Concurrency: Intro and Threads

CSE 333 Summer 2020

Instructor: Travis McGaha

Teaching Assistants:

Jeter Arellano Ramya Challa Kyrie Dowling
Ian Hsiao Allen Jung Sylvia Wang

Poll Everywhere pollev.com/cse33320su

How far are you in HW4?

A. I have passed the test_suite
B. I'm past ServerSocket
C. I'm working on ServerSocket right now
D. I have read the spec and some of the code
E. I haven't looked at it yet
F. I didn't submit / I prefer not to say

Side question:
Favourite CSE 333 topic so far?

Administrivia

- Exercise 16 due date pushed back to Friday (08/14)
  - Useful for understanding how to do ServerSocket in HW4

- HW4 due two Thursdays from now (08/20)
  - You can use ***two*** late days on HW4.

- Exercise 17 to be released Friday.
  - Due Monday 8/17 @ 10:30 am
  - 🎉 The Last Exercise 🎉

Some Common HW4 Bugs

- Your server works, but is really, really slow
  - Check the 2nd argument to the `QueryProcessor` constructor
- Funny things happen after the first request
  - Make sure you're not destroying the `HTTPConnection` object too early (*e.g.* falling out of scope in a while loop)
- Server crashes on a blank request
  - Make sure that you handle the case that `read()` (or `WrappedRead()`) returns `0`

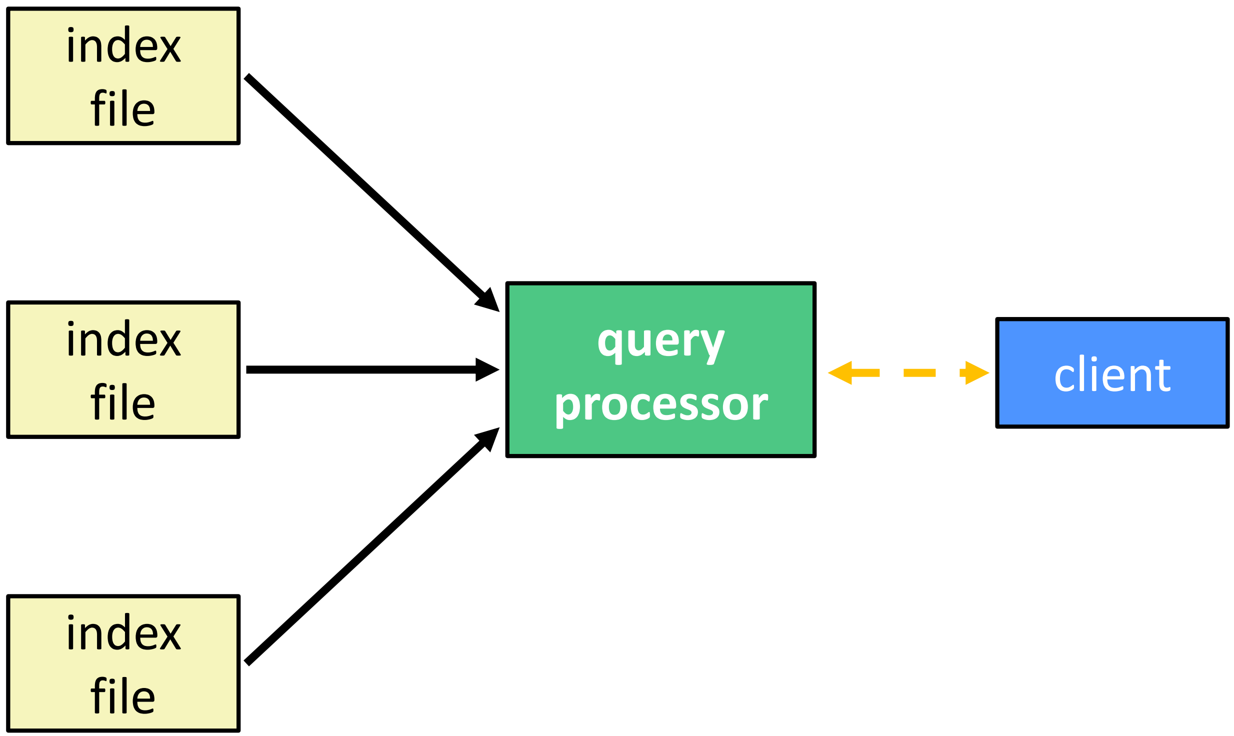
Lecture Outline

- **From Query Processing to a Search Server**
- Intro to Concurrency
- Threads and other concurrency methods
- Search Server with pthreads

Building a Web Search Engine

- We have:
  - A web index
    - A map from <*word*> to <*list of documents containing the word*>
    - This is probably *sharded* over multiple files
  - A query processor
    - Accepts a query composed of multiple words
    - Looks up each word in the index
    - Merges the result from each word into an overall result set

