CSE 1325: Object-Oriented Programming

Lecture 22

A *Very* Simple Introduction to Concurrency

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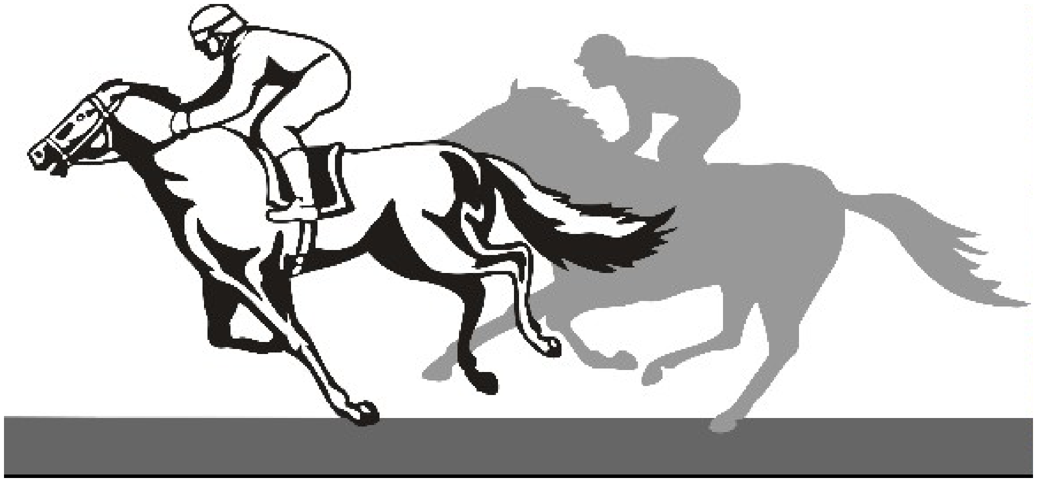
Or by appointment

A biologist, a chemist, and a statistician are hunting when a deer wanders by.
The biologist misses 5 feet to the left and the chemist 5 feet to the right.
The statistician yells "We got 'em!"

Overview: Concurrency

- Brief history
- Uses / Advantages
- C++ Support
  - Thread class
  - Sleep
  - Conflicts / Race
  - Mutex
- Examples
  - Matrix multiplication
  - Horse racing simulation



A Brief History of Concurrency

- **Moore's Law** (paraphrased): Computer tech (originally transistor density) doubles every 2 years
  - CPU speed, transistor and memory density, disk capacity, etc.
- By the 21st century, Moore's Law began to crack
  - Processor speeds topped out around 4 GHz (2.8 – 3.4 common)**
  - Transistor density continued for some time – but how to best use?
- **Multi-Core Processor** – a chip with multiple **cores**, or ALU*/register sets, each running a separate thread
  - Intel worked out use of one ALU with 2 register sets, interleaving 2 threads of execution – **Hyperthreading**
- Deployed 24 hyperthreaded core machines in 2014 – but how to utilize so many cores?

Concurrency

* Arithmetic / Logic Unit

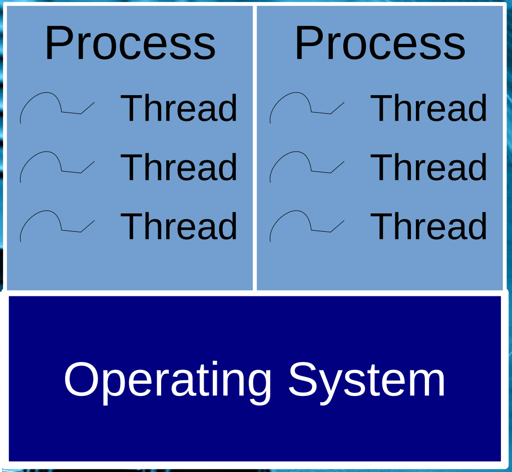
** Overlocking is a thing, though – https://valid.x86.fr/records.html

Concurrency

- "I do one thing, I do it very well, and then I move on" – Dr. Charles Emmerson Winchester III

  "Move on, Chaaarles" – Hawkeye

- **Concurrency** – Performing 2 or more algorithms (as it were) simultaneously
- **Process** – A self-contained execution environment including its own memory space.
- **Thread** – An independent path of execution within a process, running concurrently (as it appears) with others within a shared memory space.



Process

Thread

Thread

Thread

Process

Thread

Thread

Thread

Operating System

Conceptual Model

Expertise
/eks-per-tyz/
def: Special skill or knowledge in a particular subject, eg. He has expertise in his field of molecular

Good Uses for Concurrency

- Perform background processing independent of the user interface, e.g., communicating the game state to apps
- Programming logically independent program units, e.g., the behavior of each non-player character in a game
- Processing small, independent units of a large problem, e.g., calculating the shaded hue of each pixel in a rendered photograph – or rendering an entire movie frame by frame!
- Periodic updating of a display or hardware unit, e.g., updating the second hand of a clock
- Periodic collection of data, e.g., capturing wind speed from an anemometer every 15 seconds

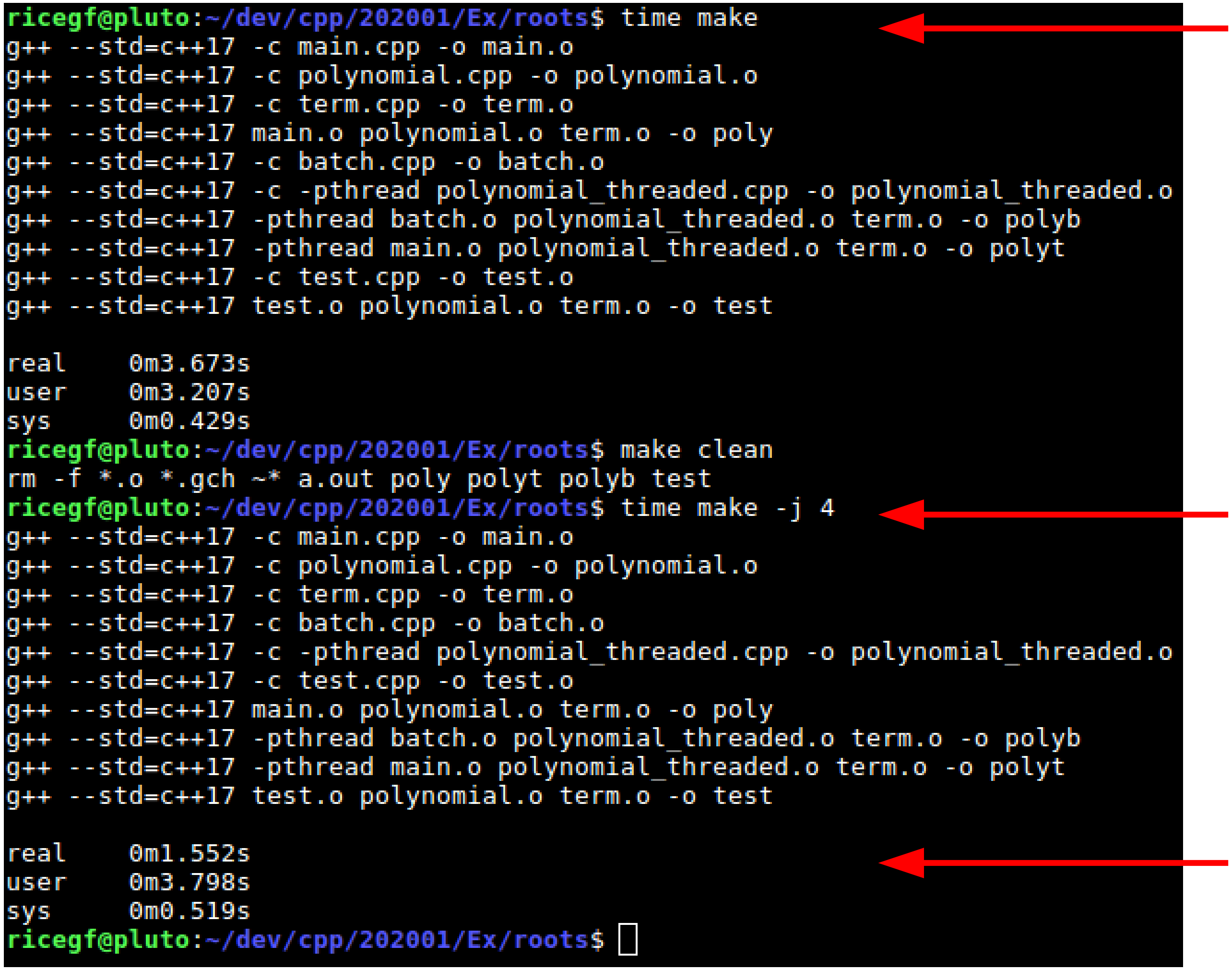
Advantages of Threads

- Better utilization of multi-core / multi-processor machines
  - On our 24-core machines, Parallel Implementation of gzip (pigz) was more than 10x faster than standard gzip – cut 3 hour compression to 15 min
- Better mapping of problem to code
  - For Chinese Checkers with 5 AI players and 1 human player, each player as a thread sharing a common board object is a more natural implementation
  - Better still, AI implementation can analyze board while other players are “thinking” - see first bullet

