Poll Everywhere

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Two Polls: About how long did Exercise 15 & 16 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 Winter 2026

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Relevant Course Information

- Homework 4 due next Thursday (3/12)
  - You can still use ***two*** late days (until Sunday, 3/15)

- Final Exam on Wednesday, 3/18 12:30-2:20 PM (110 min)
  - KNE 110 & 120
    - Look out for an Ed post with more details
  - Final review session on Friday, 3/13
    - CSE2 G10 and on Zoom 4:30-6:30 PM
  - One sheet of handwritten notes
  - Not cumulative

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`

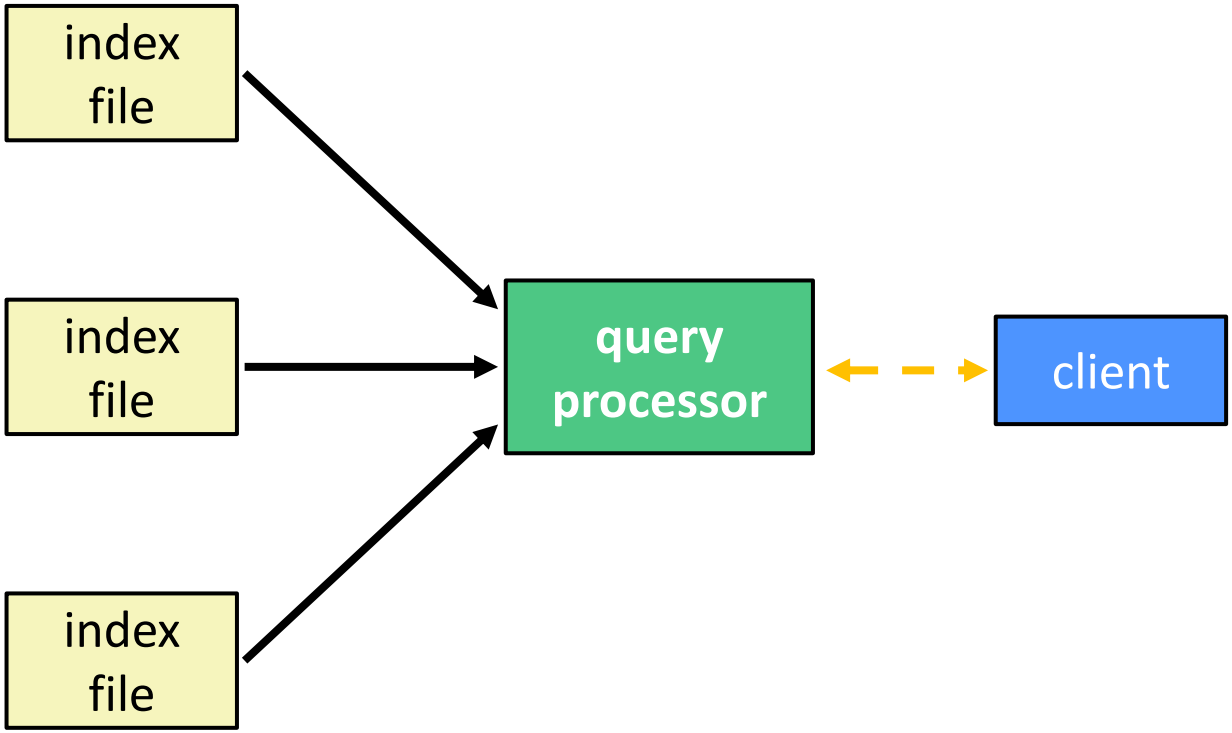
Lecture Outline

- **From Query Processing to a Search Server**
- 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)

