Principles of Software Construction:

Concurrency, Part 1

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Administrivia

- Midterm review tomorrow 7-9pm, HH B103
- Midterm on Thursday
- HW 5 team signup deadline **tonight**
  - If you're still looking for a homework 5 team, come to front of room after class

Foundations of the Software Engineering minor

- Core computer science fundamentals
- Building good software
- Organizing a software project
  - Development teams, customers, and users
  - Process, req'ts, estimation, management, & methods
- The larger context of software
  - Business, society, policy
- Engineering experience
- Communication skills
  - Written and oral

SE minor requirements

- Prerequisite: 15-214
- Two core courses
  - 15-313 Foundations of SE (fall semesters)
  - 15-413 SE Practicum (spring semesters)
- Three electives
  - Technical
  - Engineering
  - Business or policy
- Software engineering internship + reflection
  - 8+ weeks in an industrial setting, then
  - 17-413

To apply to be a Software Engineering minor

- Email clegoues@cs.cmu.edu
  - Your name, Andrew ID, expected grad date, QPA, and minor/majors
  - Why you want to be a SE minor
  - Proposed schedule of coursework
- Spring applications due Friday, 07 November 2016
  - Only 15 SE minors accepted per graduating class
- More information at:
  - http://isri.cmu.edu/education/undergrad/

“A Big Delight in Every Byte”

```
class Delight {
    public static void main(String[] args) {
        for (byte b = Byte.MIN_VALUE;
             b < Byte.MAX_VALUE; b++) {
            if (b == 0x90)
                System.out.print("Joy! ");
        }
    }
}
```

What Does It Print?

```
class Delight {
    public static void main(String[] args) {
        for (byte b = Byte.MIN_VALUE;
             b < Byte.MAX_VALUE; b++) {
            if (b == 0x90)
                System.out.print("Joy! ");
        }
    }
}
```

(a) Joy!
(b) Joy! Joy!
(c) Nothing
(d) None of the above

What Does It Print?

(a) `Joy!`
(b) `Joy! Joy!`
(c) Nothing
(d) None of the above

Program compares a `byte` with an `int`; `byte` is *promoted* with surprising results

Another Look

bytes are signed; range from -128 to 127

```
class Delight {
    public static void main(String[] args) {
        for (byte b = Byte.MIN_VALUE;
             b < Byte.MAX_VALUE; b++) {
            if (b == 0x90)  // (b == 144)
                System.out.print("Joy! ");
        }
    }
}
```

```
// (byte)0x90 == -112
// (byte)0x90 != 0x90
```

You Could Fix it Like This…

- Cast `int` to `byte`

```
  if (b == (byte)0x90)
      System.out.println("Joy!");
```

- Or convert `byte` to `int`, suppressing sign extension with mask

```
  if ((b & 0xff) == 0x90)
      System.out.println("Joy!");
```

…But This is Even Better

```
public class Delight {
    private static final byte TARGET = 0x90; // Won't compile!
    public static void main(String[] args) {
        for (byte b = Byte.MIN_VALUE; b < Byte.MAX_VALUE; b++)
            if (b == TARGET)
                System.out.print("Joy!");
    }
}
```

```
Delight.java:2: possible loss of precision
found   : int
required: byte
    private static final byte TARGET = 0x90; // Won't compile!
                                       ^
```

The Best Solution, Debugged

```
public class Delight {
    private static final byte TARGET = (byte) 0x90; // Fixed
    public static void main(String[] args) {
        for (byte b = Byte.MIN_VALUE; b < Byte.MAX_VALUE; b++)
            if (b == TARGET)
                System.out.print("Joy!");
    }
}
```

The Moral

- **byte values are signed** ☹
- Be careful when mixing primitive types
- **Compare like-typed expressions**
  - Cast or convert one operand as necessary
  - Declared constants help keep you in line
- For language designers
  - Don’t violate principle of least astonishment
  - Don’t make programmers’ lives miserable

Key concepts from Tuesday…

- Java I/O is a bit of a mess
  - There are many ways to do things
  - Use readers/writers most of the time
  - Use `Scanner` for casual use
- Reflection is tricky, but `Class.forName` and `newInstance` go a long way

