

Introduction to Concurrency

CSE 333

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Administrivia

- ❖ Ex16 due Monday!
- ❖ HW4 has an abbreviated timeline!
- ❖ Learning is supposed to be **hard**
 - But it's not supposed to cause **suffering**. It's ok to ask for help when things are too hard – many of your peers already have!
- ❖ About HW3 in particular ...
 - Just one homework out of 4, and homeworks are "only" 35% of your grade
 - This class does not attempt to "fit a curve" – if your peers do well, it doesn't mean that you will do poorly

Lecture Outline

- ❖ **Understanding Concurrency**
- ❖ **Concurrent Programming Styles**
 - Threads vs. processes
 - Asynchronous or non-blocking I/O
 - aka “Event-driven programming”

Building a Web Search Engine

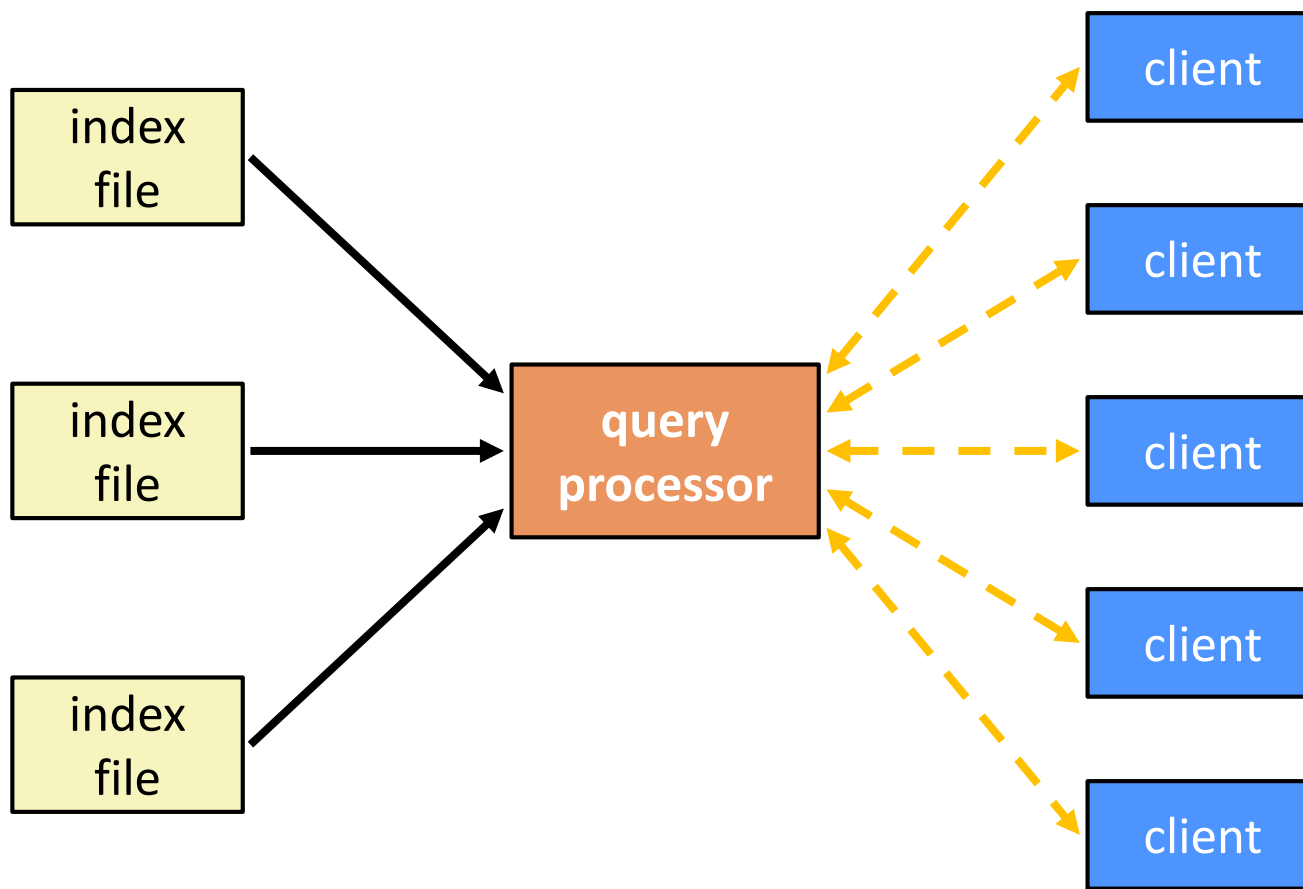
❖ We have:

