CSx55: Distributed Systems [Thread Safety]

On impending code breaks, putting the brakes, you are …

Let a reference escape, have you?
Misbehave, your code will, out of the blue

Get out, you will, of this bind
If, your objects, you have confined

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Frequently asked questions from the previous class survey

- How does the runtime for `wait/notify` contrast with that of the `Lock` interface?
- Is the `wait/notify` construct applicable beyond producer-consumer with shared buffer?
- Why can't we override the `wait/notify` methods?
- Use of `private static` fields
  - Not allowed in interfaces, but allowed in classes; most common use case is for constants and singleton instances where you *also* add final i.e., `private static final`; also in `ThreadLocal` which is a specific use-case.
- Errors if I use `Lock` inside a `synchronized` method? Which lock is acquired when that synchronized method is invoked?
- Why `synchronized` blocks? Doesn't the `synchronized` method do it all?
- Is waiting to acquire a `Lock` a blocking call?

Topics covered in this lecture

- Atomicity
- Locks& Reentrancy
- Guarding state with locks
- Sharing Objects
- Thread confinement

When should an object be thread-safe?

- Will it be accessed from multiple threads?
- The key here is *how* the object is **used**
  - Not *what* it **does**

How to make an object thread-safe

- Use *synchronization* to **coordinate** access to mutable state
- Failure to do this?
  - Data corruptions
  - Problems that manifest themselves in myriad forms

Mechanisms for synchronization in Java

- One way to achieve this is via the `synchronized` keyword
  - Exclusive locking
- Other approaches include:
  - `volatile` variables
  - Explicit **locks**
  - **Atomic** variables

Programs that omit synchronizations

- Might work for some time
  - But it ***will break*** at some point
- Far easier to design a class to be thread-safe *from the start*
  - Retrofitting it to be thread-safe is extremely hard

Thread-safety: Encapsulate your state

- Fewer code should have access to a particular variable
  - Easier to reason about *conditions* under which it might be accessed
- **DON'T:**
  - Store state in `public` fields
  - Publish reference to an **internal** object

Fixing access to mutable state variables from multiple threads

- *Don't share* state variables across threads
- Make state variables *immutable*
- Use *synchronization* to coordinate access to the state variable

Correctness of classes

- Class conforms to **specification**
- **Invariants** constrain object's state
- **Post conditions** describe the effects of operations

A Thread-safe class

- **Behaves correctly** when accessed from multiple threads
- Regardless of *scheduling or interleaving* of execution of those threads
  - By the runtime environment
- No additional synchronization or coordination by the calling code

Really?

- Thread safe classes encapsulate *any needed* synchronization
- Clients **should not** have to provide their own

Stateless objects are always thread-safe

```
public class StatelessClass implements Servlet {

     public void factorizer(ServletRequest req,
                            ServletResponse resp) {
         BigInteger i = extractFromReq(req);
         BigInteger[] factors  = factorize(i);
         encodeIntoResponse(resp, factors);
     }

}
```

Stateless objects are always thread-safe

- **Transient state** for a particular computation exists solely in *local variables*
  - Stored on the thread's stack
  - Accessible only to the executing thread

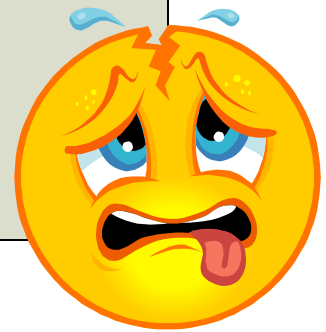
- One thread cannot influence the result of another
  - The threads have no shared state

Atomicity

- Let's look at two operations **A** and **B**
- From the perspective of thread executing **A**
- When another thread executes **B**
  - Either all of **B** has executed or none of it has
- Operations **A** and B are **atomic** *with respect to each other*

Initializing Objects

```
public class LazyInitialization {

    private ExpensiveObject instance = null;

    public ExpensiveObject getInstance() {
        if (instance == null) {
            instance = new ExpensiveObject();
        }
        return instance;
    }

}
```



