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 2022

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Relevant Course Information

- Homework 4 due 1 week from tomorrow (3/10)
  - Partner form due end of tomorrow
  - You can still use ***two*** late days (until Sunday, 3/13)

- Exercise 11 due Friday
- Exercise 12 (the last exercise™) to be released Friday
  - Consumer-producer concurrency
  - Due Wednesday 3/9 @ 11 am

- Final Exam (Sunday, 3/13 – Wednesday, 3/16)
  - 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`

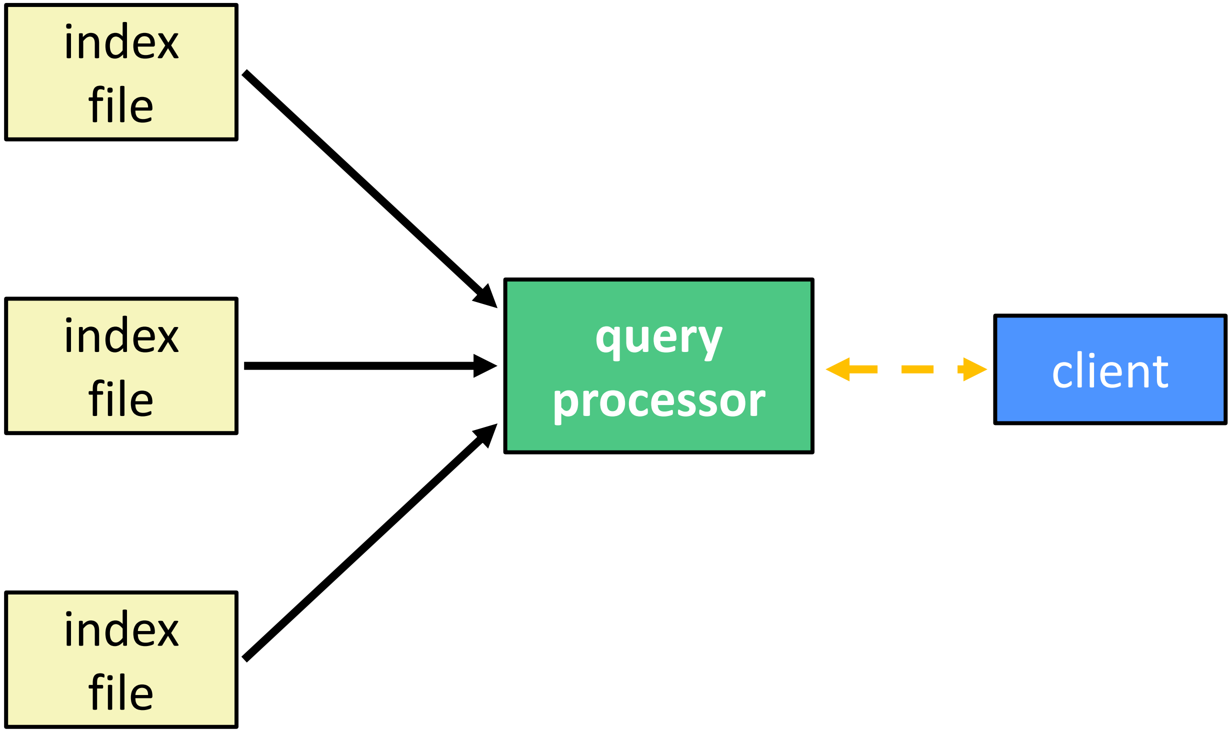
Lecture Outline

