Concurrency: Intro and Threads

CSE 333 Winter 2020

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Administrivia

- HW4 due two Thursdays from now (03/12)
  - You can use ***two*** late days on HW4.

- Exercise 17 to be released Friday.
  - Due Monday 3/09 @ 11 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`

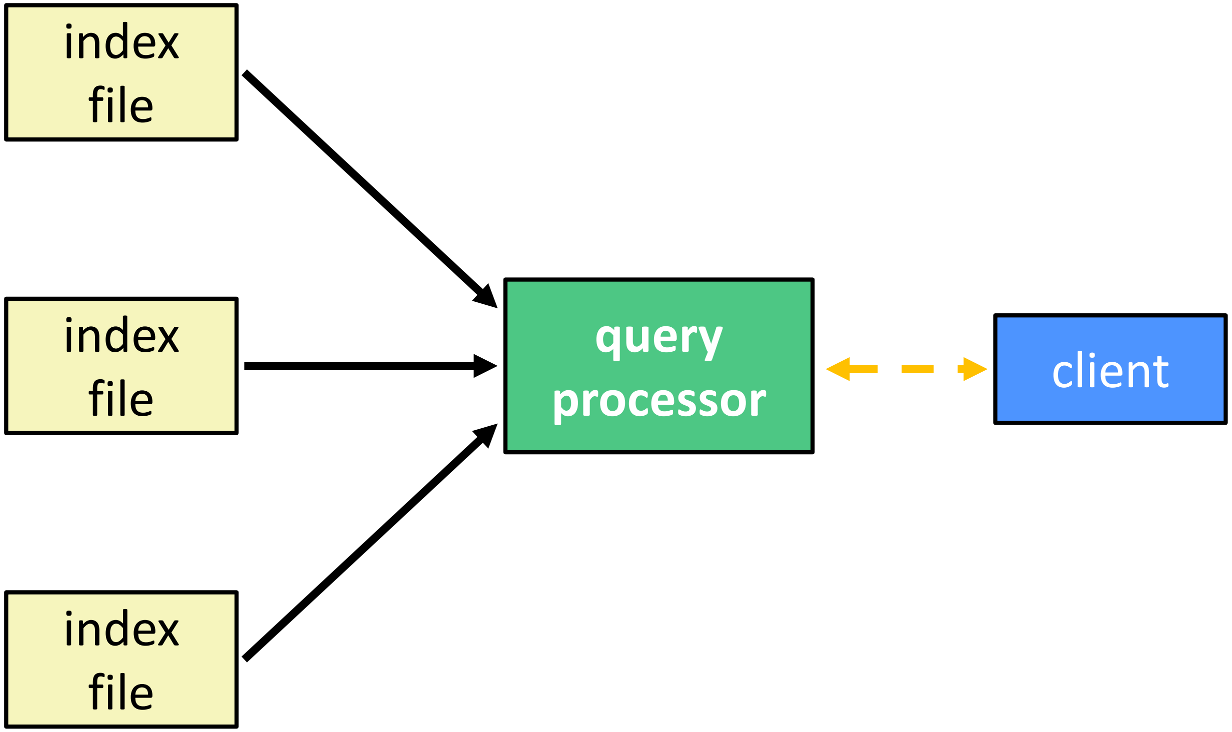
Lecture Outline

- **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

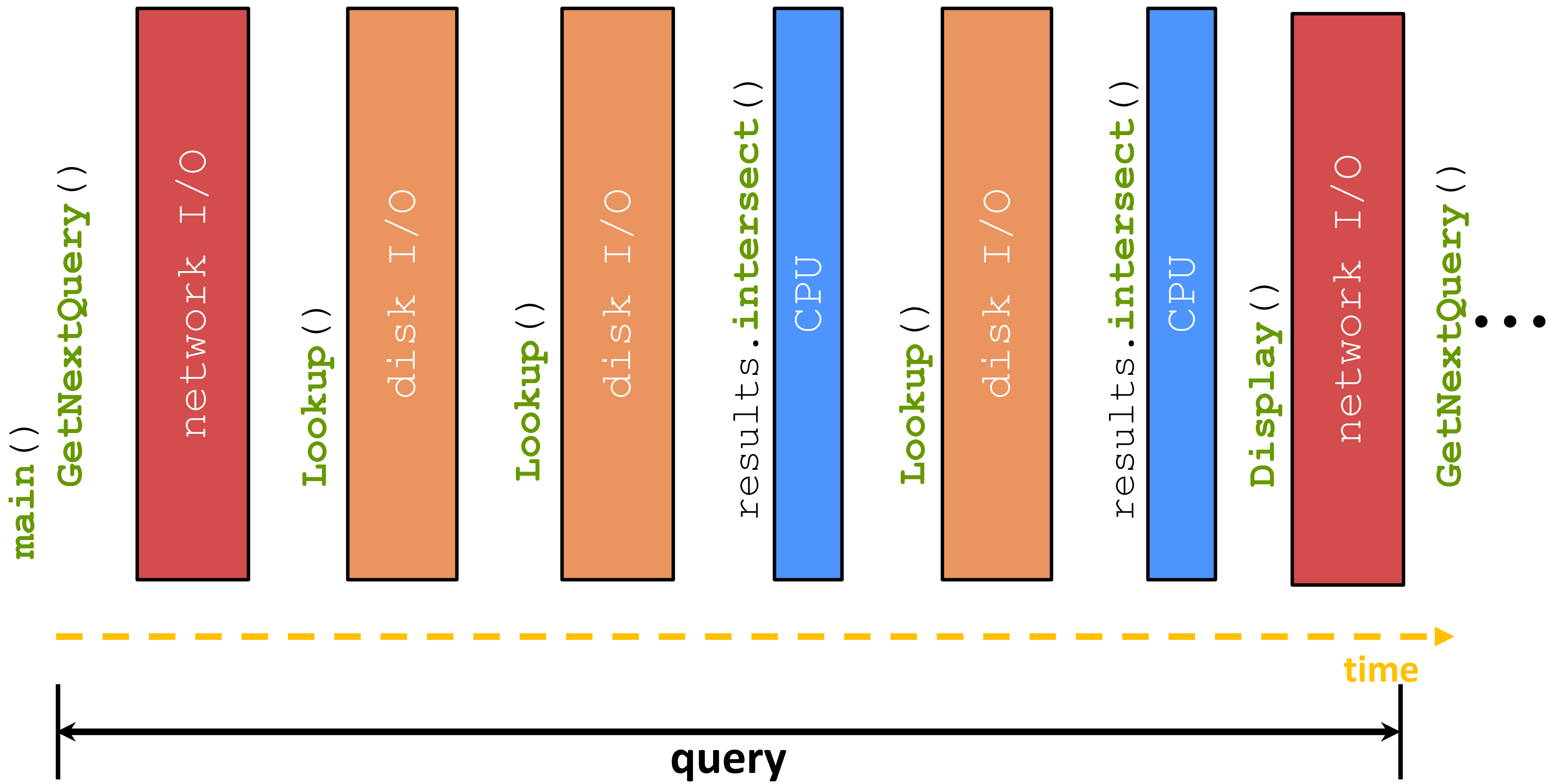
Search Engine Architecture



Search Engine (Pseudocode)

