CONCURRENCY I

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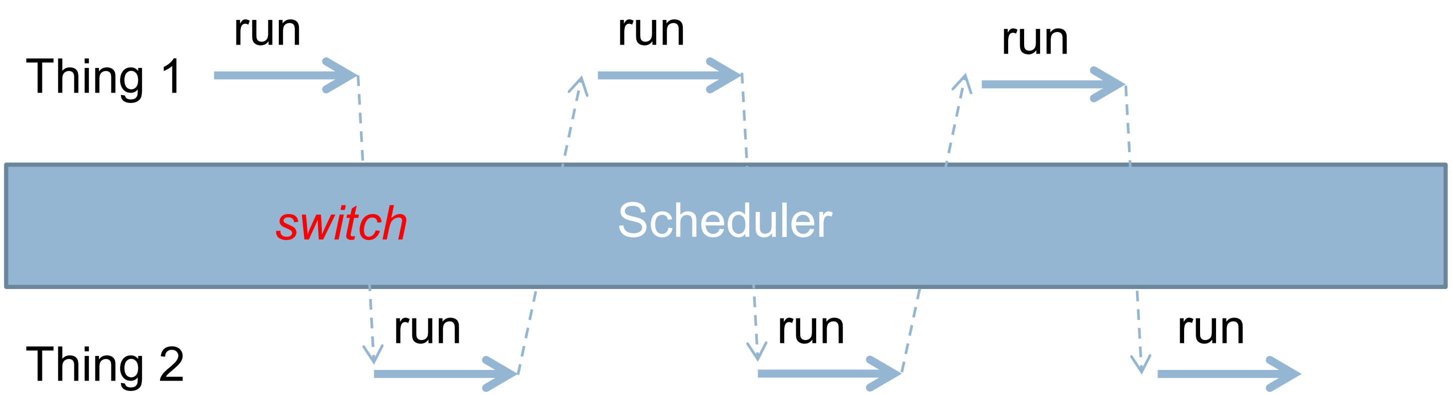
Basics

Concurrent Programming

- More than one thing at a time
- Examples:
  - Network server handling hundreds of clients
  - Data processing spread across multiple CPUs
  - App receiving input from several peripherals

Concurrency

- 1 CPU

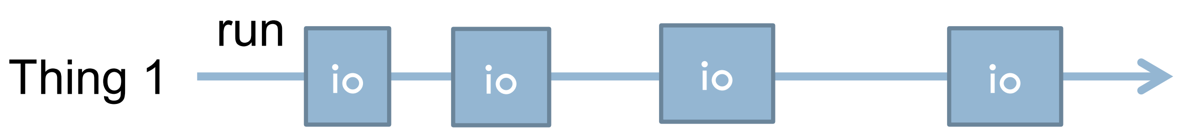


Concurrency

- Many CPUs
- When there are more things than CPUs, CPUs are shared like previous slide

Processing vs. IO

- Tasks alternate between processing and IO



- IO must wait for data
- Runtime system will resume task when data becomes available

