



pollev.com/cse333

About how long did Exercise 10 take you?

- A. [0, 2) hours
- B. [2, 4) hours
- C. [4, 6) hours
- D. [6, 8) hours
- E. 8+ Hours
- F. I didn't submit / I prefer not to say

Introduction to Concurrency

CSE 333 Summer 2023

Take 2!

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Relevant Course Information (1/2)

- ❖ Homework 4 due 1 week from Wednesday (8/16)
 - Partner form due Thursday (8/10)
 - You can still use **two** late days (until Friday, 8/18)
- ❖ Exercise 11 due Thursday (8/10) @ 1pm
- ❖ Exercise 12 (the last exercise™) to be released Wednesday
 - Consumer-producer concurrency
 - Due Monday 8/14 @ 1 pm
- ❖ Quiz 4 (Wednesday, 8/16 – Friday, 8/18)
 - Same policies as previous quizzes
 - ex10-ex12, hw4, overall course questions

Relevant Course Information (2/2)

- ❖ Homework 3 uploaded this morning
 - Please check Gradescope/email to make sure your submission shows up as you expect

- ❖ Quiz 2 Grades released
 - See Common Issues post
 - Regrades close Tuesday (8/8) @ 11:59pm

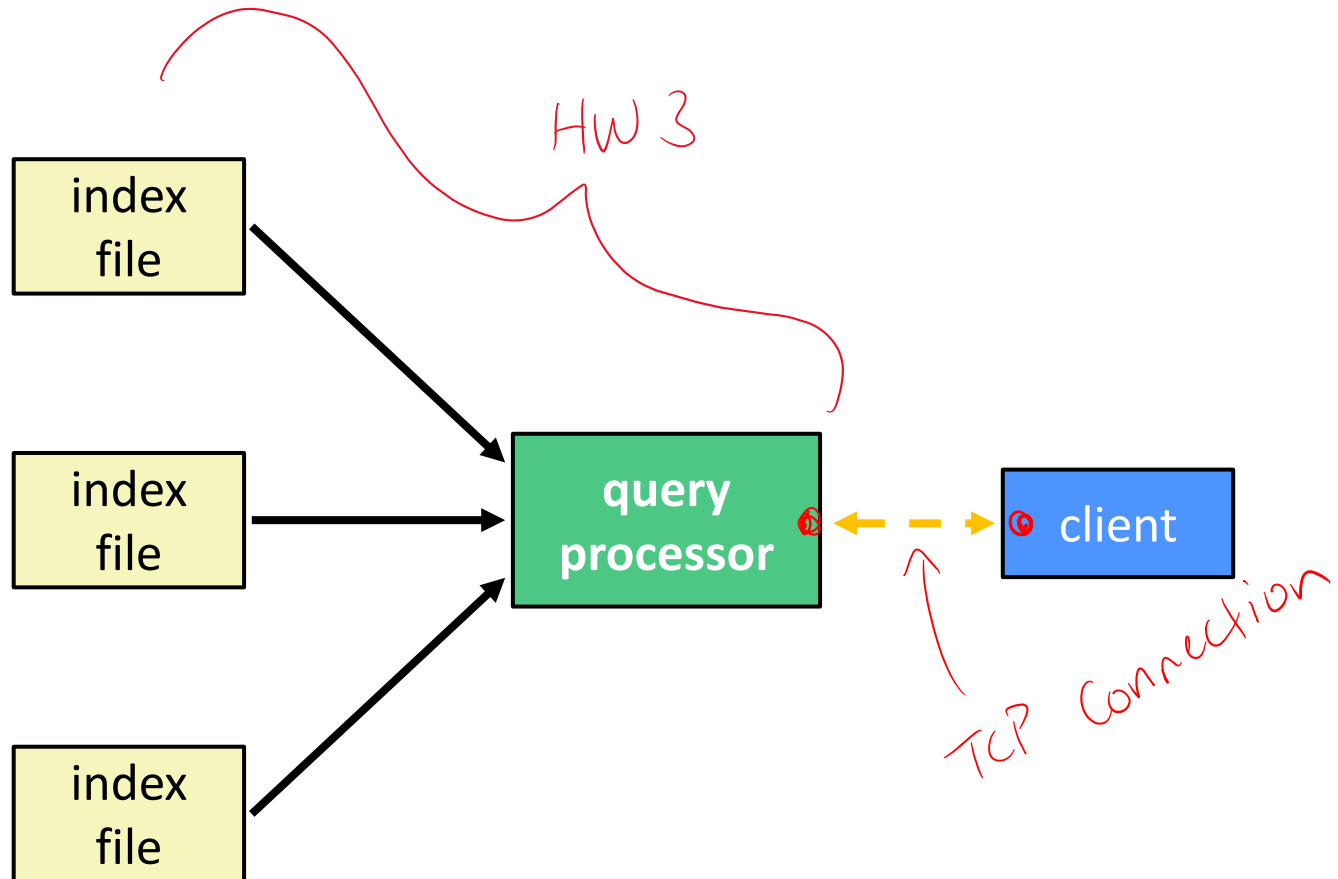
Lecture Outline

- ❖ **From Query Processing to a Search Server**
- ❖ Concurrency and Concurrency Methods

Building a Web Search Engine

- ❖ We have:
 - Some indexes
 - 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



