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

- How does notify() know/choose which thread to notify?
- You talked about benefits of Locks over synchronized blocks, advantages of synchronized blocks over locks?
- Do synchronized methods/blocks have implicit wait()/notify()?
- Can we use synchronized in interfaces to force implementations?
- Isn’t there parallelism at a single-core? We still need synchronization?
- Are updates to the acquisition counts on locks done atomically?

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
    - Sharing 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 ThisEscape$1(this));
    }
    private void doSomething(Event e) {
        …..
    }
    static void access$000(ThisEscape _this, Event event) {
        _this.doSomething(event);
    }
}
```

- 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$1 implements EventListener {
    public void onEvent(Event e) {
        ThisEscape.access$000(this, e);
    }
}
```

```
class ThisEscape$2 implements EventListener {
    public void onEvent(Event e) {
        ThisEscape.access$000(this, 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.
  - Even if you are doing so in the last line of the constructor.
- Nothing wrong with creating a thread in a constructor
  - Just don't start the Thread.
  - Expose an initialize() method.

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 an 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.

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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

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Immutable objects

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

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**IMMUTABLE OBJECTS**
**Immutable objects**

```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

*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 final 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*

**Composite 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 objects coordinate 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 new IllegalArgumentException("lower > upper!");
        lower.set(i);
    }

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

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

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

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
- Ownership
  - Not explicitly specified in the language
  - Element of program design
- 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

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 a private lock

```java
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

- https://www.javaspecialists.eu/archive/issue192b.html