Poll Everywhere

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 Winter 2023

Instructor: Justin Hsia

Teaching Assistants:

Adina Tung
Danny Agustinus
Edward Zhang
James Froelich
Lahari Nidadavolu
Mitchell Levy
Noa Ferman
Patrick Ho
Paul Han
Saket Gollapudi
Sara Deutscher
Tim Mandzyuk
Timmy Yang
Wei Wu
Yiqing Wang
Zhuochun Liu

Relevant Course Information

- Homework 4 due 1 week from tomorrow (3/9)
  - Partner form due end of tomorrow
  - You can still use ***two*** late days (until Sunday, 3/12)
- Exercise 11 due Friday
- Exercise 12 (the last exercise™) to be released Friday
  - Consumer-producer concurrency
  - Due Wednesday 3/8 @ 11 am
- Final Exam (Monday, 3/13 – Wednesday, 3/15)
  - Same policies as the midterm
  - ex8-ex12, hw3-hw4, overall course questions

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`

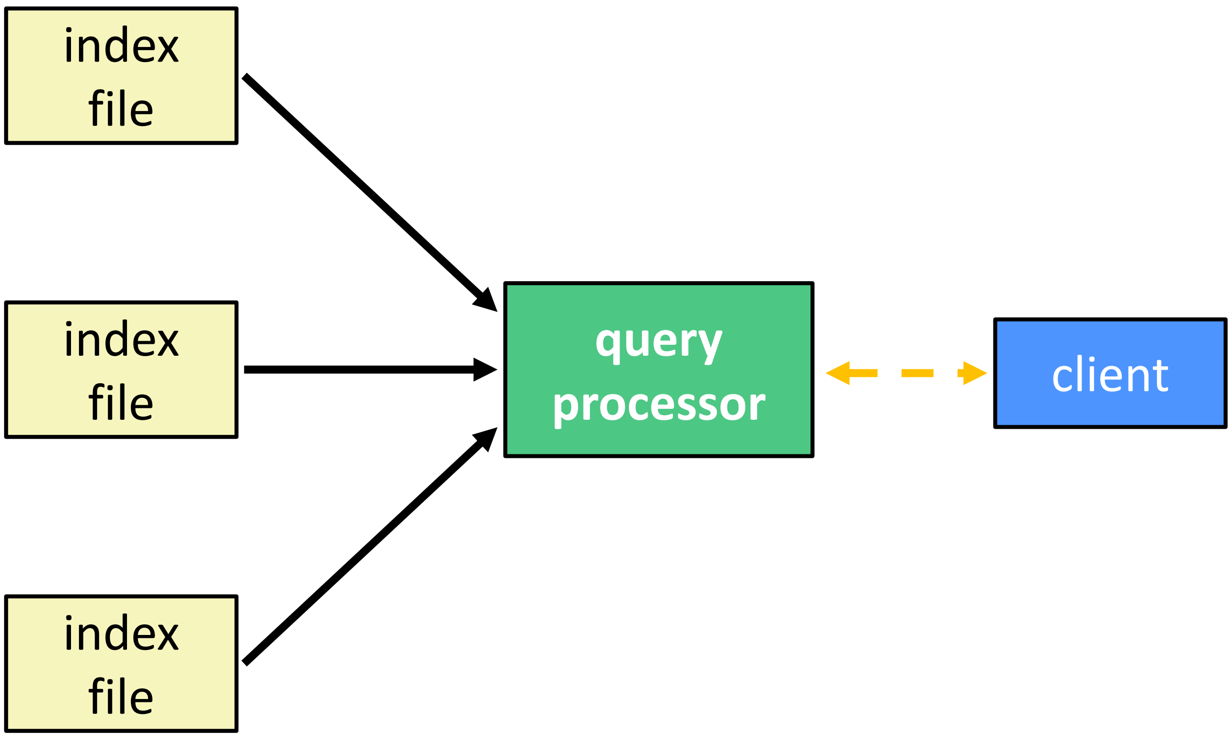
Lecture Outline

- **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)

```
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
  }
}
```

