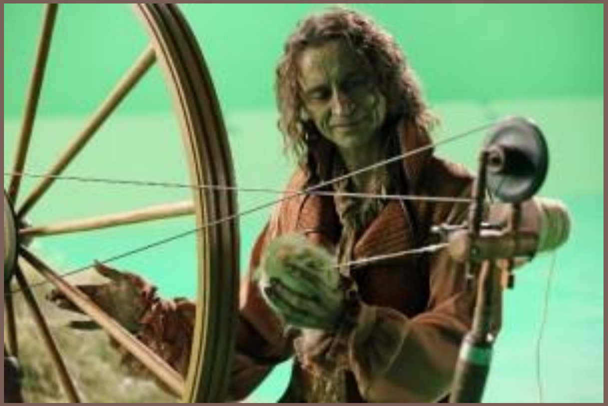


THREADS AND CONCURRENCY

Lecture 22 – CS2110 – Spring 2013

What is a Thread?

- *A separate "execution" that runs within a single program and can perform a computational task independently and concurrently with other threads*
- Many applications do their work in just a single thread: the one that called main() at startup
  - But there may still be extra threads...
  - ... Garbage collection runs in a "background" thread
  - GUIs have a separate thread that listens for events and "dispatches" upcalls
- Today: learn to create new threads of our own

What is a Thread?

- A thread is a kind of object that "independently computes"
  - Needs to be created, like any object
  - Then "started". This causes some method (like main()) to be invoked. It runs side by side with other thread in the same program and they see the same global data
- The actual execution could occur on distinct CPU cores, but doesn't need to
  - We can also simulate threads by *multiplexing* a smaller number of cores over a larger number of threads

Concurrency

- *Concurrency* refers to a single program in which several threads are running simultaneously
  - Special problems arise
  - They see the same data and hence can interfere with each other, e.g. if one thread is modifying a complex structure like a heap while another is trying to read it
- In cs2110 we focus on two main issues:
  - Race conditions
  - Deadlock

Thread class in Java

- Threads are instances of the class Thread
  - Can create many, but they do consume space & time
- The Java Virtual Machine created the thread that executes your main method.
- Threads have a priority
  - Higher priority threads are executed preferentially
  - A newly created Thread has initial priority equal to the thread that created it (but can change)

Creating a new Thread (Method 1)


```
class PrimeThread extends Thread {
    long a, b;

    PrimeThread(long a, long b) {
        this.a = a; this.b = b;
    }

    public void run() {
        //compute primes between a and b
        ...
    }
}
```

overrides **Thread.run()**

If you were to call **run()** directly no new thread is used: the calling thread will run it

```
PrimeThread p = new Prime
p.start();
```

... but if you create a new object and then call **start()**, Java invokes **run()** in new thread

Creating a new Thread (Method 2)


```java
class PrimeRun implements Runnable {
    long a, b;

    PrimeRun(long a, long b) {
        this.a = a; this.b = b;
    }

    public void run() {
        //compute primes between a and b
        ...
    }
}
```

```java
PrimeRun p = new PrimeRun(143, 195);
new Thread(p).start();
```

Example


```
public class ThreadTest extends Thread {

   public static void main(String[] args) {
      new ThreadTest().start();
      for (int i = 0; i < 10; i++) {
         System.out.format("%s %d\n",
            Thread.currentThread(), i);
      }
   }

   public void run() {
      for (int i = 0; i < 10; i++) {
         System.out.format("%s %d\n",
            Thread.currentThread(), i);
      }
   }
}
```

```
Thread[Thread-0,5,main] 0
Thread[main,5,main] 0
Thread[main,5,main] 1
Thread[main,5,main] 2
Thread[main,5,main] 3
Thread[main,5,main] 4
Thread[main,5,main] 5
Thread[main,5,main] 6
Thread[main,5,main] 7
Thread[main,5,main] 8
Thread[main,5,main] 9
Thread[Thread-0,5,main] 1
Thread[Thread-0,5,main] 2
Thread[Thread-0,5,main] 3
Thread[Thread-0,5,main] 4
Thread[Thread-0,5,main] 5
Thread[Thread-0,5,main] 6
Thread[Thread-0,5,main] 7
Thread[Thread-0,5,main] 8
Thread[Thread-0,5,main] 9
```

