# Introduction to Concurrent Software Systems

CSCI 5828: Foundations of Software Engineering
Lecture 12 — 09/29/2016

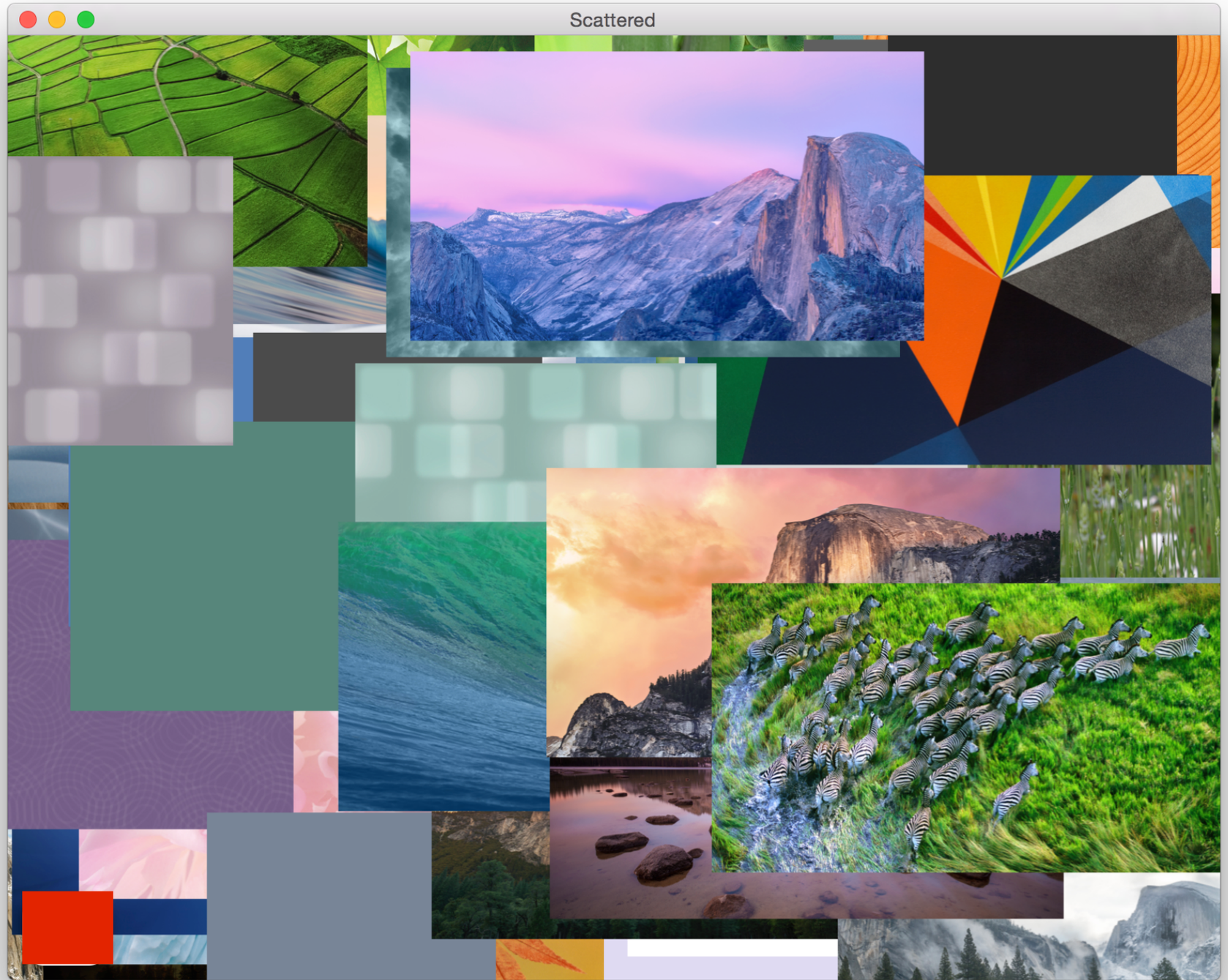
# Goals

- Present an overview of concurrency in software systems
  - Review the benefits and challenges associated with designing and implementing concurrent software systems
  - Review material from concurrency textbooks used in previous semesters
    - "Seven Concurrency Models in Seven Weeks" by Paul Butcher
    - as well as some material from the book "Programming Concurrency on the JVM" by Venkat Subramaniam
- Both books are highly recommended

# Why worry about concurrency? (I)

- “Concurrency is hard and I’ve only ever needed single-threaded programs. Why should I care about it?”
- Changing environment
    - multi-core computers (including handheld devices)
    - use of computing clusters to solve problems on the rise
- Performance
    - Growth rates for chip speed are flat;
        - You can’t wait 18 months for a 2x speed-up anymore
    - Instead, chips are becoming “wider”
        - More cores, wider bus (more data at a time), more memory

# Quick Example: Scattered from Big Nerd Ranch



# Scattered (II)

- This is an example program from Big Nerd Ranch's excellent book
  - Cocoa Programming for OS X
  - I can't distribute the code for this example, but it is freely available
- What does it do?
  - It loads a folder of images and displays them
    - Each image is loaded with an animation starting from the center of the window to a random location in the window
- Problem with single threaded version:
  - it takes a long time to load the images and they all appear at once
  - **Demo**

# Scattered (III)

- GUI applications are event based
  - there is a single thread that reads events off a queue
  - we implement *event handlers* for each event we want to process
  - the framework assumes that event handlers execute ***quickly***

- In the single-threaded version, we implement the loading **AND** displaying of images in a ***single event handler***
  - The problem? As long as we stay in the event handler the UI is BLOCKED!
  - Our application becomes non-responsive since any new events that get handed to it are simply queued; nothing else is happening

# Scattered (IV)

- How do we fix the problem?
  - By ***changing the design***
    - (this is not an easy thing to do)
  - We simply **cannot** have ***long running operations blocking*** the UI thread
- Instead, we have to view “load an image” and “display an image” as *tasks* that our application needs to perform
  - “display an image” is something the UI thread should do
    - that task should be delivered as an event and handled like all other UI events
  - “load an image” is **NOT** something the UI thread should do
    - we change the program to perform that work in background threads

**DEMO**

# Scattered (V)

- This simple example is a great demonstration of both
  - *the **benefits** of designing concurrent software systems*
    - great performance that scales with number of cores, responsive applications, happy users
  - *the **problems** associated with concurrent software systems*
    - we have to change our way of thinking about how we design our applications
    - designing for concurrency is **HARD**
      - all sorts of perils as we will see
- With this example as context, let's return to the introduction