Advantages of Threads

(For C++ Programmers)

- Faster C++ builds!*



```
ricegf@pluto:~/dev/cpp/202001/Ex/roots$ time make
g++ --std=c++17 -c main.cpp -o main.o
g++ --std=c++17 -c polynomial.cpp -o polynomial.o
g++ --std=c++17 -c term.cpp -o term.o
g++ --std=c++17 main.o polynomial.o term.o -o poly
g++ --std=c++17 -c batch.cpp -o batch.o
g++ --std=c++17 -c -pthread polynomial_threaded.cpp -o polynomial_threaded.o
g++ --std=c++17 -pthread batch.o polynomial_threaded.o term.o -o polyb
g++ --std=c++17 -pthread main.o polynomial_threaded.o term.o -o polyt
g++ --std=c++17 -c test.cpp -o test.o
g++ --std=c++17 test.o polynomial.o term.o -o test

real    0m3.673s
user    0m3.207s
sys     0m0.429s
ricegf@pluto:~/dev/cpp/202001/Ex/roots$ make clean
rm -f *.o *.gch ~* a.out poly polyt polyb test
ricegf@pluto:~/dev/cpp/202001/Ex/roots$ time make -j 4
g++ --std=c++17 -c main.cpp -o main.o
g++ --std=c++17 -c polynomial.cpp -o polynomial.o
g++ --std=c++17 -c term.cpp -o term.o
g++ --std=c++17 -c batch.cpp -o batch.o
g++ --std=c++17 -c -pthread polynomial_threaded.cpp -o polynomial_threaded.o
g++ --std=c++17 -c test.cpp -o test.o
g++ --std=c++17 main.o polynomial.o term.o -o poly
g++ --std=c++17 -pthread batch.o polynomial_threaded.o term.o -o polyb
g++ --std=c++17 -pthread main.o polynomial_threaded.o term.o -o polyt
g++ --std=c++17 test.o polynomial.o term.o -o test

real    0m1.552s
user    0m3.798s
sys     0m0.519s
ricegf@pluto:~/dev/cpp/202001/Ex/roots$ 
```

Time measures how long the make command runs
– real is what you experience
– user is total of all cores
– sys is time in system overhead

-j 4 means “use 4 threads”

A 60% reduction in build time (1.5 vs 3.7 seconds) for 3 chars!

* Wouldn’t this have been helpful *last* semester? Javac isn’t concurrent, regrettably.

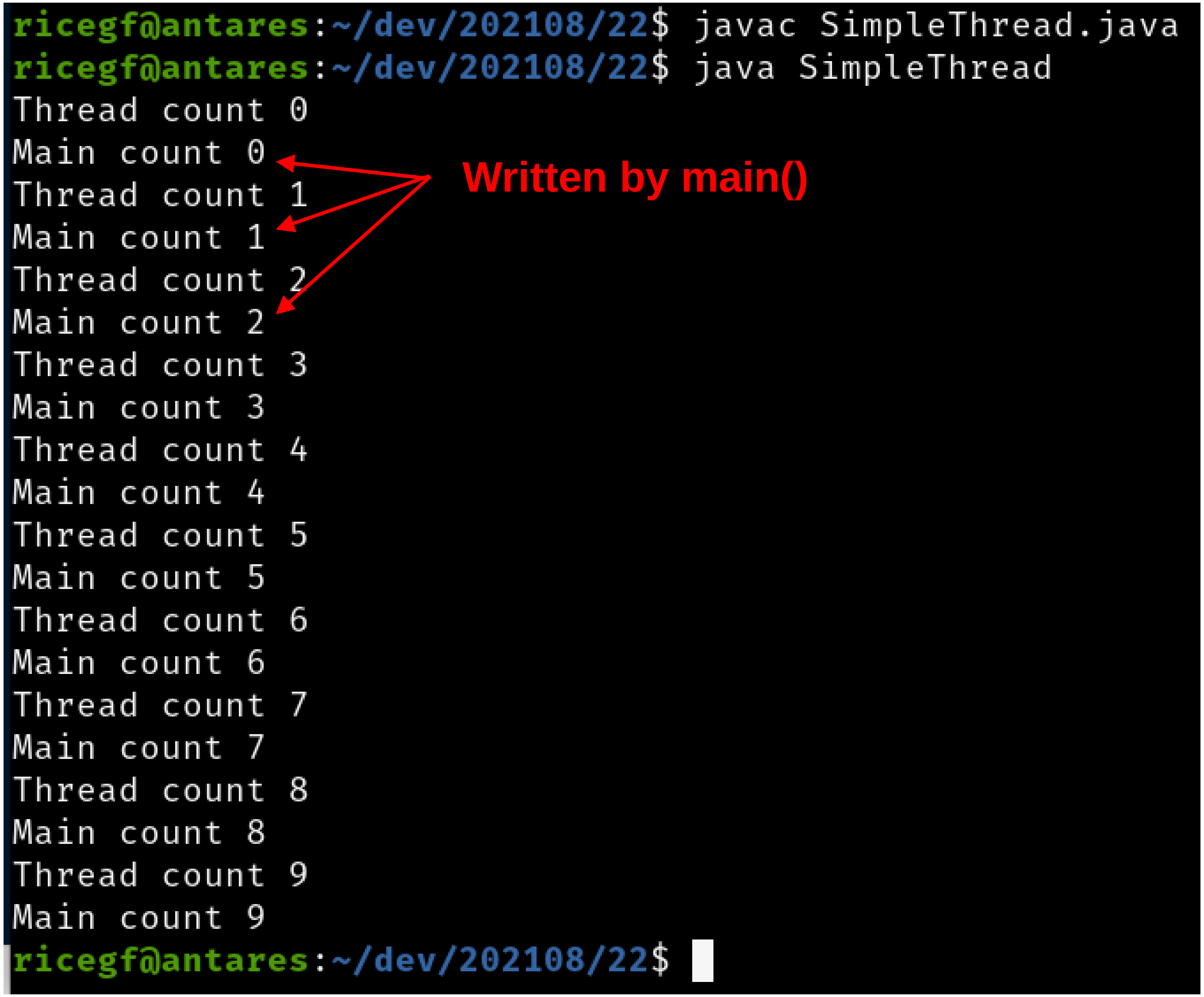
Creating a Simple Java Thread

- Class Thread represents a thread of execution
  - Each Thread has a unique thread ID (.getId())
  - Each started thread can be “joined” back to the main thread (an unstarted thread can’t)

```java
public class SimpleThread implements Runnable {
    // Interface Runnable requires overriding the run method.
    @Override
    public void run() {
        for(int i=0; i<10; ++i)
            System.out.println("Thread count " + i);
    }

    public static void main(String args[]) {
        SimpleThread st = new SimpleThread();  // runnable object
        Thread t = new Thread(st);             // Thread instance referencing st
        t.start();                             // Start st.run() in a thread!

        for(int i=0; i<10; ++i)                // Main continues while st.run() runs
            System.out.println("Main count " + i);
    }
}
```

Creating a Simple Java Thread

Written by run()



```
ricegf@antares:~/dev/202108/22$ javac SimpleThread.java
ricegf@antares:~/dev/202108/22$ java SimpleThread
Thread count 0
Main count 0
Thread count 1
Main count 1
Thread count 2
Main count 2
Thread count 3
Main count 3
Thread count 4
Main count 4
Thread count 5
Main count 5
Thread count 6
Main count 6
Thread count 7
Main count 7
Thread count 8
Main count 8
Thread count 9
Main count 9
ricegf@antares:~/dev/202108/22$ 
```

Written by main()

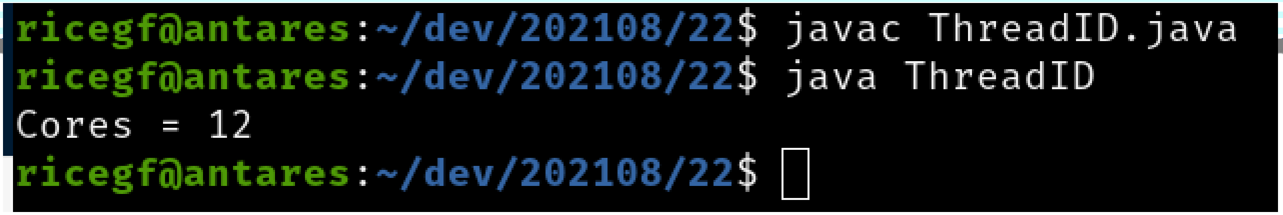
Note that in Java, I/O is automatically segregated by thread.

This is NOT true of most languages!

