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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Topics covered in this lecture

- Wrap-up of wait-notify
- Thread safety
- Compound actions
- Reentrancy
A code snippet that uses wait-notify to control the execution of the thread

```java
public class Tester implements Runnable {
    private boolean done = true;

    public synchronized run() {
        while (true) {
            if (done) wait();
            else { ... Logic ... wait(100);}
        }
    }

    public synchronized void setDone(boolean b) {
        done = b;
        if (!done) notify();
    }
}
```
About the `wait()` method

- When `wait()` executes, the synchronization lock is `released` by the JVM.
- When a notification is received?
  - The thread needs to `reacquire` the synchronization lock before returning from `wait()`.

Integration of wait-notify and synchronization

- **Tightly integrated** with the synchronization lock.
  - Feature not directly available to us.
  - Not possible to implement this: native method.
- This is typical of approach in other libraries.
  - `Condition variables` for Solaris and POSIX threads require that a mutex lock be held.
Details of the race condition in the wait-notify mechanism

- The first thread tests the condition and confirms that it must wait
- The second thread sets the condition
- The second thread calls notify()
  - This goes unheard because the first thread is not yet waiting
- The first thread calls wait()

How does the potential race condition get resolved?

- To call wait() or notify()
  - Obtain lock for the object on which this is being invoked
- It seems as if the lock has been held for the entire wait() invocation, but ...
  1. wait() releases lock prior to waiting
  2. Reacquires the lock just before returning from wait()
Is there a race condition during the time `wait()` releases and reacquires the lock?

- `wait()` is **tightly integrated** with the lock mechanism
- Object lock is **not freed until** the waiting thread is in a **state in which it can receive notifications**
  - System prevents race conditions from occurring here

If a thread receives a notification is it guaranteed that condition is set?

- No
- **Prior** to calling `wait()`, **test condition** while holding lock
- Upon **returning** from `wait()` **retest** condition to see if you should `wait()` again
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

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**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
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
Racing and synchronization [1/3]

- **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

Racing and synchronization [2/3]

- 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
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### 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
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
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

- 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
class Widget {
    public synchronized doSomething() {
        ...
    }
}
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]