Example


```java
public class ThreadTest extends Thread {

   public static void main(String[] args) {
      new ThreadTest().start();
      for (int i = 0; i < 10; i++) {
         System.out.format("%s %d\n",
            Thread.currentThread(), i);
      }
   }

   public void run() {
      currentThread().setPriority(4);
      for (int i = 0; i < 10; i++) {
         System.out.format("%s %d\n",
            Thread.currentThread(), i);
      }
   }
}
```

```
Thread[main,5,main] 0
Thread[main,5,main] 1
Thread[main,5,main] 2
Thread[main,5,main] 3
Thread[main,5,main] 4
Thread[main,5,main] 5
Thread[main,5,main] 6
Thread[main,5,main] 7
Thread[main,5,main] 8
Thread[main,5,main] 9
Thread[Thread-0,4,main] 0
Thread[Thread-0,4,main] 1
Thread[Thread-0,4,main] 2
Thread[Thread-0,4,main] 3
Thread[Thread-0,4,main] 4
Thread[Thread-0,4,main] 5
Thread[Thread-0,4,main] 6
Thread[Thread-0,4,main] 7
Thread[Thread-0,4,main] 8
Thread[Thread-0,4,main] 9
```

Example


```java
public class ThreadTest extends Thread {

   public static void main(String[] args) {
      new ThreadTest().start();
      for (int i = 0; i < 10; i++) {
         System.out.format("%s %d\n",
            Thread.currentThread(), i);
      }
   }

   public void run() {
      currentThread().setPriority(6);
      for (int i = 0; i < 10; i++) {
         System.out.format("%s %d\n",
            Thread.currentThread(), i);
      }
   }
}
```

```
Thread[main,5,main] 0
Thread[main,5,main] 1
Thread[main,5,main] 2
Thread[main,5,main] 3
Thread[main,5,main] 4
Thread[main,5,main] 5
Thread[Thread-0,6,main] 0
Thread[Thread-0,6,main] 1
Thread[Thread-0,6,main] 2
Thread[Thread-0,6,main] 3
Thread[Thread-0,6,main] 4
Thread[Thread-0,6,main] 5
Thread[Thread-0,6,main] 6
Thread[Thread-0,6,main] 7
Thread[Thread-0,6,main] 8
Thread[Thread-0,6,main] 9
Thread[main,5,main] 6
Thread[main,5,main] 7
Thread[main,5,main] 8
Thread[main,5,main] 9
```

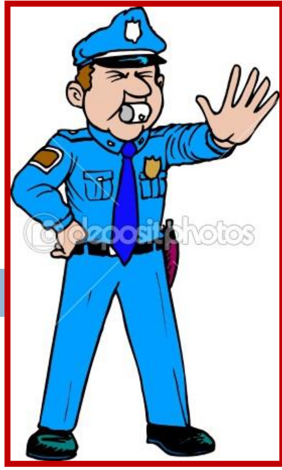
Example


```
public class ThreadTest extends Thread {
   static boolean ok = true;

   public static void main(String[] args) {
      new ThreadTest().start();
      for (int i = 0; i < 10; i++) {
         System.out.println("waiting...");
         yield();
      }
      ok = false;
   }

   public void run() {
      while (ok) {
         System.out.println("running...");
         yield();
      }
      System.out.println("done");
   }
}
```

```
waiting...
running...
waiting...
running...
waiting...
running...
waiting...
running...
waiting...
running...
waiting...
running...
waiting...
running...
done
```

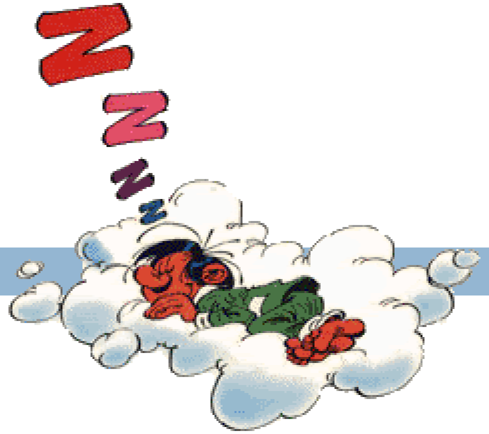
If threads happen to be sharing a CPU, yield allows other waiting threads to run. But if there are multiple cores, yield isn't needed