- **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);
  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);
  }
}
```

disk I/O

network I/O

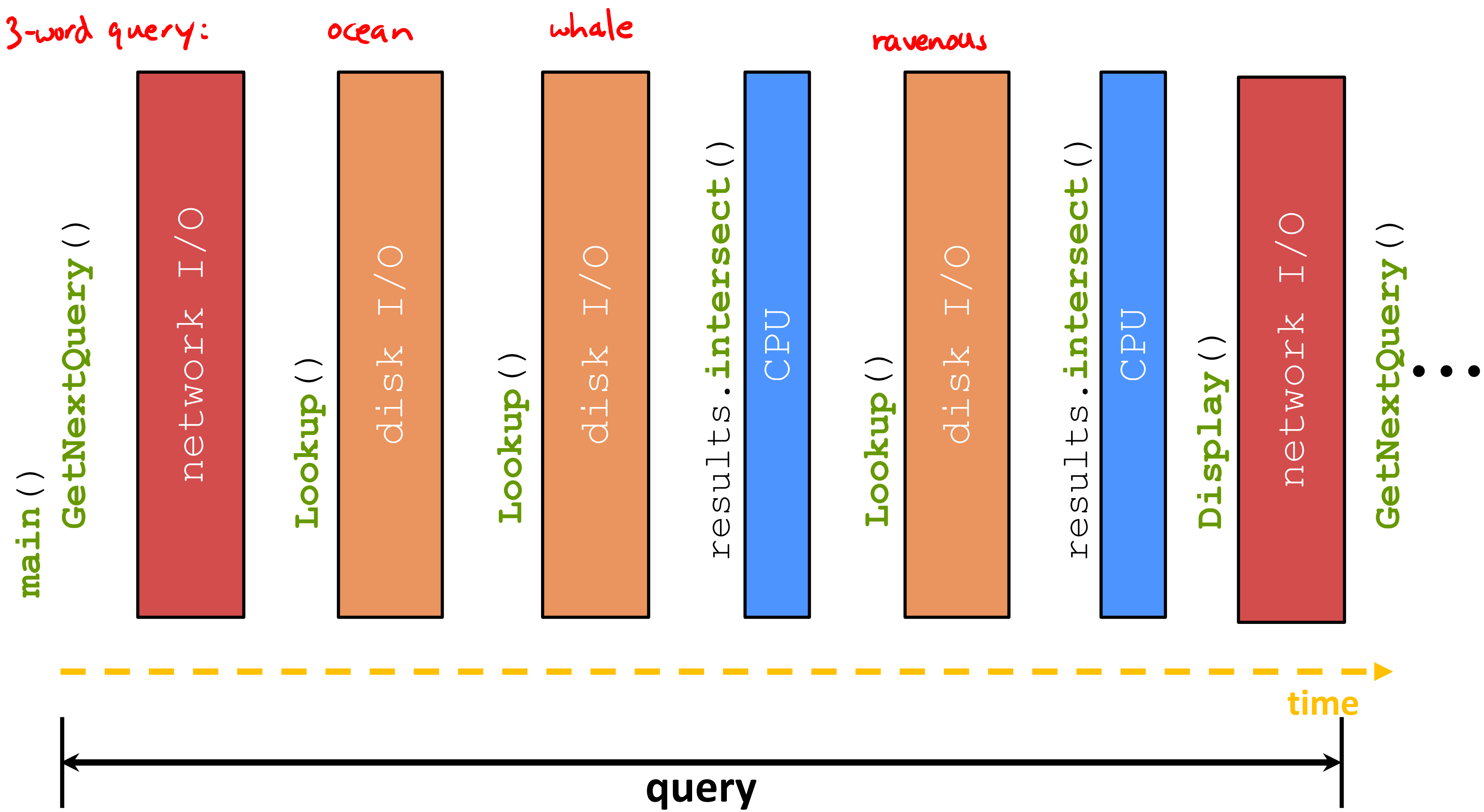
network I/O

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?

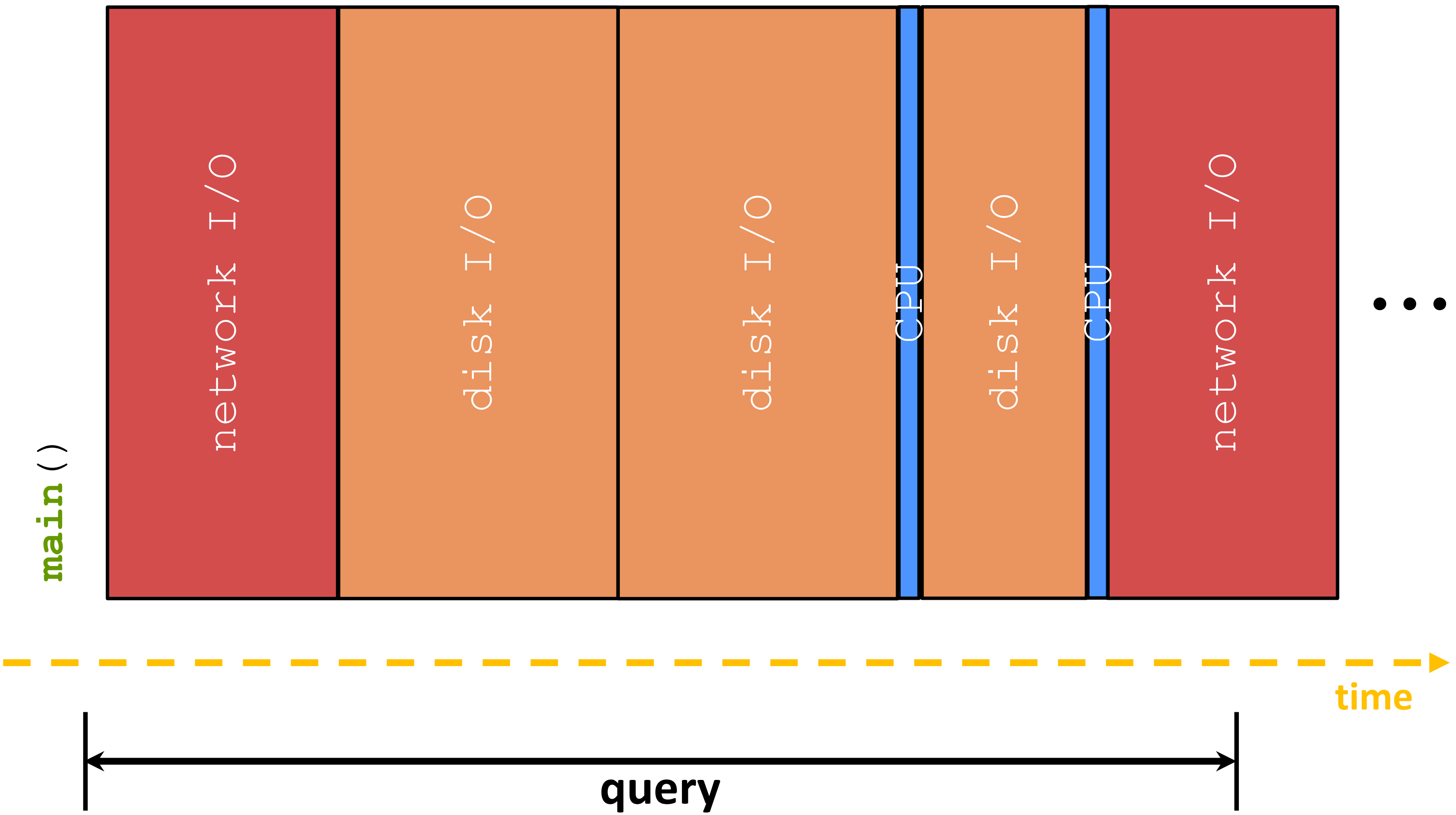