Search Engine Architecture

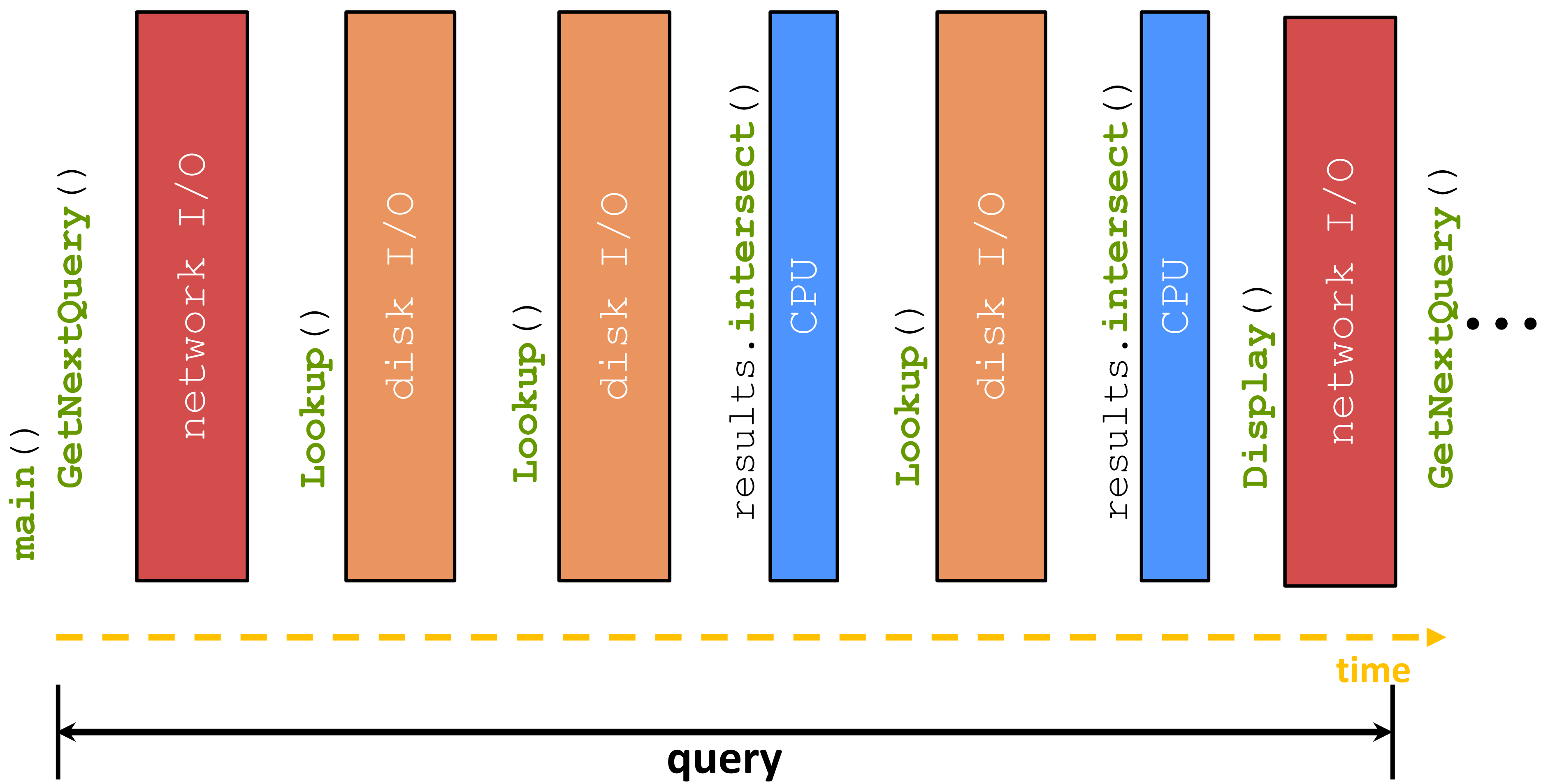


Search Engine (Pseudocode)

```
doclist Lookup(string word) {
  bucket = hash(word);
  hitlist = file.read(bucket);   ← Disk I/O
  foreach hit in hitlist {
    doclist.append(file.read(hit));
  }
  return doclist;
}

main() {
  SetupServerToReceiveConnections();
  while (1) {
    string query_words[] = GetNextQuery();   ← Network I/O
    results = Lookup(query_words[0]);
    foreach word in query[1..n] {
      results = results.intersect(Lookup(word));
    }
    Display(results);   ← Network I/O
  }
}
```

Execution Timeline: a Multi-Word Query



What About I/O-caused Latency?

- Jeff Dean’s “Numbers Everyone Should Know” (LADIS ‘09)

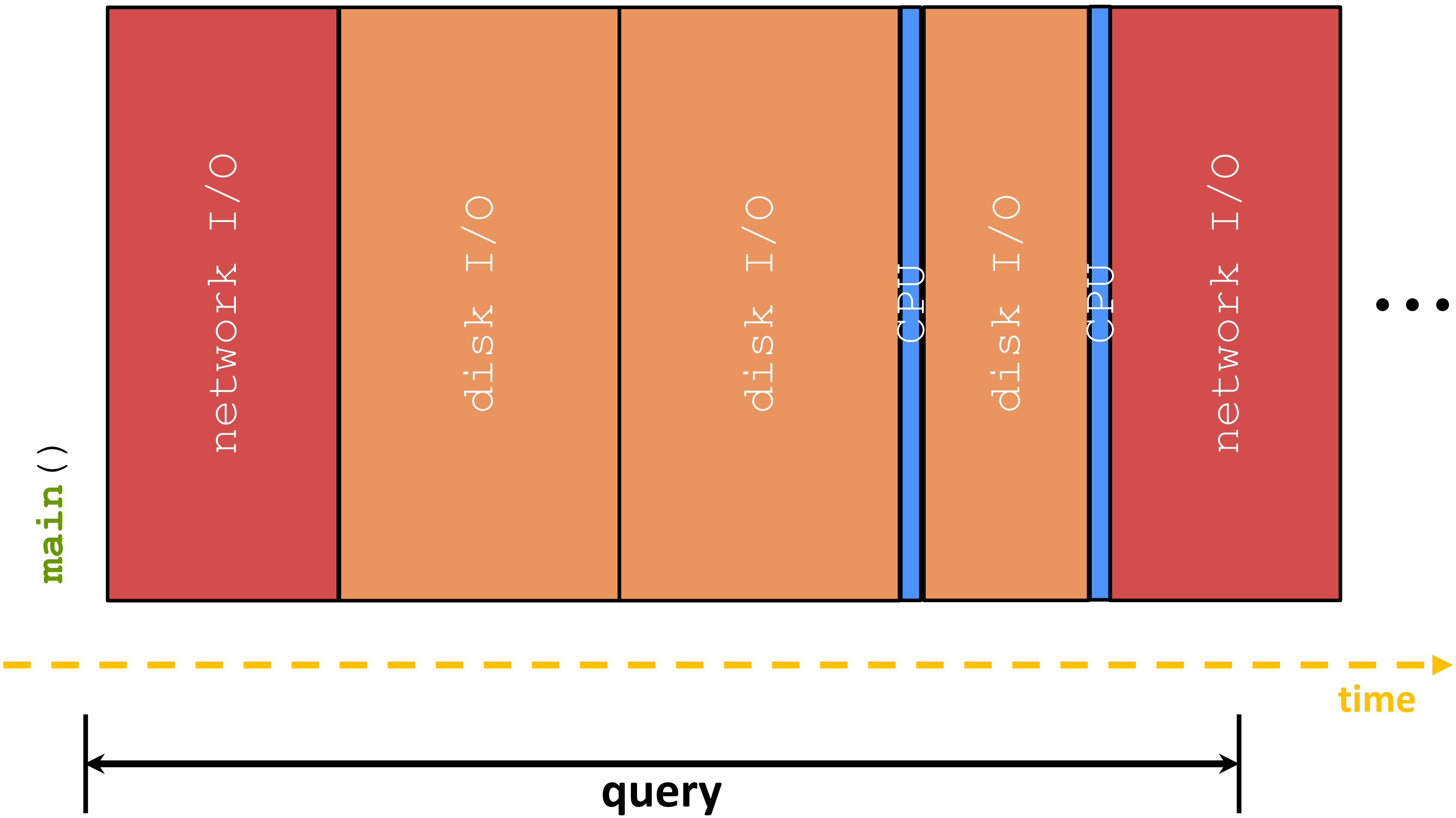
Numbers Everyone Should Know

L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	100 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	10,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns
Disk seek	10,000,000 ns
Read 1 MB sequentially from network	10,000,000 ns
Read 1 MB sequentially from disk	30,000,000 ns
Send packet CA->Netherlands->CA	150,000,000 ns