# Why worry about concurrency? (II)

- Since chips are not getting faster (in the same way they used to)
    - a single-threaded, single-process application is not going to see any significant performance gains from new hardware
- Instead, software will only see performance gains from new hardware
    - **IF** it is designed to do more work in parallel as the number of processors available to it increases
- THIS IS NOT EASY
    - the application's computations must be amenable to parallelization
        - that is, it must be possible to break its work into **tasks** that can run at the same time with no need to coordinate with each other

# Why worry about concurrency? (III)

- If you can design your system in this way, you pave the way to seeing linear speed ups as the number of processors increases
  - That is a system on n-cores will be n times faster than the same system running on a single core CPU
    - In the past few years, laptops are shipping with 8 cores, smart phones with 2-4 cores, desktops with 12-16 cores, and this is increasing
    - Some threading frameworks will allow you to send tasks to your machine's *graphics card* and these cards can have ***hundreds to thousands*** of cores (although, granted, they are designed to be used by very specific types of algorithms)
- However, it is very difficult to achieve linear speed-ups, but performance gains can still be quite significant

# In addition…

- Concurrent programming is becoming hard to ignore
  - lots of application domains in which concurrency is the norm
    - Embedded software systems, robotics, “command-and-control”, high-performance computing (use of clusters), …
    - Web programming often requires concurrency (AJAX)
    - Web browsers are themselves examples of multi-threaded GUI applications
      - without threads the UI would block as information is downloaded

# BUT…

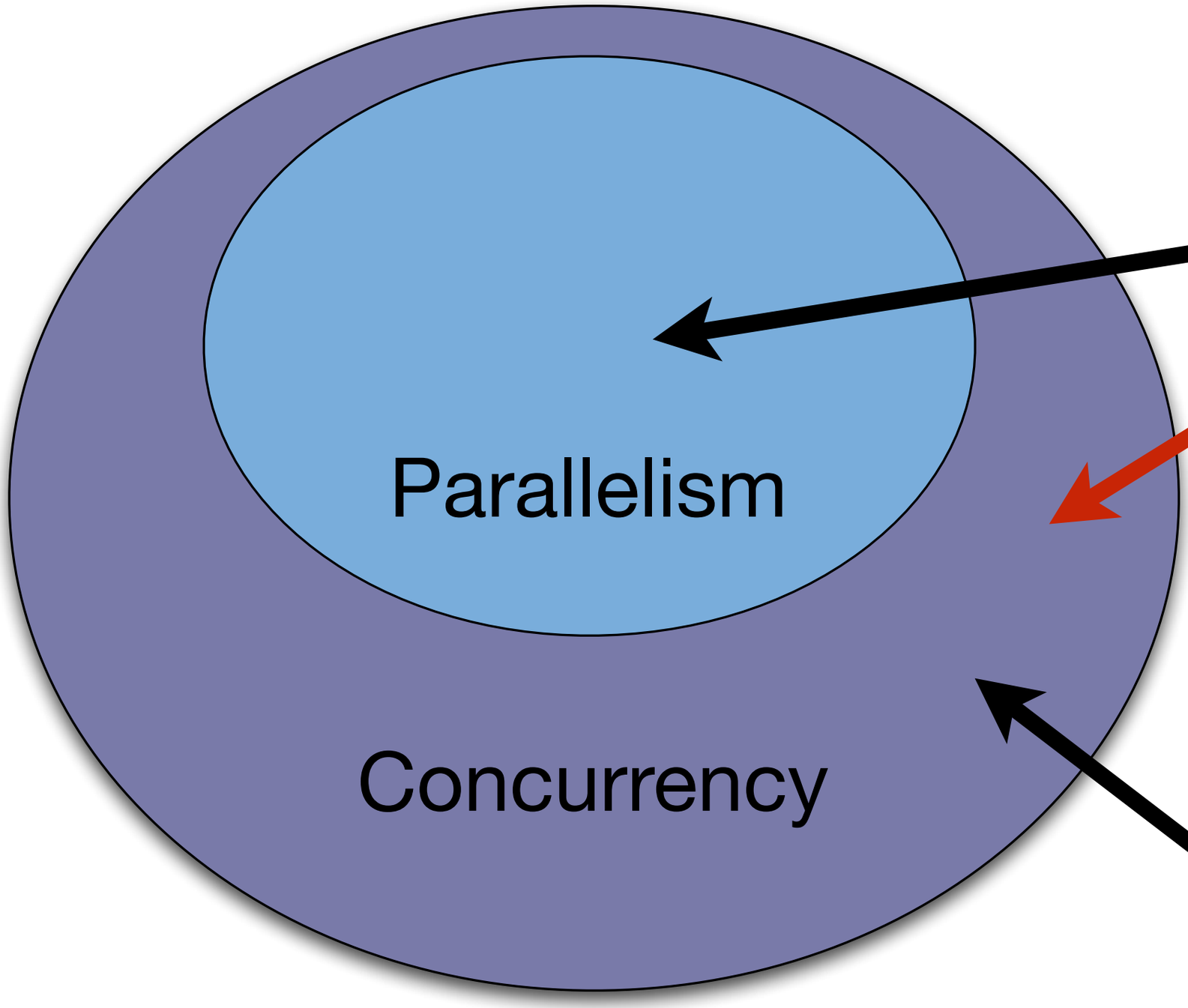
- “A DEEP CHASM OPENS BEFORE YOU…” ‡
  - Concurrency is HARD
- While concurrency is widespread, it is error prone
- Programmers trained for single-threaded programming face unfamiliar problems
  - synchronization, race conditions, deadlocks, “memory barriers”, etc.
- Let’s review some terminology

‡ — Taken from Cocoa Programming For Mac OS X, 4th Edition by Aaron Hillegass and Adam Preble

# Basic Definitions

- When we execute a **program**, we create a **process**
  - A **sequential** program has a **single thread of control**
  - A **concurrent** program has **multiple threads of control**
- A single computer can have multiple processes running at once;
  - If that machine **has a single processor**, then **the illusion of multiple processes running at once** is just that: **an illusion**
  - That illusion is maintained by the operating system; it coordinates access to the single processor by the various processes; only one process runs at a time
- If a machine **has more than a single processor**, then **true parallelism** can occur
  - you can have **N processes running simultaneously on a machine that has N processors**

