Principles of Software Construction: Objects, Design, and Concurrency

Part 3: Concurrency

Introduction to concurrency

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Administrivia

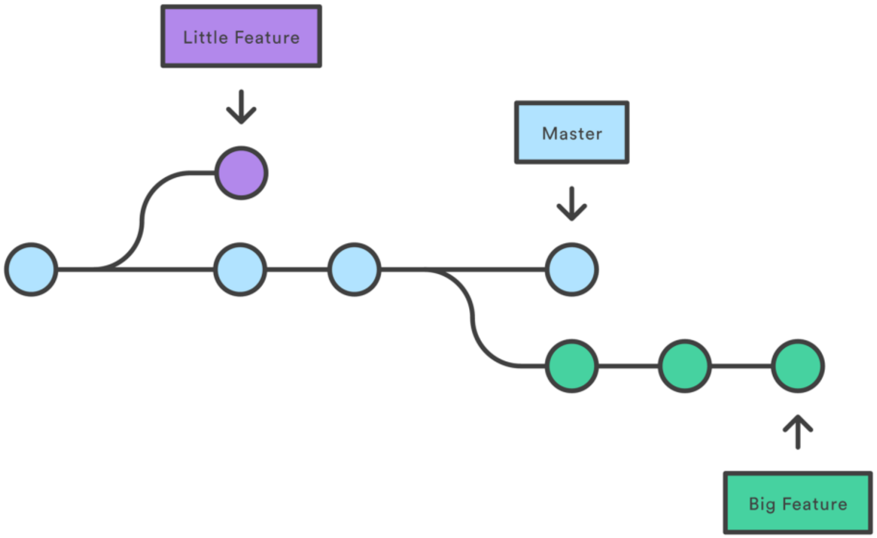
- HW 5a due 9am tomorrow
- Presentations in recitation tomorrow
- Reading due today, Java Concurrency In Practice, Sections 11.3-4
- Midterm 2 has been graded; Grades will be released after class

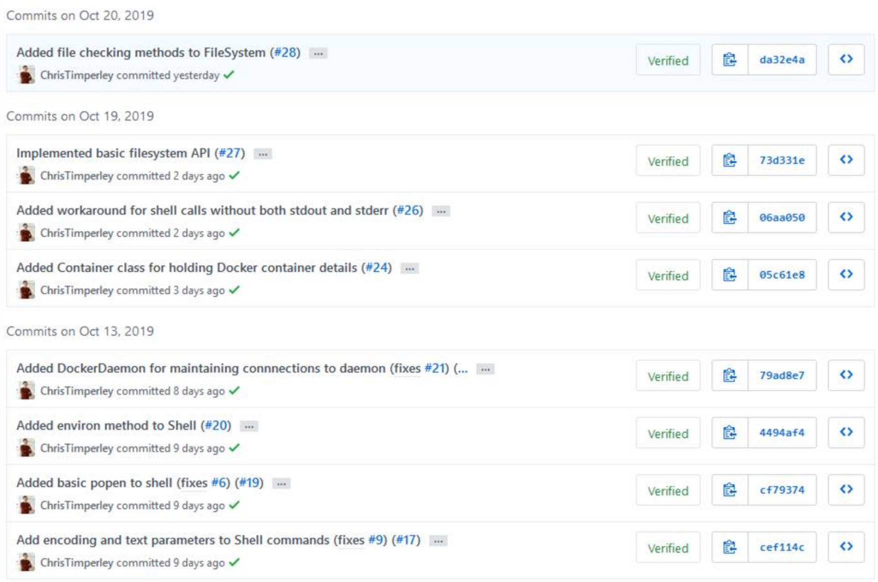
Key concepts from last Thursday

Challenges of working as a team: Aligning expectations

- How do we make decisions?

Use simple **branch-based development**





Create a new branch for each feature.

- allows parallel development
- no dealing with half-finished code
- no merge conflicts!

Every commit to “master” should pass your CI checks.

