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?
Topics covered in this lecture

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

Atomicity with compound operations

```java
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

```java
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
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?

```java
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**
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

```java
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
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

```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
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*

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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
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

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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

```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**

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

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

- 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