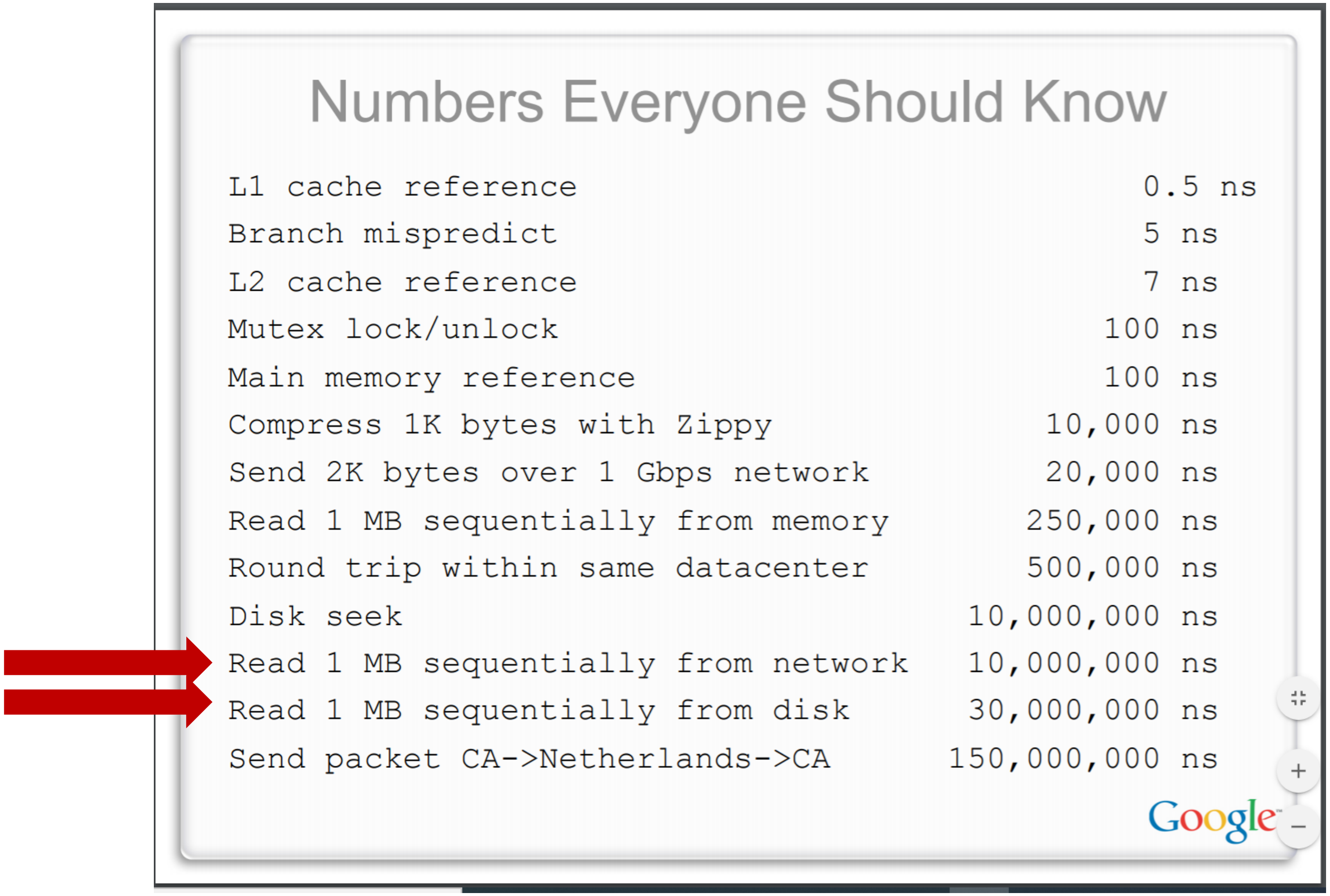
```
doclist Lookup(string word) {
  bucket = hash(word);
  hitlist = file.read(bucket);
  foreach hit in hitlist {
    doclist.append(file.read(hit));
  }
  return doclist;
}

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

Execution Timeline: a Multi-Word Query



What About I/O-caused Latency?

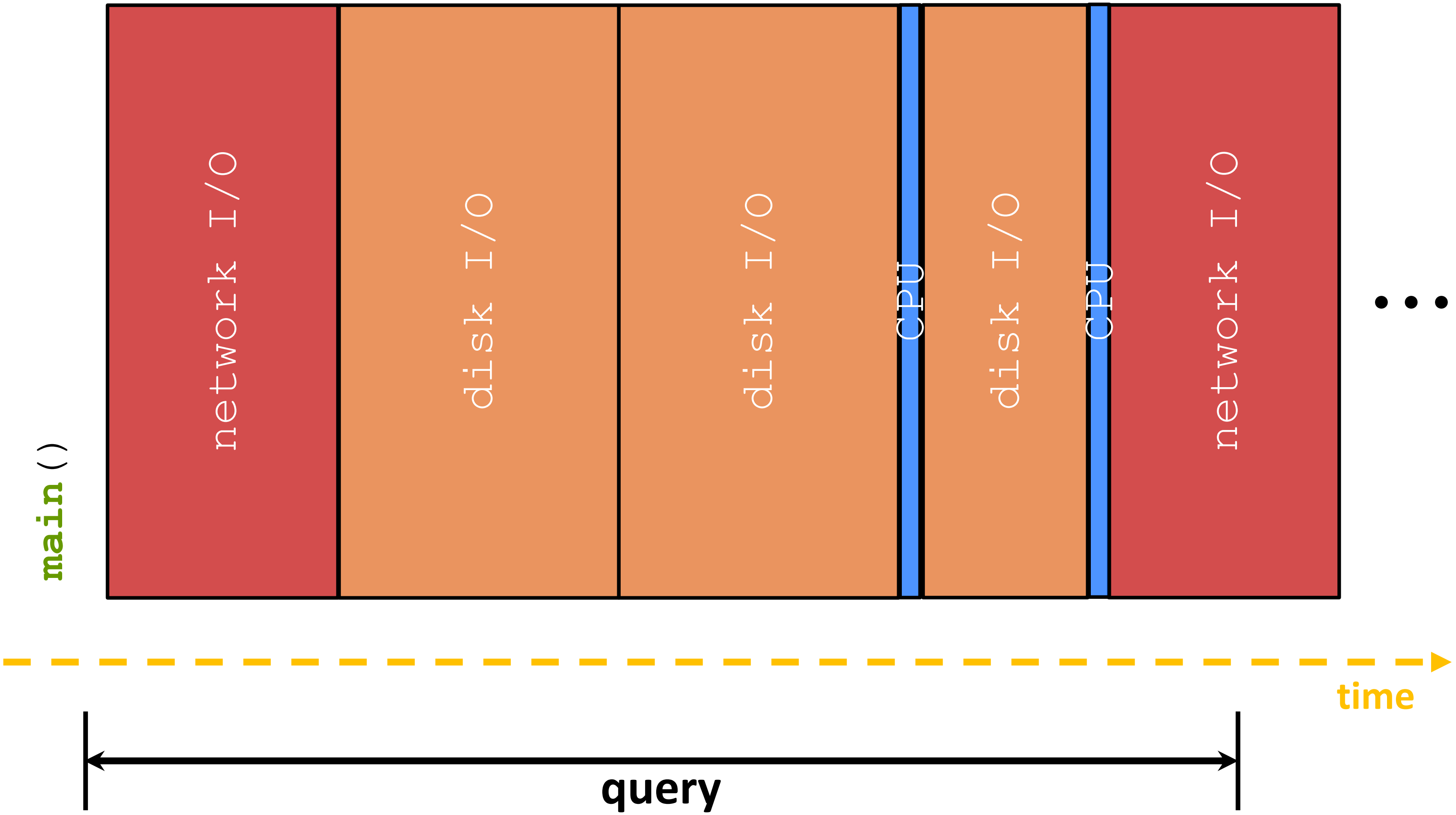
