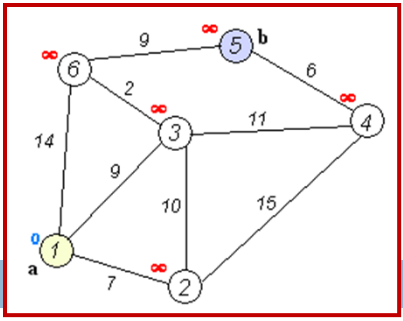
THREADS AND CONCURRENCY

Lecture 22 – CS2110 – Spring 2013

Graphs summary

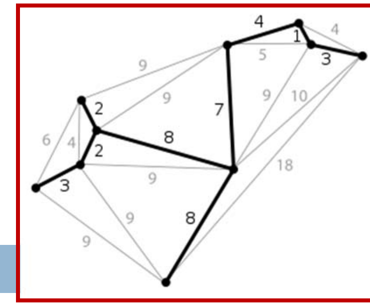


- Dijkstra: given a vertex v, finds shortest path from v to x for each vertex x in the graph
  - Key idea: maintain a 5-part invariant on three sets

1. Vertices already visited ("settled"). Distance known
2. Frontier nodes. One hop from the settled ones
3. Future nodes. > one hop from the settled ones

- Algorithm: move the "closest" frontier node to settled, then adjust frontier and future sets to restore the invariant.

Graphs summary



- Minimum spanning tree: a tree that reaches every node while minimizing the summed weight of edges
  - Prim's algorithm: repeatedly pick the lowest-weight edge that will connect some previously disconnected components. A "greedy" algorithm.
  - Kruskal's algorithm: start with the whole graph, repeatedly remove the highest-weight edge that won't disconnect the spanning tree. Also "greedy".
- In all three cases, correctness is established using inductive proofs that focus on maintaining invarients!

Today: Start a new topic

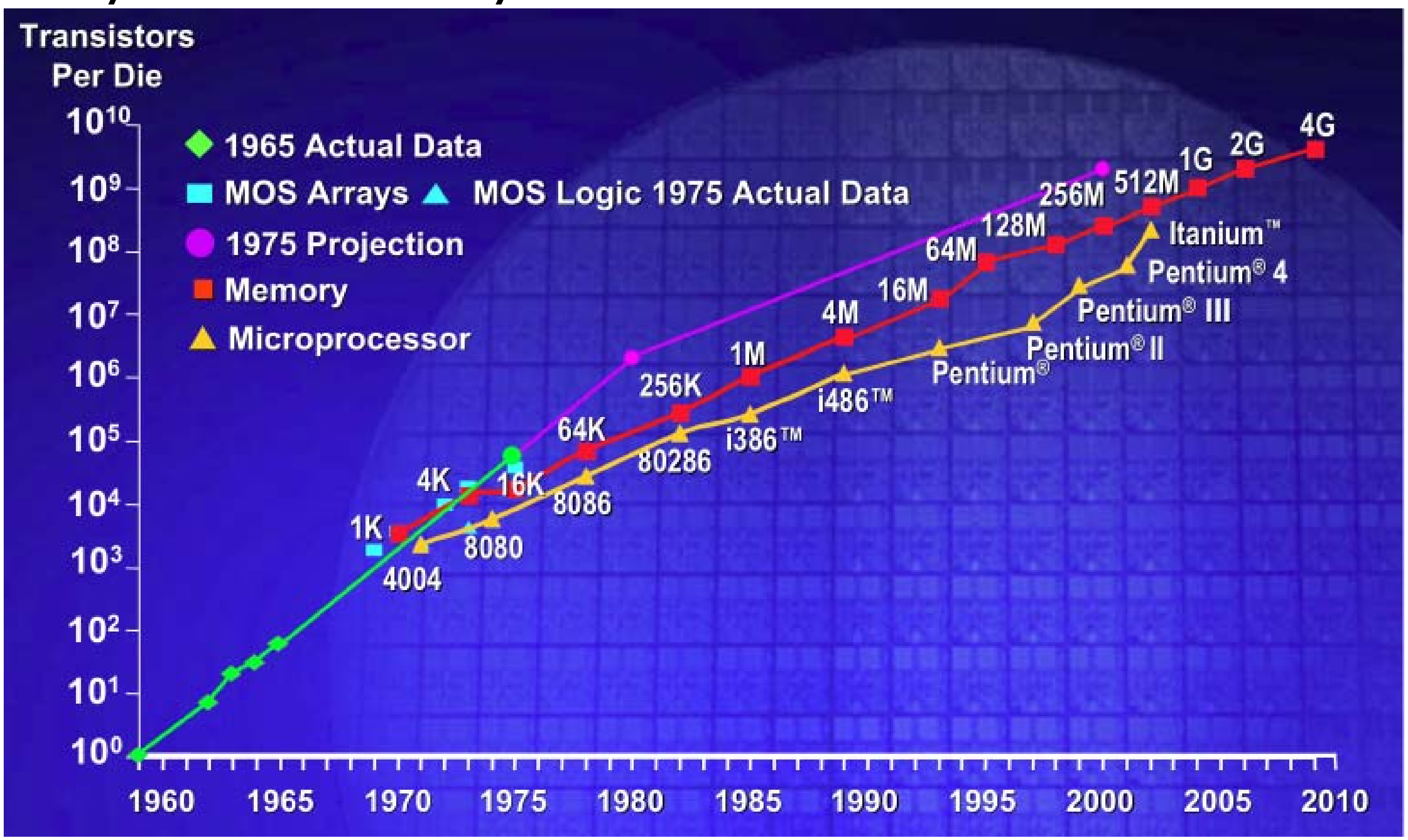
- Modern computers have "multiple cores"
  - Instead of a single CPU on the chip
  - 5-10 common. Intel has prototypes with 80!