Google

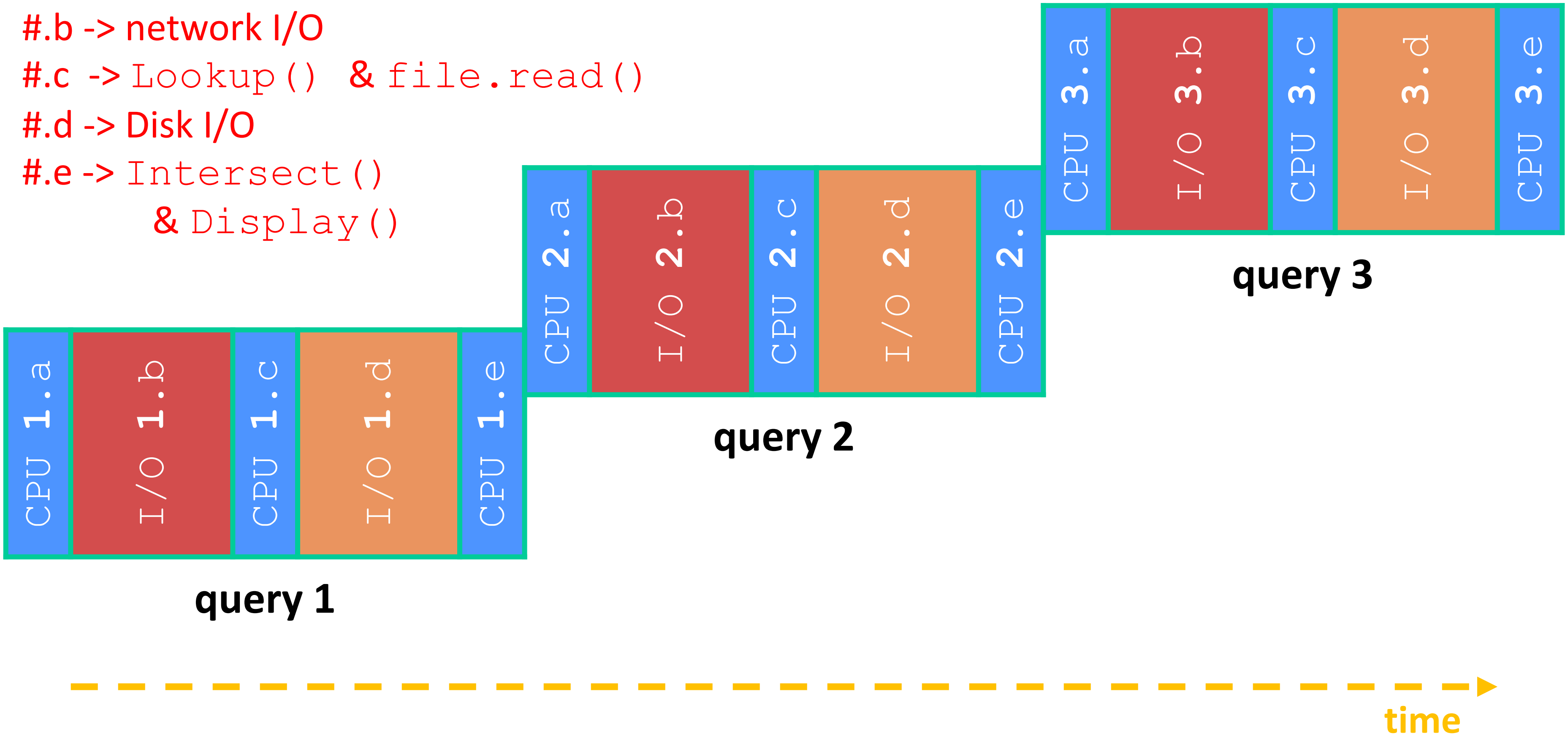
Execution Timeline: To Scale

Model isn't perfect:
Technically also some cpu usage to setup I/O.
Network output also (probably) won't block program .....

