CSx55: Distributed Systems [Threads & 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

- When to use synchronized (implicit) vs explicit locks?
- When to use `tryLock()` over `lock()`?
- `Condition` on the `Lock` interface?

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Topics covered in this lecture

- wait-notify
- Thread safety

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Objects and communications

- Every object has a lock
- Every object also includes mechanisms that allow it to be a **waiting area**
  - Allows *communication* between threads

Conditions

- One thread needs a **condition** to exist
  - Assumes another thread will *create* that condition
- When another thread creates the condition?
  - It **notifies** the first thread that has been **waiting** for that condition

`wait(), notify()` and the `Object` class

```
public class Object {

   public void wait();

   public void wait(long timeout);

   public void notify();
}
```


`wait(), notify()` and the `Object` class

- Wait-and-notify mechanisms are available for every object
  - Accomplished by **method invocations**
- Synchronized mechanism is handled by using a *keyword*

Wait-and-notify relate to synchronization, but …

- It is more of a **communications mechanism**
- Allows one thread to communicate to another that a **condition** has occurred
  - Does not specify *what* that specific condition is

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Can wait-and-notify replace the synchronized mechanism?

- No
- <u>Does not</u> solve the race condition that the synchronized mechanism solves
- Must be used in **conjunction** with the synchronized lock
  - Prevents race condition that exists in the `wait-notify` mechanism itself