- 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

❖ We need:

- Something that turns HTTP requests into well-formed queries

Web Search Architecture



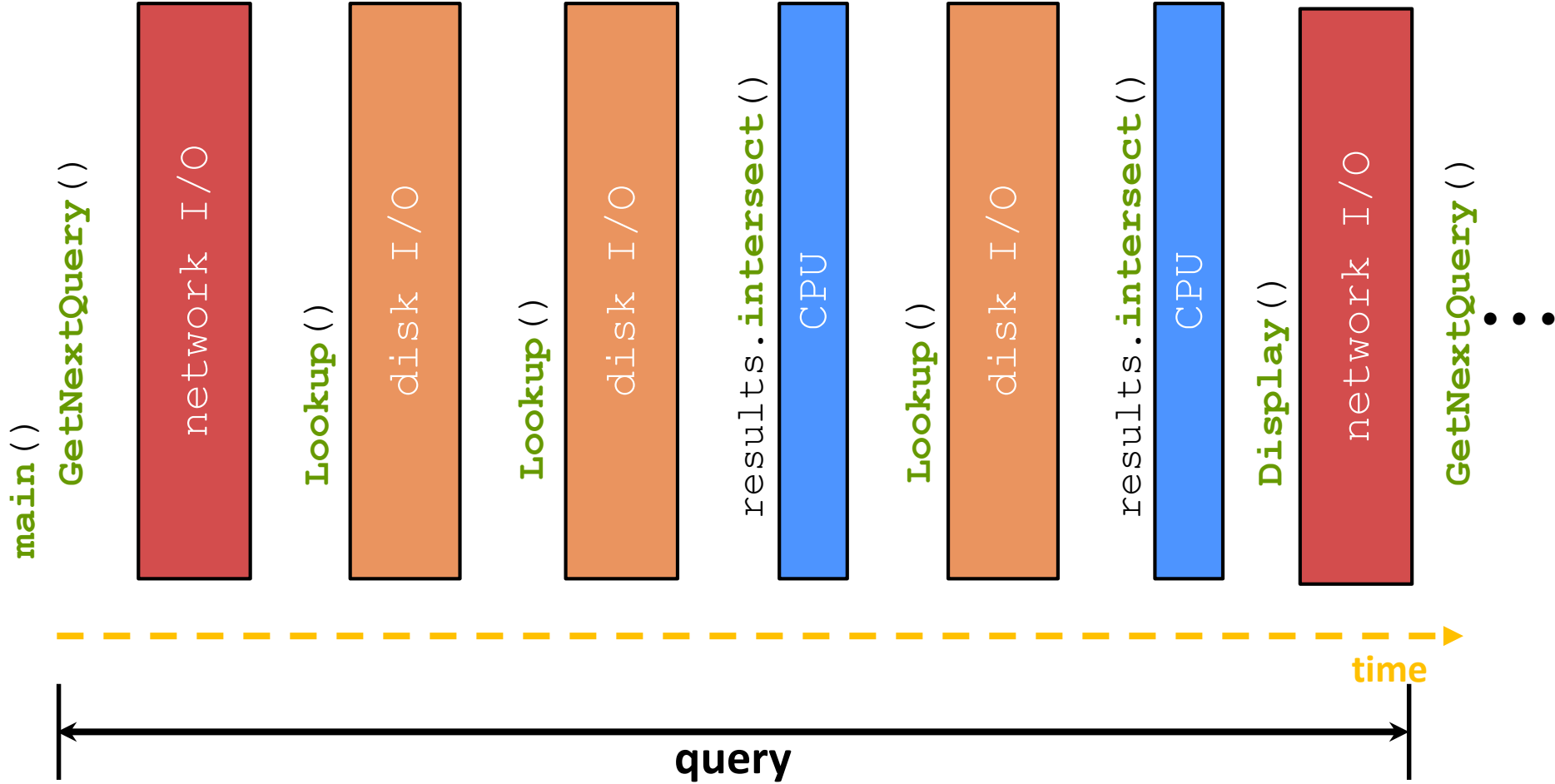
Sequential Implementation

- ❖ Pseudocode for sequential query processor:

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

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

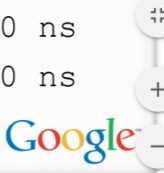

Execution Timeline: a Multi-Word Query



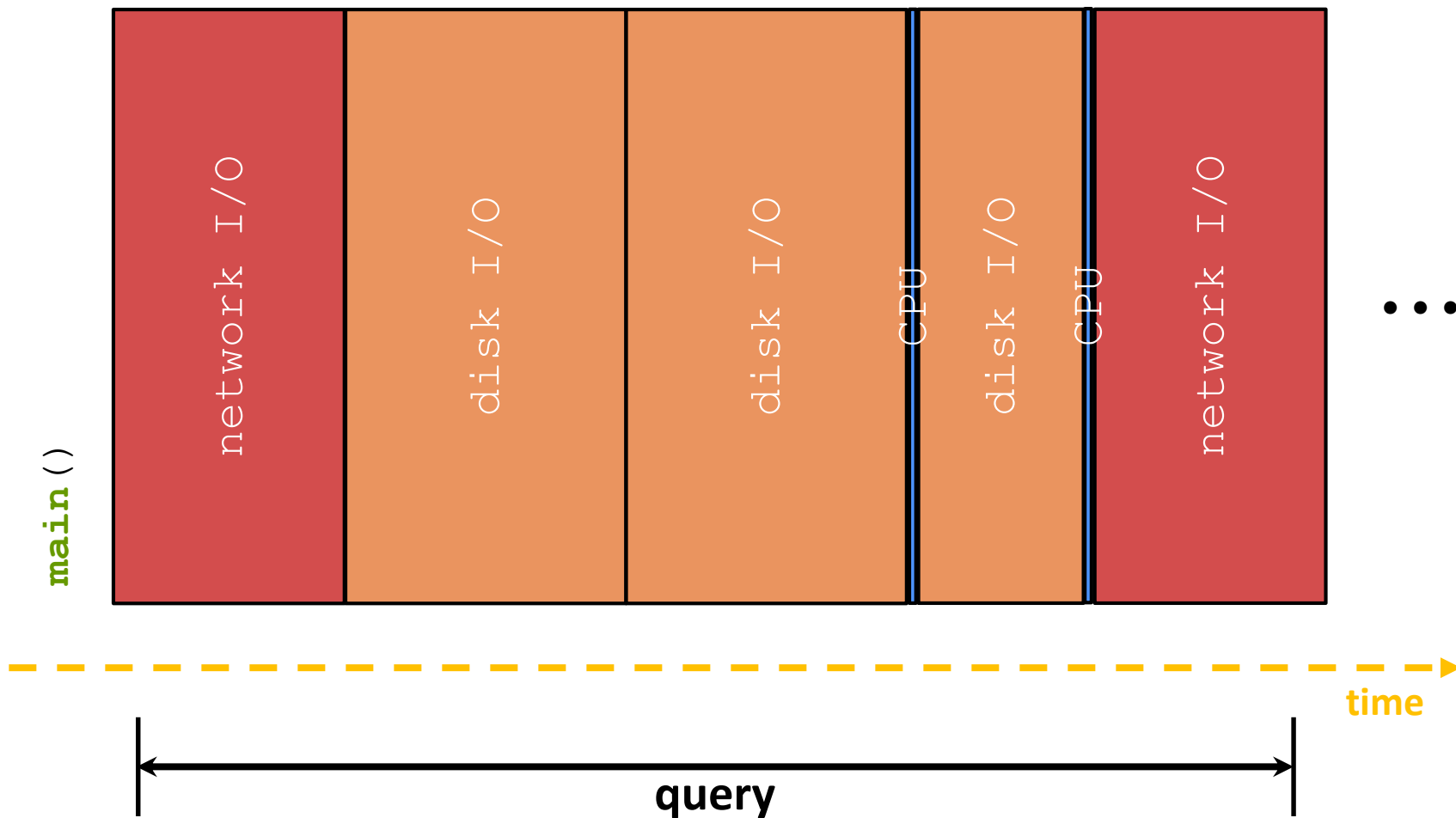
What About I/O-caused Latency?

