
4. If take() succeeds → test fails
5. If thread exits without taking → test succeeds

From the buffer test example

```
void testTakeBlocksWhenEmpty() {
    final SemaphoreBoundedBuffer<Integer> bb = new SemaphoreBoundedBuffer<Integer>(10);
    Thread taker = new Thread() {
        public void run() {
            try {
                int unused = bb.take();
                fail(); // if we get here, it's an error
            } catch (InterruptedException success) { // thread exits
            }
        }
    };
    try {
        taker.start();
        Thread.sleep(LOCKUP_DETECT_TIMEOUT);
        taker.interrupt();
        taker.join(LOCKUP_DETECT_TIMEOUT);
        assertFalse(taker.isAlive());  // verify join returned successfully as thread will be dead
    } catch (Exception unexpected) {
        fail();
    }
}
```

From https://jcip.net/listings.html, (listing 12.3)

From the buffer test example

```
void testTakeBlocksWhenEmpty() {
    final SemaphoreBoundedBuffer<Integer> bb = new SemaphoreBoundedBuffer<Integer>(10);
    Thread taker = new Thread() {
        public void run() {
            try {
                int unused = bb.take();
                fail(); // if we get here, it's an error
            } catch (InterruptedException success) { // thread exits
            }
        }
    };
    try {
        taker.start();
        Thread.sleep(LOCKUP_DETECT_TIMEOUT);
        taker.interrupt();
        taker.join(LOCKUP_DETECT_TIMEOUT);
        assertFalse(taker.isAlive());  // verify join returned successfully as thread will be dead
    } catch (Exception unexpected) {
        fail();
    }
}
```

empty buffer

From https://jcip.net/listings.html, (listing 12.3)

From the buffer test example

```
void testTakeBlocksWhenEmpty() {
    final SemaphoreBoundedBuffer<Integer> bb = new SemaphoreBoundedBuffer<Integer>(10);
    Thread taker = new Thread() {
        public void run() {
            try {
                int unused = bb.take();
                fail(); // if we get here, it's an error
            } catch (InterruptedException success) { // thread exits
            }
        }
    };
    try {
        taker.start();
        Thread.sleep(LOCKUP_DETECT_TIMEOUT);
        taker.interrupt();
        taker.join(LOCKUP_DETECT_TIMEOUT);
        assertFalse(taker.isAlive());  // verify join returned successfully as thread will be dead
    } catch (Exception unexpected) {
        fail();
    }
}
```

”Taker” thread

From https://jcip.net/listings.html, (listing 12.3)

From the buffer test example

```
void testTakeBlocksWhenEmpty() {
    final SemaphoreBoundedBuffer<Integer> bb = new SemaphoreBoundedBuffer<Integer>(10);
    Thread taker = new Thread() {
        public void run() {
            try {
                int unused = bb.take();
                fail(); // if we get here, it's an error
            } catch (InterruptedException success) { // thread exits
            }
        }
    };
    try {
        taker.start();
        Thread.sleep(LOCKUP_DETECT_TIMEOUT);
        taker.interrupt();
        taker.join(LOCKUP_DETECT_TIMEOUT);
        assertFalse(taker.isAlive());  // verify join returned successfully as thread will be dead
    } catch (Exception unexpected) {
        fail();
    }
}
```

The buffer should block this

From https://jcip.net/listings.html, (listing 12.3)

From the buffer test example

```
void testTakeBlocksWhenEmpty() {
    final SemaphoreBoundedBuffer<Integer> bb = new SemaphoreBoundedBuffer<Integer>(10);
    Thread taker = new Thread() {
        public void run() {
            try {
                int unused = bb.take();
                fail(); // if we get here, it's an error
            } catch (InterruptedException success) { // thread exits
            }
        }
    };
    try {
        taker.start();
        Thread.sleep(LOCKUP_DETECT_TIMEOUT);
        taker.interrupt();
        taker.join(LOCKUP_DETECT_TIMEOUT);
        assertFalse(taker.isAlive());  // verify join returned successfully as thread will be dead
    } catch (Exception unexpected) {
        fail();
    }
}
```

Bad

From https://jcip.net/listings.html, (listing 12.3)