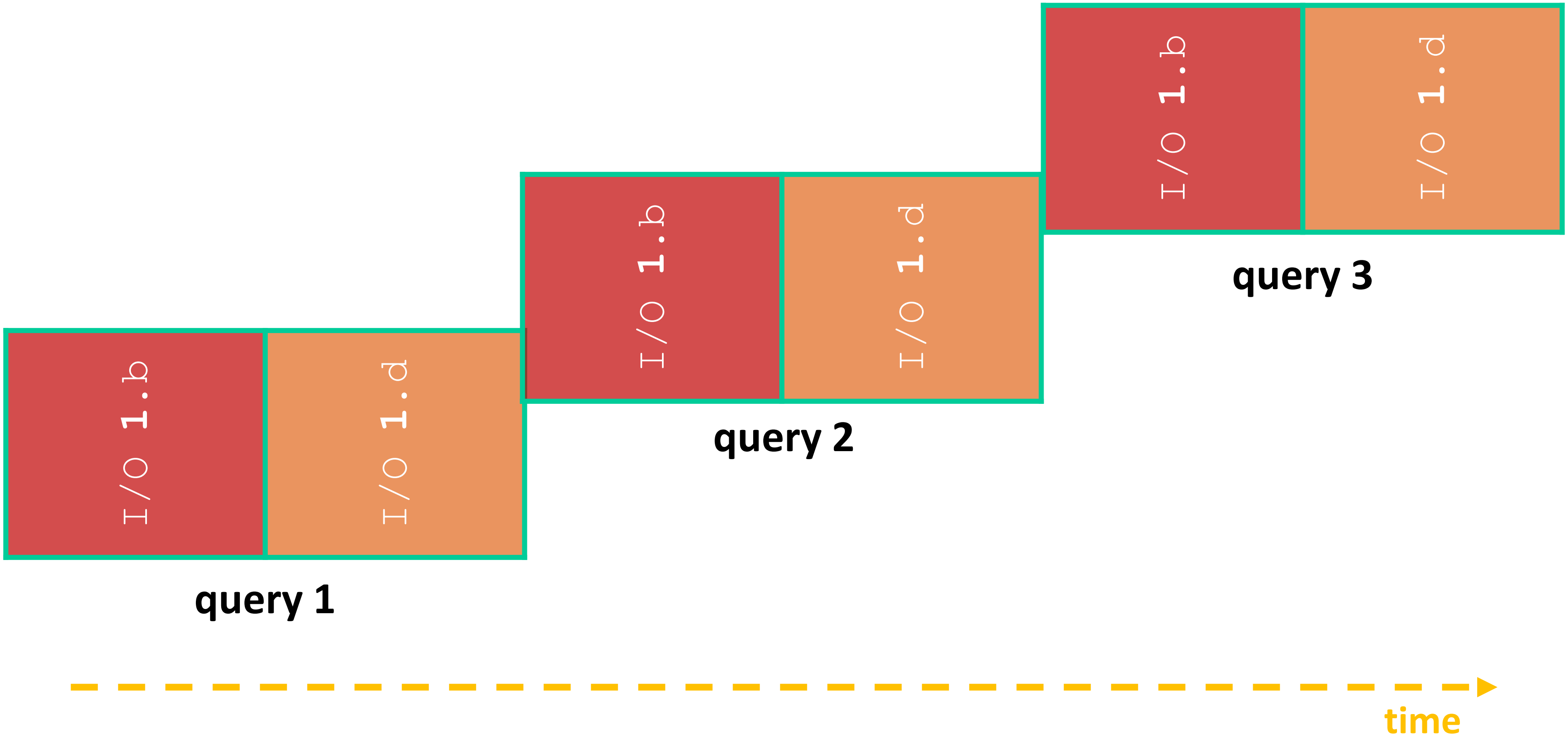


Multiple (Single-Word) Queries

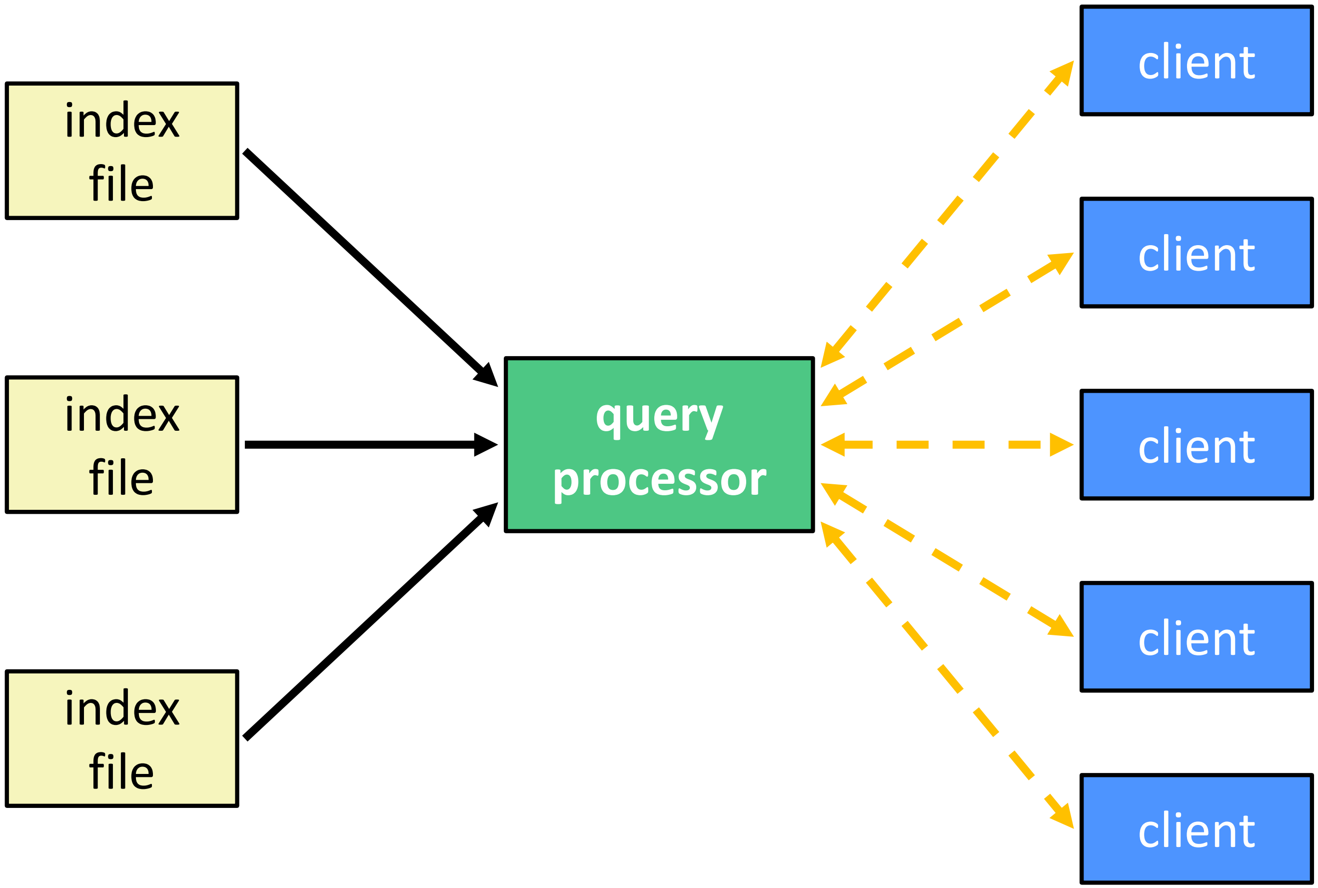
is the Query Number
#.a -> `GetNextQuery()`
#.b -> network I/O
#.c -> `Lookup()` & `file.read()`
#.d -> Disk I/O
#.e -> `Intersect()` & `Display()`