Java Offers a *Hint* at HW Support

- Runtime's availableProcessors() returns a rough estimate of the number of *concurrent* threads supported by the VM
  - This may represent cores or hyperthreaded half-cores
  - This may return 0 or nothing relevant at all
  - In general, strive to avoid hardware dependencies

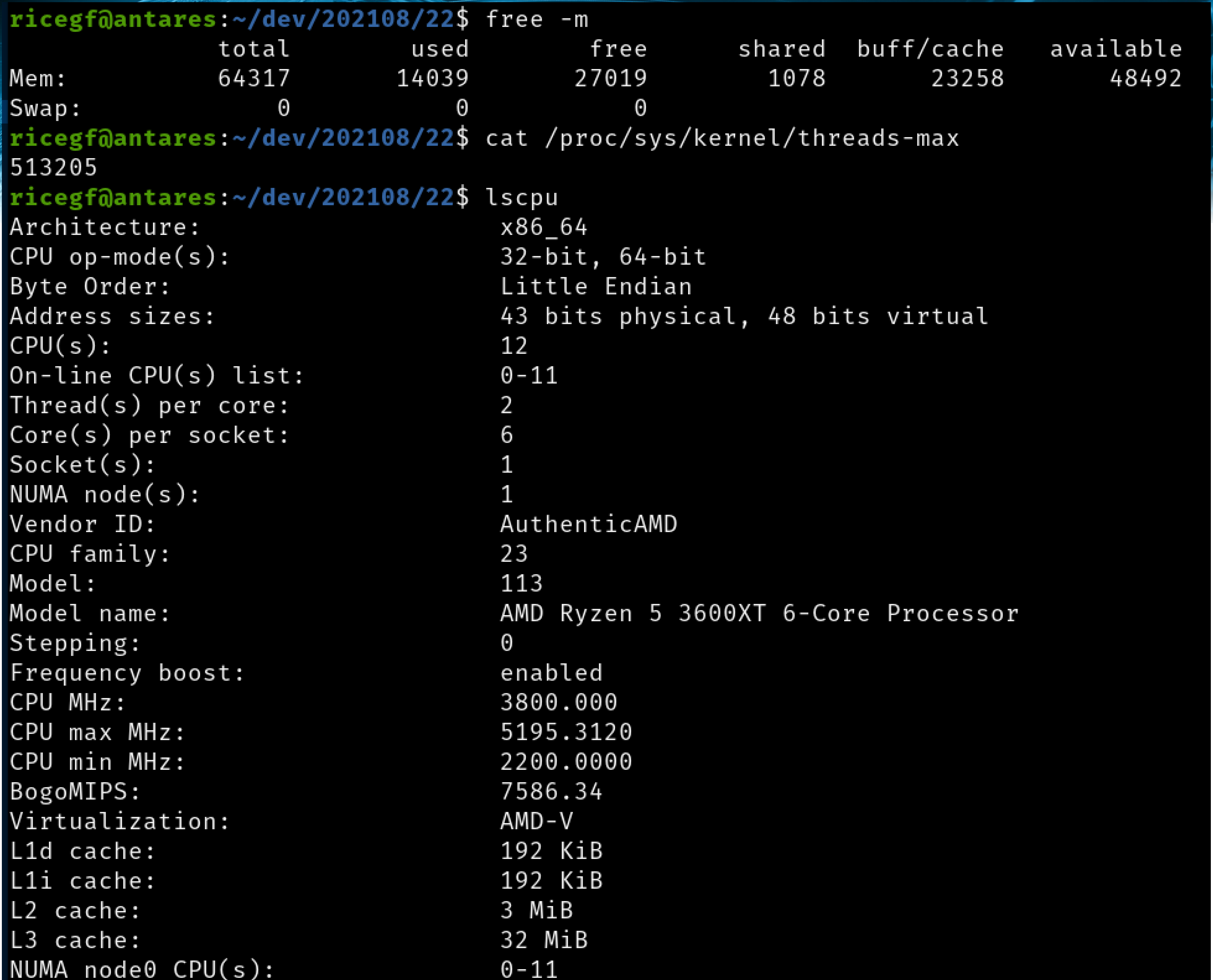
```java
public class ThreadID {
    public static void main(String[] args) {
        System.out.println("Cores = "
            + Runtime.getRuntime().availableProcessors());
    }
}
```



```
ricegf@antares:~/dev/202108/22$ javac ThreadID.java
ricegf@antares:~/dev/202108/22$ java ThreadID
Cores = 12
ricegf@antares:~/dev/202108/22$ 
```

Max Threads Depends on the OS

- **You can run *far* more threads than you have cores**
  - The OS swaps threads onto cores as needed
  - The maximum number of threads varies by OS
- **Linux** simply treats threads as processes sharing memory, and the limit is set by your hardware configuration
  - **`lscpu`** will tell you all about your CPUs
  - **`free`** will tell you how much RAM you have
    (add **`–m`** to get numbers in megabytes or **`–g`** for gigabytes)
  - **`cat /proc/sys/kernel/threads-max`** will tell you max threads
- **Windows (NT)** threads are limited by available memory – about 2000 for a minimum system to about 250,000 for a large server
  - Microsoft recommends the thread pool API if you need lots of threads
- **Mac OS X (Unix)** supports 2048 threads per process



```
ricegf@antares:~/dev/202108/22$ free -m
              total        used        free      shared  buff/cache   available
Mem:          64317       14039       27019        1078       23258       48492
Swap:             0           0           0
ricegf@antares:~/dev/202108/22$ cat /proc/sys/kernel/threads-max
513205
ricegf@antares:~/dev/202108/22$ lscpu
Architecture:                    x86_64
CPU op-mode(s):                  32-bit, 64-bit
Byte Order:                      Little Endian
Address sizes:                   43 bits physical, 48 bits virtual
CPU(s):                          12
On-line CPU(s) list:             0-11
Thread(s) per core:              2
Core(s) per socket:              6
Socket(s):                       1
NUMA node(s):                    1
Vendor ID:                       AuthenticAMD
CPU family:                      23
Model:                           113
Model name:                      AMD Ryzen 5 3600XT 6-Core Processor
Stepping:                        0
Frequency boost:                 enabled
CPU MHz:                         3800.000
CPU max MHz:                     5195.3120
CPU min MHz:                     2200.0000
BogoMIPS:                        7586.34
Virtualization:                  AMD-V
L1d cache:                       192 KiB
L1i cache:                       192 KiB
L2 cache:                        3 MiB
L3 cache:                        32 MiB
NUMA node0 CPU(s):               0-11
```

Sleeping a Thread

- It's tempting to pause a thread using a “busy loop”

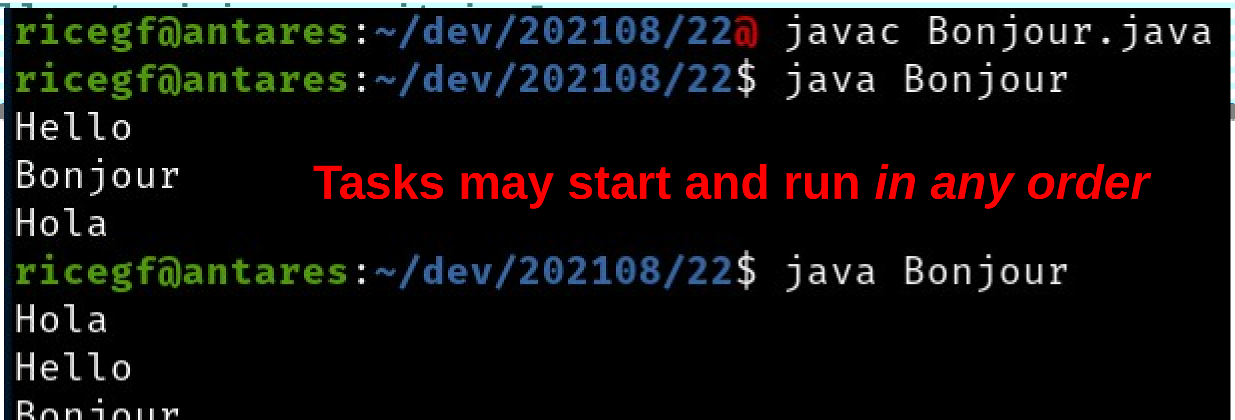
```
for (int i = 0; i < 100000; ++i) { } // Wait a while
```

- This is *very* problematic
  - Compilers are very smart nowadays, and may optimize away the useless loop
  - Processor speeds vary widely, so timing is uncertain
  - If it runs the instructions, it's burning valuable CPU cycles that could be used by other threads
- Instead, use Thread.sleep(milliseconds)

```
Thread.sleep(6000); // Sleep for (at least) 6 seconds
```

Sleeping 3 Threads Randomly

```java
public class Bonjour implements Runnable {
    String message;
    public Bonjour(String message) {
        this.message = message;
    }
    @Override
    public void run() {
        try {
            Thread.sleep(100 + (int)(Math.random() * 300));
        } catch (InterruptedException e) {
            System.err.println(message + " abort: " + e);
        }
        System.out.println(message);
    }
    public static void main(String[] args) {
        (new Thread(new Bonjour("Hello"))).start();
        (new Thread(new Bonjour("Hola"))).start();
        (new Thread(new Bonjour("Bonjour"))).start();
        // Threads wi
    }
}
```



```
ricegf@antares:~/dev/202108/22@ javac Bonjour.java
ricegf@antares:~/dev/202108/22$ java Bonjour
Hello
Bonjour
Hola
ricegf@antares:~/dev/202108/22$ java Bonjour
Hola
Hello
Bonjour
```

Tasks may start and run *in any order*

Better Core Utilization

Matrix Multiplication

- We’ll create a CPU-intensive challenge that can be threaded – multiplying huge square matrices
  - Class Matrix stores an NxN matrix of integers (N is the constructor parameter)
    - fill() randomly populates each cell between 1 and 20
    - multiply(Matrix) multiplies to another matrix, returning the result
    - xor() returns the exclusive or of every cell
    - get and set access individual cells in the Matrix
  - Class MatrixMultiply includes run() and main(), the latter accepting 2 CLI parameters
    - numMultiplies for the number of matricies to multiply
    - numThreads (optional) if given is the number of threads AND number of matricies (and the first parameter is ignored)

Better Core Utilization

Matrix

(1 of 2)

```
public class Matrix {
    public Matrix(int size) {
        this.SIZE = size;
        matrix = new int[SIZE][SIZE];
    }
    public void fill() {
        for (int row = 0; row < SIZE; ++row) {
            for (int col = 0; col < SIZE; ++col)
                matrix[row][col] = 1 + (int) (20*Math.random());
        }
    }
    public Matrix multiply(Matrix rhs) {
        Matrix result = new Matrix(SIZE);

        for (int row = 0; row < SIZE; row++) {
            for (int col = 0; col < SIZE; col++)
                result.set(row, col, multiplyCell(rhs, row, col));
        }
        return result;
    }
    private int multiplyCell(Matrix rhs, int row, int col) {
        int cell = 0;
        for (int i = 0; i < SIZE; i++)
            cell += matrix[row][i] * rhs.get(i, col);
        return cell;
    }
}
```

We burn most of our time here!