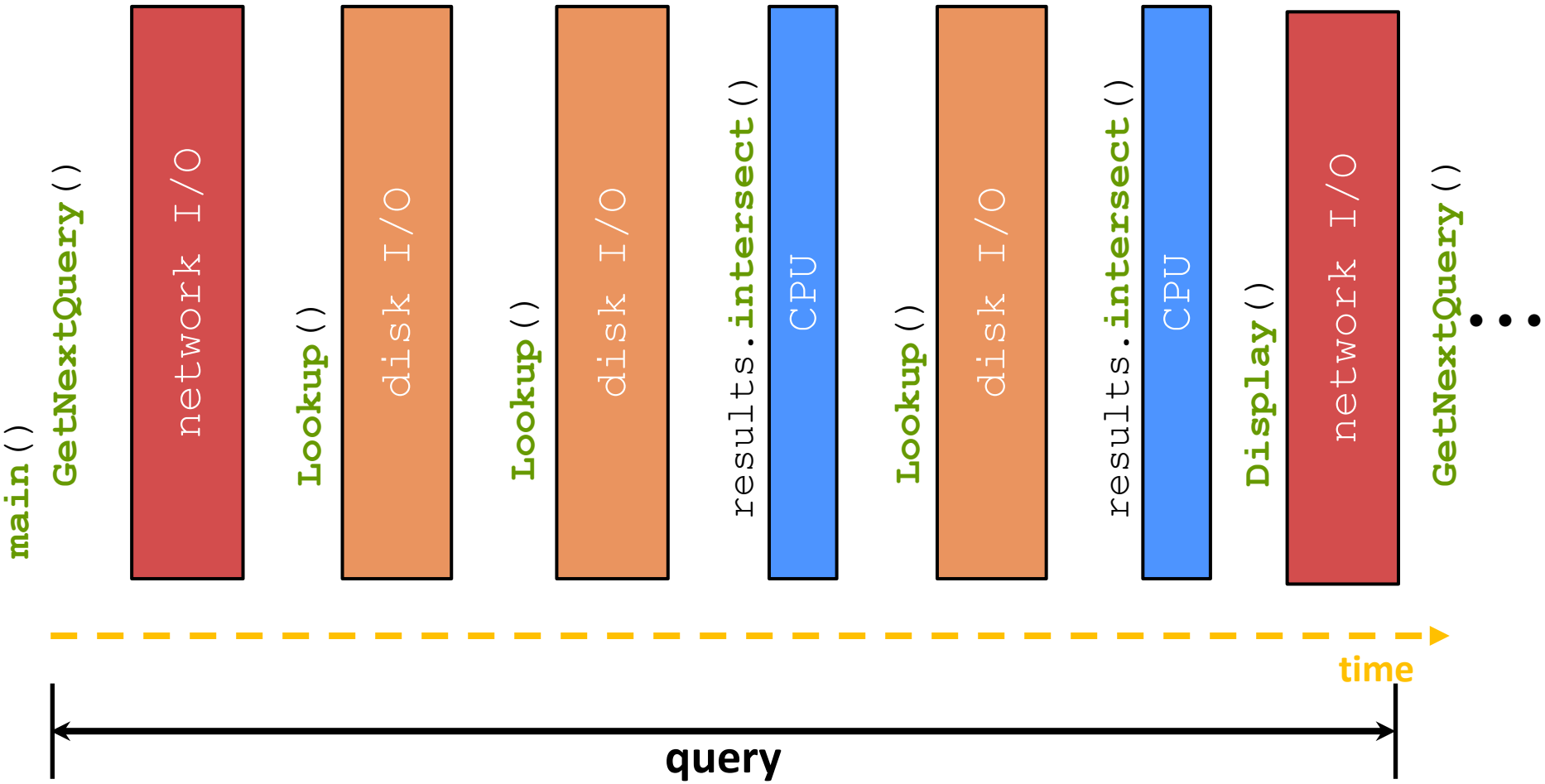
```
fn Lookup(string word) -> doclist:
  bucket = hash(word)
  hitlist = file.read(bucket)
  foreach hit in hitlist:
    doclist.append(file.read(hit))
  return doclist

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

Full implementation in `searchserver_sequential/`

Why Sequential?

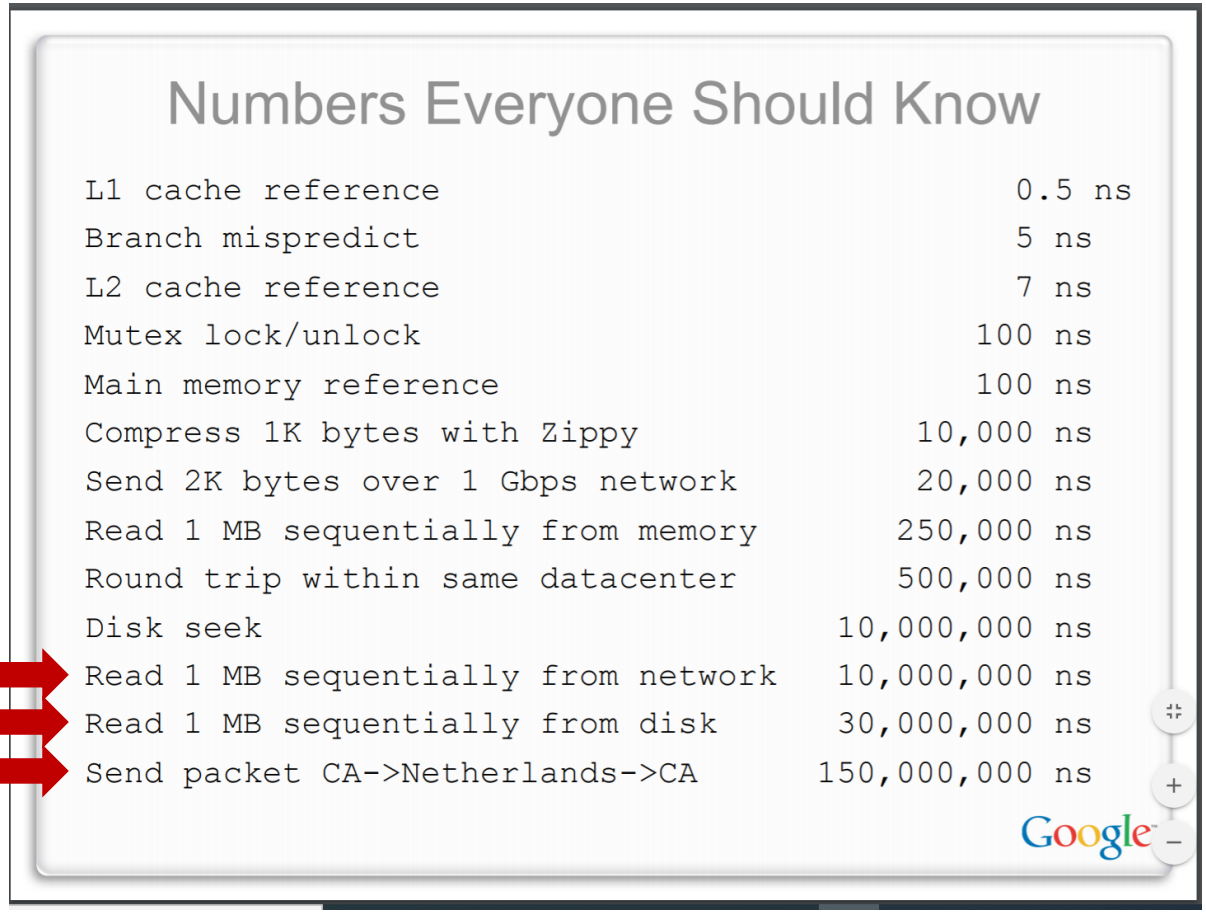
- Advantages:
  - Super(?) simple to build/write