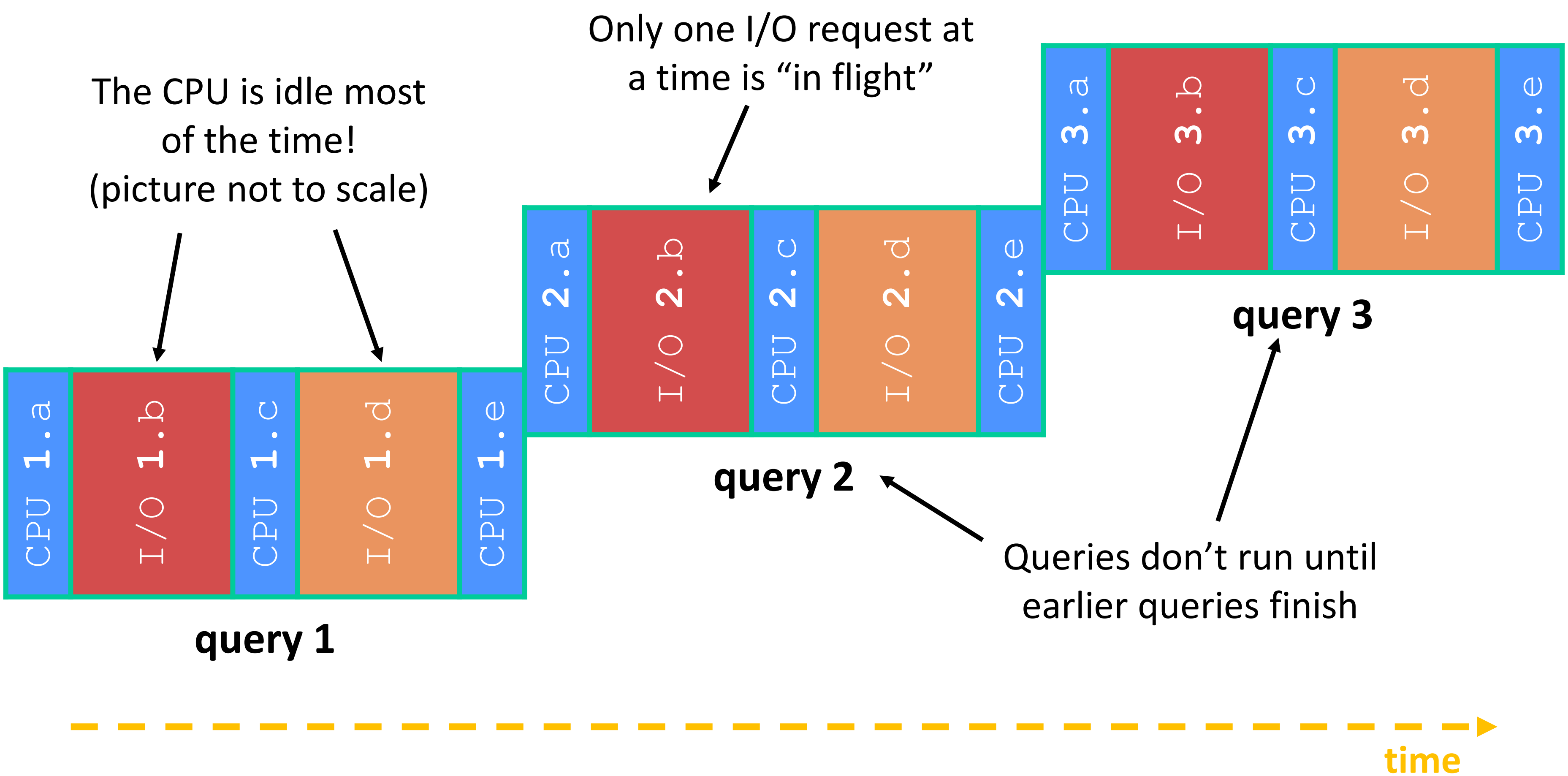
Multiple Queries: To Scale



Uh-Oh (1 of 2)


index
file
index
file
index
file
query
processor
client
client
client
client
client

Uh-Oh (2 of 2)


The CPU is idle most of the time! (picture not to scale)
Only one I/O request at a time is "in flight"
CPU 1.a
I/O 1.b
CPU 1.c
I/O 1.d
CPU 1.e
query 1
CPU 2.a
I/O 2.b
CPU 2.c
I/O 2.d
CPU 2.e
query 2
CPU 3.a
I/O 3.b
CPU 3.c
I/O 3.d
CPU 3.e
query 3
Queries don't run until earlier queries finish
time

Sequential Can Be Inefficient

- Only one query is being processed at a time
  - All other queries queue up behind the first one
  - And clients queue up behind the queries …
- Even while processing one query, the CPU is idle the vast majority of the time
  - It is *blocked* waiting for I/O to complete
    - Disk I/O can be very, very slow (10 million times slower …)
- At most one I/O operation is in flight at a time
  - Missed opportunities to speed I/O up
    - Separate devices in parallel, better scheduling of a single device, etc.

Lecture Outline

- From Query Processing to a Search Server
- **Intro to Concurrency**
- Concurrent Programming Styles
- Threads
- Search Server with pthreads

Concurrency

- Our search engine could run concurrently:
  - Example: Execute queries one at a time, but issue *I/O requests* against different files/disks simultaneously
    - Could read from several index files at once, processing the I/O results as they arrive
  - Example: Our web server could execute multiple *queries* at the same time
    - While one is waiting for I/O, another can be executing on the CPU
- Concurrency != parallelism
  - Concurrency is doing multiple tasks at a time
  - Parallelism is executing multiple CPU instructions *simultaneously*

A Concurrent Implementation

- Use multiple "workers"
  - As a query arrives, create a new "worker" to handle it
    - The "worker" reads the query from the network, issues read requests against files, assembles results and writes to the network
    - The "worker" uses blocking I/O; the "worker" alternates between consuming CPU cycles and blocking on I/O
  - The OS context switches between "workers"
    - While one is blocked on I/O, another can use the CPU
    - Multiple "workers'" I/O requests can be issued at once
- So what should we use for our "workers"?

Lecture Outline

- From Query Processing to a Search Server
- Intro to Concurrency
- **Threads and other concurrency methods**
- Search Server with pthreads

Review: Processes

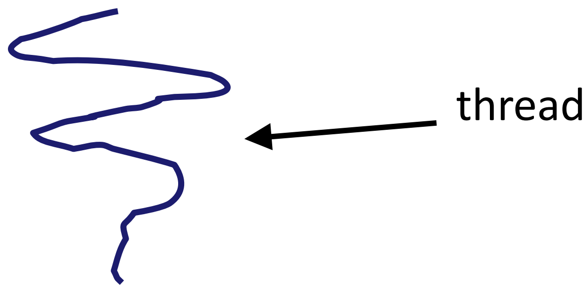
- The components of a "process" are:
  - Resources such as file descriptors and sockets
  - An address space (page tables, ect.)

- Different Processes have independent components:
  - Most importantly: Isolated address spaces.

- An address space of a process can hold stack(s) that distinguish different "threads" of execution

Introducing Threads

- Separate the concept of a process from the "*thread of execution*"
  - Threads are contained within a process
  - Usually called a thread, this is a sequential execution stream within a process



- In most modern OS's:
  - Threads are the *unit of scheduling.*

Multi-threaded Search Engine (Pseudocode)

```
main() {
  while (1) {
    string query_words[] = GetNextQuery();
    CreateThread(ProcessQuery(query_words));
  }
}
```