# Thus…




Concurrent program on a multicore machine

Note: this is still possible. Ruby's GIL, for instance, does not allow concurrent programs to run in parallel

Concurrent program on a single core machine

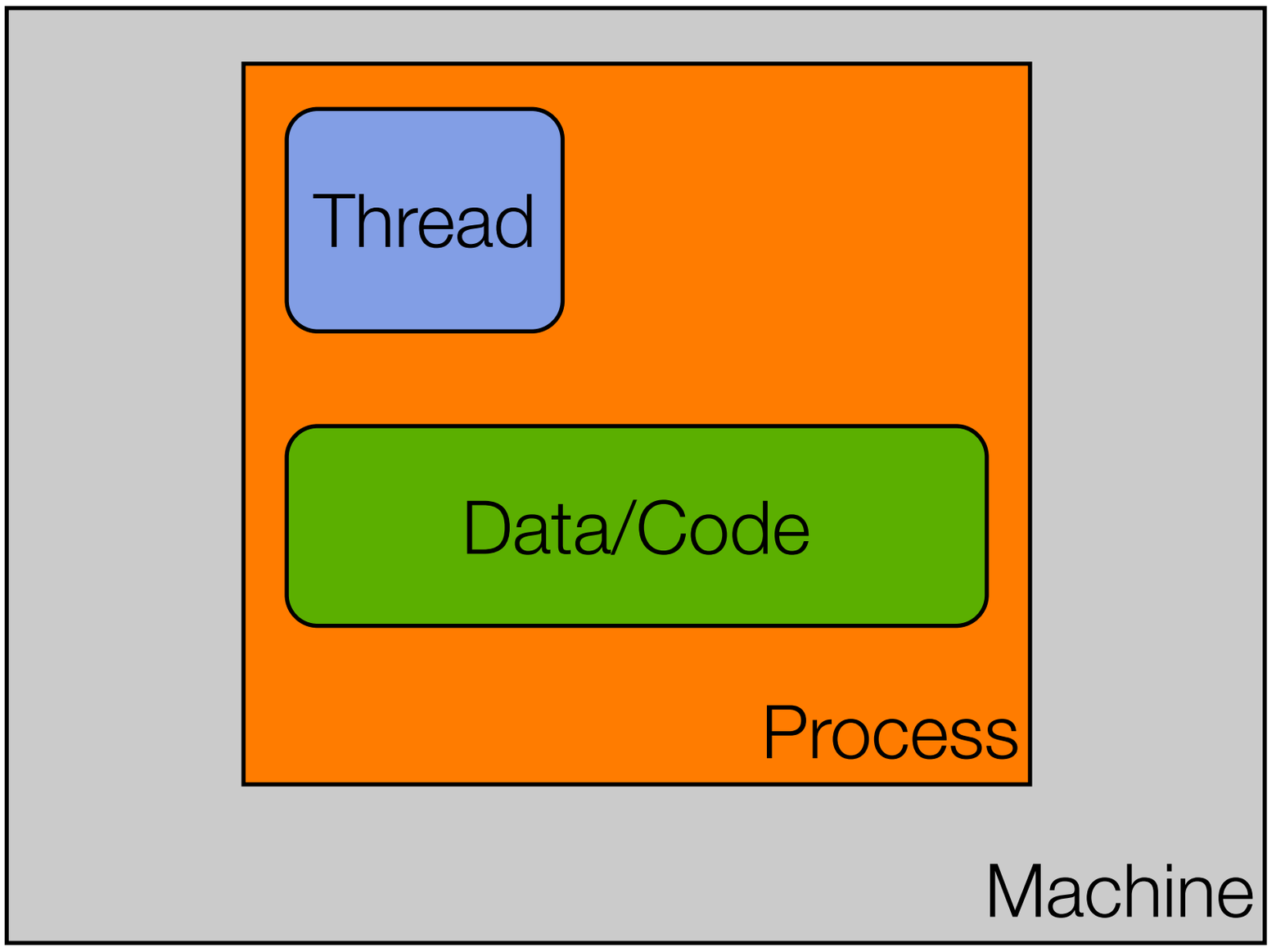
# Concurrency Textbook Definitions (Adapted)

- A **concurrent** program has *multiple* **logical** THREADS OF CONTROL. These threads may or may not run in parallel.
- A **parallel** program has the ability to execute **multiple computations** *simultaneously*. It may or may not have more than one logical thread of control (typically it does, but in data parallelism it might not).

- Alternative way of thinking about it
  - Concurrency is part of the ***problem domain***
    - multiple events can happen at the same time
  - Parallelism is an aspect of the ***solution domain***
    - we design a program such that computations occur simultaneously