From the buffer test example

```
void testTakeBlocksWhenEmpty() {
    final SemaphoreBoundedBuffer<Integer> bb = new SemaphoreBoundedBuffer<Integer>(10);
    Thread taker = new Thread() {
        public void run() {
            try {
                int unused = bb.take();
                fail(); // if we get here, it's an error
            } catch (InterruptedException success) { // thread exits
            }
        }
    };
    try {
        taker.start();
        Thread.sleep(LOCKUP_DETECT_TIMEOUT);
        taker.interrupt();
        taker.join(LOCKUP_DETECT_TIMEOUT);
        assertFalse(taker.isAlive()); // verify join returned successfully as thread will be dead
    } catch (Exception unexpected) {
        fail();
    }
}
```

Good

From https://jcip.net/listings.html, (listing 12.3)

From the buffer test example

```
void testTakeBlocksWhenEmpty() {
      final SemaphoreBoundedBuffer<Integer> bb = new SemaphoreBoundedBuffer<Integer>(10);
      Thread taker = new Thread() {
         public void run() {
            try {
               int unused = bb.take();
               fail(); // if we get here, it's an error
            } catch (InterruptedException success) { // thread exits
            }
         }
      };
      try {
         taker.start();
         Thread.sleep(LOCKUP_DETECT_TIMEOUT);
         taker.interrupt();
         taker.join(LOCKUP_DETECT_TIMEOUT);
         assertFalse(taker.isAlive());  // verify join returned successfully as thread will be dead
      } catch (Exception unexpected) {
         fail();
      }
   }
```

Run the taker → should be blocked

From https://jcip.net/listings.html, (listing 12.3)

From the buffer test example

```
void testTakeBlocksWhenEmpty() {
    final SemaphoreBoundedBuffer<Integer> bb = new SemaphoreBoundedBuffer<Integer>(10);
    Thread taker = new Thread() {
        public void run() {
            try {
                int unused = bb.take();
                fail(); // if we get here, it's an error
            } catch (InterruptedException success) { // thread exits
            }
        }
    };
    try {
        taker.start();
        Thread.sleep(LOCKUP_DETECT_TIMEOUT);
        taker.interrupt();
        taker.join(LOCKUP_DETECT_TIMEOUT);
        assertFalse(taker.isAlive()); // verify join returned successfully as thread will be dead
    } catch (Exception unexpected) {
        fail();
    }
}
```

sleep a little → taker should still be blocked

From https://jcip.net/listings.html, (listing 12.3)

From the buffer test example

```
void testTakeBlocksWhenEmpty() {
    final SemaphoreBoundedBuffer<Integer> bb = new SemaphoreBoundedBuffer<Integer>(10);
    Thread taker = new Thread() {
        public void run() {
            try {
                int unused = bb.take();
                fail(); // if we get here, it's an error
            } catch (InterruptedException success) { // thread exits
            }
        }
    };
    try {
        taker.start();
        Thread.sleep(LOCKUP_DETECT_TIMEOUT);
        taker.interrupt();
        taker.join(LOCKUP_DETECT_TIMEOUT);
        assertFalse(taker.isAlive());  // verify join returned successfully as thread will be dead
    } catch (Exception unexpected) {
        fail();
    }
}
```

interrupt taker

From https://jcip.net/listings.html, (listing 12.3)

From the buffer test example

```
void testTakeBlocksWhenEmpty() {
    final SemaphoreBoundedBuffer<Integer> bb = new SemaphoreBoundedBuffer<Integer>(10);
    Thread taker = new Thread() {
        public void run() {
            try {
                int unused = bb.take();
                fail(); // if we get here, it's an error
            } catch (InterruptedException success) { // thread exits
            }
        }
    };
    try {
        taker.start();
        Thread.sleep(LOCKUP_DETECT_TIMEOUT);
        taker.interrupt();
        taker.join(LOCKUP_DETECT_TIMEOUT);
        assertFalse(taker.isAlive());  // verify join returned successfully as thread will be dead
    } catch (Exception unexpected) {
        fail();
    }
}
```

wait some more to ensure operation completes

From https://jcip.net/listings.html, (listing 12.3)

From the buffer test example

```
void testTakeBlocksWhenEmpty() {
    final SemaphoreBoundedBuffer<Integer> bb = new SemaphoreBoundedBuffer<Integer>(10);
    Thread taker = new Thread() {
        public void run() {
            try {
                int unused = bb.take();
                fail(); // if we get here, it's an error
            } catch (InterruptedException success) { // thread exits
            }
        }
    };
    try {
        taker.start();
        Thread.sleep(LOCKUP_DETECT_TIMEOUT);
        taker.interrupt();
        taker.join(LOCKUP_DETECT_TIMEOUT);
        assertFalse(taker.isAlive());  // verify join returned successfully as thread will be dead
    } catch (Exception unexpected) {
        fail();
    }
}
```

check that taker is dead

From https://jcip.net/listings.html, (listing 12.3)