Sequential 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(); // Steps 1-3 of server side
    while (1) {
        string query_words[] = GetNextQuery();
        results = Lookup(query_words[0]);
        foreach word in query[1..n] {
            results = results.intersect(Lookup(word));
        }
        Display(results);
    }
}
```

Handwritten annotations:

- Red arrows point from "Disk I/O" to the `file.read(bucket)` and `file.read(hit)` lines.
- Red arrows point from "Network I/O" to the `GetNextQuery()` and `Display(results)` lines.

See [searchserver_sequential/](#)

Why Sequential?

❖ Advantages:

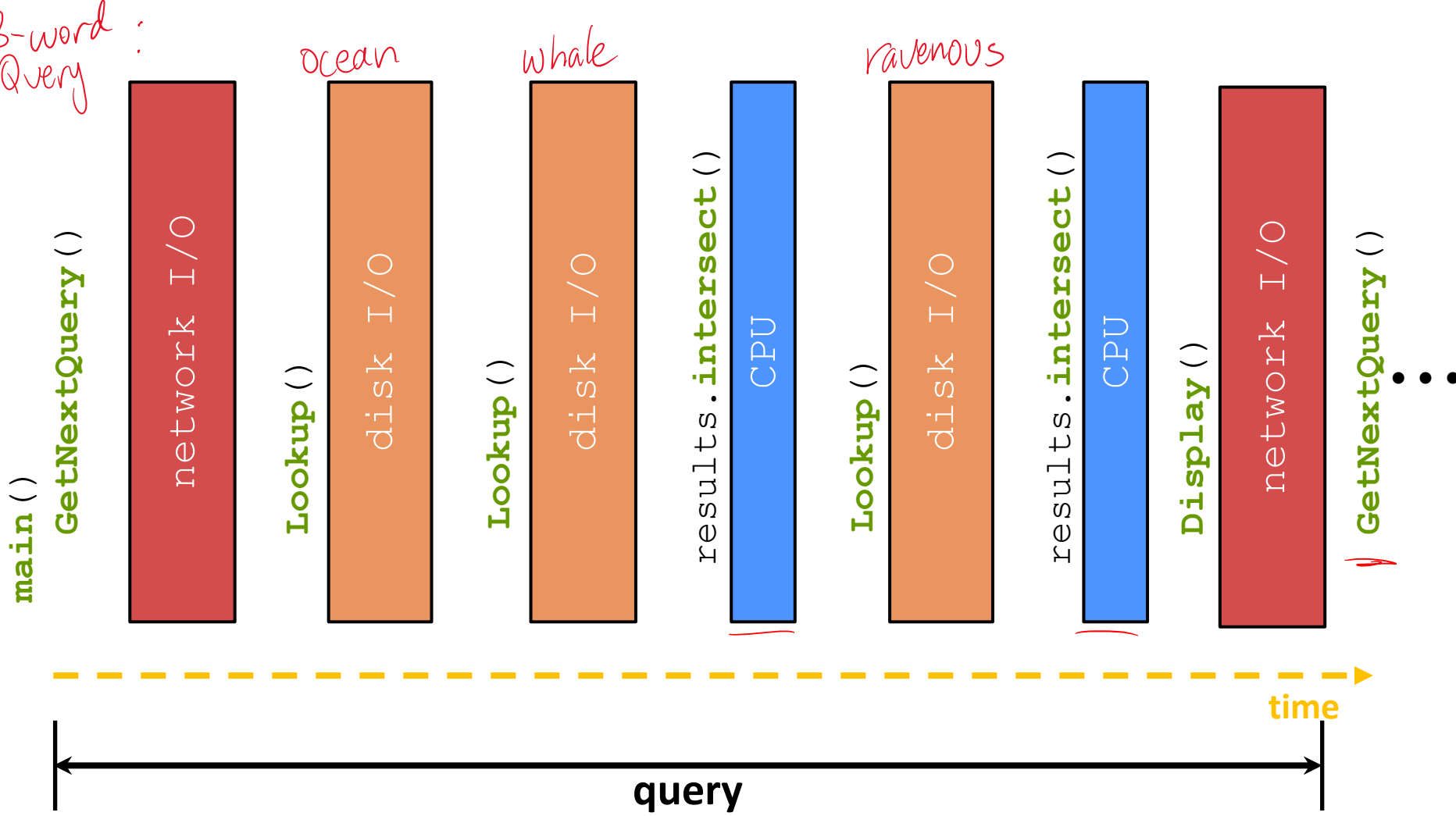
- Super(?) simple to build/write

❖ Disadvantages:

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

Execution Timeline: a Multi-Word Query



3-word Query