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

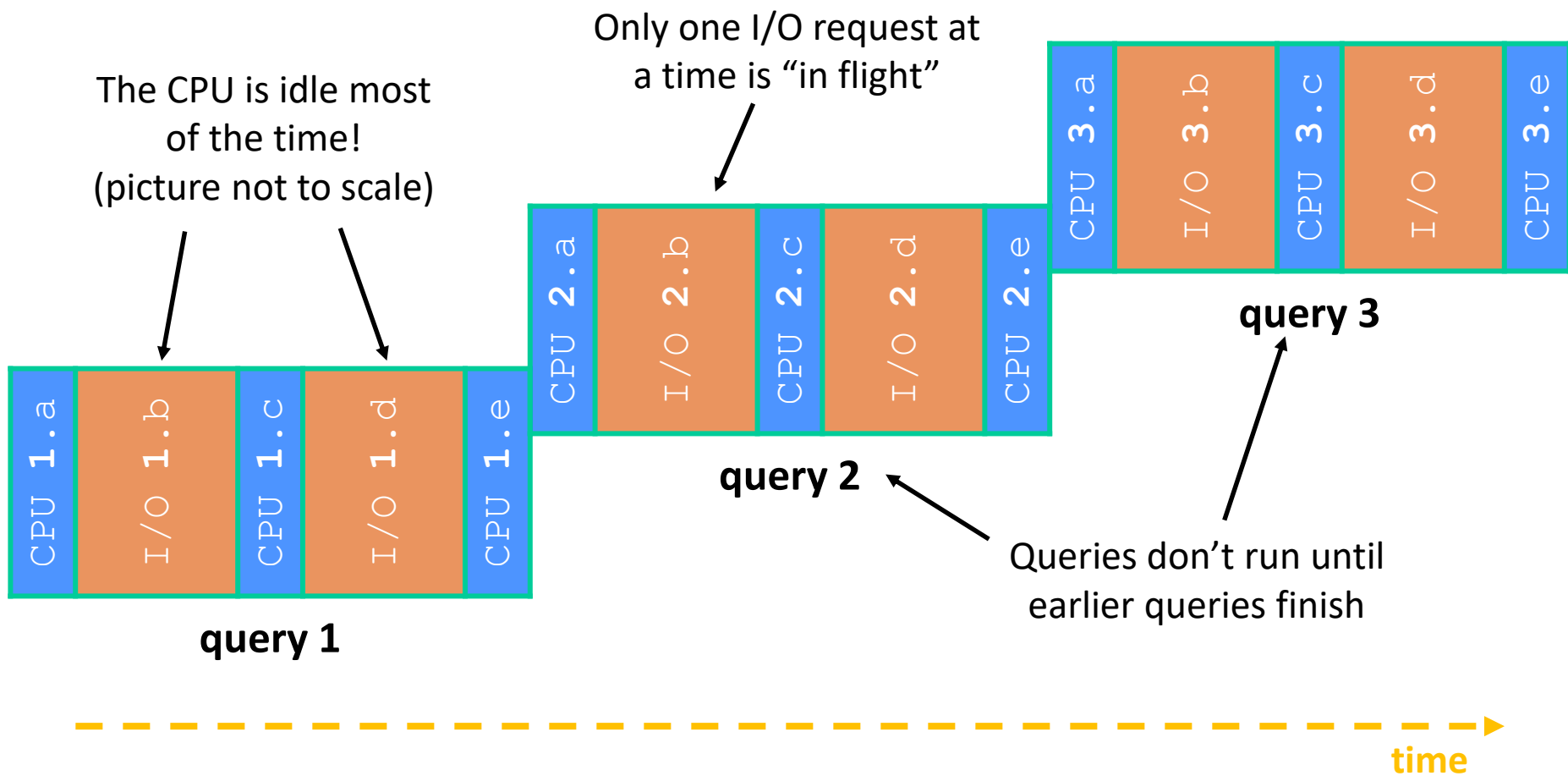
L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	100 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	10,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns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