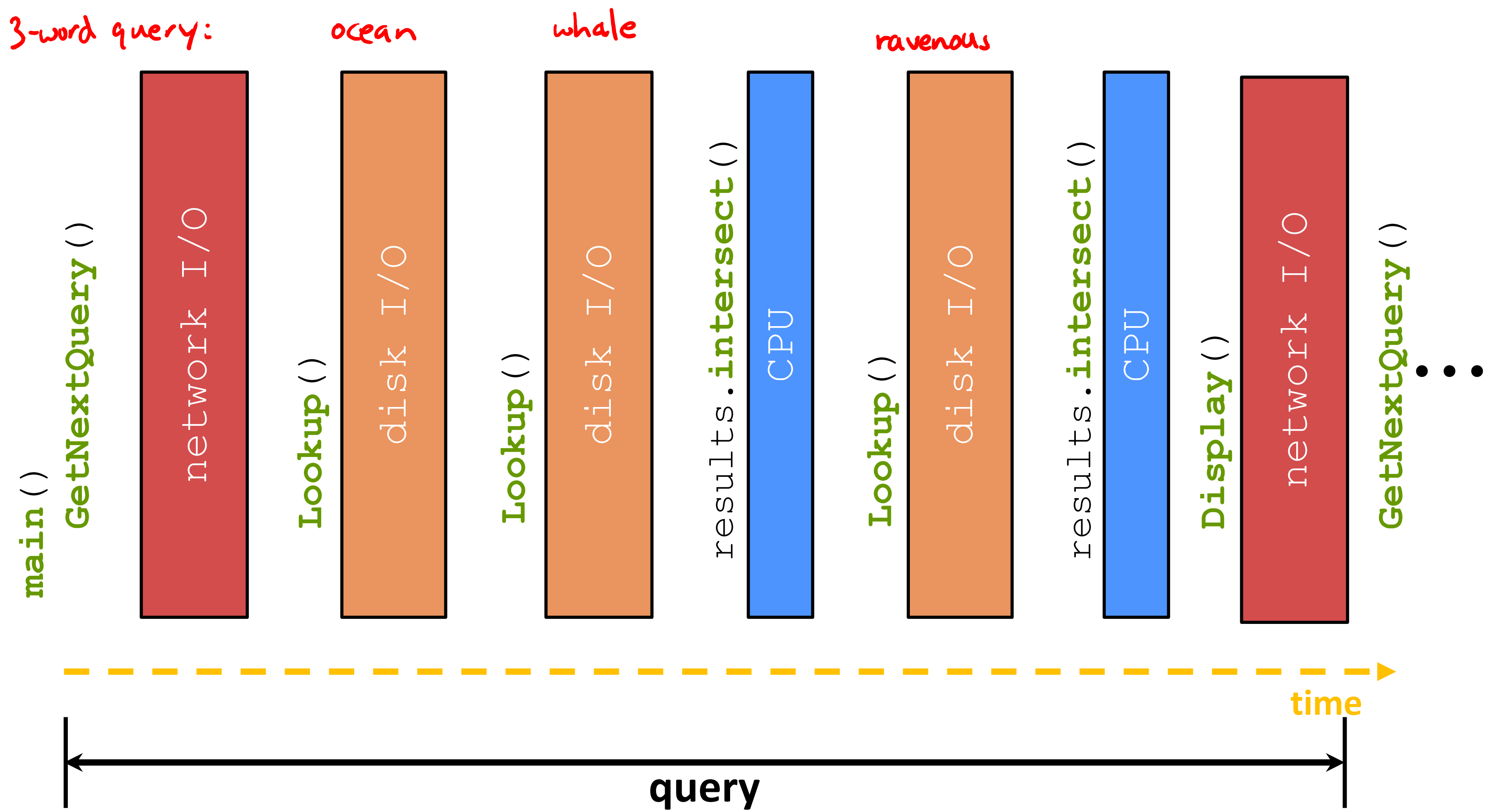
See `searchserver_sequential/`

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