Testing for race conditions

- Tricky
- Tests need to be multi-threaded, can be complex
- Tests should affect non-determinism as little as possible:
  - Adding synchronization impacts order of execution → can obscure deadlocks

Testing the buffer for race conditions

Test goal:

- Everything put into the buffer comes out (and nothing else)

Basic approach:

- Each producer calculates a checksum for all data it produces
- Each consumer calculates a checksum for all data it receives
- When all producers/consumers complete → checksums should be equal

Testing the buffer for race conditions

Test data should be generated randomly

- Minimizes chances of tests accidentally passing

Example: test by putting integers in the buffer

- Use your own random number generator to generate data to put into the buffer. Why?
  - Built in generators are thread-safe → impact synchronization
  - If each producer generates own random data → doesn't need to be thread safe
  - Create data based on time → different values every test
- We'll see this in code soon...

Testing the buffer for race conditions

To introduce more randomness, coordinate starting and termination of threads:

- Ensure sequential thread operation doesn't introduce some determinism
- Ensure testing of checksums is done after all threads finished
- Use CyclicBarrier to coordinate start and end behavior

Exercise: testing the buffer for race conditions

Spend a few minutes looking at

http://jcip.net/listings/PutTakeTest.java

Easier to find: search "JCIP listings" → scroll to 12.6.

Can you understand how it works?

- We'll walk through it shortly

PutTakeTest.java

```
public class PutTakeTest extends TestCase {
    protected static final ExecutorService pool = Executors.newCachedThreadPool();
    protected CyclicBarrier barrier;
    protected final SemaphoreBoundedBuffer<Integer> bb;
    protected final int nTrials, nPairs;
    protected final AtomicInteger putSum = new AtomicInteger(0);
    protected final AtomicInteger takeSum = new AtomicInteger(0);

    public static void main(String[] args) throws Exception {
        new PutTakeTest(10, 10, 100000).test(); // sample parameters
        pool.shutdown();
    }

    public PutTakeTest(int capacity, int npairs, int ntrials) {
        this.bb = new SemaphoreBoundedBuffer<Integer>(capacity);
        this.nTrials = ntrials;
        this.nPairs = npairs;
        this.barrier = new CyclicBarrier(npairs * 2 + 1); // initialize the barrier  +1 for main thread
    }
```

cached pool

PutTakeTest.java

```
public class PutTakeTest extends TestCase {
    protected static final ExecutorService pool = Executors.newCachedThreadPool();
    protected CyclicBarrier barrier;
    protected final SemaphoreBoundedBuffer<Integer> bb;
    protected final int nTrials, nPairs;
    protected final AtomicInteger putSum = new AtomicInteger(0);
    protected final AtomicInteger takeSum = new AtomicInteger(0);

    public static void main(String[] args) throws Exception {
        new PutTakeTest(10, 10, 100000).test(); // sample parameters
        pool.shutdown();
    }

    public PutTakeTest(int capacity, int npairs, int ntrials) {
        this.bb = new SemaphoreBoundedBuffer<Integer>(capacity);
        this.nTrials = ntrials;
        this.nPairs = npairs;
        this.barrier = new CyclicBarrier(npairs * 2 + 1); // initialize the barrier  +1 for main thread
    }
```

to coordinate start/temination

PutTakeTest.java

```
public class PutTakeTest extends TestCase {
    protected static final ExecutorService pool = Executors.newCachedThreadPool();
    protected CyclicBarrier barrier;
    protected final SemaphoreBoundedBuffer<Integer> bb;
    protected final int nTrials, nPairs;
    protected final AtomicInteger putSum = new AtomicInteger(0);
    protected final AtomicInteger takeSum = new AtomicInteger(0);

    public static void main(String[] args) throws Exception {
        new PutTakeTest(10, 10, 100000).test(); // sample parameters
        pool.shutdown();
    }

    public PutTakeTest(int capacity, int npairs, int ntrials) {
        this.bb = new SemaphoreBoundedBuffer<Integer>(capacity);
        this.nTrials = ntrials;
        this.nPairs = npairs;
        this.barrier = new CyclicBarrier(npairs * 2 + 1); // initialize the barrier  +1 for main thread
    }
```