- And even with a single core your program may have more than one thing "to do" at a time
  - Argues for having a way to do many things at once

- Finally, we often run many programs all at once

Why Multicore?

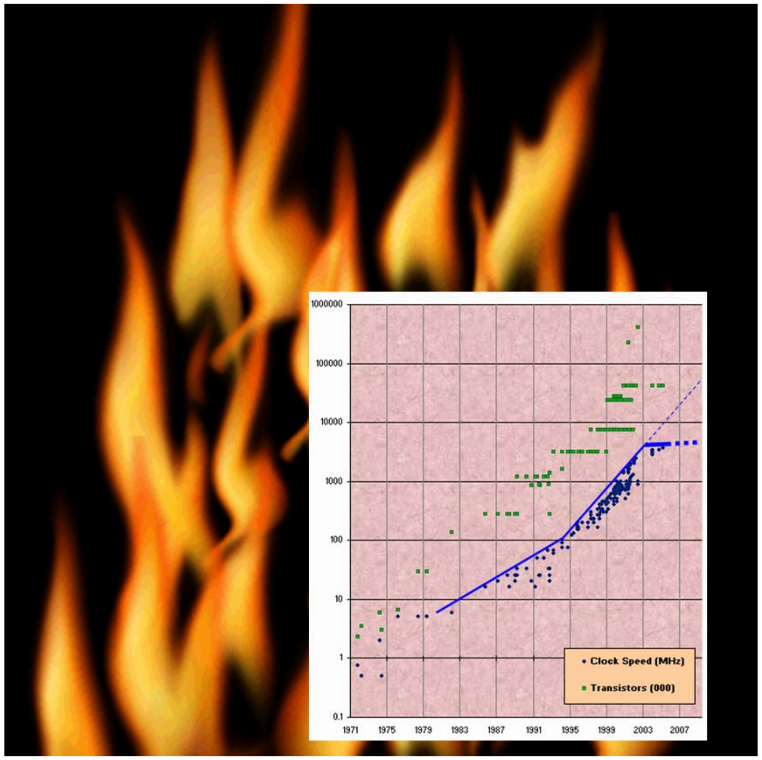
- Moore's Law: Computer speeds and memory densities nearly double each year



But a fast computer runs hot

- Power dissipation rises as the square of the CPU clock rate
- Chips were heading towards melting down!

- Multicore: with four CPUs (cores) on one chip, even if we run each at half speed we get more overall performance!



