6.005 Elements of Software Construction
Fall 2008

6.005 elements of software construction

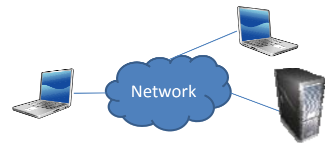
Concurrency

Rob Miller
Fall 2008

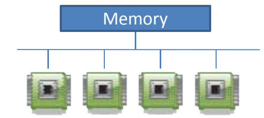
Concurrency

Multiple computations running at the same time

➢ Concurrency is everywhere, whether we like it or not



Multiple computers in a network



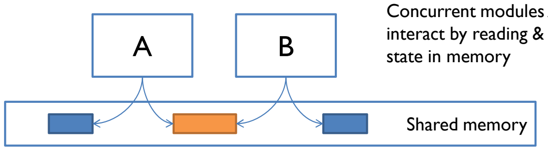
Multiple processors in a computer (or multiple **cores** in a single chip)

➢ Concurrency is useful, too
- Splitting up a computation into concurrent pieces is often faster
- Many apps must handle multiple simultaneous users (e.g. web sites)
- Even single-user applications are better with concurrency (e.g. Eclipse compiling your Java code in the background while you're editing it)

Models for Concurrent Programming

Shared Memory

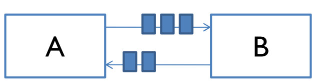
➢ Analogy: two processors in a computer, sharing the same physical memory



Concurrent modules A and B interact by reading & writing shared state in memory

Message Passing

➢ Analogy: two computers in a network, communicating by network connections

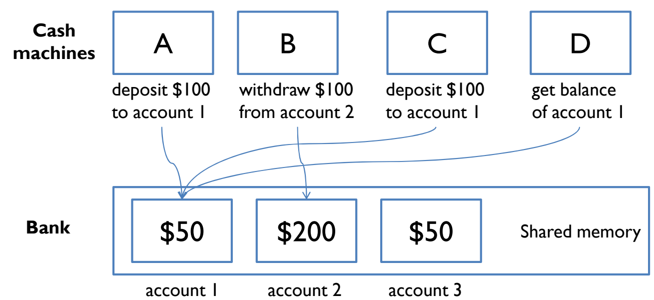


A and B interact by sending messages to each other through a communication channel

Shared Memory Example

Four customers using cash machines simultaneously

➢ Shared memory model – each cash machine reads and writes the account balance directly



Race Condition

Suppose A and C run at the same time

A	get balance	$50	**C**	get balance	$50
	add deposit	+ $100		add deposit	+ $100
	write back total	$150		write back total	$150

- Neither answer is right!

This is an example of a race condition

- A **race condition** means that the correctness of the program depends on the relative timing of events in concurrent computations
  - "A is in a race with C"
- Some interleavings of events may be OK, e.g.: but other interleavings produce wrong answers

A	get balance	$50
	add deposit	+ $100
	write back total	$150
C	get balance	$150
	add deposit	+ $100
	write back total	$250

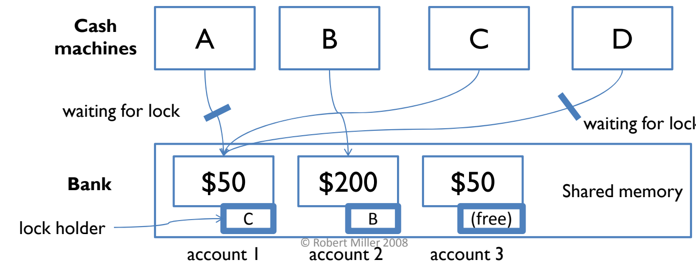
Correctness of a concurrent program should not depend on accidents of timing

- Race conditions are nasty bugs -- may be rarely observed, hard to reproduce, hard to debug, but may have very serious effects

Synchronization

A and C need to synchronize with each other

- **Locks** are a common synchronization mechanism
- Holding a lock means "I'm changing this; don't touch it right now"
- Suppose C acquires the lock first; then A must wait to read and write the balance until C finishes and releases the lock
- Ensures that A and C are synchronized, but B can run independently on a different account (with a different lock)



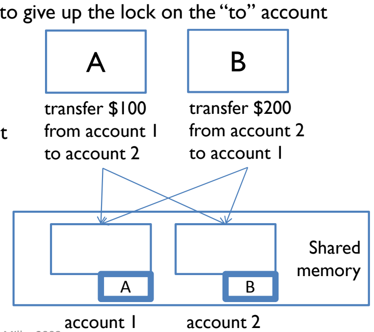
Deadlocks

Suppose A and B are making simultaneous transfers

- A transfer between accounts needs to lock both accounts, so that money can't disappear from the system
- A and B each acquire the lock on the "from" account
- Now each must wait for the other to give up the lock on the "to" account
- Stalemate! A and B are frozen, and the accounts are locked up.

