CS 455: Introduction To 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

- What if A calls B, which is atomic, and B fails?
- Externally visible behavior of an object?
- Is a class with private final objects thread safe?

Topics covered in this lecture

- Sharing & Composing Objects
- Making a class thread-safe
- Multivariable invariants and thread-safety
- Adding functionality to a thread-safe class

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 a `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 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**

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 a object to a thread
- Thread confinement is an element of **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

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() {return stooges.contains(name);}
}
```

Design makes it impossible to modify after construction

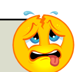
The stooges reference is final
All object state reached through a final field

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

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

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

State Ownership

State ownership

- Defining which variables form an object's state
  - We wish to consider only that which the object owns
- Ownership
  - Not explicitly specified in the language
  - **Element of program design**

State ownership: Encapsulation and ownership go together

- Object encapsulates the state it owns
  - Owns the state it encapsulates
- Owner gets to decide on the **locking protocol**
- If you publish a reference to a mutable object?
  - You no longer have exclusive control

Instance confinement

- Object may not be thread-safe
  - But we could still use it in a thread-safe fashion
- Ensure that:
  - It is accessed by only one thread
  - All accesses guarded by a lock

Confinement and locking working together

```
public class PersonSet {
   private final Set<Person> mySet = new HashSet<Person>();

   public synchronized void addPerson(Person p) {
      mySet.add(p);
   }

   public synchronized boolean containsPerson(Person p) {
      return mySet.contains(p);
   }
}
```

Looking at our previous example

- State of `PersonSet` managed by `HashSet`, which is not thread-safe
- But `mySet` is
  - Private
  - Not allowed to escape
  - Confined to `PersonSet`

But we have made no assumptions about `Person`

- If it is mutable, additional synchronization is needed
  - When accessing `Person` from `PersonSet`
- Reliable way to achieve this?
  - Make `Person` thread-safe
- Less-reliable way?
  - Guard `Person` objects with a lock
  - Ensure that clients follow protocol of acquiring appropriate lock, before accessing `Person`

Instance confinement is the easiest way to build thread-safe classes

- Class that confines it state can be analyzed for thread-safety
  - Without having to examine the whole program

GUARDING STATE WITH PRIVATE LOCKS

Guarding state with a private lock

```
public class PrivateLock {
   private final Object myLock = new Object();

   private Widget widget; //guarded by myLock

   public void someMethod() {
      synchronized(myLock) {
         //Access and modify the state of the widget

      }
   }
}
```


Why guard state with a private lock?

- Doing so encapsulates the lock
  - **Client code cannot acquire it!**
- Publicly accessible lock allows client code to participate in its synchronization policy
  - Correctly or incorrectly
- Clients that improperly acquire an object's lock cause *liveness* issues
- Verifying correctness with public locks requires examining the entire program not just a class

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 3 and 4]