- Jeff Dean's "Numbers Everyone Should Know" (LADIS '09)

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

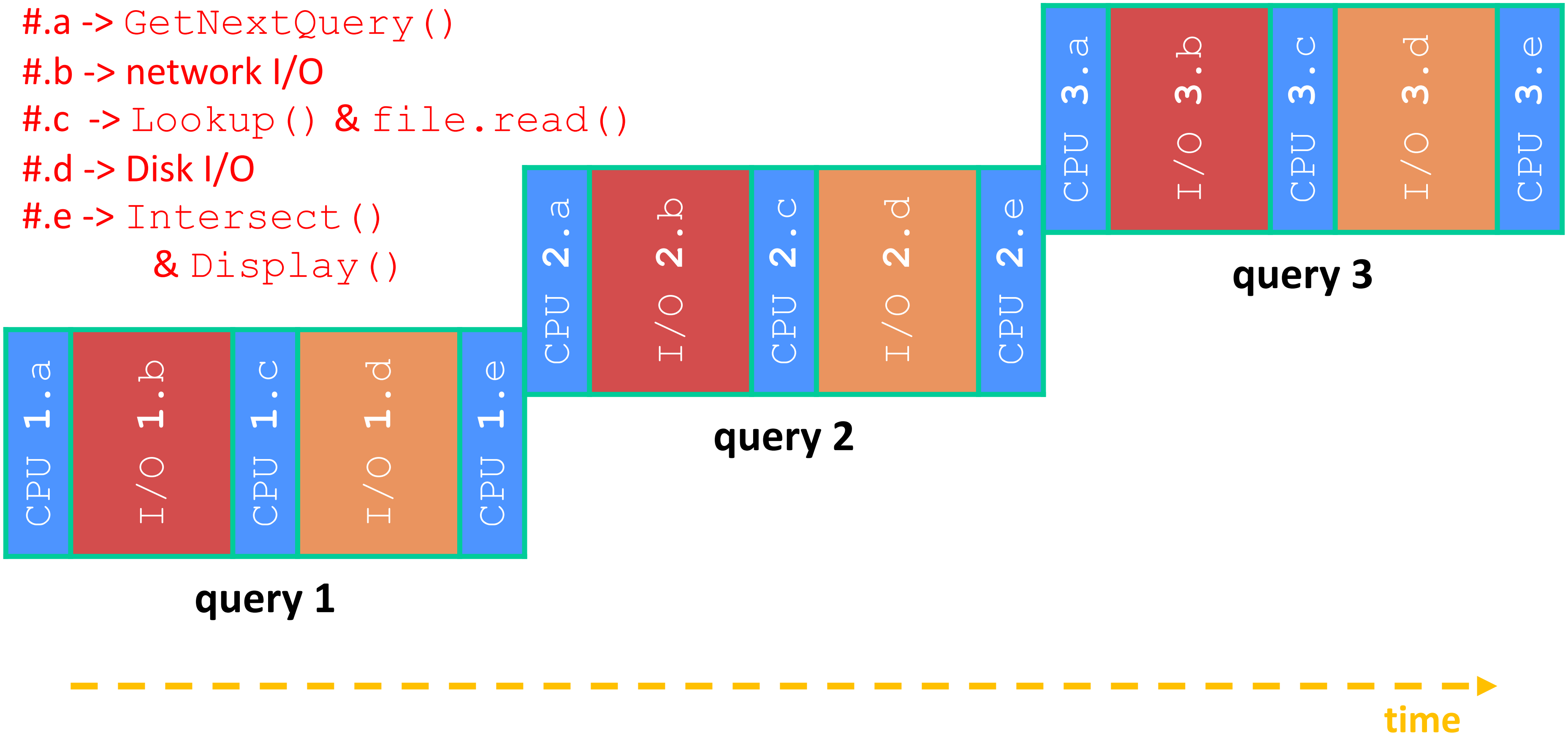
Google

Execution Timeline: (Loosely) To Scale

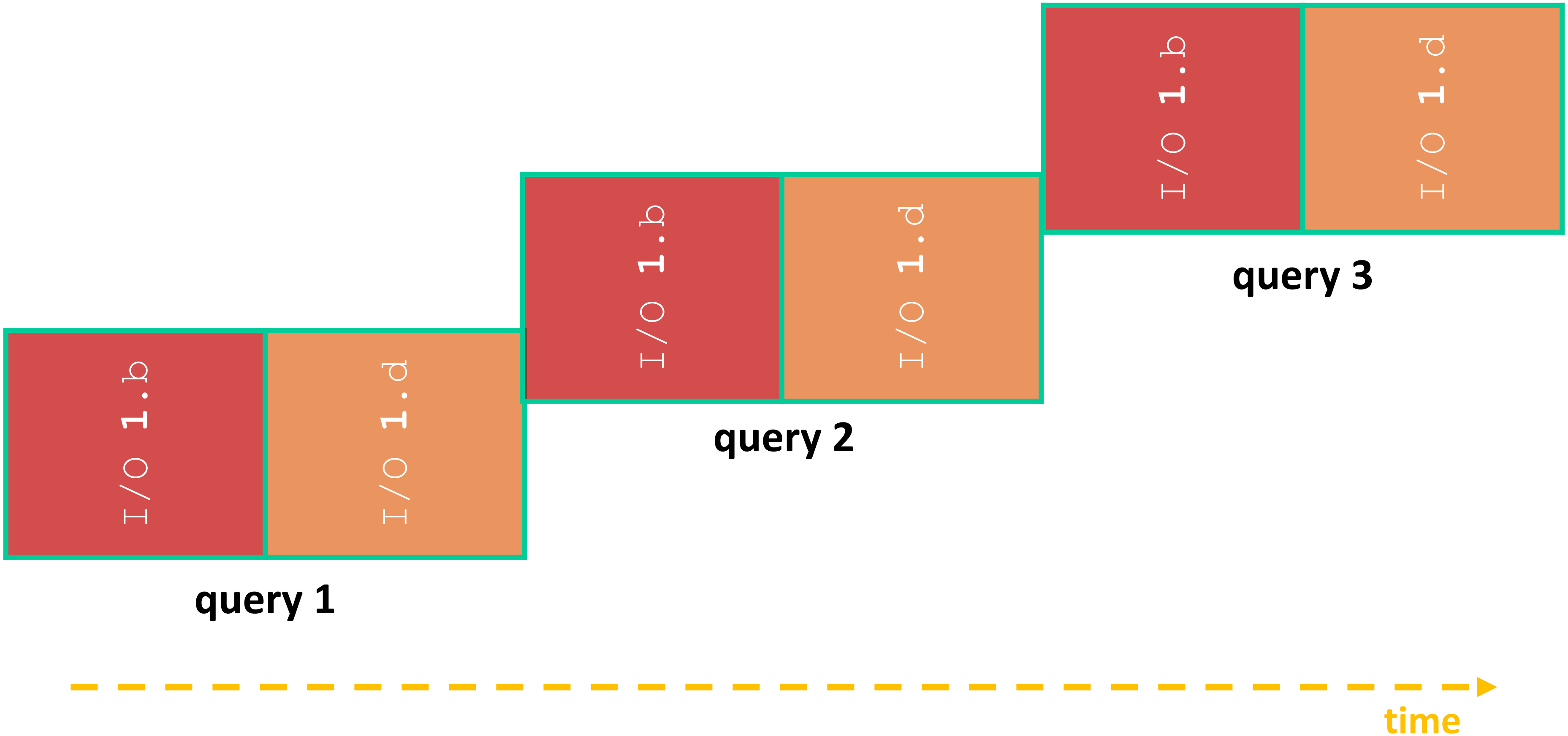


Multiple (Single-Word) Queries

