RACE CONDITIONS AND SYNCHRONIZATION

Lecture 21 – CS2110 – Fall 2010

Reminder

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- 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)

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```
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

Java Synchronization (Locking)

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

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

is equivalent to

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

How locking works

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- 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

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- 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

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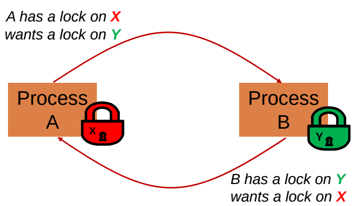

Deadlocks always involve cycles

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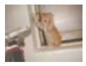
- They can include 2 or more threads or processes in a waiting cycle
- Other properties:
  - The locks need to be mutually exclusive (no sharing of the objects being locked)
  - The application won't give up and go away (no timer associated with the lock request)
  - There are no mechanisms for one thread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

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



Dealing with deadlocks

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- 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

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- 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

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- 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

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```
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

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- 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

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- 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

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```
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

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```
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

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- 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

```
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….

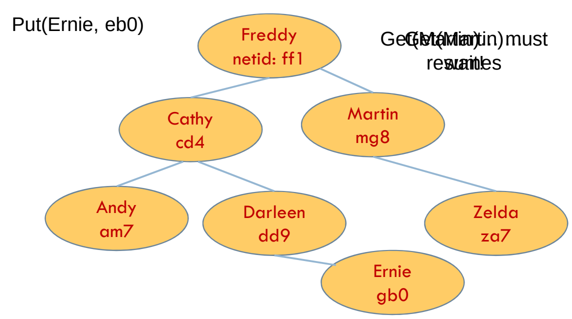
Safe version: Attempt #1

```
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



Attempt #2

- 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! It only looks different but in fact is doing exactly the same thing

Attempt #3

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

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

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

- 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

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```
// 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(right==null) return null; else checkRight = right;
      }
    }
    if (checkLeft != null) return checkleft.get(goal);
    if (checkRight != null) return checkright.get(goal);

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

- 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

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- 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?

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- 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

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- 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

```
Lock someLock = new Lock();

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

More tricky things to know about

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- Needs try/finally

```
Lock someLock = new Lock();

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

  - Complication: someLock.unlock() can only be called by 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

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- 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

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- 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

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- 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**