Reminder

- A “race condition” arises if two threads try and share some data
- One updates it and the other reads it, or both update the data
- In such cases it is possible that we could see the data “in the middle” of being updated
  - A “race condition”: correctness depends on the update racing to completion without the reader managing to glimpse the in-progress update
  - Synchronization (aka mutual exclusion) solves this
Java Synchronization (Locking)

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

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

- Put critical operations in a `synchronized` block
- The `stack` object acts as a lock
- Only one thread can own the lock at a time
Java Synchronization (Locking)

• You can lock on any object, including `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”
Visualizing deadlock

A has a lock on X
wants a lock on Y

B has a lock on Y
wants a lock on X
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”
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 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
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
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
    }
}
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;
    }
}
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 unsafe

```java
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…. 
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”!
Put(Ernie, eb0)

Freddy
netid: ff1

Cathy
cd4

Martin
mg8

Darleen
dd9

Zelda
za7

Ernie
gb0

Andy
am7

Get(Martin) must
resumes

Get(Martin)
Attempt #2

- put uses synchronized in method declaration
  - So it locks every node it visits

- get tries to be fancy:

```java
// 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! It only looks different but in fact is doing exactly the same thing
Risk: “get” (read-only) threads sometimes look at nodes without locks, but “put” always updates those same nodes.

According to JDK rules this is unsafe.
Attempt #4

- This version is safe: only accesses the shared variables left and right while holding locks
- In fact it should work (I think)
Attempt #3 illustrates risks

- The hardware itself actually needs us to use locking and attempt 3, although it looks right in Java, could actually malfunction in various ways

- **Issue:** put updates several fields:
  - parent.left (or parent.right) for its parent node
  - this.left and this.right and this.name and this.value

- When locking is used correctly, multicore hardware will correctly implement the updates

- But if you look at values without locking, as we did in Attempt #3, hardware can behave oddly!
Why can **hardware** cause bugs?

- Issue here is covered in cs3410 & cs4410
  - Problem is that the hardware was designed under the requirement that if threads contend to access shared memory, then readers and writers must use locks
  - Solutions #1 and #2 used locks and so they worked, but had no concurrency
  - Solution #3 violated the hardware rules and so you could see various kinds of garbage in the fields you access!
  - Solution #4 should be correct, but perhaps not optimally concurrent (doesn’t allow concurrency while even one “put” is active)
- It’s hard to design concurrent data structures!
More tricky things to know about

- Java has actual “lock” objects
  - They support lock/unlock operations
- But it isn’t easy to use them correctly
  - Always need a try/finally structure

```java
Lock someLock = new Lock();

try {
    someLock.lock();
    do-stuff-that-needs-a-lock();
} finally {
    someLock.unlock();
}
```
More tricky things to know about

- Needs try/finally

```java
Lock someLock = new Lock();
try {
  someLock.lock();
  do-stuff-that-needs-a-lock();
} finally {
  someLock.unlock();
}
```

- Complication: `someLock.unlock()` can only be called by the same thread that called lock.

- Advanced issue: If your code catches exceptions and the thread that called `lock()` might terminate, the lock can’t be released! It remains locked forever... bad news...
More tricky things to know about

- With 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”
Debugging concurrent code

- There are Eclipse features to help you debug concurrent code that uses locking
  - These include packages to detect race conditions or non-deterministic code paths
  - Packages that will track locks in use and print nice summaries if needed
  - Packages for analyzing performance issues
    - Heavy locking can kill performance on multicore machines
    - Basically, any sharing between threads on different cores is a performance disaster
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)
- Nice tutorial at http://docs.oracle.com/javase/tutorial/essential/concurrency/index.html