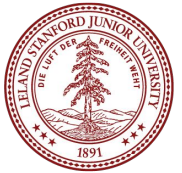
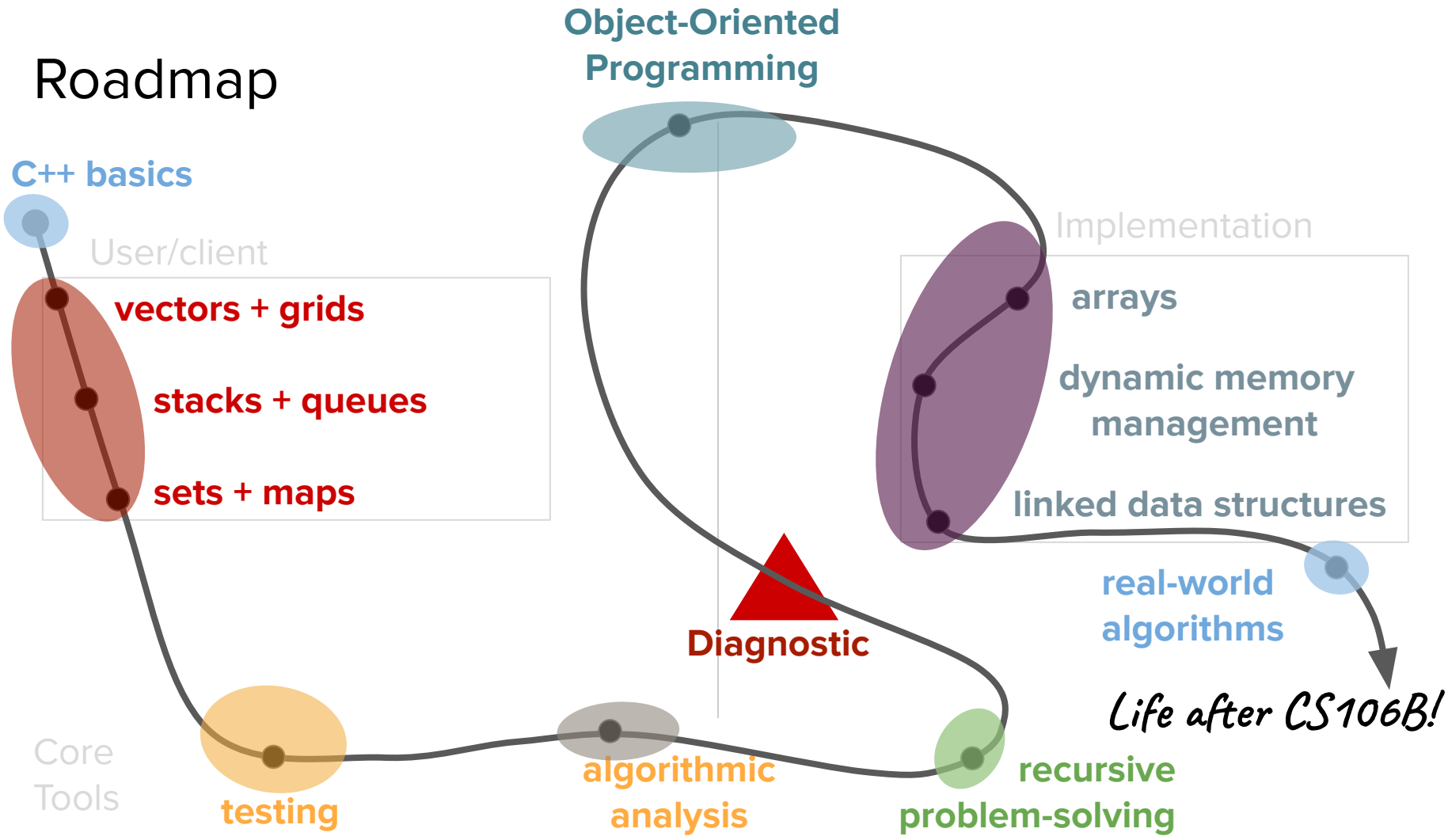
Multithreading and Parallel Computing

What do you think Trip has been up to this quarter?

(wrong answers only in the chat)



Roadmap


Object-Oriented Programming
C++ basics
User/client
vectors + grids
stacks + queues
sets + maps
Implementation
arrays
dynamic memory management
linked data structures
real-world algorithms
Diagnostic
Life after CS106B!
Core Tools
testing
algorithmic analysis
recursive problem-solving

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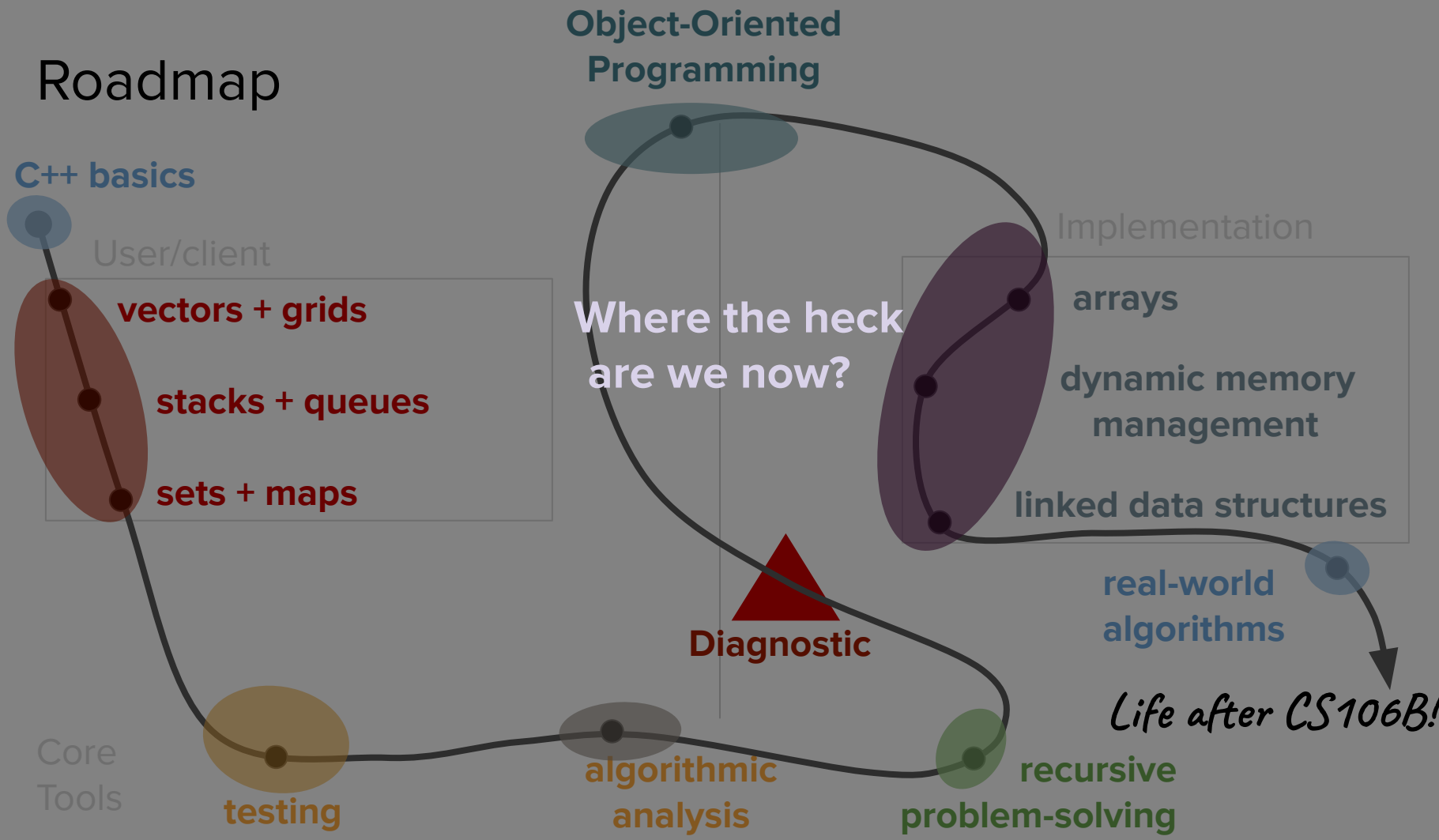
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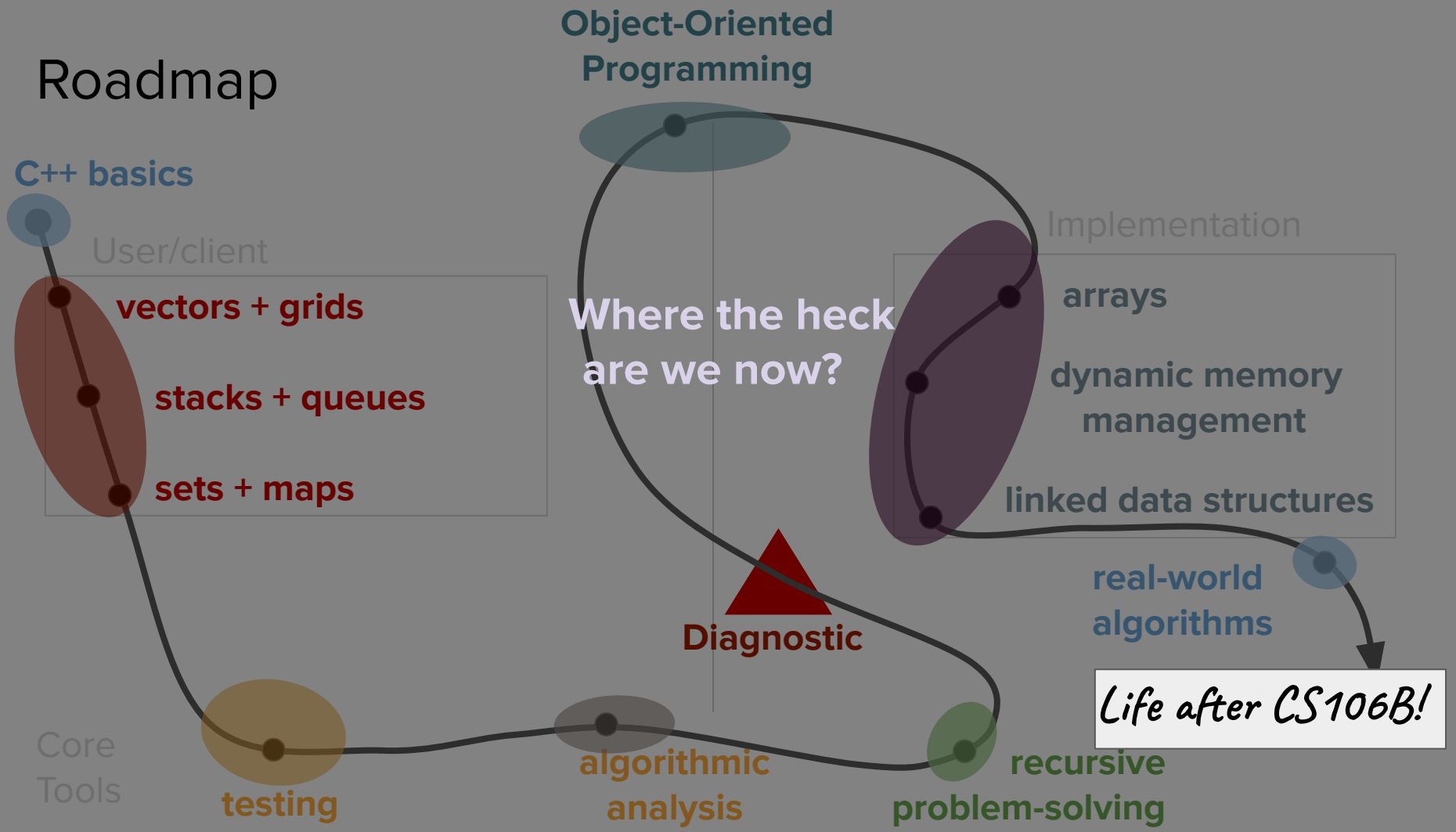
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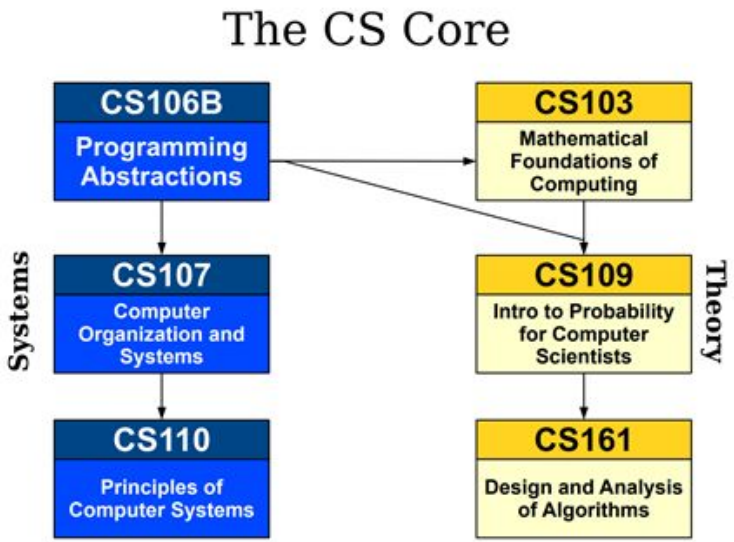