"Deadly embrace"

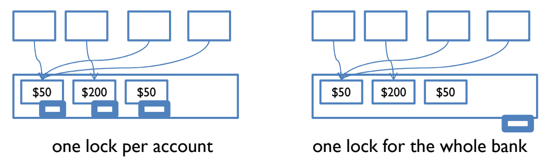
- **Deadlock** occurs when concurrent modules are stuck waiting for each other to do something
- A deadlock may involve more than two modules (e.g., a cycle of transfers among N accounts)
- You can have deadlock without using locks – example later



Lock Granularity

Preventing the deadlock

- One solution is to change the locking **granularity** – e.g. use one lock on the entire bank, instead of a lock on each account



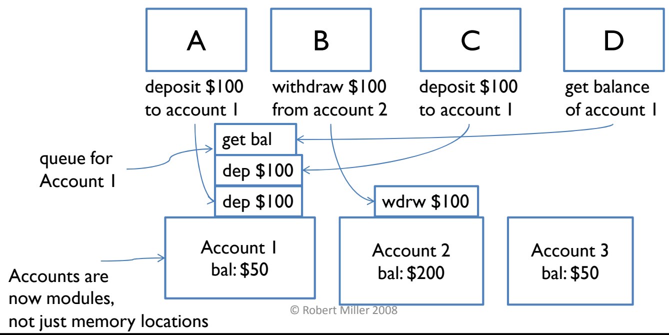
Choosing lock granularity is hard

- If locking is too coarse, then you lose concurrency (e.g. only one cash machine can run at a time)
- If locking is too fine, then you get race conditions and/or deadlocks
- Easy to get this wrong

Message Passing Example

Modules interact by sending messages to each other

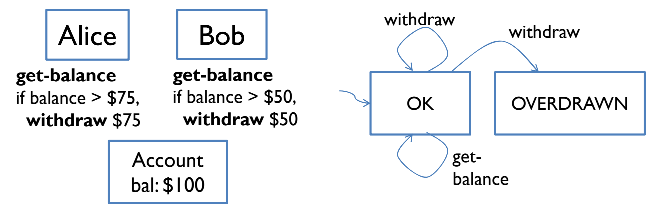
- Incoming requests are placed in a **queue** to be handled one at a time
- Sender doesn't stop working while waiting for an answer to its request; it handles more requests from its own queue
- Reply eventually comes back as another message



Message Passing Has the Same Risks

Message passing doesn't eliminate race conditions

- Suppose the account state machine supports **get-balance** and **withdraw** operations (with corresponding messages)
- Can Alice and Bob always stay out of the OVERDRAWN state?



- Lesson: need to carefully choose the **atomic** (indivisible) operations of the state machine – **withdraw-if-sufficient-funds** would be better

Message-passing can have deadlocks too

- Particularly when using finite queues that can fill up

Concurrency Is Hard to Test

Poor coverage

- Recall our notions of coverage
  - all states, all transitions, or all paths through a state machine
- Given two concurrent state machines (with N states and M states), the combined system has N x M states (and many more transitions and paths)
- As concurrency increases, the state space explodes, and achieving sufficient coverage becomes infeasible

Poor reproducibility

- Transitions are **nondeterministic**, depending on relative timing of events that are strongly influenced by the environment
  - Delays can be caused by other running programs, other network traffic, operating system scheduling decisions, variations in processor clock speed, etc.
- Test driver can't possibly control all these factors
- So even if state coverage were feasible, the test driver can't reliably reproduce particular paths through the combined state machine

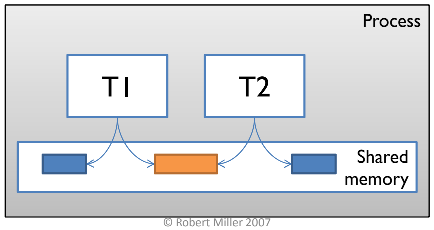
Use Message Passing in 6.005

We'll focus on message passing, not shared memory

- Locking strategy for shared-memory paradigm is hard to get right
- Message-passing paradigm often aligns directly with the real-world workflow of a problem
- But message passing is less suited to some problems, e.g. a big shared data structure

