Waiting

- Synchronized methods introduce one kind of coordination between threads.
- Sometimes we need a thread to wait until a specific condition has arisen.

Waiting by “Polling”

- For example in a Counter class we might want to wait until the count is 0 or less.
- We could do this

```java
class Counter {
    private int count;

    public Counter(int count) {
        this.count = count;
    }

    synchronized void decrement() {
        count--;
    }

    synchronized int getCount() {
        return count;
    }

    void waitForZeroOrLess() { // Polling loop
        while (getCount() > 0) /*do nothing*/;
    }
}
```

Note that `waitForZeroOrLess` is not synchronized.

Waiting by “Polling”

- Slightly improving this we can write

```java
void waitForZeroOrLess() { // Polling loop
    while (getCount() > 0)
        Thread.yield();
}
```

which keeps the thread from hogging the CPU while polling.
**Waiting by `wait` and `notifyAll`**

- Better, we can have a thread wait until it is notified that the condition has (or may have) come about.
- While waiting, the thread relinquishes ownership and waits until some later time.
- To wait, a thread sends the object a `wait` message.
- To allow other threads to stop waiting, threads send a `notifyAll` message to the object.
- `wait` and `notifyAll` are methods of class `Object`.

**The “Room metaphor”**

![Diagram of a room metaphor](image)

- When a thread in the room sends a `wait` message, it leaves the room and enters the waiting room.
- Later another thread enters.
- All threads in the waiting room move to the antechamber.
- And so they can reenter when the room is empty.

**`wait` and `notifyAll` example.**

```java
class Counter {
    private int count;

    public Counter( int count ) { this.count = count; }

    synchronized void decrement() {
        count -= 1;
        if( count <= 0 ) notifyAll();
    }

    synchronized void waitForZero() {
        while( count > 0 ) {
            try { wait(); }
            catch( InterruptedException e ) {} 
        }
    }
}
```

- Note that `waitForZeroOrLess` is synchronized.

**A possible sequence**

- One thread
  - Calls `waitForZero` enters the room.
  - Sees count is 1.
  - Calls `wait`, enters the waiting room.
  - Waits in waiting room.
  - Reenters the room.
  - Returns from `wait`.
  - Sees count is 0 and returns.

- Another thread
  - Calls `decrement` enters the room.
  - Count--
  - Calls `notifyAll`, moving other thread to wait queue for the lock.
  - Returns leaving the room.
Passing messages

- We want to pass messages between any number of producers and consumers executing on any number of threads.

```
:Mailbox
{} 0
```

Passing messages

- We want to pass messages between threads so that
  - Each message is received no more than once
  - No message is overwritten before it is received.
  - A receiver may have to wait until a new message is sent
  - A sender may have to wait until there is room in the queue
  - Up to 100 messages can be sent but not yet received.

```
send(0) receive()
```

Passing messages

- Receivers may need to wait.
  - Suppose the mailbox initially has no messages

```
send(1) receive()
```

Passing messages

- Producers may need to wait.
  - Suppose the capacity is 5 and the mailbox is full
Passing messages – incomplete

```java
class Mailbox<MessageType> {
    private static final int CAP = 100;
    private Queue<MessageType> q = new Queue<MessageType>();
    // invariant: q.size() <= CAP

    public synchronized void send(MessageType mess) {
        // wait until q.size()< CAP
        q.put( mess );
    }

    public synchronized MessageType receive() {
        // wait until q.size() > 0
        return q.take();
    }
}
```

Passing messages – add waits

```java
class Mailbox<MessageType> {
    private static final int CAP = 100;
    private Queue<MessageType> q = new Queue<MessageType>();
    // invariant: q.size() <= CAP

    public synchronized void send(MessageType mess) {
        // wait until q.size()< CAP
        while( q.size()==CAP ) {
            try {
                wait(); } catch( InterruptedException e ) {} 
        }
        q.put( mess );
    }

    public synchronized MessageType receive() {
        // wait until q.size() > 0
        while( q.size()==0 ) {
            try {
                wait(); } catch( InterruptedException e ) {} 
        }
        return q.take();
    }
}
```

Passing messages – add notifications

```java
class Mailbox<MessageType> {
    private static final int CAP = 100;
    private Queue<MessageType> q = new Queue<MessageType>();
    // invariant: q.size() <= CAP

    public synchronized void send(MessageType mess) {
        // wait until q.size()< CAP
        while( q.size()==CAP ) {
            try {
                wait(); } catch( InterruptedException e ) {} 
        }
        q.put( mess );
        notifyAll();
    }

    public synchronized MessageType receive() {
        // wait until q.size() > 0
        while( q.size()==0 ) {
            try {
                wait(); } catch( InterruptedException e ) {} 
        }
        return q.take();
    }
}
```

Even better than wait and notifyAll

- As software gets more complex, using “wait” and “notifyAll” can be a bit awkward and is easy to mess up.
- An improvement is to use Dr. Norvell’s “monitor” package.
- See
  http://www.engr.mun.ca/~theo/Misc/monitors/monitors.html
Deadlock

- While waiting can solve “safety” issues
  - (e.g. ensuring noncorruption of data, nonduplication of messages, nonloss of messages),
- it can cause “liveness” problems.
- In particular
  - if one thread is waiting for another to do something, and
  - the other thread is waiting for the first to do something,
  - then we have “deadlock”