Thread-safe initialization

```
public class Singleton {
   private static final Singleton instance = new Singleton();

   // Private constructor prevents instantiation from other
   // classes
   private Singleton() { }

   public static Singleton getInstance() {
      return instance;
   }
}
```

The `final` keyword

- You cannot extend a `final` class
  - E.g., `java.lang.String`
- You cannot override a `final` method
- You can only initialize a `final` variable **once**
  - Either via an initializer or an assignment statement

Blank `final` instance variable of a class

- Must be assigned *within every constructor* of the class
- Attempting to set it outside the constructor will result in a compilation error
- The value of a `final` variable is not necessarily known at compile time

Atomicity with compound operations

```
public class CountingFactorizer {
   private long count = 0;

   public long getCount() {return count;}

   public void factorizer(int i) {
     int[] factors = factor(i);
     count++;
   }

}
```

Atomicity with compound operations

```
public class CountingFactorizer {
   private final AtomicLong count = new AtomicLong(0);

   public long getCount() {return count;}

   public void factorizer(int i) {
     int[] factors = factor(i);
     count.incrementAndGet();
   }

}
```

Compound actions & thread-safety

- Compound actions
  - Check-then-act
  - Read-modify-write
- Must be executed atomically for thread-safety

Locks & Reentrancy

Reentrancy

- When thread requests lock held by another thread?
  - Requesting thread blocks
- If a thread attempts to acquire a lock it already holds?
  - Succeeds
- Locks are acquired on a **per-thread** rather than on a per-invocation basis

How reentrancy works [1/2]

- For each lock two items are maintained
  - Acquisition count
  - Owning thread
- When the count is zero?
  - Lock is free
- If a thread acquires lock for the first time?
  - Count is one

How reentrancy works [2/2]

- If owning thread acquires lock again, count is incremented
- When owning thread exits synchronized block, count is decremented
  - If it is zero …. Lock is released

Does this result in a deadlock?

```
public class Widget {
  public synchronized doSomething() {
    ...
  }

}

public class LoggingWidget extends Widget {

  public synchronized void doSomething() {
    System.out.println(toString()+"Calling doSomething());
    super.doSomething();
  }
}
```

No! Intrinsic locks are reentrant

GUARDING STATE WITH LOCKS

Guarding state with locks

- A *mutable*, *shared* variable that may be accessed by multiple threads must be guarded by the **same lock**

- For every invariant that involves more than one variable?
  - *All variables* must be guarded by the **same lock**

Watch for indiscriminate use of synchronization

- Every method in `Vector` is synchronized
- But this does not render compound actions on `Vector` atomic

```
if (!vector.contains(element)) {
   vector.add(element);
}
```