- Jeff Dean’s “Numbers Everyone Should Know” (LADIS ‘09)



Numbers Everyone Should Know

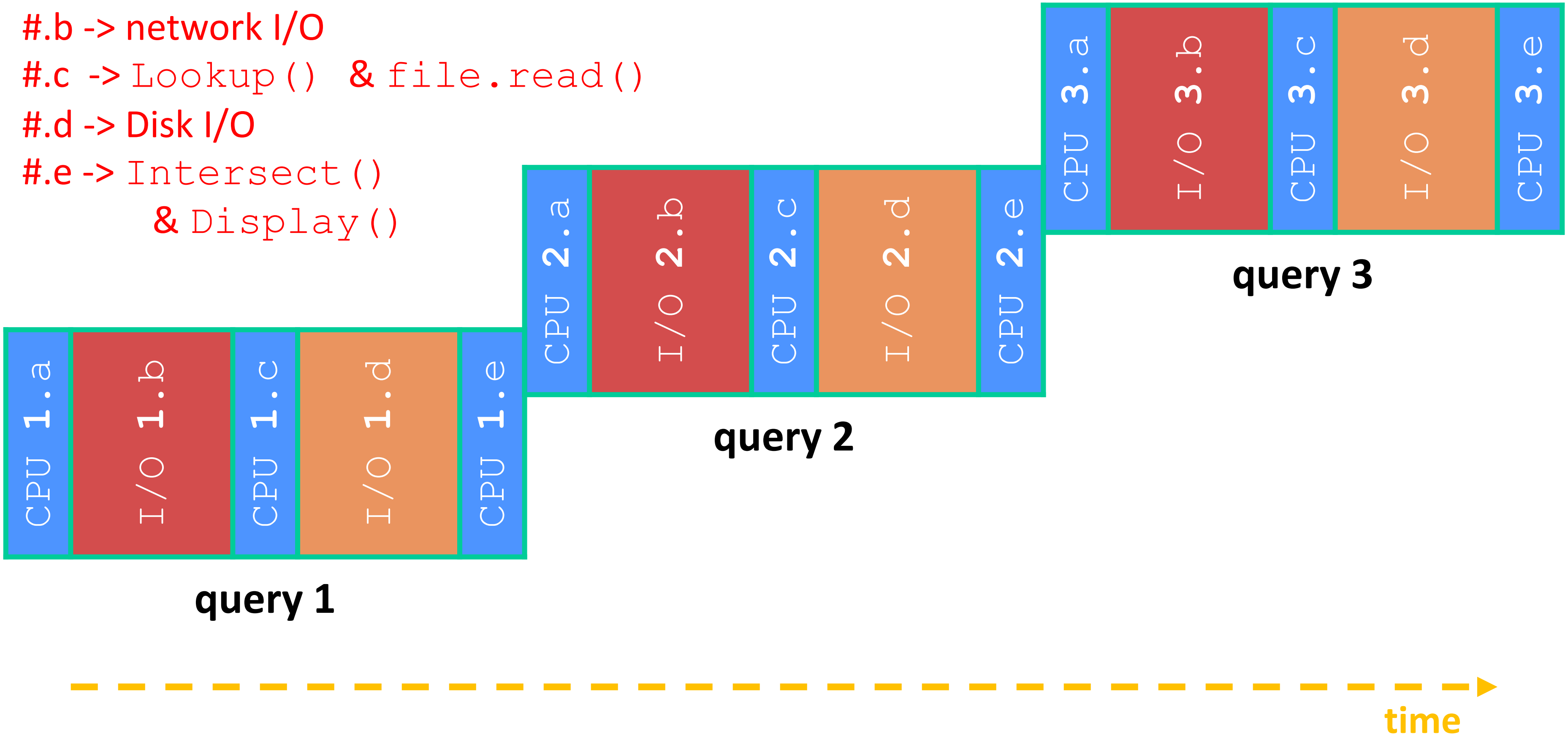
L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	100 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	10,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns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