- Disadvantages:
  - Incredibly poor performance
    - One slow client will cause *all* others to block
    - Poor utilization of resources (CPU, network, disk)

Execution Timeline: a Multi-Word Query

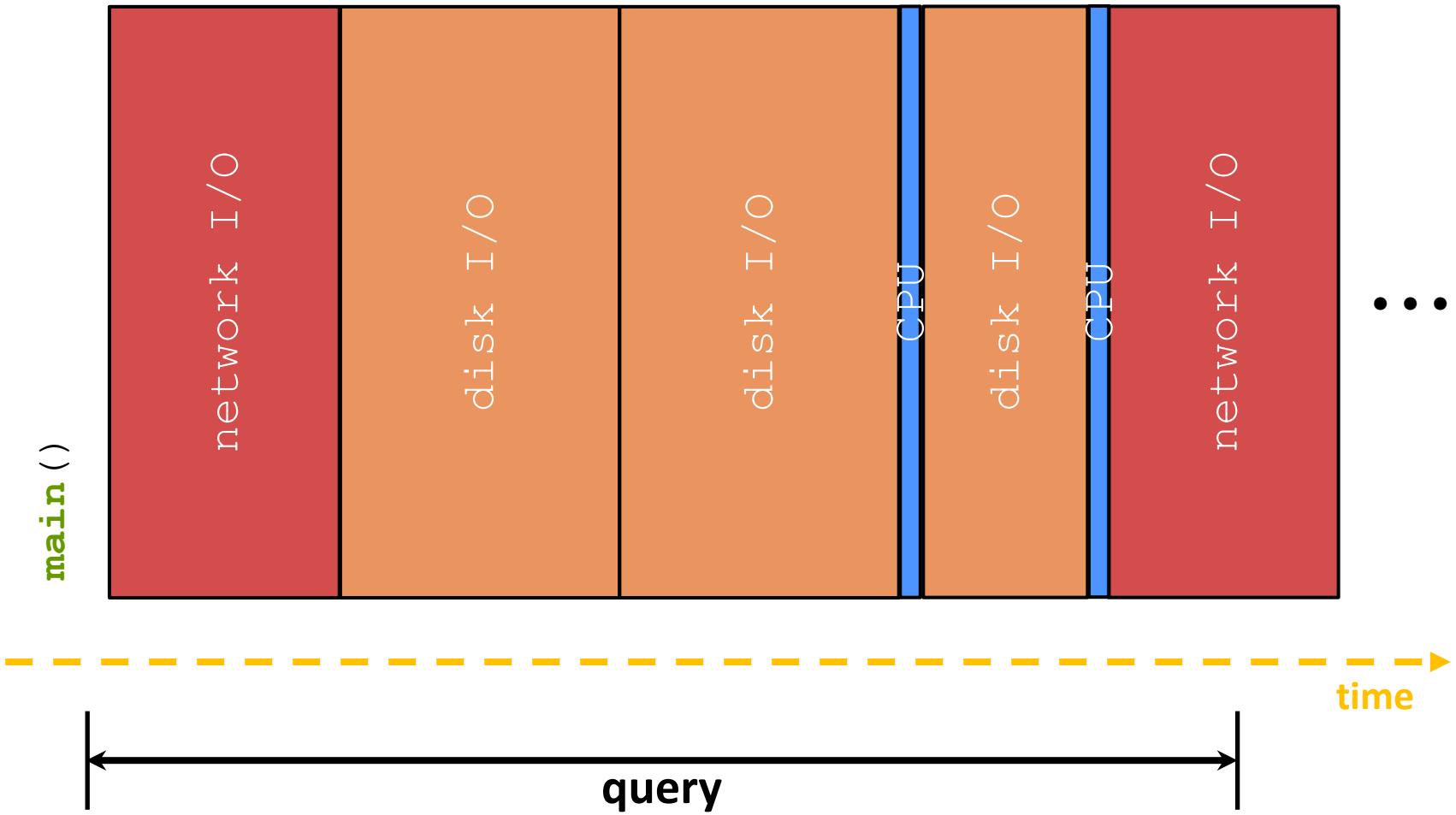


What About I/O-caused Latency?

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

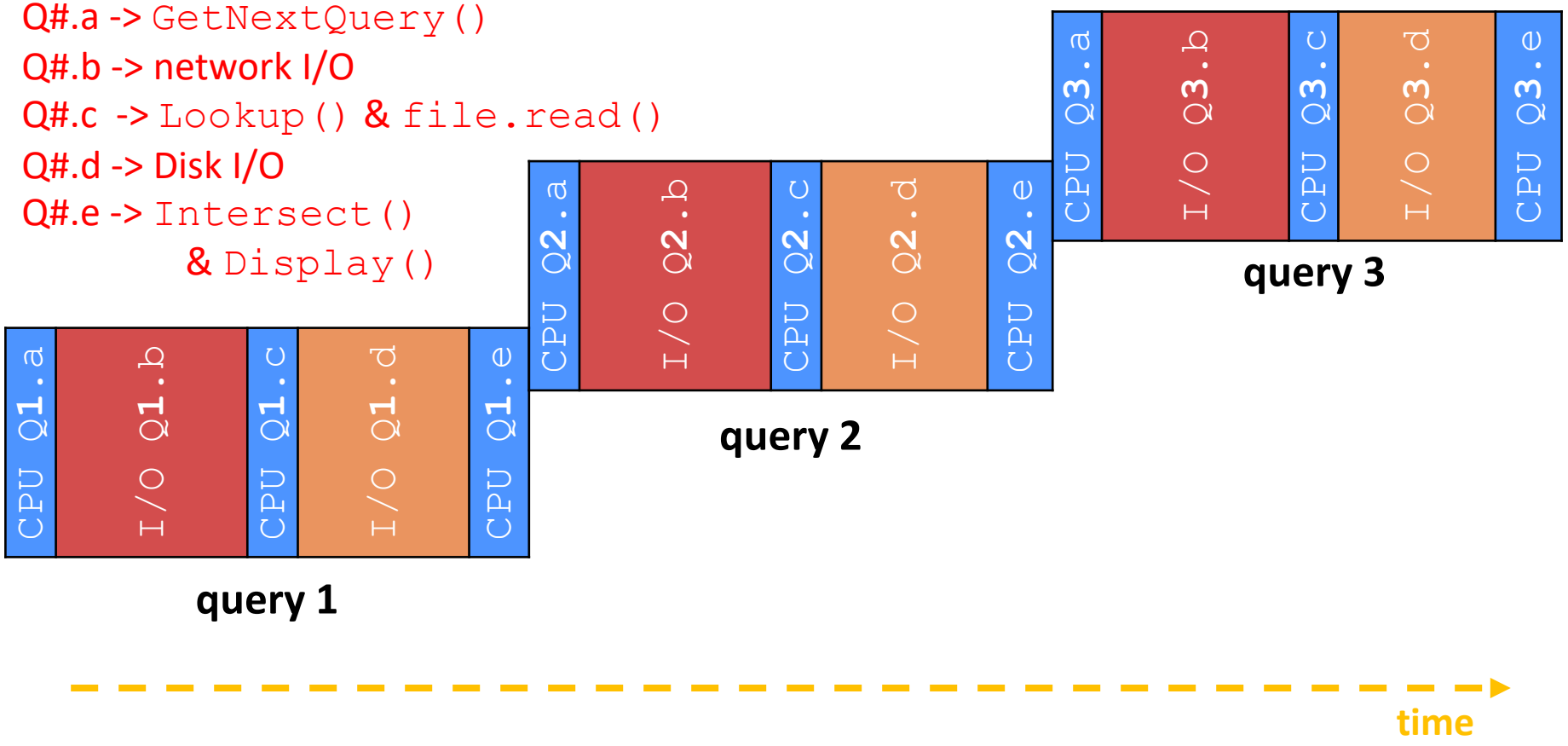


Execution Timeline: (Loosely) To Scale