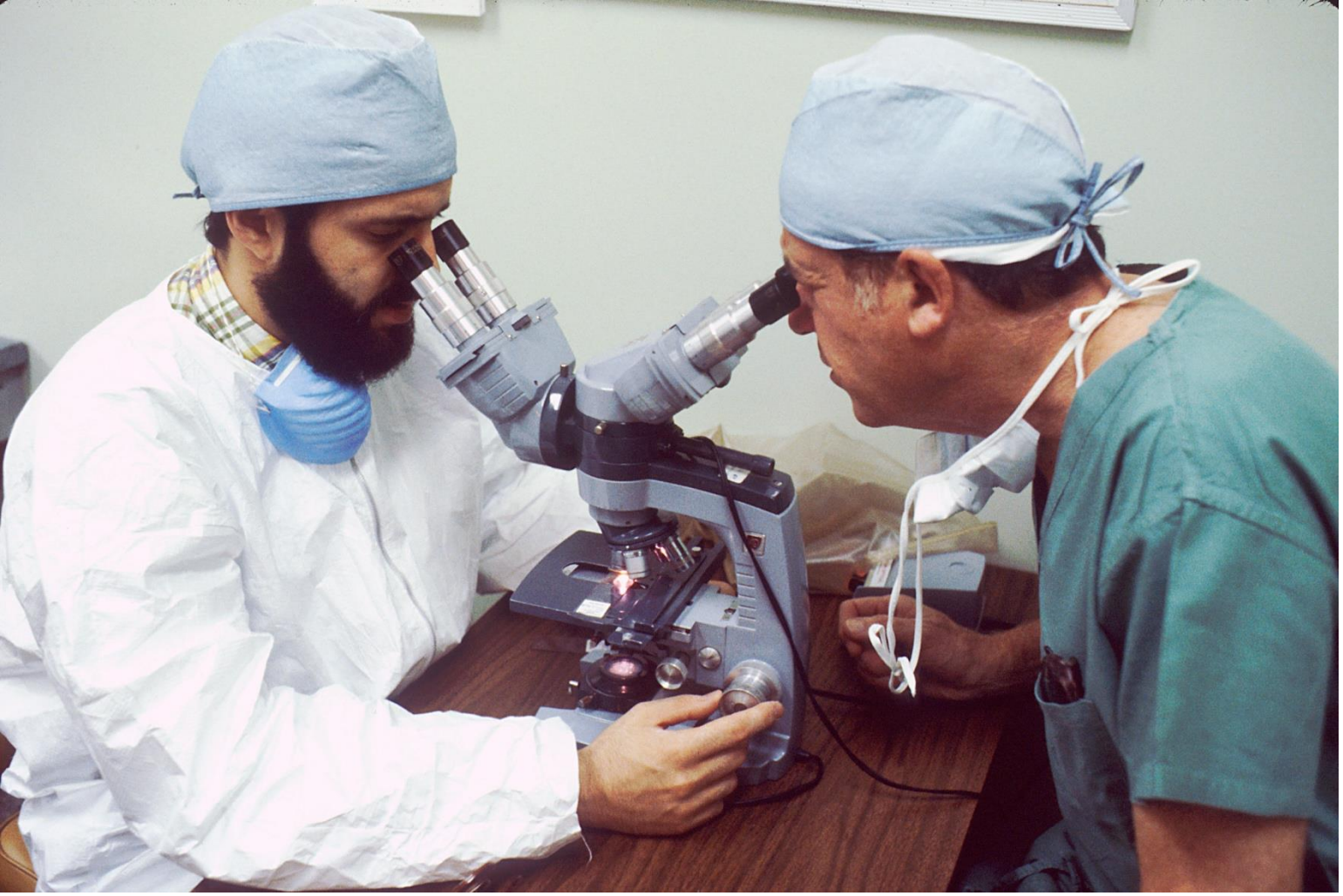
- Snippet has *race condition* even though `add` and `contains` are atomic
- **Additional locking needed for compound actions**

Pitfalls of over synchronization

- Number of simultaneous invocations?
  - Not limited by processor resources, but is limited by the application structure
  - **Poor concurrency**

Antidote for poor concurrency

- Control the **scope** of the lock
  - Too large: Invocations become sequential
  - Don't make it too small either
    - Operations that are atomic should not be in `synchronized` block



Sharing Objects

What we will be looking at

- Techniques for sharing and publishing objects
  - Safe access from multiple threads
- Together with synchronization, sharing objects lays foundation for thread-safe classes

Synchronization

- What we have seen so far:
  - Atomicity and demarcating *critical sections*
- But it is also about **memory visibility**
  - We *prevent* one thread from modifying object state while another is using it
  - When *state of an object is modified*, other thread can **see** the changes that were made

Publication and Escape

- Publishing an object
  - Makes it available *outside* current scope
    - Storing a reference to it, returning from a non-private method, passing it as an argument to another method
- **Escape**
  - An object that is published when it should not have been

Pitfalls in publication

- Publishing internal state variables
  - Makes it **difficult** to preserve invariants
- Publishing objects before they are constructed
  - Compromises thread-safety

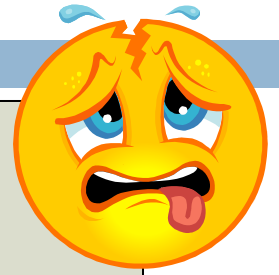
Most blatant form of publication

- Storing a reference in a `public static` field

```
public static Set<Secret> knownSecrets;

public void initialize() {
   knownSecrets = new HashSet<Secret>();
}
```