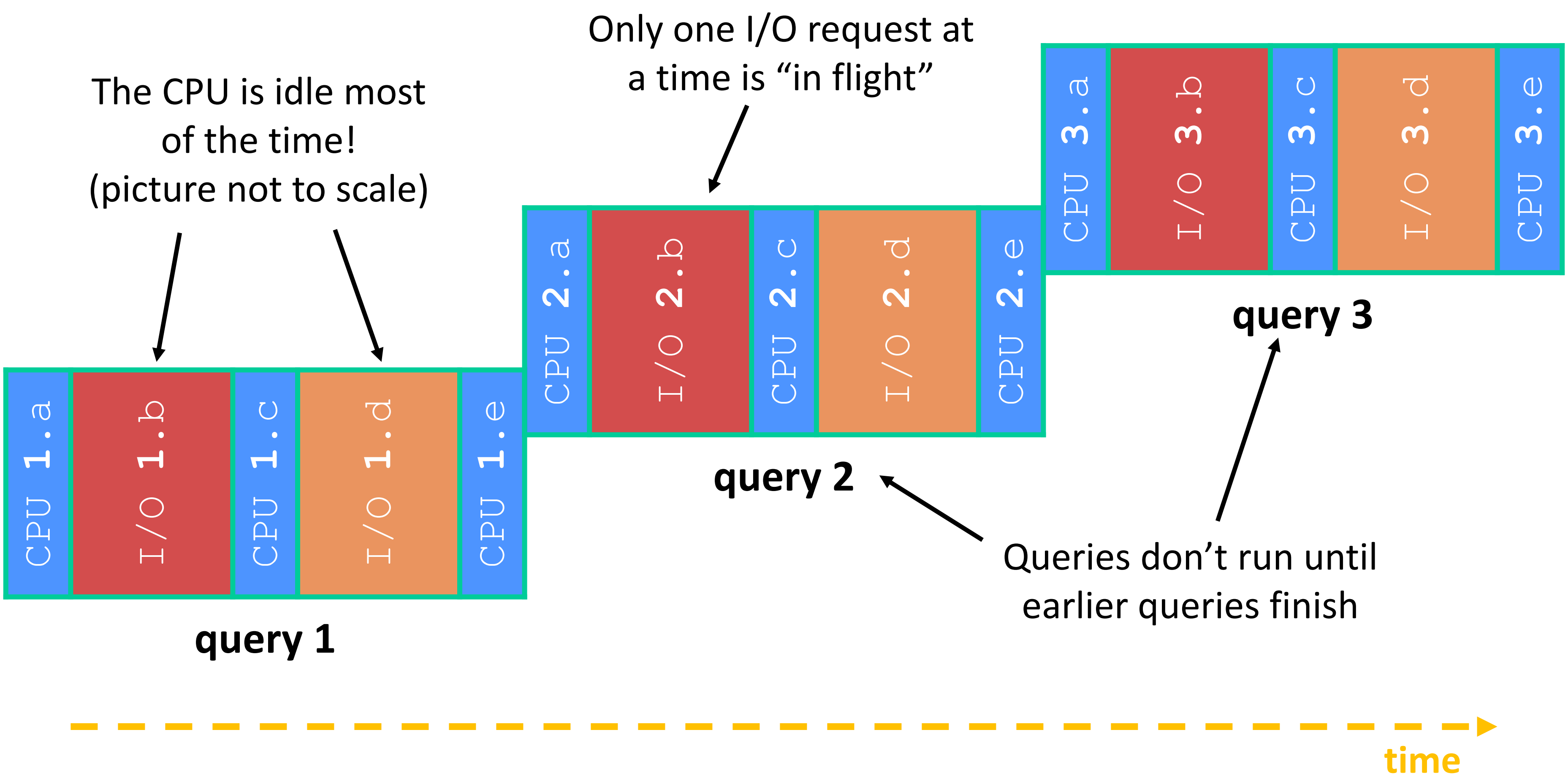
is the Query Number
#.a -> `GetNextQuery()`
#.b -> network I/O
#.c -> `Lookup()` & `file.read()`
#.d -> Disk I/O
#.e -> `Intersect()` & `Display()`



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)

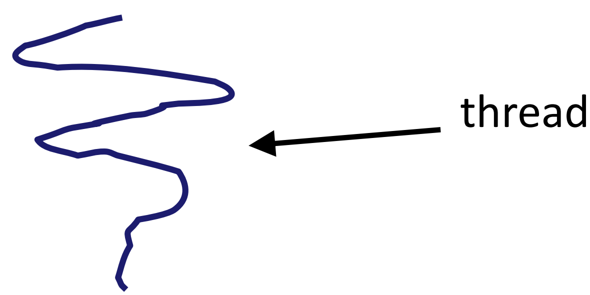
Why Processes?

