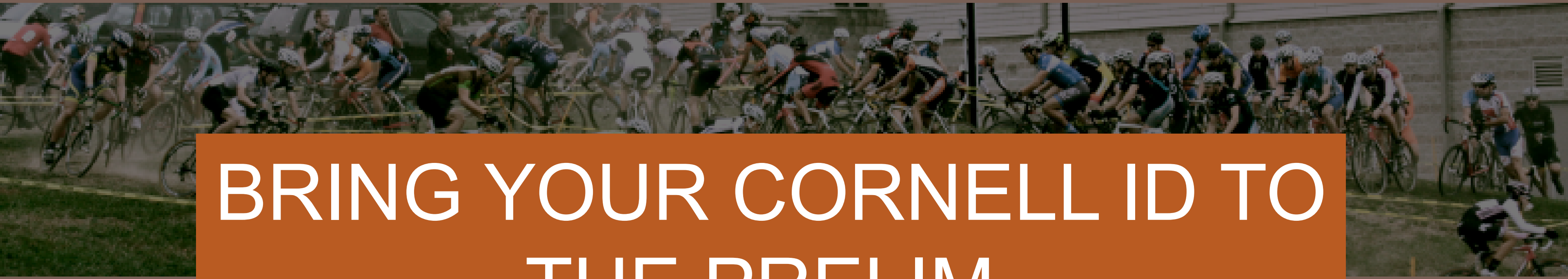


BRING YOUR CORNELL ID TO THE PRELIM.

You need it to get in

# Threads & Concurrency

Lecture 23– CS2110 – Fall 2016

# Today: New topic: concurrency



- Modern computers have “multiple cores”
  - Instead of a single CPU (central processing unit) on the chip 5-10 common. Intel has prototypes with 80!

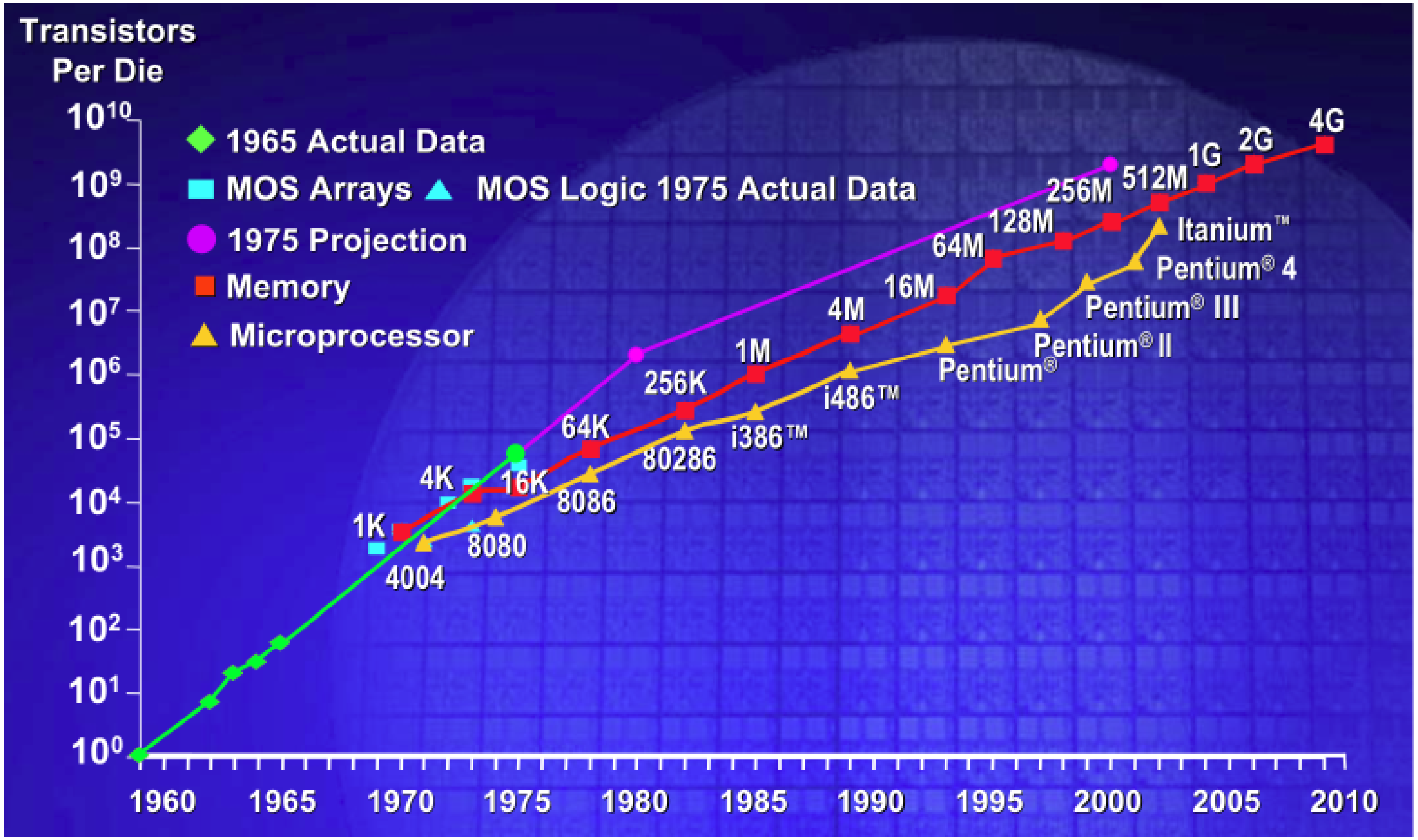
- We often run many programs at the same time