  - If you add a `Secret` to `knownSecrets`?
    - You also end up publishing that `Secret`

Allowing internal mutable state to escape

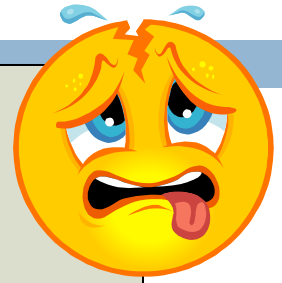


```
public class PublishingState {
   private String[] states = new String[] {
       "AK", "AL", …
   };

   public String[] getStates() {return states;}
}
```

- `states` has *escaped* its intended scope
  - What should have been private is now public
- **Any caller can modify its contents**

Another way to publish internal state

```
public class ThisEscape {

   public ThisEscape(EventSource source) {
      source.registerListener(
         new EventListener() {
               public void onEvent(Event e) {
                  doSomething(e);
               }
          });
   }
}
```



- When `EventListener` is published, it publishes the enclosing `ThisEscape` instance
- **Inner class instances contain hidden reference to enclosing instance**

Abbreviated view of the classes generated by the javac

```
public class ThisEscape {

    public ThisEscape(EventSource source) {
        source.registerListener(new ThisEscape$1(this));
    }

    private void doSomething(Event e) {
        .....
    }

    static void access$000(ThisEscape _this, Event event) {
        _this.doSomething(event);
    }
}
```

```
class ThisEscape$1 implements EventListener {
    final ThisEscape this$0;

    ThisEscape$1(ThisEscape thisescape) {
        this$0 = thisescape;    super();  }

    public void onEvent(Event e) {
        ThisEscape.access$000(this$0, e);  }
}
```

Safe construction practices

- An object is in a predictable, consistent state *only after its constructor returns*
- Publishing an object within its constructor?
  - You are publishing an incompletely constructed object
  - Even if you are doing so in the last line of the constructor
- RULE: Don't allow `this` to escape during construction

A common mistake is to start a thread from a constructor

- When an object creates a thread in its constructor
  - Almost always shares its `this` reference with the new thread
    - Explicitly: Passing it to the constructor
    - Implicitly: The `Thread` or `Runnable` is an inner class of the owning object
- Nothing wrong with creating a thread in a constructor
  - Just don't start the `Thread`
  - Expose an `initialize()` method

Thread Confinement

Thread confinement

- Accessing shared, mutable data requires synchronization
  - Avoid this by *not sharing*
- If data is only accessed from a single thread?
  - No synchronization is needed
- When an object is **confined** to a thread?
  - Usage is **thread-safe** *even if the object is not*

Thread confinement

- Language has no means of confining an object to a thread
- Thread confinement is an element of a **program's design**
  - Enforced by implementation
- Language and core libraries provide mechanisms to help with this
  - Local variables and the `ThreadLocal` class

Stack confinement

- Object can only be reached through local variables
- Local variables are **intrinsically confined** to the executing thread
  - Exist on executing thread's stack
  - Not accessible to other threads

Thread confinement of reference variables

```
public int loadTheArk() {
   SortedSet<Animal> animals;

   // animals confined to method don't let
   // them escape

   return numPairs;
}
```

If you were to publish a reference to `animals`**, stack confinement would be violated**

ThreadLocal

- Allows you to associate a per-thread value with a value-holding object
- Provides `set` and `get` accessor methods
  - Maintains a separate copy of value for each thread that uses it
  - `get` returns the most recent value passed to `set`
    - From the currently executing thread