Today's lecture: concurrency motivation and primitives

- Why concurrency?
  - Motivation, goals, problems, …
- Concurrency primitives in Java
- Coming soon (not today):
  - Higher-level abstractions for concurrency
  - Program structure for concurrency
  - Frameworks for concurrent computation

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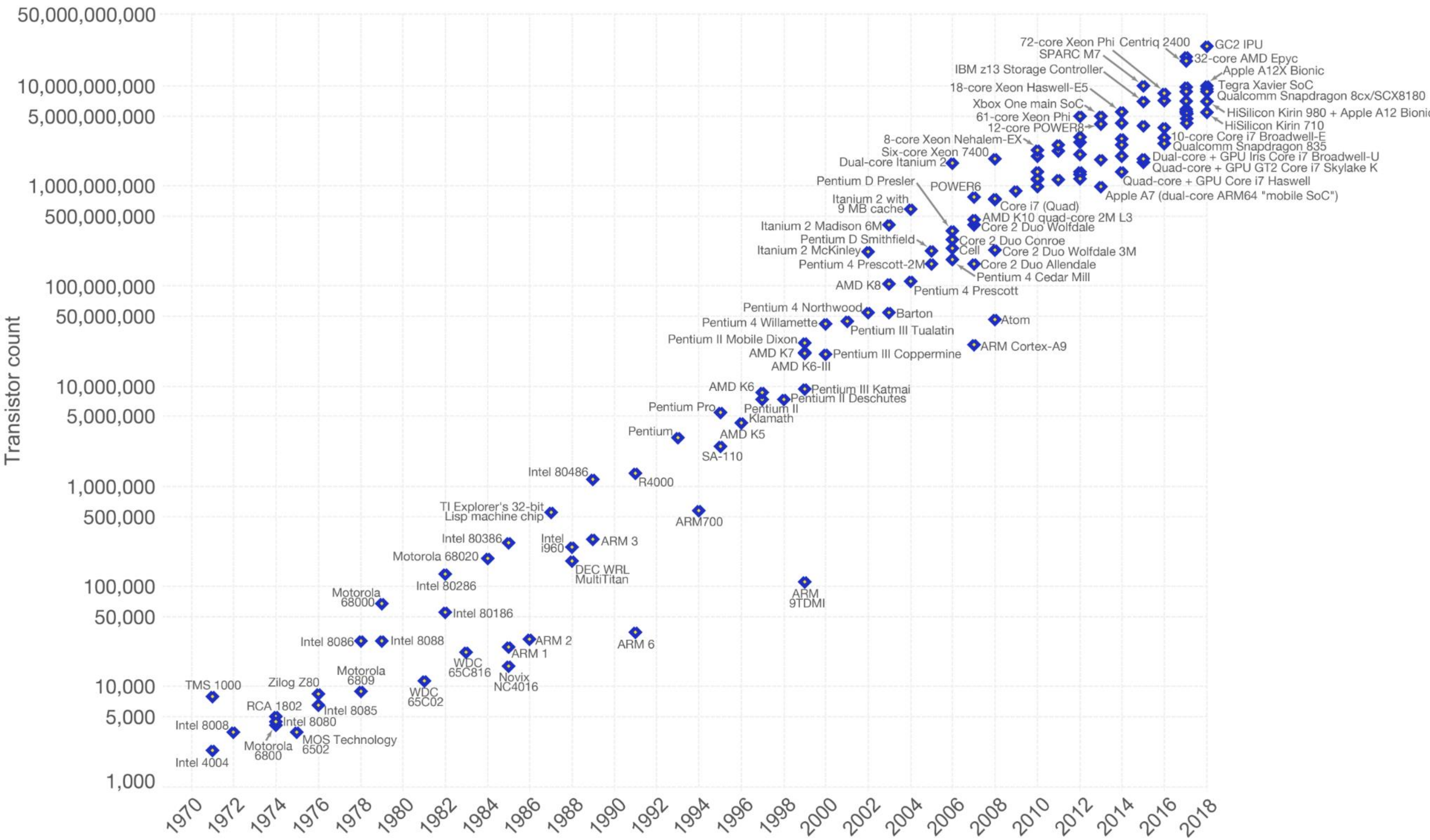
Moore's Law (1965) – number of transistors on a chip doubles every two years



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CPU Performance and Power Consumption

