RACE CONDITIONS AND SYNCHRONIZATION

Lecture 25 – CS2110 – Fall 2014

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

Working Example: "SummationJob"


```
public class SummationJob implements Runnable {

  public static       int X        = 0;
  public static       int NDONE    = 0;
  public static final int NTHREADS = 2;

  /** Increments X 1000 times. */
  public void run() {
    for(int k=0; k<1000; k++) {
       X = X + 1; // (WARNING: MAIN RACE CONDITION)
    }
    NDONE += 1; // (WARNING: ANOTHER RACE CONDITION)
  }

  /** Launches NTHREADS SummationJob objects that try to increment X to NTHREADS*1000 */
  public static void main(String[] args) {
    try {
      Thread[] threads = new Thread[NTHREADS];
      for(int k=0; k<NTHREADS; k++)
         threads[k] = new Thread(new SummationJob());

      for(int k=0; k<NTHREADS; k++)
          threads[k].start();

      while(NDONE < NTHREADS) Thread.sleep(100);

      System.out.println("X="+X);

    }catch(Exception e) {
       e.printStackTrace();
       System.out.println("OOPS"+e);
    }
  }
}
```

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

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

Solution – Locking

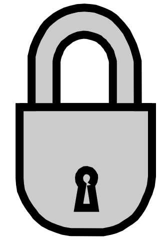
- You can lock on any object, including `this`

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

is equivalent to

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

How locking works



- Only one thread can "hold" a lock at a time
  - If several request the same lock, Java somehow decides which will get it
- The lock is released when the thread leaves the synchronization block
  - synchronized(someObject) { *protected code* }
  - The protected code has a *mutual exclusion* guarantee: At most one thread can be in it
- When released, some other thread can acquire the lock

Locks are associated with objects

- Every Object has its own built-in lock
  - Just the same, some applications prefer to create special classes of objects to use just for locking
  - This is a stylistic decision and you should agree on it with your teammates or learn the company policy if you work at a company
- Code is "thread safe" if it can handle multiple threads using it… otherwise it is "unsafe"

Working Example: “SummationJob”


```
public class SummationJob implements Runnable {

  public static       int X        = 0;
  public static       int NDONE    = 0;
  public static final int NTHREADS = 2;

  /** Increments X 1000 times. */
  public void run() {
    for(int k=0; k<1000; k++) {
       X = X + 1; // (WARNING: MAIN RACE CONDITION)
    }
    NDONE += 1; // (WARNING: ANOTHER RACE CONDITION)
  }

  /** Launches NTHREADS SummationJob objects that try to increment X to NTHREADS*1000 */
  public static void main(String[] args) {
    try {
      Thread[] threads = new Thread[NTHREADS];
      for(int k=0; k<NTHREADS; k++)
         threads[k] = new Thread(new SummationJob());

      for(int k=0; k<NTHREADS; k++)
          threads[k].start();

      while(NDONE < NTHREADS) Thread.sleep(100);

      System.out.println("X="+X);

    }catch(Exception e) {
       e.printStackTrace();
       System.out.println("OOPS"+e);
    }
  }
}
```

How can we use locks to update results?
(keeping silly +1 computation).

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

Finer grained synchronization

- Java allows you to do fancier synchronization
  - But can only be used <u>inside</u> a synchronization block
  - Special primitives called **wait/notify**
    - In java.lang.Object