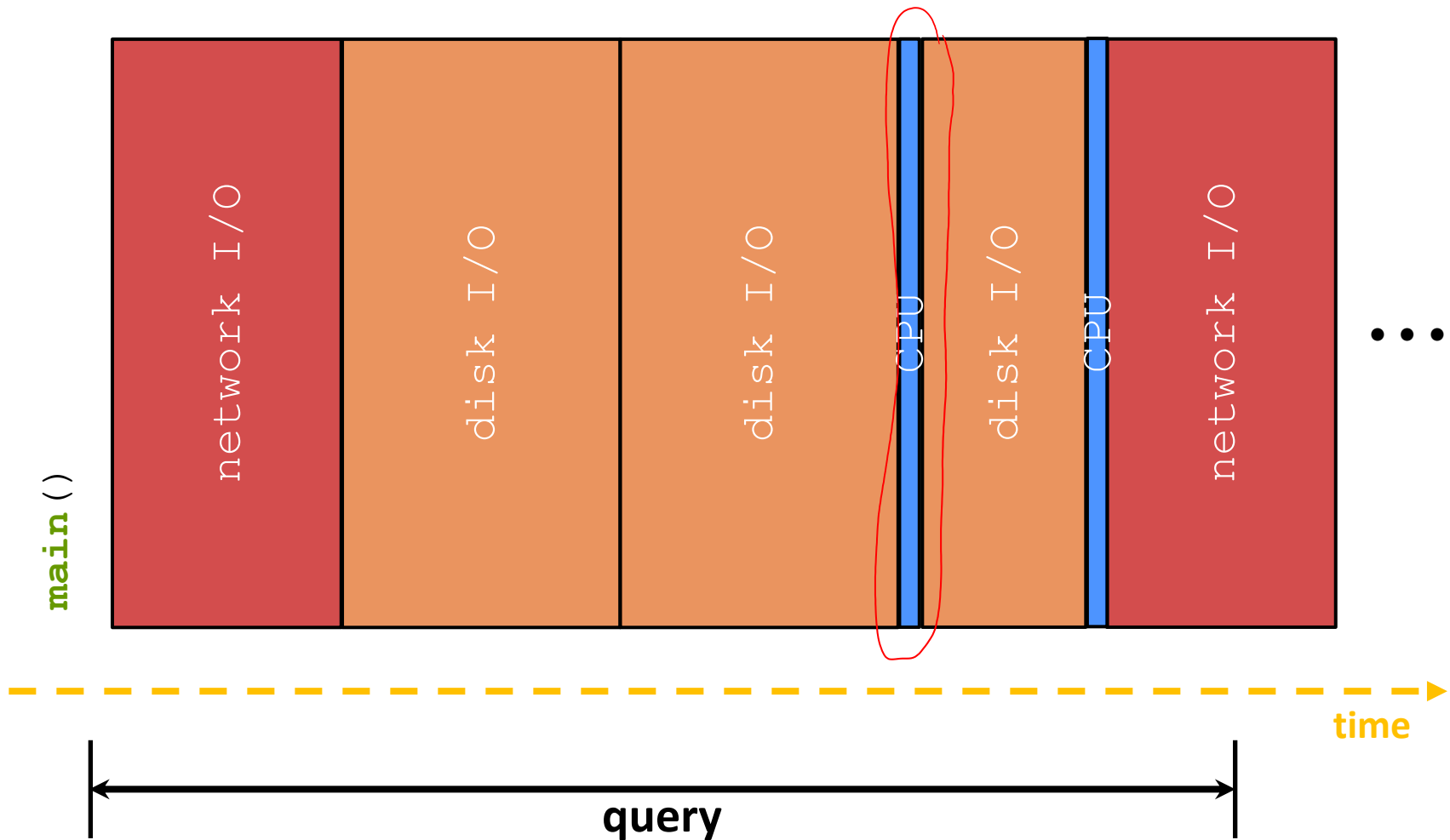
What About I/O-caused Latency?

- ❖ Jeff Dean's "Numbers Everyone Should Know" (LADIS '09)

| | |
|-------------------------------------|----------------------|
| L1 cache reference | <u>0.5 ns</u> |
| Branch mispredict | 5 ns |
| L2 cache reference | 7 ns |
| Mutex lock/unlock | 100 ns |
| Main memory reference | 100 ns |
| Compress 1K bytes with Zip | 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 | <u>30,000,000 ns</u> |
| Send packet CA->Netherlands->CA | 150,000,000 ns |



Execution Timeline: (Loosely) To Scale



Multiple (Single-Word) Queries

is the Query Number

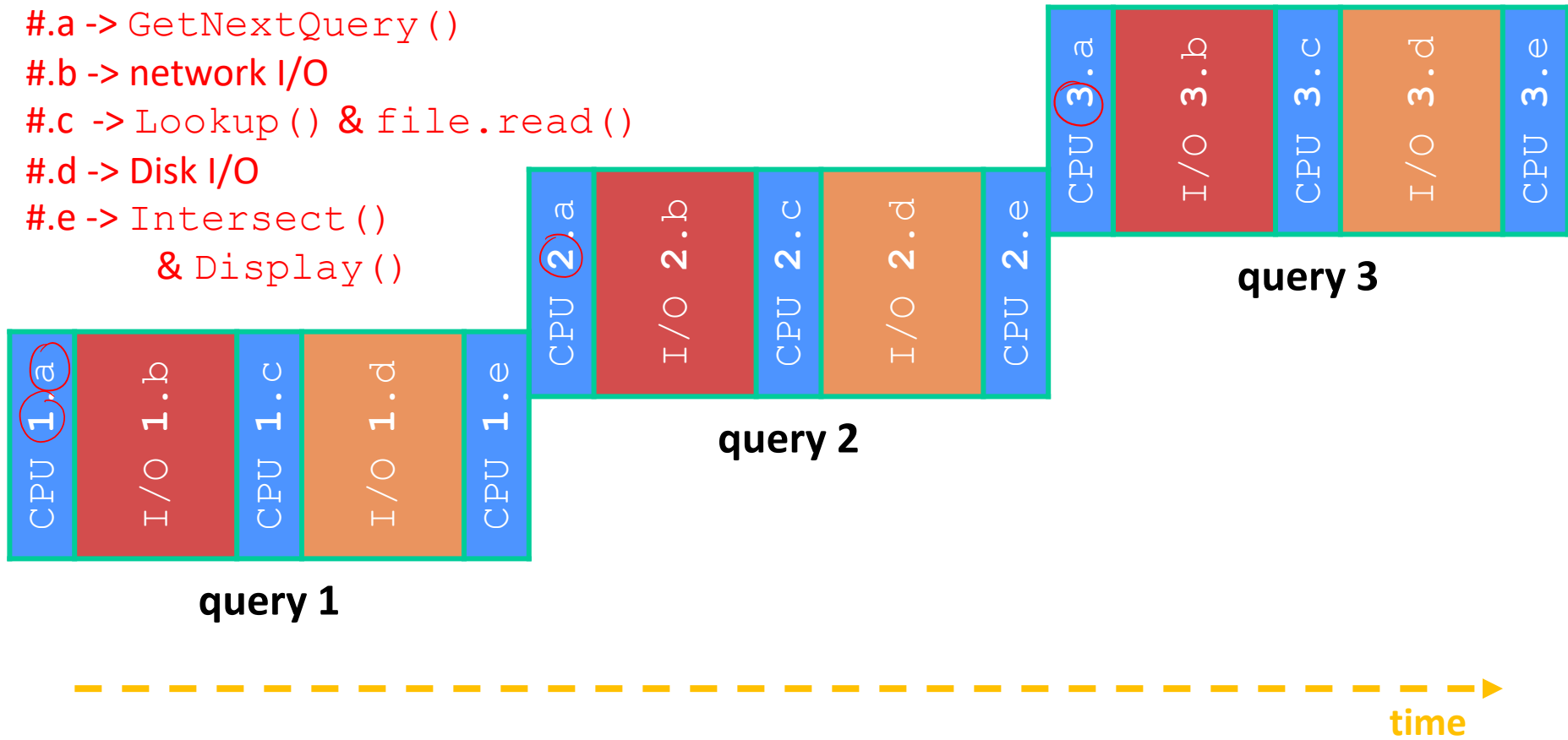
#.a -> GetNextQuery()

#.b -> network I/O

#.c -> Lookup() & file.read()

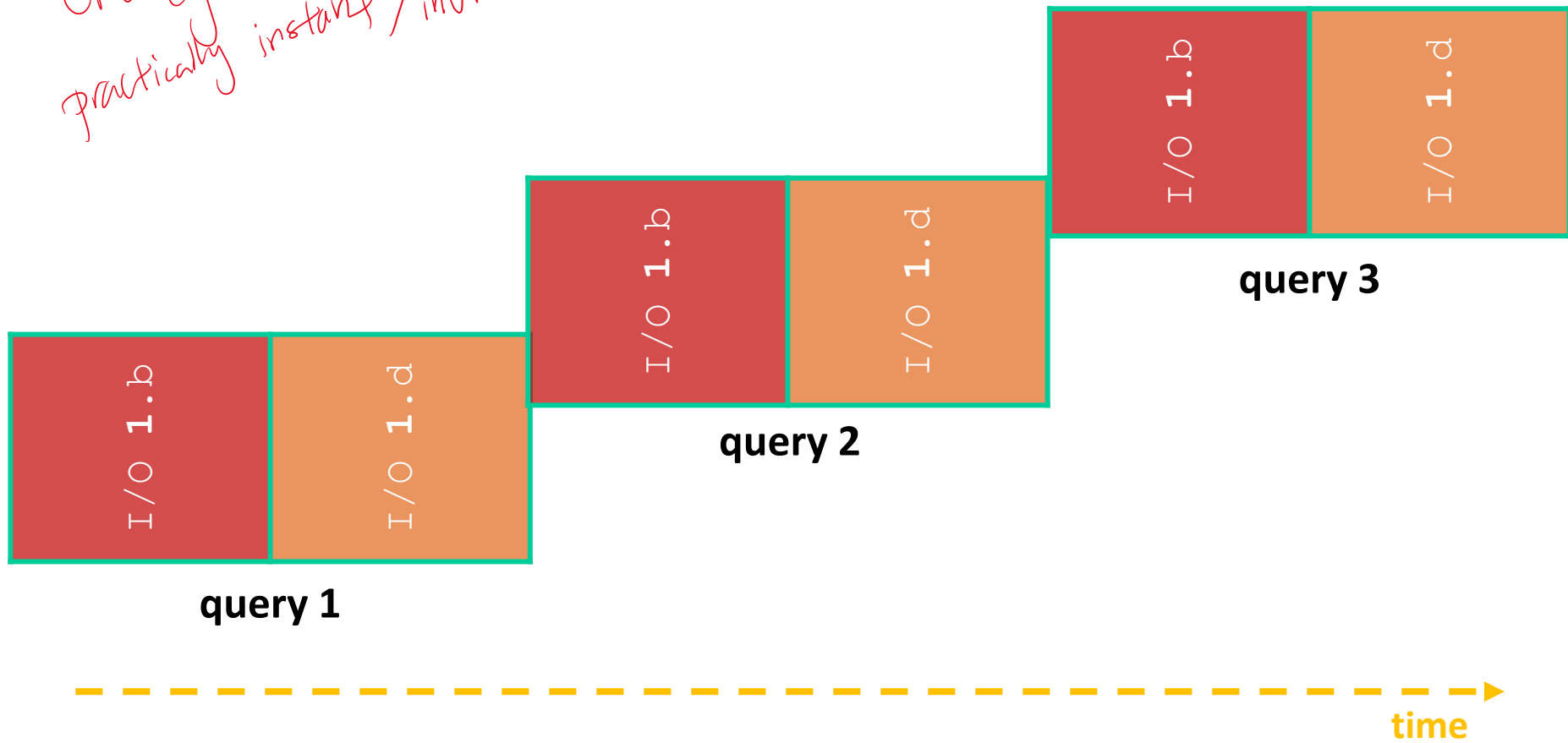
#.d -> Disk I/O

#.e -> Intersect()