- 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

# Why multicore?



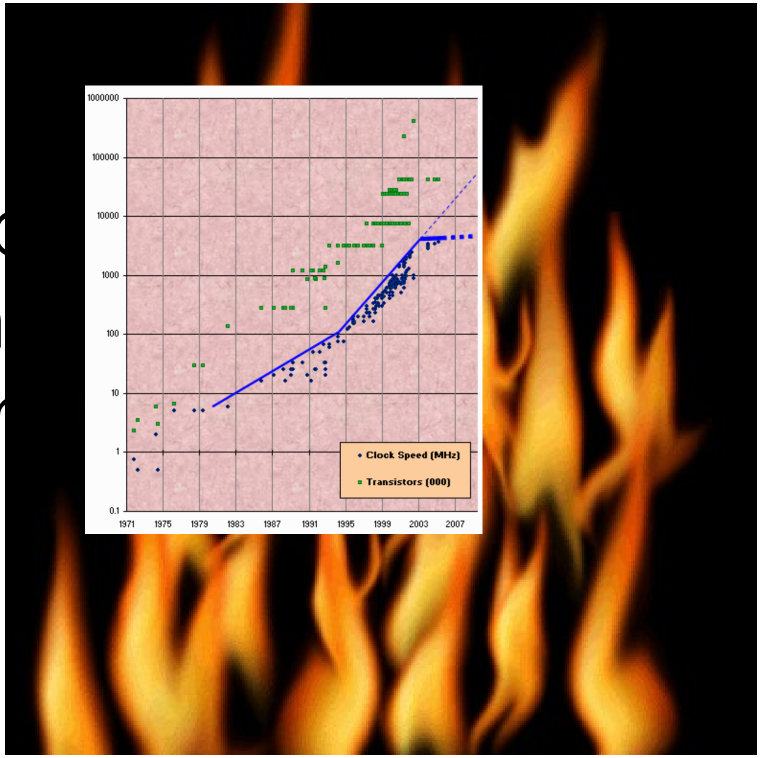
- Moore’s Law: Computer speeds and memory densities nearly double each year



# But a fast computer runs hot



- Power dissipation rises as square of the clock rate
- Chips were heading toward melting down!
- Multicore: with four CPUs (cores) on one chi
  even if we run each at h
  speed we can perform m
  overall computations!



# Programming a Cluster...



- Sometimes you want to write a program that is executed on many machines!
- Atlas Cluster (at Cornell):
- 768 cores
- 1536 GB RAM
- 24 TB Storage
- 96 NICs (Network Interface Controller)

# Many processes are executed simultaneously on your computer



- Operating system provides support for multiple "processes"
- Usually fewer processors than processes
- Processes are an abstraction:
  at hardware level, lots of multitasking
  - memory subsystem
  - video controller
  - buses
  - instruction prefetching

# Part of Activity Monitor in Gries's laptop



>100 processes are competing for time. Here's some of them:

| Process Name | % CPU | CPU Time | Threads |
|---|---|---|---|
| Grab | 4.1 | 3.33 | 7 |
| ReportCrash | 2.3 | 0.78 | 6 |
| Eclipse | 1.5 | 1:48:30.07 | 54 |
| SuperTab | 1.4 | 1:40:44.59 | 5 |
| Activity Monitor | 1.4 | 10.57 | 10 |
| https://www.wunderground.c... | 1.1 | 1:34.19 | 23 |
| Creative Cloud | 0.8 | 58:32.81 | 27 |
| Microsoft PowerPoint | 0.6 | 3:24.02 | 9 |
| Safari Networking | 0.4 | 26:53.25 | 10 |
| loginwindow | 0.3 | 16:14.79 | 4 |
| Google Drive | 0.3 | 6.33 | 22 |
| Safari | 0.3 | 50:09.48 | 24 |

