CSx55: Distributed Systems [Thread Safety]

Putting the brakes, on impending code breaks

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

- Stateless? Final?
  - Why? How does this help
- Is it not possible to observe a standard data structure in an inconsistent state?

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Topics covered in this lecture

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

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

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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

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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

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GUARDING STATE WITH LOCKS

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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**

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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**

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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<Secrets> knownSecrets;

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

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

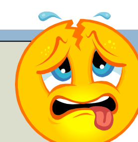
Allowing internal mutable state to escape

```
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

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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*

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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

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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

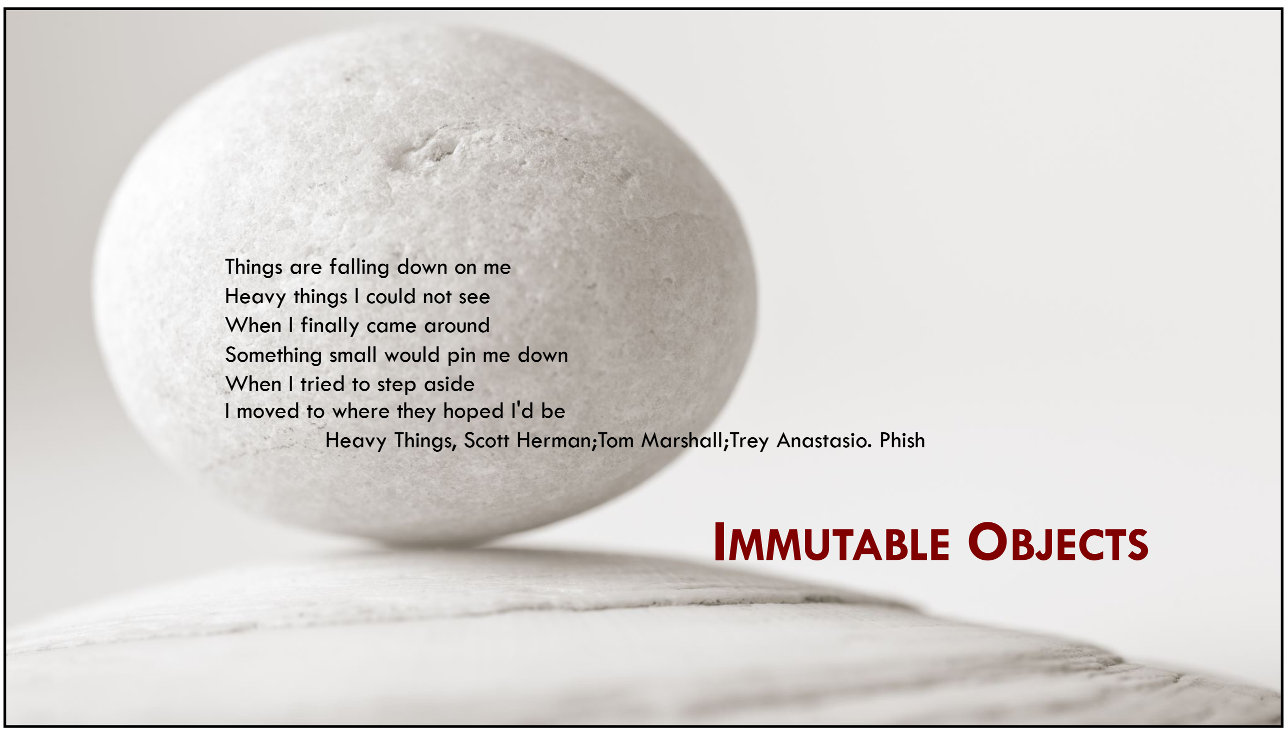
```
private static ThreadLocal<Connection> connectionHolder
   = new ThreadLocal<Connection>() {
        public Connection initialValue() {
          return DriverManager.getConnection(DB_URL);
        }
      };

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



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);
   }
}
```

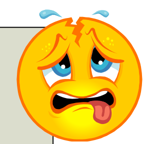
Design makes it impossible to modify after construction

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

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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

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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 <u>combination</u> of:
  - Immutability
  - Thread confinement
  - Locking

  } To maintain Thread Safety

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**

Looking at a case where invariants constrain multiple state variables

```
public class NumberRange {
   private final AtomicInteger lower = new AtomicInteger(0);
   private final AtomicInteger upper = new AtomicInteger(0);

   public void setLower(int i) {
      if (i > upper.get() )
         throw IllegalArgumentException(“lower > upper!”);
      lower.set(i);
   }

   public void setUpper(int i) {
      if (i < lower.get() )
         throw IllegalArgumentException(“upper < lower!”);
      upper.set(i);
   }

   public boolean isInRange(int i){
      return (i >= lower.get() && i <= upper.get());
   }
}
```

Problems with `NumberRange`

- Does not preserve invariant that constrains `lower` and `upper`
- The methods `setLower` and `setUpper` *attempt* this preservation
  - But they do so poorly!
  - They are *check-then-act* sequences that use *insufficient locking* that precludes atomicity

Problems with `NumberRange`

- If the number range **(0, 10)** holds
- One thread calls `setLower(`**5**`)` while another calls `setUpper(`**4**`)`
- With unlucky timing?
  - Both calls will pass checks in the setters
  - Both modifications will be applied
- Range is now `(5,4)` ... an invalid state
- `AtomicInteger` is thread-safe, the composite class is not

Multivariable invariants

- Related variables must be *fetched or updated* in an **atomic** operation
- Don't:
  - Update one
  - Release and reacquire lock, and …
  - Then update others
- The lock that guards the variables
  - Must be **held for the duration of any operation** that accesses them

State-dependent operations

- Objects may have state-based **pre-conditions**
  - E.g., cannot remove item from an empty queue
- In a single-threaded program
  - Operations simply fail
- In a concurrent program
  - Precondition may be *true later* because of the actions of another thread

State dependent operations: Mechanisms

- `wait()/notify()`
  - Supported by the JVM and closely tied with intrinsic locking
- Other possibilities
  - Use classes such as blocking queues or semaphores

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