Synchronization
Slight difference in two prelims; we’ll curve as we did last time. Wait until all regrade requests have been answered.

Open up for regrade requests around noon.

No lunch meeting with me today. Instead, I am in my office to talk to people from 11:30 to 3:00.

Please don’t use Piazza for questions about prelim. Talk to a consultant/TA/instructor, email instructors.
Concurrent Programs

A thread or thread of execution is a sequential stream of computational work.

Concurrency is about controlling access by multiple threads to shared resources.

Last time: Learned about

1. Race conditions
2. Deadlock
3. How to create a thread in Java.
Purpose of this lecture

Show you Java constructs for eliminating race conditions, allowing threads to access a data structure in a safe way but allowing as much concurrency as possible.

This requires

- (1) The locking of an object so that others cannot access it, called synchronization.
- (2) Use of two new Java methods: \texttt{wait()} and \texttt{notifyAll()}

As an example, throughout, we use a bounded buffer.

Look at JavaHyperText, entry Thread !!!!!!!
An Example: bounded buffer

finite capacity (e.g. 20 loaves)
implemented as a queue

Threads A: *produce* loaves of bread and put them in the queue

Threads B: *consume* loaves by taking them off the queue
An Example: bounded buffer

Separation of concerns:
1. How do you implement a queue in an array?
2. How do you implement a bounded buffer using the queue, which allows producers to add to it and consumers to take things from it, all in parallel?

Threads A: produce loaves of bread and put them in the queue
Threads B: consume loaves by taking them off the queue
### Array Queue

**Array** `b[0..5]`

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>b.length</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>5</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Put values 5 3 6 2 4 into queue
ArrayQueue

Array b[0..5]

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b 5 3 6 2 4

put values 5 3 6 2 4 into queue

get, get, get
ArrayQueue

Array b[0..5]

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<tr>
<td>b</td>
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<td>5</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>Values wrap around!!</td>
</tr>
</tbody>
</table>

put values 5 3 6 2 4 into queue

get, get, get

put values 1 3 5
ArrayQueue

```java
int[] b; // 0 <= h < b.length. The queue contains the
int h;   // n elements b[h], b[h+1], b[h+2], ...
int n;   // b[h+n-1] (all indices mod b.length)

/** Pre: there is space */
public void put(int v){
    b[(h+n) % b.length]= v;
    n= n+1;
}

/** Pre: not empty */
public int get(){
    int v= b[h];
    h= (h+1) % b.length;
    n= n-1;
    return v;
}
```

Values wrap around!!
/** An instance maintains a bounded buffer of fixed size */
class BoundedBuffer&lt;E&gt; {

   ArrayQueue&lt;E&gt; aq;

   /** Put v into the bounded buffer. */
   public void produce(E v) {
      if (!aq.isFull()) {
         aq.put(v);
      }
   }

   /** Consume v from the bounded buffer. */
   public E consume() {
      return aq.isEmpty() ? null : aq.get();
   }
}
/** An instance maintains a bounded buffer of fixed size */
class BoundedBuffer<E> {

    ArrayQueue<E> aq;

    /** Put v into the bounded buffer. */
    public void produce(E v) {
        if (!aq.isFull()) {
            aq.put(v);
        }
    }

    }
/** An instance maintains a bounded buffer of fixed size */
class BoundedBuffer<E> {
    
    ArrayQueue<E> aq;
    
    /** Put v into the bounded buffer. */
    public void produce(E v) {
        if (!aq.isFull()) {
            aq.put(v);
        }
    }

    After finding aq not full, but before putting v, another chef might beat you to it and fill up buffer aq! race condition
Key is hanging the outhouse. Anyone can grab the key, go inside, and lock the door. They have the key.

When they come out, they lock the door and hang the key by the front door. Anyone (only one) person can then grab the key, go inside, lock the door.

That’s what synchronized implements!
/** An instance maintains a bounded buffer of fixed size */
class BoundedBuffer<E> {

    ArrayQueue<E> aq;

    /** Put v into the bounded buffer. */
    public void produce(E v) {
        synchronized (aq) {
            if (!aq.isFull()) {
                aq.put(v);
            }
        }
    }
}
You can synchronize (lock) any object, including this.

```java
public void produce(E v) {
    synchronized(this) {
        if (!aq.isFull()) { aq.put(v);
    }
}
```

Synchronized blocks
Synchronized Methods

You can synchronize (lock) any object, including `this`.

```java
public void produce(E v) {
    synchronized(this) {
        if (!aq.isFull()) { aq.put(v); }
    }
}
```

Or you can synchronize methods
This is the same as wrapping the entire method implementation in a `synchronized(this)` block.

```java
public synchronized void produce(E v) {
    if (!aq.isFull()) { aq.put(v); }
}
```
/** An instance maintains a bounded buffer of fixed size */
class BoundedBuffer<E> {
    ArrayQueue<E> aq;

    /** Put v into the bounded buffer. */
    public synchronized void produce(E v) {
        if (!aq.isFull()) {
            aq.put(v);
        }
    }

    /** Consume v from the bounded buffer. */
    public synchronized E consume() {
        return aq.isEmpty() ? null : aq.get();
    }
}

What happens of aq is full?