Execution Timeline: To Scale

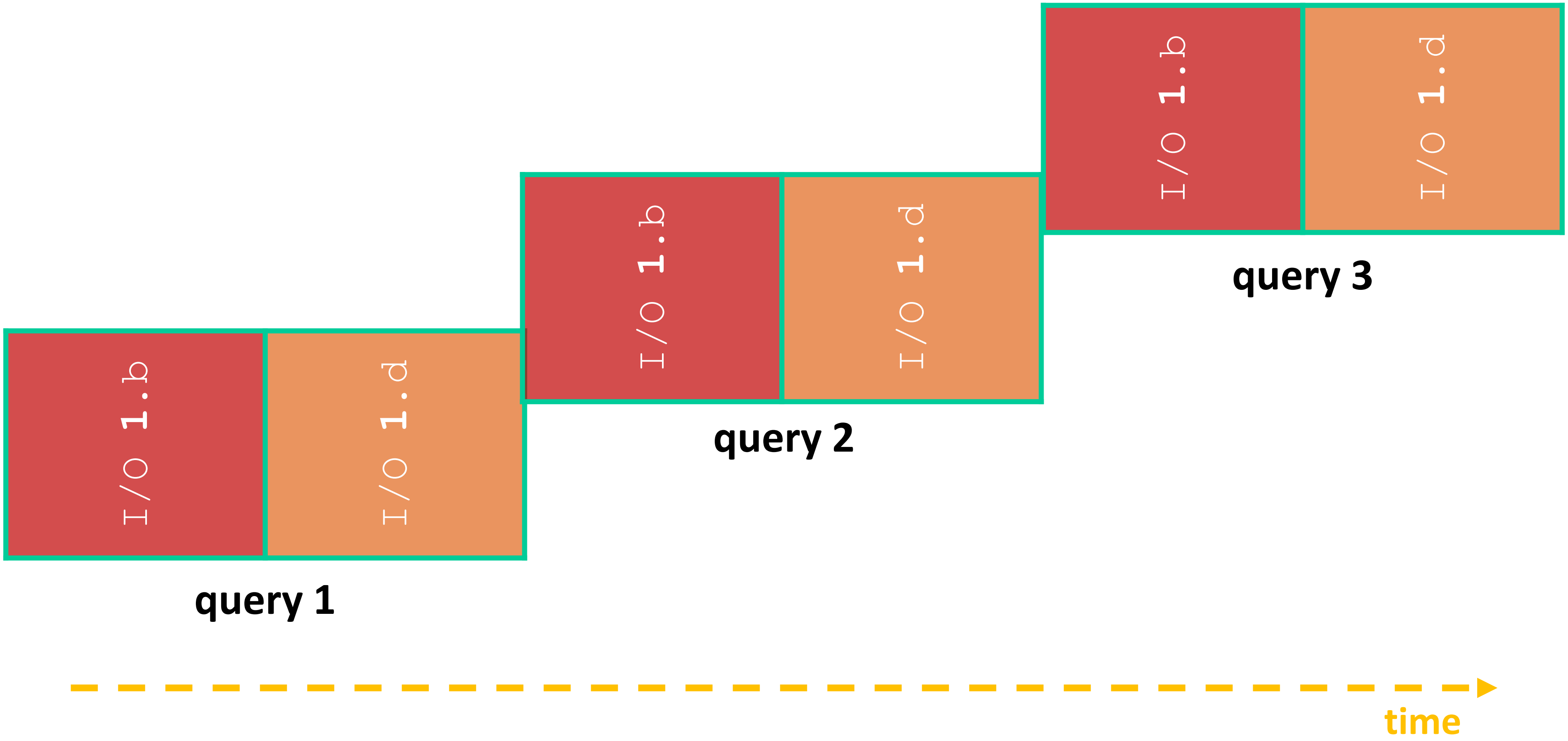


Multiple (Single-Word) Queries

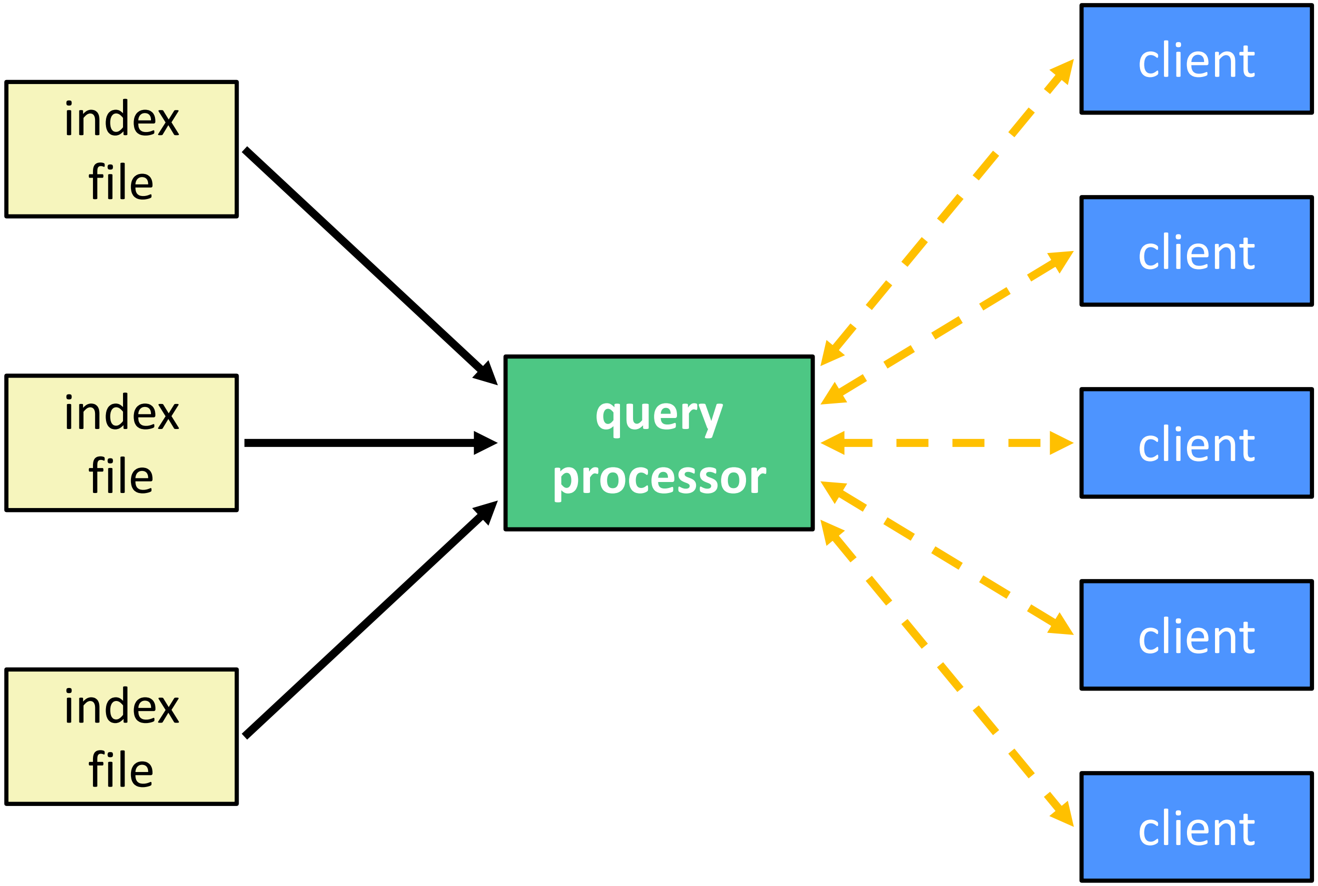
is the Query Number
#.a -> `GetNextQuery()`
#.b -> network I/O
#.c -> `Lookup()` & `file.read()`
#.d -> Disk I/O
#.e -> `Intersect()`
& `Display()`



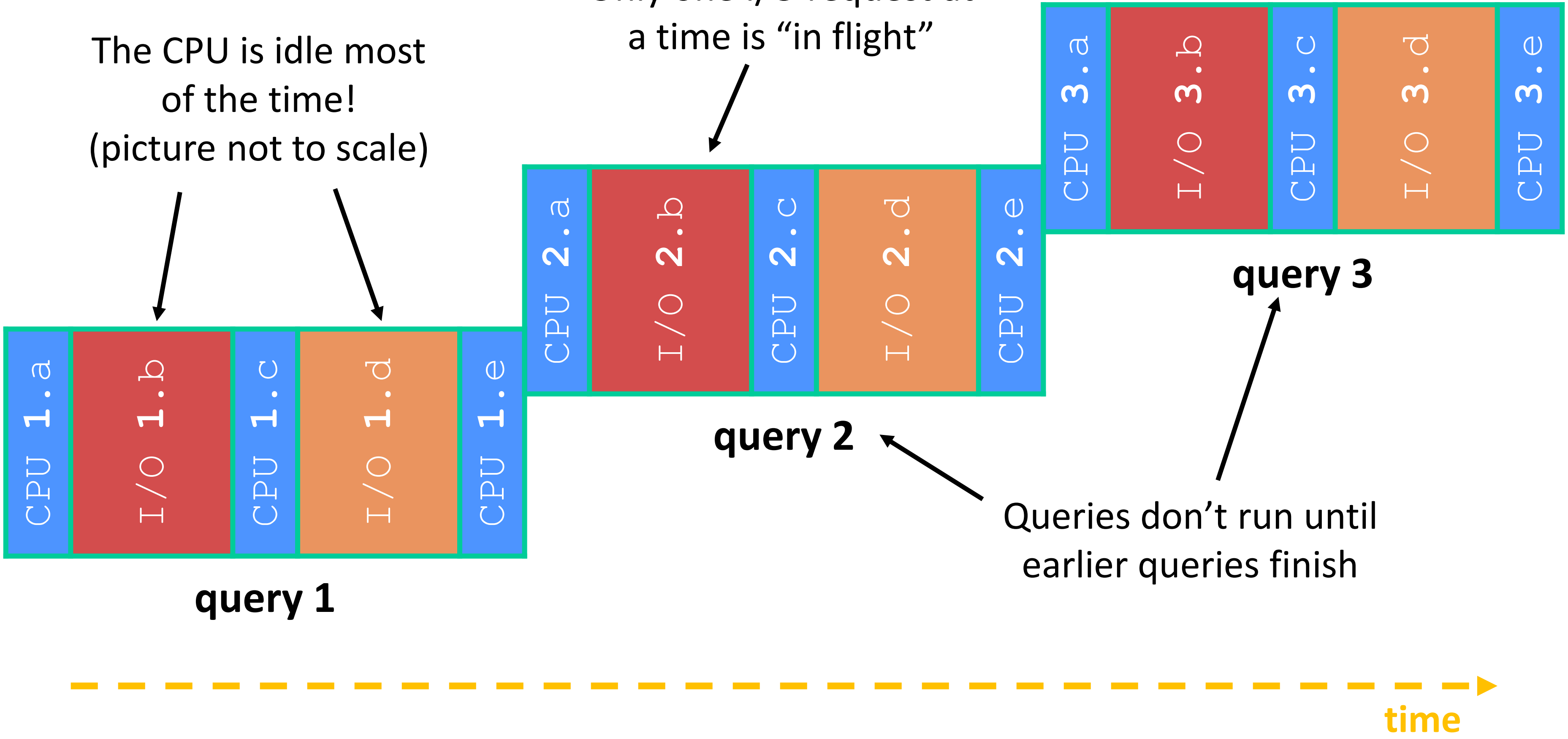
Multiple Queries: To Scale