What About I/O-caused Latency?

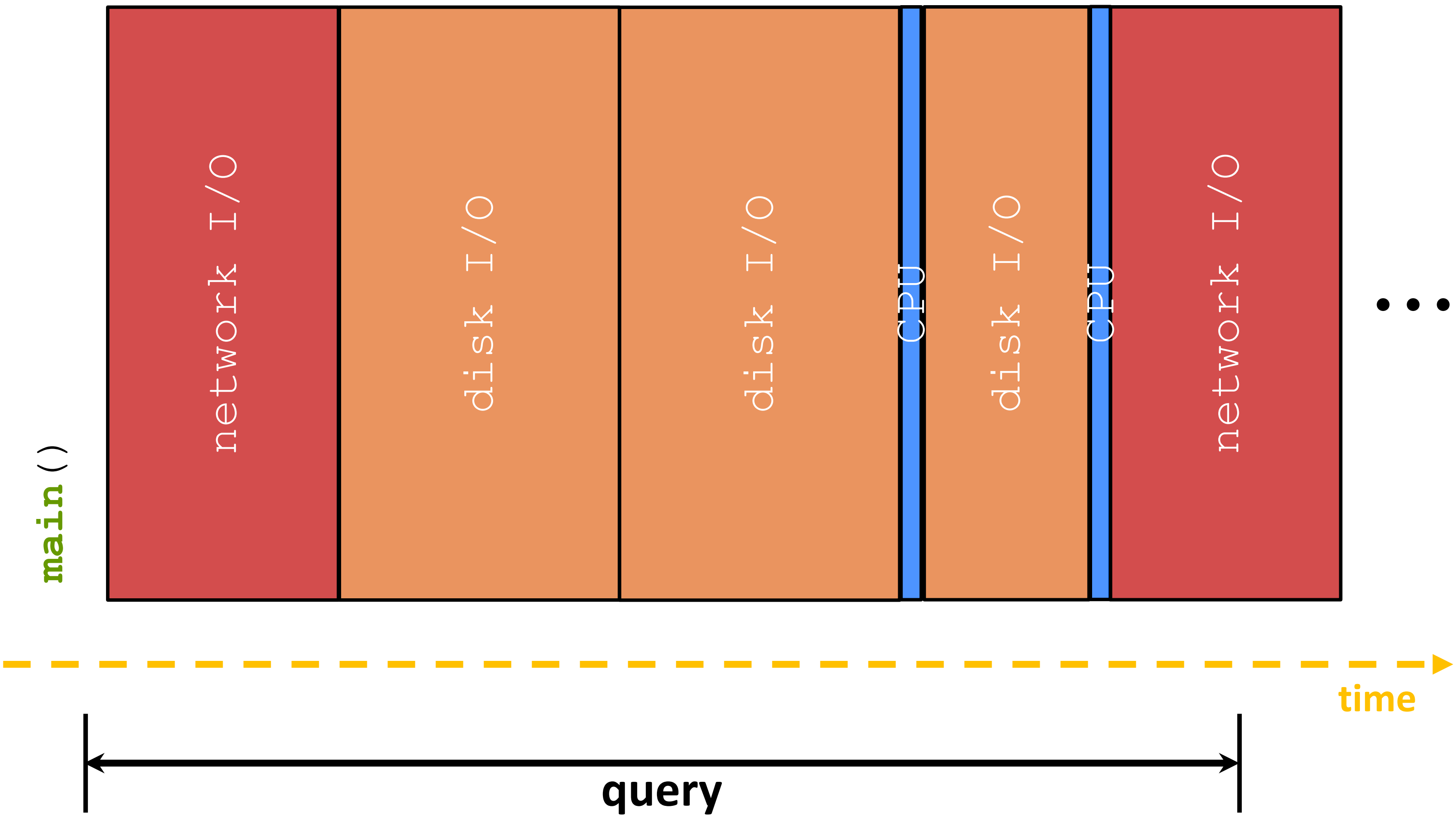
- Jeff Dean's "Numbers Everyone Should Know" (LADIS '09)