Constructor Summary

java.lang.Object

Constructors

Constructor and Description
`Object()`

Method Summary

Methods

Modifier and Type	Method and Description
`protected Object`	`clone()` Creates and returns a copy of this object.
`boolean`	`equals(Object obj)` Indicates whether some other object is "equal to" this one.
`protected void`	`finalize()` Called by the garbage collector on an object when garbage collection determines that there are no more references to the object.
`Class<?>`	`getClass()` Returns the runtime class of this `Object`.
`int`	`hashCode()` Returns a hash code value for the object.
`void`	`notify()` Wakes up a single thread that is waiting on this object's monitor.
`void`	`notifyAll()` Wakes up all threads that are waiting on this object's monitor.
`String`	`toString()` Returns a string representation of the object.
`void`	`wait()` Causes the current thread to wait until another thread invokes the `notify()` method or the `notifyAll()` method for this object.
`void`	`wait(long timeout)` Causes the current thread to wait until either another thread invokes the `notify()` method or the `notifyAll()` method for this object, or a specified amount of time has elapsed.
`void`	`wait(long timeout, int nanos)` Causes the current thread to wait until another thread invokes the `notify()` method or the `notifyAll()` method for this object, or some other thread interrupts the current thread, or a certain amount of real time has elapsed.

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

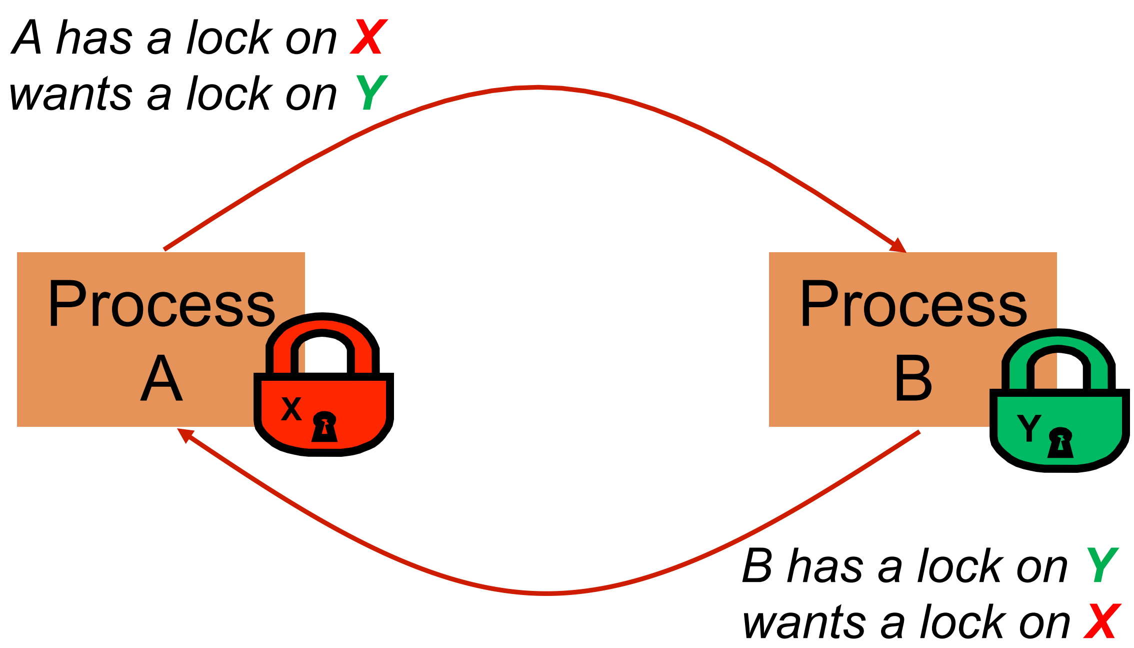
Deadlock

- 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...

Visualizing deadlock



Deadlocks always involve cycles

- They can include 2 or more threads or processes in a waiting cycle
- Other properties:
  - The locks need to be mutually exclusive (no sharing of the objects being locked)
  - The application won't give up and go away (no timer associated with the lock request)
  - There are no mechanisms for one thread to take locked resources away from another thread – no "preemption"

"... drop that mouse or you'll be down to 8 lives"

Dealing with deadlocks

- We recommend designing code to either
  - Acquire a lock, use it, then promptly release it, or
  - ... acquire locks in some "fixed" order

- Example, suppose that we have objects a, b, c, ...
- Now suppose that threads sometimes lock sets of objects but always do so in alphabetical order
  - Can a lock-wait cycle arise?
  - ... without cycles, no deadlocks can occur!