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”

Queries don’t run until earlier queries finish

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

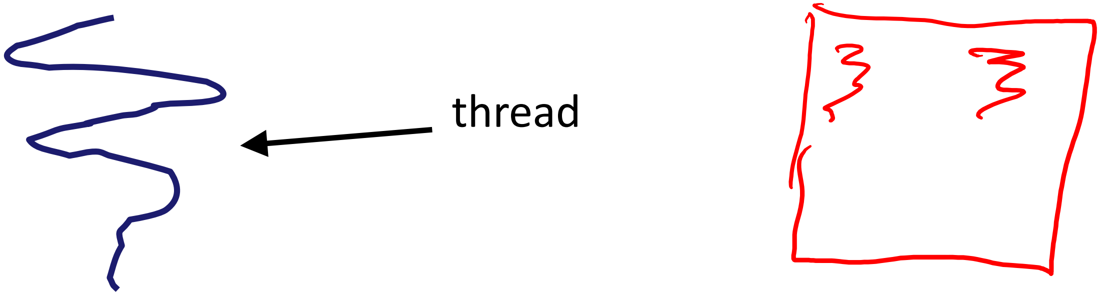
- The components of a “process” are:
  - Resources such as file descriptors and sockets
  - An address space (page tables, ect.)

- 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.*