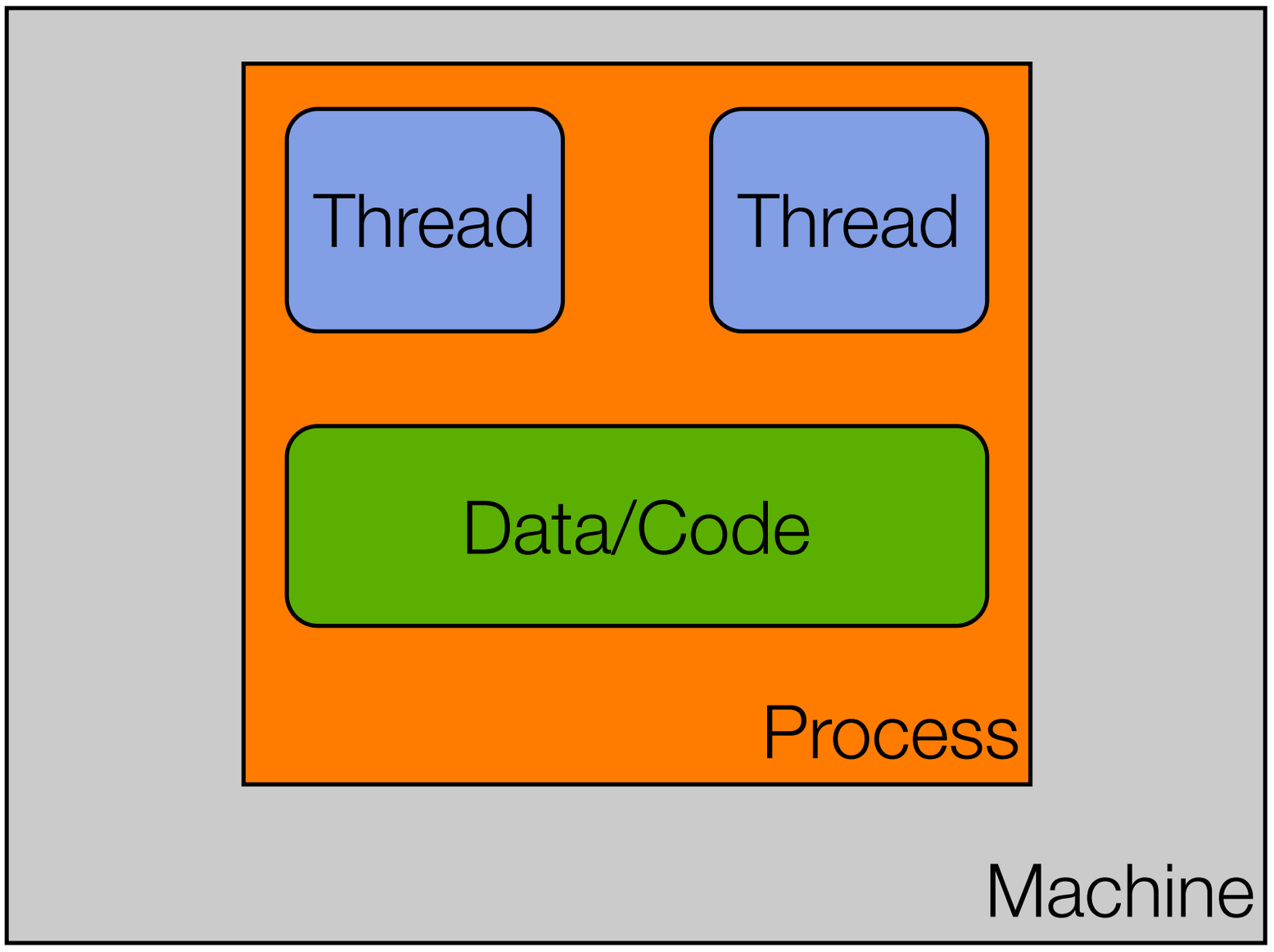
# Basics: **Single** Thread, **Single** Process, **Single** Machine