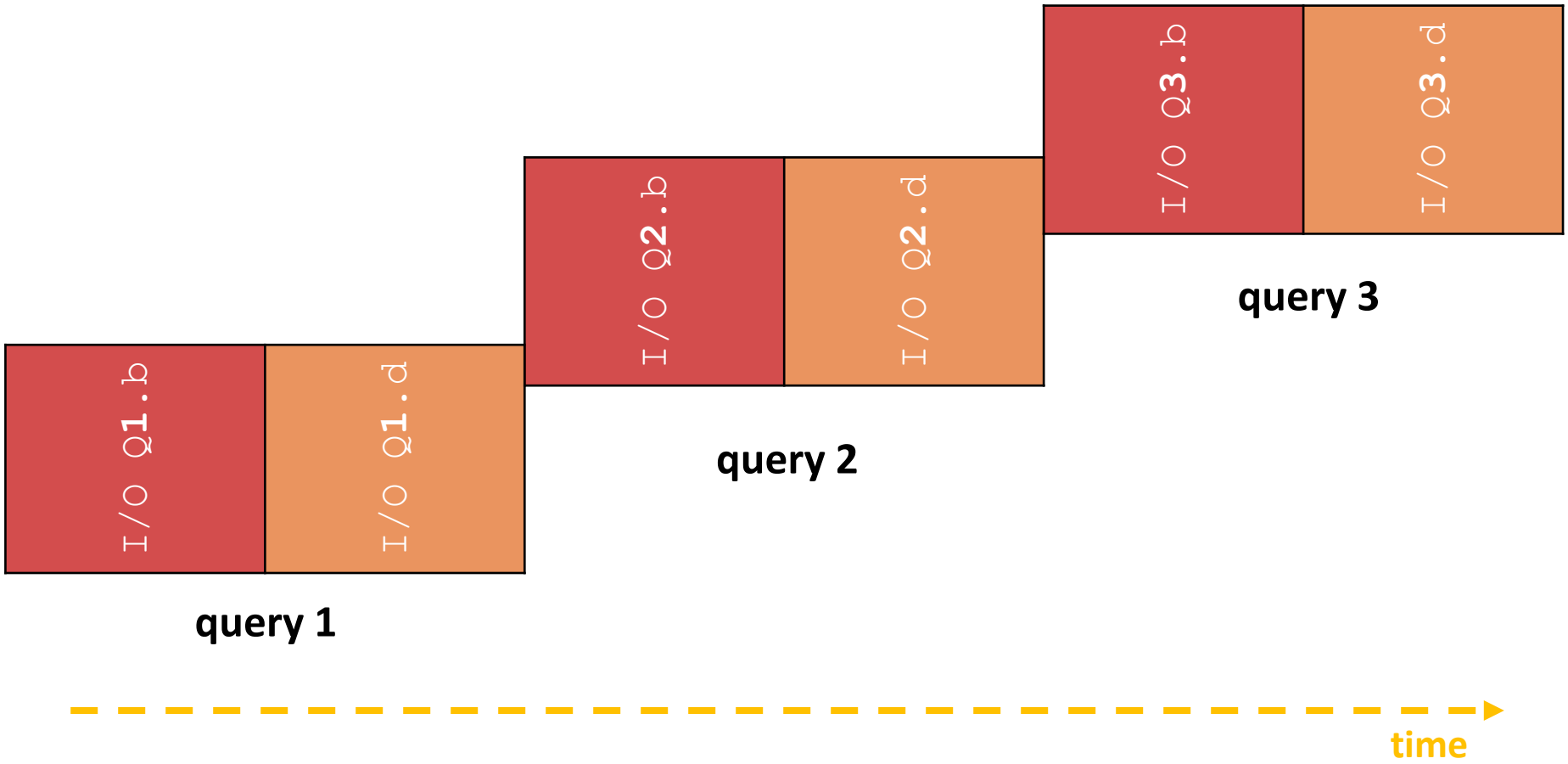


Multiple (Single-Word) Queries

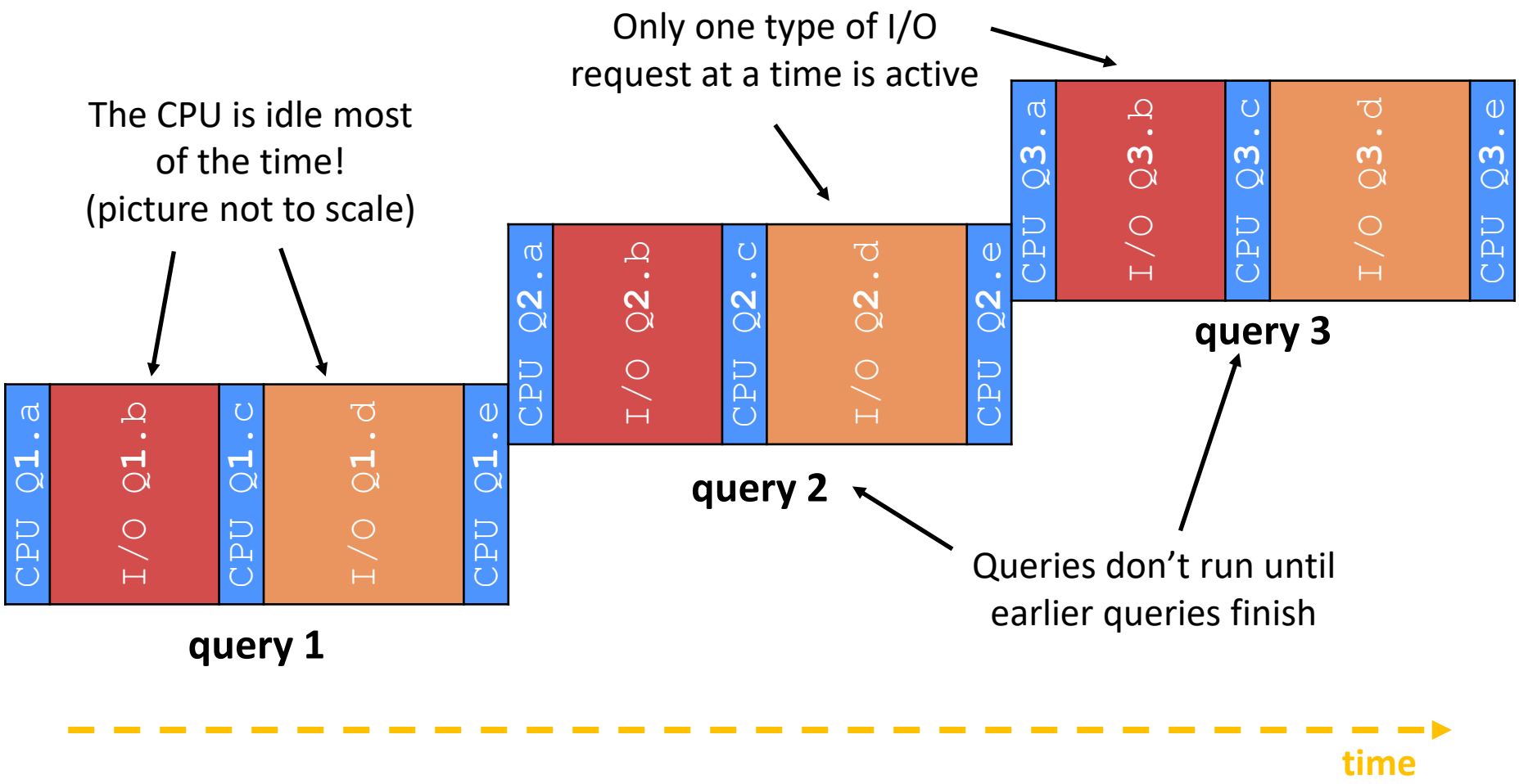
Q# is the Query Number
Q#.a -> `GetNextQuery()`
Q#.b -> network I/O
Q#.c -> `Lookup()` & `file.read()`
Q#.d -> Disk I/O
Q#.e -> `Intersect()` & `Display()`



Multiple Queries: (Loosely) To Scale



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 and network I/O can be very slow (10 million times slower …)