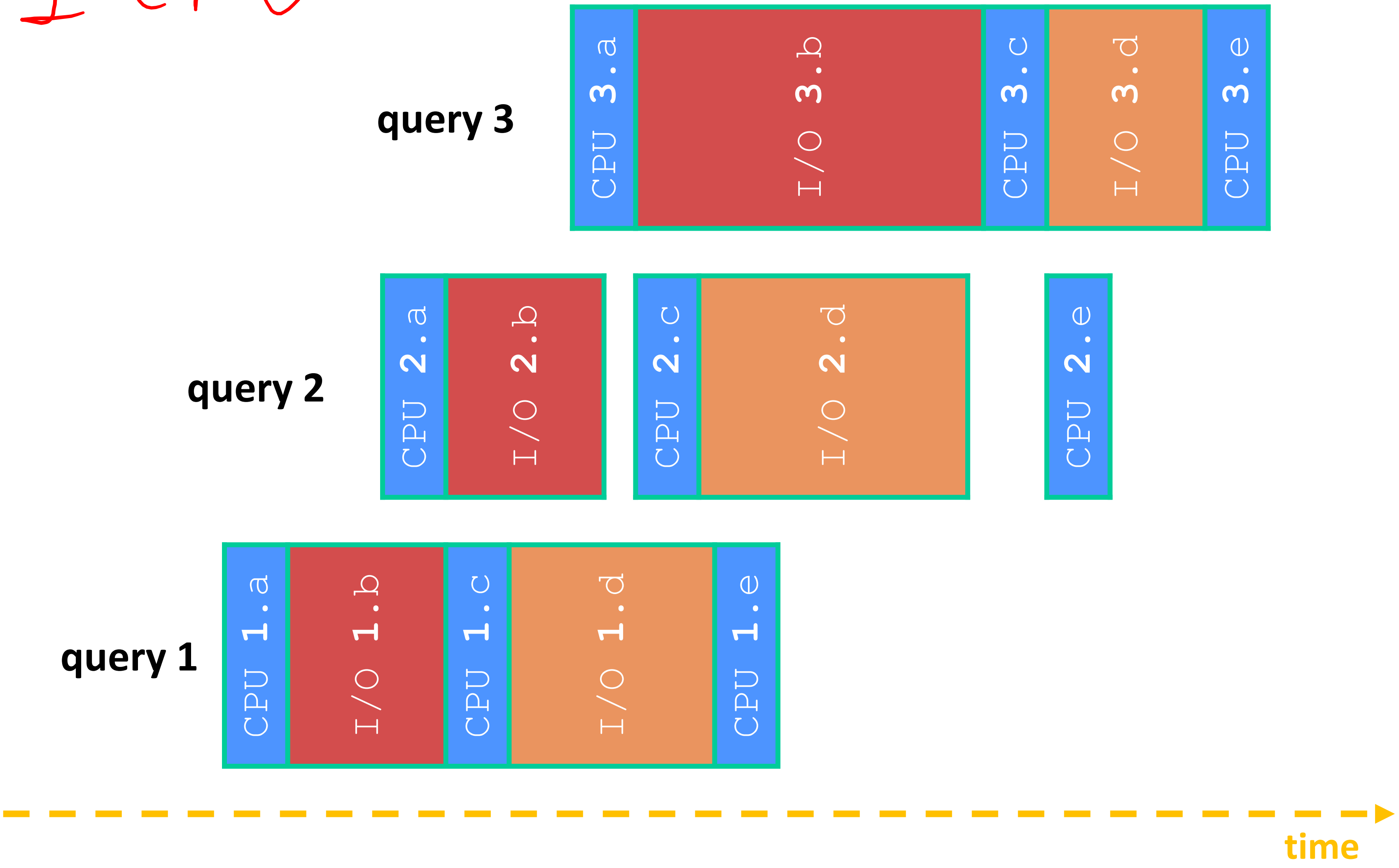
Multi-threaded Search Engine (Pseudocode)

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

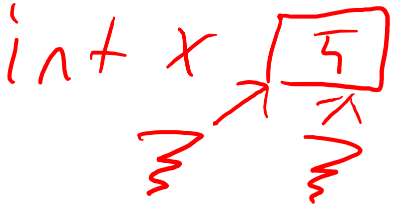
```
doclist Lookup(string word) {
  bucket = hash(word);
  hitlist = file.read(bucket);
  foreach hit in hitlist
    doclist.append(file.read(hit));
  return doclist;
}