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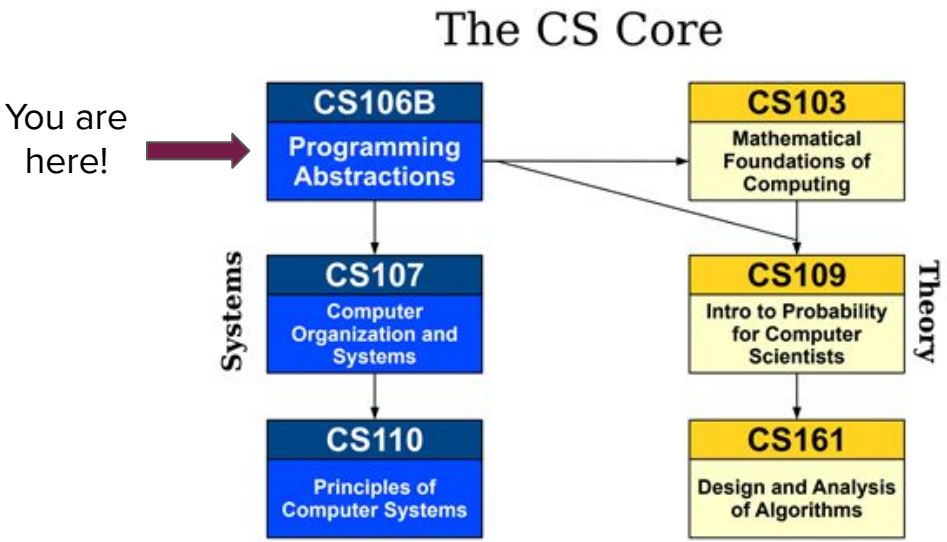

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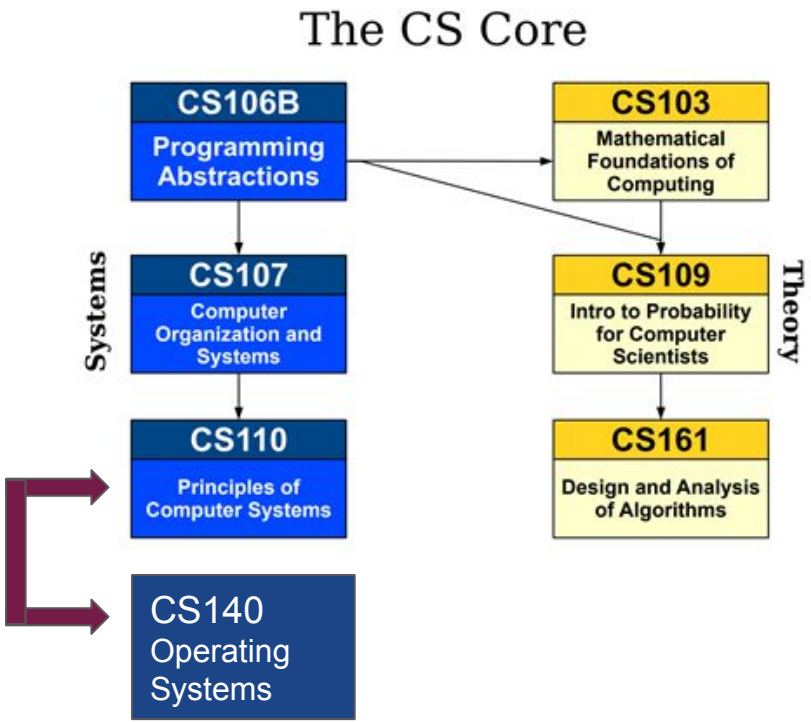

Multithreading!

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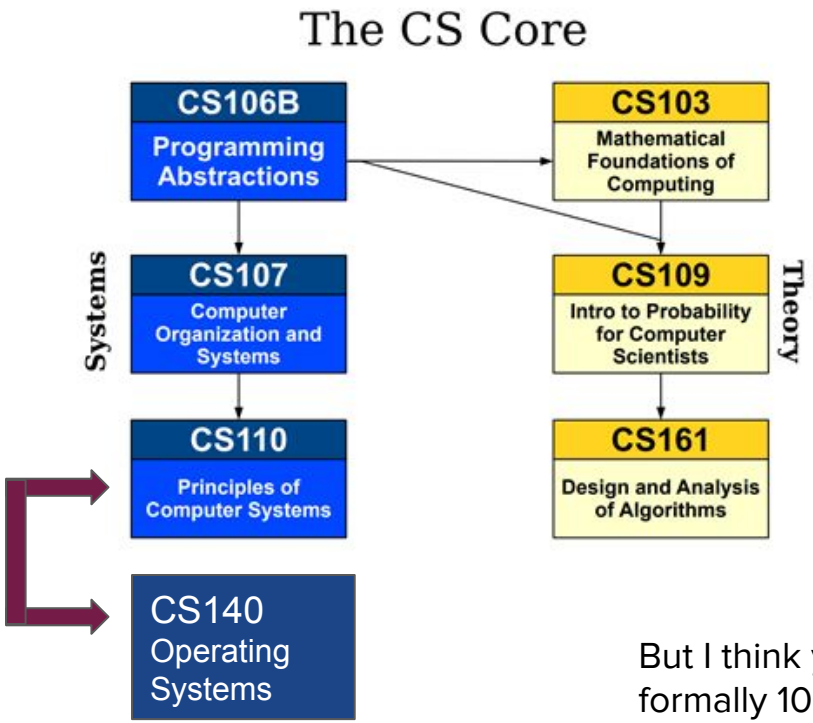


Multithreading!

But I think you'll see why it was taught formally 106B in quarters of yore :)

Today's question

How can we harness the cores in our computer in order to parallelize a workload safely?

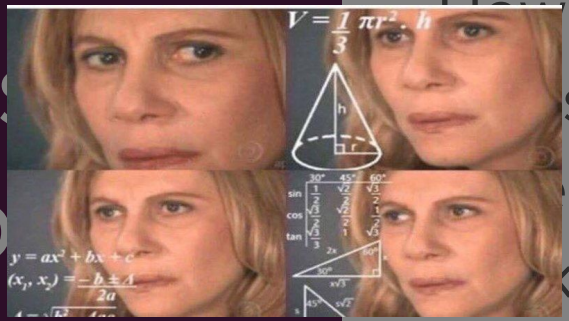
Today's question

woah. How can we harness the cores in our computer in order to parallelize a workload safely?

Multiple cores?

Parallelize work??

Today's question



How can we harness the
s in our computer in
r to parallelize a
kload safely?

Today's topics

1. Review (short!)
2. Some Computer Architecture (Threads & Processors)
3. Thread Safety

Review (short!)