- Only one type of I/O request is active 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 != 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 use `fork` to "clone" itself
  - These two processes 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)

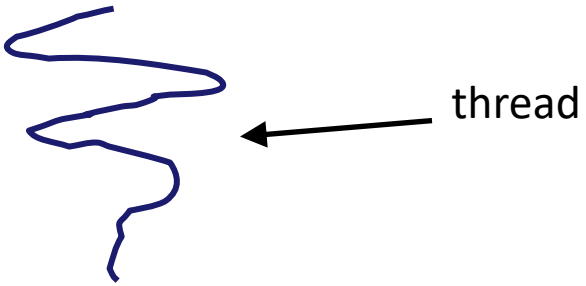
Why Processes?

- 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`)

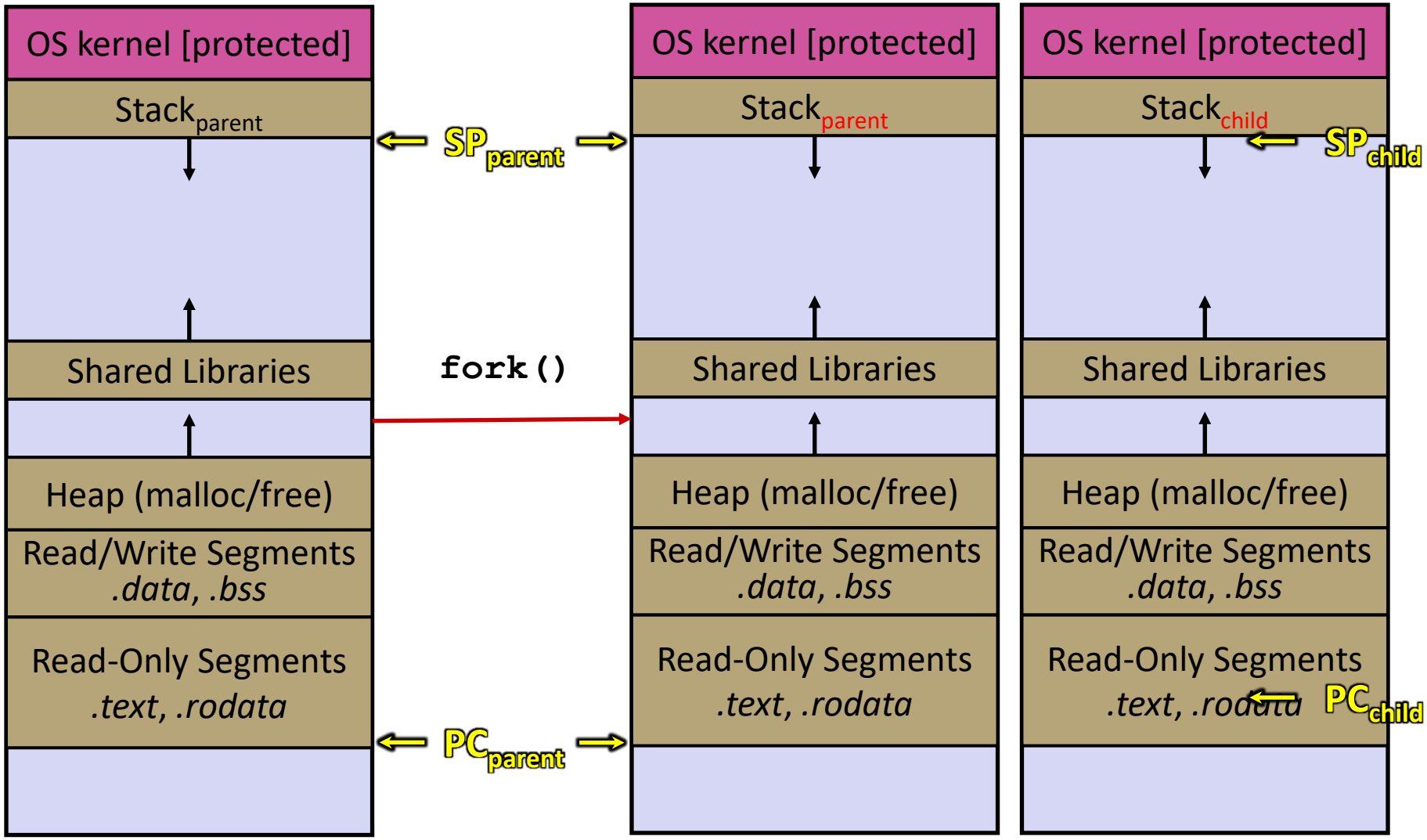
- Disadvantages:
  - A lot of overhead during creation and context switching
  - Cannot easily share memory between processes
    - Typically must communicate through the file system
    - *e.g.*, POSIX pipe/FIFO: one way data stream between two processes

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



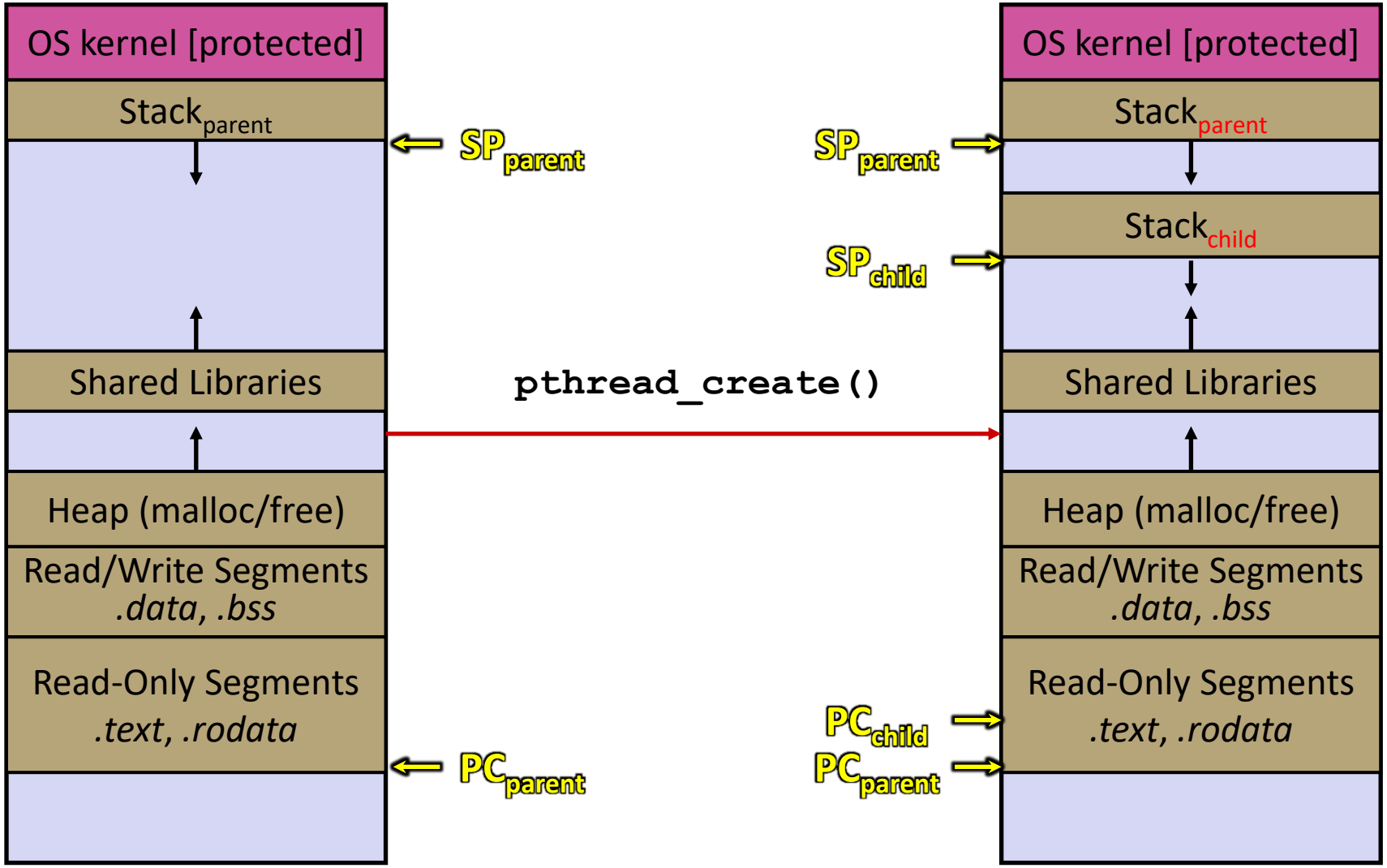
Threads vs. Processes



Before

After

Threads vs. Processes



Multi-threaded Search Engine (Pseudocode)