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)

1 CPU.



Why Threads?



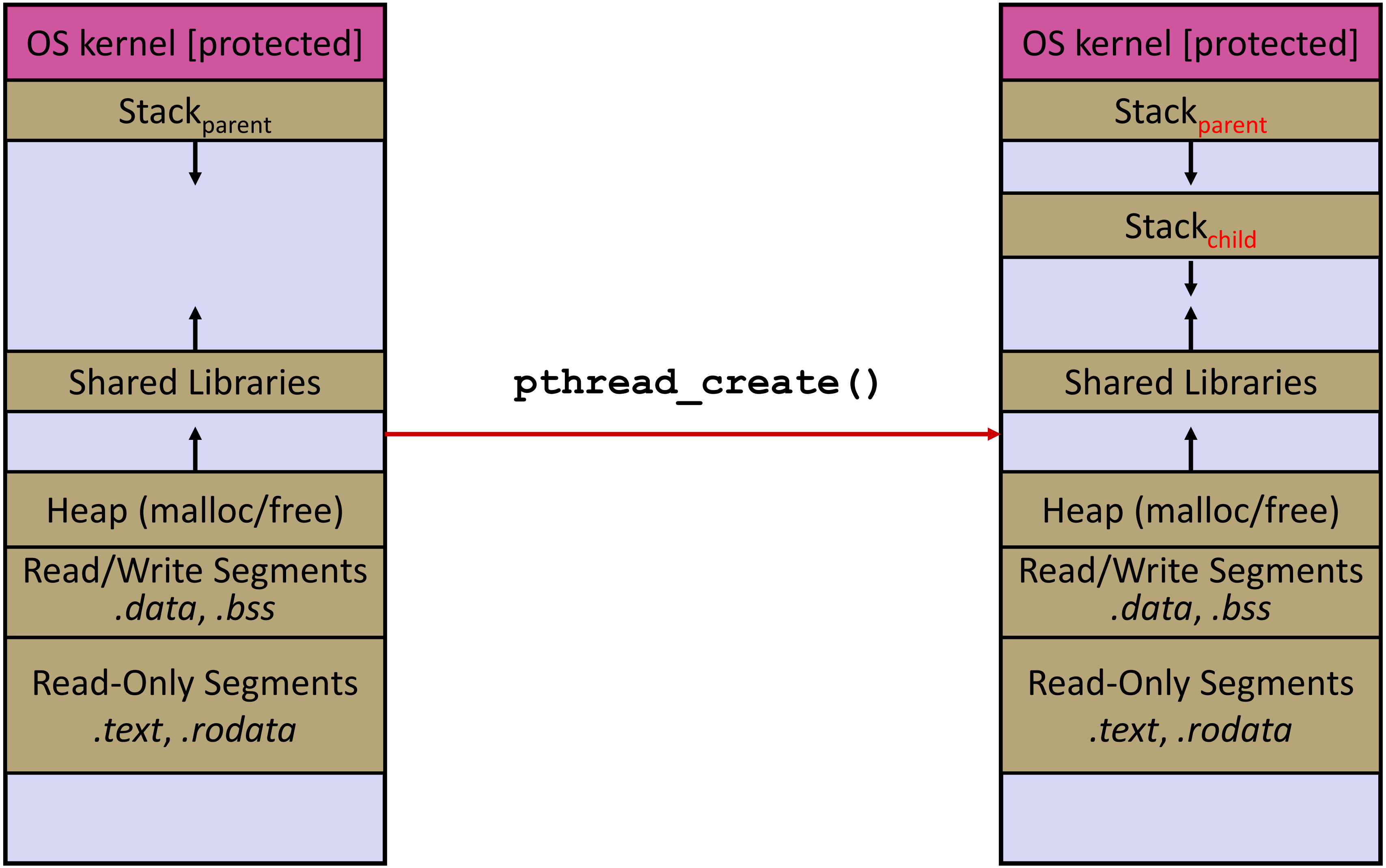
- Advantages:
  - You (mostly) write sequential-looking code
  - Threads can run in parallel if you have multiple CPUs/cores

- 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

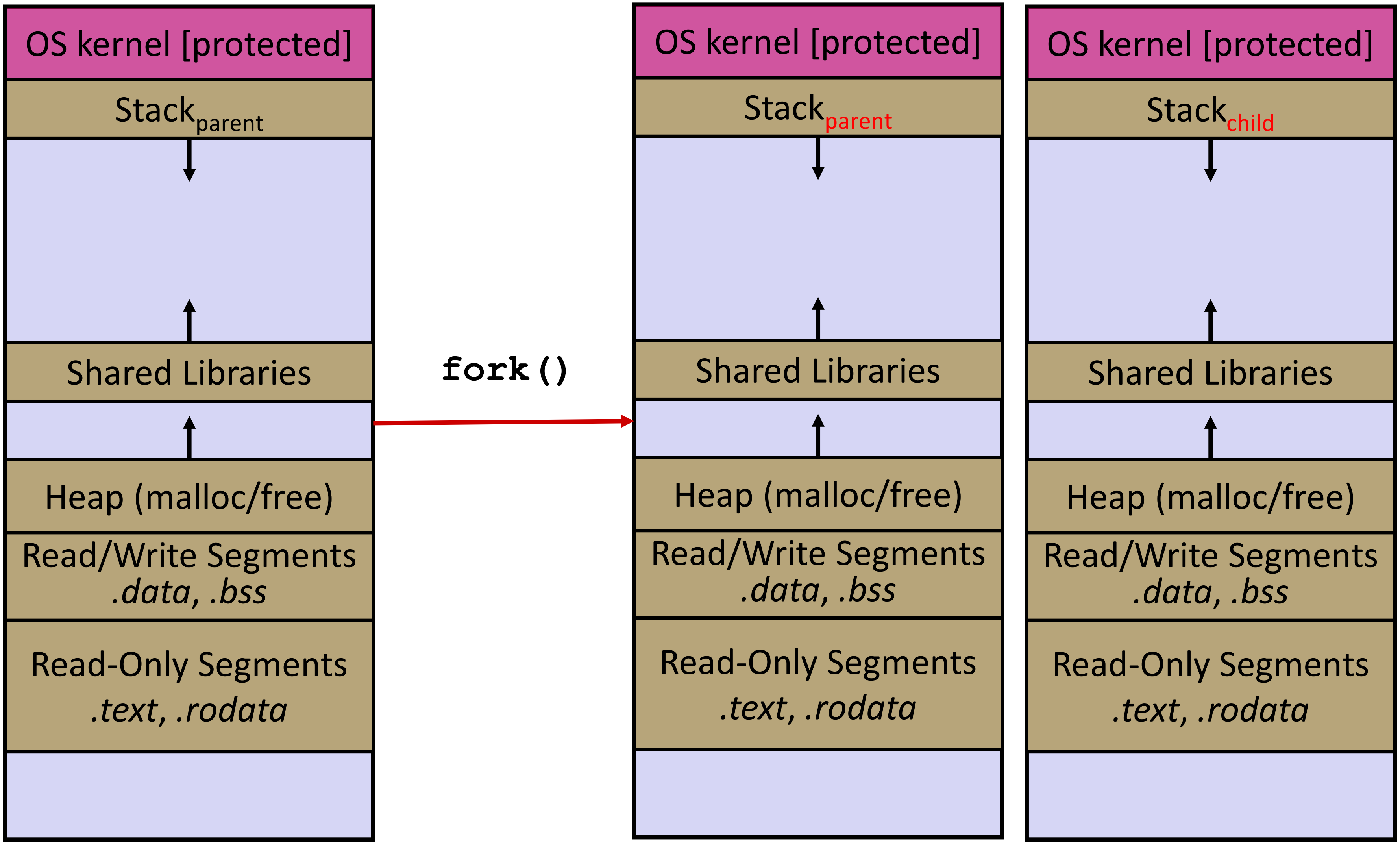
Threads vs. Processes

- 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



OS kernel [protected]

$\text{Stack}_{\text{parent}}$

Shared Libraries

Heap (malloc/free)

Read/Write Segments
.data, .bss

Read-Only Segments
.text, .rodata

`fork()`

OS kernel [protected]

$\text{Stack}_{\text{parent}}$

Shared Libraries

Heap (malloc/free)

Read/Write Segments
.data, .bss

Read-Only Segments
.text, .rodata

OS kernel [protected]

$\text{Stack}_{\text{child}}$

Shared Libraries

Heap (malloc/free)

Read/Write Segments
.data, .bss

Read-Only Segments
.text, .rodata

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) fcntl()
  - 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

Outline (next two lectures)

- We'll look at different `searchserver` implementations
  - Sequential
  - Concurrent via dispatching threads – **`pthread_create`**`()`
  - Concurrent via forking processes – **`fork`**`()`
    - 🎉Lecture With Andrew Hu! 🎉

- 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?