& Display()

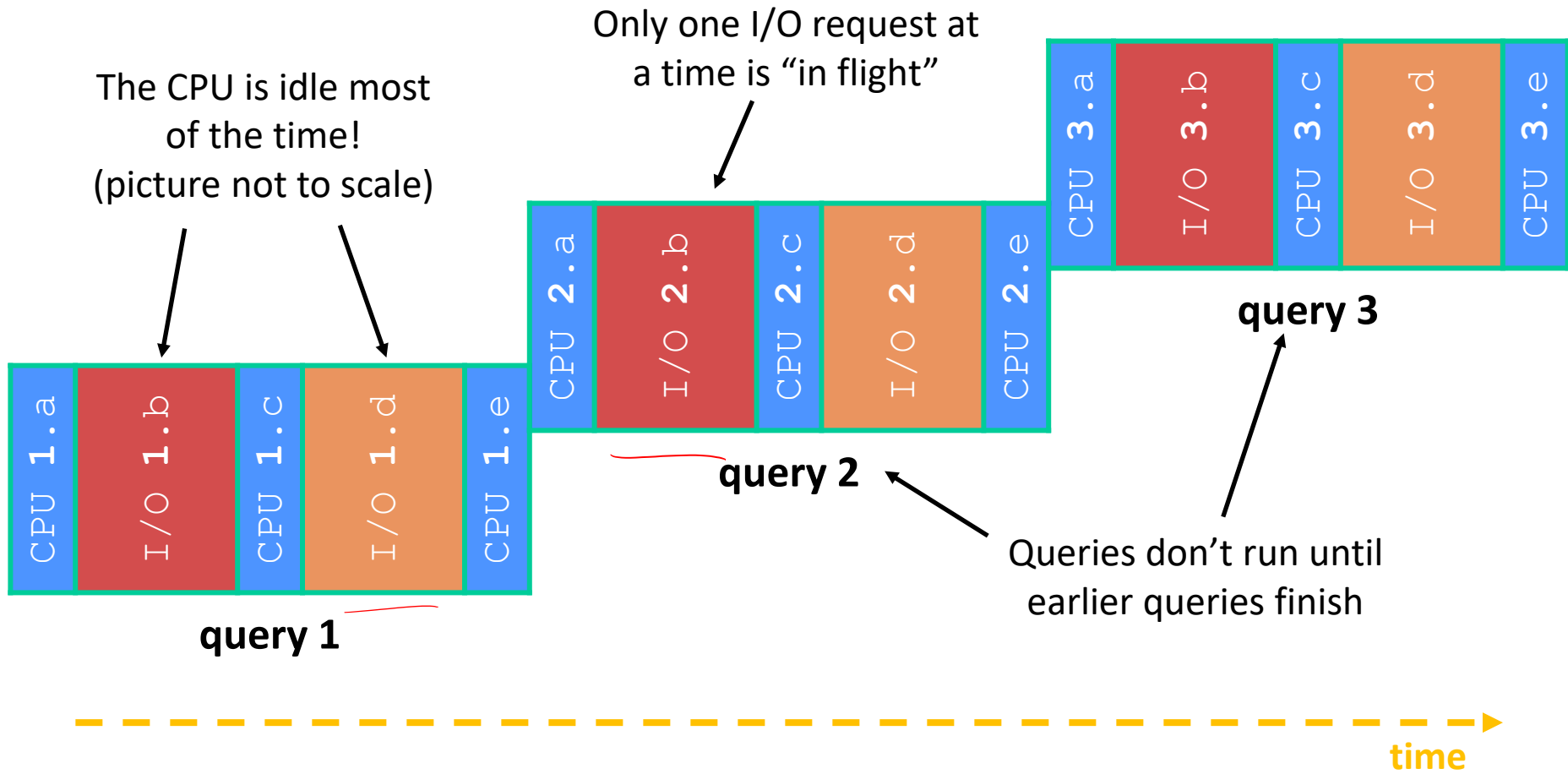


Multiple Queries: (Loosely) To Scale

CPU cycles are practically instant/invisible



Sequential Issues



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
- ❖ **Concurrency and Concurrency Methods**

Concurrency

- ❖ Concurrency \neq parallelism
 - **Concurrency is working on multiple tasks with overlapping execution times**
 - Parallelism is executing multiple CPU instructions *simultaneously*
- ❖ Our search engine could run concurrently in multiple different ways:
 - Example: 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: Execute multiple ***queries*** at the same time
 - While one is waiting for I/O, another can be executing on the CPU

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 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”?