**Note: Repetition is good!**



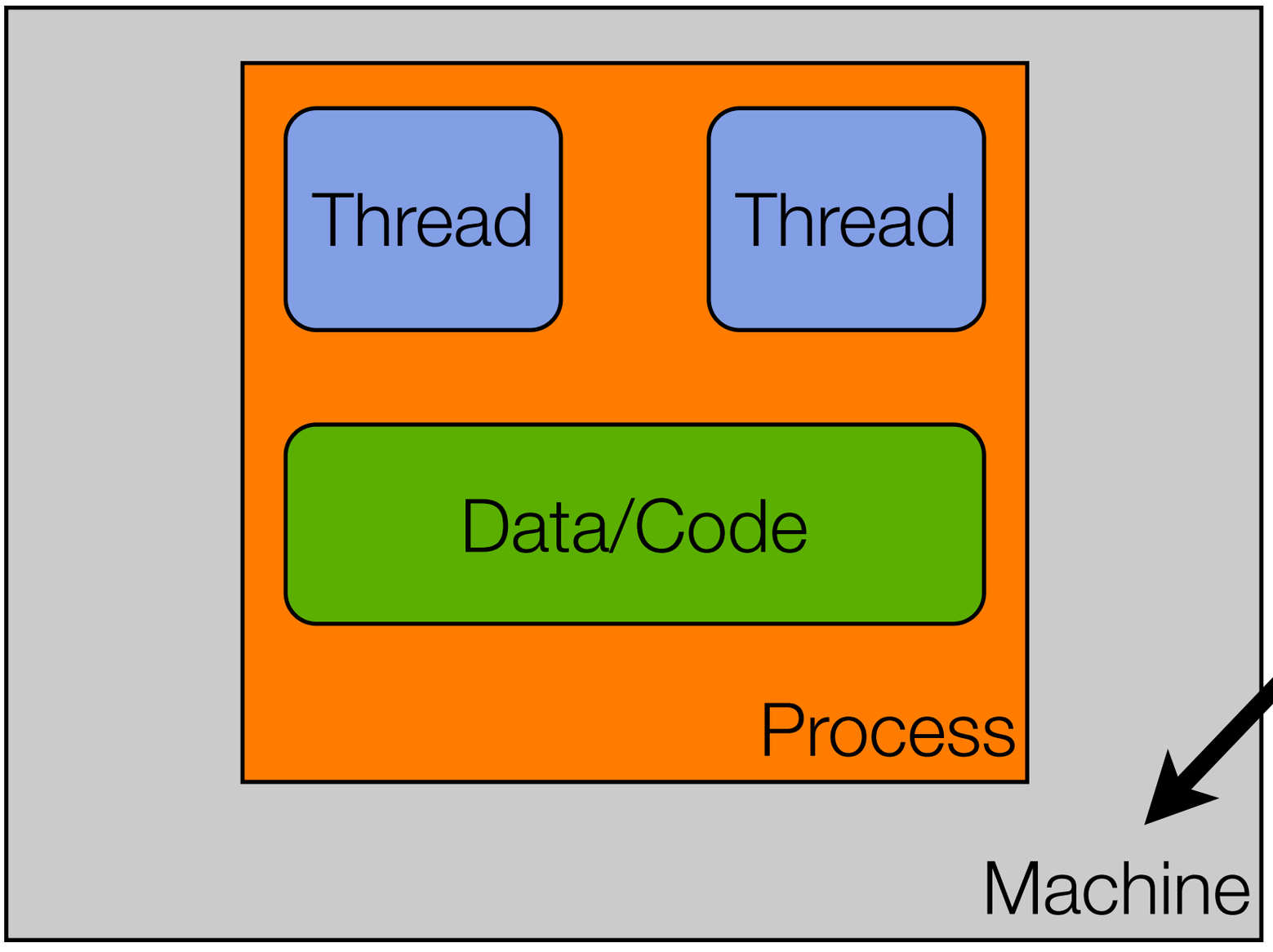

**Sequential Program == Single Thread of Control**

# Basics: **Multiple** Thread, Single Process, Single Machine




**Concurrent Program == Multiple Threads of Control**

# Multi-Thread: **But is it truly parallel?**



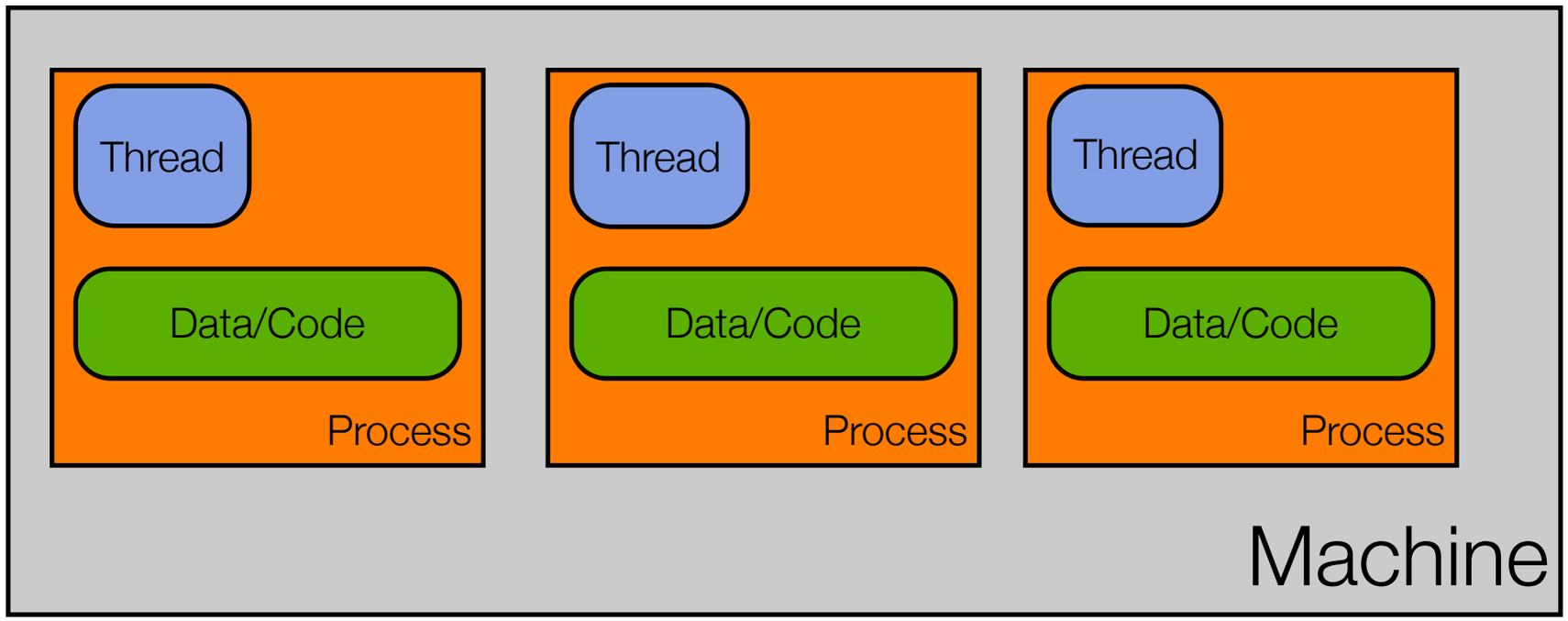

We may have multiple threads in this process, but we may not have events truly occurring in parallel. Why not?

It depends on the machine!

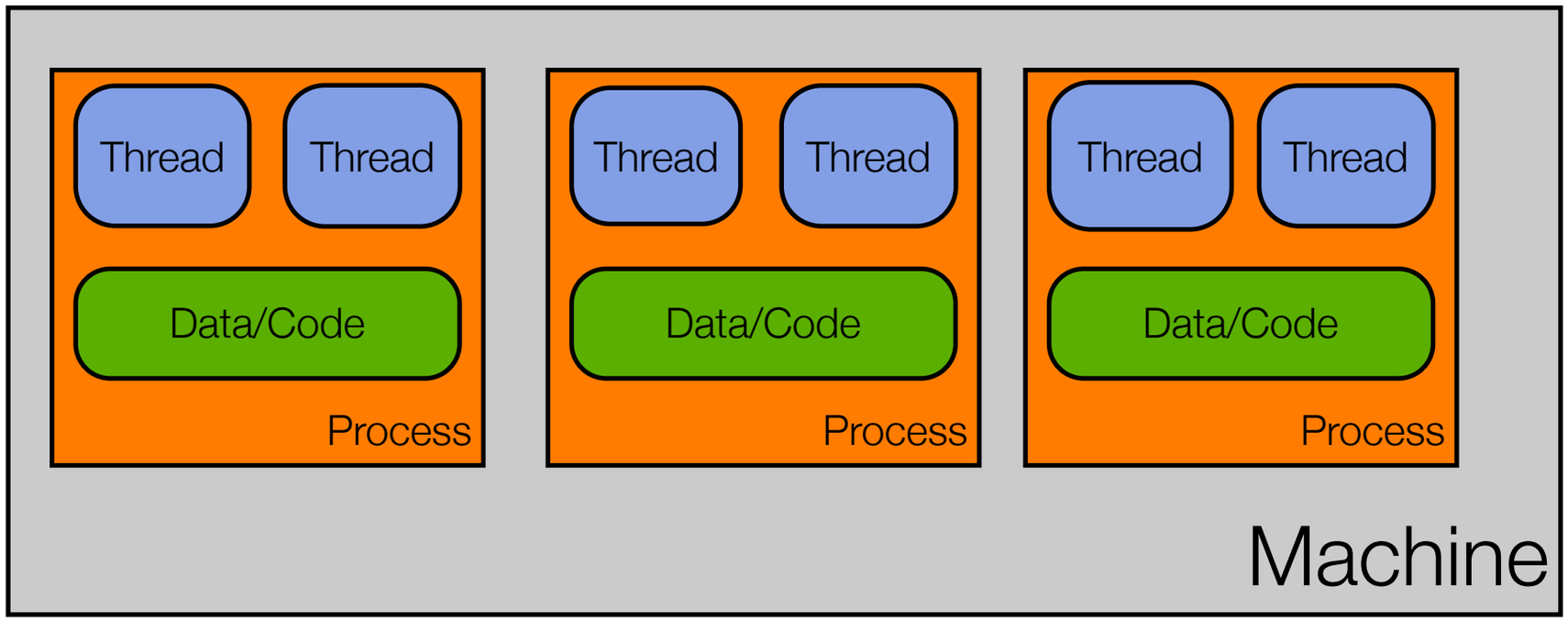
If the machine has multiple processors, then **true parallelism can occur**. Otherwise, parallelism is **simulated**