- *Dennard Scaling* (1974) – each time you double transistor density:
  - Speed (frequency) goes up by about 40% (Why?)
  - While power consumption of the chip stays constant (proportional to area)
- Combined w/ Moore's law, every 4 years the number of transistors quadruples, speed doubles, and power consumption stays constant
- It was great while it lasted
  - Came to a grinding halt around 2004 due to *leakage currents* ☹
  - More power required at higher frequency, generating more heat
  - There's a limit to how much heat a chip can tolerate

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One option: fix the symptom

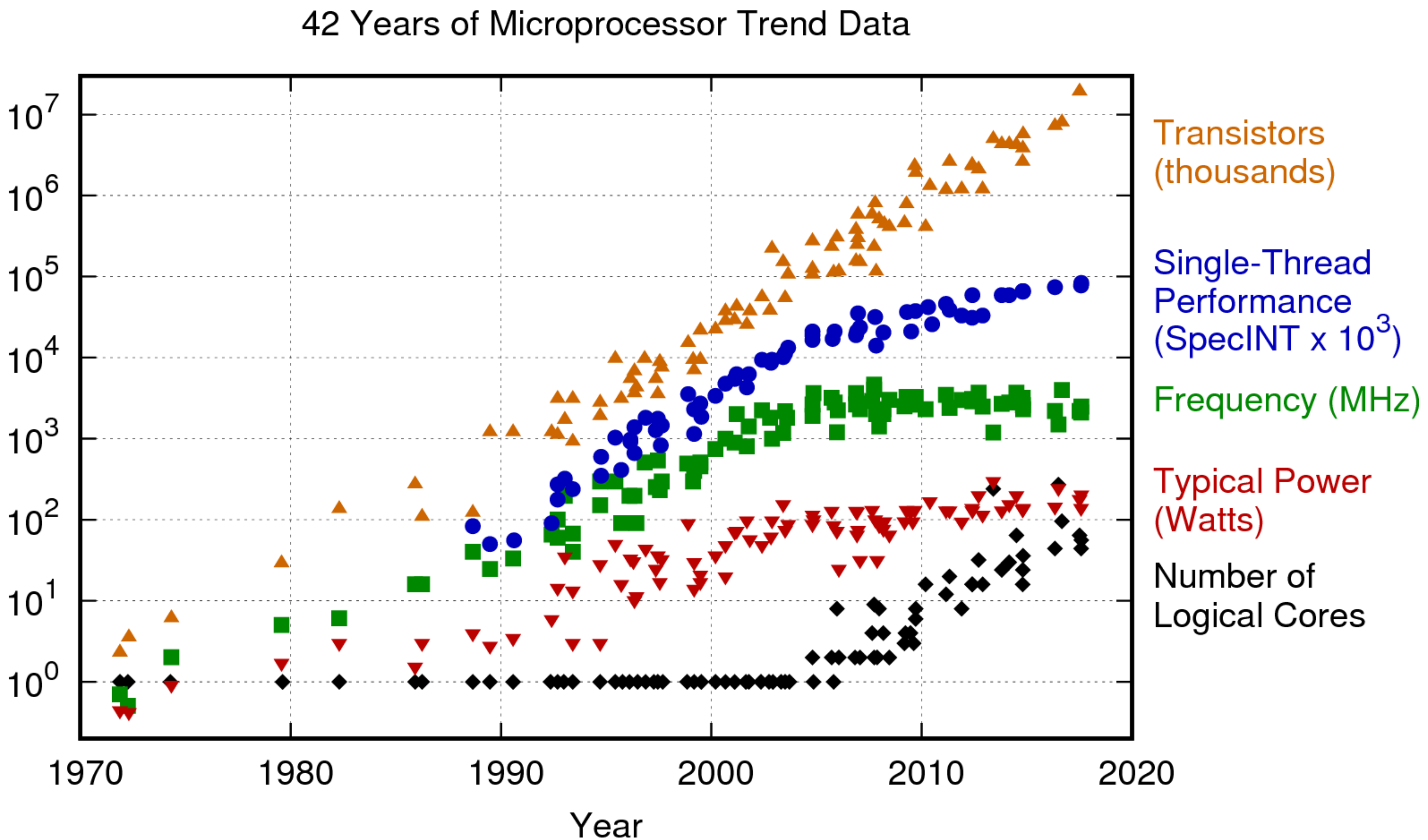
- Dissipate the heat

One option: fix the symptom

- Better(?): Dissipate the heat with liquid nitrogen

by **Paul Lilly** — Monday, December 16, 2019, 10:14 AM EDT

AMD Ryzen 9 3900X 12-Core Beast Chip Hits 5.6GHz To Claim World Record



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2017 by K. Rupp

Concurrency then and now

- In the 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
- To utilize modern processors, we must write multithreaded code
- Good news: a lot of it is written for you
  – Excellent libraries exist (e.g., `java.util.concurrent`)
- Bad news: you still must understand fundamentals
  – …to use libraries effectively
  – …to debug programs that make use of them

Aside: Concurrency vs. parallelism, visualized

- Concurrency without parallelism:

- Concurrency with parallelism:

Basic concurrency in Java

- An interface representing a task

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

- A class to execute a task in a CPU thread

```
public class Thread {
    public Thread(Runnable task);
    public void start();
    public void join();
    …
}
```

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)

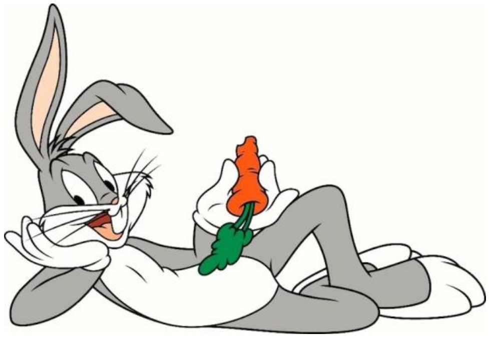
What would you expect this program to print?

```
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 < 1_000_000; i++)
            transferFrom(daffy, bugs, 100);
    });

    Thread daffyThread = new Thread(()-> {
        for (int i = 0; i < 1_000_000; 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 had a *race condition* for shared data
  - Transfers did not happen in sequence