Worker Option 1: Processes (Review)

- ❖ Processes can `fork` “cloned” processes that have a parent-child relationship
 - Work almost entirely independent of each other
- ❖ The major components of a **process** are:
 - An address space to hold data and instructions
 - Open resources such as file descriptors
 - Current state of execution
 - Includes values of registers (including program counter and stack pointer) and parts of memory (the Stack, in particular)

Why Processes?

❖ Advantages:

- Processes are isolated from one another
 - No shared memory between processes
 - If one crashes, the other processes keep going
- No need for language support (OS provides `fork`)

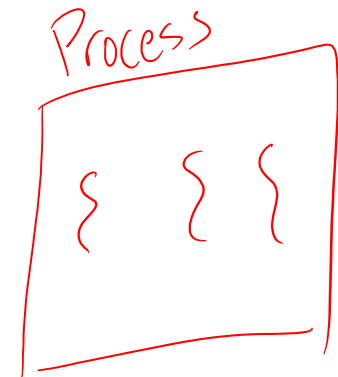
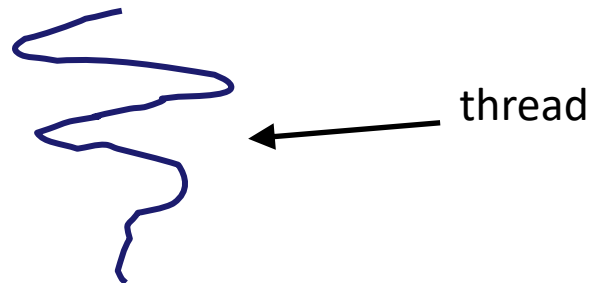
❖ Disadvantages:

- A lot of overhead during creation and context switching