We want to wait until it becomes non-full — until there is a place to put v.
Somebody has to buy a loaf of bread before we can put more bread on the shelf.
Two lists for a synchronized object

For every synchronized object $sobj$, Java maintains:

1. **locklist**: a list of threads that are waiting to obtain the lock on $sobj$

2. **waitlist**: a list of threads that had the lock but executed `wait()`
   - e.g. because they couldn't proceed

Method `wait()` is defined in `Object`
class BoundedBuffer<E> {

    ArrayQueue<E> aq;

    /**  Put v into the bounded buffer.*/
    public synchronized void produce(E v) {
        while (aq.isFull()) {
            try { wait(); } 
            catch(InterruptedException e) {} 
        }
        aq.put(v);
        notifyAll();
    }

    locklist

    waitlist

}
notify() and notifyAll()

- Methods `notify()` and `notifyAll()` are defined in Object.
- `notifyAll()` moves all threads on the waitlist to the locklist.
- `notify()` moves one thread from the waitlist to the locklist.
- Note: which thread is moved is arbitrary.
/** An instance maintains a bounded buffer of fixed size */
class BoundedBuffer<E> {
    ArrayQueue<E> aq;
    /** Put v into the bounded buffer. */
    public synchronized void produce(E v) {
        while (aq.isFull()) {
            try {
                wait();
            } catch (InterruptedException e) {}  
        }
        aq.put(v);
        notifyAll();
    }
    ...
WHY use of notify() may hang.

Work with a bounded buffer of length 1.
1. Consumer W gets lock, wants White bread, finds buffer empty, and wait()s: is put in set 2.
2. Consumer R gets lock, wants Rye bread, finds buffer empty, wait()s: is put in set 2.
3. Producer gets lock, puts Rye in the buffer, does notify(), gives up lock.
4. The notify() causes one waiting thread to be moved from set 2 to set 1. Choose W.
5. No one has lock, so one Runnable thread, W, is given lock. W wants white, not rye, so wait()s: is put in set 2.
6. Producer gets lock, finds buffer full, wait()s: is put in set 2.

All 3 threads are waiting in set 2. **Nothing more happens.**
Should one use `notify()` or `notifyAll()`

But suppose there are two kinds of bread on the shelf—and one still picks the head of the queue, if it’s the right kind of bread.

Using `notify()` can lead to a situation in which no one can make progress.

`notifyAll()` always works; you need to write documentation if you optimize by using `notify()`
Eclipse Example

**Producer:** produce random ints *(rye or white bread)*

**Consumer 1:** even ints *(buy only rye bread)*

**Consumer 2:** odd ints *(buy only white bread)*

**Dropbox:** 1-element bounded buffer *(1 loaf of bread)*

**Locklist**

Threads wanting the Dropbox

**Waitlist**

Threads who had Dropbox and waited

Dropbox: empty or 1 integer *(loaf of bread)*
Key is hanging by front door. Anyone can grab the key, go inside, and lock the door. They have the key.

When they come out, they lock the door and hang the key by the front door. Anyone (only one) person can then grab the key, go inside, lock the door.

That’s what synchronized implements!

BUT: You leave the back door open and tell your friends to go in whenever they want

Threads that don’t synchronize can get in. Dangerous but useful to increase efficiency.

Word of warning with synchronized
Using Concurrent Collections...

Java has a bunch of classes to make synchronization easier.
It has synchronized versions of some of the Collections classes
It has an Atomic counter.
... this implementation is not synchronized. If multiple threads access a hash set concurrently, and at least one of the threads modifies the set, it must be synchronized externally. This is typically accomplished by synchronizing on some object that naturally encapsulates the set. If no such object exists, the set should be "wrapped" using method Collections.synchronizedSet. This is best done at creation time, to prevent accidental unsynchronized access to the set:

    Set s = Collections.synchronizedSet(new HashSet(...));
Race Conditions

Initially, i = 0

Thread 1

load i;  
Load 0 from memory

tmp = tmp + 1;
store tmp to i;

Thread 2

Load 0 from memory

tmp = load i;

Store 1 to memory

tmp = tmp + 1;
store tmp to i;

Finally, i = 1
import java.util.concurrent.atomic.*;

public class Counter {
    private static AtomicInteger counter;

    public Counter() {
        counter = new AtomicInteger(0);
    }

    public static int getCount() {
        return counter.getAndIncrement();
    }
}
Fancier forms of locking

Java. *synchronized* is the core mechanism

But. Java has a class Semaphore. It can be used to allow a limited number of threads (or kinds of threads) to work at the same time. Acquire the semaphore, release the semaphore

Semaphore: a kind of synchronized counter (invented by Dijkstra in 1962-63, THE multiprogramming system)

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

Python: acquire a **lock**, release the **lock**. Has semaphores
Use of multiple processes and multiple threads within each process can exploit concurrency
- may be real (multicore) or virtual (an illusion)

Be careful when using threads:
- synchronize shared memory to avoid race conditions
- avoid deadlock

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