Terminating Threads is tricky



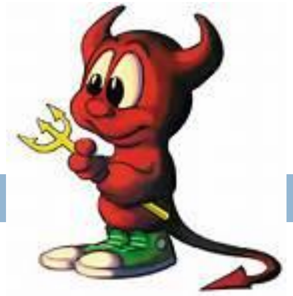
- Easily done... but only in certain ways
  - *The safe way to terminate a thread is to have it return from its run method*
  - *If a thread throws an uncaught exception, whole program will be halted (but it can take a second or too...)*
- There are some old APIs but they have issues: stop(), interrupt(), suspend(), destroy(), etc.
  - Issue: they can easily leave the application in a "broken" internal state.
  - Many applications have some kind of variable telling the thread to stop itself.

Threads can pause



- When active, a thread is "runnable".
  - It may not actually be "running". For that, a CPU must schedule it. Higher priority threads could run first.
- A thread can also pause
  - It can call Thread.sleep(k) to sleep for k milliseconds
  - If it tries to do "I/O" (e.g. read a file, wait for mouse input, even open a file) this can cause it to pause
  - Java has a form of locks associated with objects. When threads lock an object, one succeeds at a time.

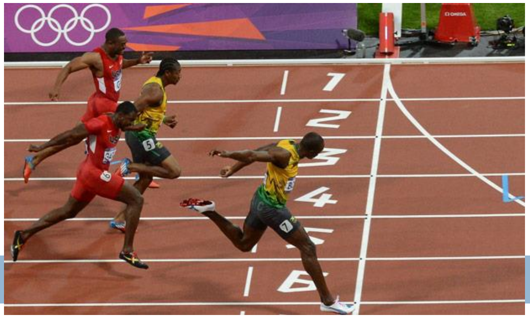
Background (daemon) Threads



- In many applications we have a notion of "foreground" and "background" (daemon) threads
  - Foreground threads are the ones doing visible work, like interacting with the user or updating the display
  - Background threads do things like maintaining data structures (rebalancing trees, garbage collection, etc)

- On your computer, the same notion of background workers explains why so many things are always running in the task manager.

Race Conditions



- A "race condition" arises if two or more threads access the same variables or objects concurrently and at least one does updates
- Example: Suppose t1 and t2 simulatenously execute the statement x = x + 1; for some static global x.
  - Internally, this involves loading x, adding 1, storing x
  - If t1 and t2 do this concurrently, we execute the statement twice, but x may only be incremented once
  - t1 and t2 "race" to do the update

Race Conditions

- Suppose X is initially 5

Thread t1	Thread t2
LOAD X	...
	LOAD X
ADD 1	ADD 1
	STORE X
STORE X	

- ... after finishing, X=6! We "lost" an update

Settings where race conditions matter

- Two or more threads try to access something, and one or more want to change it
- A for-each loop is iterating over a collection, but some thread modifies the collection concurrently
- You want your program to do one thing at a time, e.g. so that the user can fill in a form without being interrupted to fill in some other form
- … this list is very partial!

Race Conditions

- Race conditions are bad news
  - Sometimes you can make code behave correctly despite race conditions, but more often they cause bugs
  - And they can cause many kinds of bugs, not just the example we see here!
  - A common cause for "blue screens", null pointer exceptions, damaged data structures

Example – A Lucky Scenario


```
private Stack<String> stack = new Stack<String>();

public void doSomething() {
    if (stack.isEmpty()) return;
    String s = stack.pop();
    //do something with s...
}
```

Suppose threads A and B want to call **`doSomething()`**, and there is one element on the stack

1. thread A tests **`stack.isEmpty()`** false
2. thread A pops ⇒ stack is now empty
3. thread B tests **`stack.isEmpty()`** ⇒ true
4. thread B just returns – nothing to do

Example – An Unlucky Scenario


```java
private Stack<String> stack = new Stack<String>();

public void doSomething() {
    if (stack.isEmpty()) return;
    String s = stack.pop();
    //do something with s...
}
```

Suppose threads A and B want to call **`doSomething()`**, and there is one element on the stack

1. thread A tests **`stack.isEmpty()`** ⇒ false
2. thread B tests **`stack.isEmpty()`** ⇒ false
3. thread A pops ⇒ stack is now empty
4. thread B pops ⇒ Exception!