(simple code flow)

How code is run

- How does the computer read and run your code?
  - Logically, **it** should read your code from top to bottom!

```
int main () {

    int yeet = 9338;
    double foo = 2.4;

    doSomeMath(yeet);

    cout << "time to go home!" << endl;

    return 0;
}
```

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int main () {

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    double foo = 2.4;

    doSomeMath(yeet);

    cout << "time to go home!" << endl;

    return 0;
}
```

...but *who* is **it**? What's the thing that encapsulates and runs your code?

Definition

thread
An abstraction that represents a sequential execution of code.

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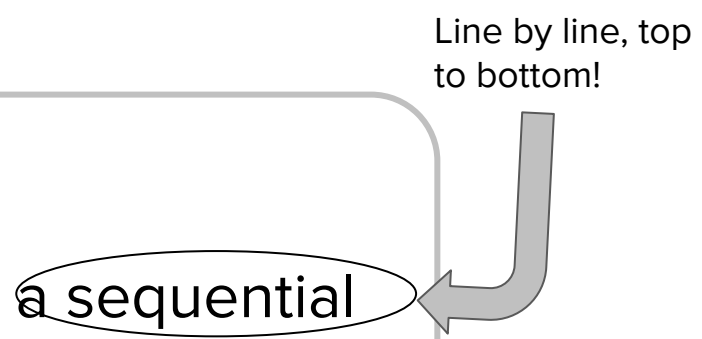

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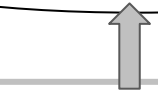

Anything that's code!

How to think about threads

- When talking about a **thread**, you'll very frequently see it referenced as a "**thread** of execution."
  - Think about the line on the right as a program's execution. You start at **main()**, which might call other functions, which might return to **main()** or call other helper functions. Although the execution flow of your program may involve many function calls, it will eventually go from the top of **main()** to the bottom.
  - The flow would almost looks like a **thread**, or a piece of string!

Thread examples

- Right now, your computer probably has a few threads running right now!
  - What are some examples of threads running on your PC?

Thread Examples

- Are you on Zoom right now?

Thread Examples

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Thread Examples

- Do you have a web browser open? (Chrome, Safari?)

Thread Examples

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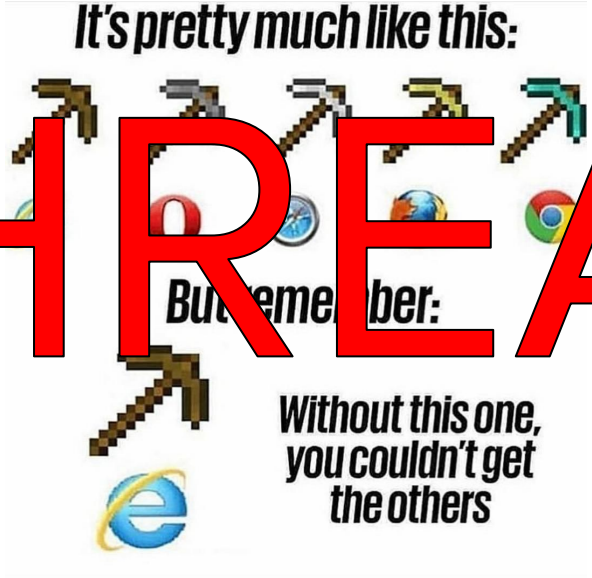

*unless you're using Chrome, sort of.

Thread Examples

- Are you watching TikToks during lecture?

Thread Examples

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Stanford announces Charli D'Ameli as 2020 Commencement Speaker

"Charli undeniably captures the same spirit of ingenuity we try to cultivate at our different schools," said President Marc Tessier-Lavigne. (Photo Edit: RICHARD COCA/The Stanford Daily)

THREAD

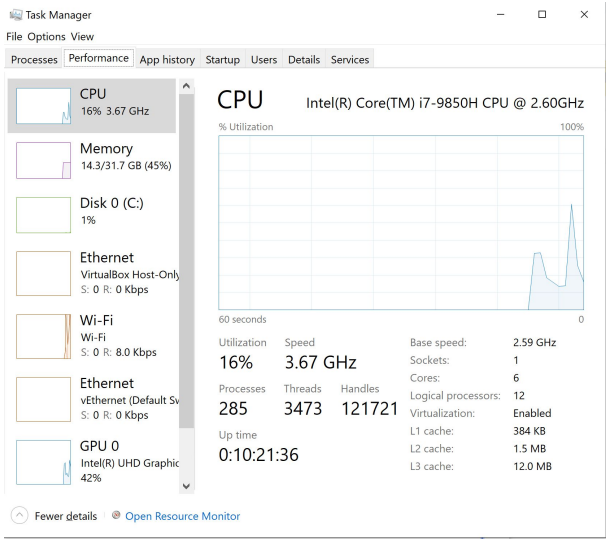
I have been told Ms. D'Ameli is a TikTok #influencer

Question:

How many threads do you think my computer had active when I was making this slide?

Thread examples

- Right now, your computer is executing a bunch of threads!
  - At the time of making this slide show, my computer was handline 3473 threads!
- Many large programs (your web browsers!) need **multiple threads** to run. That's because they have so many moving parts!



Question:

When you run a program in Qt Creator, is a thread executing your code?

Answer:

Er... Yes, sort of!

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Er... Yes, sort of!

Yes, when you run a program in Qt, a thread encapsulating your code is being **executed**.

Answer:

Er... Yes, sort of!

Yes, when you run a program in Qt, a thread encapsulating your code is being **executed**.

However, a thread alone isn't enough to run your code!

Definitions

software
Programs and and abstractions (code). Not a physical entity.

hardware
Physical parts of a computer.

The hardware-software boundary

- A thread **alone** cannot run your program.
  - A thread is just **software** that is an **abstraction** for some code.
- A thread needs to work with the computer's **hardware** in order to run the code it encapsulates!