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

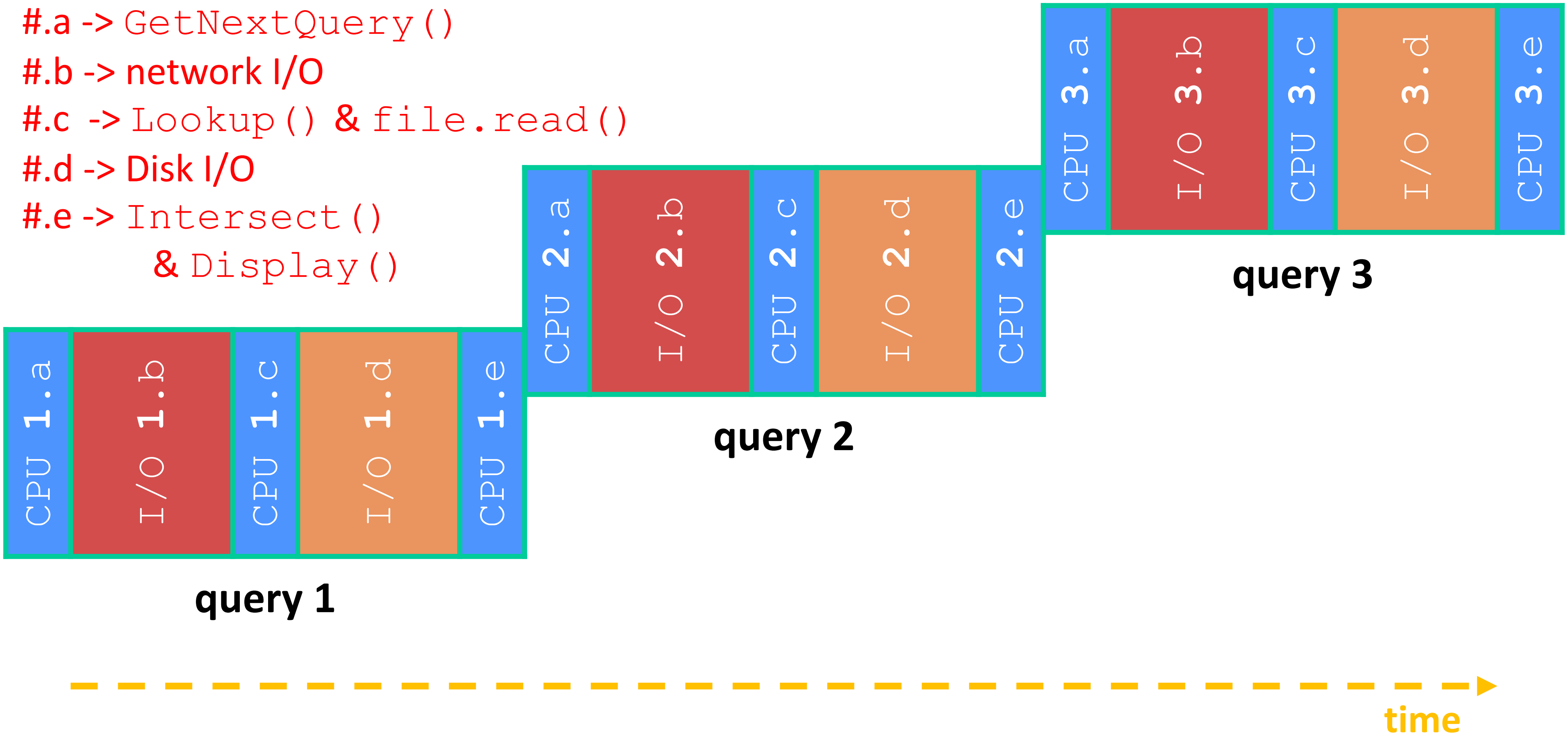
Google

Execution Timeline: (Loosely) To Scale

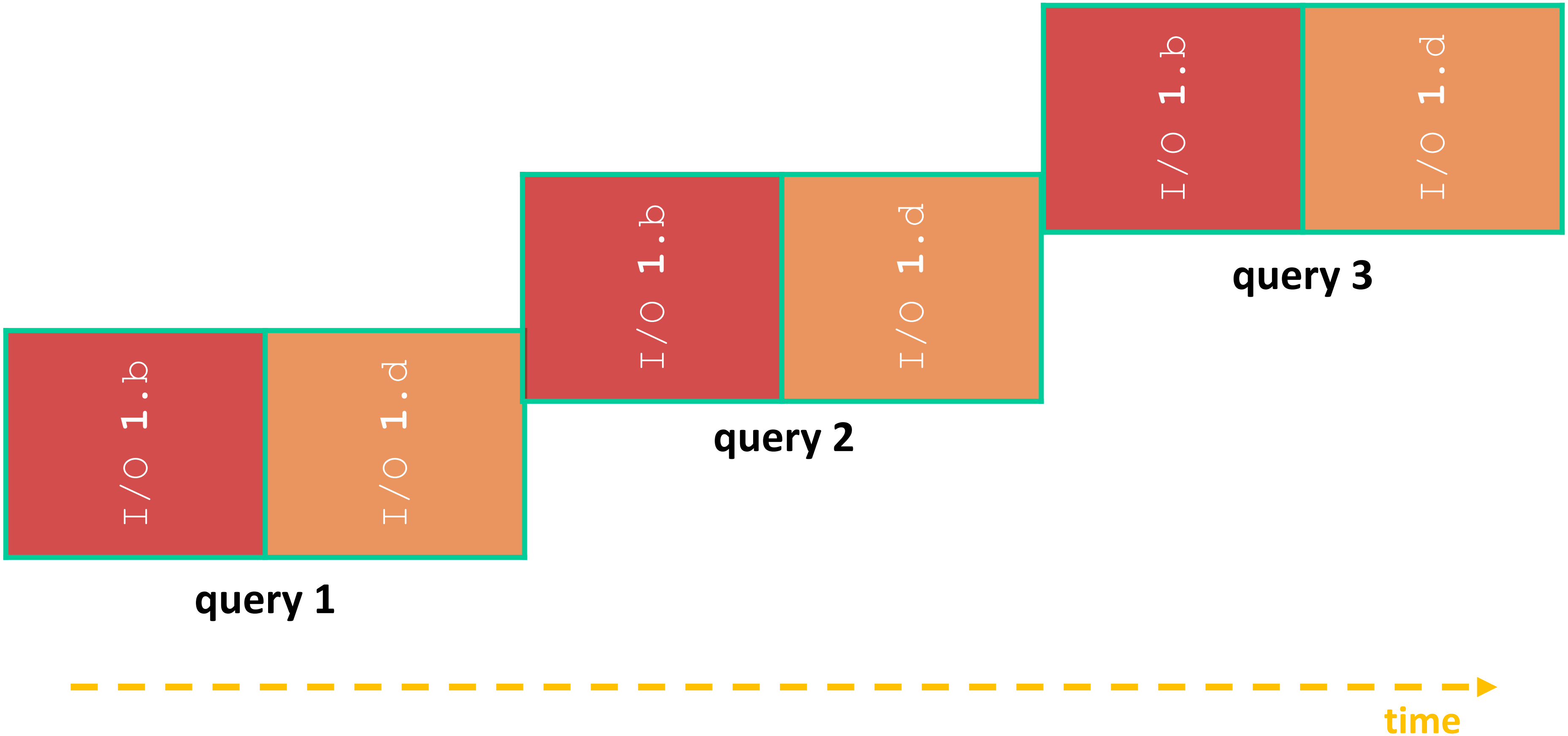


Multiple (Single-Word) Queries

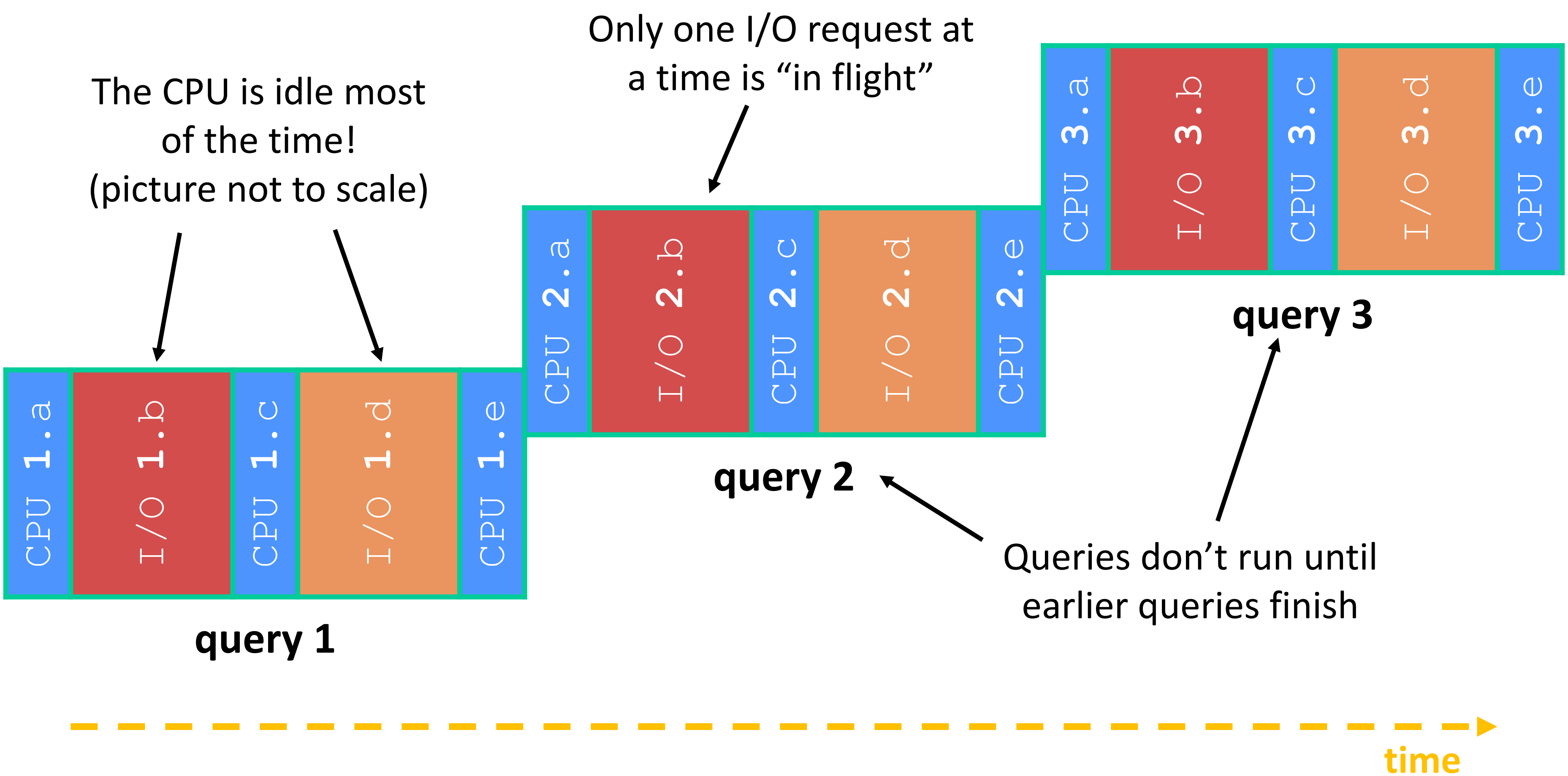
is the Query Number
#.a -> `GetNextQuery()`
#.b -> network I/O
#.c -> `Lookup()` & `file.read()`
#.d -> Disk I/O
#.e -> `Intersect()` & `Display()`



Multiple Queries: (Loosely) To Scale



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 != 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)

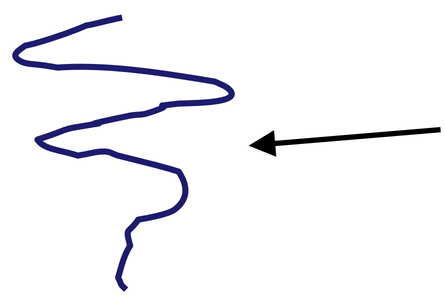
Why Processes?

- 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`)

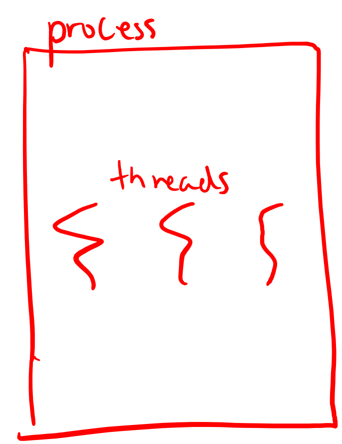
- Disadvantages:
  - A lot of overhead during creation and context switching
  - Cannot easily share memory between processes – typically must communicate through the file system