- Cannot easily share memory between processes – typically must communicate through the file system

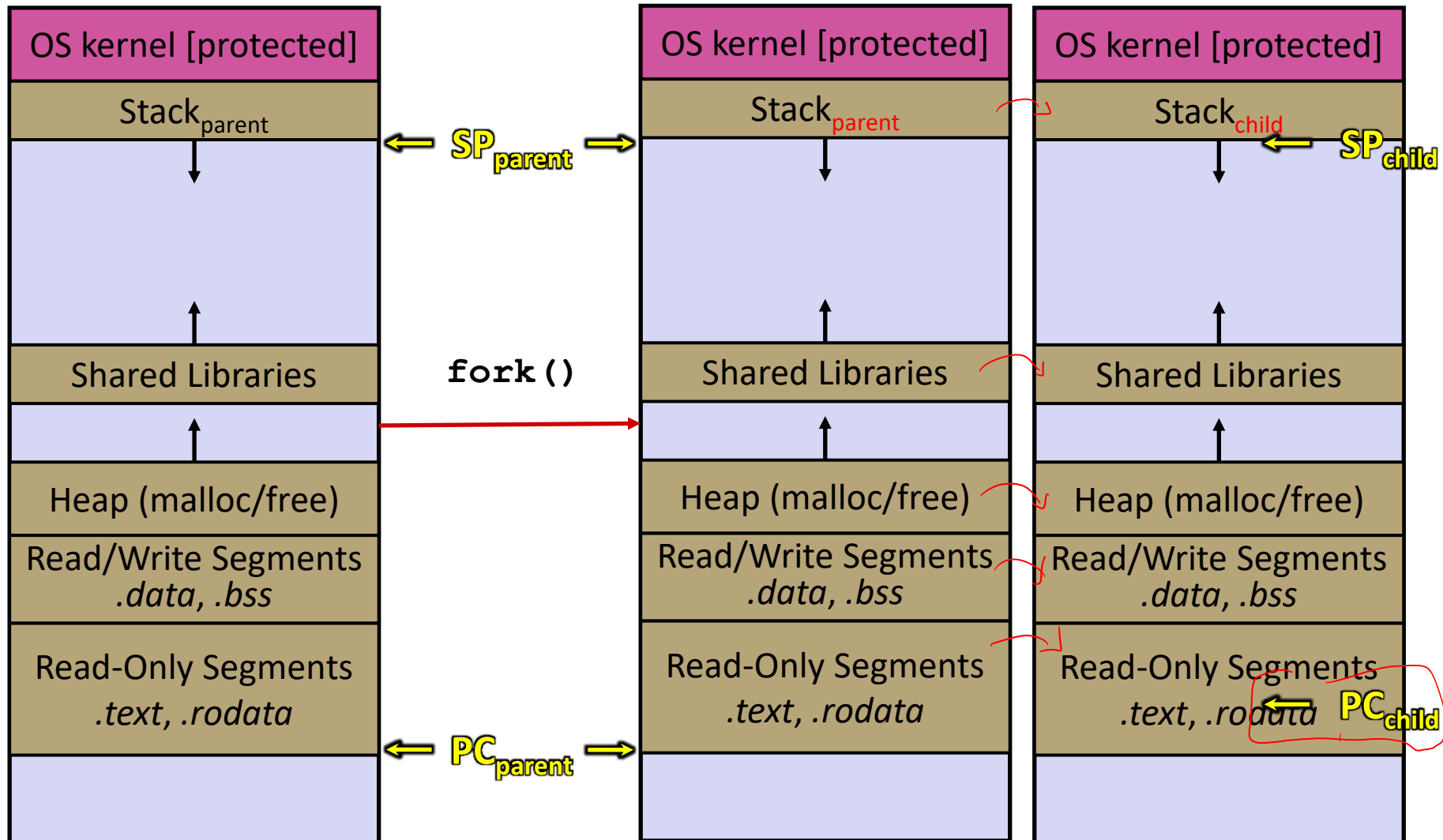
Worker Option 2: Threads

- ❖ From within a process, we can separate out the concept of a “thread of execution” (**thread** for short)
 - Processes are the containers that hold shared resources and attributes
 - e.g., address space, file descriptors, security attributes
 - Threads are independent, sequential execution streams (*units of scheduling*) within a process
 - e.g., stack, stack pointer, program counter, registers

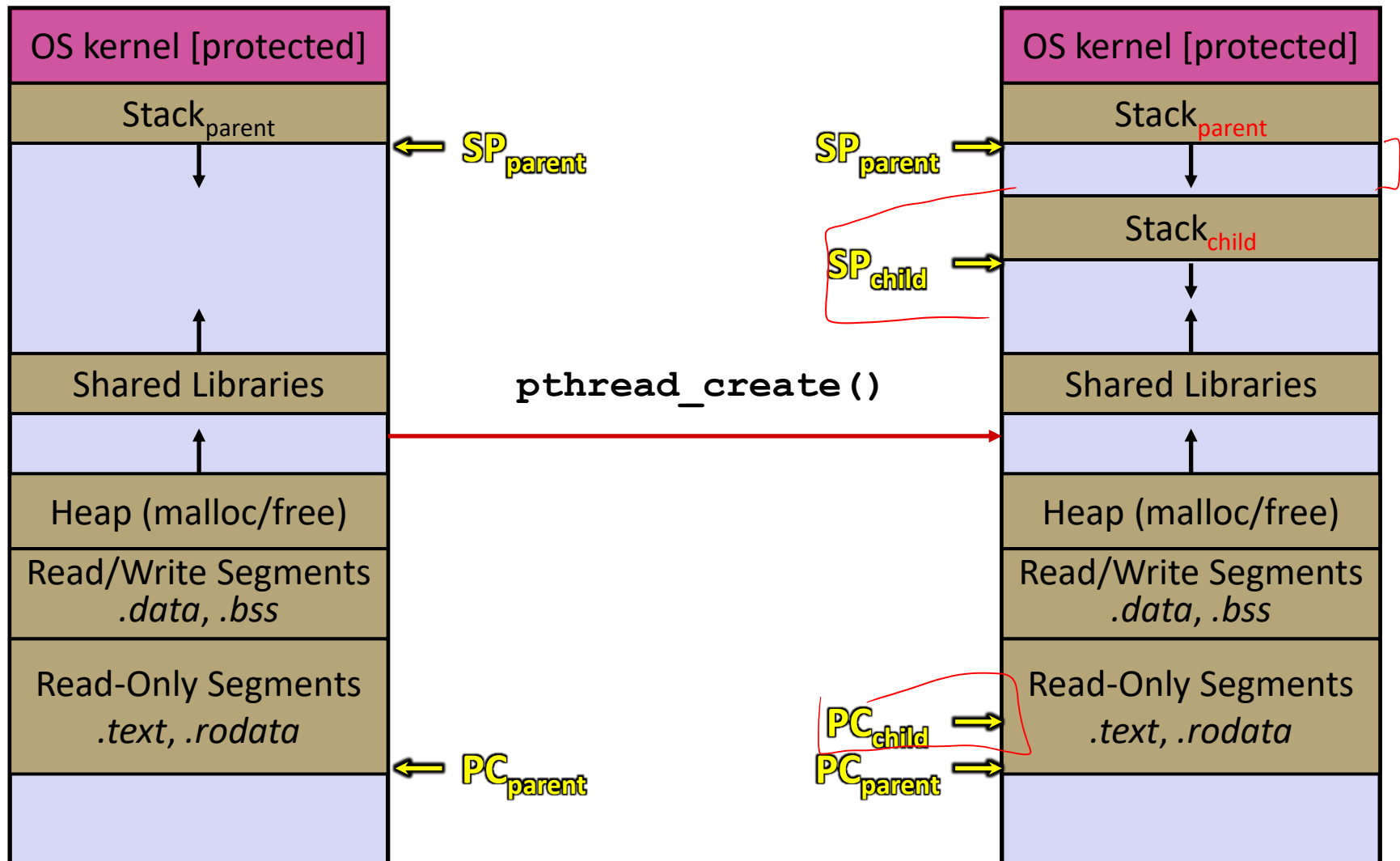
One process can hold many threads



Threads vs. Processes



Threads vs. Processes



Multi-threaded Search Engine (Pseudocode)

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

↳ swap w/ fork()