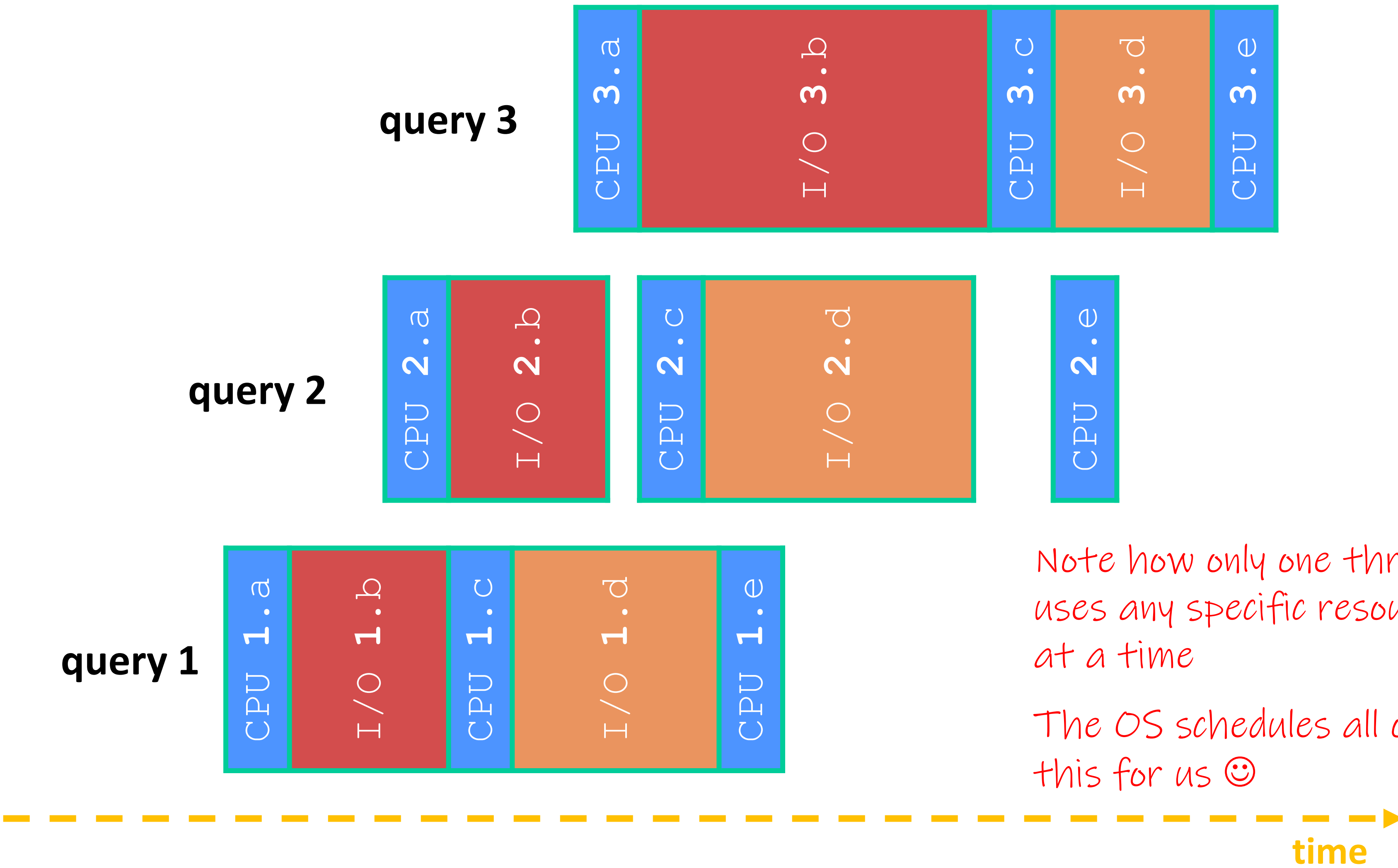
All we did was put the code into a function, and create a thread that invokes it

```
doclist Lookup(string word) {
  bucket = hash(word);
  hitlist = file.read(bucket);
  foreach hit in hitlist
    doclist.append(file.read(hit));
  return doclist;
}

ProcessQuery(string query_words[]) {
  results = Lookup(query_words[0]);
  foreach word in query[1..n]
    results = results.intersect(Lookup(word));
  Display(results);
}
```

Multi-threaded Search Engine (Execution)

*Running with 1 CPU



Note how only one thread uses any specific resource at a time

The OS schedules all of this for us ☺

Why Threads?

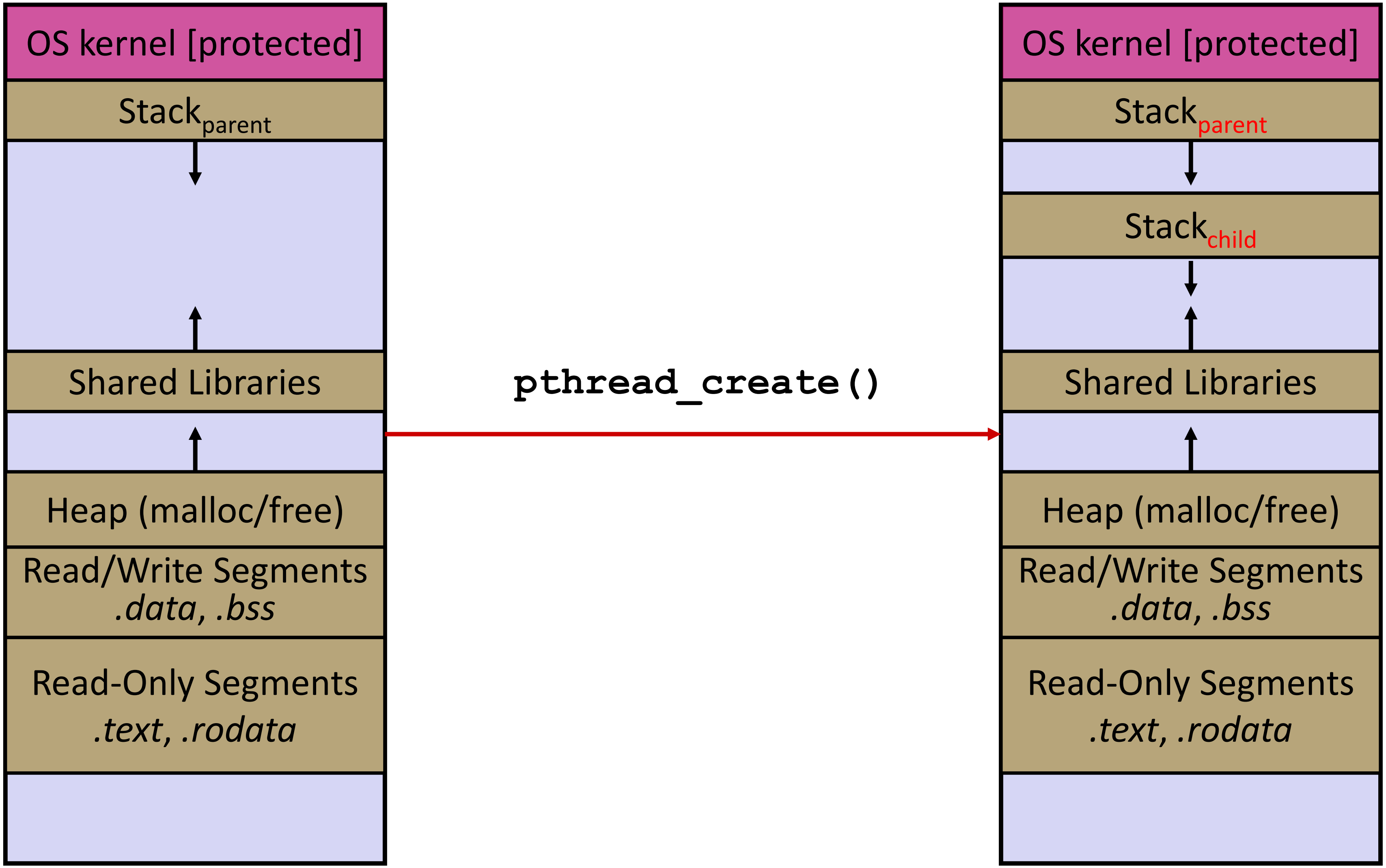
- Advantages:
  - You (mostly) write sequential-looking code
  - Threads can run in parallel if you have multiple CPUs/cores

- Disadvantages:
  - If threads share data, you need locks or other synchronization
    - Very bug-prone and difficult to debug
  - Threads can introduce overhead
    - Lock contention, context switch overhead, and other issues
  - Need language support for threads