Higher level abstractions

- Locking is a very low-level way to deal with synchronization
  - Very nuts-and-bolts

- So many programmers work with higher level concepts. Sort of like ADTs for synchronization
  - We'll just look at one example today
  - There are many others; take CS4410 "Operating Systems" to learn more

A producer/consumer example

- Thread A produces loaves of bread and puts them on a shelf with capacity K
  - For example, maybe K=10
- Thread B consumes the loaves by taking them off the shelf
  - Thread A doesn't want to overload the shelf
  - Thread B doesn't wait to leave with empty arms

producer

shelves

consumer

Producer/Consumer example


```
class Bakery {
    int nLoaves = 0;    // Current number of waiting loaves
    final int K = 10;   // Shelf capacity

    public synchronized void produce() {
        while(nLoaves == K) this.wait();   // Wait until not full
        ++nLoaves;
        this.notifyall();                  // Signal: shelf not empty
    }

    public synchronized void consume() {
        while(nLoaves == 0) this.wait();   // Wait until not empty
        --nLoaves;
        this.notifyall();                  // Signal: shelf not full
    }
}
```

Things to notice

- Wait needs to wait on the same object that you used for synchronizing (in our example, “this”, which is this instance of the Bakery)

- Notify wakes up just one waiting thread, notifyall wakes all of them up

- We used a while loop because we can’t predict exactly which thread will wake up “next”

Bounded Buffer

- Here we take our producer/consumer and add a notion of passing something from the producer to the consumer
  - For example, producer generates strings
  - Consumer takes those and puts them into a file
- Question: why would we do this?
  - Keeps the computer more steadily busy

Producer/Consumer example


```
class Bakery {
    int nLoaves = 0;    // Current number of waiting loaves
    final int K = 10;   // Shelf capacity

    public synchronized void produce() {
        while(nLoaves == K) this.wait();  // Wait until not full
        ++nLoaves;
        this.notifyall();                 // Signal: shelf not empty
    }

    public synchronized void consume() {
        while(nLoaves == 0) this.wait();  // Wait until not empty
        --nLoaves;
        this.notifyall();                 // Signal: shelf not full
    }
}
```

Bounded Buffer example


```
class BoundedBuffer<T> {
    int putPtr = 0, getPtr = 0;  // Next slot to use
    int available = 0;           // Items currently available
    final int K = 10;            // buffer capacity
    T[] buffer = new T[K];

    public synchronized void produce(T item) {
        while(available == K) this.wait();  // Wait until not full
        buffer[putPtr++ % K] = item;
        ++available;
        this.notifyall();                   // Signal: not empty
    }

    public synchronized T consume() {
        while(available == 0) this.wait(); // Wait until not empty
        --available;
        T item = buffer[getPtr++ % K];
        this.notifyall();                   // Signal: not full
        return item;
    }
}
```

In an ideal world…

- Bounded buffer allows producer and consumer to both run concurrently, with neither blocking
  - This happens if they run at the same average rate
  - … and if the buffer is big enough to mask any brief rate surges by either of the two

- But if one does get ahead of the other, it waits
  - This avoids the risk of producing so many items that we run out of computer memory for them. Or of accidentally trying to consume a non-existent item.

Trickier example

- Suppose we want to use locking in a BST
  - Goal: allow multiple threads to search the tree
  - But don't want an insertion to cause a search thread to throw an exception

Code we're given is thread unsafe

```
class BST {
    Object name;       // Name of this node
    Object value;      // Value of associated with that name
    BST left, right;   // Children of this node

    // Constructor
    public void BST(Object who, Object what) { name = who; value = what; }

    // Returns value if found, else null
    public Object get(Object goal) {
        if(name.equals(goal)) return value;
        if(name.compareTo(goal) < 0) return left==null? null: left.get(goal);
        return right==null? null: right.get(goal);
    }

    // Updates value if name is already in the tree, else adds new BST node
    public void put(Object goal, object value) {
        if(name.equals(goal)) { this.value = value; return; }
        if(name.compareTo(goal) < 0) {
            if(left == null) { left = new BST(goal, value); return; }
            left.put(goal, value);
        } else {
            if(right == null) { right = new BST(goal, value); return; }
            right.put(goal, value);
        }
    }
}
```

Attempt #1

- Just make both put and get synchronized:
  - public synchronized Object get(…) { … }
  - public synchronized void put(…) { … }

- Let's have a look….