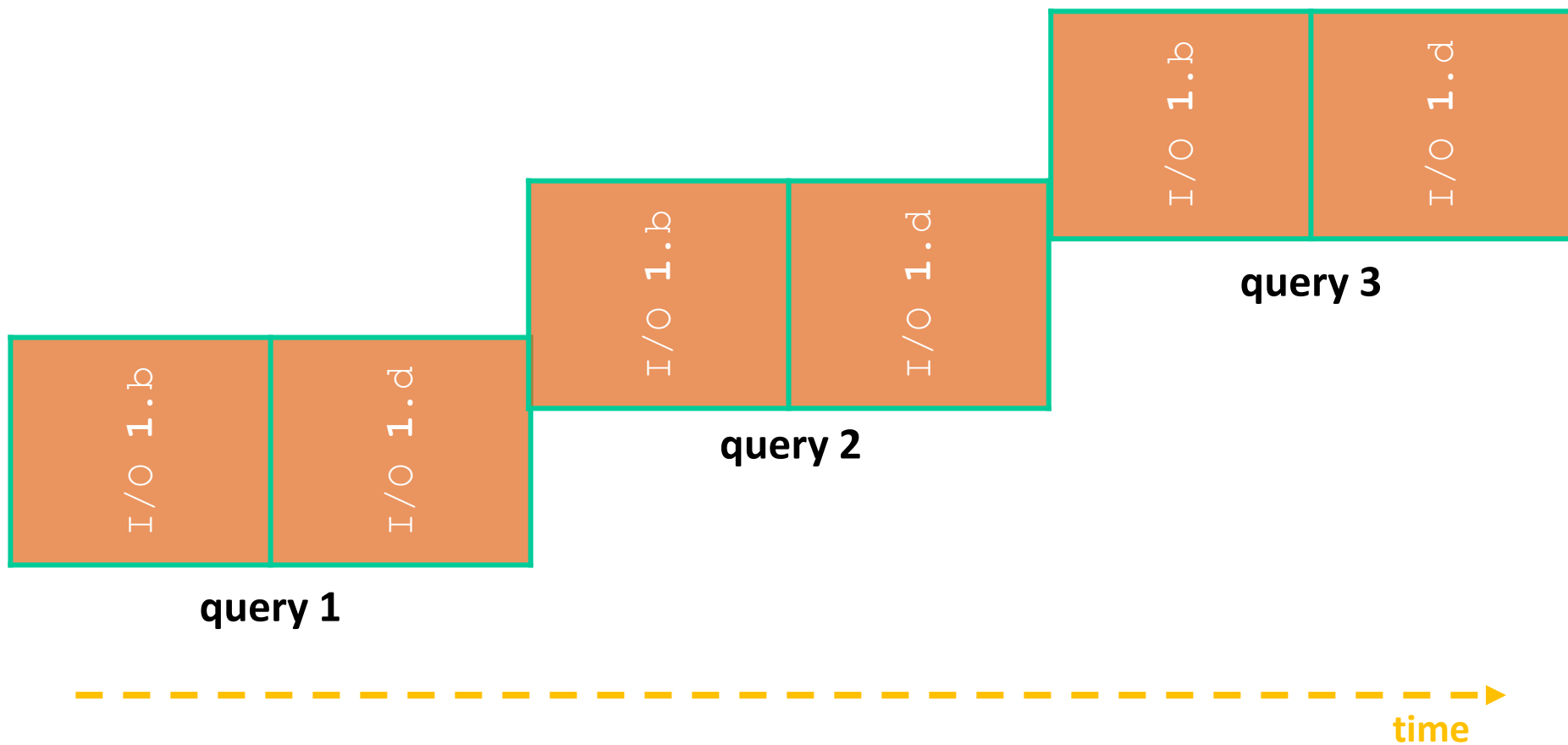
Execution Timeline: To Scale



Sequential Queries – Simplified



Sequential Queries: To Scale



Sequential Can Be Inefficient

- ❖ Only one query is being processed at a time
 - All other queries queue up behind the first one
- ❖ The CPU is idle most of the time
 - It is *blocked* waiting for I/O to complete
 - Disk I/O can be very, very slow
- ❖ 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.

Concurrency

- ❖ A version of the program that executes multiple tasks simultaneously
 - 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
 - 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
- ❖ Concurrency != parallelism
 - Parallelism is when multiple CPUs work simultaneously on 1 job

A Concurrent Implementation

- ❖ Use multiple threads or processes
 - As a query arrives, fork a new thread (or process) to handle it
 - The thread reads the query from the console, issues read requests against files, assembles results and writes to the console
 - The thread uses blocking I/O; the thread alternates between consuming CPU cycles and blocking on I/O

- ❖ The OS context switches between threads/processes