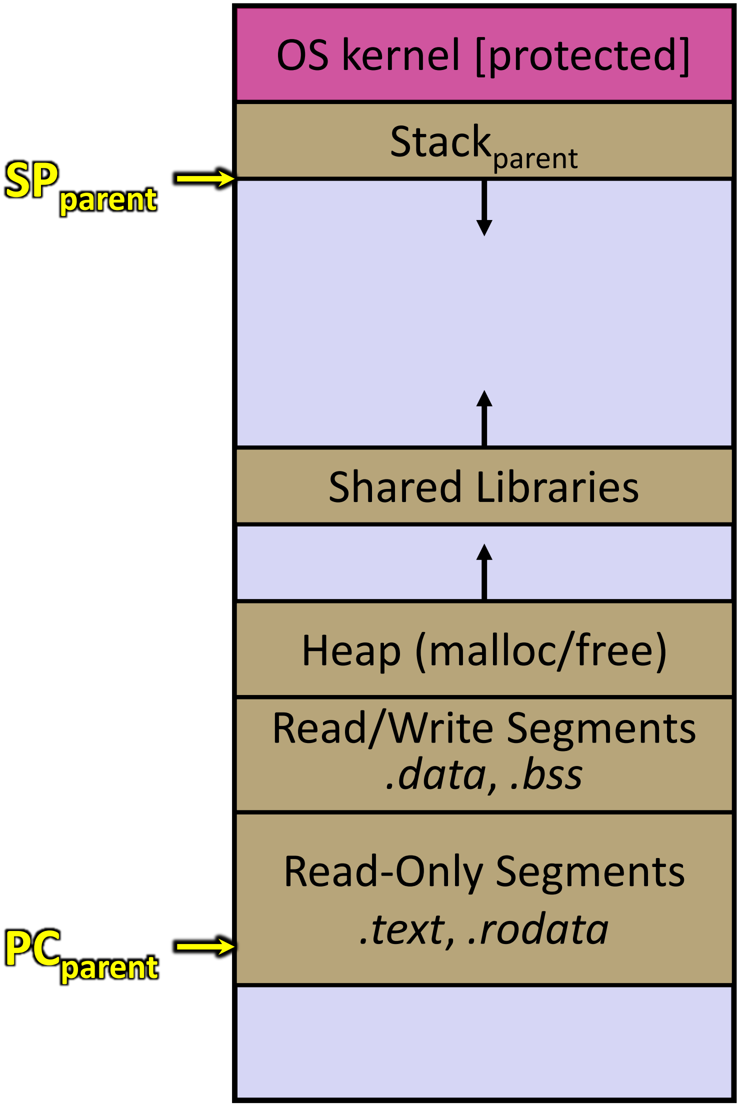
- Advantages:
  - Super(?) simple to build/write

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

Threads

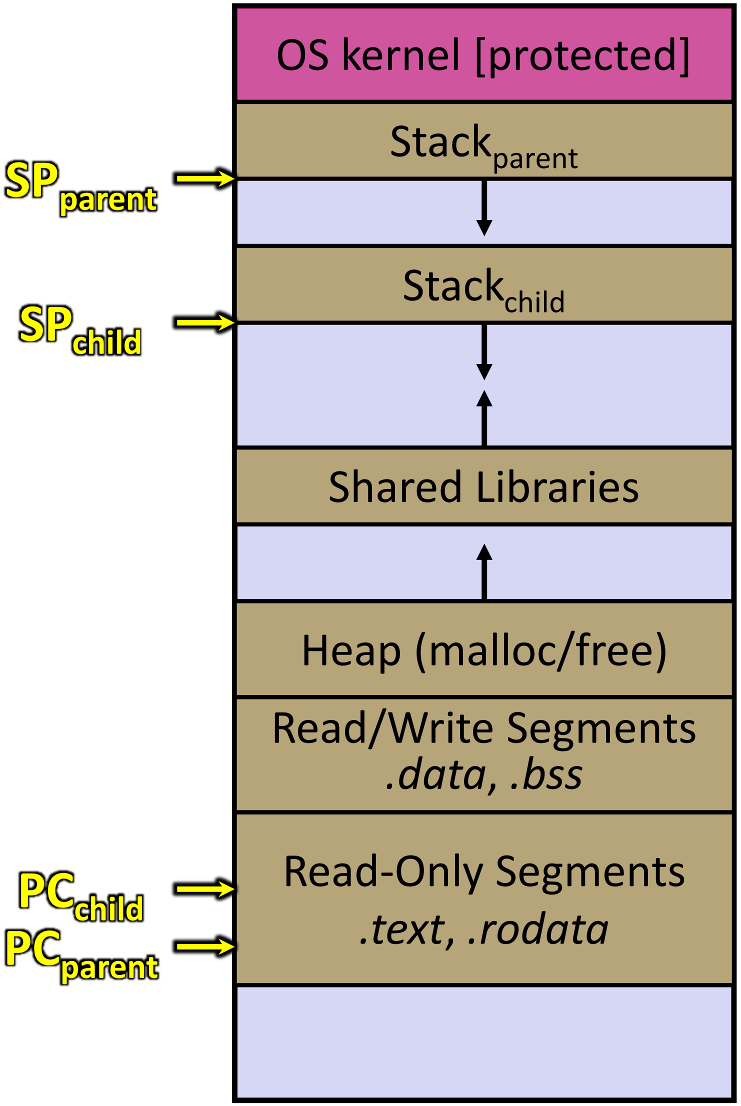
- Threads are like lightweight processes
  - They execute concurrently like processes
    - Multiple threads can run simultaneously on multiple CPUs/cores
  - Unlike processes, threads cohabitate the same address space
    - Threads within a process see the same heap and globals and can communicate with 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
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- **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 param

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