Outline

I. Introduction to concurrency

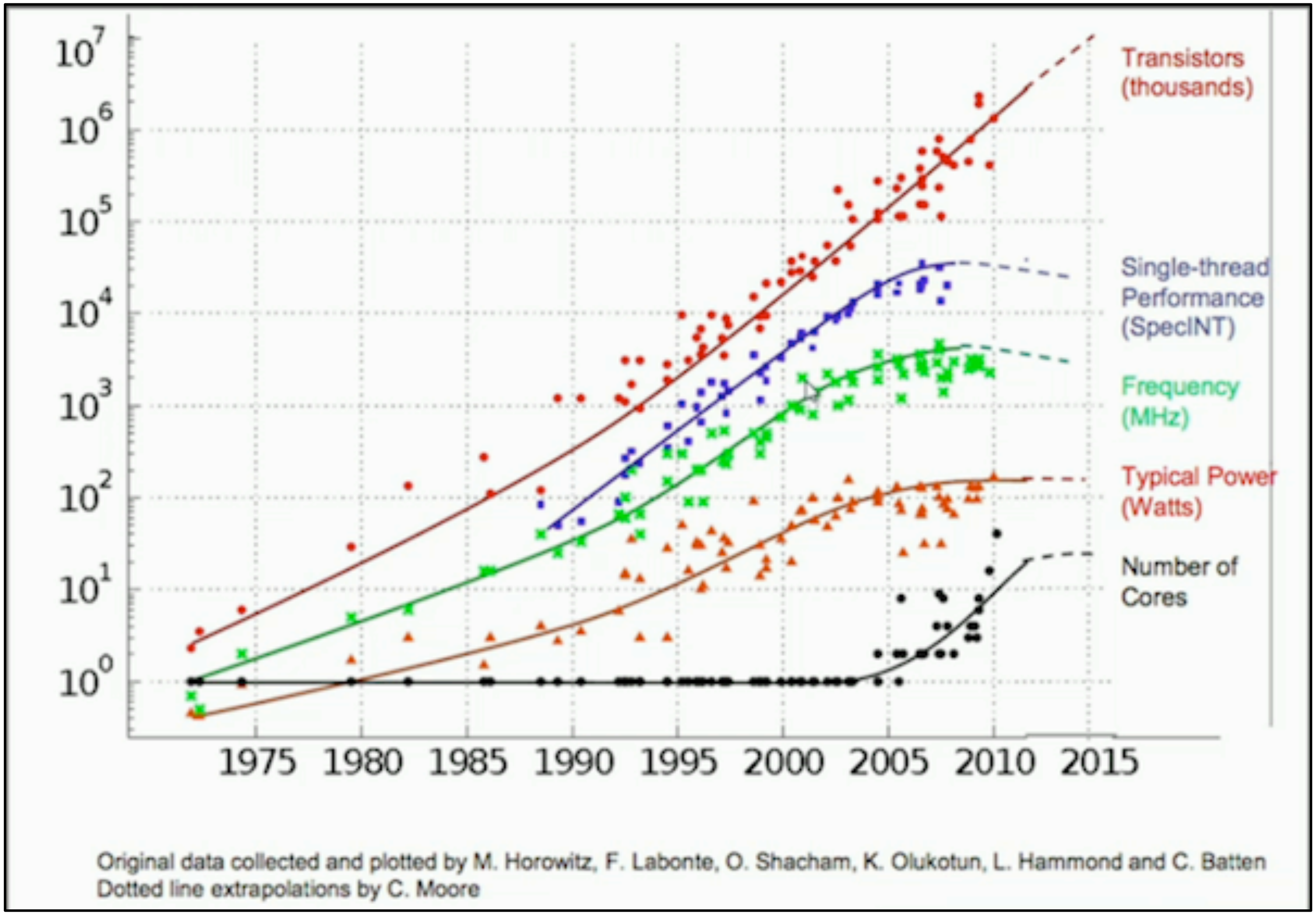
II. Threading Basics

III. Synchronization

What is a thread? (review)

- Short for *thread of execution*
- Multiple threads run in same program concurrently
- Threads share the same address space
  - Changes made by one thread may be read by others
- Multithreaded programming
  - Also known as shared-memory multiprocessing

Processor characteristics over time



Original data collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond and C. Batten
Dotted line extrapolations by C. Moore

Power requirements of a CPU

- power = capacitance × voltage^2 × frequency
- To increase performance
  - More transistors, thinner wires
    - More power leakage: increase voltage
  - Increase clock frequency
    - Change electrical state faster: increase voltage
- *Dennard scaling* – as transistors get smaller, power density is approximately constant…
  - …until early 2000s
- Now: Power is super-linear in CPU performance