 - While one is blocked on I/O, another can use the CPU
 - Multiple threads' I/O requests can be issued at once

Lecture Outline

- ❖ Understanding Concurrency
- ❖ Concurrent Programming Styles
 - **Threads vs. processes**
 - Asynchronous or non-blocking I/O
 - aka “Event-driven programming”

- ❖ To implement a “process”, the operating system gives us:
 - Resources such as file handles and sockets
 - Call stack + registers to support (eg, PC, SP)
 - Virtual memory (page tables, TLBs, etc ...)
- ❖ If we want concurrency, what is the “minimal set” we need to execute a single line of code?

“Worker” 1

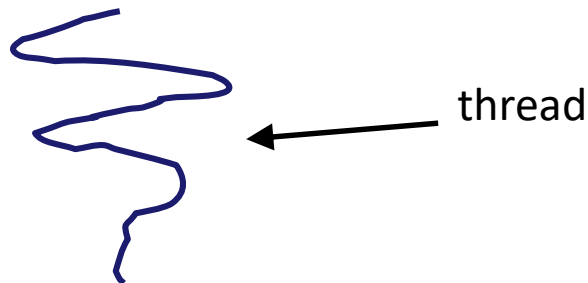
```
bucket = hash(word);  
hitlist = file.read(bucket);
```

“Worker” 2

```
foreach hit in hitlist {  
    doclist.append(file.read(hit));  
}
```


Introducing Threads

- ❖ Separate the concept of a **process** from an individual “*thread of control*”
 - Usually called a **thread** (or a *lightweight process*), this is a sequential execution stream within a process



- ❖ In most modern OS's:
 - Process: address space, OS resources/process attributes
 - Thread: 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