```
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);  
}
```

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

Does communication w/ client too

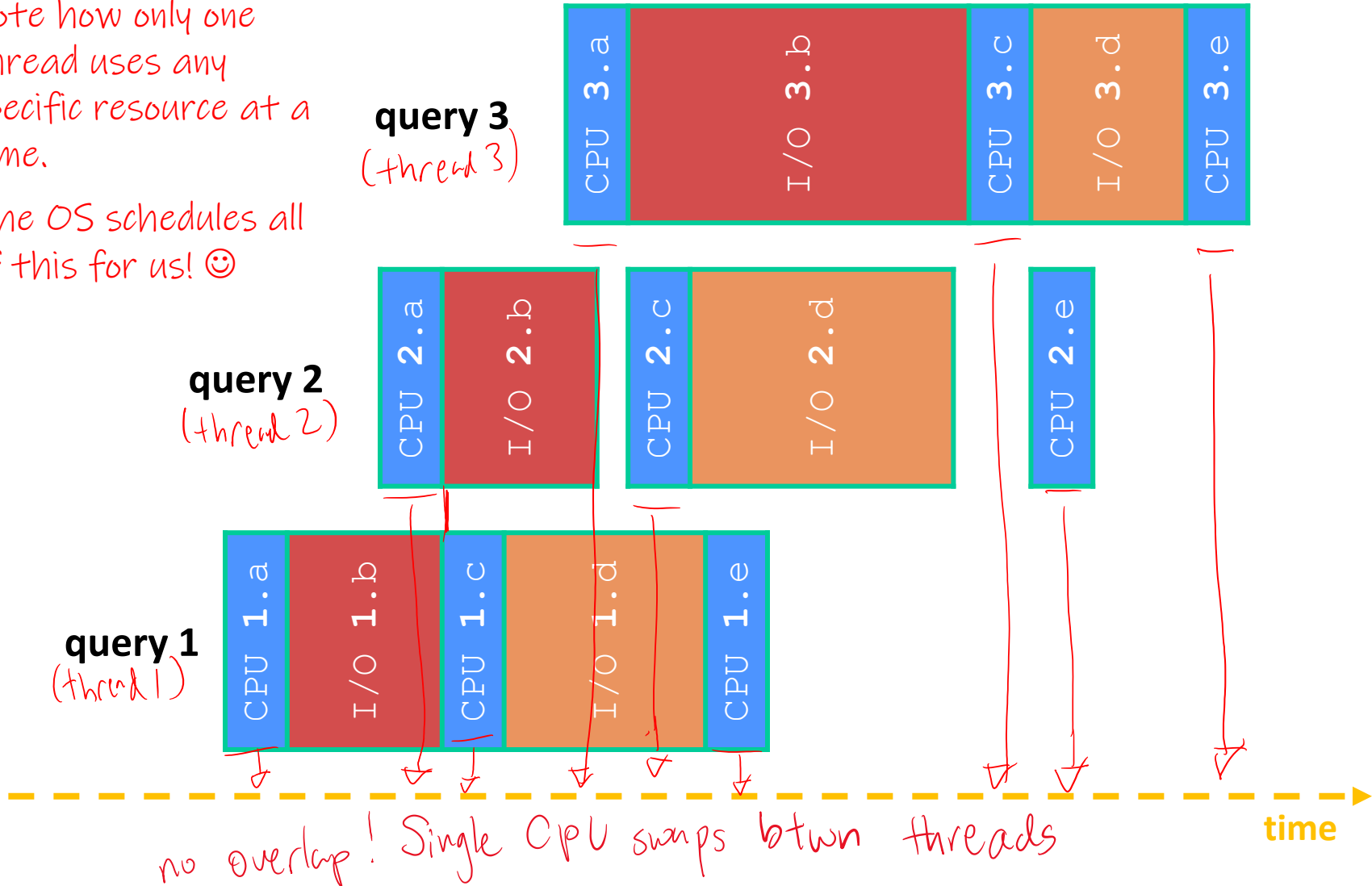
calls

Multi-threaded Search Engine (Execution)

(single 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
- Less overhead than processes during creation and context switching
- 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 ← *swapping still costs something*
 - Lock contention, context switch overhead, and other issues

- ❖ Need language support for threads

Alternate: 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 *fcntl()* *O_NONBLOCK*
 - Your program issues **read()** and **write()** system calls
 - If the read/write would block, the system call returns immediately *(errno == EWOULDBLOCK)* ↙ reports an error
 - Program can ask the OS which file descriptors are readable/writable *select()* or *poll()*
 - Program can choose to block while no file descriptors are ready

Alternate: Asynchronous I/O

- ❖ Using **asynchronous** I/O, your program (almost never) *blocks* on 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 by delivering an *event*

Event-Driven Programming

- ❖ Your program is structured as an *event-loop*