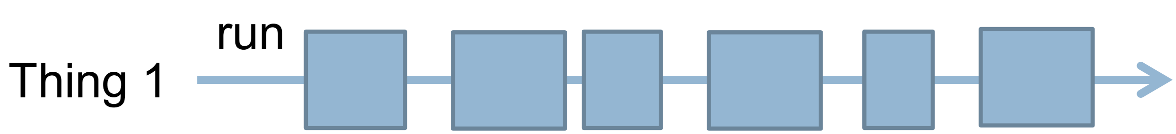
CPU-bound tasks

- When it spends most of the time processing
  - CPU is busy

- Examples:
  - Math
  - Image processing

IO-bound tasks

- When it spends most of the time doing IO
  - CPU is idle

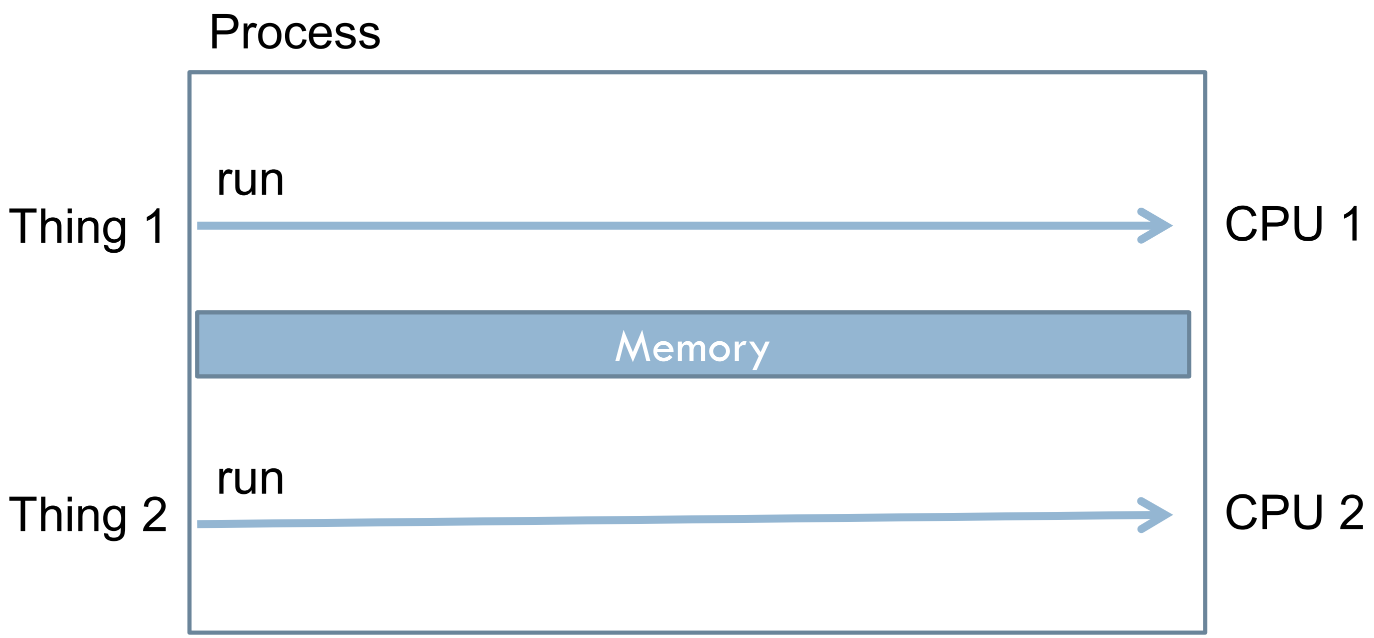


- Examples:
  - User input
