CS 455: Introduction To Distributed Systems [Thread Safety]

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Frequently asked questions from the previous class survey

- `synchronize` in interfaces?
- Multiple inheritance and `synchronized`
  - Java supports *multiple inheritance of type* NOT implementation
- If a Thread A calls a `synchronized` method in Thread B, does it acquire the object lock for B … what would happen to A?
- Any other way to bypass using volatile (without wait-notify or `synchronized`)
- wait-notify and the Lock interface
- When using synchronized block in a synchronized method which locks would you acquire?
- What if an unsynchronized method calls a synchronized method? Can other threads execute in the unsynchronized method?
- Are locks inherited?

Topics covered in this lecture

- Thread safety
- Compound actions
- Reentrancy
- Sharing objects and confinement

A code snippet that uses wait-notify to control the execution of the thread

```
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();
   }
}
```


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

Threads and locks

- **Locks are held by threads**
  - A thread can hold multiple locks
    - Any thread that tries to obtains 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
  - 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 [3/3]

- 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 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

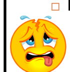
- One way to achieve this is via the `synchronized` keyword
  - Exclusive locking
- Other approaches include:
  - `volatile` variables
  - Explicit **locks**
  - **Atomic** variables

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 thread-safe

```
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
- Operation **A** and B are **atomic** *with respect to each other*

Initializing Objects

```
public class LazyInitialization {

    private ExpensiveObject instance = null;

    public ExpensiveObject getInstance() {
       if (instance == null) {
         instance = new ExpensiveObject();
       }
       return instance;
    }
}
```

Thread-safe initialization

```
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

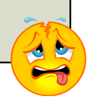
Atomicity with compound operations

```
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

```
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

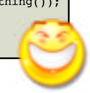
How reentrancy works [2/2]

- 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?

```
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

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

```
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 Threads. Scott Oaks and Henry Wong. 3rd Edition. O'Reilly Press. ISBN: 0-596-00782-5/978-0-596-00782-9.* [Chapter 3, 4]
- *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]*