The hardware-software boundary

- A thread **alone** cannot run your program.
  - A thread is just **software** that is an **abstraction** for some code.
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... but what piece of hardware does this?

Definitions

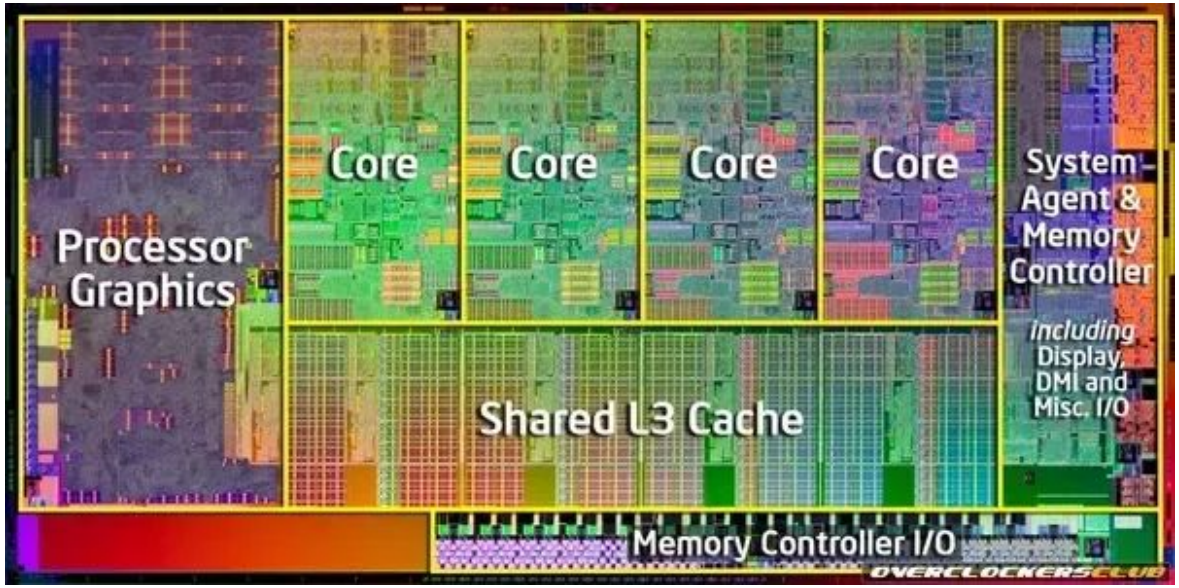
CPU (Central Processing Unit)

A piece of hardware responsible for executing instructions that make up a computer program

Core

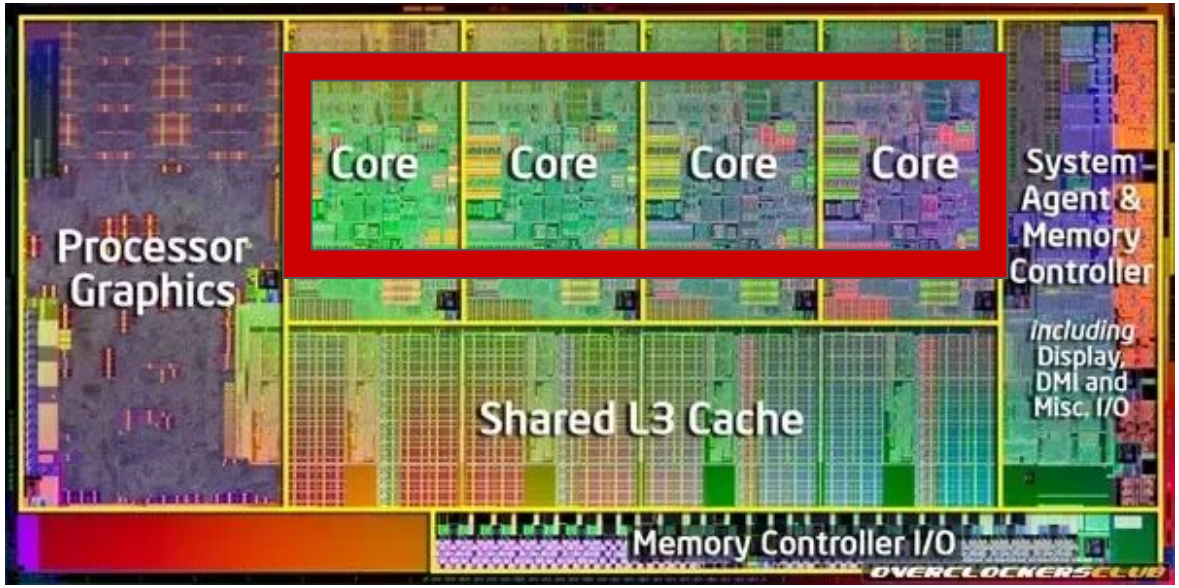
An individual processor inside of a **CPU**. Each **core** is able to execute code independently of other **cores**.

Inside a CPU…



Don’t worry about the other stuff -- we just care about the **cores!**

Inside a CPU…



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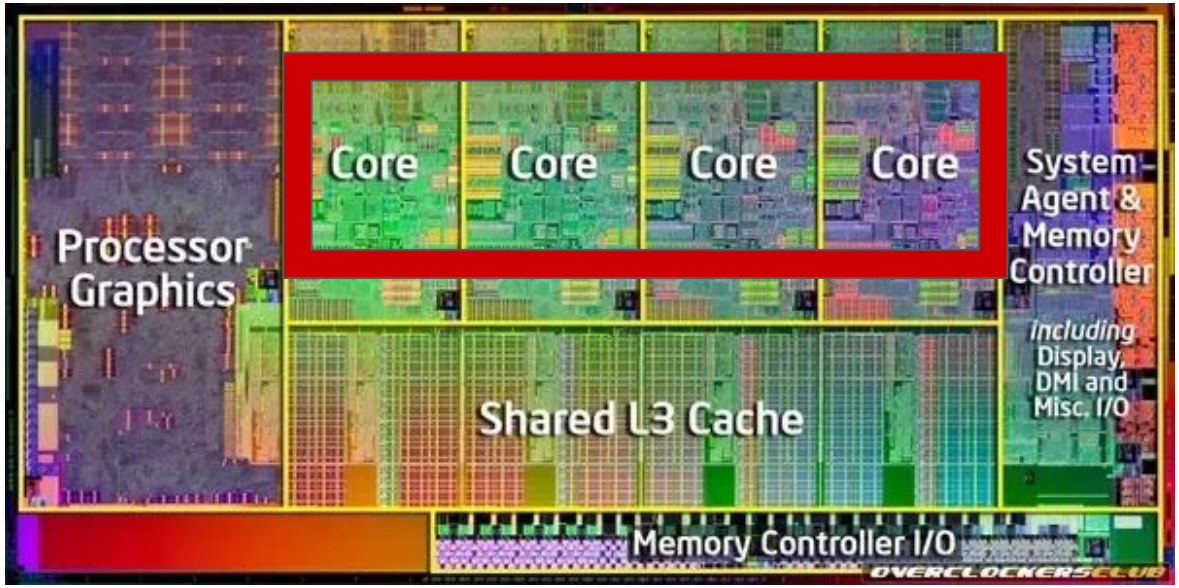
Inside a CPU…

How many concurrent programs can this CPU run?



Don’t worry about the other stuff -- we just care about the **cores!**

Threads ‘n cores

- In order for a **thread** to be able to execute some code, it must be running on a **CPU core.**
- If all **cores** are currently busy, a thread must **wait** for a **core** to free up before it can hop on that **core** and begin executing its own code!

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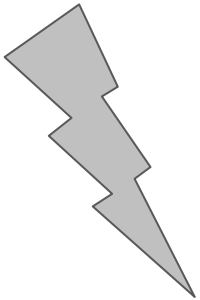
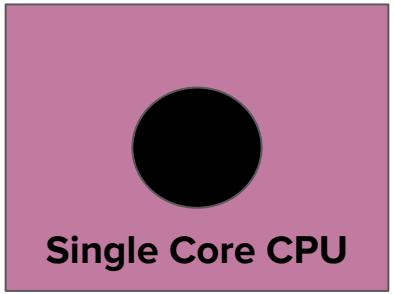


Thread 1



Let’s assume this computer has a CPU with only **one core.**

Threads ‘n cores

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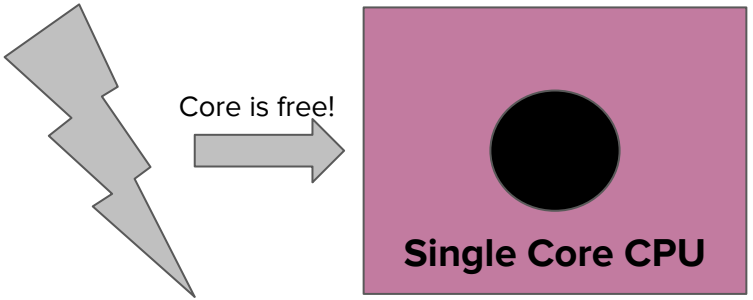

Question: if the core is free, how is anything getting done :o

Threads ‘n cores

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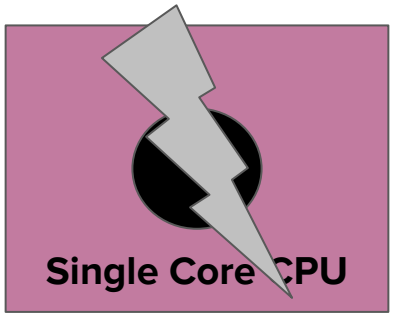

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Threads ‘n cores

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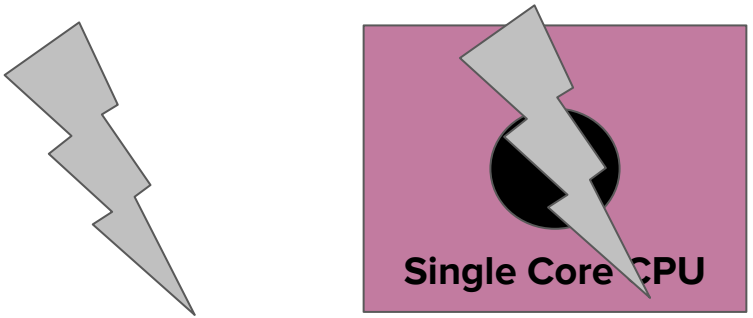

Thread 2

Thread 1

Threads ‘n cores

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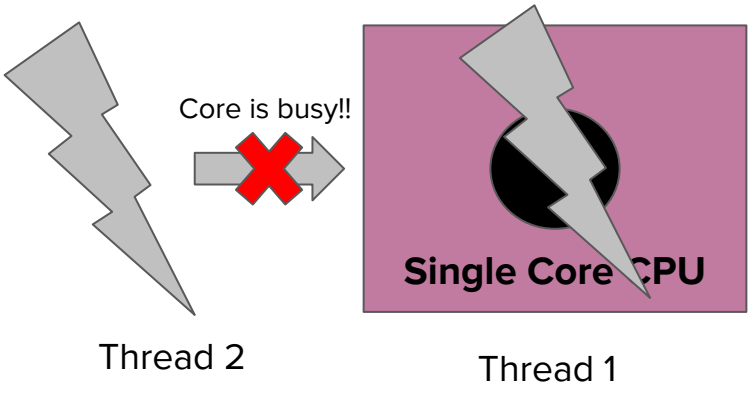

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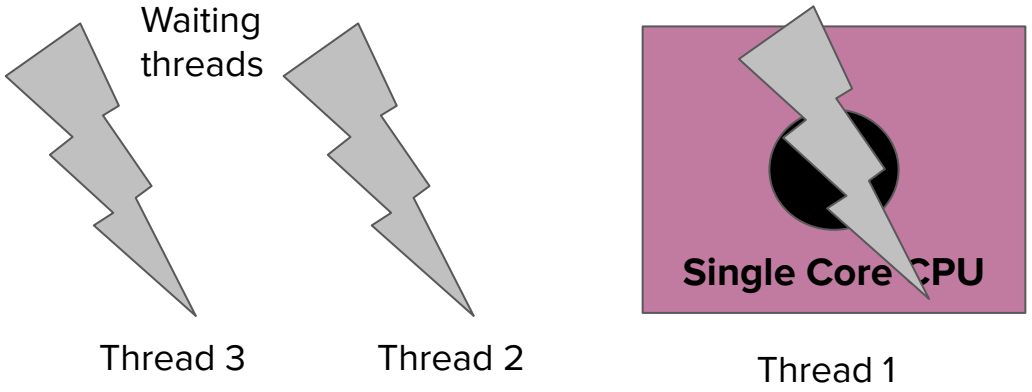


Question:

Who decides how long a thread should be able to run on a processor? Who decides which thread should run next?

What was running when the single-core was free in the example???

Definition

Operating System
Code that manages the relationship between a computer's **hardware** and **software.**

Thread Scheduling

- The **Operating System**, determines both **how long a thread should run** on a core, AND **which thread should run next.**
  - Want to learn how to implement these strategies? Take **CS140!**
- For the purposes of this lecture, let's assume that a **thread** will run on a **core** until its program terminates or it is **forced off** the **processor**.
  - There are many reasons why a **thread** may be booted from a **core**: sometimes the **operating system** deems a thread needs to vacate its spot, and other times a thread will voluntarily yield its core.

Code example

- Let’s take a break from all of this low-level jazz and write a simple program!
- Let’s say you wanted to revise your **A2 Search Engine** program by ~~cheating and~~ making it ping the internet with queries.
    - Such a task is called **I/O Bound**, because the performance bottleneck is the waiting that happens between sending your request and getting your data! (We call this, and anything involving communication with the outside world, **I/O**)

Code example

- Let's write a program that repeatedly executes the below **I/O bound function**. (Forget the search engine thing; that's just an example of such a task).