Deadlock Example

- Suppose we have a bank account class
  ```java
  class Account {
      private int balance = 0;
      public synchronized void addFunds(int amount) {
          balance += amount;
      }
      public void transfer(int amount, Account toAccount) {
          if (balance >= amount) {
              toAccount.addFunds(amount);
              balance -= amount;
          } else { … } }
      …
  }
  ```

Deadlock Example

- There is a subtle problem here.
- The intent is that one should not be able to transfer out of an account more money than it has. (A safety problem.)
- But, if two threads attempt to transfer from the same account at about the same time, then they might both succeed, even though the final balance will be negative.
- To fix this, we make transfer synchronized.

```java
class Account {
    private int balance = 0;
    public synchronized void addFunds(int amount) {
        balance += amount;
    }
    public synchronized void transfer(int amount, Account toAccount) {
        if (balance >= amount) {
            toAccount.addFunds(amount);
            balance -= amount;
        } else { … } }
    …
}
```
Deadlock Example

- But now deadlock is possible.
- Suppose thread 0 tries to transfer from account x to account y.
- At roughly the same time thread 1 attempts to transfer from account y to account x.

A possible sequence

- Thread 0
  - calls x.transfer(100, y)
  - obtains a lock on x
  - calls y.addFunds()
  - waits for lock on y
  - waits for lock on y
  - waits for lock on y
  - waits for lock on y
  - ad infinitum

- Thread 1
  - calls y.transfer(50, x)
  - obtains a lock on y
  - calls x.addFunds()
  - waits for lock on x
  - waits for lock on x
  - waits for lock on x
  - waits for lock on x
  - ad infinitum

The Threads are now deadlocked!

A solution to deadlock

- One solution is to always lock objects in a particular order.
- e.g. give each lockable object a globally unique #
- The following example uses synchronized blocks

```java
public void transfer(int amount, Account toAccount) {
    boolean choice = this.serialNum() <= toAccount.serialNum();
    synchronized(choice ? this : toAccount) {
        synchronized(choice ? toAccount : this) {
            if(balance >= amount) {
                toAccount.addFunds(amount);
                balance -= amount;
            } else {
            }
        }
    }
}
```

Testing Concurrent Programs

- You cannot effectively test concurrent programs to show that they are error free.
- Because of race conditions, a test may pass millions of times “by chance”.
- Tests that fail are useful. They tell us we have a bug.
- Tests that pass only tell us that it is possible for the code to compute the correct result.
I wanted to illustrate how race conditions can cause data corruption.

So I wrote a program with two threads sharing an int variable \( x \).
- Initially \( x \) was set to 0
- One thread incremented \( x \) a thousand times
- The other thread decremented \( x \) a thousand times.

```
class Incrementor extends Thread {
    public void run() {
        for(int i=0 ; i < 1000; ++i) ++x ;
    }
}

class Decrementor extends Thread {
    public void run() {
        for(int i=0 ; i < 1000; ++i) --x ;
    }
}
```

I ran the two threads concurrently
```
System.out.println( "The initial value of x is: " + x ) ;
Thread p = new Incrementor() ;
Thread q = new Decrementor() ;
p.start() ; q.start();
```
// Wait for threads to finish using “joins” (not shown)
```
System.out.println( "After "+1000+" increments and "+1000+" decrements" ) ;
System.out.println( "the final value of x is: " + x ) ;
```

What do you think happened?

Here’s the output:
```
The initial value of x is: 0
After 1000 increments and 1000 decrements
the final value of x is: 0
```

Even though I deliberately wrote a faulty program and gave it 1 thousand chances to fail the test, it passed anyway..
- I tried 10,000. Then 100,000.
- Same result
Testing: A True Story

- And why did it pass?
  - The JVM happened to give each thread time slices so long that the incrementing thread completed its 100,000 increments before the main thread had a chance to even start the decrementing thread.
  - Changing to 1,000,000 increments and decrements revealed the bug.

- I had fallen victim to optimism.
- I had optimistically assumed that such an obvious bug would cause a thorough test to fail.
- If tests designed to reveal blatant bugs, which we know are in the program, fail to reveal them, should we expect testing to reliably reveal subtle bugs we do not know about?

If you can’t test, then what?

- The good news is that
  - although testing is insufficient to reveal bugs,
  - there are design and analysis techniques that allow you to prove your programs correct.

Concurrency

- What every computer engineer needs to know about concurrency:
  - Concurrency is to untrained programmers as matches are to small children.
  - It is all too easy to get burned.
  - Race conditions
  - Deadlock
  - Insufficiency of testing
Summary of terminology

- **concurrency**: multiple agents running at the same time, interacting
- **thread**: an independent path of control
- **Thread**: a Java class representing threads
- **race condition**: a hazard caused by the unpredictability of execution timing
- **synchronized access**: locking of objects to obtain *exclusive* access
- **wait** and **notifyAll**: threads may wait until notified
- **deadlock**: a cycle of threads mutually waiting for each other
- **safety property**: a property that says something (bad) will never happen
- **liveness property**: a property that says something (good) will eventually happen