# Concurrency



- *Concurrency* refers to a single program in which several processes, called threads, are running simultaneously
  - Special problems arise
  - They see the same data and hence can interfere with each other, e.g. one process modifies a complex structure like a heap while another is trying to read it
- CS2110: we focus on two main issues:
  - Race conditions
  - Deadlock

# Race conditions



- A "race condition" arises if two or more processes access the same variables or objects concurrently and at least one does updates
- Example: Processes t1 and t2     x= x + 1;     for some static global x.

Process t1                    Process t2

…                    …

x= x + 1;          x= x + 1;

But x= x+1; is not an "atomic action": it takes several steps

# Race conditions



- Suppose x is initially 5

| Thread t1 | Thread t2 |
|---|---|
| LOAD x | ... |
| | LOAD x |
| | ADD 1 |
| | STORE x |
| ADD 1 | |
| STORE x | |

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

# Race conditions



- Typical race condition: two processes wanting to change a stack at the same time. Or make conflicting changes to a database at the same time.
- Race conditions are bad news
  - Race conditions can cause many kinds of bugs, not just the example we see here!
  - Common cause for "blue screens": null pointer exceptions, damaged data structures
  - Concurrency makes proving programs correct much harder!

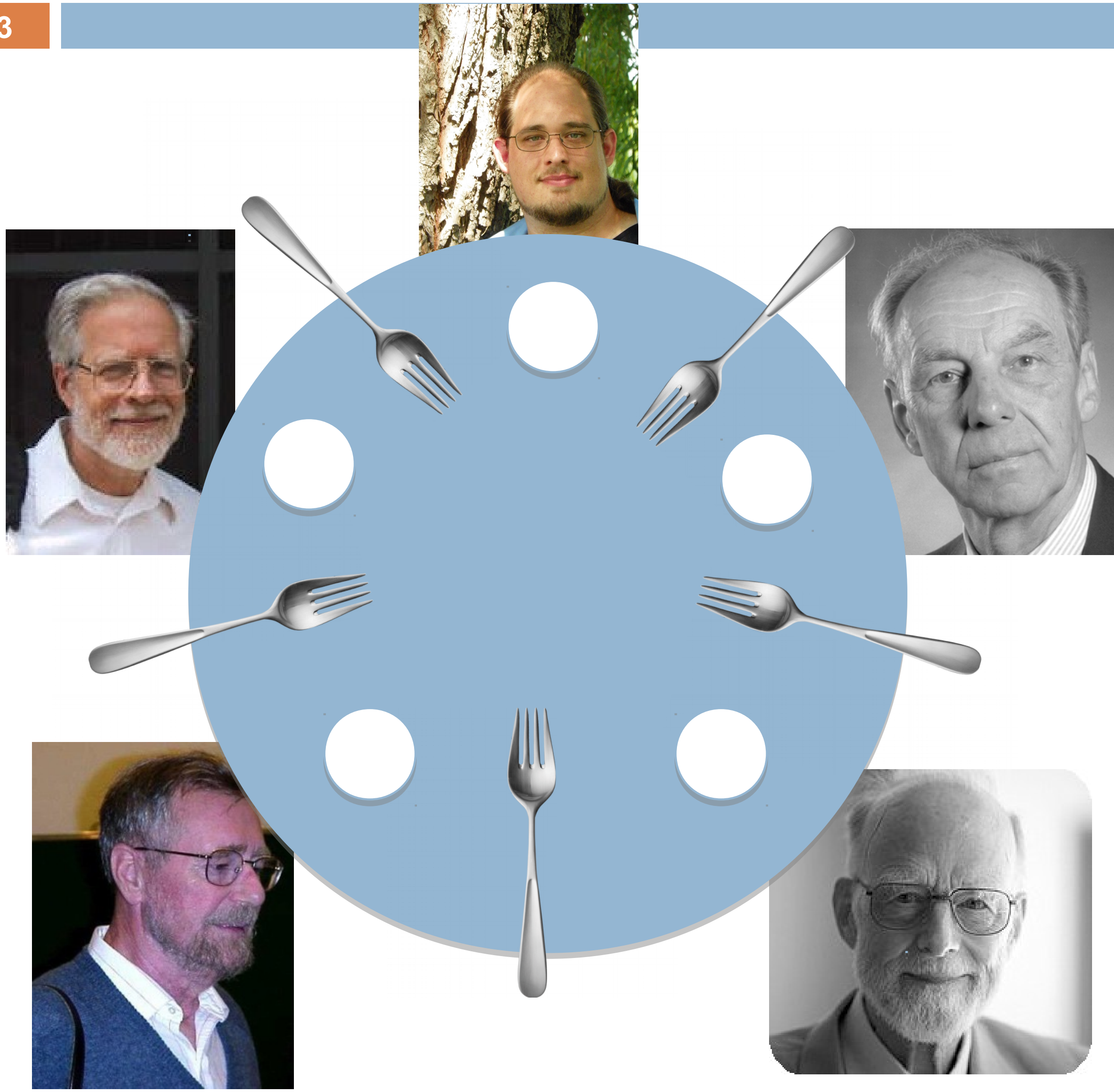
# Deadlock




- To prevent race conditions, one often requires a process to "acquire" resources before accessing them, and only one process can "acquire" a given resource at a time.
- Examples of resources are:
  - A file to be read
  - An object that maintains a stack, a linked list, a hash table, etc.
- But if processes have to acquire two or more resources at the same time in order to do their work, **deadlock** can occur. This is the subject of the next slides.

# Dining philosopher prob





Five philosophers sitting at a table.

Each repeatedly does this:

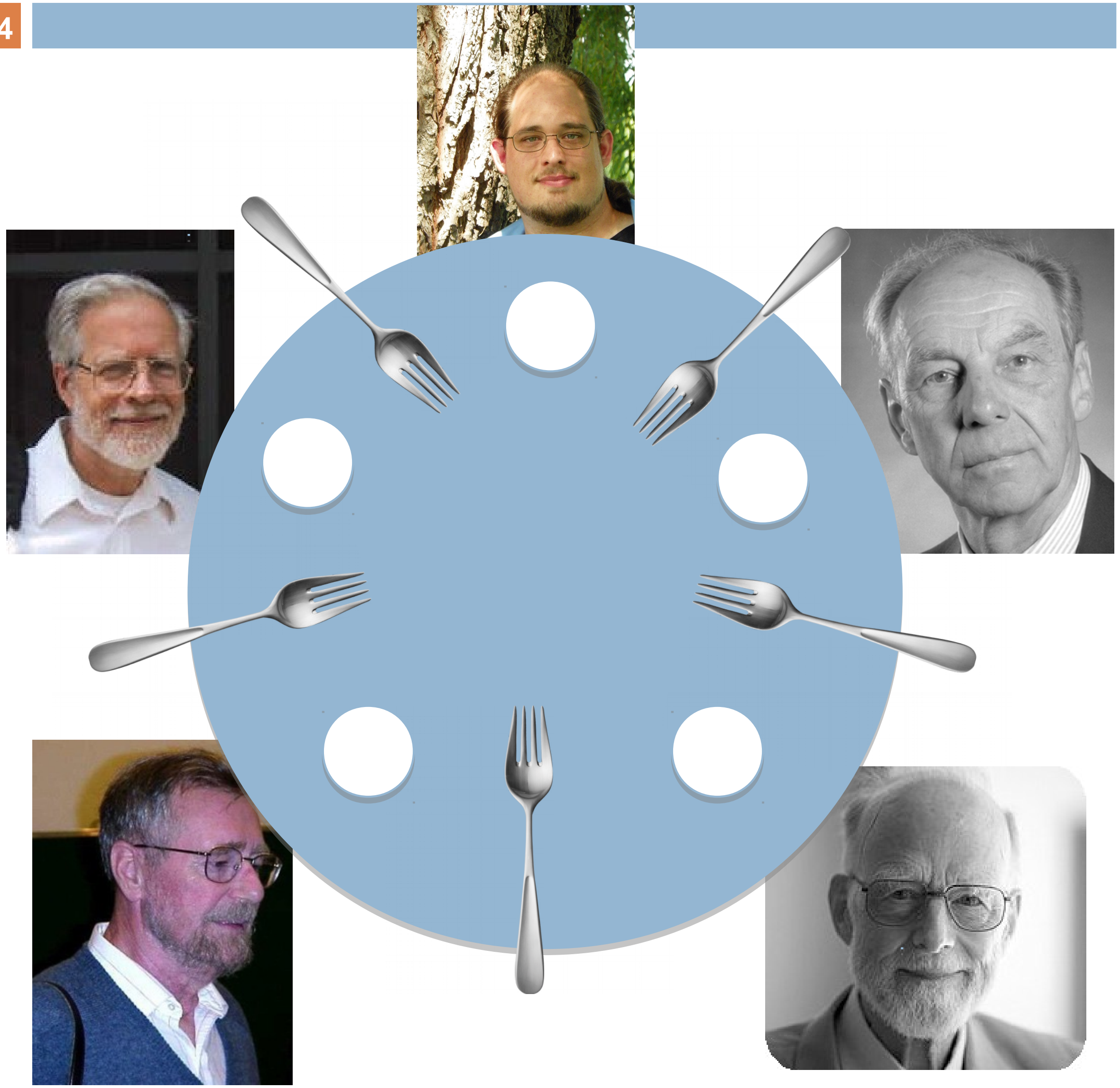
1. think
2. eat

What do they eat?
spaghetti.

Need TWO forks to eat spaghetti!

# Dining philosopher prob





Each does repeatedly :