```
static void task (int input);
```

- I've already implemented **task** for you; all you need to do is call it repeatedly!

Code example

- Let's write a program that repeatedly executes an **I/O bound function**. (Forget the search engine thing, let's just say it's any old **I/O bound function**).
- I've already written the **I/O bound function** for you; all you need to do is call it repeatedly and store the many return values in a **Vector**.

- Let's do it!

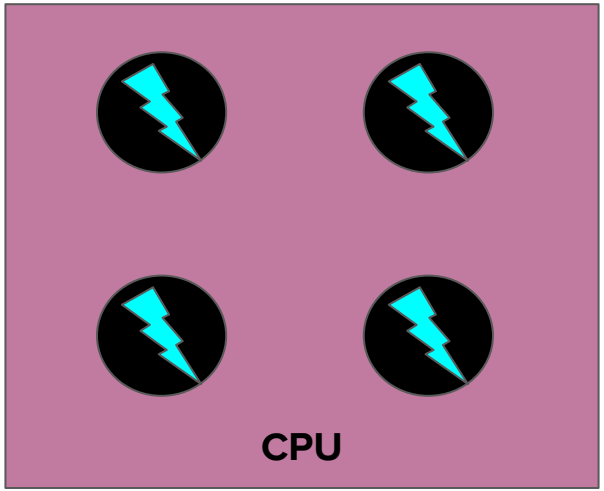
Code example

- What happened there?

Code example

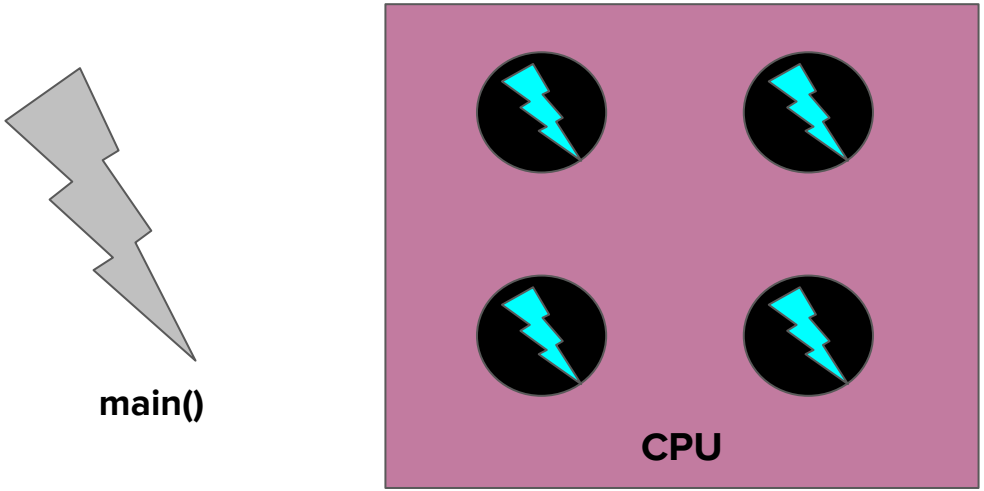
- What happened there?
  - Our code was slow as heck! This shouldn’t be surprising, however. Here’s what happened:

Code example: what happened?



Before you run your program, your **CPU** is probably chugging away at other tasks!

Code example: what happened?



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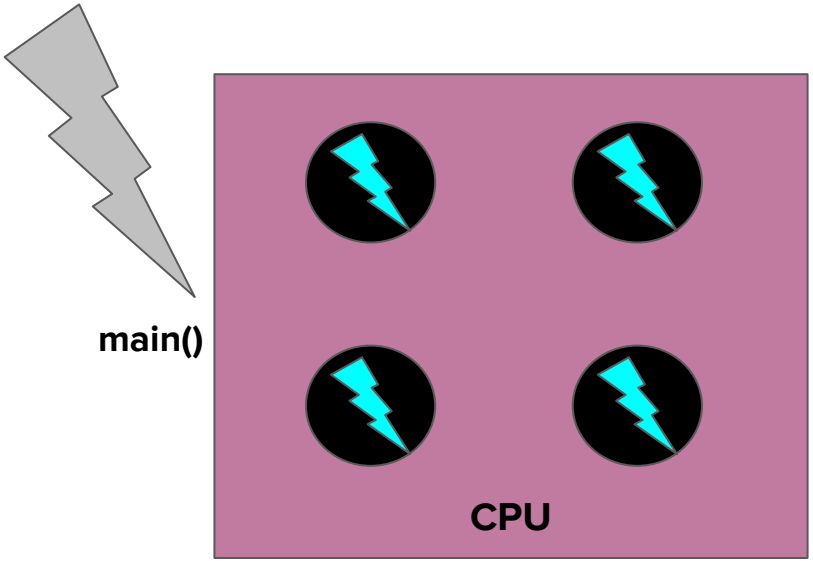
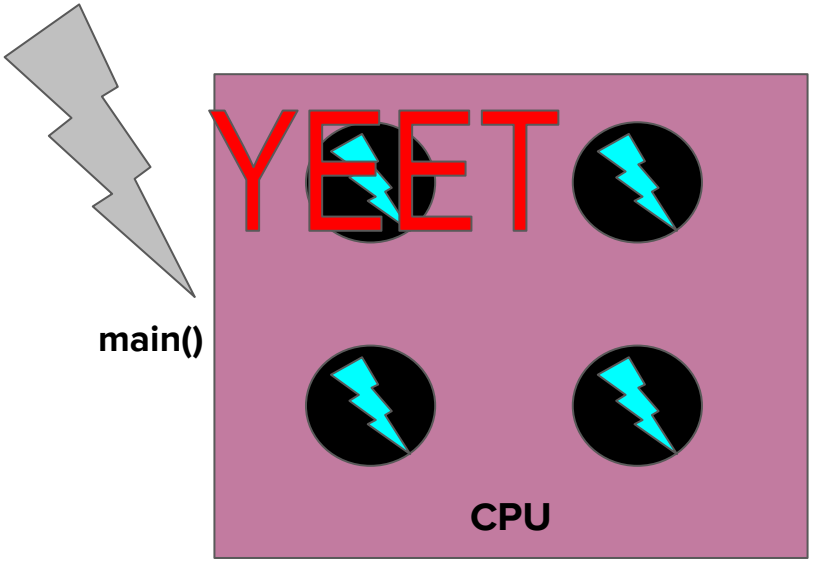


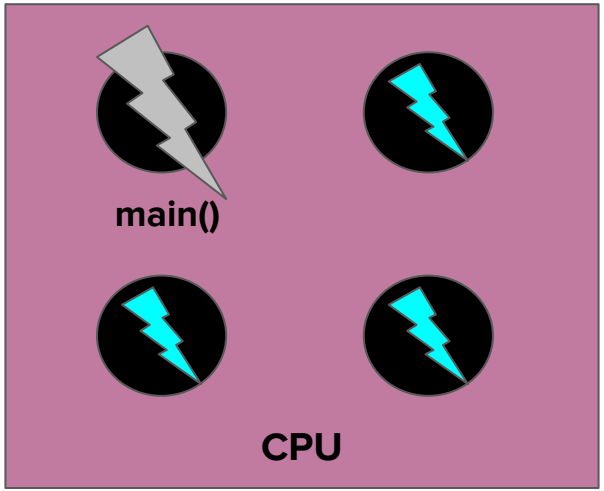
main() is a pretty important thread, so it has the power to boot another thread off a core!

Code example: what happened?



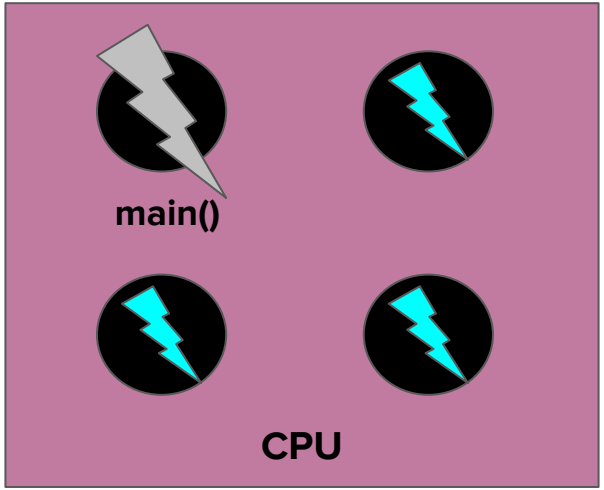
This transition is where your tuition money is going...

Code example: what happened?



Code example: what happened?

- When you call the **I/O bound** function **task()** from **main()**, the **thread** will remove itself from the processor, as it is waiting on an **I/O** and therefore unable to do any work. Another **thread** will take its place immediately.



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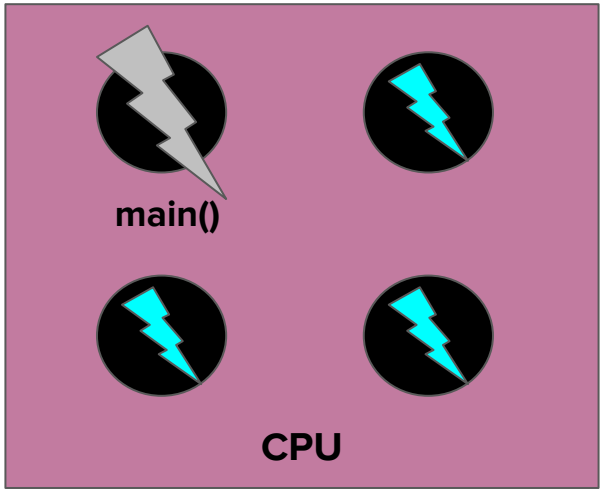

Question for yourselves: why does self-removal make sense here?

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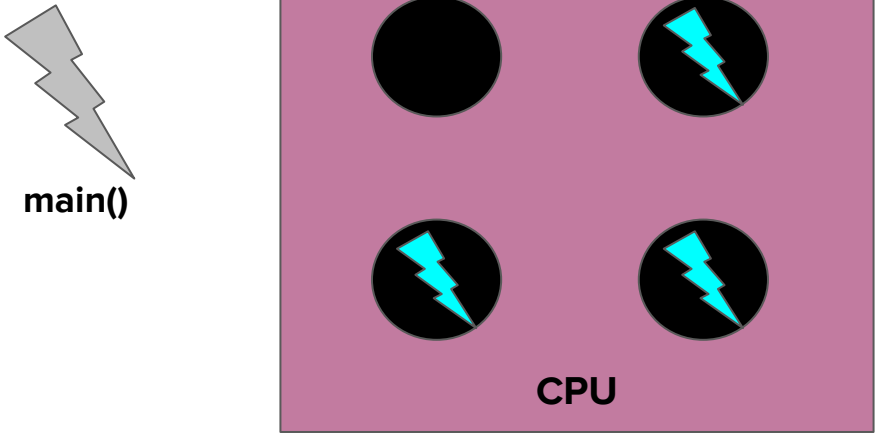

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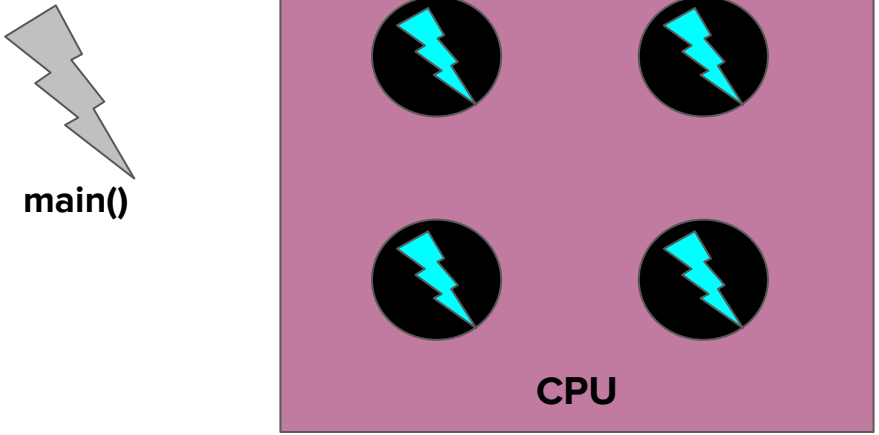