Better Core Utilization
Matrix
(2 of 2)

```
    public int xor() {
        int result = 0;
        for (int row = 0; row < SIZE; ++row) {
            for (int col = 0; col < SIZE; ++col) {
                result ^= matrix[row][col];
            }
        }
        return result;
    }

    public int get(int row, int col) {return matrix[row][col];}
    public void set(int row, int col, int value) {matrix[row][col] = value;}

    private int[][] matrix;
    public final int SIZE;
}
```

xor() performs a bitwise-XOR operation on every integer cell in the matrix, returning the resulting integer. Thus, every cell matters to the “answer”.

When benchmarking, ensure that **EVERY calculation** is used as part of the printed result. Otherwise, a good compiler may eliminate the calculation entirely and destroy your benchmark!

Yes, I still have the scars...

Better Core Utilization

Matrix Multiply

(1 of 2)

```
public class MatrixMultiply implements Runnable {
    public final int SIZE = 500;

    @Override
    public void run() {
        Matrix m1 = new Matrix(SIZE); m1.fill();
        Matrix m2 = new Matrix(SIZE); m2.fill();
        Matrix m3 = m1.multiply(m2);
        System.out.println(m3.xor());
    }
```

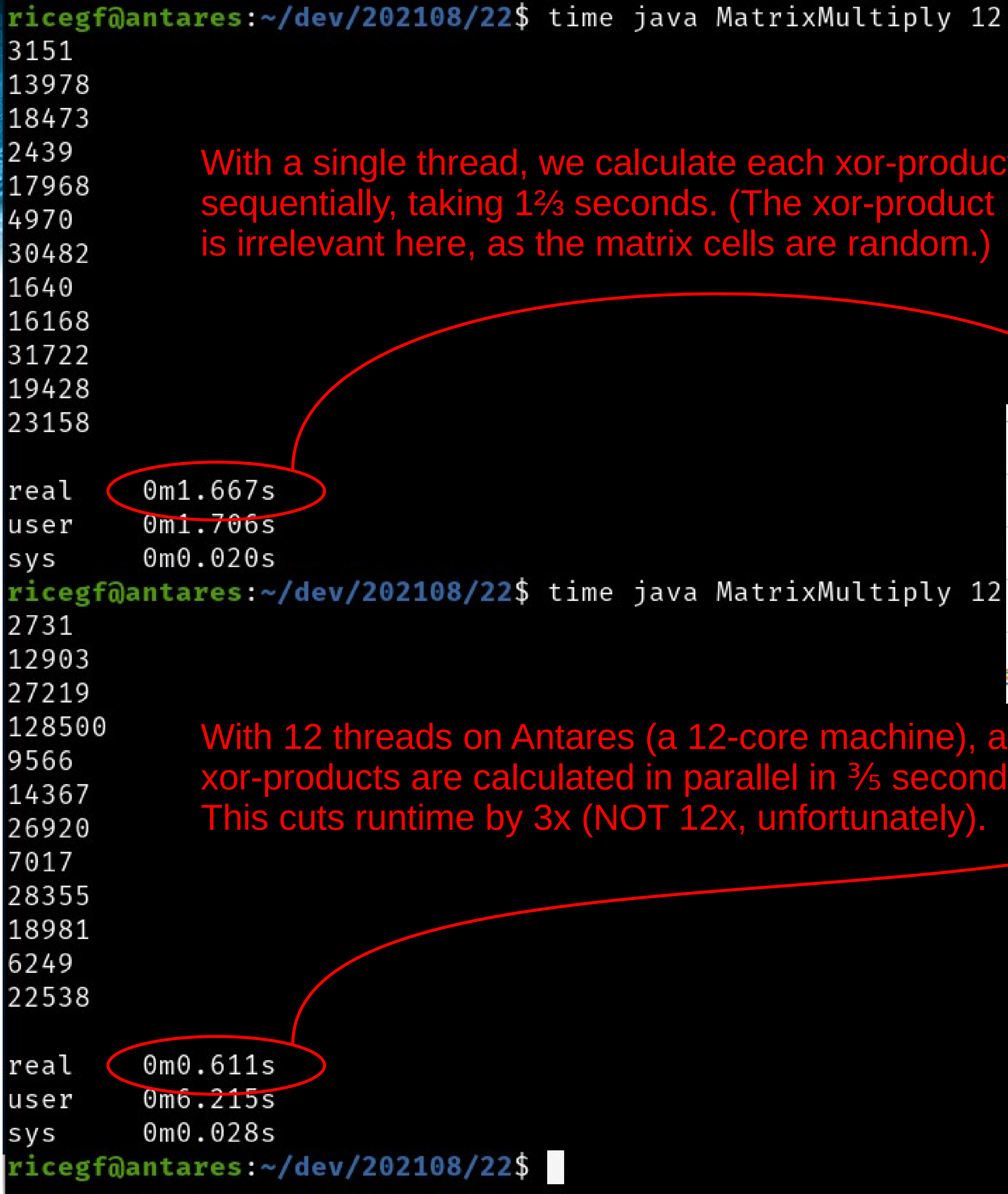
run() does the actual multiplication of 2 500x500 integer matrices.

Better Core Utilization
Matrix Multiply
(2 of 2)

```
    public static void main(String[] args) {
        int numMultiplies = 1;  int numThreads = 1;
        if(args.length == 0 || args.length > 2) {
            System.err.println("Usage: java MatrixMultiply numMultiplies [numThreads]");
            System.exit(0);
        }
        if(args.length > 0) numMultiplies = Integer.parseInt(args[0]);
        if(args.length > 1) numThreads = Integer.parseInt(args[1]);

        if(numThreads == 1) {
            MatrixMultiply mm = new MatrixMultiply();
            for(int i=0; i<numMultiplies; ++i) mm.run();
        } else {
            try {
                Thread[] threads = new Thread[numThreads];
                for(int i=0; i<numThreads; ++i) {
                    threads[i] = new Thread(new MatrixMultiply());
                    threads[i].start();
                }
                for(int i=0; i<numThreads; ++i) {
                    threads[i].join();
                }
            } catch (InterruptedException e) {
                System.err.println("Abort: " + e);
            }
        }
    }
}
```

For 1 thread, we just calculate the matrix product sequentially in the main thread.

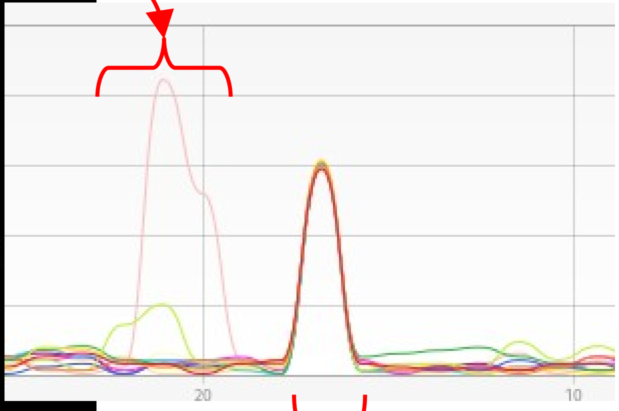
For 2+ threads, we calculate each matrix product in a separate concurrent thread. The main thread waits until they finish, then exits.



```
ricegf@antares:~/dev/202108/22$ time java MatrixMultiply 12
3151
13978
18473
2439
17968
4970
30482
1640
16168
31722
19428
23158

real    0m1.667s
user    0m1.706s
sys     0m0.020s
ricegf@antares:~/dev/202108/22$ time java MatrixMultiply 12
2731
12903
27219
128500
9566
14367
26920
7017
28355
18981
6249
22538

real    0m0.611s
user    0m6.215s
sys     0m0.028s
ricegf@antares:~/dev/202108/22$ 
```

With a single thread, we calculate each xor-product sequentially, taking 1⅔ seconds. (The xor-product is irrelevant here, as the matrix cells are random.)