Using `ThreadLocal` for thread confinement

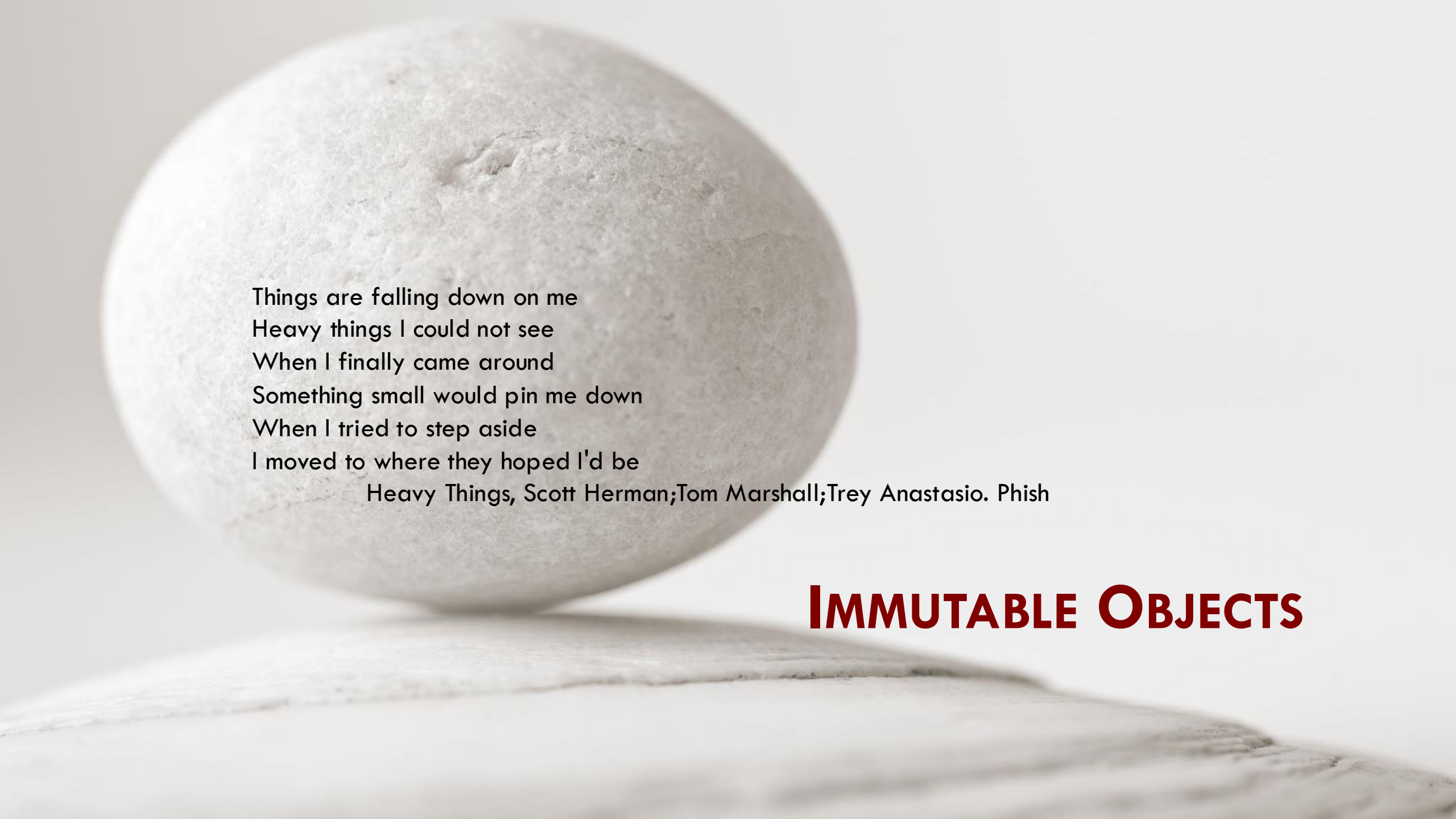
```
private static ThreadLocal<Connection> connectionHolder
   = new ThreadLocal<Connection>() {
        public Connection initialValue() {
          return DriverManager.getConnection(DB_URL);
        }
      };

public static Connection getConnection() {
    return connectionHolder.get();
}
```

Each thread will have its own connection

When thread calls ThreadLocal.get for the first time?
initialValue() provides the initial value

Common use of `ThreadLocal`

- Used when a frequently used operation requires a temporary object
  - Wish to avoid reallocating temporary object on each invocation
- `Integer.toString()`
  - Before 5.0 used `ThreadLocal` to store a 12-byte buffer for formatting result