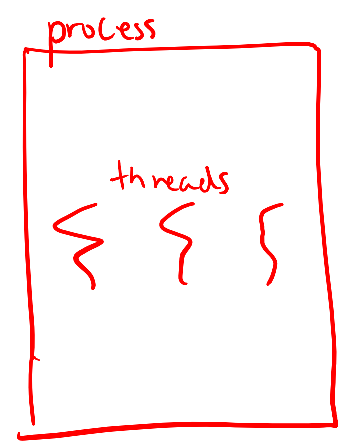
- Advantages:
  - Processes are isolated from one another
    - No shared memory between processes
    - If one crashes, the other processes keep going
  - No need for language support (OS provides `fork`)

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

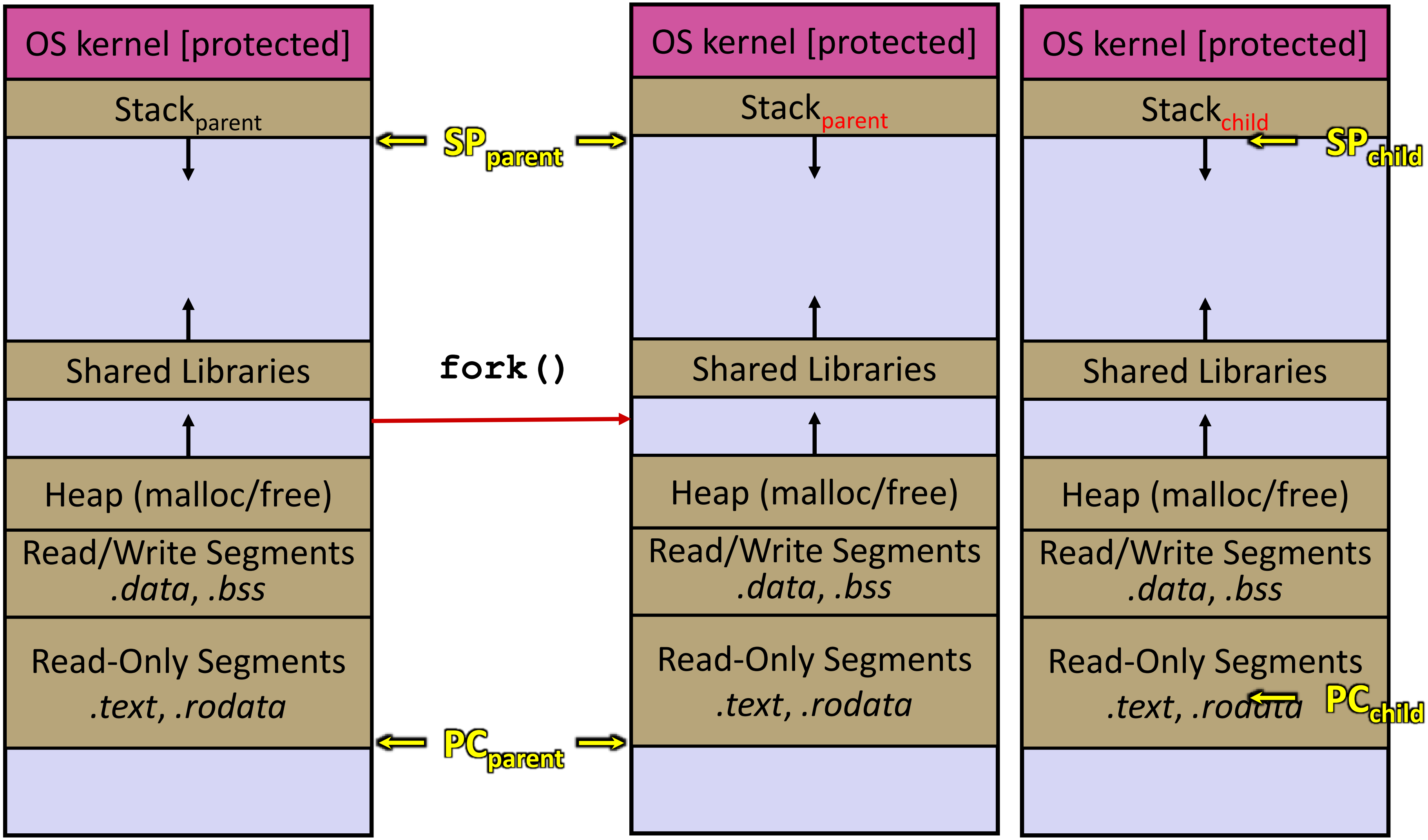