With 12 threads on Antares (a 12-core machine), all xor-products are calculated in parallel in ⅗ second. This cuts runtime by 3x (NOT 12x, unfortunately).



Concurrency is Harder than Single-Threaded

- Non-reentrant code can lose data
  - **Reentrant** – An algorithm that can be paused while executin and then safely executed by a different thread
  - Non-reentrant code can experience **Thread Interference**
- Methods that aren't **thread safe** enable Threads to corrupt objects
  - Thread A updates a portion of the object's data, while Thread B updates a dependent portion, leaving the object in an inconsistent state – the bug's impact occurs much later!
- Memory Consistency Errors
  - Because variables may be cached, one thread's change may never be incorporated by a different thread's algorithm
- Concurrent bugs tend to appear only when multiple threads happen to align, thus appearing to be both rare and random
  - Nightmare debugging scenario

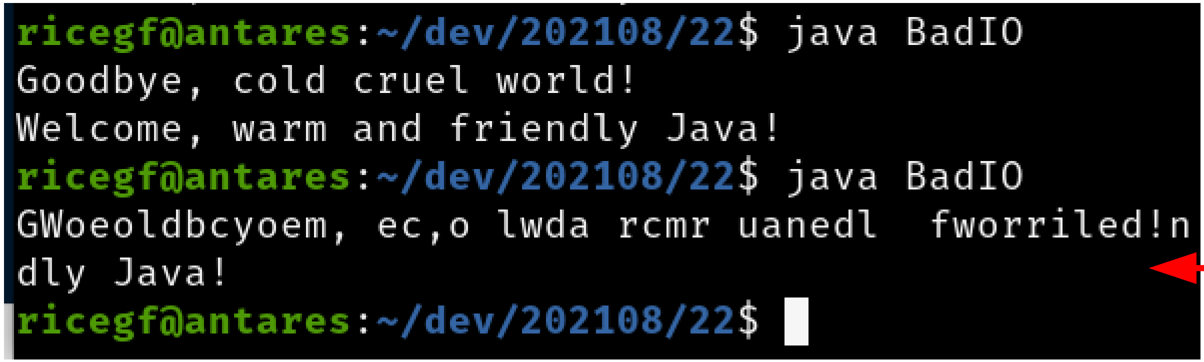
Thread Interference

```java
public class BadIO implements Runnable {
    private static boolean go = false;
    public void run() {
        String s = "Hello, cold cruel world!";
        go = true;
        for(char c : s.toCharArray()) {System.out.print(c); System.out.flush();}
    }
    public static void main(String[] args) {
        (new Thread(new BadIO())).start();
        String s = "Welcome, warm and friendly Java!";
        while(!go) ;
        for(char c : s.toCharArray()) {System.out.print(c); System.out.flush();}
    }
}
```

- Both main() and run() execute independently
  - Threads can switch execution *between microprocessor instructions* (not Java lines) at any time. This can garble output!

Ungarbled output

Garbled output



```
ricegf@antares:~/dev/202108/22$ java BadIO
Goodbye, cold cruel world!
Welcome, warm and friendly Java!
ricegf@antares:~/dev/202108/22$ java BadIO
GWoeoldbcyoem, ec,o lwda rcmr uanedl  fworriled!n
dly Java!
ricegf@antares:~/dev/202108/22$ 
```

Woops!

Measuring Thread Interference

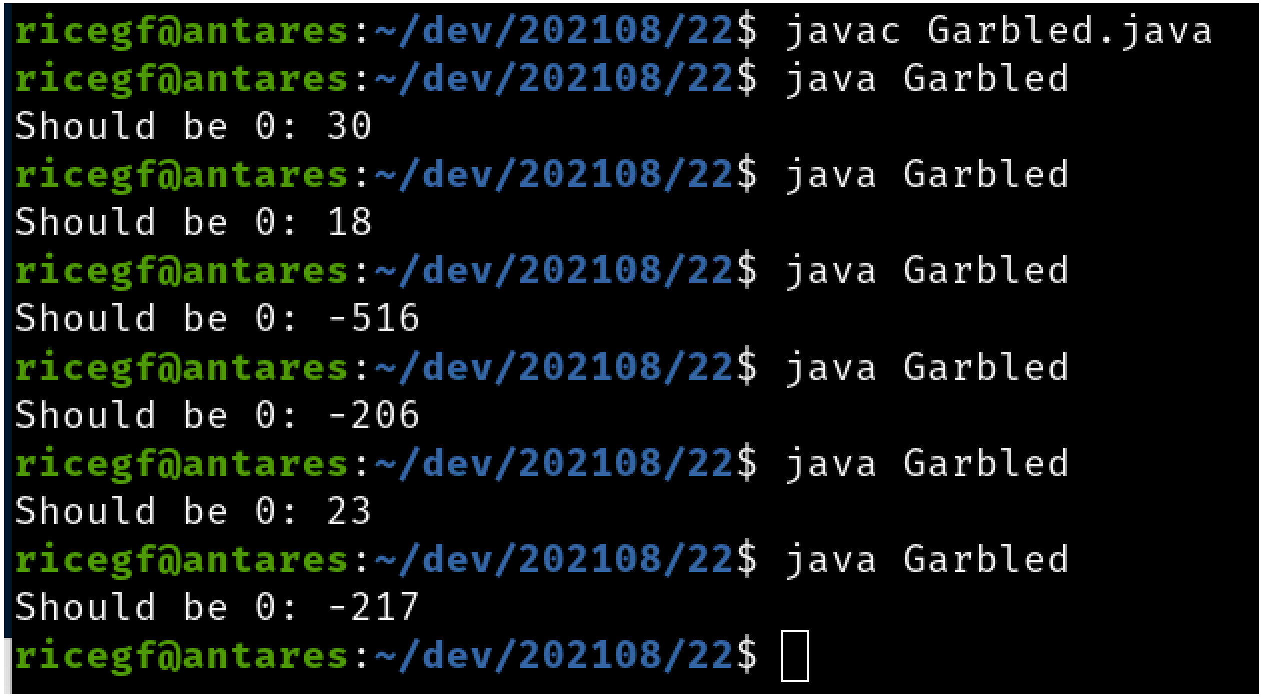
```java
class Counter {
    private int  count = 0;
    public  void increment() {count++;}
    public  void decrement() {count--;}
    public  int  getCount()  {return count;}
}
public class Garbled implements Runnable {
    private static Counter counter = new Counter();

    public void run() {
        for(int i=0; i<50000; ++i) {
            if(i%2 == 0) counter.increment();
            else counter.decrement();
        }
    }
    public static void main(String[] args) throws InterruptedException {
        Thread[] threads = new Thread[10];
        for(int i=0; i<10; ++i) {
            threads[i] = new Thread(new Garbled());
            threads[i].start();
        }
        for(int i=0; i<10; ++i) {
            threads[i].join();
        }
        System.out.println("Should be 0: " + counter.getCount());
    }
}
```

Class Counter offers to increment or decrement its internal count.

Each thread alternately increments and decrements the static Counter. The final result should be 0.

But when many threads do this simultaneously, they interfere and cause our Counter instance to fail.

Measuring Thread Interference



```
ricegf@antares:~/dev/202108/22$ javac Garbled.java
ricegf@antares:~/dev/202108/22$ java Garbled
Should be 0: 30
ricegf@antares:~/dev/202108/22$ java Garbled
Should be 0: 18
ricegf@antares:~/dev/202108/22$ java Garbled
Should be 0: -516
ricegf@antares:~/dev/202108/22$ java Garbled
Should be 0: -206
ricegf@antares:~/dev/202108/22$ java Garbled
Should be 0: 23
ricegf@antares:~/dev/202108/22$ java Garbled
Should be 0: -217
ricegf@antares:~/dev/202108/22$ 
```

A different failure every time –
one of the many joys of concurrency!

Monk character ©2002 by USA Network
Fair use for education is asserted

Solving the Thread Interference Problem
Digging Into the Bytecode

(**`javap -c Counter.class`** disassembles the bytecode)

```
public class Counter {
    private int count = 0;

    public void increment() {
        count++;
    }

    public void decrement() {
        count--;
    }

    public int getCount() {
        return count;
    }
}
```

```
public void increment();
  Code:
     0: aload_0
     1: dup
     2: getfield       #2
          // Field count:I
     5: iconst_1
     6: iadd
     7: putfield       #2
          // Field count:I
    10: return
```

Thread A paused here with count already loaded on its stack

```
public void decrement();
  Code:
     0: aload_0
     1: dup
     2: getfield       #2
          // Field count:I
     5: iconst_1
     6: isub
     7: putfield       #2
          // Field count:I
    10: return
```

Thread B decrements count in memory

Thread A resumes...

The change made by decrement in Thread B is overwritten by the obsolete stack data in Thread A.

$+1-1 \overset{?}{=} 1$

Hint: Immutable Classes!

- If the data can't change, synchronization issues can't crop up *in that class*
  - Create and use immutable classes when practical
  - In an immutable class, mark all data fields as const to indicate those fields won't change
  - This isn't always possible...
  -

General Java Solution: Synchronize!