  - Networking
  - Files

Shared memory

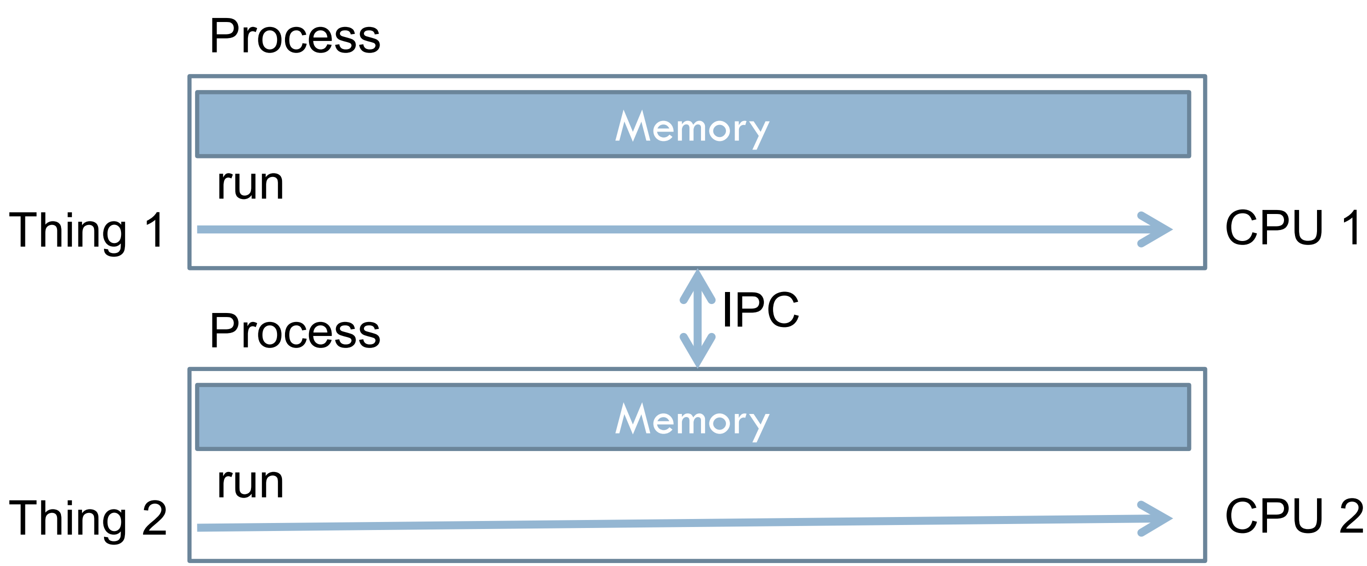
- Simultaneous access to memory space

same process share memory, different processes share data



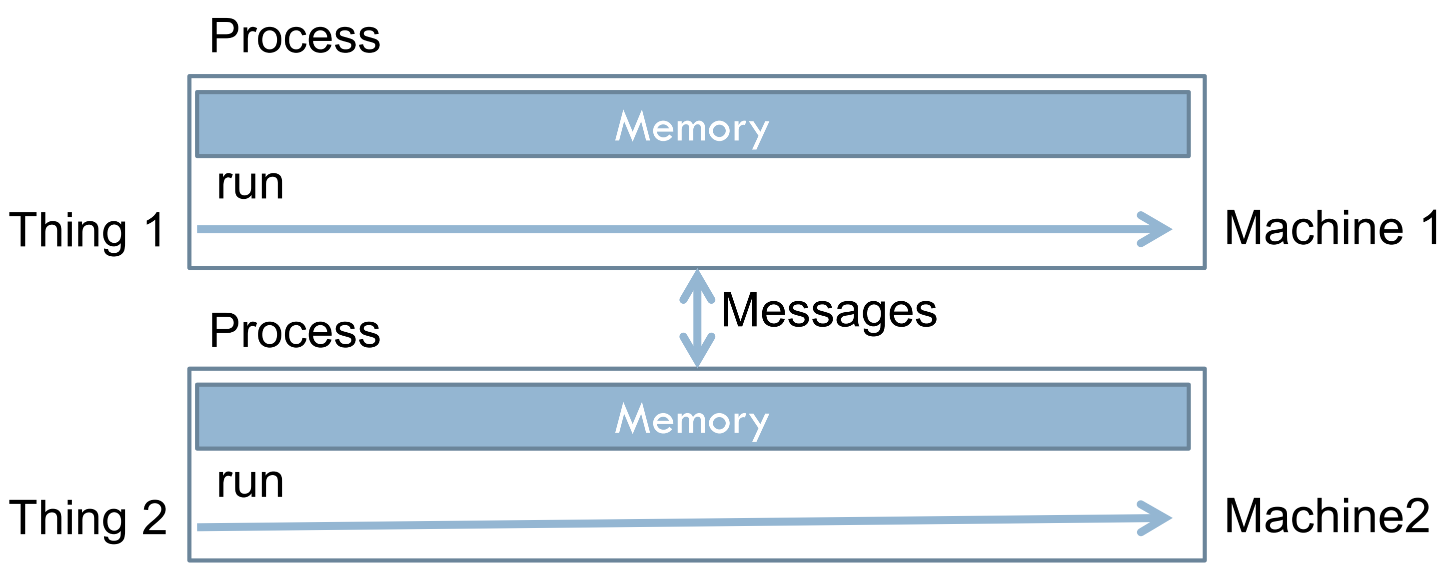
Separate processes, shared machine

- No shared memory
  - Inter-Process Communication (IPC)