Worker Option 2: Threads

- 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

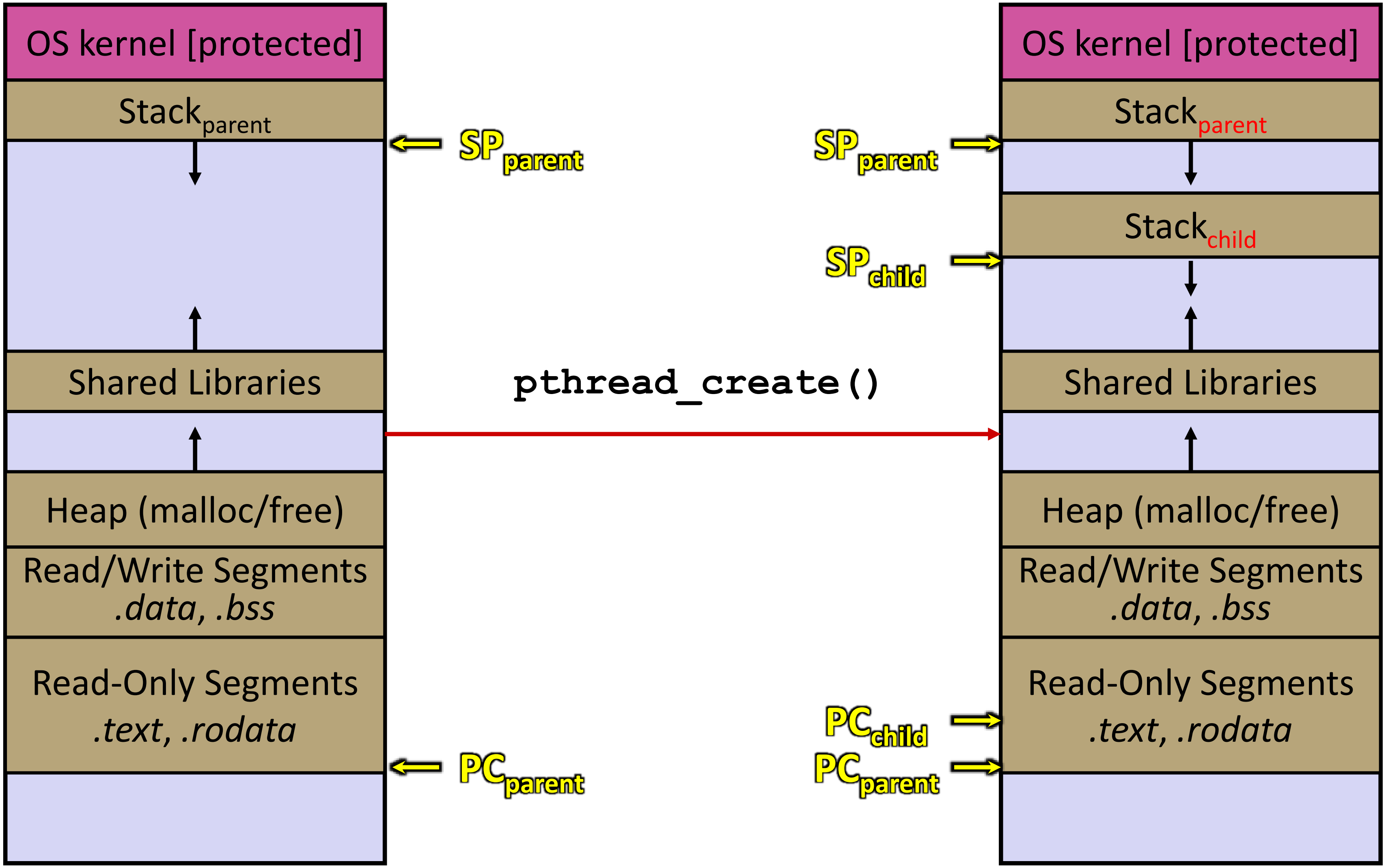




Threads vs. Processes



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);
}
```

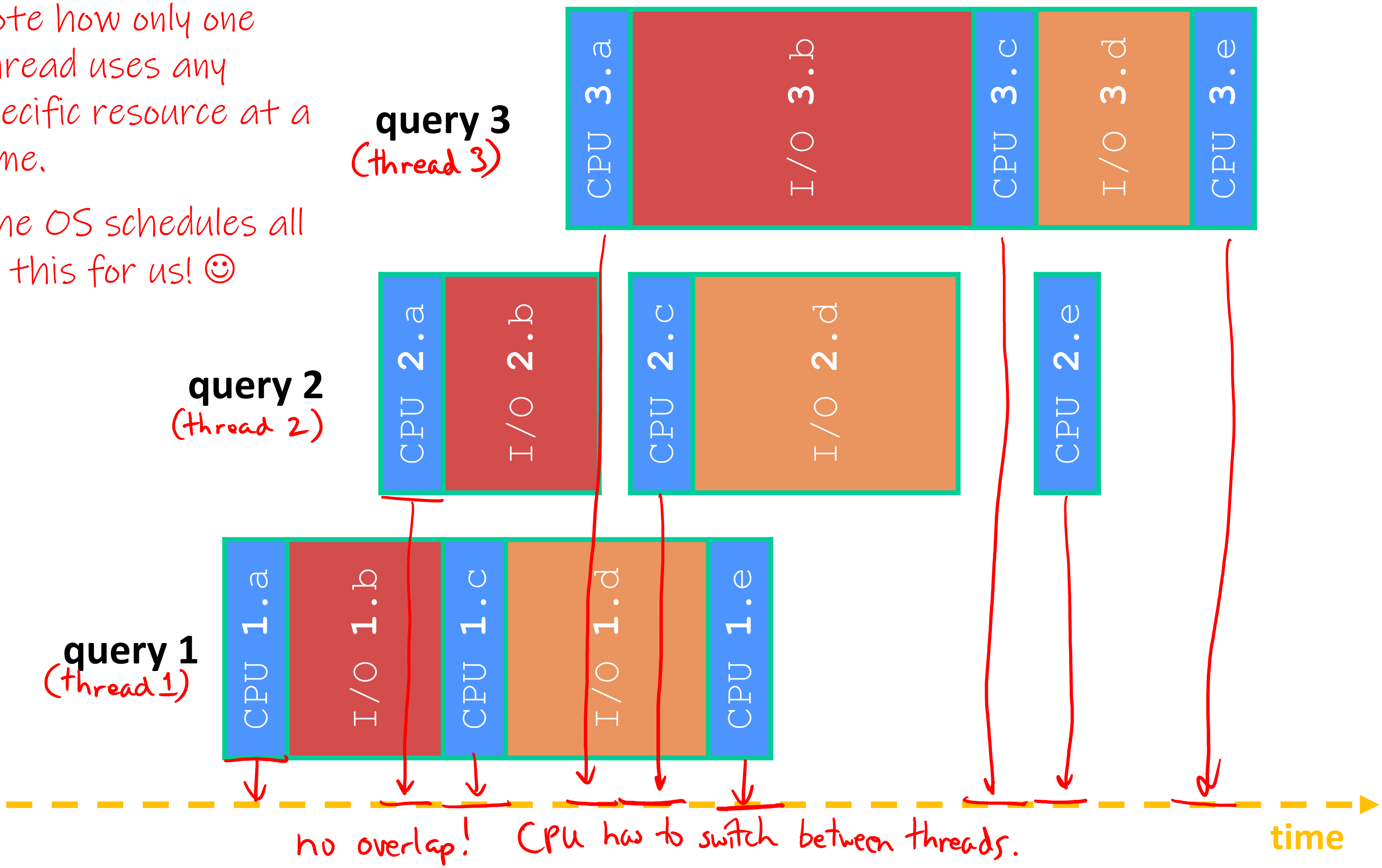
All we did was put the code into a function, and create a thread that invokes it!