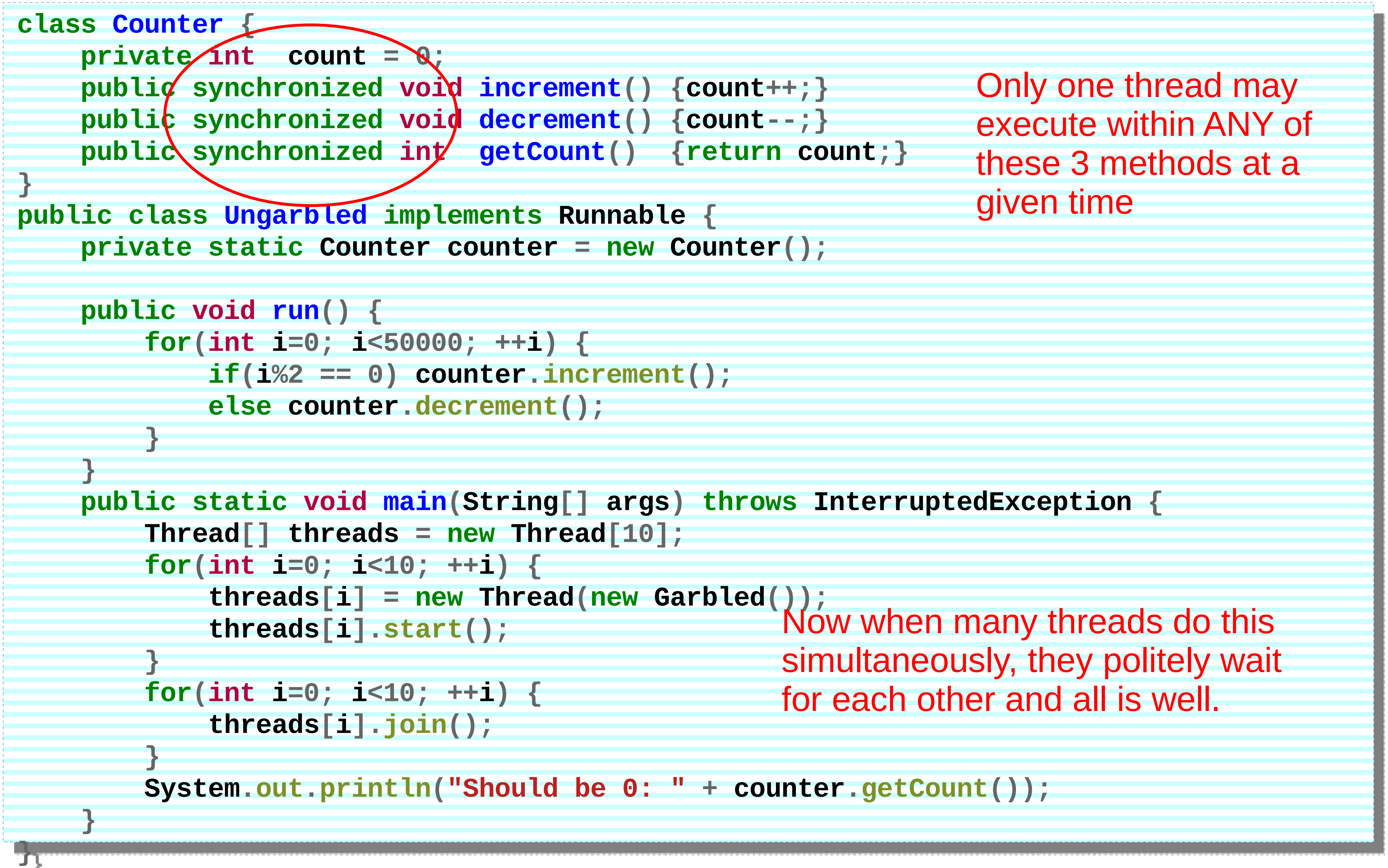
- Assume a crowd of people want to use an old-fashioned phone booth. The first to grab the door handle gets to use it first, but must hang on to the handle to keep the others out. When finished, the person exits the booth and releases the door handle. The next person to grab the door handle gets to use the phone booth next.
- A **thread** is: Each person
  The **mutex** is: The door handle
  The **lock** is: The person's hand
  The **resource** is: The phone

Hat tip to Nav on Stack Overflow for this analogy

Inferring a Mutex

- Java can often handle the mutual exclusion (mutex) object for you
  - If thread interference is limited to a class (Counter)...
  - If the methods in which the interference occurs execute briefly and return (increment, decrement)...
  - Then simply mark those methods “synchronized”
- Java will ensure that only one thread will be executing within ANY synchronized method of that class at a time

Solving Thread Interference with Synchronized Methods

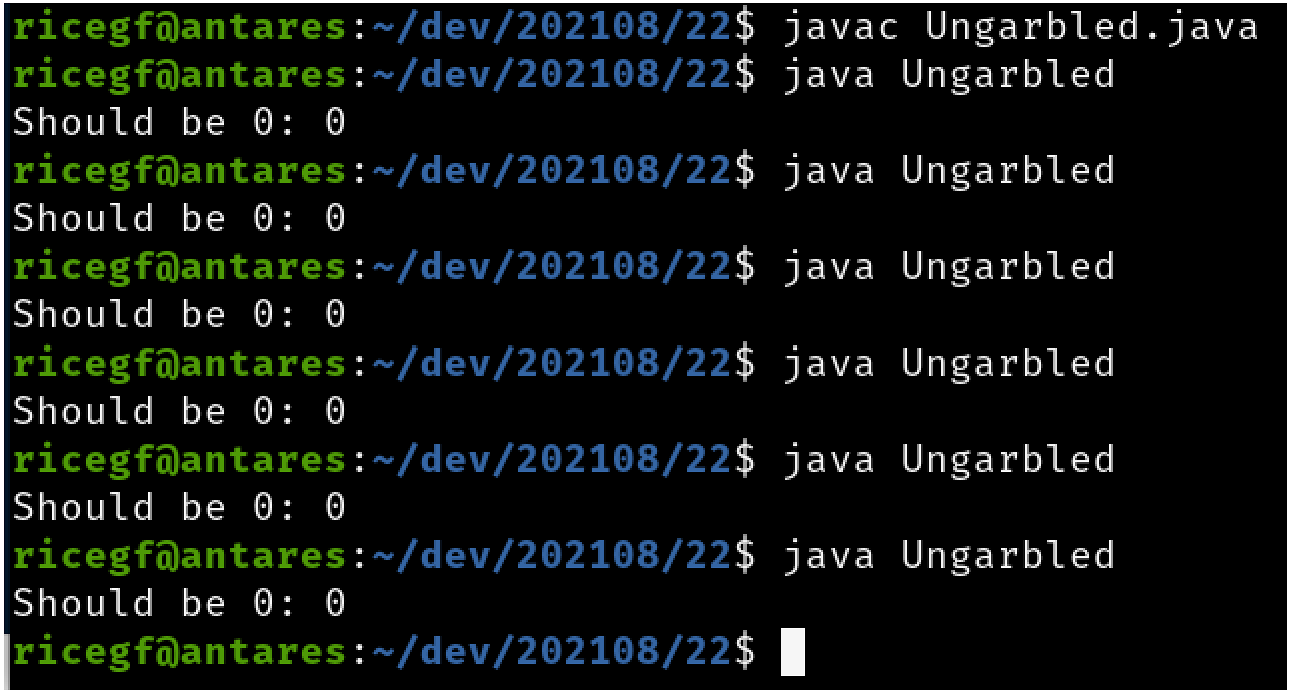


```
class Counter {
    private int  count = 0;
    public synchronized void increment() {count++;}
    public synchronized void decrement() {count--;}
    public synchronized int  getCount()  {return count;}
}
public class Ungarbled implements Runnable {
    private static Counter counter = new Counter();

    public void run() {
        for(int i=0; i<50000; ++i) {
            if(i%2 == 0) counter.increment();
            else counter.decrement();
        }
    }
    public static void main(String[] args) throws InterruptedException {
        Thread[] threads = new Thread[10];
        for(int i=0; i<10; ++i) {
            threads[i] = new Thread(new Garbled());
            threads[i].start();
        }
        for(int i=0; i<10; ++i) {
            threads[i].join();
        }
        System.out.println("Should be 0: " + counter.getCount());
    }
}
```

Only one thread may execute within ANY of these 3 methods at a given time

Now when many threads do this simultaneously, they politely wait for each other and all is well.