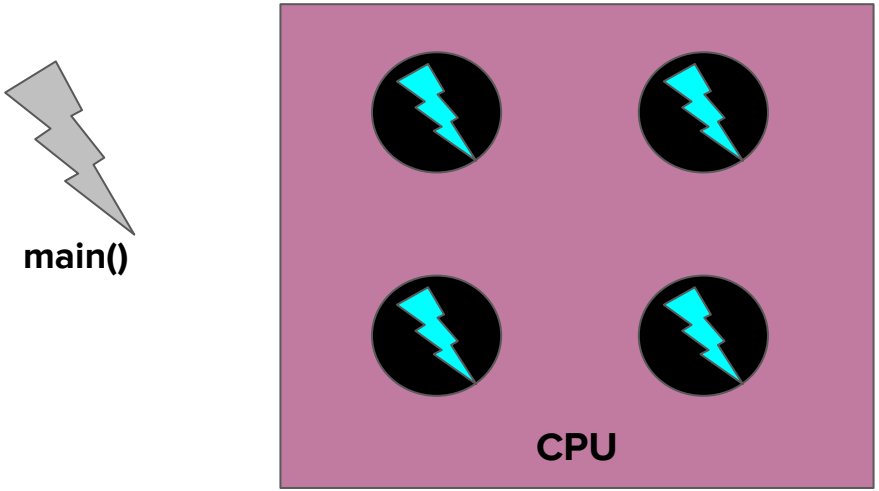


Code example: what happened?

- When the **I/O bound** task completes, your **thread** will attempt to get back on a core as soon as possible in order to continue (but its order in line is up to your **Operating System**)



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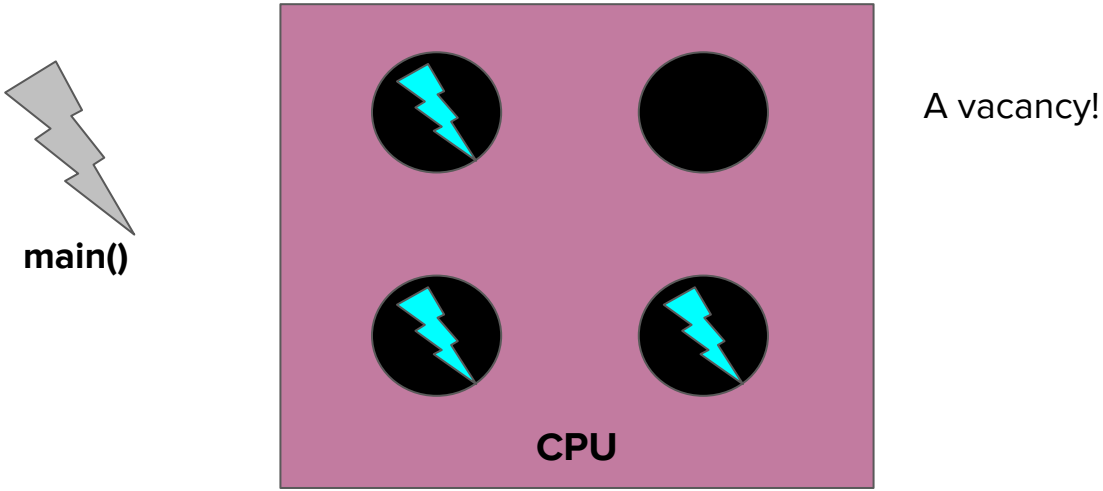

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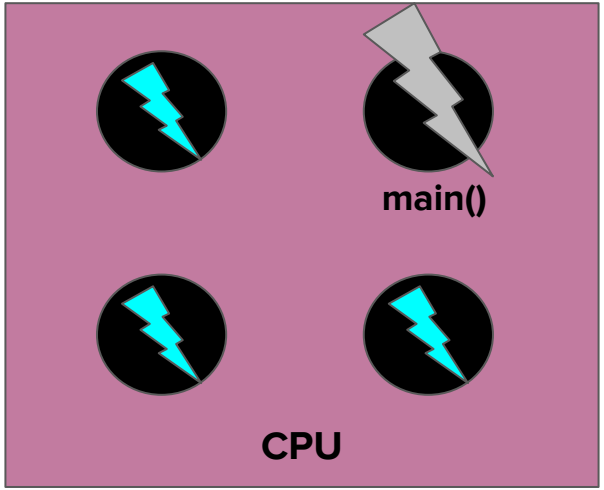
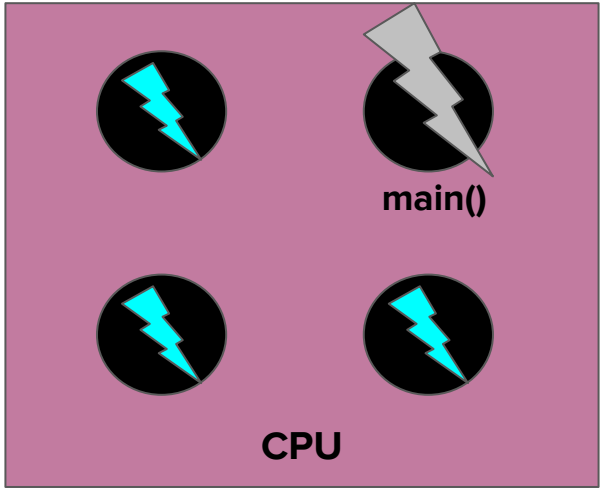


Note how we're **core agnostic**. This doesn't need to be the case in some OS schedulers.

Questions about these events?



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  - Can we do better?
  - But first...

Announcements

Announcements

- Make sure to sign up for a final presentation time slot if you haven't already!
- Assignment 6 is due **tomorrow at 11:59pm PDT**. Remember that this is a hard deadline and there is no grace period!
- In lecture tomorrow, we will be having an "Ask Us Anything" component for the last part of lecture. We'll be collecting questions in advance as well – if you have any burning inquiries on your mind, go ahead and fill out this Google form!
- Remember that there is **no section this week**!

Back to the action!

Code example: what happened?

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- In the words of a sectionee last quarter...
  - *“Let’s parallelize this bad boy”*

Multithreading

- Let’s try and implement this same routine using **multithreading**.
  - That means we’ll try and use multiple threads instead of one in order to **parallelize** the workflow!

Multithreading

- Let's try and implement this same routine using **multithreading**.
  - That means we'll try and use multiple threads instead of one in order to **parallelize** the workflow!
- Before you can make threads, you'll **first** need to:

```
#include <thread>
```

- Bonus points: this is a **standard c++** library, so no Stanford-only woes!

Multithreading

- To instantiate a thread, it's pretty simple!

```
thread newthread = thread(funcName);
```

- This should look pretty vanilla, except for the parameter!
    - *funcName* is the name of a the function you want to execute!

Multithreading

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- This should look pretty vanilla, except for the parameter!
    - *funcName* is the name of a the function you want to execute!
    - Let's make new threads that encapsulate **task()!**

Thread joining

- Woah woah woah, hold your horses, eager beaver.
- **As soon as you instantiate a thread, it begins to run**.

Thread joining

- Woah woah woah, hold your horses, eager beaver. Two things to think about:
  - **As soon as you instantiate a thread, it begins to run**. Be sure you're ready before you dispatch them.
  - Threads are somewhat resource intensive, so when we dispatch them, we need to keep track of them so that we can clean up their memory once they've completed.
    - This is very much like the **new** and **delete** keywords you've used!

Thread joining

- After you've spawned a thread, simply call **threadName.join()** to clean it up.
  - This usually requires storing your threads in a collection! **Note**: Stanford's Vector can't store threads because it needs an update :(

Questions about creating / joining threads?

- You can call join() from your **main()** thread immediately after spawning the thread. Don’t worry, **main()** will wait for your thread to finish :).
- To pass params to a thread, just include them as the subsequent parameters.

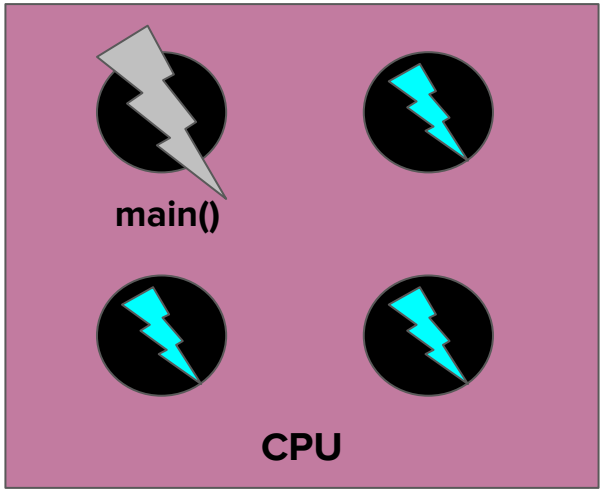
Let’s Parallelize!

What happened?

- Wow, that was super fast!

What happened?

- When our **main()** thread spawned up a new **thread**, the **new thread** might have taken a new core on the processor!
  - note* we don’t know exactly what happened, but it could have done this!



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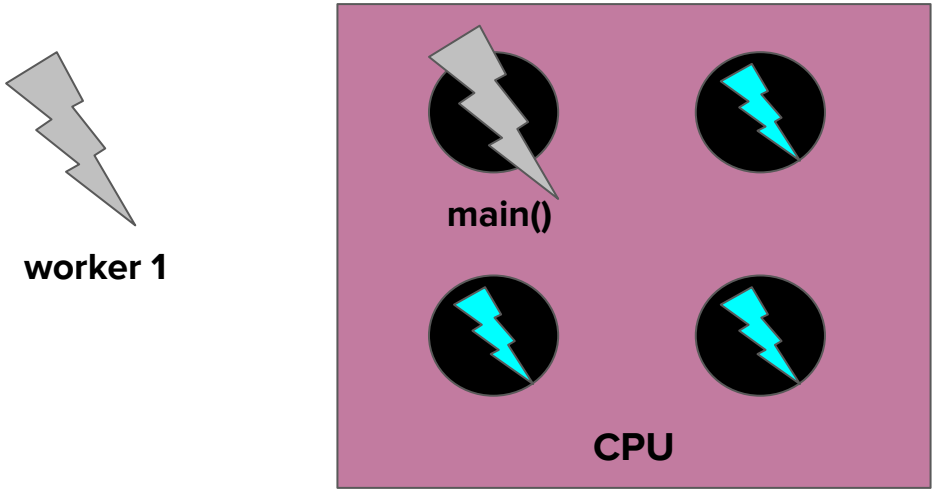

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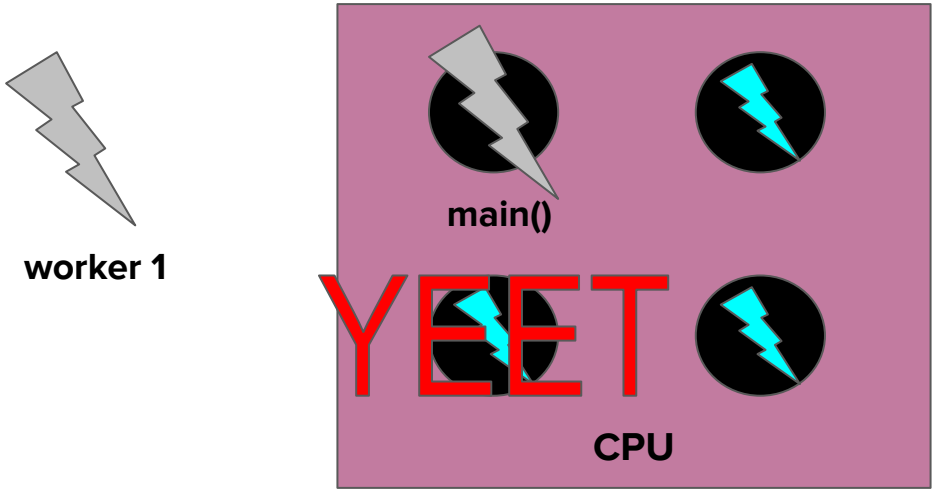

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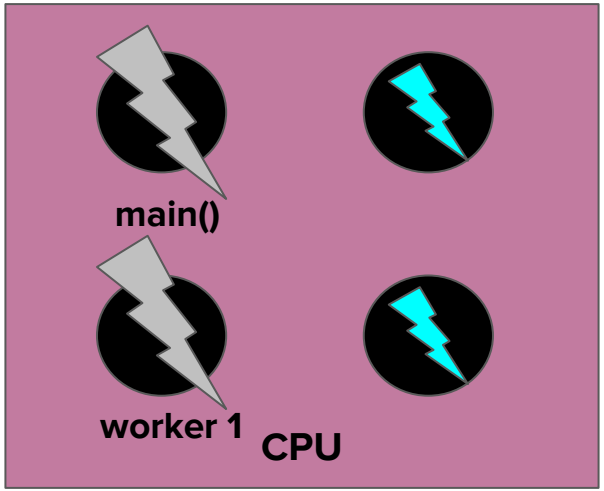
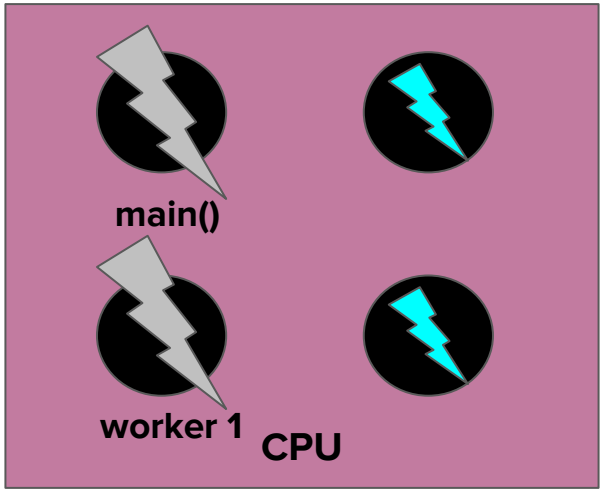


What happened?

- Note now that both **main()** and **worker 1** are running **concurrently!**



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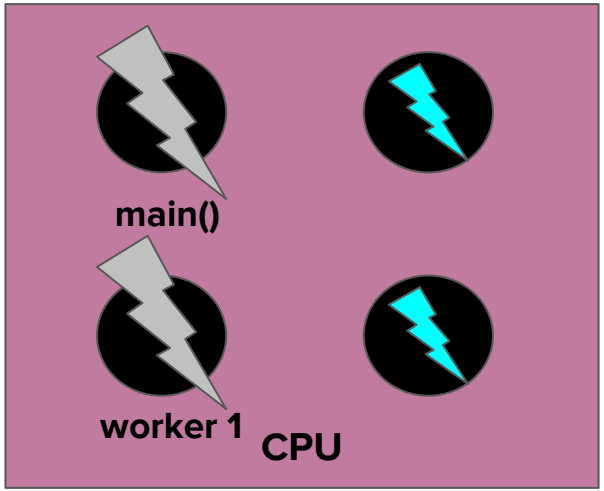

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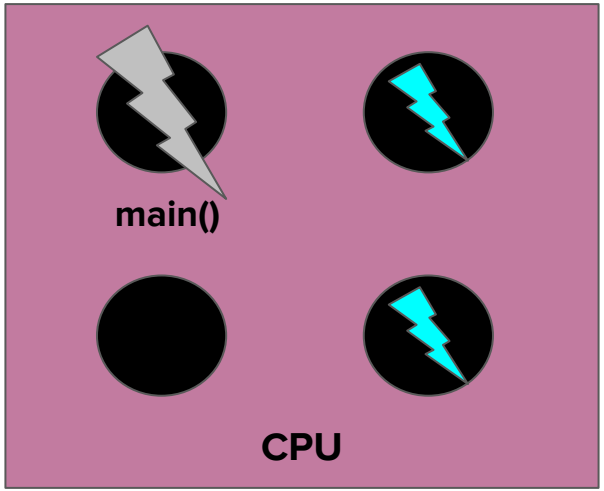

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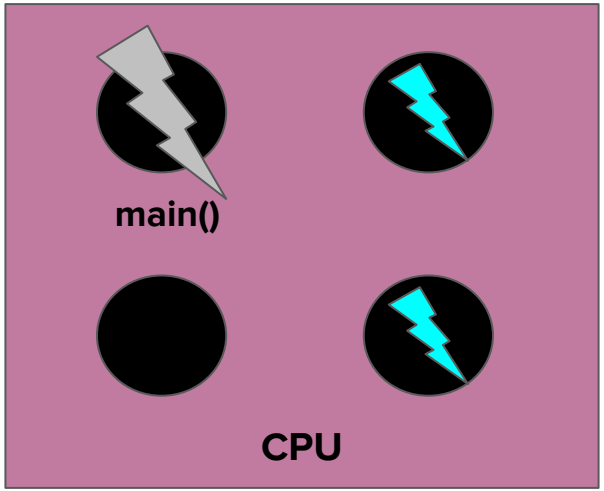

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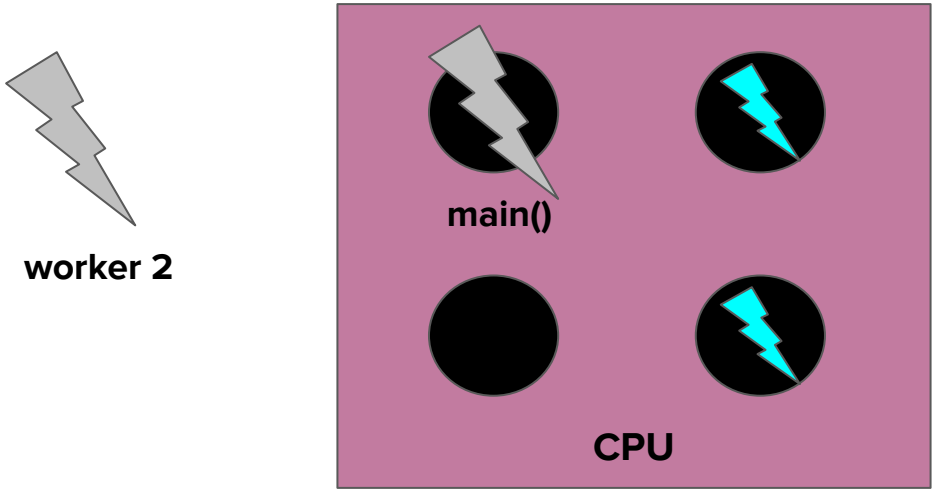
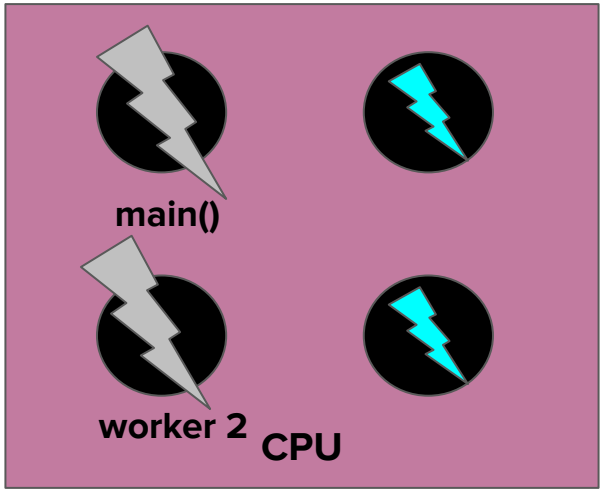


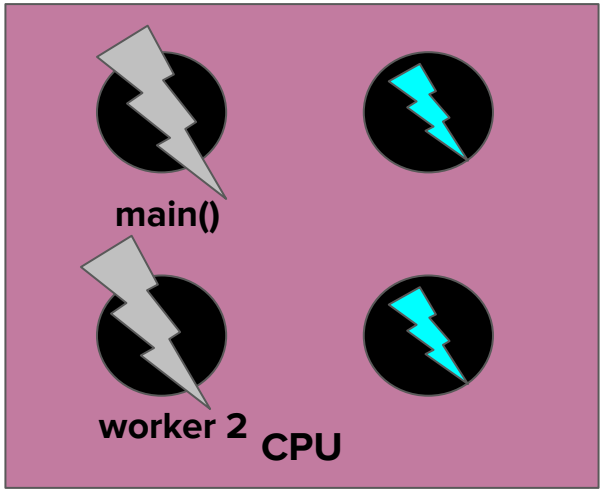
What happened?

- **Worker 1** will start its **I/O** and **remove itself from the core, getting replaced**
- But lo! Who is that in the distance?
- While **worker 1** was waiting for its I/O, **main()** was busy spinning up new threads!



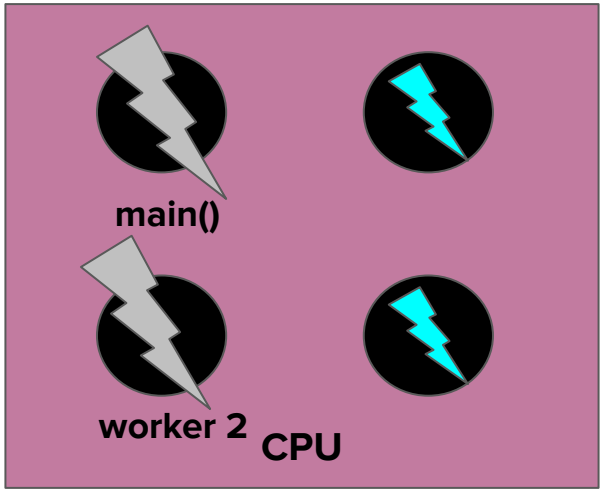
What happened?

- This process will continue -- each **worker thread** will only need to be on a core for a fraction of a second, just to set up the **I/O**, and then it can leave the processor and let a new **worker thread** set up its **I/O**.



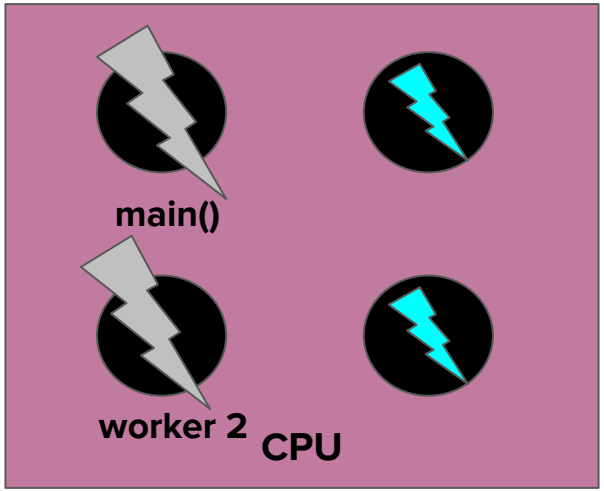
What happened?

- A similar thing will happen at completion time!
  - Each **thread** will be able to retake a core, but the core will only be needed for a few instructions! Then the **task()** will finish, and a new **thread** will try and complete!



What happened?

- A fair warning -- you can’t predict which worker thread will begin working first! It might seem like **worker 1** should always start first, but the OS and CPU work in unpredictable ways!



What happened?

- The example you saw was blazing fast because the **task** at hand only needed to be on the processor for a **short period of time**.
- As you can see, the process of yielding a core to another worker takes an almost imperceptible amount of time!
  - That’s because your OS is doing it constantly :o
- Parallelization is less successful when you don’t have long **I/O** waits.
  - Take CS140 to find out more :)

Questions?

Bonus! Race Conditions

- Remember when I said that we can’t really determine the order that threads will run in? Let’s show that!
- Let’s add **logging** to our code to show the order that threads show up!
- It’s easy! Just add a print statement inside inside **task()** and keep a counter variable!

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- Let’s try it!

woah...

Definition

Race Condition

A bug that is the product of two threads “racing” against each other and operating on the same state in the incorrect order.

Bonus: Race Conditions

- Congratulations, you've experienced your first **race condition!**
- It turns out that **cout** is not **thread-safe**, meaning that it will not behave predictably if you have multiple threads calling it at the same time!
    - Every time you printed to the console, you had some jumbling of all 10 cout statements!

Bonus: Race Conditions

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    - Every time you printed to the console, you had some jumbling of all 10 cout statements!

- How can we fix this?

Definition

Atomic

A state that can only be observed or superseded **before** or **after** an operation occurs, **not during.**

Mutex

- To make code **atomic**, we can use something called a **mutex.**
  - Sounds like Mut(ual) Ex(clusion)!

Mutex

- To make code **atomic**, we can use something called a **mutex.**
  - Sounds like Mut(ual) Ex(clusion)!
- To make a mutex, you'll need this library:

```
#include <mutex>
```

- and you'll want to declare a single mutex like this:

```
mutex m;
```

Mutex

- You'll want to make a **single** mutex, and pass it as a **pointer** to your worker threads.

```
thread t = thread (funcName, &mutexName);
```

- In order to make code **atomic**, all you need to do is wrap the code in question around these two statements:

```
mutexName->lock();

mutexName->unlock();
```

Mutex

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mutexName->lock();

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- When you **lock** a **mutex**, any other threads trying to lock that **mutex** will be forced to wait until you **unlock** it.
    - Once you **unlock**, the **Operating System** decides which thread can **lock** the **mutex** next!

Let’s try it!

We’re still not done!?

- Why is everything 10?

```
Setting the program up...
Let's process 10 numbers!
Starting in 3...
2...
1...
GO!!
Hello from worker 10
Hello from worker 10
Hello from worker 10
Hello from worker 10
Hello from worker 10
Hello from worker 10
Hello from worker 10
Hello from worker 10
Hello from worker 10
Hello from worker 10
All done! The total time spent working was 1353 milliseconds (roughly 1 second!)
```

We’re still not done!?

- Remember how we passed **id** by reference? (using a pointer)
- The problem is that **the threads <u>share</u>** the variable “i”
- This actually indicates that **main()** finished the for loop that created **all ten threads** (therefore increasing **i** to the max value) before a **single worker could complete**.
    - This should make sense because even the first worker had to wait a full second before it could print anything!

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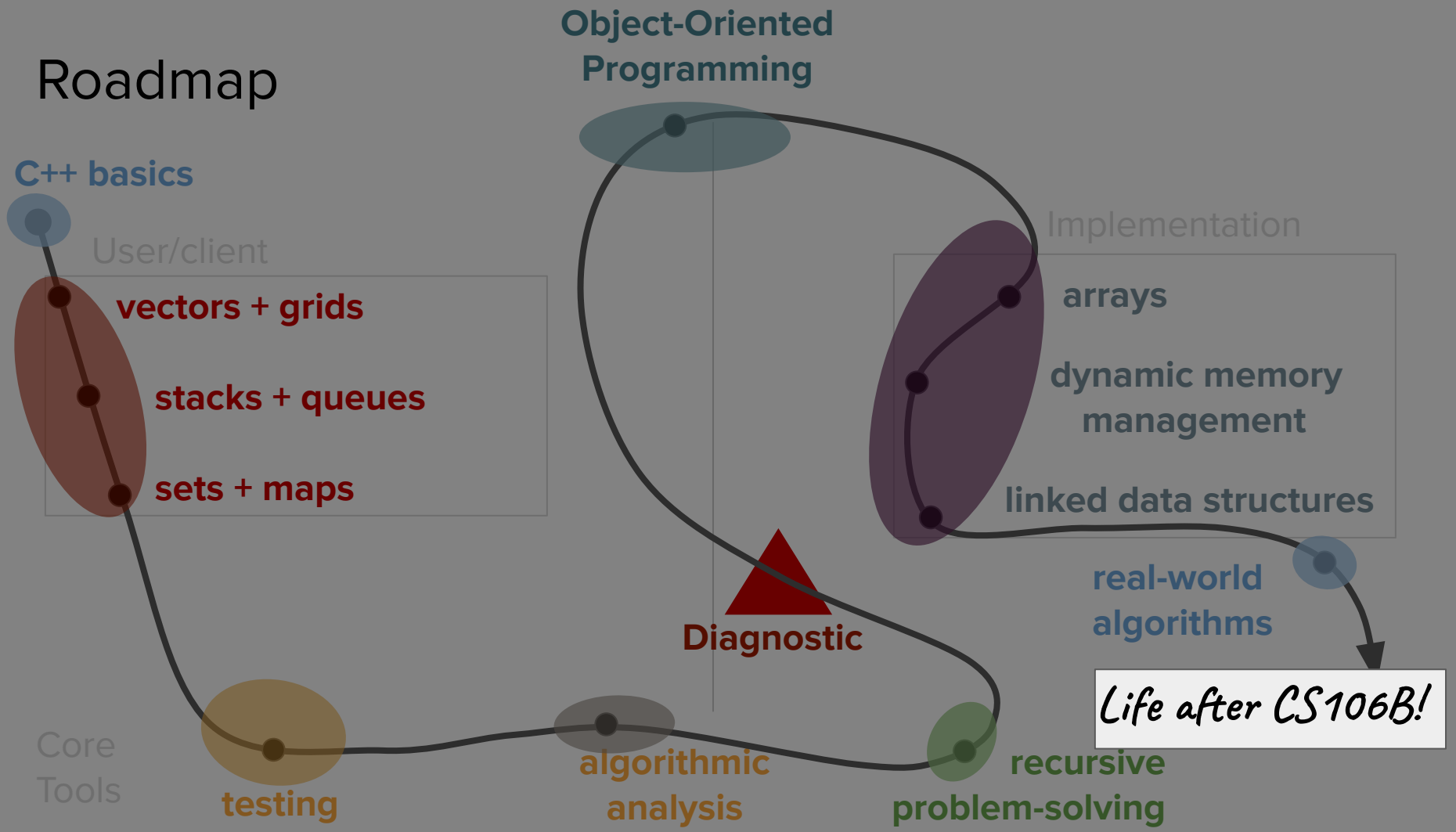
- How do we fix this?

Final thoughts

- Multithreading is an incredibly powerful tool that lets you parallelize work among your CPU's cores.
- Threads are a fundamental building block of computing that play an important role in **Operating Systems!**
- When using multiple threads, be wary of **any** data that is **shared** between them.
  - Using a **mutex** allows you to enforce **atomicity** in sections of code, but sometimes even that isn't enough!
  - If all of your code is **atomic**, there's no parallelization at all!
- If you liked this topic, CS110 and CS140 (and CS149) go into more depth :)

What’s next?

Roadmap


Object-Oriented Programming
C++ basics
User/client
vectors + grids
stacks + queues
sets + maps
Implementation
arrays
dynamic memory management
linked data structures
real-world algorithms
Diagnostic
Life after CS106B!
Core Tools
testing
algorithmic analysis
recursive problem-solving