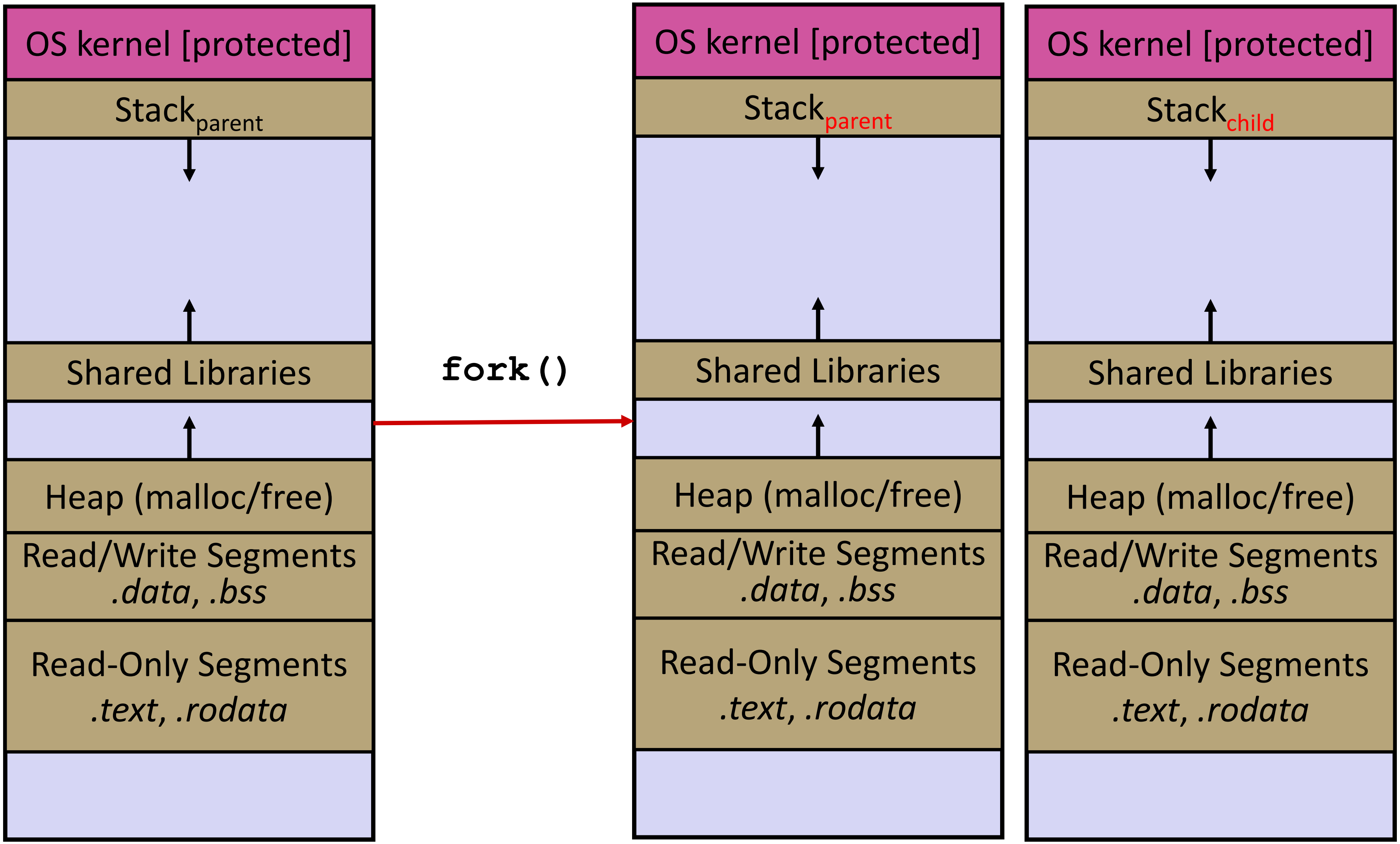
Threads vs. Processes

- In most modern OS's:
  - A Process has a unique: address space, OS resources,
    & security attributes
  - A Thread has a unique: stack, stack pointer, program counter,
    & registers
  - Threads are the *unit of scheduling* and processes are their *containers*; every process has at least one thread running in it

Threads vs. Processes



Threads vs. Processes



Alternative: Processes

- What if we forked processes instead of threads?

- Advantages:
  - No shared memory between processes
  - No need for language support; OS provides "fork"
  - Processes are isolated. If one crashes, other processes keep going

- Disadvantages:
  - More overhead than threads during creation and context switching
  - Cannot easily share memory between processes – typically communicate through the file system

Alternate: Different I/O Handling

- Use asynchronous or non-blocking I/O

- Your program begins processing a query
  - When your program needs to read data to make further progress, it registers interest in the data with the OS and then switches to a different query
  - The OS handles the details of issuing the read on the disk, or waiting for data from the console (or other devices, like the network)
  - When data becomes available, the OS lets your program know

- Your program (almost never) blocks on I/O

Non-blocking I/O

- Reading from the network can truly *block* your program
  - Remote computer may wait arbitrarily long before sending data

- Non-blocking I/O (network, console)
  - Your program enables non-blocking I/O on its file descriptors
  - Your program issues **`read`**`()` and **`write`**`()` system calls
    - If the read/write would block, the system call returns immediately
  - Program can ask the OS which file descriptors are readable/writeable
    - Program can choose to block while no file descriptors are ready

Poll Everywhere

pollev.com/cse33320su

- If I wanted to make a web browser, what concurrency model should I use?
  - Note that a web browser may need to request many resources over the network and combine them together to load a page

A. Do it sequentially
B. Use threads
C. Use processes
D. We're lost…

Poll Everywhere

pollev.com/cse33320su

- If I wanted to make a web browser, what concurrency model should I use?
  - Note that a web browser may need to request many resources over the network and combine them together to load a page

A. Do it sequentially
B. Use threads
C. Use processes
D. We're lost…

Concurrency will make more efficient use of time

We will need to share the data we request across "workers"

We want to be fast

Outline (next two lectures)

- We'll look at different `searchserver` implementations
  - Sequential
  - Concurrent via dispatching threads – **`pthread_create`**`()`
  - Concurrent via forking processes – **`fork`**`()`

- Reference: *Computer Systems: A Programmer's Perspective*, Chapter 12 (CSE 351 book)

Sequential

- Pseudocode:

```
listen_fd = Listen(port);

while (1) {
  client_fd = accept(listen_fd);
  buf = read(client_fd);
  resp = ProcessQuery(buf);
  write(client_fd, resp);
  close(client_fd);
}
```

- See `searchserver_sequential/`

Why Sequential?

