Multithreading and Parallel Computing

What’s an example of multitasking that you do in your everyday life?
Today’s question

How can we harness the cores in our computer in order to parallelize a workload?
Today’s question: How can we harness the cores in our computer in order to parallelize a workload safely?
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How can we harness the cores in our computer in order to parallelize a workload safely?

Multiple cores?

Parallelize work??
Today’s topics

1. Review (short!)
2. Some Computer Architecture (Threads & Processors)
3. Multithreading Perils (If we have time!)
Review (short!)
(simple code flow)
How code is run

- At a *high level*, how does the computer run your code?
  - Logically, it should interpret your code from top to bottom!
How code is run

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

...but who is it? What’s the abstraction that encapsulates and executes your main() function?
**Definition**

**thread**
An abstraction that represents a sequential execution of code.
Definition

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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.”
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.
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 \texttt{main()}, which might call other functions, which might return to \texttt{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 \texttt{main()} to the bottom.
  - The flow would almost look 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?
Thread Examples

- Do you have a web browser open?

*unless you’re using Chrome, sort of.*
Thread Examples

- Are you watching TikToks during lecture?
Thread Examples

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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 handling 3473 threads!
Thread examples

● Right now, your computer is executing a bunch of threads!
  ○ At the time of making this slide show, my computer was handling 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!
Answer:

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 abstractions (code). Not a physical entity.

**hardware**
Physical parts of a computer.
The hardware-software boundary

- A thread **alone** cannot run your program.
The hardware-software boundary

- A thread **alone** cannot run your program.
  - A thread is just **software** that is an **abstraction** for some code.
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

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  - 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!

... 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!
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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.
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!
Threads ‘n cores

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Let’s assume this computer has a CPU with only **one core**.
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- 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!
Question:

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

What program 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.
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- A **thread** will run on a **core** until its program terminates or it is **forced off** the **processor** by the Operating System.
Thread Scheduling

- The **Operating System**, determines both **how long a thread should run** on a core, AND **which thread should run next**.
- A thread will run on a **core** until its program terminates or it is **forced off** the **processor** by the Operating System.
  - 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!
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Let’s say I wanted to call this non-computational, but expensive function a certain number of times:

```c
void task (int id);
```
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void call_function(int id);
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Code example

- I’ve already implemented **task** for you; all you need to do is call it repeatedly and see how long it takes!

```c
void task (int id);
```
Code example

- I’ve already implemented **task** for you; all you need to do is call it repeatedly and see how long it takes!
- **Let’s code it up!**

```c
void task (int id);
```
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?

main()
Code example: what happened?

`main()` is a pretty important thread, so it has the power to boot another thread off a core!
Code example: what happened?

main()

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 `main()` 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.
Code example: what happened?

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Question for yourselves: why does self-removal make sense here?
Code example: what happened?

- When the **I/O bound** task completes, the **main 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**).
Code example: what happened?

- When the I/O bound task completes, the main 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).

A vacancy!

main()
When the **I/O bound** task completes, the **main 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**).

Note how we’re **core agnostic**. This doesn’t need to be the case in some OS schedulers.
Questions about these events?
Code example: what happened?

- This process of getting on a **core**, removing ourselves and waiting, and reacquiring a **core** happened **every time** we called `task()`
Code example: what happened?

- This process of getting on a core, removing ourselves and waiting, and reacquiring a core happened every time we called `task()`.
- In other words, every time we call `task()` we have to deal with I/O wait times that don’t depend on how fast our CPU is.
Code example: what happened?

- This process of getting on a core, removing ourselves and waiting, and reacquiring a core happened every time we called task().
- In other words, every time we call task() we have to deal with I/O wait times that don’t depend on how fast our CPU is.
  - Can we do better?
Idea: 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!
Idea: 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!
Idea: 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 function you want to execute!
Idea: Multithreading

- To instantiate a thread, it’s pretty simple!
  
  \[
  \text{thread newthread} = \text{thread}(funcName);
  \]

- 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()`, it’s not that hard... right?
Thread joining

- Woah woah woah, hold your horses, eager beaver:
Thread joining

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  - 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.
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- **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.
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 :( 
More 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 :).
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- 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 in the `thread()` instantiation.
Questions so far?
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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- 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!
What happened?

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

- **Worker 1** will start its I/O and **remove itself from the core**, getting replaced.
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- But lo! Who is that in the distance?
What happened?

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- **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?

- At this point, we’re here in the code:

```java
thread arr[kArrSize];
for (int i = 0; i < kArrSize; i++) {
    arr[i] = thread(task, i);
}
for (int i = 0; i < kArrSize; i++) {
    arr[i].join();
}
```
What happened?

- At this point, we’re here in the code:

```cpp
thread arr[kArrSize];
for (int i = 0; i < kArrSize; i++) {
    arr[i] = thread(task, i);
}
for (int i = 0; i < kArrSize; i++) {
    arr[i].join();
}
```

Check your understanding: What are the worker threads doing right now?
What happened?

- 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.
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What happened?

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- 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, because then task completion depends on chip speed!
  - Take an Operating Systems class to find out more :}


Questions?
Bonus! Race Conditions

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  - Recall that we can add parameters to our thread instantiation by simply appending the parameter to our thread instantiation

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thread newthread = thread(funcName, param1);
```
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```python
thread newthread = thread(funcName, param1);
```

- 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!
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- 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!
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.
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!

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How can we fix this?
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How can we fix this? **Take a systems class :D**
Any Last Questions?
What’s next?