Keeping those cores busy

- The operating system provides support for multiple “processes”
- In reality there there may be fewer processors than processes
- Processes are an illusion – at the hardware level, lots of multitasking
  - memory subsystem
  - video controller
  - buses
  - instruction prefetching
- Virtualization can even let one machine create the illusion of many machines (they share disks, etc)

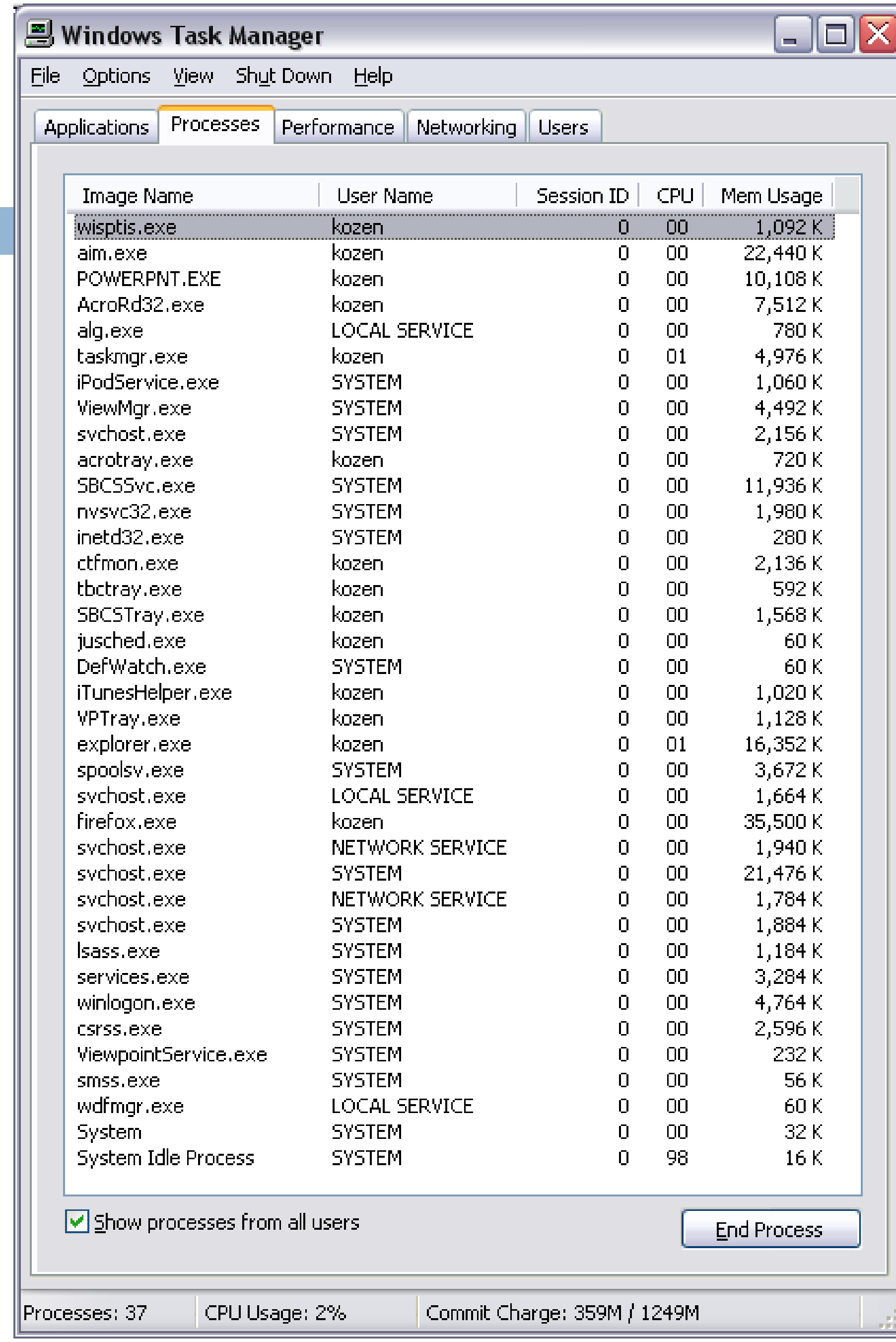


Image Name	User Name	Session ID	CPU	Mem Usage
wisptis.exe	kozen	0	00	1,092 K
aim.exe	kozen	0	00	22,440 K
POWERPNT.EXE	kozen	0	00	10,108 K
AcroRd32.exe	kozen	0	00	7,512 K
alg.exe	LOCAL SERVICE	0	00	780 K
taskmgr.exe	kozen	0	01	4,976 K
iPodService.exe	SYSTEM	0	00	1,060 K
ViewMgr.exe	SYSTEM	0	00	4,492 K
svchost.exe	SYSTEM	0	00	2,156 K
acrotray.exe	kozen	0	00	720 K
SBCSSvc.exe	SYSTEM	0	00	11,936 K
nvsvc32.exe	SYSTEM	0	00	1,980 K
inetd32.exe	SYSTEM	0	00	280 K
ctfmon.exe	kozen	0	00	2,136 K
tbctray.exe	kozen	0	00	592 K
SBCSTray.exe	kozen	0	00	1,568 K
jusched.exe	kozen	0	00	60 K
DefWatch.exe	SYSTEM	0	00	60 K
iTunesHelper.exe	kozen	0	00	1,020 K
VPTray.exe	kozen	0	00	1,128 K
explorer.exe	kozen	0	01	16,352 K
spoolsv.exe	SYSTEM	0	00	3,672 K
svchost.exe	LOCAL SERVICE	0	00	1,664 K
firefox.exe	kozen	0	00	35,500 K
svchost.exe	NETWORK SERVICE	0	00	1,940 K
svchost.exe	SYSTEM	0	00	21,476 K
svchost.exe	NETWORK SERVICE	0	00	1,784 K
svchost.exe	SYSTEM	0	00	1,884 K
lsass.exe	SYSTEM	0	00	1,184 K
services.exe	SYSTEM	0	00	3,284 K
winlogon.exe	SYSTEM	0	00	4,764 K
csrss.exe	SYSTEM	0	00	2,596 K
ViewpointService.exe	SYSTEM	0	00	232 K
smss.exe	SYSTEM	0	00	56 K
wdfmgr.exe	LOCAL SERVICE	0	00	60 K
System	SYSTEM	0	00	32 K
System Idle Process	SYSTEM	0	98	16 K

What is a Thread?

- *A separate "execution" that runs within a single program and can perform a computational task independently and concurrently with other threads*
- Many applications do their work in just a single thread: the one that called main() at startup
  - But there may still be extra threads...
  - ... Garbage collection runs in a "background" thread
  - GUIs have a separate thread that listens for events and "dispatches" upcalls