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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();
   }
}
```


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

Threads and locks: Summary

- **Locks are held by threads**
  - A thread can hold <u>multiple locks</u>
    - 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

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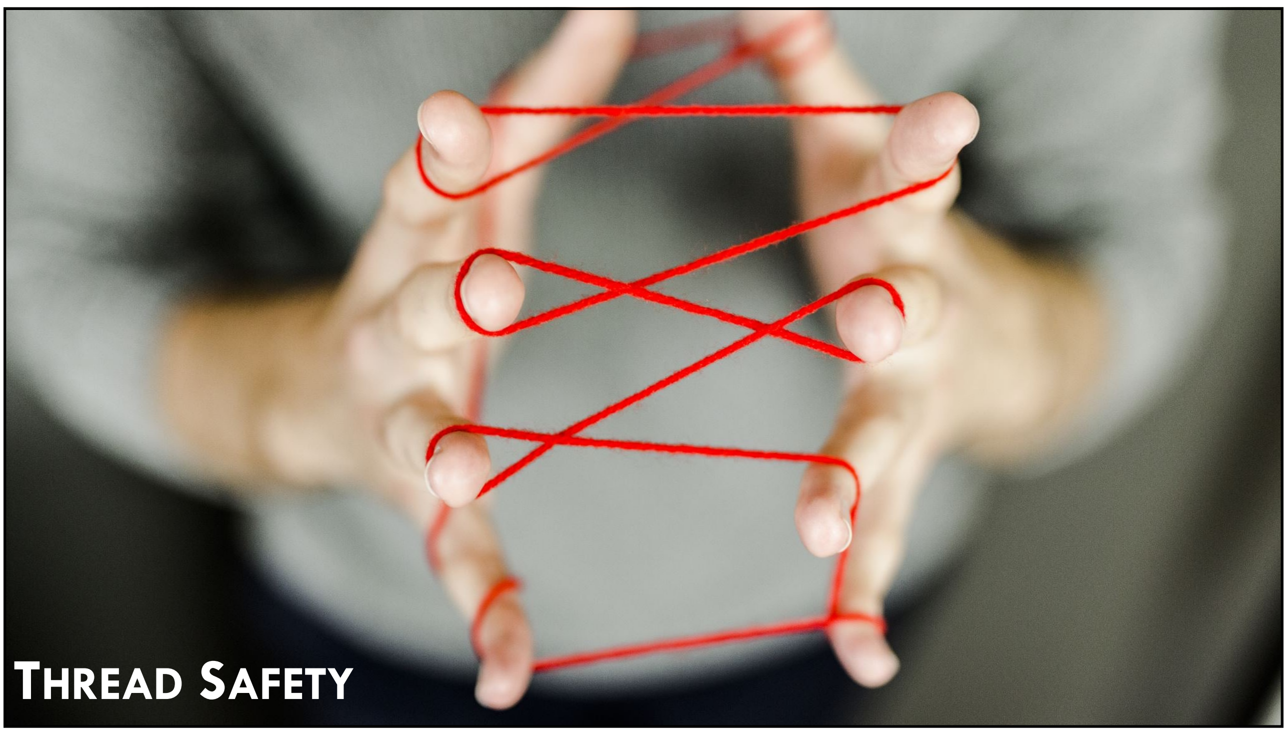

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Race conditions

- 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 previous example of 2 friends trying to meet up for coffee on campus without specifying which of the 2 locations

Racing and synchronization [1/3]

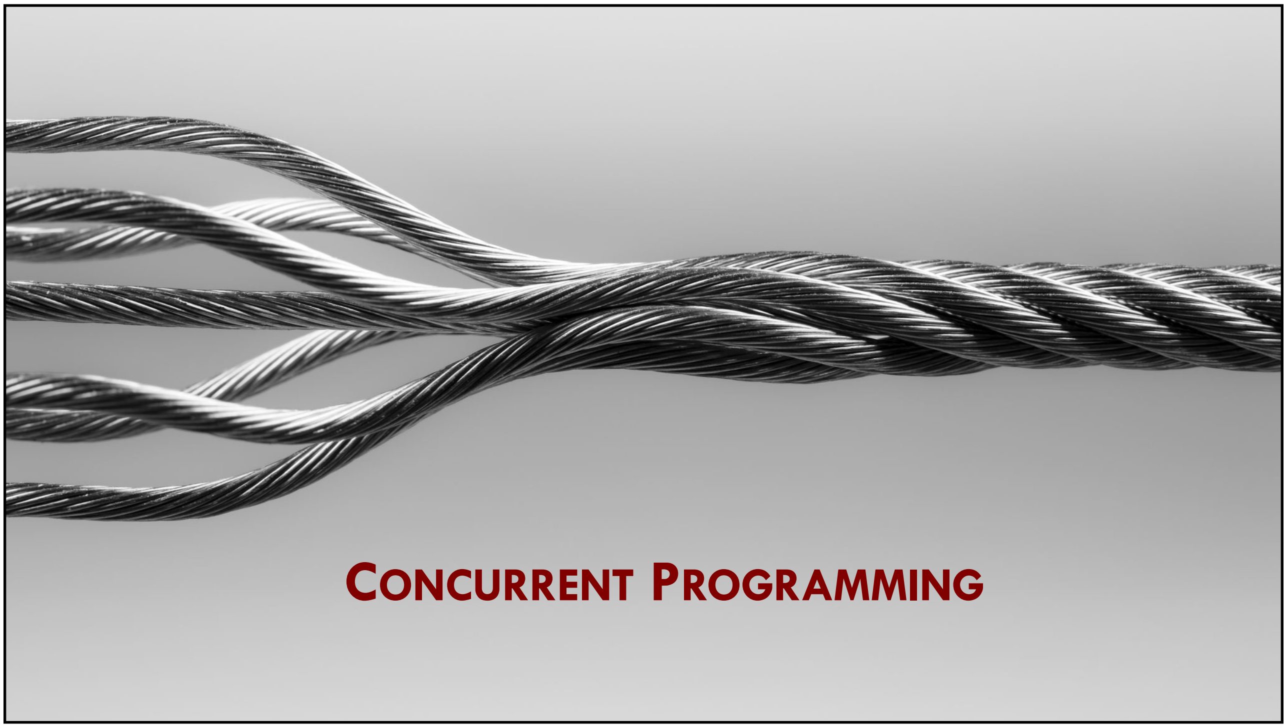
- Purpose of **synchronization**?
  - Prevent race conditions that can cause data to be found in either an inconsistent or intermediate state
- Threads are not allowed to race during sections of code protected by synchronization
  - But this does not mean outcome or order of execution of threads is deterministic
    - 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 [3/3]

- Not all races should be avoided
  - This is a subtle but important point: If you do this … everything 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 requires minimal synchronization)



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Concurrent programming

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

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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

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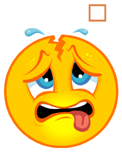
Thread-safety: Encapsulate your state

- 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



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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 <u>additional synchronization or coordination</u> by the calling code

Really?

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

Stateless objects are always 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
- Operations **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

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.* [Chapters 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]*