Worker Option 2: Threads

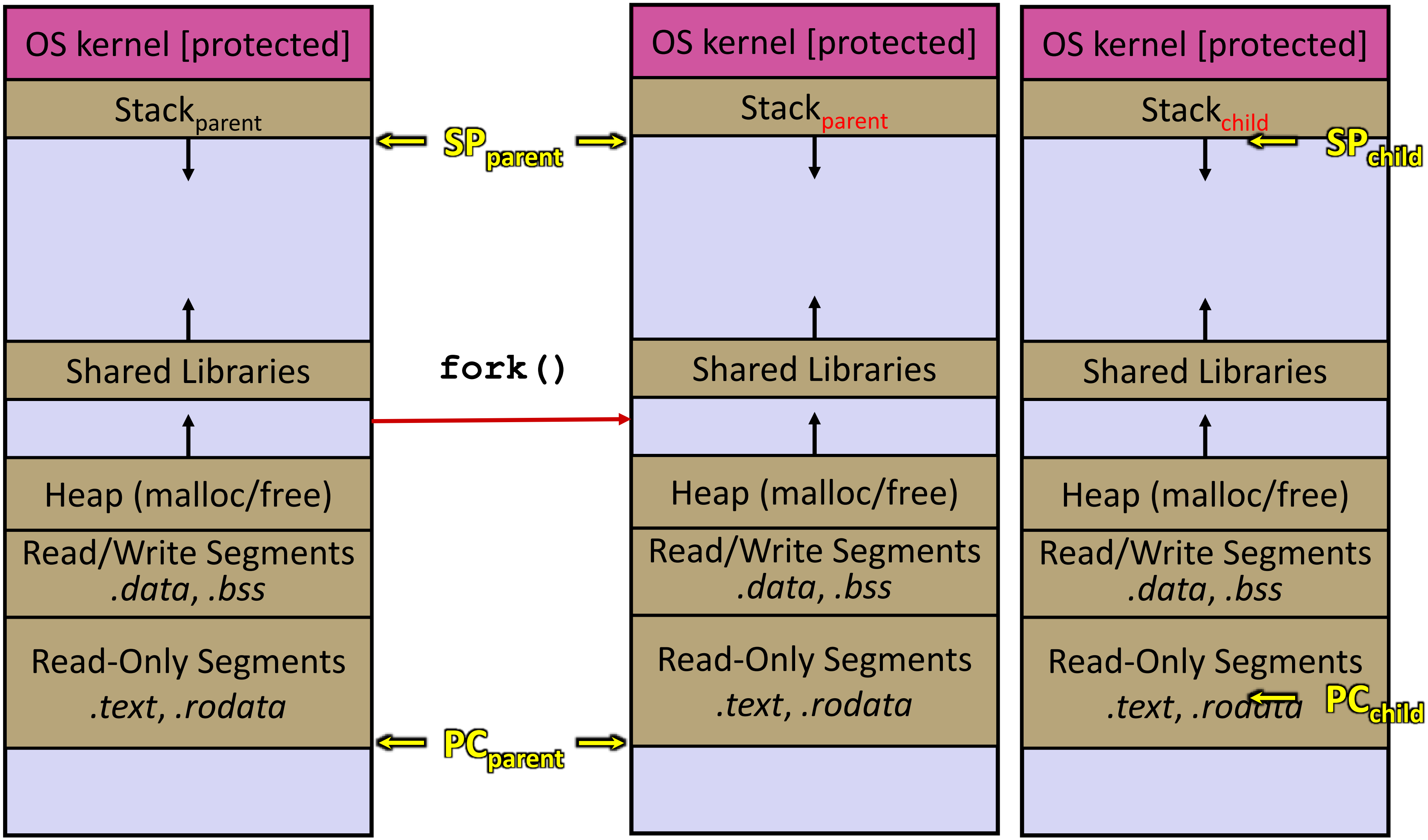
- From within a process, we can separate out the concept of a "thread of execution" (thread for short)
  - Processes are the containers that hold shared resources and attributes
    - *e.g.*, address space, file descriptors, security attributes
  - Threads are independent, sequential execution streams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