- Today: learn to create new threads of our own

What is a Thread?

- A thread is a kind of object that "independently computes"
  - Needs to be created, like any object
  - Then "started". This causes some method (like main()) to be invoked. It runs side by side with other thread in the same program and they see the same global data
- The actual execution could occur on distinct CPU cores, but doesn't need to
  - We can also simulate threads by *multiplexing* a smaller number of cores over a larger number of threads

Concurrency

- *Concurrency* refers to a single program in which several threads are running simultaneously
  - Special problems arise
  - They see the same data and hence can interfere with each other, e.g. if one thread is modifying a complex structure like a heap while another is trying to read it
- In cs2110 we focus on two main issues:
  - Race conditions
  - Deadlock

Thread class in Java

- Threads are instances of the class Thread
  - Can create many, but they do consume space & time
- The Java Virtual Machine created the thread that executes your main method.
- Threads have a priority
  - Higher priority threads are executed preferentially
  - A newly created Thread has initial priority equal to the thread that created it (but can change)

Creating a new Thread (Method 1)


```
class PrimeThread extends Thread {
   long a, b;

   PrimeThread(long a, long b) {
      this.a = a; this.b = b;
   }

   public void run() {
      //compute primes between a and b
      ...
   }
}
```

overrides **`Thread.run()`**

If you were to call **`run()`** directly no new thread is used: the calling thread will run it

```
PrimeThread p = new Prime
p.start();
```

... but if you create a new object and then call **`start()`**, Java invokes **`run()`** in new thread

Creating a new Thread (Method 2)


```
class PrimeRun implements Runnable {
   long a, b;

   PrimeRun(long a, long b) {
      this.a = a; this.b = b;
   }

   public void run() {
      //compute primes between a and b
      ...
   }
}
```

```
PrimeRun p = new PrimeRun(143, 195);
new Thread(p).start();
```