**Concurrent Program == Multiple Threads of Control**

# Basics: Single Thread, **Multiple** Process, Single Machine

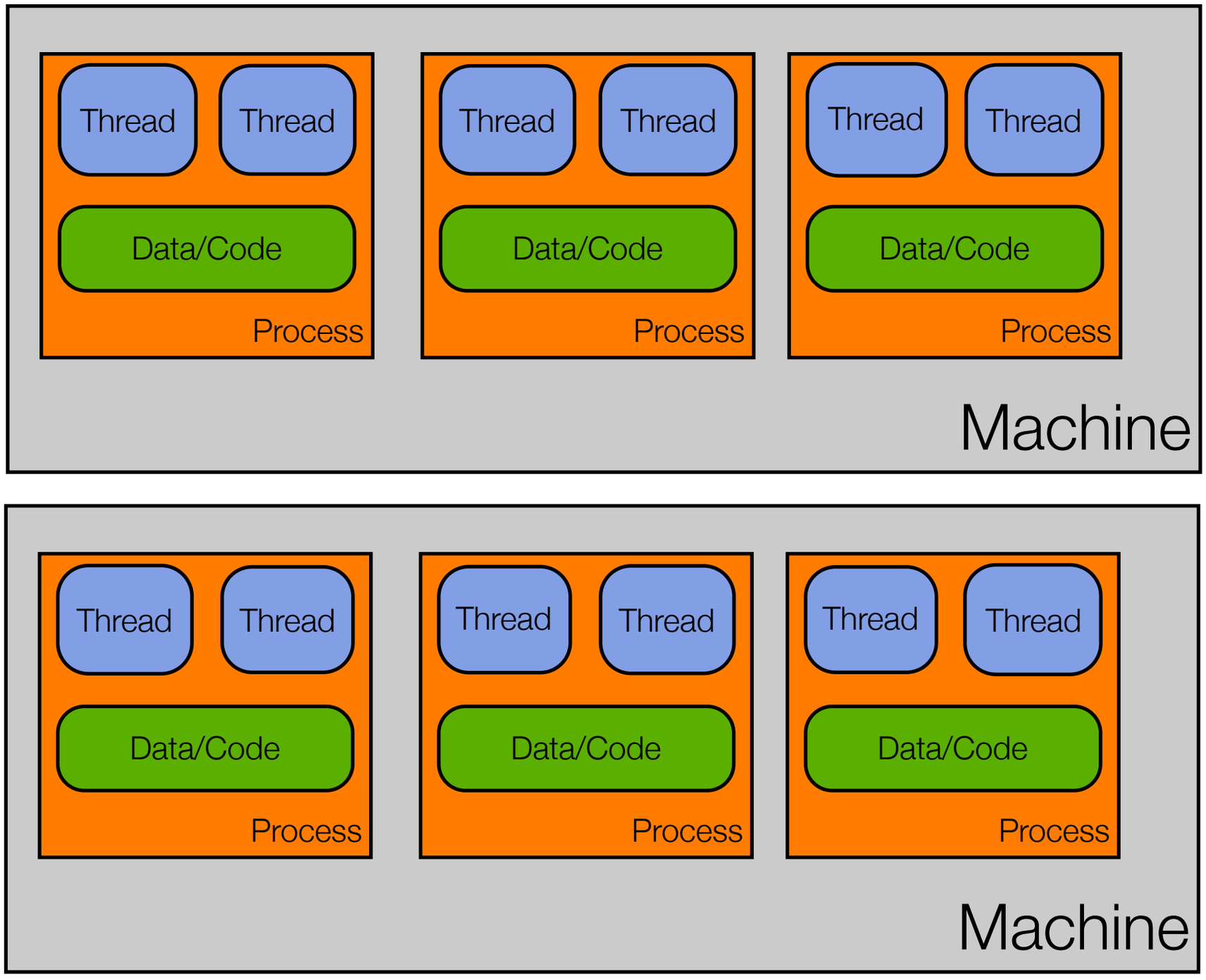


# Basics: **Multi**-thread, **Multi**-Process, Single Machine




Note: You can have way more than just two threads per process.