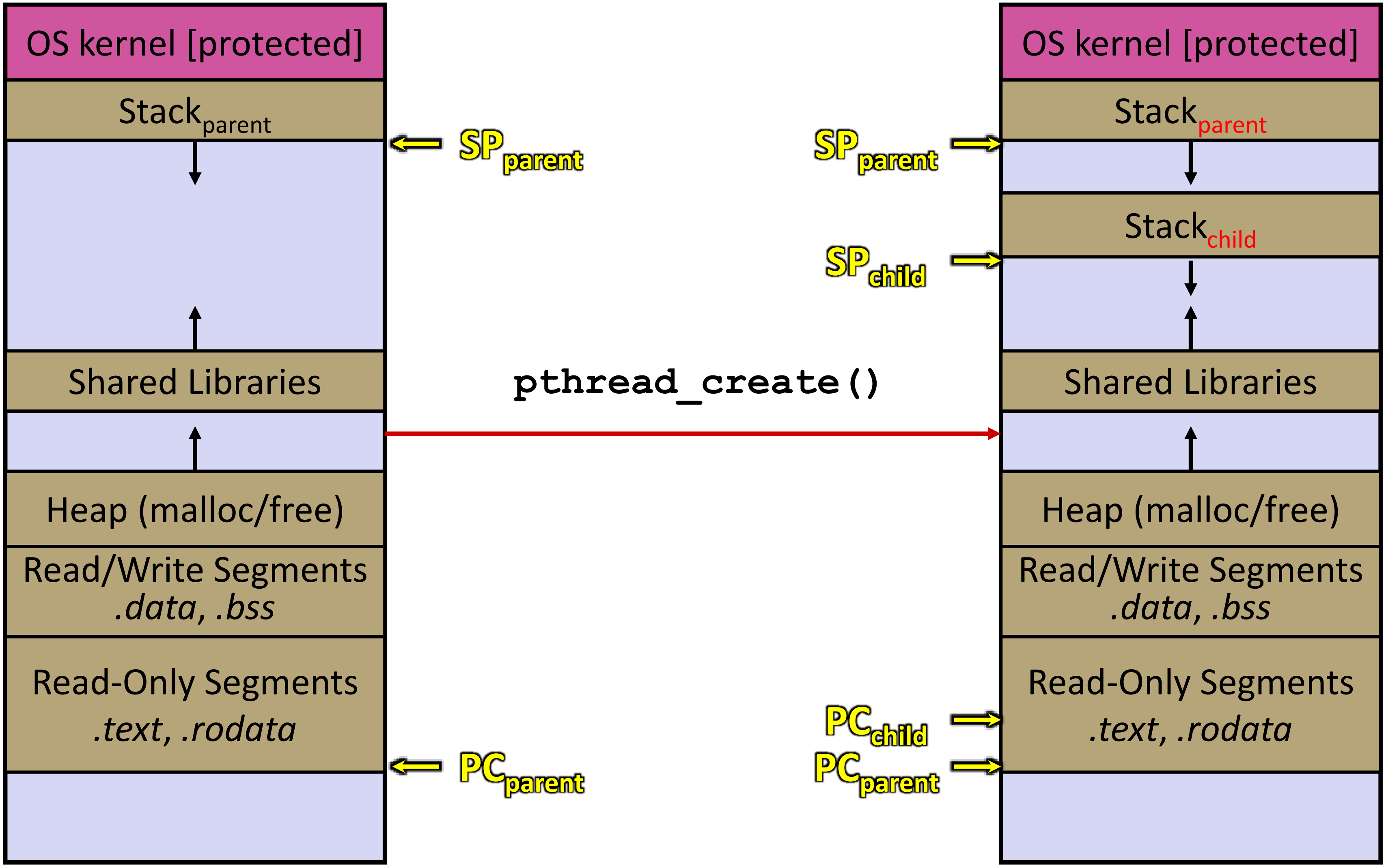
thread



Threads vs. Processes



Threads vs. Processes



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);
}
```

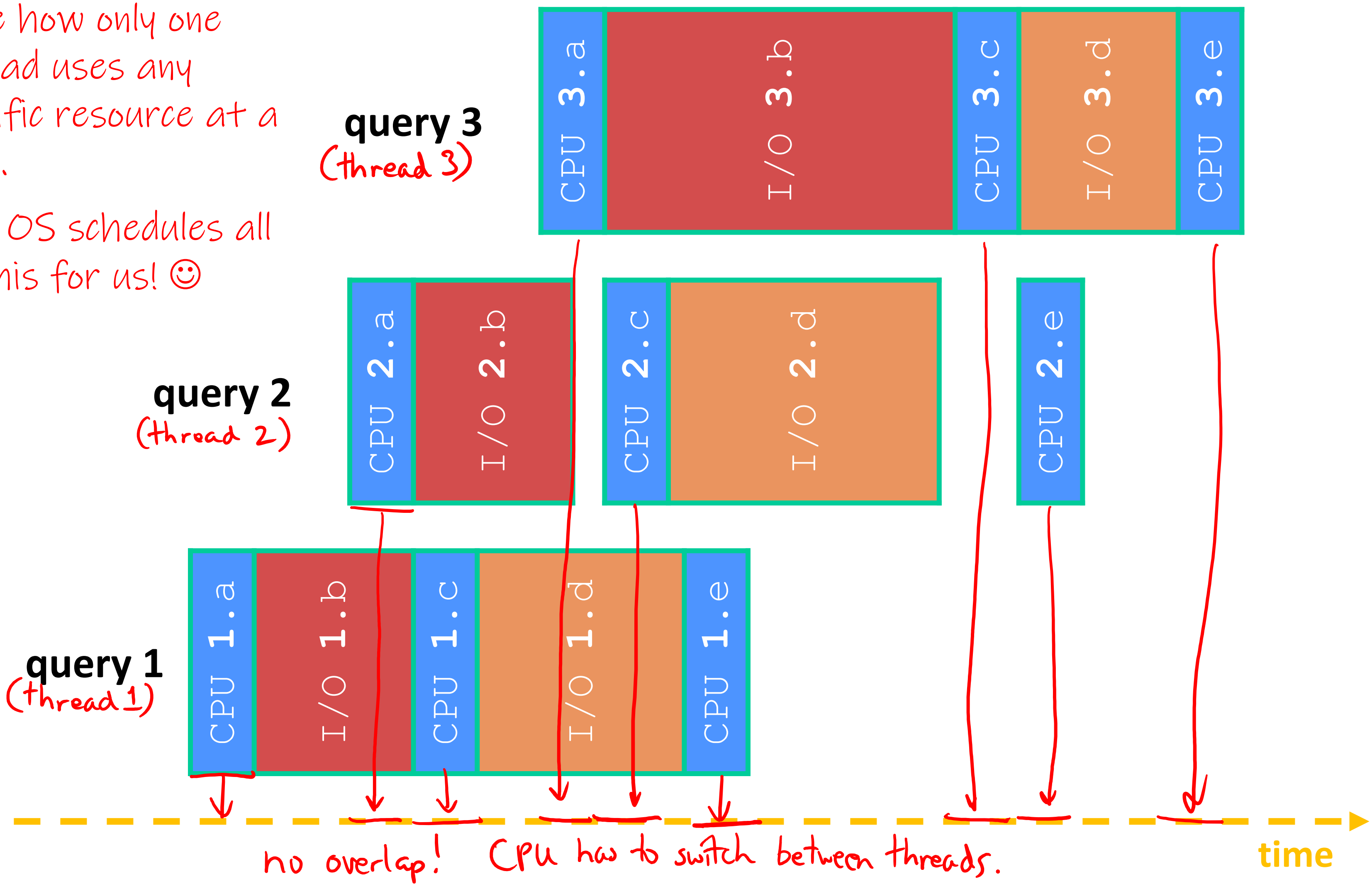
All we did was put the code into a function, and create a thread that invokes it!

Multi-threaded Search Engine (Execution)

(still one 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
    - 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)
  - O_NONBLOCK
  - 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 (errno == EWOULDBLOCK)
  - Program can ask the OS which file descriptors are readable/writeable 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***

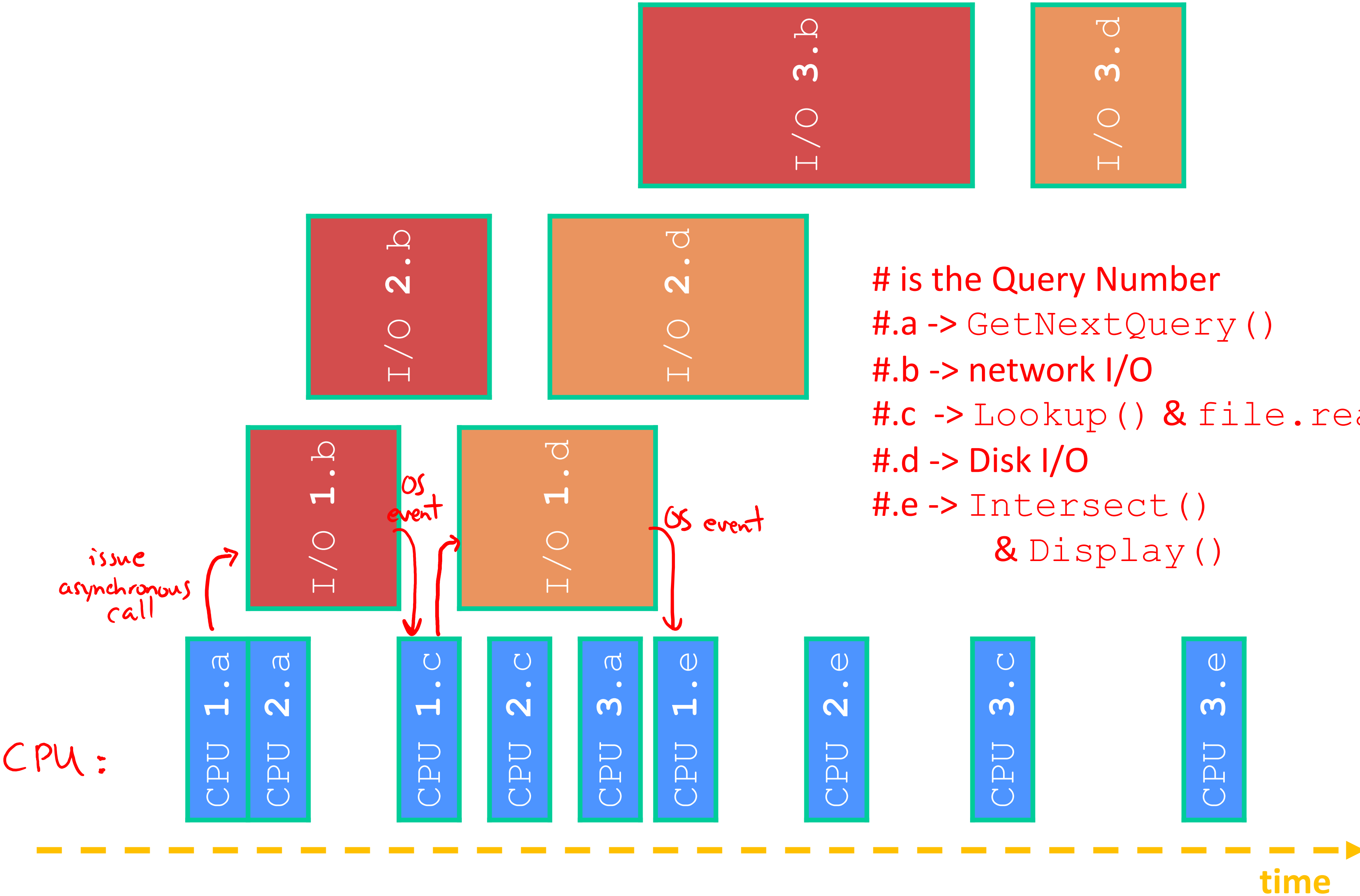
Event-Driven Programming

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

```
void dispatch(task, event) {
  switch (task.state) {        ← what we do depends on where we are in program ("state") and what event came in.
    case READING_FROM_CONSOLE:
      query_words = event.data;
      async_read(index, query_words[0]);   ← asynchronous notice to OS
      task.state = READING_FROM_INDEX;
      return;
    case READING_FROM_INDEX:
      ...
  }
}

while (1) {
  event = OS.GetNextEvent();   ← OS sends events back to process as they occur/finish
  task = lookup(event);
  dispatch(task, event);
}
```

Asynchronous, Event-Driven



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

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

Outline (next two lectures)

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

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