CS 455: INTRODUCTION TO DISTRIBUTED SYSTEMS

[THREAD SAFETY]

Threads have you in a bind?
With Objects and Concurrency at play
Are nerves about to fray?
Here’s something to have those worries abate
It’s just about access to shared, mutable state

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Frequently asked questions from the previous class survey

- Why would we want to synchronize static methods?
- Can you call a static synchronized at the same time as a synchronized method? Yes.
- Can too much synchronization lead to starvation? Yes.
- How can you have a lock object over multiple methods?
Topics covered in this lecture

- Thread safety
- Compound actions
- Reentrancy

Wrap-up of Wait-Notify
What if `notify()` is called and no thread is waiting?

- Wait-and-notify mechanism has no knowledge about the condition about which it notifies
- If `notify()` is called when no other thread is waiting?
  - The notification is lost

What happens when more than 1 thread is waiting for a notification?

- Language specification does not define which thread gets the notification
  - Based on JVM implementation, scheduling and timing issues
- No way to determine which thread will get the notification
**notifyAll()**

- All threads that are waiting on an object are notified
- When threads receive this, they must work out
  ① Which thread should continue
  ② Which thread(s) should call `wait()` again
  - All threads wake up, but they **still have to reacquire the object lock**
  - Must wait for the lock to be freed

**Threads and locks**

- **Locks are held by threads**
  - A thread can hold multiple locks
  - Any thread that tries to obtain these locks? Placed into a wait state
  - If the thread deadlocks? It results in all locks that it holds becoming unavailable to other threads

- If a lock is held by some other thread?
  - The thread **must wait** for it to be free: There is no preemption of locks!
  - If the lock is unavailable (or held by a deadlocked thread) it blocks all the waiting threads
Thread Safety

Race conditions

- Getting the right answer depends on lucky timing
  - E.g. check-then-act: When stale observations are used to make a decision on what to do next

- Real world example
  - Our example from last class of 2 friends trying to meet up for coffee on campus without specifying which of the 2 locations
Purpose of synchronization?
- Prevent race conditions that can cause data to be found in either an inconsistent or intermediate state.
- Threads are not allowed to race during sections of code protected by synchronization.
- But this does not mean outcome or order of execution of threads is deterministic.
  - Threads may be racing prior to the synchronized section of code.

If threads are waiting on the same lock
- The order in which the synchronized code is executed is determined by order in which lock is granted.
  - Which is platform-specific and non-deterministic.
Racing and synchronization

- Not all races should be avoided
  - This is a subtle but important point: If you do this … every thing is serialized
  - Only race-conditions within thread-unsafe sections of the code are considered a problem
    ① Synchronize code that prevents race condition
    ② Design code that is thread-safe without the need for synchronization (or minimal synchronization)
Concurrent programming

- Concurrent programs require the correct use of threads and locks
- But these are just mechanisms

Object State

- Includes its data
  - Stored in instance variables or static fields
  - Fields from dependent objects
    - HashMap’s state also depends on Map.Entry<K, V> objects
  - Encompasses any data that can affect its externally visible behavior
The crux of developing thread safe programs

- Managing access to **state**
  - In particular *shared, mutable state*

- Shared
  - Variables could be accessed by multiple threads

- Mutable
  - Variable's values change over its lifetime

- Thread-safety
  - Protecting data from uncontrolled concurrent access

When to coordinate accesses

- Whenever more than one thread accesses a state variable, and one of them **might write** to it?
  - They must all coordinate their access to it

- Avoid temptation to think that there are special situations when you can disregard this
When should an object be thread-safe?

- Will it be accessed from multiple threads?
- The key here is how the object is used
  - Not what it does

How to make an object thread-safe

- Use synchronization to coordinate access to mutable state
- Failure to do this?
  - Data corruptions
  - Problems that manifest themselves in myriad forms
Mechanisms for synchronization in Java

- One way to achieve this is via the `synchronized` keyword
  - Exclusive locking
- Other approaches include:
  - `volatile` variables
  - Explicit locks
  - `Atomic` variables

Programs that omit synchronizations

- Might work for some time
  - But it `will break` at some point
- Far easier to design a class to be thread-safe `from the start`
  - Retrofitting it to be thread-safe is extremely hard
Thread-safety: Encapsulate your state

- Fewer code should have access to a particular variable
  - Easier to reason about *conditions* under which it might be accessed

- **DON'T:**
  - Store state in public fields
  - Publish reference to an *internal* object

Fixing access to mutable state variables from multiple threads

- *Don’t share* state variables across threads
- Make state variables *immutable*
- Use *synchronization* to coordinate access to the state variable
Correctness of classes

- Class conforms to **specification**
- **Invariants** constrain object’s state
- **Post conditions** describe the effects of operations

A Thread-safe class

- **Behaves correctly** when accessed from multiple threads
- Regardless of **scheduling or interleaving** of execution of those threads
  - By the runtime environment
- No **additional synchronization or coordination** by the calling code
Really?

- Thread safe classes encapsulate *any needed* synchronization
- Clients **should not** have to provide their own

Stateless objects are always thread-safe

```java
public class StatelessClass implements Servlet {
    public void factorizer(ServletRequest req, ServletResponse resp) {
        BigInteger i = extractFromReq(req);
        BigInteger[] factors = factorize(i);
        encodeIntoResponse(resp, factors);
    }
}
```
Stateless objects are always thread-safe

- **Transient state** for a particular computation exists solely in *local* variables
  - Stored on the thread’s stack
  - Accessible only to the executing thread

- One thread cannot influence the result of another
  - The threads have no shared state

Atomicity

- Let’s look at two operations A and B
- From the perspective of thread executing A
- When another thread executes B
  - Either all of B has executed or none of it has
- Operations A and B are *atomic* with respect to each other
Initializing Objects

```java
public class LazyInitialization {
    private ExpensiveObject instance = null;
    public ExpensiveObject getInstance() {
        if (instance == null) {
            instance = new ExpensiveObject();
        }
        return instance;
    }
}
```

Thread-safe initialization

```java
public class Singleton {
    private static final Singleton instance = new Singleton();

    // Private constructor prevents instantiation from other classes
    private Singleton() {
    }

    public static Singleton getInstance() {
        return instance;
    }
}
```
The final keyword

- You cannot extend a final class
  - E.g. java.lang.String
- You cannot override a final method
- You can only initialize a final variable once
  - Either via an initializer or an assignment statement

Blank final instance variable of a class

- Must be assigned within every constructor of the class
- Attempting to set it outside the constructor will result in a compilation error
- The value of a final variable is not necessarily known at compile time
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

Locks & Reentrancy
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

- 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
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

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]