```
void dispatch(task, event) {  
  switch (task.state) {  
    case READING_FROM_CONSOLE:  
      query_words = event.data;  
      async_read(index, query_words[0]);  
      task.state = READING_FROM_INDEX;  
      return;  
    case READING_FROM_INDEX:  
      ...  
  }  
}
```

```
while (1) {  
  event = OS.GetNextEvent();  
  task = lookup(event);  
  dispatch(task, event);  
}
```

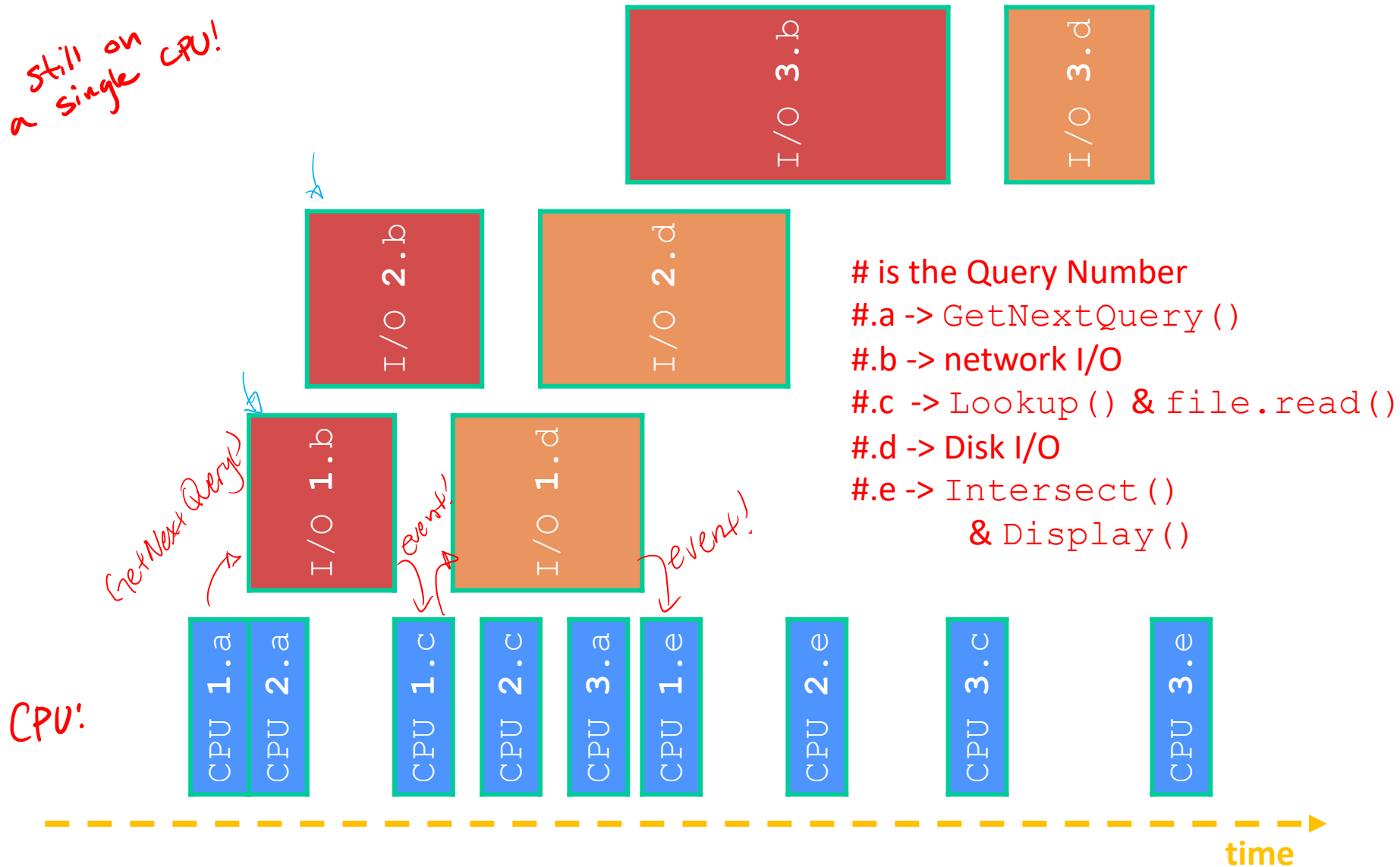
what code gets run depends on where we are in the program ("state") and what event we're handling

asynchronous notice to OS for Disk I/O

OS tells us what to handle next as things occur/finish

Asynchronous, Event-Driven

still on a single CPU!



Why Events?

❖ Advantages:

- Don't have to worry about locks and race conditions
- For some kinds of programs, especially GUIs, leads to a very simple and intuitive program structure
 - One event handler for each UI event

❖ Disadvantages:

- Can lead to very complex structure for programs that do lots of disk and network I/O
- * Sequential code gets broken up into a jumble of small event handlers
 - You have to package up all task state between handlers

lots of
small functions

↳ what if there are 100 words
in our query?

Outline (next two lectures)

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

Friday

Wednesday

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