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?
Topics covered in this lecture

- wait-notify
- Thread safety
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-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
- **Does not** 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**
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
Threads and locks: Summary

- **Locks are held by threads**
  - A thread can hold **multiple locks**
    - Any thread that tries to obtain these locks is 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 previous example of 2 friends trying to meet up for coffee on campus without specifying which of the 2 locations

Racing and synchronization

- 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)
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);
    }
}
```

- **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

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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]