Example


```
public class ThreadTest extends Thread {

   public static void main(String[] args) {
      new ThreadTest().start();
      for (int i = 0; i < 10; i++) {
         System.out.format("%s %d\n",
            Thread.currentThread(), i);
      }
   }

   public void run() {
      for (int i = 0; i < 10; i++) {
         System.out.format("%s %d\n",
            Thread.currentThread(), i);
      }
   }
}
```

```
Thread[Thread-0,5,main] 0
Thread[main,5,main] 0
Thread[main,5,main] 1
Thread[main,5,main] 2
Thread[main,5,main] 3
Thread[main,5,main] 4
Thread[main,5,main] 5
Thread[main,5,main] 6
Thread[main,5,main] 7
Thread[main,5,main] 8
Thread[main,5,main] 9
Thread[Thread-0,5,main] 1
Thread[Thread-0,5,main] 2
Thread[Thread-0,5,main] 3
Thread[Thread-0,5,main] 4
Thread[Thread-0,5,main] 5
Thread[Thread-0,5,main] 6
Thread[Thread-0,5,main] 7
Thread[Thread-0,5,main] 8
Thread[Thread-0,5,main] 9
```

Example


```
public class ThreadTest extends Thread {

   public static void main(String[] args) {
      new ThreadTest().start();
      for (int i = 0; i < 10; i++) {
         System.out.format("%s %d\n",
            Thread.currentThread(), i);
      }
   }

   public void run() {
      currentThread().setPriority(4);
      for (int i = 0; i < 10; i++) {
         System.out.format("%s %d\n",
            Thread.currentThread(), i);
      }
   }
}
```

```
Thread[main,5,main] 0
Thread[main,5,main] 1
Thread[main,5,main] 2
Thread[main,5,main] 3
Thread[main,5,main] 4
Thread[main,5,main] 5
Thread[main,5,main] 6
Thread[main,5,main] 7
Thread[main,5,main] 8
Thread[main,5,main] 9
Thread[Thread-0,4,main] 0
Thread[Thread-0,4,main] 1
Thread[Thread-0,4,main] 2
Thread[Thread-0,4,main] 3
Thread[Thread-0,4,main] 4
Thread[Thread-0,4,main] 5
Thread[Thread-0,4,main] 6
Thread[Thread-0,4,main] 7
Thread[Thread-0,4,main] 8
Thread[Thread-0,4,main] 9
```

Example


```java
public class ThreadTest extends Thread {

   public static void main(String[] args) {
      new ThreadTest().start();
      for (int i = 0; i < 10; i++) {
         System.out.format("%s %d\n",
            Thread.currentThread(), i);
      }
   }

   public void run() {
      currentThread().setPriority(6);
      for (int i = 0; i < 10; i++) {
         System.out.format("%s %d\n",
            Thread.currentThread(), i);
      }
   }
}
```

```
Thread[main,5,main] 0
Thread[main,5,main] 1
Thread[main,5,main] 2
Thread[main,5,main] 3
Thread[main,5,main] 4
Thread[main,5,main] 5
Thread[Thread-0,6,main] 0
Thread[Thread-0,6,main] 1
Thread[Thread-0,6,main] 2
Thread[Thread-0,6,main] 3
Thread[Thread-0,6,main] 4
Thread[Thread-0,6,main] 5
Thread[Thread-0,6,main] 6
Thread[Thread-0,6,main] 7
Thread[Thread-0,6,main] 8
Thread[Thread-0,6,main] 9
Thread[main,5,main] 6
Thread[main,5,main] 7
Thread[main,5,main] 8
Thread[main,5,main] 9
```

Example

```
public class ThreadTest extends Thread {
   static boolean ok = true;

   public static void main(String[] args) {
      new ThreadTest().start();
      for (int i = 0; i < 10; i++) {
         System.out.println("waiting...");
         yield();
      }
      ok = false;
   }

   public void run() {
      while (ok) {
         System.out.println("running...");
         yield();
      }
      System.out.println("done");
   }
}
```

```
waiting...
running...
waiting...
running...
waiting...
running...
waiting...
running...
waiting...
running...
waiting...
running...
waiting...
running...
done
```

If threads happen to be sharing a CPU, yield allows other waiting threads to run. But if there are multiple cores, yield isn't needed

Terminating Threads is tricky

- Easily done... but only in certain ways
  - *The safe way to terminate a thread is to have it return from its run method*
  - *If a thread throws an uncaught exception, whole program will be halted (but it can take a second or too...)*
- There are some old APIs but they have issues: stop(), interrupt(), suspend(), destroy(), etc.
  - Issue: they can easily leave the application in a “broken” internal state.
  - Many applications have some kind of variable telling the thread to stop itself.

