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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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
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

```java
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

```java
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

```java
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`

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

    public ThisEscape$1(EventSource source) {
        ThisEscape$1(this$0);  
        source.registerListener(new ThisEscape$1(this));  
        this$0 = thisescape;  
    }

    public void onEvent(Event e) {
        ThisEscape.access$000(t
    }

    private void doSomething(Event e) {
        ..
    }

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

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**
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

```java
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

```java
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

```java
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

```java
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

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Class at risk of failure if not published properly

```java
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

- 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

```java
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

```java
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 \(\text{setLower}(5)\) while another calls \(\text{setUpper}(4)\)
- 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

- 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

```java
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 its state can be analyzed for thread-safety
- Without having to examine the whole program
Guarding state with a private lock

```java
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

- https://www.javaspecialists.eu/archive/Issue192b.html