Synchronization

- Java has one "primary" tool for preventing these problems, and you must use it by carefully and explicitly – it isn't automatic.
  - Called a "synchronization barrier"
  - We think of it as a kind of lock
    - Even if several threads try to acquire the lock at once, only one can succeed at a time, while others wait
    - When it releases the lock, the next thread can acquire it
    - You can't predict the order in which contending threads will get the lock but it should be "fair" if priorities are the same

Java synchronizations: several forms…

- One popular option is called a **Semaphore**
  - An object: Semaphore mySema = new Semaphore(n);
  - mySema.acquire() – locks the semaphore. n+1'st call will block (e.g. if n was 0, first call will block, etc)
  - mySema.release() – unlocks the semaphore object

- Simple and popular, but can be a bit "unstructured" and in complex code, a common source of problems

Solution – with synchronization


```
private Stack<String> stack = new Stack<String>();

public void doSomething() {
    synchronized (stack) {
        if (stack.isEmpty()) return;
        String s = stack.pop();
    }
    //do something with s...
}
```

synchronized block

- Put critical operations in a **synchronized** block
- The **stack** object acts as a lock
- Only one thread can own the lock at a time

Second Solution – Object Locking

- You can lock on any object, including **`this`**

```
public synchronized void doSomething() {
    ...
}
```

is equivalent to

```
public void doSomething() {
    synchronized (this) {
        ...
    }
}
```

Synchronization+priorities

- Combining mundane features can get you in trouble
- Java has priorities... and synchronization
  - But they don't "mix" nicely
  - High-priority runs before low priority
  - ... The lower priority thread "starves"

- Even worse...
  - With many threads, you could have a second high priority thread stuck waiting on that starving low priority thread! Now <u>both</u> are starving...

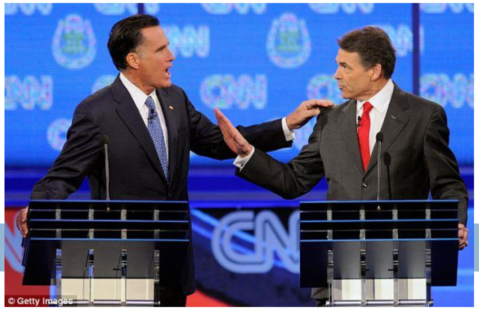
Fancier forms of locking

- Java developers have created various synchronization ADTs
  - Semaphores: a kind of synchronized counter
  - Event-driven synchronization

- The Windows and Linux and Apple O/S all have kernel locking features, like file locking

- But for Java, **synchronized** is the core mechanism

Deadlock



- The downside of locking – deadlock
- A deadlock occurs when two or more competing threads are waiting for one-another… forever
- Example:
  - Thread t1 calls synchronized b inside synchronized a
  - But thread t2 calls synchronized a inside synchronized b
  - t1 waits for t2… and t2 waits for t1…

Finer grained synchronization

- Java allows you to do fancier synchronization
  - But can only be used inside a synchronization block
  - Special primatives called wait/notify

wait/notify

Suppose we put this inside an object called animator:

```
boolean isRunning = true;

public synchronized void run() {
    while (true) {
        while (isRunning) {
            //do one step of simulation
        }
        try {
            wait();
        } catch (InterruptedException ie) {}
        isRunning = true;
    }
}
```

must be synchronized!

relinquishes lock on **animator** – awaits notification

```
public void stopAnimation() {
    animator.isRunning = false;
}

public void restartAnimation() {
    synchronized(animator) {
        animator.notify();
    }
}
```

notifies processes waiting for **animator** lock

Summary

- Use of multiple processes and multiple threads within each process can exploit concurrency
  - Which may be real (multicore) or “virtual” (an illusion)
- But when using threads, beware!
  - Must lock (synchronize) any shared memory to avoid non-determinism and race conditions
  - Yet synchronization also creates risk of deadlocks
  - Even with proper locking concurrent programs can have other problems such as “livelock”
- Serious treatment of concurrency is a complex topic (covered in more detail in cs3410 and cs4410)