Threads can pause

- When active, a thread is "runnable".
  - It may not actually be "running". For that, a CPU must schedule it. Higher priority threads could run first.
- A thread can also pause
  - It can call Thread.sleep(k) to sleep for k milliseconds
  - If it tries to do "I/O" (e.g. read a file, wait for mouse input, even open a file) this can cause it to pause
  - Java has a form of locks associated with objects. When threads lock an object, one succeeds at a time.

Background (daemon) Threads

- In many applications we have a notion of "foreground" and "background" (daemon) threads
  - Foreground threads are the ones doing visible work, like interacting with the user or updating the display
  - Background threads do things like maintaining data structures (rebalancing trees, garbage collection, etc)

- On your computer, the same notion of background workers explains why so many things are always running in the task manager.

Race Conditions

- A “race condition” arises if two or more threads access the same variables or objects concurrently and at least one does updates
- Example: Suppose t1 and t2 simulatenously execute the statement x = x + 1; for some static global x.
  - Internally, this involves loading x, adding 1, storing x
  - If t1 and t2 do this concurrently, we execute the statement twice, but x may only be incremented once
  - t1 and t2 “race” to do the update

Race Conditions

- Suppose X is initially 5

Thread t1	Thread t2
LOAD X	...
	LOAD X
ADD 1	ADD 1
	STORE X
STORE X	

- ... after finishing, X=6! We "lost" an update

Race Conditions

- Race conditions are bad news
  - Sometimes you can make code behave correctly despite race conditions, but more often they cause bugs
  - And they can cause many kinds of bugs, not just the example we see here!
  - A common cause for “blue screens”, null pointer exceptions, damaged data structures

Example – A Lucky Scenario


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

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

Suppose threads A and B want to call **`doSomething()`**, and there is one element on the stack

1. thread A tests **`stack.isEmpty()`** false
2. thread A pops $\Rightarrow$ stack is now empty
3. thread B tests **`stack.isEmpty()`** $\Rightarrow$ true
4. thread B just returns – nothing to do

Example – An Unlucky Scenario


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

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

Suppose threads A and B want to call **`doSomething()`**, and there is one element on the stack

1. thread A tests **`stack.isEmpty()`** ⇒ false
2. thread B tests **`stack.isEmpty()`** ⇒ false
3. thread A pops ⇒ stack is now empty
4. thread B pops ⇒ Exception!

Synchronization

- Java has one "primary" tool for preventing these problems, and you must use it by carefully and explicitly – it isn't automatic.
  - Called a "synchronization barrier"
  - We think of it as a kind of lock
    - Even if several threads try to acquire the lock at once, only one can succeed at a time, while others wait
    - When it releases the lock, the next thread can acquire it
    - You can't predict the order in which contending threads will get the lock but it should be "fair" if priorities are the same

Solution – with synchronization


```
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

Solution – Locking

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

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

is equivalent to

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

Synchronization+priorities

- Combining mundane features can get you in trouble
- Java has priorities... and synchronization
  - But they don't "mix" nicely
  - High-priority runs before low priority
  - ... The lower priority thread "starves"

- Even worse...
  - With many threads, you could have a second high priority thread stuck waiting on that starving low priority thread! Now <u>both</u> are starving...

Fancier forms of locking

- Java developers have created various synchronization ADTs
  - Semaphores: a kind of synchronized counter
  - Event-driven synchronization
- The Windows and Linux and Apple O/S all have kernel locking features, like file locking
- But for Java, **synchronized** is the core mechanism

Deadlock

- The downside of locking – deadlock
- A deadlock occurs when two or more competing threads are waiting for one-another… forever
- Example:
  - Thread t1 calls synchronized b inside synchronized a
  - But thread t2 calls synchronized a inside synchronized b
  - t1 waits for t2… and t2 waits for t1…

Finer grained synchronization

- Java allows you to do fancier synchronization
  - But can only be used inside a synchronization block
  - Special primatives called wait/notify

wait/notify

Suppose we put this inside an object called animator:

```
boolean isRunning = true;

public synchronized void run() {
   while (true) {
      while (isRunning) {
         //do one step of simulation
      }
      try {
         wait();
      } catch (InterruptedException ie) {}
      isRunning = true;
   }
}
```

must be synchronized!

relinquishes lock on **animator** – awaits notification

```
public void stopAnimation() {
   animator.isRunning = false;
}

public void restartAnimation() {
   synchronized(animator) {
      animator.notify();
   }
}
```

notifies processes waiting for **animator** lock

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)