Failure of Dennard Scaling forced our hand

- Must reduce heat by limiting power
- Limit power by reducing frequency and/or voltage
- In other words, build slower cores…
  - …but build more of them
- Adding cores ups power linearly with performance
- **But concurrency is required to utilize multiple cores**

Concurrency then and now

- In past multi-threading just a convenient abstraction
  - GUI design: event dispatch thread
  - Server design: isolate each client's work
  - Workflow design: isolate producers and consumers
- Now: **required** for scalability and performance

We are all concurrent programmers

- Java is inherently multithreaded
- In order to utilize our multicore processors, we must write multithreaded code
- Good news: a lot of it is written for you
  - Excellent libraries exist (`java.util.concurrent`)
- Bad news: you still must understand fundamentals
  - to use libraries effectively
  - to debug programs that make use of them

Outline

I. Introduction to concurrency
II. Threading Basics
III. Synchronization

The `Runnable` interface - represents the work to be done by a thread

An instance is passed to each thread when it is created

```
public interface Runnable {
    void run();
}
```

A simple example: running a task asynchronously

```
public class Background {
    public static void runInBackground(Runnable task) {
        Thread t = new Thread(task);
        t.start();
    }

    // Sample use
    public static void main(String[] args) {
        runInBackground(Background::slowTask);
    }

    private static void slowTask() {
        try {
            TimeUnit.SECONDS.sleep(5); // Represents computation
        } catch (InterruptedException ie) {
            throw new AssertionError(ie);
        }
    }
}
```

Multithreaded driver (déjà vu)

```
public static void main(String[] args) throws InterruptedException {
    int n = Integer.parseInt(args[0]);
    int wordsPerThread = words.length / n;
    Thread[] threads = new Thread[n];
    String[][] results = new String[n][];
    for (int i = 0; i < n; i++) {
        int start = i == 0 ? 0 : i * wordsPerThread - 2;
        int end = i == n-1 ? words.length : (i + 1) * wordsPerThread;
        int m = i; // Only constants can be captured by lambdas
        threads[i] = new Thread(() ->
            { results[m] = cryptarithms(words, start, end); });
    }
    for (Thread t : threads) t.start();
    for (Thread t : threads) t.join();

    System.out.println(Arrays.deepToString(results));
}
```

Outline

I. Introduction to concurrency

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III. Synchronization

Example: Money-Grab (1)

```
public class BankAccount {
    private long balance;

    public BankAccount(long balance) {
        this.balance = balance;
    }
    static void transferFrom(BankAccount source,
                           BankAccount dest, long amount) {
        source.balance -= amount;
        dest.balance   += amount;
    }
    public long balance() {
        return balance;
    }
}
```

Example: Money-Grab (2)

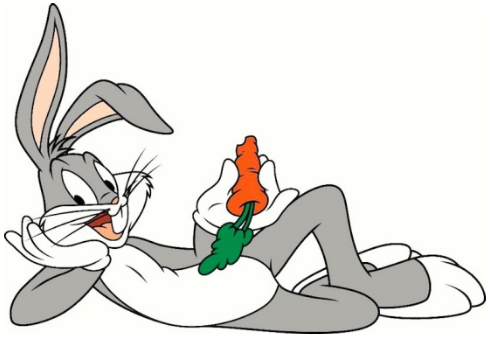
What would you expect this to print?

```
public static void main(String[] args) throws InterruptedException {
    BankAccount bugs = new BankAccount(100);
    BankAccount daffy = new BankAccount(100);

    Thread bugsThread = new Thread(()-> {
        for (int i = 0; i < 1000000; i++)
            transferFrom(daffy, bugs, 100);
    });

    Thread daffyThread = new Thread(()-> {
        for (int i = 0; i < 1000000; i++)
            transferFrom(bugs, daffy, 100);
    });

    bugsThread.start(); daffyThread.start();
    bugsThread.join(); daffyThread.join();
    System.out.println(bugs.balance + daffy.balance());
}
```



What went wrong?