1. think
2. eat (2 forks)

eat is then:

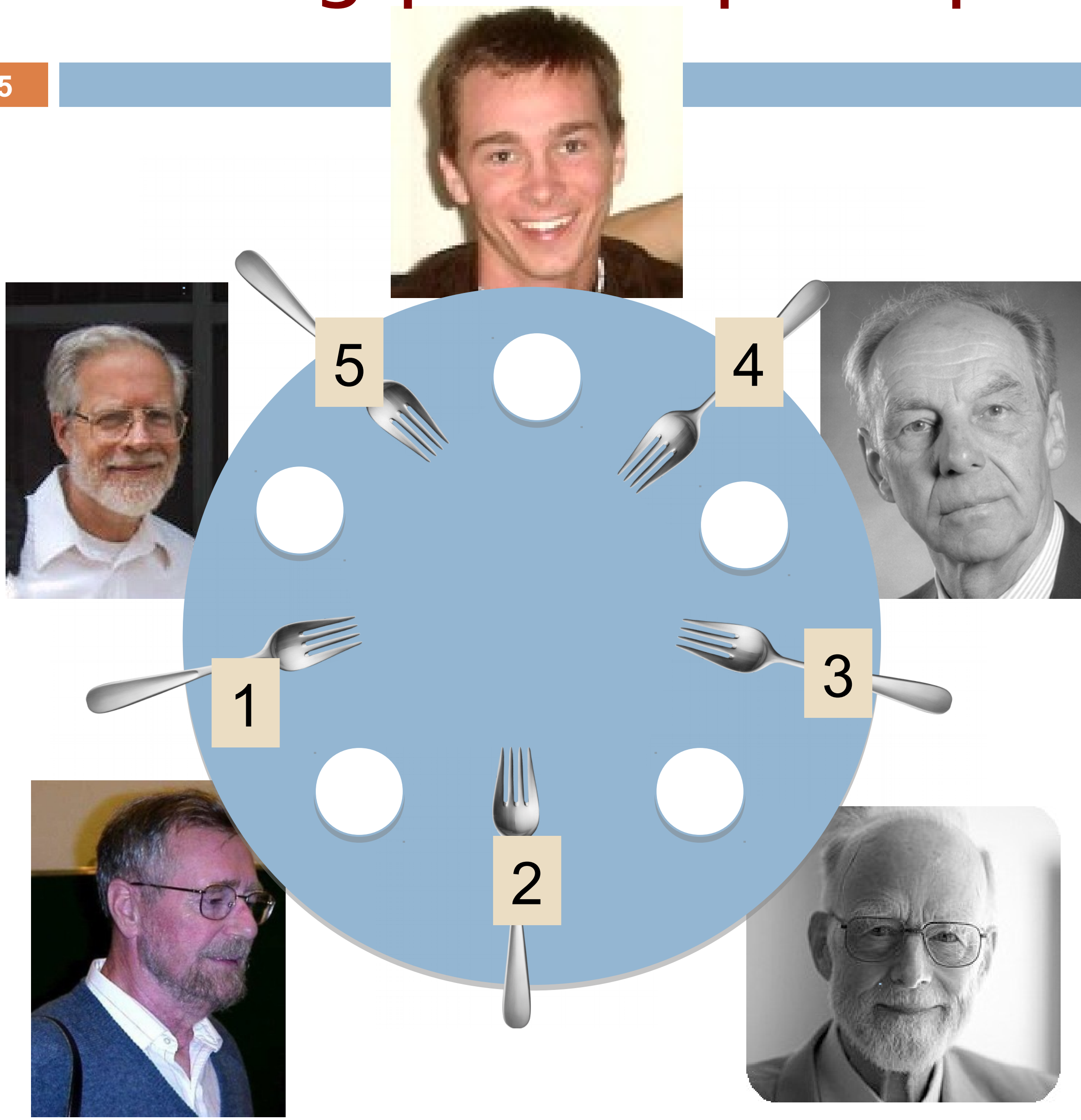
pick up left fork
pick up right fork
pick up food, eat
put down left fork
put down rght fork