Different machines, distributed computing

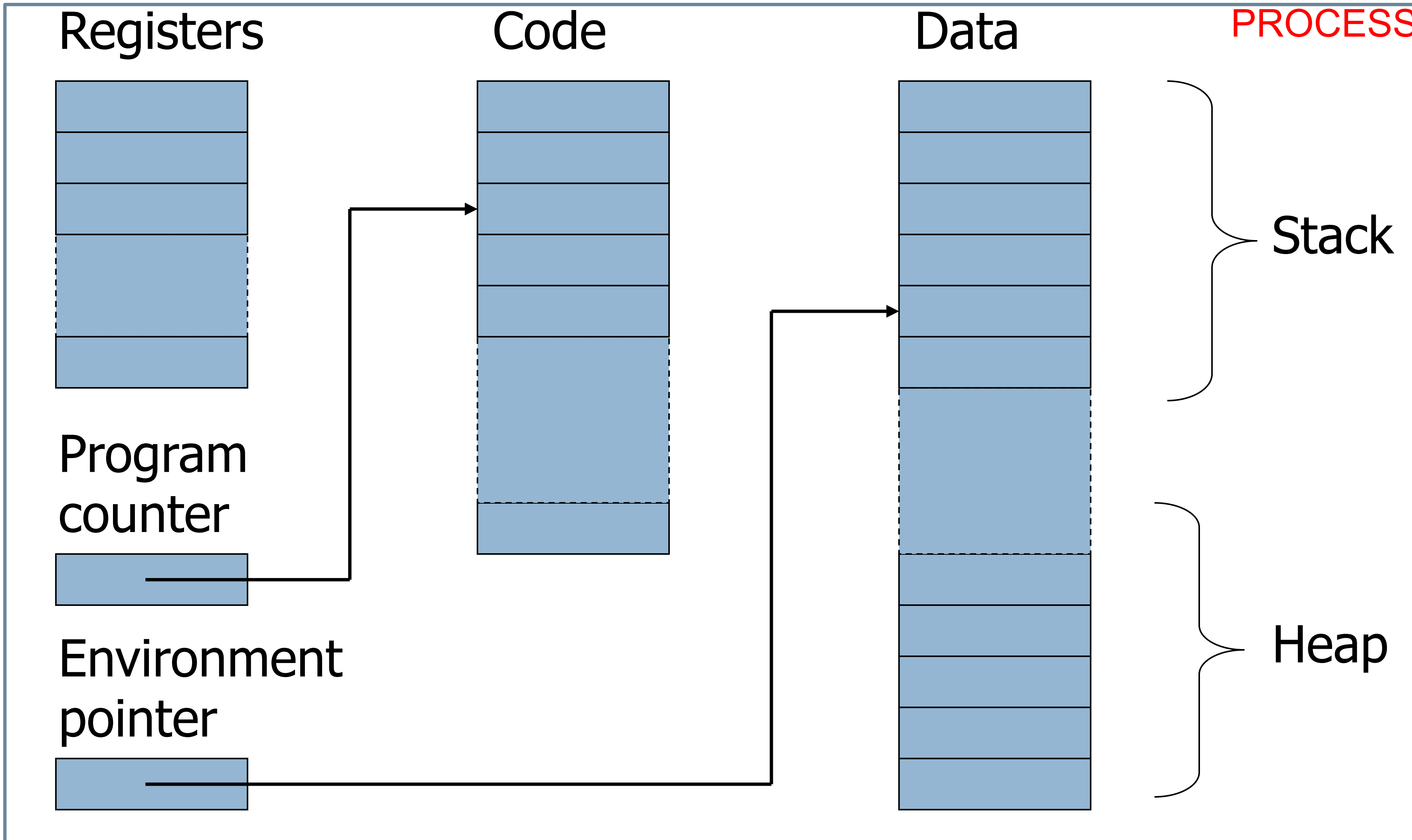
- Network
  - Sockets



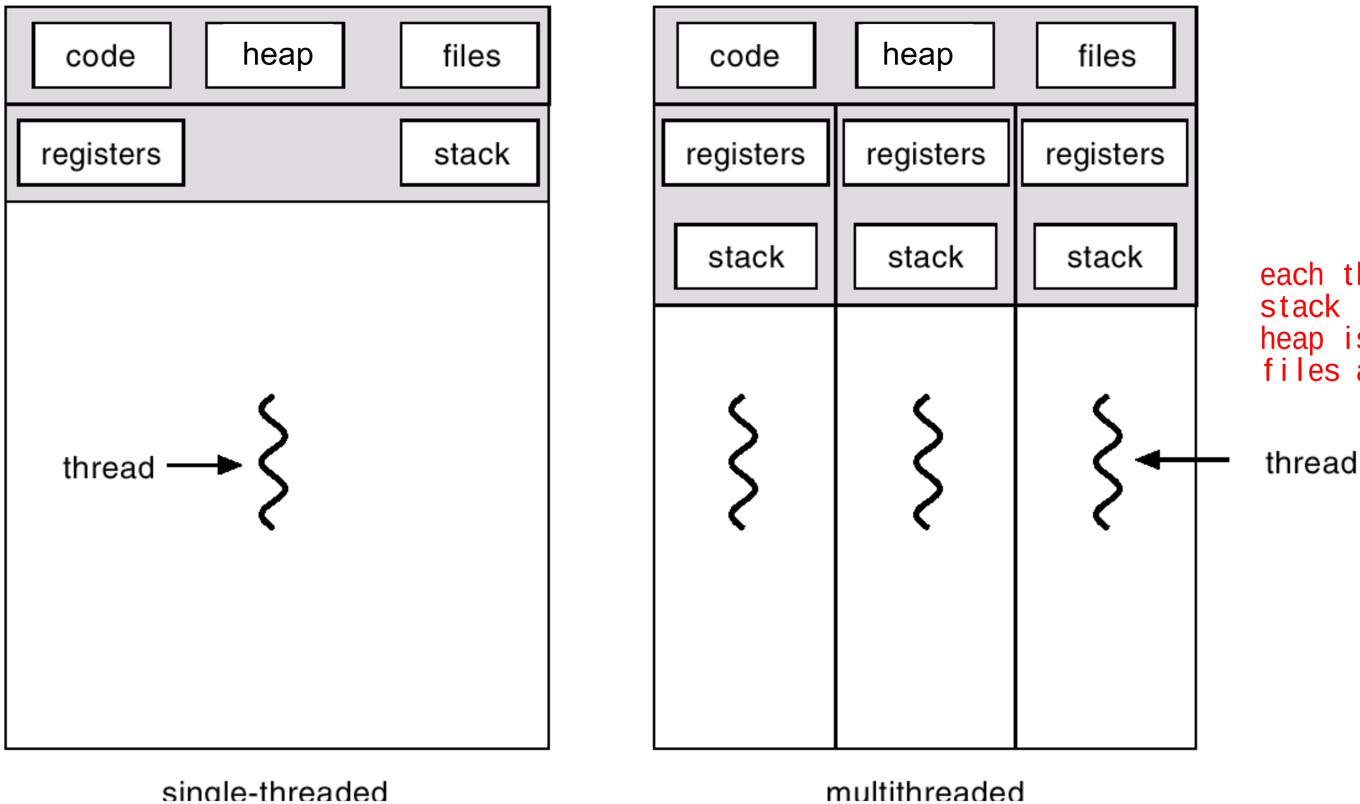
Shared Memory

Threads

Simplified Machine Model



Threads



each thread has its stack
heap is shared
files are shared

Threads: benefits

- Responsiveness
- Resource sharing
- [Performance in multi-core machines]

Threads: pitfalls

- Race conditions
- Heisenbugs happen once, can't control its appearance
- Easy to end up with a colossal code mess
- Heavy startup time for new threads create it is slow
  - [Thread pools to the rescue]

Two Types of Threads

- User-level threads libraries:

  - POSIX *Pthreads*

  - Java Threads

  - .NET Threads

  - Python Threads

  - ...

This course

- Kernel threads

Thread API Examples

OOP Threads (Java/C#/PHP/Python) v.1–instantiate Thread

start→run

```
class ThreadedObject implements Runnable {
    Thread t;
    ThreadedObject() {
        // Create a thread
        t = new Thread(this, "Demo Thread");
        System.out.println("Child thread: " + t);
        t.start(); // Start the thread
    }
```

Thread runtime calls run

```
    // This is the entry point for the ThreadedObject thread.
    public void run() {
        for (int i = 5; i > 0; i--) {
            System.out.println("Child Thread: " + i);
            // Let the thread sleep for a while.
            Thread.sleep(50);
        }
        System.out.println("Exiting child thread.");
    }
}
```

OOP Threads (Java/C#/PHP/Python) v.1–instantiate Thread

```
public class ThreadDemo {
   public static void main(String args[]) {
      new ThreadedObject(); // create a new thread
      for (int i = 5; i > 0; i--) {
        System.out.println("Main Thread: " + i);
        Thread.sleep(100);
      }
      System.out.println("Main thread exiting.");
   }
}
```

OOP Threads (Java/C#/PHP/Python) (v2—extend Thread)

```
class ThreadedObject extends Thread {
    ThreadedObject() {
        super("Demo Thread");
        System.out.println("Child thread: " + this);
        start(); // Start the thread
    }
                    Thread runtime calls run

    // This is the entry point for the thread.
    public void run() {
        for (int i = 5; i > 0; i--) {
            System.out.println("Child Thread: " + i);
            // Let the thread sleep for a while.
            Thread.sleep(50);
        }
        System.out.println("Exiting child thread.");
    }
}
```