Safe version: Attempt #1

```
class BST {
    Object name;        // Name of this node
    Object value;       // Value of associated with that name
    BST left, right;    // Children of this node

    // Constructor
    public void BST(Object who, Object what) { name = who; value = what; }

    // Returns value if found, else null
    public synchronized Object get(Object goal) {
        if(name.equals(goal)) return value;
        if(name.compareTo(goal) < 0) return left==null? null: left.get(goal);
        return right==null? null: right.get(goal);
    }

    // Updates value if name is already in the tree, else adds new BST node
    public synchronized void put(Object goal, Object value) {
        if(name.equals(goal)) { this.value = value; return; }
        if(name.compareTo(goal) < 0) {
            if(left == null) { left = new BST(goal, value); return; }
            left.put(goal, value);
        } else {
            if(right == null) { right = new BST(goal, value); return; }
            right.put(goal, value);
        }
    }
}
```

Attempt #1

- Just make both **put** and **get** synchronized:
  - public synchronized Object **get**(…) { … }
  - public synchronized void **put**(…) { … }

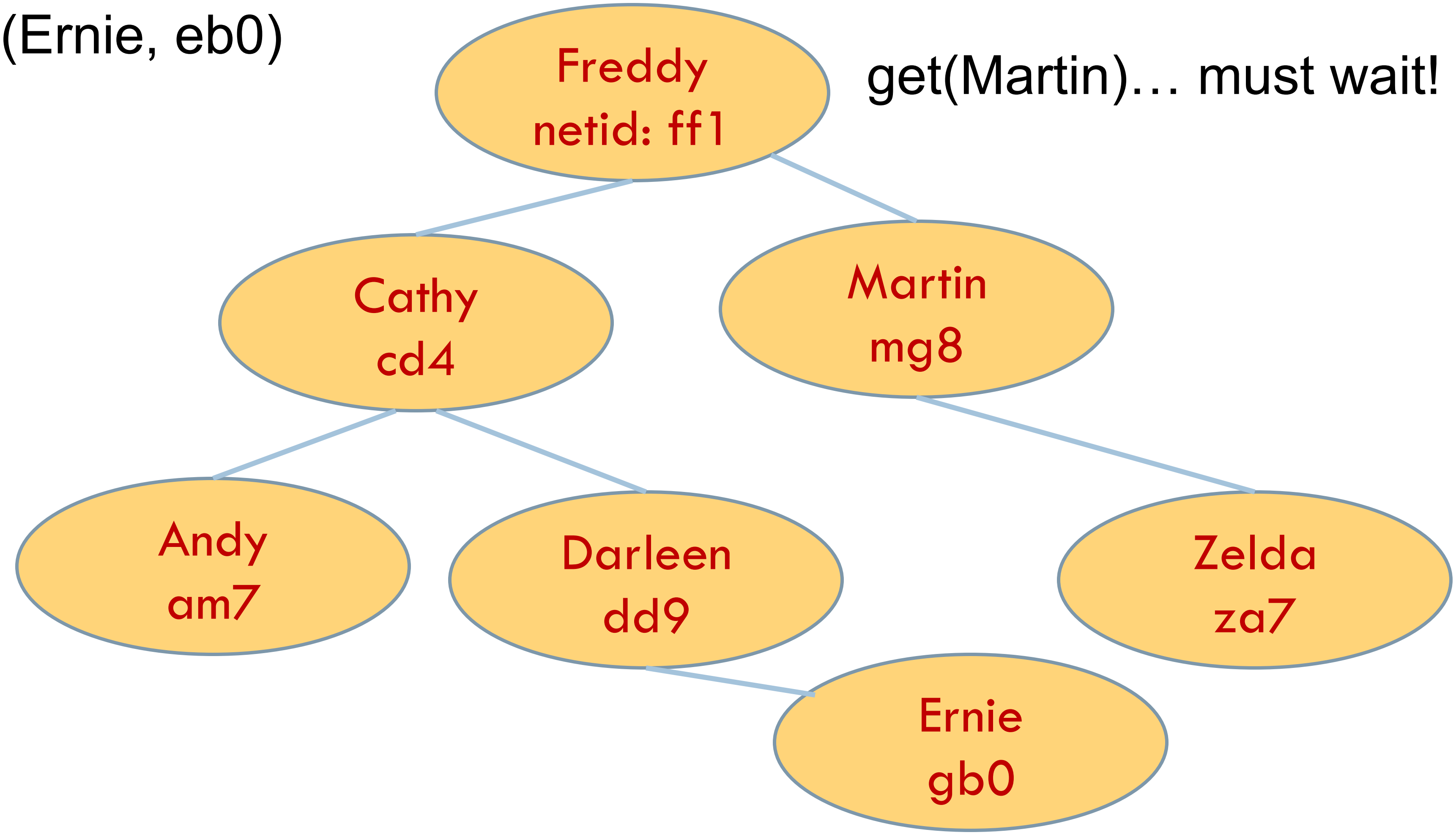
- This works but it kills ALL concurrency
  - Only one thread can look at the tree at a time
  - Even if all the threads were doing "**get**"!