Threads

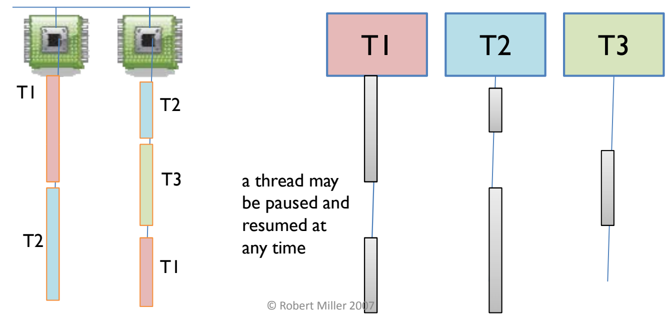
- A **thread** is a locus of control (i.e. program counter + stack, representing a position in a running program)
  - Simulates a **fresh processor** running the same program in a different place
- A process always has at least one thread (the **main thread**)
- Threads can share any memory in the process, as long as they can get a reference to it
- Threads must set up message passing explicitly (e.g. by creating queues)



Time Slicing

How can I have many concurrent threads with only one or two processors in my computer?

- When there are more threads than processors, concurrency is simulated by **time slicing** (processor switches between threads)
- Time slicing happens unpredictably and nondeterministically



Threads in Java

A thread is represented by java.lang.Thread object

- To define a thread, either override Thread or implement Runnable

```
T1 extends Thread      R1 implements Runnable
```

Thread lifecycle

- Starting arguments can be given to the constructor

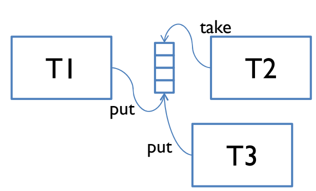
```
new T1(arg1, ...)      new Thread(new R1(arg1, ...))
```

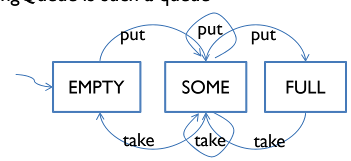
- Thread is spawned by calling its start() method
- New thread starts its life by calling its own run() method
- Thread dies when run() returns or throws an uncaught exception

Message Passing with Threads

Use a synchronized queue for message-passing between threads

- interface java.util.concurrent.BlockingQueue is such a queue



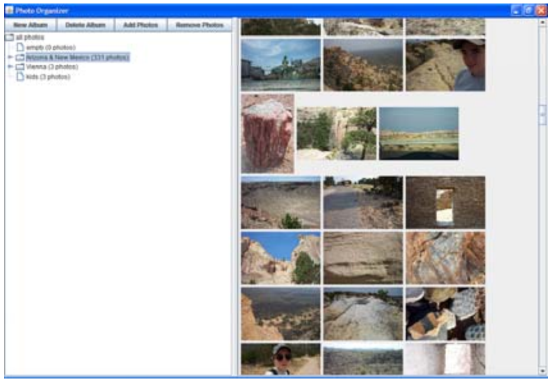


no *take* transition in EMPTY state, so a thread that tries to *take* from an empty queue must **block** (wait) until it can

- ArrayBlockingQueue is a fixed-size queue that uses an array representation
- LinkedBlockingQueue is a growable queue (no FULL state) using a linked-list representation

Case Study: Photo Organizer

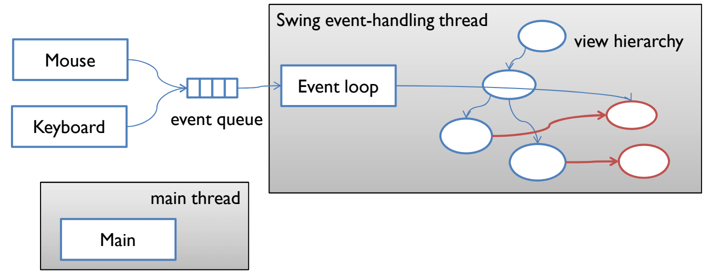
What happens when the UI displays a large album?