```
fn main():
  while (true):
    string[] query_words = GetNextQuery()
    CreateThread(job=ProcessQuery, input=query_words)
```

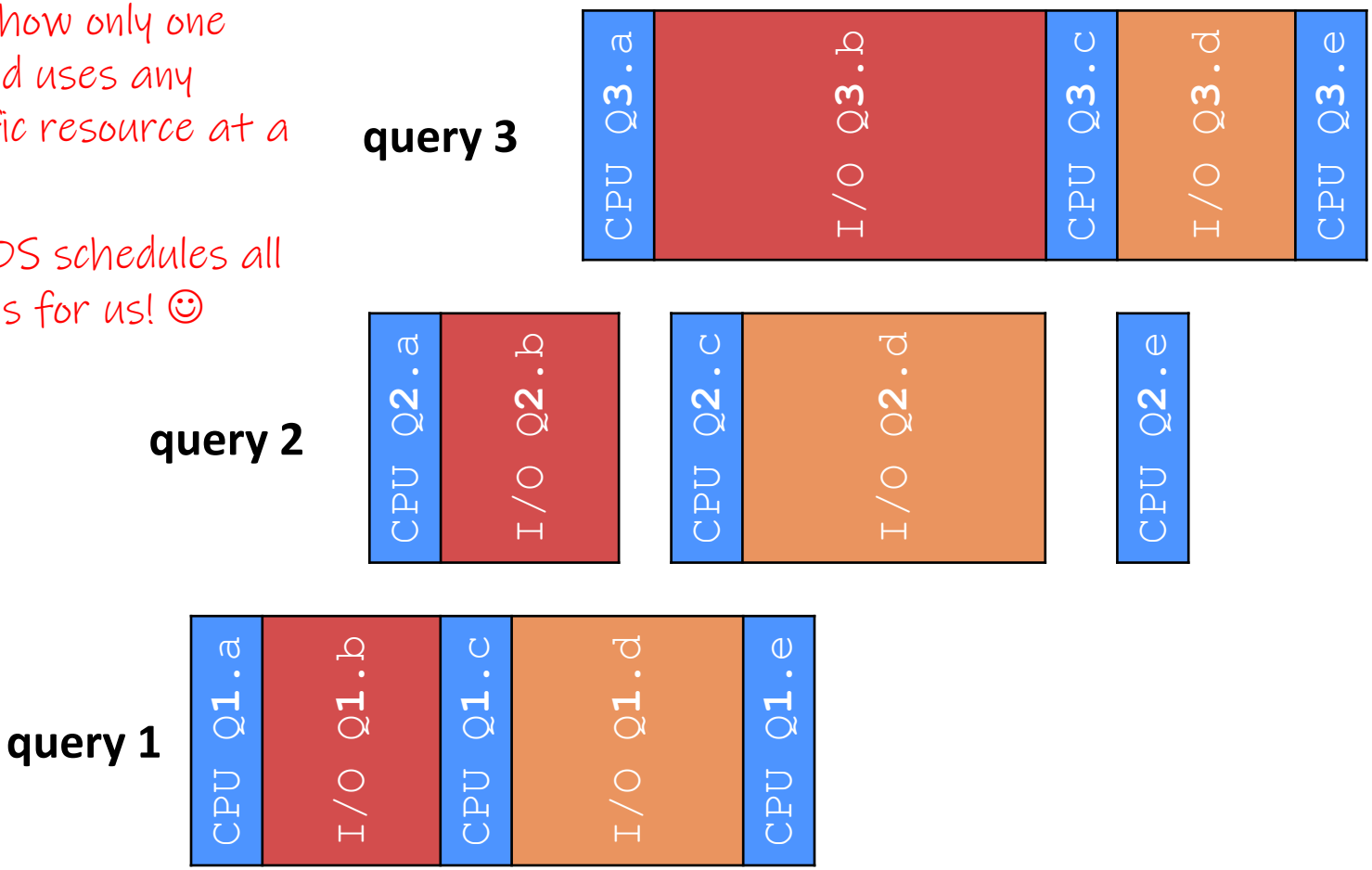
```
fn Lookup(string word) -> doclist:
  bucket = hash(word)
  hitlist = file.read(bucket)
  foreach hit in hitlist
    doclist.append(file.read(hit))
  return doclist