- Reads and writes interleaved randomly
  - Random results ensued

The challenge of concurrency control

- Not enough concurrency control: *safety failure*
  - Incorrect computation
- Too much concurrency control: *liveness failure*
  - Possibly no computation at all (*deadlock* or *livelock*)

Shared mutable state requires concurrency control

- Three basic choices:
  1. Don't mutate: share only immutable state
  2. Don't share: isolate mutable state in individual threads
  3. If you must share mutable state: *synchronize to achieve safety*

An easy 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;
    }
}
```

Concurrency control with Java's *intrinsic* locks

- `synchronized (lock) { … }`
  - Synchronizes entire block on object `lock`; cannot forget to unlock
  - Intrinsic locks are *exclusive*: One thread at a time holds the lock
  - Intrinsic locks are *reentrant*: A thread can repeatedly get same lock

Concurrency control with Java's *intrinsic* locks

- `synchronized (lock)` { … }
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  - Intrinsic locks are *exclusive*: One thread at a time holds the lock
  - Intrinsic locks are *reentrant*: A thread can repeatedly get same lock
- `synchronized` on an instance method
  - Equivalent to `synchronized (this)` { … } for entire method
- `synchronized` on a static method in class Foo
  - Equivalent to `synchronized (Foo.class)` { … } for entire method

Another example: serial number generation

What would you expect this program 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?

- An action is *atomic* if it is indivisible
  - Effectively, it happens all at once
    - No effects of the action are visible until it is complete
    - No other actions have an effect during the action
- Java's ++ (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 long nextSerialNumber = 0;

    public static synchronized 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());
    }
}
```


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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());
    }
}
```

Some actions *are* atomic

Precondition:

```
int i = 7;
```

Thread A:

```
i = 42;
```

Thread B:

```
ans = i;
```

- What are the possible values for `ans`?