Concurrency in GUIs

Mouse and keyboard events are accumulated in an event queue

- Event loop reads an input event from the queue and dispatches it to listeners on the view hierarchy
- In Java, the event loop runs on a special **event-handling thread,** started automatically when a user interface object is created



Java Swing Is Not Threadsafe

The view hierarchy is a big meatball of shared state

- And there's no lock protecting it at all
- It's OK to access user interface objects from the event-handling thread (i.e., in response to input events)
- But the Swing specification forbids touching – reading *or* writing – any Component objects from a different thread
  - See "Threads and Swing", http://java.sun.com/products/jfc/tsc/articles/threads/threads1.html
  - The truth is that Swing's implementation does have *one big lock* (Component.getTreeLock()) but only some Swing methods use it (e.g. layout)

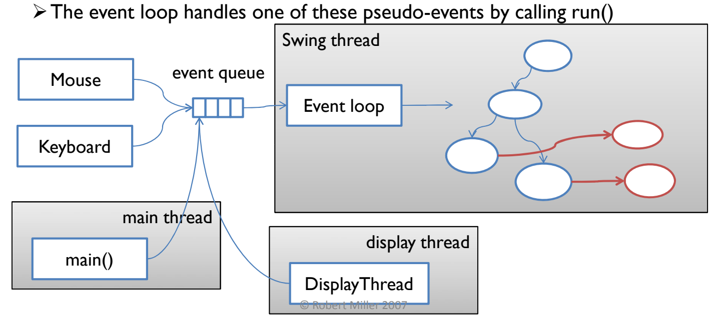
Message Passing Via the Event Queue

The event queue is also a message-passing queue

- To access or update Swing objects from a different thread, you can put a message (represented as a Runnable object) on the event queue

```
SwingUtilities.invokeLater(new Runnable() {
        public void run() { content.add(thumbnail); …} });
```

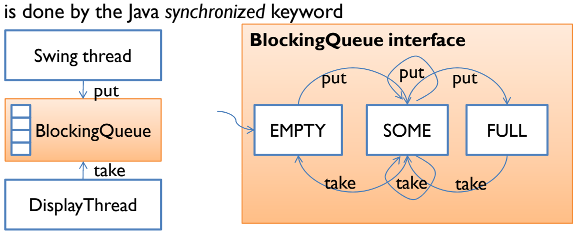
- The event loop handles one of these pseudo-events by calling run()



Thread Safety

BlockingQueue is itself a shared state machine

- But it's OK to use from multiple threads because it has an **internal lock** that prevents race conditions within the state machine itself
  - So state transitions are guaranteed to be **atomic**
  - This is done by the Java *synchronized* keyword



- BlockingQueue is therefore **thread-safe** (able to be called by multiple threads safely without threat to its invariants)
- HashSet is not thread-safe; neither is the Swing view hierarchy

Other Thread-Safe Classes

Lists, Sets, and Maps can be made thread-safe by a wrapper function

- t = Collections.synchronizedSet(s) returns a thread-safe version of set s, with a lock that prevents more than one thread from entering it at a time, forcing the others to block until the lock is free
- So we could imagine synchronizing all our sets:

  thumbnails = Collections.synchronizedSet(new HashSet<Thumbnail> ());

This doesn't fix all race conditions!

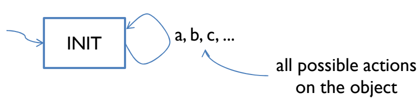
- Doesn't help preserve invariants involving more than one data structure

  thumbnails.add(t);
  content.add(t);

  these operations need to be atomic *together*, to avoid breaking the rep invariant of PreviewPane (that all thumbnails are children of content)

More Thread-Safe Classes

Objects that never change state are usually* thread-safe



- **Immutable** objects never change state
  - e.g., java.lang.String is immutable, so threads can share strings as much as they like without fear of race conditions, and without any need for locks or queues

* Caveat: some apparently immutable objects may have hidden state: e.g. memoizing (caching) method return values.

Summary

Concurrency

- Multiple computations running simultaneously

Shared-memory & message-passing paradigms

- Shared memory needs a synchronization mechanism, like locks
- Message passing synchronizes on communication channels, like queues

Pitfalls

- **Race** when correctness of result depends on relative timing of events
- **Deadlock** when concurrent modules get stuck waiting for each other

Design advice

- Share only immutable objects between threads
- Use blocking queues and SwingUtilities.invokeLater()