fn 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!

Multi-threaded Search Engine (Execution)

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
    - Lock contention, context switch overhead, and other issues
  - Need language support for threads

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Which of the following statements about threads and processes are TRUE?

A. Each thread has its own Stack and Heap

B. Each thread runs on a separate CPU core

C. Threads within the same process share file descriptors

D. Parent and child processes initially share file descriptors

E. We're lost…

Alternative 1: 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
    - Use **`poll`**`()`, **`epoll`**`()` (Linux), or **`kqueue`**`()` (macOS)
    - Set a timeout parameter
      - 0 ms = non-blocking
      - 100 ms = short blocking
      - -1 ms = block until ready

Alternative 2: Async I/O via Events

- Using asynchronous I/O, your program (almost never) *blocks* on I/O

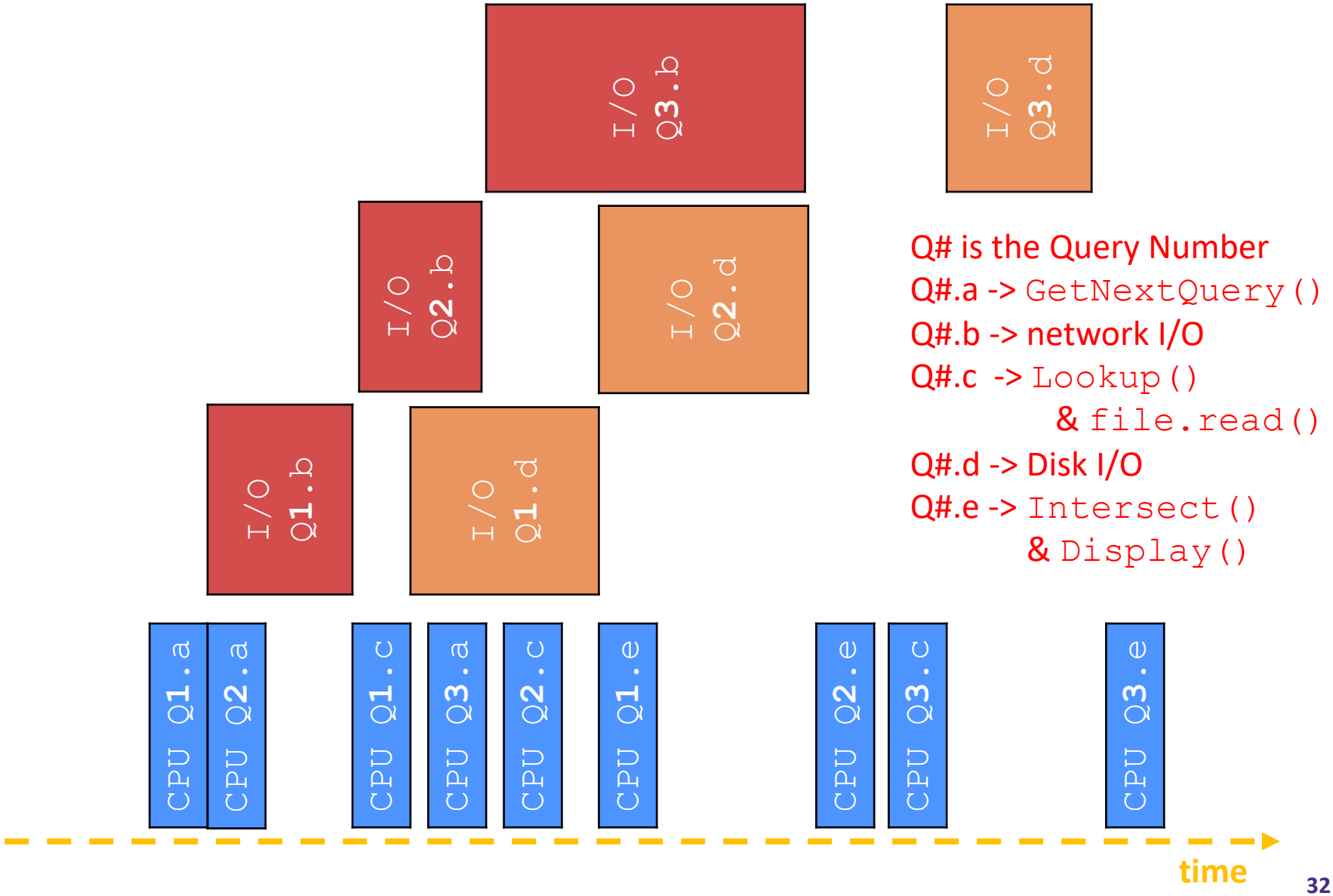
- Event-driven programming is the main paradigm for async
  - When you need to read more data, you register interest in the data with the OS and then switch to a separate task
    - The OS handles the details of issuing the read from the disk, network, console, etc.
  - When data becomes available, the OS lets you know by delivering an ***event***
  - It is common to register interest by storing a pointer to the function you would like to run when the event happens
    - This is referred to as a "callback function"

Event-Driven Programming (Pseudocode)

```
let fd_group = event_group()

fn main():
  let listener_fd = listen("localhost:8080")
  fd_group.register_callback(listener_fd, AcceptClient)

  while(true):
    let event = event_poll_wait(fd_group)
    event.callback(event.fd, event.arg)

fn AcceptClient(listener_fd):
  let connection_fd = accept(listener_fd)
  fd_group.register_callback(connection_fd, HandleRequest)

fn HandleRequest(connection_fd):
  let request_text = read(connection_fd)
  let filename = extract_filename(request_text)
  let file_fd = open(filename)
  let file_body = read(file_fd)
  write(connection_fd, file_body)
  close(file_fd)
```

C++ implementation using ***epoll*** in `event_server/`

Asynchronous, Event-Driven



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Why Events?

- Advantages:
  - Don't have to worry about locks and data races
  - 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 complex structure for programs that do lots of 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
    - "Callback Hell", "Callback Pyramid"

Event-Driven vs. Threads

- "Node.js Is Bad Ass Rock Star Tech" (2012) [1:15-2:15]
- *"[JavaScript] uses a single-threaded loop that dispatches events to handlers. It's a proven model that solves some concurrency problems, but at the cost of* ***code complexity****…*
- *[You must be] on the lookout for blocking operations that should be* ***split into little pieces****, each perfectly tailored to optimize throughput…*
  - *Do you know what this reminds me of?... The invention of threads.*
- *Threading libraries do exactly what you are doing manually. They break up pieces of code to be executed, intermittently switching from instructions that are waiting on I/O to instructions that are ready to run, but your sequential code stays intact.* ***You may recall sequential code. That's the code you can read****."*

Outline (next two lectures)

- We'll look at different `searchserver` implementations
  - Concurrent via dispatching threads – **`pthread_create()`**
    - **Introduced in section tomorrow**!
  - Concurrent via forking processes – **`fork()`**

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