OOP Threads (Java/C#/PHP/Python) (v2—extend Thread)

```
public class ThreadDemo {
    public static void main(String args[]) {
        new ThreadedObject(); // create a new thread
        for (int i = 5; i > 0; i--) {
          System.out.println("Main Thread: " + i);
          Thread.sleep(100);
        }
        System.out.println("Main thread exiting.");
    }
}
```

Functional Threads (C/C++/Perl/**Racket**)

Function to run

```
#lang racket

(thread (lambda ()
          (for ([i 10])
            (sleep 2)
            (printf "thread 1\n"))))


(thread (lambda ()
          (for ([i 20])
            (sleep 1)
            (printf "thread 2\n"))))
```

Functional Threads (C/C++/Perl/Racket)

```
#include <string>
#include <iostream>
#include <thread>
using namespace std;

//The function we want to make the thread run.
void task1(string msg)
{
    cout << "task1 says: " << msg;
}

int main()
{
    // Constructs the new thread and runs it. Does not block
    thread t1(task1, "Hello");

    //Makes the main thread wait for the new thread to finish
    t1.join();
}
```

Function to run

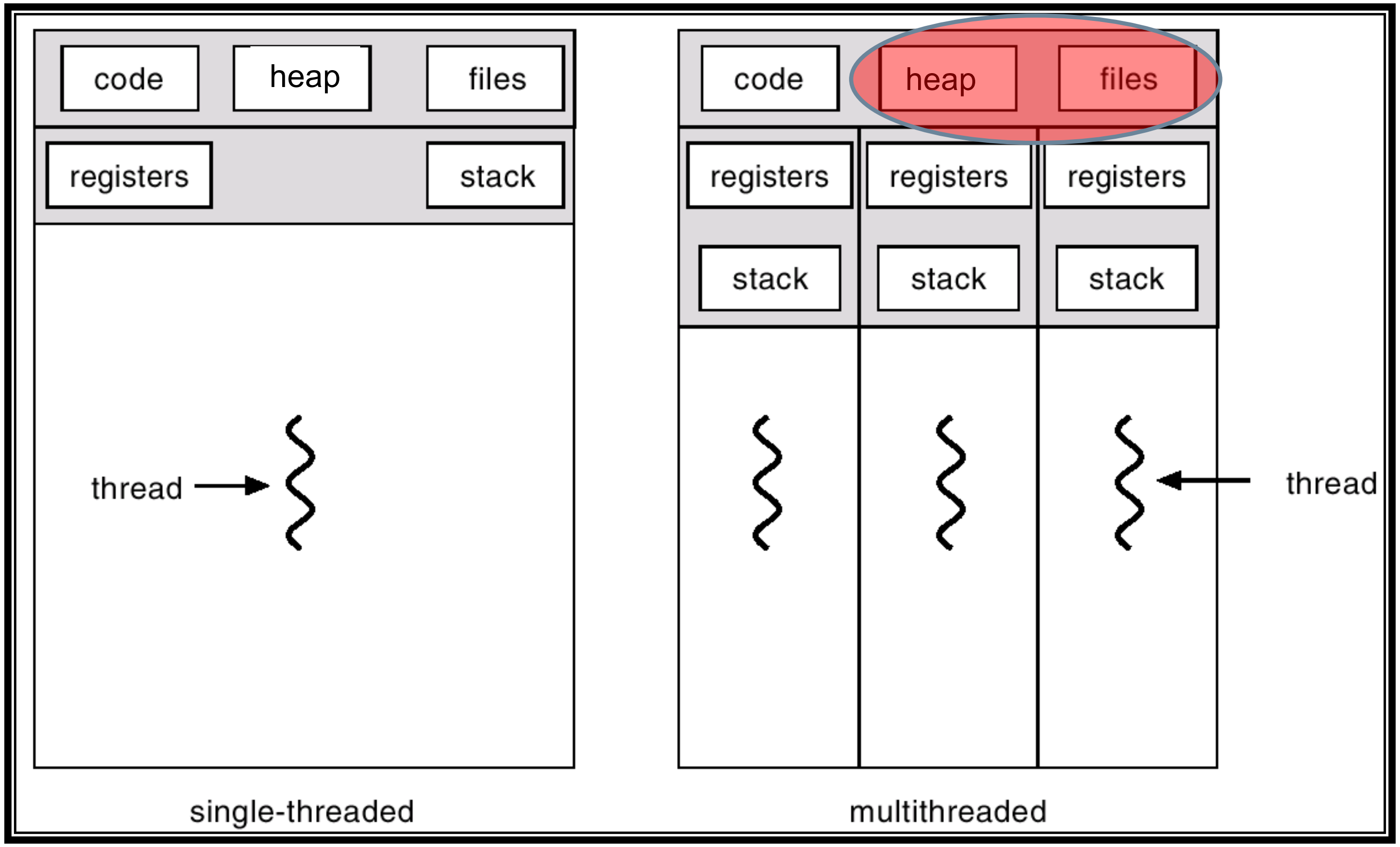
Common operations on threads

- Create
- Start
- Sleep
- Suspend
- Resume
- Yield
- Stop

- (you'll find most of these in most thread APIs)

Concurrency Control

Threads – shared resources



Shared data problems

```
class ThreadedObject extends Thread {
 Counter c;
 ThreadedObject(Counter _c) {
      super("Demo Thread");
      System.out.println("Child thread: " + this);
      c = _c;
      start(); // Start the thread
   }

   public void run() {
      for (int i = 500; i > 0; i--) {
         System.out.println("Child Thread: " + i);
         if (i % 2 == 0) c.increment();
         else c.decrement();
         Thread.sleep(50);
      }
      System.out.println("Exiting child thread.");
   }
}
```

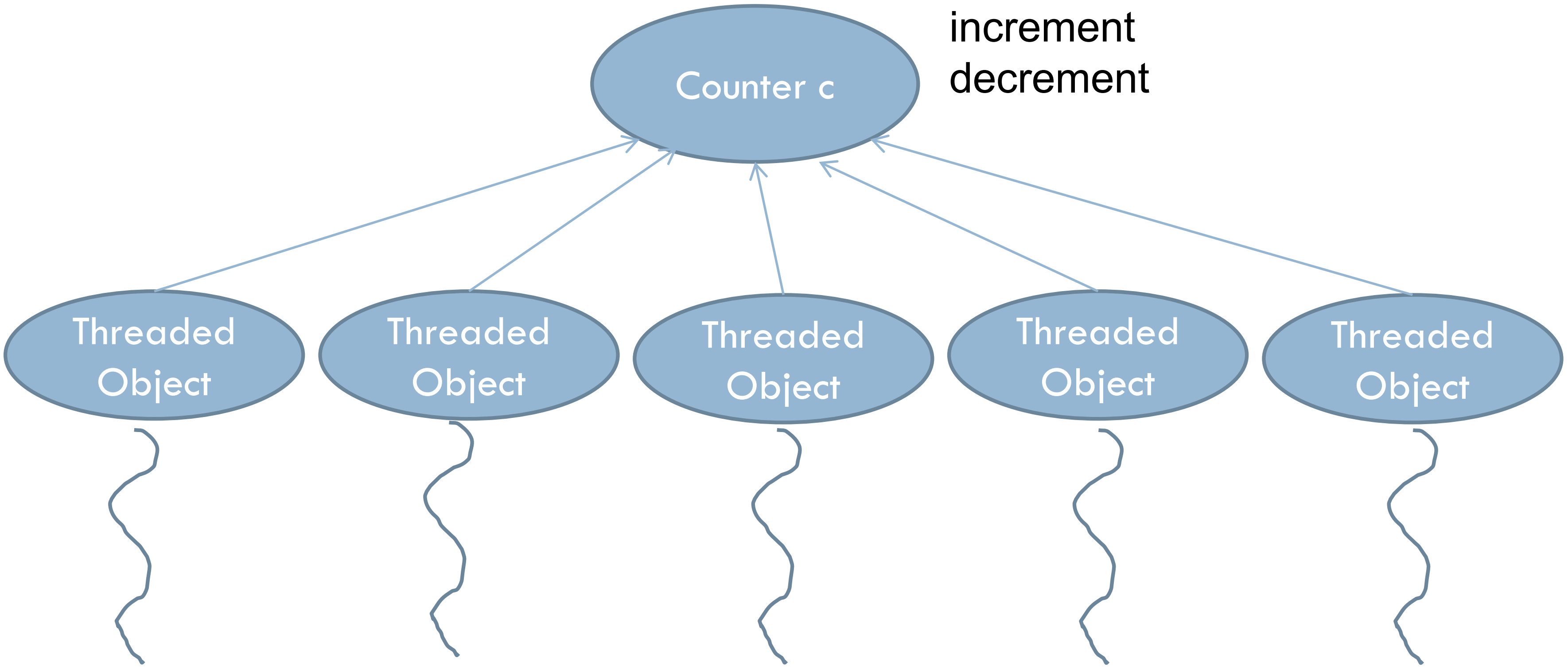
Shared data problems

```
class Counter {
    private int c = 0;

    public void increment() {
        c = c + 1;
    }

    public void decrement() {
        c = c - 1;
    }
}
```