to calculate checksums

PutTakeTest.java

```
public class PutTakeTest extends TestCase {
    protected static final ExecutorService pool = Executors.newCachedThreadPool();
    protected CyclicBarrier barrier;
    protected final SemaphoreBoundedBuffer<Integer> bb;
    protected final int nTrials, nPairs;
    protected final AtomicInteger putSum = new AtomicInteger(0);
    protected final AtomicInteger takeSum = new AtomicInteger(0);

    public static void main(String[] args) throws Exception {
        new PutTakeTest(10, 10, 100000).test(); // sample parameters
        pool.shutdown();
    }

    public PutTakeTest(int capacity, int npairs, int ntrials) {
        this.bb = new SemaphoreBoundedBuffer<Integer>(capacity);
        this.nTrials = ntrials;
        this.nPairs = npairs;
        this.barrier = new CyclicBarrier(npairs * 2 + 1); // initialize the barrier  +1 for main thread
    }
```

we know exactly how many threads there will be

PutTakeTest.java

The test entry point (main thread):

```
void test() {
      try {
         for (int i = 0; i < nPairs; i++) {   //  create the threads
            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());
      } catch (Exception e) {
         throw new RuntimeException(e);
      }
   }
```

2 await() calls in main thread

PutTakeTest.java: Producer

```
class Producer implements Runnable {
      public void run() {
          try {
              int seed = (this.hashCode() ^ (int) System.nanoTime());
              int sum = 0;
              barrier.await();
              for (int i = nTrials; i > 0; --i) {
                  bb.put(seed);
                  sum += seed;
                  seed = xorShift(seed);
              }
              putSum.getAndAdd(sum);
              barrier.await();
          } catch (Exception e) {
              throw new RuntimeException(e);
          }
      }
  }
```

executed nPair times by main thread

2 await calls per Producer thread

PutTakeTest.java: Producer

```
class Producer implements Runnable {
    public void run() {
        try {
            int seed = (this.hashCode() ^ (int) System.nanoTime());
            int sum = 0;
            barrier.await();
            for (int i = nTrials; i > 0; --i) {
                bb.put(seed);
                sum += seed;
                seed = xorShift(seed);
            }
            putSum.getAndAdd(sum);
            barrier.await();
        } catch (Exception e) {
            throw new RuntimeException(e);
        }
    }
}
```

seed for simple custom random number generator

- uses system time to ensure randomness

PutTakeTest.java: Producer

```
class Producer implements Runnable {
      public void run() {
          try {
              int seed = (this.hashCode() ^ (int) System.nanoTime());
              int sum = 0;
              barrier.await();
              for (int i = nTrials; i > 0; --i) {
                  bb.put(seed);
                  sum += seed;
                  seed = xorShift(seed);
              }
              putSum.getAndAdd(sum);
              barrier.await();
          } catch (Exception e) {
              throw new RuntimeException(e);
          }
      }
  }
```

generate nTrials random numbers and put them in the buffer

PutTakeTest.java: Producer

```
class Producer implements Runnable {
    public void run() {
        try {
            int seed = (this.hashCode() ^ (int) System.nanoTime());
            int sum = 0;
            barrier.await();
            for (int i = nTrials; i > 0; --i) {
                bb.put(seed);
                sum += seed;
                seed = xorShift(seed);
            }
            putSum.getAndAdd(sum);
            barrier.await();
        } catch (Exception e) {
            throw new RuntimeException(e);
        }
    }
}
```

track the sum of all random data added to the buffer

PutTakeTest.java: Consumer

```
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);
            }
        }
    }
```

executed nPair times by main thread

2 await calls per Consumer thread

PutTakeTest.java: Consumer

```
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);
        }
    }
}
```

take out nTrials data

track all the received data

PutTakeTest.java

Back to the main thread...

```
void test() {
    try {
      for (int i = 0; i < nPairs; i++) {   //  create the threads
        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());
    } catch (Exception e) {
      throw new RuntimeException(e);
    }
  }
```

the actual test

- data in matches data out

Wrap up: testing concurrent code

- Test cases can be more complex than code
  - See previous example
- Other things to test:
  - Resource management (see testLeak in http://jcip.net/listings, 12.2)
  - Performance
    - Add timing information
  - Scalability
    - Requires large volume tests, coordination of more resources

Want to learn more?

- Review testing code listings at http://jcip.net/listings
- Take Dr. Gorton’s Distributed Systems class

Summary

- Threads can be used to parallelize independent loop iterations & independent recursive calls
- Scalability requires careful design & is always limited by serialization
- Testing concurrent systems is tricky due to large amount of failure modes & non-determinism