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Some actions *are* atomic

Precondition:

```
int i = 7;
```

Thread A:

```
i = 42;
```

Thread B:

```
ans = i;
```

- What are the possible values for `ans`?

i: 00000…00000111

⋮

i: 00000…00101010

ans: 00000…00101111

Some actions *are* atomic

Precondition:

```
int i = 7;
```

Thread A:

```
i = 42;
```

Thread B:

```
ans = i;
```

- What are the possible values for `ans`?

i: 00000…00000111

⋮

i: 00000…00101010

- In Java:
  - Reading an `int` variable is atomic
  - Writing an `int` variable is atomic
  - Thankfully, ~~ans: 00000…00101111~~ is not possible

Bad news: some simple actions are not atomic

- Consider a single 64-bit `long` value

high bits	low bits

  - Concurrently:
    - Thread A writing high bits and low bits
    - Thread B reading high bits and low bits

Precondition:

```
long i = 10_000_000_000;
```

Thread A:

```
i = 42;
```

Thread B:

```
ans = i;
```

`ans:` 01001…00000000 (10,000,000,000)

`ans:` 00000…00101010 (42)

`ans:` 01001…00101010 (10,000,000,042)

All are possible!

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Yet another example: cooperative thread termination

How long would you expect this program 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
- **JVMs can and do perform this optimization ("hoisting"):**

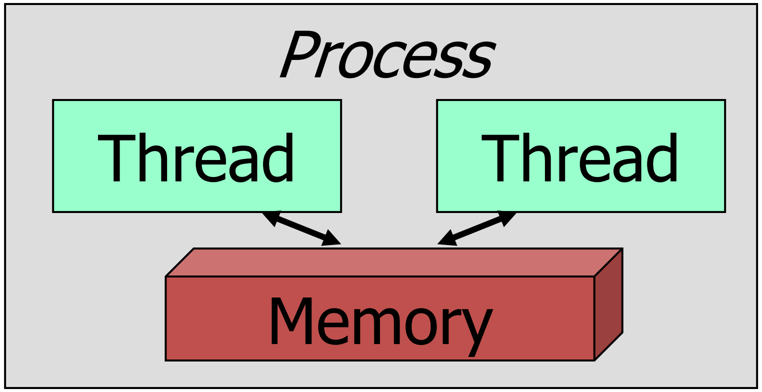
```
while (!done)
    /* do something */ ;
```

becomes:

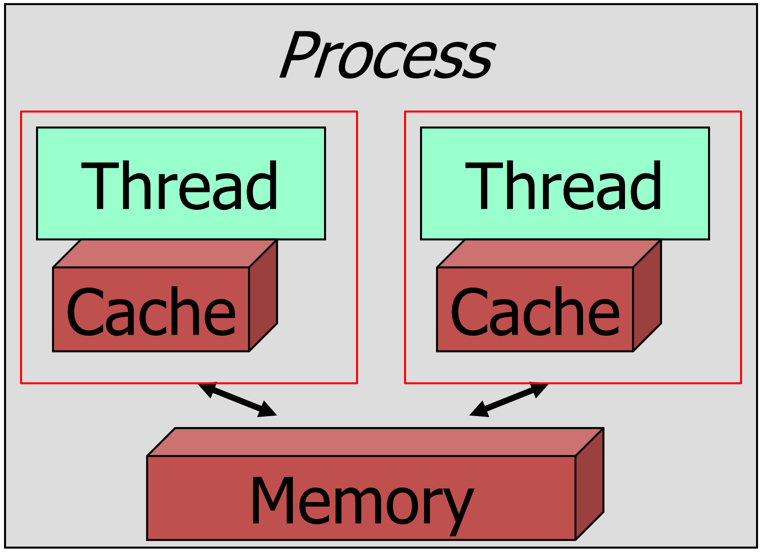
```
if (!done)
    while (true)
        /* do something */ ;
```

Why is synchronization required for communication among threads?

- Naively:
  - Thread state shared in memory



- A (slightly) more accurate view:
  - Separate state stored in registers and caches, even if shared



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(10);
        requestStop();
    }
}
```

A better(?) solution

`volatile` *is synchronization without 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(10);
        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
- Even atomic operations require synchronization
  - e.g., `stopRequested = true`
- Some things that look atomic aren't (e.g., `val++`)

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