Things are falling down on me
Heavy things I could not see
When I finally came around
Something small would pin me down
When I tried to step aside
I moved to where they hoped I'd be

Heavy Things, Scott Herman;Tom Marshall;Trey Anastasio. Phish

Immutable Objects

Immutable objects

- State cannot be modified after construction
- All its fields are `final`
- Properly constructed
  - The `this` reference does not escape during construction

Immutable objects

```
public final class ThreeStooges {
   private final Set<String> stooges = new HashSet<String>();

   public ThreeStooges() {
     stooges.add("Moe");
     stooges.add("Larry");
     stooges.add("Curly");
   }

   public boolean isStooge(String name) {
        return stooges.contains(name);
   }
}
```

Design makes it impossible to modify after construction

The stooges reference is final

All object state reached through a final field

Safe publication of objects

- Storing reference to an object into a public field is **not enough** to publish that object safely

```
public Holder holder;

public void initialize() {
   holder = new Holder(42);
}
```

`Holder` **could appear to be in an inconsistent state**

Even though invariants may have been established by constructor

Class at risk of failure if not published properly

```
public class Holder {
   private int n;

   public Holder(int n) {this.n = n}

   public void assertSanity() {
      if (n != n) {
         throw new AssertionError("Statement is false");
      }
   }
}
```

Thread may see a stale value first time it reads the field and an up-to-date value the next time

Pearls and swine bereft of me
Long and weary my road has been
I was lost in the cities
Alone in the hills
No sorrow or pity for leaving, I feel, yeah

I am not your rolling wheels
I am the highway
I am not your carpet ride
I am the sky

I Am the Highway, Audioslave

Composing Objects

Composing Objects

- We don't want to have to analyze *each memory access* to ensure program is thread-safe
- We wish to take thread-safe components and **compose** them into larger components or programs

Basic elements of designing a thread-safe class

- Identify **variables** that *form* the object's state
- Identify **invariants** that *constrain* the state variables
- Establish a **policy** for managing *concurrent access* to the object's state

Synchronization policy

- Defines how object *coordinates access* to its state
  - Without violating its invariants or post-conditions
- Specifies a combination of:
  - Immutability
  - Thread confinement
  - Locking

Looking at a counter

```
public final class Counter {
   private long value=0;

   public synchronized long getValue() {
        return value;
   }

   public synchronized long increment() {
     if (value == Long.MAX_VALUE) {
        throw new IllegalStateException("Counter Overflow");
     }
     value++;
     return value;
   }
}
```

Making a class thread-safe

- Ensure that invariants hold under concurrent access
  - We need to *reason* about state
- Object and variables have **state space**
  - ***Range*** of possible states
  - ***Keep this small*** so that it is easier to reason about

Classes have invariants that tag certain states as valid or invalid

- Looking back at our **`Counter`** example
- The `value` field is a `long`
- The state space ranges from `Long.MIN_VALUE` to `Long.MAX_VALUE`
- The class places constraints on `value`
  - Negative values are not allowed

Operations may have post conditions that tag state transitions as invalid

- Looking back at our **`Counter`** example
- If the current state of `Counter` is `17`
  - The *only* valid next state is `18`
  - When the next state is *derived from the current state*?
    - **Compound action**
- Not all operations impose state transition constraints
  - For e.g., if a variable tracks current temperature? Previous state doesn't impact current state

Constraints and synchronization requirements

- If certain states are invalid?
  - Underlying state variables should be **encapsulated**
    - If not, client code can put it in an *inconsistent* state
- If an operation has invalid state transitions?
  - It must be made **atomic**

The contents of this slide-set are based on the following references

- *Java Concurrency in Practice. Brian Goetz, Tim Peierls, Joshua Bloch, Joseph Bowbeer, David Holmes, and Doug Lea. Addison-Wesley Professional. ISBN: 0321349601/978-0321349606. [Chapters 1, 2, 3 and 4]*
- https://www.javaspecialists.eu/archive/Issue192b.html