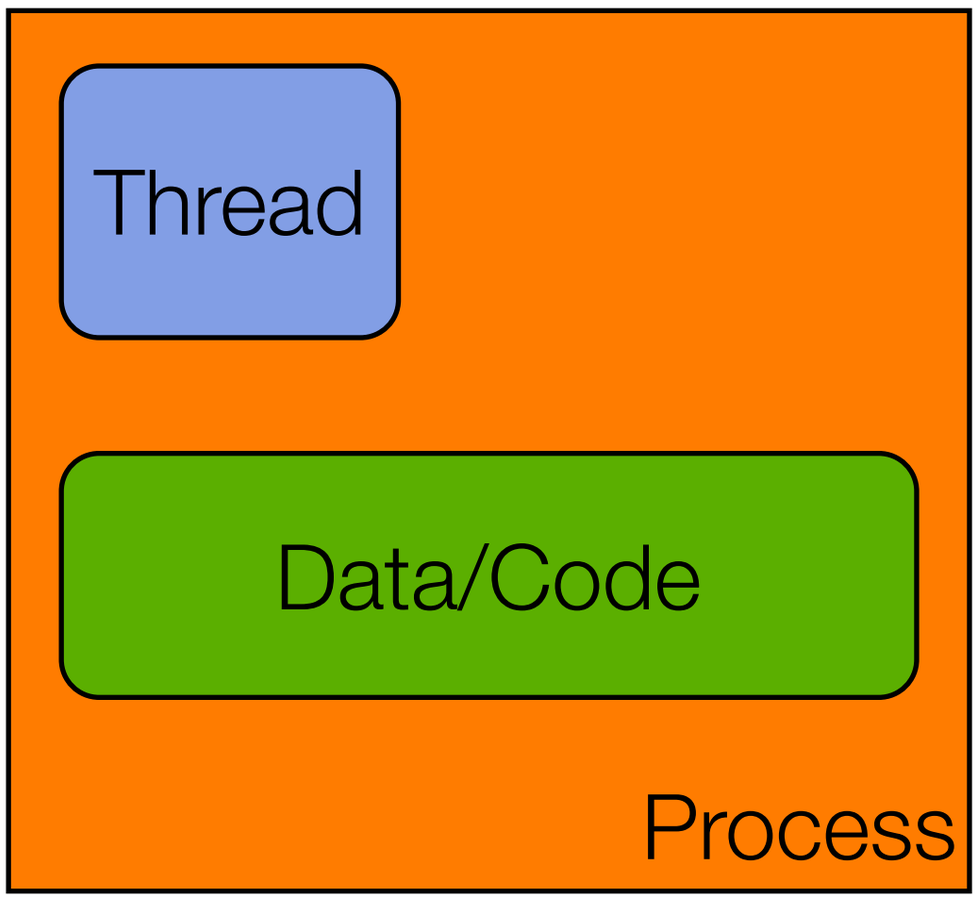
# Basics: **Multi-everything**



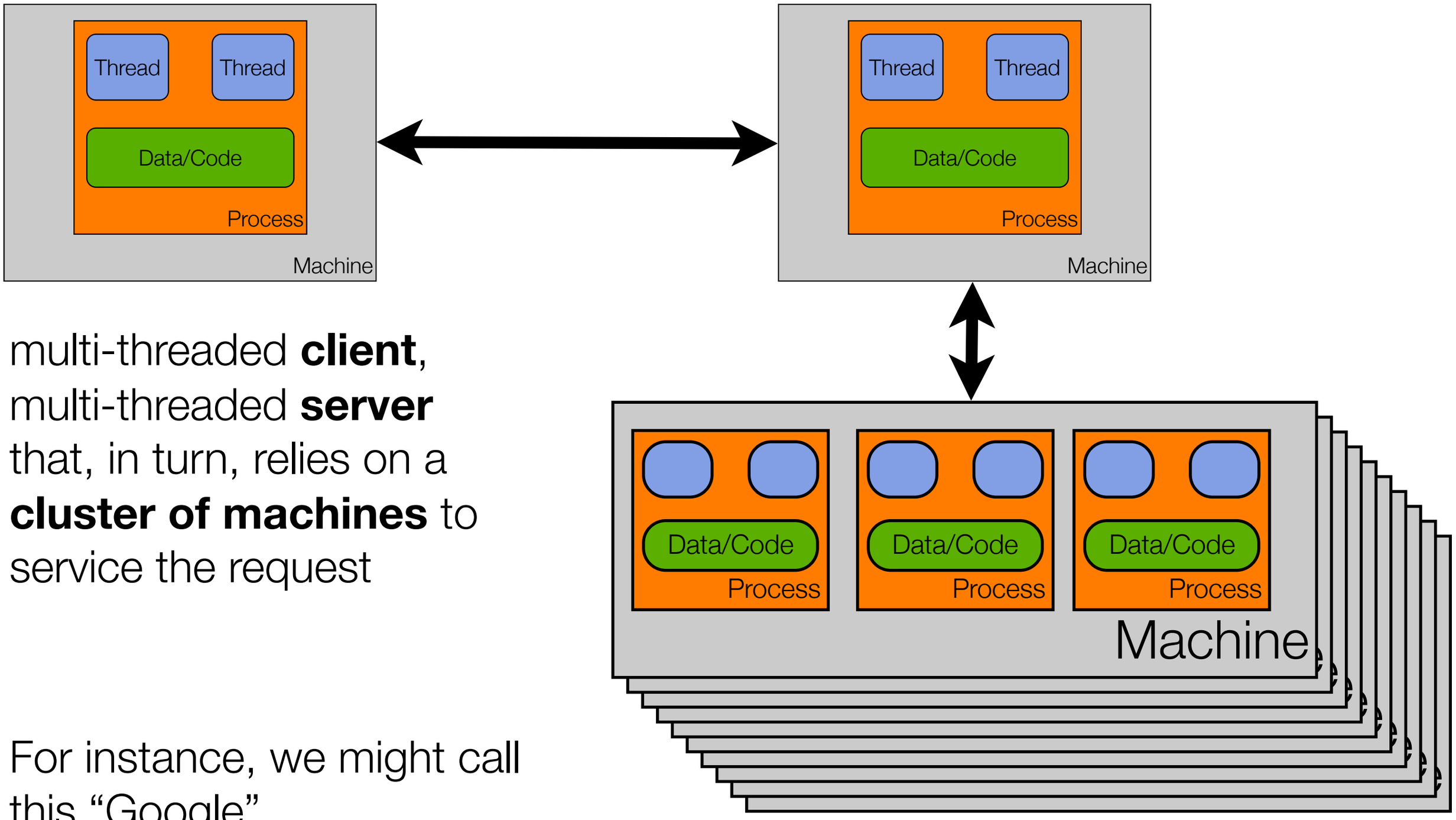
# Applications are Dead! Long Live Applications!

Due to the ability to have multiple threads, multiple processes, and multiple machines work together on a single problem, the notion of an application is changing. It used to be that:

Application ==



# Now… we might refer to this as “an application”




multi-threaded **client**,
multi-threaded **server**
that, in turn, relies on a
**cluster of machines** to
service the request

For instance, we might call this “Google”

# Parallel Architecture

- Within a single machine, there are many levels of parallelism
  - which may or may not have an impact on our concurrent systems
- Bit-Level Parallelism
  - A 32-bit computer can process 32-bit numbers faster than an 8-bit computer
- Instruction-Level Parallelism
  - Processor techniques such as pipelining, out-of-order execution, and speculative execution can impact the behaviors we see in parallel code
- Data Parallelism
  - GPUs can process lots of data in parallel with a single instruction
- Task-Level Parallelism
  - Multiple threads of control executing simultaneously under a particular memory model (i.e. do we allow threads to share memory or not)

# Software Architecture Design Choices

- When designing a modern application, we now have to ask
  - How many machines are involved?
  - What software components will be deployed on each machine?
  - For each component
    - Does it need concurrency?
    - If so, how will we achieve that concurrency?
      - multiple threads?
      - multiple processes?
      - both?