At one point, they all pick up their left forks

**DEADLOCK!**

# Dining philosopher pro






**Simple solution to deadlock:**

Number the forks. Pick up smaller one first

1. think
2. eat (2 forks)

eat is then:

pick up smaller fork
pick up bigger fork
pick up food, eat
put down bigger fork
put down smallerfork

# Java: 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" calls to methods to process them
- Today: learn to create new threads of our own in

# Thread



- A thread is an object that "independently computes"
  - Needs to be created, like any object
  - Then "started" --causes some method to be called. It runs side by side with other threads in the same program; they see the same global data
- The actual executions could occur on different CPU cores, but but don't have to
  - We can also simulate threads by *multiplexing* a smaller number of cores over a larger number of threads

# Java class Thread



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

# 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()`**

Call **`run()`** directly?
no new thread is used:
Calling thread will run it

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

Do this and
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



Thread name, priority, thread group

```
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



Thread name, priority, thread group

```
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

Thread name, priority, thread group

```
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



```java
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...

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

If threads happen to be sharing a CPU, yield allows other waiting threads to run.

# Terminating Threads is tricky




- Easily done... but only in certain ways
  - *Safe way to terminate a thread*: *return from method run*
  - *Thread throws uncaught exception? whole program will be halted (but it can take a second or two ... )*
- Some old APIs have issues: stop(), interrupt(), suspend(),
  destroy(), etc.
  - Issue: Can easily leave application in a "broke n" 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 pause
  - Call Thread.sleep(k) to sleep for k milliseconds
  - Doing I/O (e.g. read file, wait for mouse input, open file) can cause thread to pause
  - Java has a form of locks associated with objects.  When threads lock an object, one succeeds at a time.

# Background (daemon) Thread



- In many applications we have a notion of “foreground” and “background” (daemon) threads
  - Foreground threads are 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.

# 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 ⇒ stack is now empty
3. thread B tests `stack.isEmpty()` ⇒ 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 race conditions.
  you must use it by carefully and explicitly – it isn't automatic.
  - Called a synchronization barrier
  - 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, another thread can acquire it
    - Can't predict the order in which contending threads get the lock but it should be "fair" if

# Solution: use 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
- Can't be interrupted by other **synchronized blocks on the same object**
- Can run concurrently with non-synchronized code
- Or code synchronized on a different object!

# Solution: locking



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

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

Syntactic sugar for the above:

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

# 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 pri
  - ... The lower priority thread "sta

- 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 abstract data types
  - Semaphores: a kind of synchronized counter (invented by Dijkstra)
  - Event-driven synchronization
- The Windows and Linux and Apple O/S have kernel locking features, like file locking
- But for Java, **synchronized** is the core mechanism

# Blocking and communication



- Java allows you to do fancier synchronization
  - But can only be used inside a synchronization block
  - Special primatives called wait/notify
    - **Wait:** sleep until nudged
    - **Notify:** nudge
  - Wait/notify easy to misuse!!
    - we’ll cover correct/incorrect usage next time

# wait/notify

**Suppose we put this inside an object called animator:**

```
boolean isRunning = true;

public synchronized                                () {
   while (true) {
      while (!isRunning) wait();
      //do one step of simulation
      isRunning = true;
   }
}

public synchronized void startAnimation() {
    isRunning = true;
    notifyAll();
}

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

must be synchronized!

# Summary



- Use of multiple processes and multiple threads within each process can exploit concurrency
  - Which may be real (multicore) or "virtual" (an illusion)
- When using threads, beware!
  - Synchronize any shared memory to avoid race conditions
  - Synchronize objects in certain order to avoid deadlocks
  - Even with proper synchronization, concurrent programs can have other problems such as "livelock"
- Serious treatment of concurrency is a complex