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)
  - Your program enables non-blocking I/O on its file descriptors O_NONBLOCK
  - 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

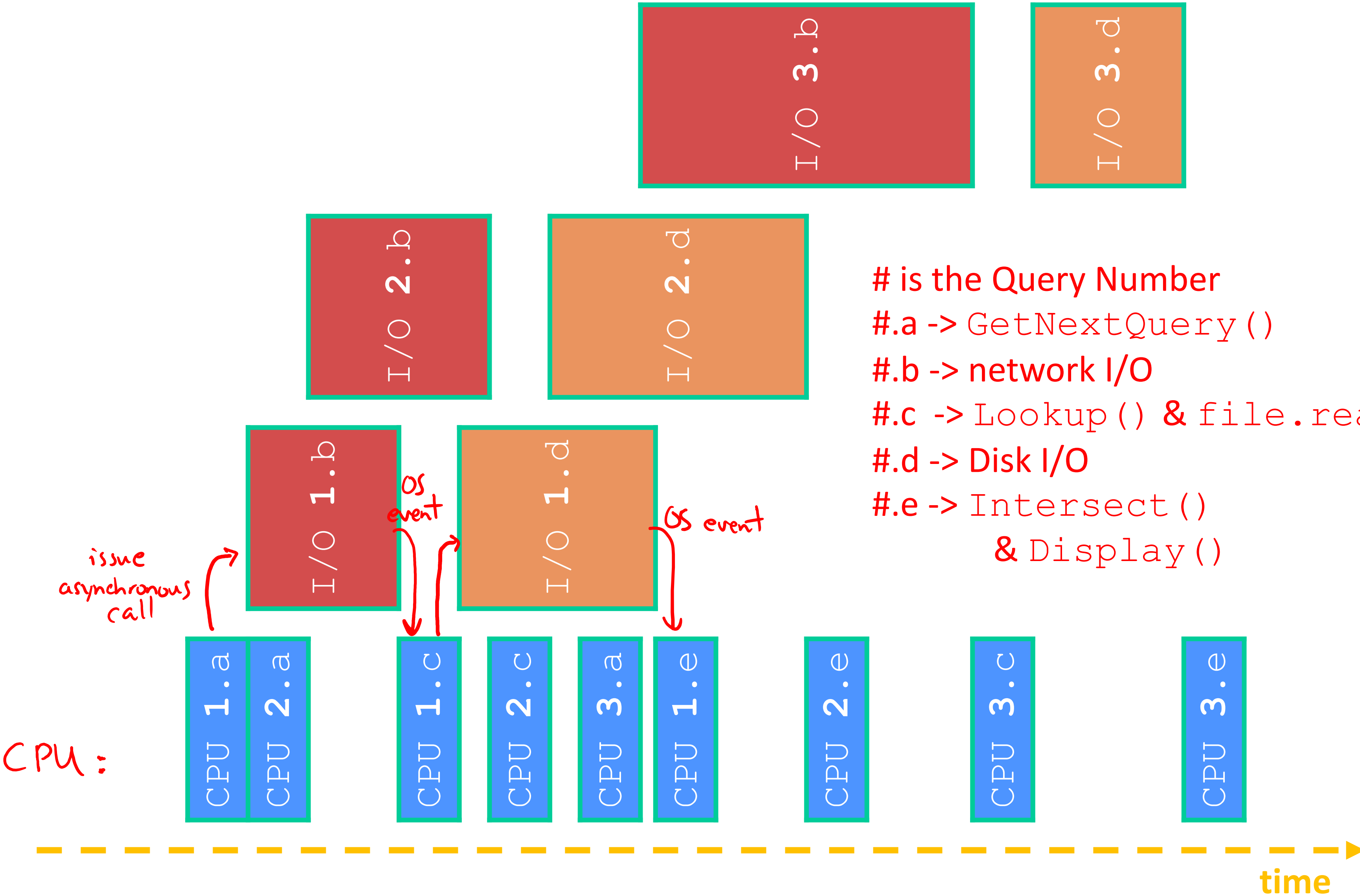
- Your program is structured as an *event-loop*

```
void dispatch(task, event) {
  switch (task.state) {
    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 we do depends on where we are in program ("state") and what event came in.
- asynchronous notice to OS
- OS sends events back to process as they occur/finish

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)