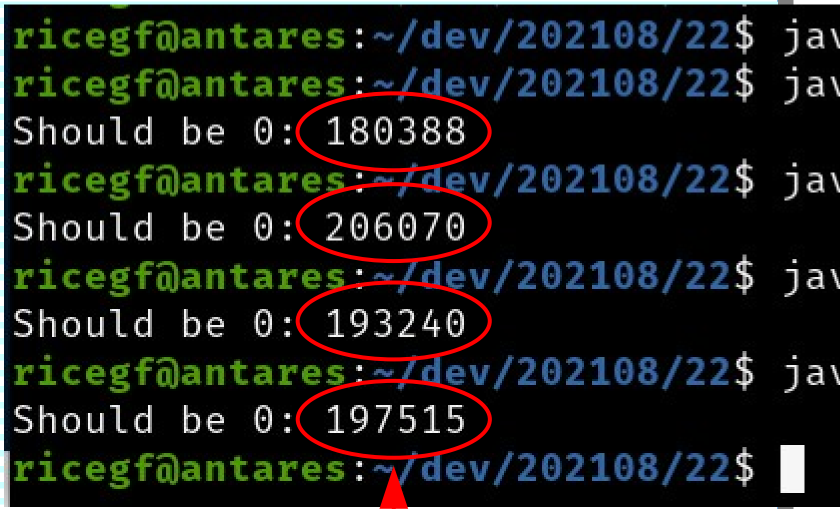
Solving Thread Interference with Synchronized Methods



```
ricegf@antares:~/dev/202108/22$ javac Ungarbled.java
ricegf@antares:~/dev/202108/22$ java Ungarbled
Should be 0: 0
ricegf@antares:~/dev/202108/22$ java Ungarbled
Should be 0: 0
ricegf@antares:~/dev/202108/22$ java Ungarbled
Should be 0: 0
ricegf@antares:~/dev/202108/22$ java Ungarbled
Should be 0: 0
ricegf@antares:~/dev/202108/22$ java Ungarbled
Should be 0: 0
ricegf@antares:~/dev/202108/22$ java Ungarbled
Should be 0: 0
ricegf@antares:~/dev/202108/22$ 
```

Non-Method Synchronization

```
public class NoSync implements Runnable {
    private final static int numThreads = 50;
    private final static int numDecrements = 5000;
    private static int counter = numThreads * numDecrements;

    // Our thread simply decrements counter numDecrements times
    @Override
    public void run() {
        for(int i=0; i<numDecrements; ++i) {
            --counter;
        }
    }
    public static void main(String[] args)
            throws InterruptedException {

        Thread[] threads = new Thread[numThreads];

        for(int i=0; i<numThreads; ++i) {
            threads[i] = new Thread(new NoSync());
            threads[i].start();  // Start decrementing
        }

        for(int i=0; i<numThreads; ++i)
            threads[i].join();

        System.out.println("Should be 0: " + counter);
    }
}
```



```
ricegf@antares:~/dev/202108/22$ jav
ricegf@antares:~/dev/202108/22$ jav
Should be 0: 180388
ricegf@antares:~/dev/202108/22$ jav
Should be 0: 206070
ricegf@antares:~/dev/202108/22$ jav
Should be 0: 193240
ricegf@antares:~/dev/202108/22$ jav
Should be 0: 197515
ricegf@antares:~/dev/202108/22$
```

Allow 5000 chances for thread interference per thread – and we see 10s of thousands! (Your machine may vary.)

The Need for Synchronization Objects

- Here’s we can’t just mark run() **`synchronized`**
  - It’s invoked by Thread
  - The synchronization problem is *inside* the method
- For these cases we can use synchronized objects (“locks”)
  - Any object will do (including **`this`** if appropriate)
  - Then create a synchronized scope, and Java will ensure 2 threads are never executing within a locked scope simultaneously

```
// This object "locks" counter while it is updated
private static Object lock = new Object();
```

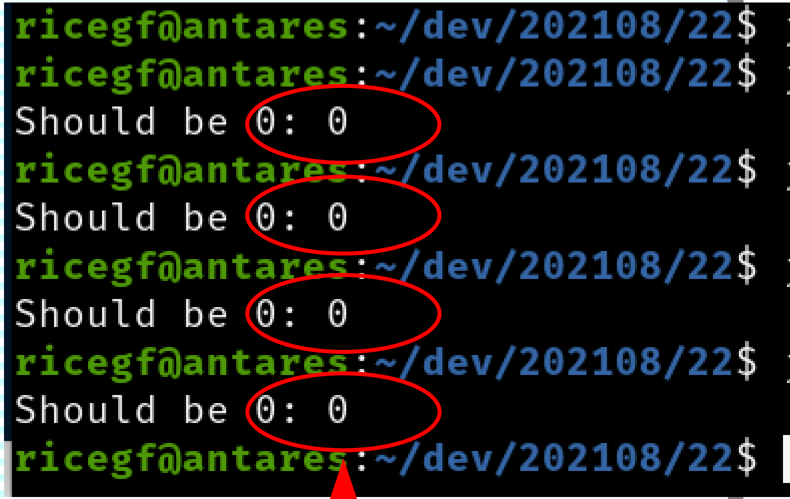
`static` is critical here – we must ensure that every thread uses the SAME lock!

```
// Our thread simply decrements counter numDecrements times
@Override
public void run() {
    for(int i=0; i<numDecrements; ++i) {
        synchronized(lock) {
            --counter;
        }
    }
}
```

Now all other threads must wait while this thread finishes decrementing counter.

Using Non-Method Synchronization

```
public class Sync implements Runnable {
    private final static int numThreads = 50;
    private final static int numDecrements = 5000;
    private static int counter = numThreads * numDecrements;
    @Override
    public void run() {
        for(int i=0; i<numDecrements; ++i) {
            synchronized(lock) {
                --counter;
            }
        }
    }
    public static void main(String[] args)
            throws InterruptedException {

        Thread[] threads = new Thread[numThreads];
        for(int i=0; i<numThreads; ++i) {
            threads[i] = new Thread(new Sync());
            threads[i].start();  // Start decrementing
        }
        for(int i=0; i<numThreads; ++i)
            threads[i].join();
        System.out.println("Should be 0: " + counter);
    }

    // This object "locks" counter while it is updated
    private static Object lock = new Object();
}
```



```
ricegf@antares:~/dev/202108/22$
ricegf@antares:~/dev/202108/22$
Should be 0: 0
ricegf@antares:~/dev/202108/22$
Should be 0: 0
ricegf@antares:~/dev/202108/22$
Should be 0: 0
ricegf@antares:~/dev/202108/22$
Should be 0: 0
ricegf@antares:~/dev/202108/22$
```

Synchronized for the win!

Better Mapping of Problem to Code

Kentucky Derby Simulator

- Threads work great for stochastic simulations such as (ahem) games
- We’ll let 20 horses (threads) count down their distance from the finish line
  - Competing to be first to grab the mutex that enables them to write THEIR name into the winner’s String!

Better Mapping of Problem to Code – Kentucky Derby

Horse (excluding thread)

```java
public class Horse implements Runnable {
    public Horse(String name, int speed) {
        this.name = name;
        this.speed = speed;
        this.position = 30;
    }

    // TODO: Should use StringBuffer here!
    String view() { // text for this horse's row in the Track
        String result = "";
        for (int i = 0; i < position; ++i) result += (i%5 == 0 ? ':' : '.');
        result += " " + name;
        return result;
    }

    String name() {return name;}
    public static String winner() {
        String result;
        synchronized(lock) {
            result = winner;
        }
        return result;
    }
```

Better Mapping of Problem to Code – Kentucky Derby

Horse thread

```
    @Override
    public void run() {
        while(winner().isEmpty()) {      // Exit if another wins (bummer)
            if(position > 0) --position; // Still not there – keep racing!
            if(position > 0) {           // Pause before taking next step
                try {Thread.sleep(speed + (int) (200 * Math.random()));}
                catch (InterruptedException e) {}
            } else {                     // We’re there – are we first?
                synchronized(lock) {
                    if(winner.isEmpty()) winner = name;  // Winner!!!
                }
            }
        }
    }

    private final String name;    // What the horse is called on the Track
    private int position;         // Distance from the finish line
    private int speed;            // Rough time between steps (in ms)

    private static Object lock = new Object();   // Mutex - write access to winner
    private static String winner = "";  // 1st horse across the finish line
}
```

Better Mapping of Problem to Code – Kentucky Derby

Track Constructor

```
import java.util.Collections;    import java.util.List;
import java.util.Arrays;         import java.util.ArrayList;

public class Track {
    public final int HORSES; // Number of horses to race
    public Track(int numHorses) {
        this.HORSES = numHorses;

        // Randomly assign vaguely clever names to each horse
        names = Arrays.asList(
            "Legs of Spaghetti", "Ride Like the Calm", "Duct-taped Lightning",
            "Flash Light", "Speedphobia", "Cheat Ah!", "Go For Broken",
            "Whining Racer", "Spectacle", "Cannons a'Boring", "Plodding Prince",
            "Lucky Snooze", "Wrong Way", "Fawlty Powers", "Broken Tip",
            "American Zero", "Exterminated", "Great Regret", "Manual", "Lockout",
            "2 Biggaherd");
        Collections.shuffle(names);

        // Instance the horses
        horses = new ArrayList<>();
        for (int i=0; i<HORSES; ++i)
            horses.add(new Horse(names.get(Math.min(i, names.size()-1)),
                                 100 + (int) (Math.random()*100)));
        // Create the threads
        threads = new ArrayList<>();
        for (int i=0; i<HORSES; ++i)
            threads.add(new Thread(horses.get(i)));
    }
```

Better Mapping of Problem to Code – Kentucky Derby

Track Methods

```
    public void startRace() {
        for(Thread t : threads) t.start();
    }
    public void showTrack() {
        System.out.println("\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n");
        for(Horse horse : horses) {
            System.out.println(horse.view());
        }
    }
    public void endRace() {
        for(Thread t : threads)
            try {t.join();}
            catch (InterruptedException e) {}
    }
```