# Consider Chrome

- Google made a splash in 2008 by announcing the creation of a new web browser that was
  - multi-process (one process per tab) and
  - multi-threaded (multiple threads handle loading of content within each tab)
- They documented their engineering choices via a comic book
  - http://www.google.com/googlebooks/chrome/index.html

# Chrome Advantages

- Some of the advantages they cite for this design
  - **stability**
    - single-process, multi-threaded browsers are vulnerable to having a crash in one tab bring down the entire browser
  - **speed**
    - multi-process browsers can be more responsive due to OS support
  - **security**
    - exploits in single-process browsers are easier if malware loaded in one tab can grab information contained in another tab; much harder to grab information across processes

# Chrome Demo

- You can use an operating system's support for process monitoring to verify that Chrome is indeed multi-process and multi-threaded

Activity Monitor (All Processes)

CPU | Memory | Energy | Disk | Network

chr

| Process Name | % CPU | CPU Time | Threads | Idle Wake Ups | PID | User | Energy Impact |
|---|---|---|---|---|---|---|---|
| Google Chrome | 0.0 | 3.65 | 36 | 0 | 33464 | kena | 0.0 |
| Google Chrome Helper | 0.0 | 0.37 | 12 | 1 | 33474 | kena | 0.0 |
| Google Chrome Helper | 0.0 | 0.47 | 13 | 0 | 33472 | kena | 0.0 |
| Google Chrome Helper | 0.0 | 0.42 | 12 | 0 | 33475 | kena | 0.0 |
| Google Chrome Helper | 0.0 | 1.06 | 13 | 0 | 33473 | kena | 0.0 |
| Google Chrome Helper | 0.0 | 0.41 | 4 | 0 | 33469 | kena | 0.0 |
| Google Chrome Helper | 0.0 | 0.87 | 14 | 0 | 33486 | kena | 0.0 |
| Google Chrome Helper | 0.0 | 1.07 | 15 | 1 | 33488 | kena | 0.1 |
| Google Chrome Helper | 0.0 | 0.33 | 11 | 0 | 33491 | kena | 0.0 |
| Google Chrome Helper | 0.0 | 0.73 | 13 | 0 | 33490 | kena | 0.0 |
| Google Chrome Helper | 0.0 | 0.52 | 12 | 0 | 33489 | kena | 0.0 |
| Google Chrome Helper | 0.0 | 0.46 | 12 | 0 | 33492 | kena | 0.0 |

| | | | | |
|---|---|---|---|---|
| System: | 3.69% | CPU LOAD | Threads: | 1768 |
| User: | 2.59% | | Processes: | 342 |
| Idle: | 93.72% | | | |

This was the result of running Chrome with seven open tabs on OS X

# Other benefits to multi-process design ‡

- Lots of existing applications that do useful things
  - Think of all the powerful command line utilities found in Unix-based platforms; You can take advantage of that power in your own application
    - Create a sub-process, execute the desired tool in that process, send it input, make use of its output
- Memory leaks in other programs are not YOUR memory leaks
  - As soon as the other program is done, kill the sub-process and the OS cleans up
- Flexibility: An external process can run as a different user, can run on a different machine, can be written in a different language, …

‡ — Also taken from Cocoa Programming For Mac OS X, 4th Edition by Aaron Hillegass and Adam Preble

# Two Reasons for Using Concurrency

- Making applications more responsive
  - As we saw with the Scattered App
- Making applications faster
  - In particular, computationally intensive apps (compute bound) or data processing apps (I/O bound)

# The Dangers of Concurrency (I)

- Starvation
  - All threads are active in the system but none of them are making progress
    - Thread A is waiting for an input that takes a long time to arrive
    - It's not blocked but it's not making progress
    - Generic solution:
      - **Timeouts**: have Thread A do something else once a timeout occurs
- Deadlock
  - Thread A is waiting for B to give up resource C
  - Thread B is waiting for A to give up resource D
  - Both are blocked and will never be unblocked
  - Generic solution: Have threads acquire resources in the same order

# The Dangers of Concurrency (II)

- Race Conditions
  - If two threads access the same resource, we may have a race condition
  - In particular, if two threads have access to the same variable, they may attempt to change its value at the same time
    - this can result in the value getting set to an inconsistent state
- You can also get into problems even when one thread is doing the writing and a second thread is doing the reading

# The Dangers of Concurrency (III)

- First Example of Race Condition
  - threads A and B have access to an integer variable C
  - C currently equals 0 and then both A & B execute the code “C = C + 1”
  - A reads the value 0 and gets suspended
  - then B reads the value 0 and updates it to 1
  - then A wakes up and updates the value to 1
- **DEMO**
  - Final value should have been 30; typically, the value was much less than that, due to the problem above; note: code had to be made way more complex than normal to make the problem appear consistently

# The Dangers of Concurrency (IV)

- Second Example of Race Condition
  - Thread A is designed to loop until a boolean variable switches from true to false
  - Thread B creates A, then goes to sleep for a bit, then changes the boolean variable from true to false
    - Observed behavior: sometime the program works, sometimes it does not
      - See example in source code that comes with Programming Concurrency on the JVM
- The problem?
  - Thread A cached the value of the boolean variable and B's write never "crosses the memory barrier" to allow A to see the updated value

# The memory barrier (I)

- The term “memory barrier” simply refers to transferring values from main memory into working memory and back again
  - Each thread has its own flow of execution and this means that it has
    - its own program stack
    - its own set of values for the machine’s registers
- Each thread also shares access to the program’s heap and static data

# The memory barrier (II)

- In order to make a program run faster, the compiler will look for ways to optimize memory reads/writes.
    - It may choose to cache a value stored in main memory into its set of registers
    - once that occurs, only certain types of operations will cause a change in the cached value to be synced back to its home in main memory
- If the cached value corresponds to a value accessed by more than one thread, then problems can occur when changes made by one thread to shared memory are not made visible to another thread

# The memory barrier (III)

- To avoid the race condition in our second example, we must do something to ensure that B's change to the shared boolean variable is made visible to A
  - Examples of techniques that cause the write to pass the memory barrier
    - Tagging the variable with the keyword "volatile"
    - Tagging methods that access the variable with the keyword "synchronized"
    - Creating a synchronized block on an object and updating the shared variable within that block
- As we have seen, having values that can be changed, shared between multiple threads (a.k.a. shared mutability) can lead to incorrect behavior, unstable systems, crashes, locked apps, etc.

# The Response: Avoid Shared Mutability

- To get around the problems associated with shared mutability, we must
  - AVOID SHARED MUTABILITY
- As the Programming Concurrency on the JVM textbook author says
  - “Shared mutability is pure evil. Avoid it!”

- In our upcoming lectures
  - we will look at Elixir's approach to avoiding shared mutability
    - As we learned, Elixir has no mutable values
      - that's a big step in the right direction!

# Summary

- Introduced the subject of concurrency in software systems
  - why it is important
  - why we cannot really avoid it
  - what problems occur when dealing with concurrency
    - starvation, deadlock, race conditions
- learned about shared mutability and why to avoid it
- learned about the “memory barrier” which is related to Java’s memory model and contributes to some of the problems of shared mutability