- Daffy & Bugs threads were stomping each other
- Transfers did not happen in sequence
- Constituent reads and writes interleaved randomly
- Random results ensued

It’s easy to fix!

```
public class BankAccount {
   private long balance;

   public BankAccount(long balance) {
      this.balance = balance;
   }
   static synchronized void transferFrom(BankAccount source,
                           BankAccount dest, long amount) {
       source.balance -= amount;
       dest.balance   += amount;
   }
    public long balance() {
       return balance;
   }
}
```

Example: serial number generation

What would you expect this to print?

```
public class SerialNumber {
    private static long nextSerialNumber = 0;
    public static long generateSerialNumber() {
        return nextSerialNumber++;
    }

    public static void main(String[] args) throws InterruptedException {
        Thread threads[] = new Thread[5];
        for (int i = 0; i < threads.length; i++) {
            threads[i] = new Thread(() -> {
                for (int j = 0; j < 1_000_000; j++)
                    generateSerialNumber();
            });
            threads[i].start();
        }
        for(Thread thread : threads) thread.join();
        System.out.println(generateSerialNumber());
    }
}
```

What went wrong?

- The ++ (increment) operator is not atomic!
  - It reads a field, increments value, and writes it back
- If multiple calls to `generateSerialNumber` see the same value, they generate duplicates

Again, the fix is easy

```
public class SerialNumber {
    private static int nextSerialNumber = 0;
    public static synchronized int generateSerialNumber() {
        return nextSerialNumber++;
    }

    public static void main(String[] args) throws InterruptedException{
        Thread threads[] = new Thread[5];
        for (int i = 0; i < threads.length; i++) {
            threads[i] = new Thread(() -> {
                for (int j = 0; j < 1_000_000; j++)
                    generateSerialNumber();
            });
            threads[i].start();
        }
        for(Thread thread : threads) thread.join();
        System.out.println(generateSerialNumber());
    }
}
```

But you can do better!

java.util.concurrent *is your friend*

```
public class SerialNumber {
    private static AtomicLong nextSerialNumber = new AtomicLong();
    public static long generateSerialNumber() {
        return nextSerialNumber.getAndIncrement();
    }
    public static void main(String[] args) throws InterruptedException{
        Thread threads[] = new Thread[5];
        for (int i = 0; i < threads.length; i++) {
            threads[i] = new Thread(() -> {
                for (int j = 0; j < 1_000_000; j++)
                    generateSerialNumber();
            });
            threads[i].start();
        }
        for(Thread thread : threads) thread.join();
        System.out.println(generateSerialNumber());
    }
}
```

Example: cooperative thread termination

How long would you expect this to run?

```
public class StopThread {
    private static boolean stopRequested;

    public static void main(String[] args) throws Exception {
        Thread backgroundThread = new Thread(() -> {
            while (!stopRequested)
                /* Do something */ ;
        });
        backgroundThread.start();

        TimeUnit.SECONDS.sleep(1);
        stopRequested = true;
    }
}
```

What went wrong?

- **In the absence of synchronization, there is no guarantee as to when, if ever, one thread will see changes made by another!**
- VMs can and do perform this optimization:

```
while (!done)
    /* do something */ ;
```

becomes:

```
if (!done)
    while (true)
        /* do something */ ;
```

How do you fix it?

```
public class StopThread {
    private static boolean stopRequested;
    private static synchronized void requestStop() {
        stopRequested = true;
    }
    private static synchronized boolean stopRequested() {
        return stopRequested;
    }

    public static void main(String[] args) throws Exception {
        Thread backgroundThread = new Thread(() -> {
            while (!stopRequested())
                /* Do something */ ;
        });
        backgroundThread.start();

        TimeUnit.SECONDS.sleep(1);
        requestStop();
    }
}
```

You can do better (?)

`volatile` *is synchronization sans mutual exclusion*

```
public class StopThread {
    private static volatile boolean stopRequested;

    public static void main(String[] args) throws Exception {
        Thread backgroundThread = new Thread(() -> {
            while (!stopRequested)
                /* Do something */ ;
        });
        backgroundThread.start();

        TimeUnit.SECONDS.sleep(1);
        stopRequested = true;
    }
}
```

Summary

- Like it or not, you’re a concurrent programmer
- **Ideally, avoid shared mutable state**
- If you can’t avoid it, synchronize properly
  – Failure to do so causes safety and liveness failures
  – **If you don’t sync properly, your program won’t work**
- Even atomic operations require synchronization
  – e.g., `stopRequested = true`
  – And some things that look atomic aren’t (e.g., `val++`)