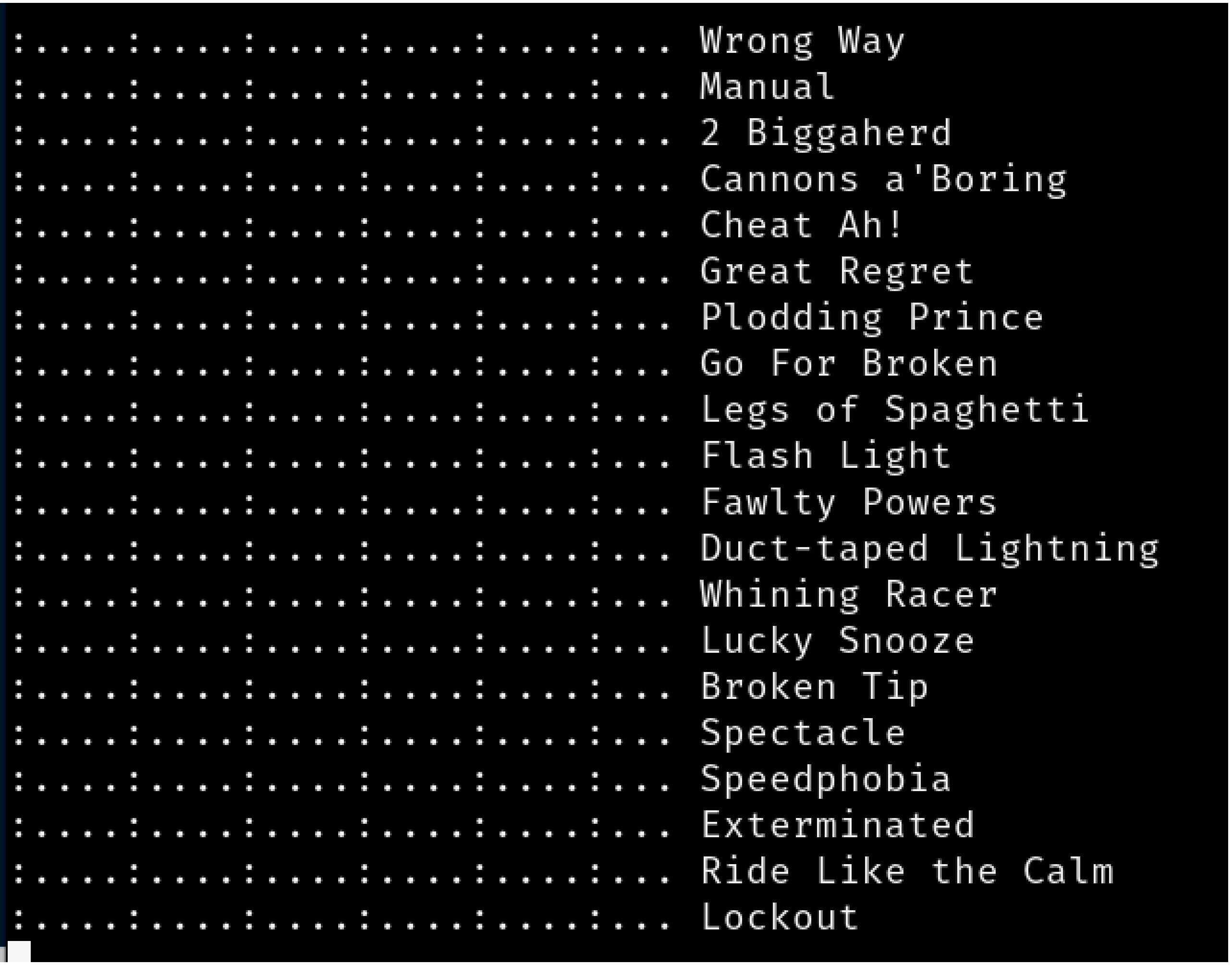
Better Mapping of Problem to Code – Kentucky Derby

Track Main

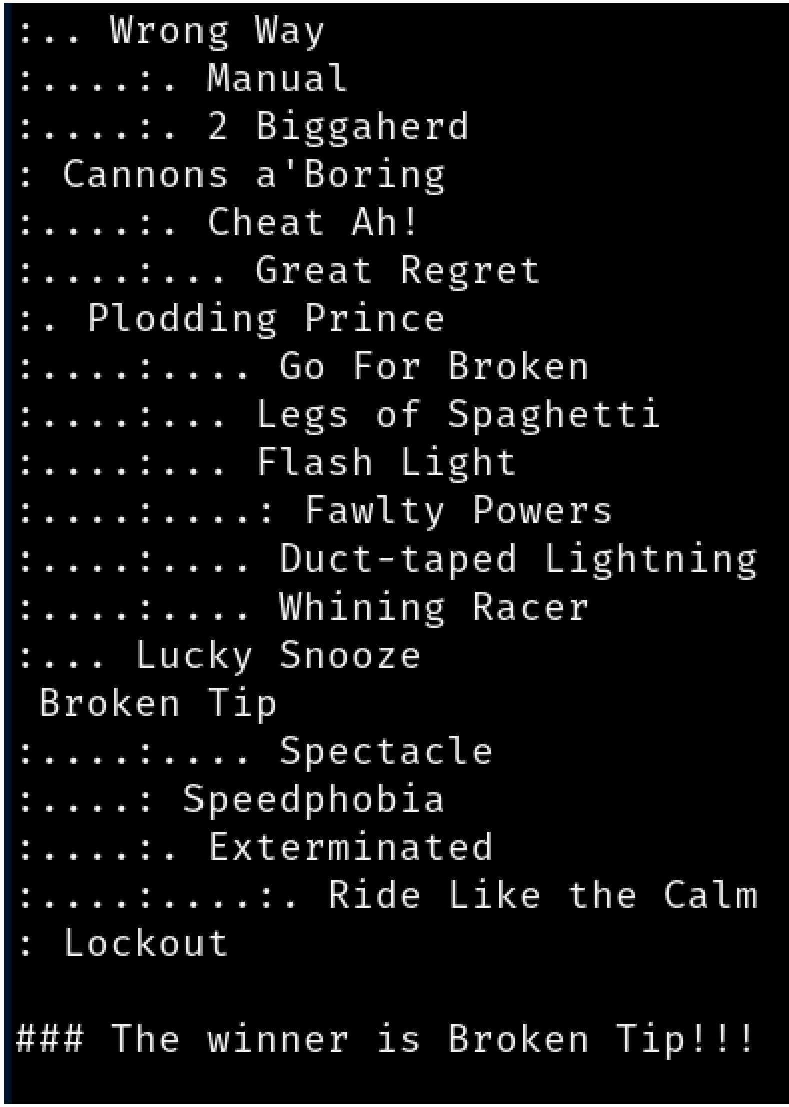
```
    public static void main(String[] args) {
        Track track = new Track(20);
        track.startRace(); // And they're off!!!

        while(Horse.winner().isEmpty()) {
            try {Thread.sleep(100);}
            catch (InterruptedException e) {}
            track.showTrack();
        }

        track.endRace();
        System.out.println("\n### The winner is " + Horse.winner() + "!!!\n");
    }

    public final List<String> names;
    public ArrayList<Horse> horses;
    public ArrayList<Thread> threads;
}
```

Running the Kentucky Derby

(It's a lot easier to follow live!)



```
:....:....:....:....:....:... Wrong Way
:....:....:....:....:....:... Manual
:....:....:....:....:....:... 2 Biggaherd
:....:....:....:....:....:... Cannons a'Boring
:....:....:....:....:....:... Cheat Ah!
:....:....:....:....:....:... Great Regret
:....:....:....:....:....:... Plodding Prince
:....:....:....:....:....:... Go For Broken
:....:....:....:....:....:... Legs of Spaghetti
:....:....:....:....:....:... Flash Light
:....:....:....:....:....:... Fawlty Powers
:....:....:....:....:....:... Duct-taped Lightning
:....:....:....:....:....:... Whining Racer
:....:....:....:....:....:... Lucky Snooze
:....:....:....:....:....:... Broken Tip
:....:....:....:....:....:... Spectacle
:....:....:....:....:....:... Speedphobia
:....:....:....:....:....:... Exterminated
:....:....:....:....:....:... Ride Like the Calm
:....:....:....:....:....:... Lockout
```



```
:.. Wrong Way
:....:. Manual
:....:. 2 Biggaherd
: Cannons a'Boring
:....:. Cheat Ah!
:....:... Great Regret
:. Plodding Prince
:....:.... Go For Broken
:....:... Legs of Spaghetti
:....:... Flash Light
:....:....: Fawlty Powers
:....:.... Duct-taped Lightning
:....:.... Whining Racer
:... Lucky Snooze
 Broken Tip
:....:.... Spectacle
:....: Speedphobia
:....:. Exterminated
:....:....:. Ride Like the Calm
: Lockout

### The winner is Broken Tip!!!
```

Warning

- This just scratches the surface of concurrency
  - Avoiding race conditions is exceptionally tricky
  - Other dangers lurk, e.g., priority inversion
  - Bugs in concurrent systems are often catastrophic, but appear only once in a blue moon
- This lecture gives you just enough knowledge to get in trouble... or to motivate you to learn much more about a field growing in importance
  - Your decision...