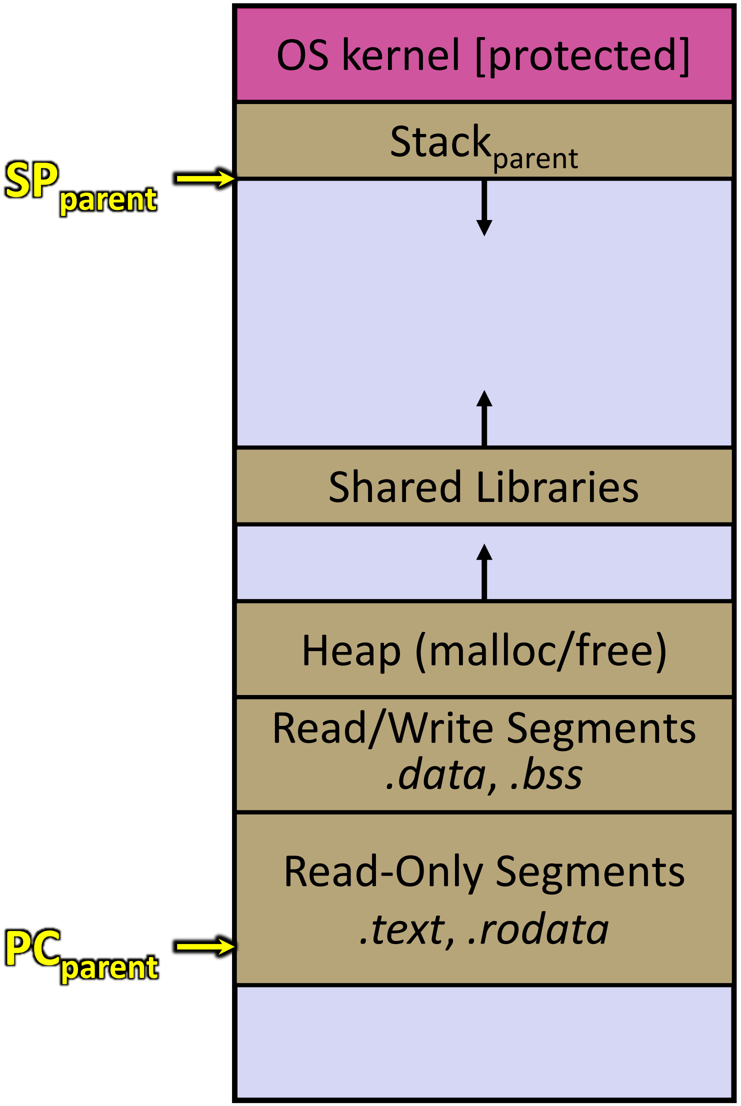
- Advantages:
  - Super(?) simple to build/write

- Disadvantages:
  - Incredibly poor performance
    - One slow client will cause *all* others to block
    - Poor utilization of resources (CPU, network, disk)

Threads

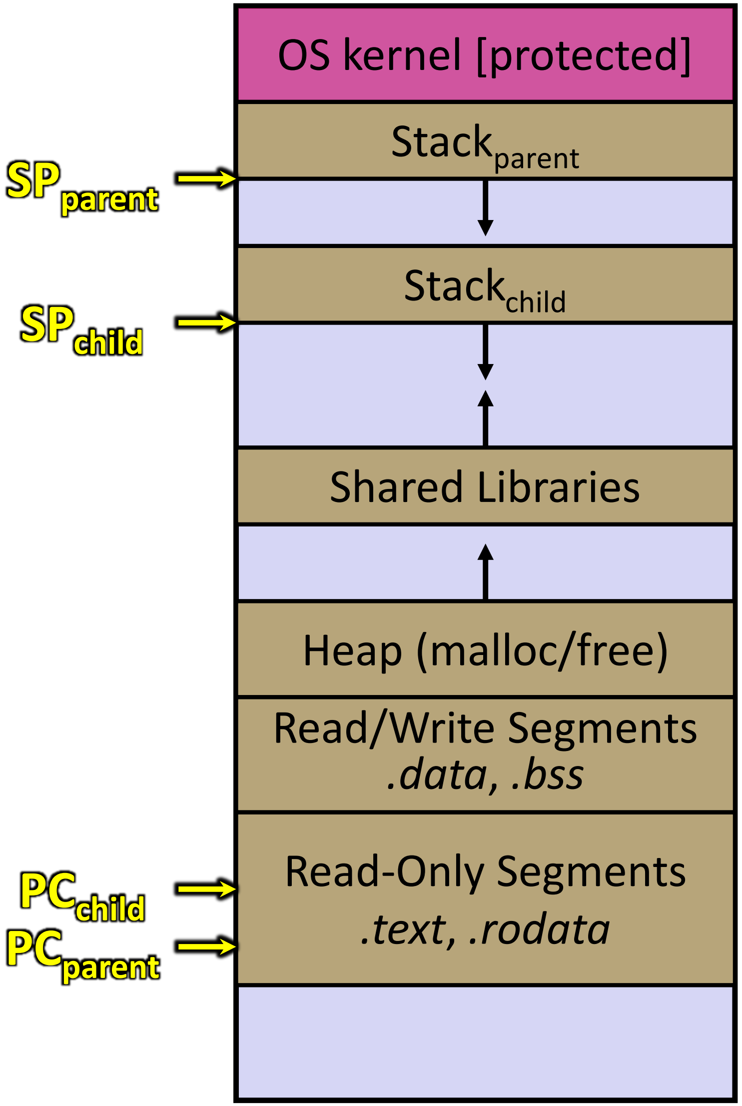
- Threads are like lightweight processes
  - They execute concurrently like processes
    - Multiple threads can run simultaneously on multiple CPUs/cores
  - Unlike processes, threads cohabitate the same address space
    - Threads within a process see the same heap and globals and can communicate with each other through variables and memory
      - But, they can interfere with each other – need synchronization for shared resources
    - Each thread has its own stack

Single-Threaded Address Spaces



- Before creating a thread
  - One thread of execution running in the address space
    - One PC, stack, SP
  - That main thread invokes a function to create a new thread
    - Typically `pthread_create()`

Multi-threaded Address Spaces



- After creating a thread
  - *Two* threads of execution running in the address space
    - Original thread (parent) and new thread (child)
    - New stack created for child thread
    - Child thread has its own *values* of the PC and SP
  - Both threads share the other segments (code, heap, globals)
    - They can cooperatively modify shared data

Lecture Outline

- From Query Processing to a Search Server
- Intro to Concurrency
- Threads
- **Search Server with pthreads**

POSIX Threads (pthreads)

- The POSIX APIs for dealing with threads
  - Declared in `pthread.h`
    - Not part of the C/C++ language (cf. Java)
  - To enable support for multithreading, must include `-pthread` flag when compiling and linking with `gcc` command
    - `gcc -g -Wall -std=c11 -pthread -o main main.c`

Creating and Terminating Threads

Output parameter.
Gives us a "thread_descriptor"

```
int pthread_create(
        pthread_t* thread,
        const pthread_attr_t* attr,
        void* (*start_routine)(void*),
        void* arg);
```

Function pointer!
Takes & returns void*
to allow "generics" in C

Argument for the thread function

- Creates a new thread into `*thread`, with attributes `*attr` (`NULL` means default attributes)
- Returns **0** on success and an error number on error (can check against error constants)
- The new thread runs **`start_routine`**`(arg)`

```
void pthread_exit(void* retval);
```

- Equivalent of **`exit`**`(retval);` for a thread instead of a process
- The thread will automatically exit once it returns from **`start_routine`**`()`