Visualizing attempt #1

put(Ernie, eb0)

get(Martin)… resumes

get(Martin)… must wait!



Attempt #2: Improving "get"

- **put** uses synchronized in method declaration
  - So it locks every node it visits
- **get** tries to be fancy:

```
// Returns value if found, else null
public Object get(Object goal) {
    synchronized(this) {
      if(name.equals(goal)) return value;
      if(name.compareTo(goal) < 0) return left==null? null: left.get(goal);
      return right==null? null: right.get(goal);
    }
}
```

- Actually this is identical to attempt 1!
  - `public synchronized Object get(Object goal)`
  - Looks different but does exactly the same thing
- Still locks during recursive tree traversal

Attempt #3: An improved "get"


```
// Returns value if found, else null
public Object get(Object goal) {
    BST checkLeft = null, checkRight = null;
    synchronized(this) {
      if(name.equals(goal)) return value;
      if(name.compareTo(goal) < 0) {
           if (left==null) return null; else checkLeft = left;
      } else {
           if(ri                                              ght;
      }
    }
    if (checkLeft  != null) return checkleft.get(goal);
    if (checkRight != null) return checkright.get(goal);

    /* Never executed but keeps Java happy */
    return null;
}
```

relinquishes lock on **this** – next lines are "unprotected"

- Locks node when accessing fields, but not during subsequent traversal

More tricky things to know about

- With thread priorities Java can be very annoying
  - ALWAYS runs higher priority threads before lower priority threads if scheduler must pick
  - The lower priority ones might never run at all

- Consequence: risk of a "**priority inversion**"
  - High-priority thread t1 is waiting for a lock, t2 has it
  - Thread t2 is runnable, but never gets scheduled because t3 is higher priority and "busy"

NVIDIA GTX Titan

Teaser: Threads super important for GPUs

http://www.extremetech.com/gaming/148674-nvidias-gtx-titan-brings-supercomputing-performance-to-consumers

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!
  - A "race condition" can arise if two threads try and share data
  - 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"
- Nice tutorial at
  - **http://docs.oracle.com/javase/tutorial/essential/concurrency/index.html**
- Serious treatment of concurrency is a complex topic (covered in more detail in cs3410 "systems" and cs4410 "OS")