Shared data problems

```java
public class ThreadDemo {
   public static void main(String args[]) {
     Counter c = new Counter();
     ThreadedObject[] ao = new ThreadedObject[5];
     // Create 5 threads
     for (int i = 5; i > 0; i--)
       ao[i] = new ThreadedObject(c); // create a new thread

     // Wait for the threads to finish
     for (ThreadedObject a : ao)
        a.join();
     System.out.println("Main thread exiting.");
   }
}
```

Shared data problems



Things that can go wrong

```
class Counter {
    private int c = 0;

    public void increment() {
        c = c + 1;
    }

    public void decrement() {
        c = c - 1;
    }
}
```

T1 T2

***One action lost**:*
T1 enters the method
T1 reads value of c (e.g. 3)
T1 is interrupted by scheduler
T2 enters the method
T2 reads value of c (3)
T2 adds 1 to c (4)
T2 assigns c to the new value (4)
T2 returns
T1 is resumed
T1 adds 1 to [old] value of c (4)
T1 assigns c to that value (4)

Race condition

Things that can go wrong

```
class Counter {
    private int c = 0;                  T1

    public void increment() {
        c = c + 1;
    }                                    T2

    public void decrement() {
        c = c - 1;
    }
}
```

***One action lost**:*
T1 enters increment
T2 enters decrement
T1 reads value of c (e.g. 3)
T2 reads value of c (3)
T1 adds 1 to its value of c (4)
T2 subtracts 1 to its value of c (2)
T1 assigns new value to c (4)
T2 assigns c (2)

Race condition

Race conditions

- Corruption of shared data due to thread scheduling
- Very hard to deal with
  - Non-deterministic
  - Hard to reproduce
  - Program may be ok for long time until it hits a race condition

Concurrency control

- Primitives for controlling the execution of concurrent threads over the same code

Concurrency control (Java)

```
class Counter {
    private int c = 0;

    public synchronized void increment() {
        c = c + 1;
    }

    public synchronized void decrement() {
        c = c - 1;
    }
}
```

Only one thread at a time can enter the synchronized methods

Concurrency control (Java)

```
class Counter {
    private int c = 0;
    Object o = new Object();

    public void increment() {
        lock (this) {
            c = c + 1;
        }
    }

    public void decrement() {
        lock (this) {
             c = c - 1;
        }
    }
}
```

Only one thread at a time can enter the locked blocks

Concurrency control (others)

```
class Counter {
    private int c = 0;
    Object o = new Object();

    public void increment() {
        lock (o) {
            c = c + 1;
        }
    }

    public void decrement() {
        lock (o) {
             c = c - 1;
        }
    }
}
```

Only one thread at a time can enter the locked blocks

Concurrency control (others)

```
class Counter {
    private int c = 0;
    Lock o = new Lock();

    public void increment() {
        o.acquire();
        c = c + 1;
        o.release();
    }

    public void decrement() {
        o.acquire();
        c = c - 1;
        o.release();
    }
}
```

Only one thread at a time can enter the locked blocks

Locks

- They seem easy
- They are **very hard** to manage

Lock management

- Acquired locks must always be released
  - Including when exceptions occur
  - A lock that is not released will prevent any other thread from entering the block forever

Over-locking → Deadlocks

```
class Counter {
    private int c = 0;
    Object o1 = new Object();
    Object o2 = new Object();
    public void increment() {
        lock (o1) {
          lock (o2) {
            c = c + 1;
        }
    }

    public void decrement() {
        lock (o2) {
          lock (o1) {
            c = c - 1;
        }
    }
}
```

o1, then o2

o2, then o1

AVOID!

Deadlocks vs. Data Races

Too much concurrency control

Not enough concurrency control

deadlocks

data races

Threads Summary

- Nice, but...
  - Synchronization primitives are hard to get right
    - Deadlocks
    - Race conditions
  - Many corner cases
  - Bugs hard to reproduce
  - Potentially bad performance (locking is heavy)

- Many reasons to avoid threads!
  - Must use them under strict constraints