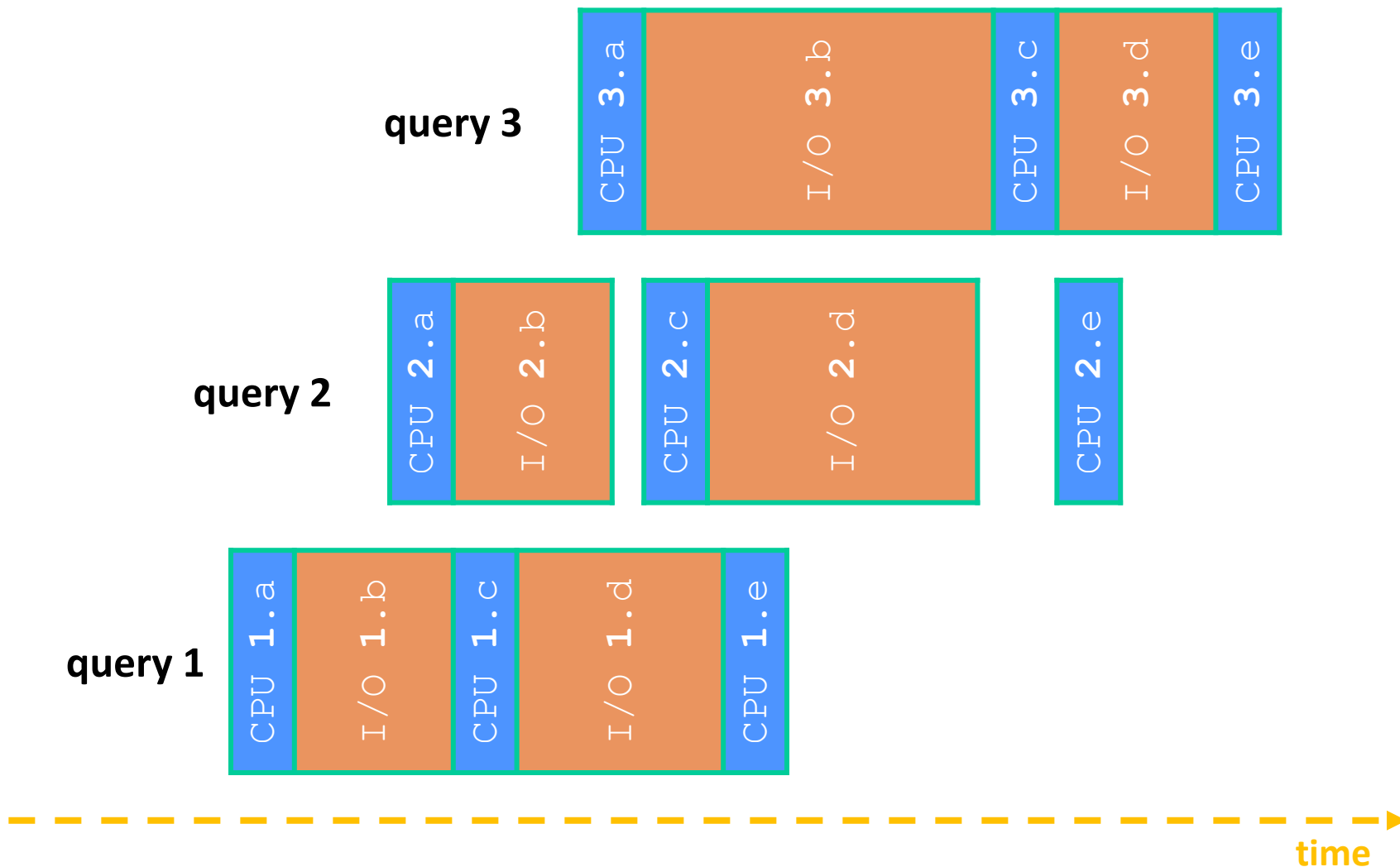
- ❖ Threads were formerly called “lightweight processes”
 - They execute concurrently like processes
 - OS’s often treat them, not processes, as the unit of scheduling
 - Parallelism for free! If you have multiple CPUs/cores, can run them simultaneously
 - Unlike processes, threads cohabit the same address space
 - Threads within a process see the same heap and globals and can communicate with each other through variables and memory
 - But can interfere with each other – need synchronization for shared resources
 - Each thread has its own stack
- ❖ What does the OS do when you switch processes?
 - How does that differ from switching threads?

Multithreaded Pseudocode

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

```
doclist Lookup(string word) {  
    bucket = hash(word);  
    hitlist = file.read(bucket);  
    foreach hit in hitlist  
        doclist.append(file.read(hit));  
    return doclist;  
}  
  
ProcessQuery() {  
    results = Lookup(query_words[0]);  
    foreach word in query[1..n]  
        results = results.intersect(Lookup(word));  
    Display(results);  
}
```

Multithreaded Queries – Simplified



Why Threads?

❖ Advantages:

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

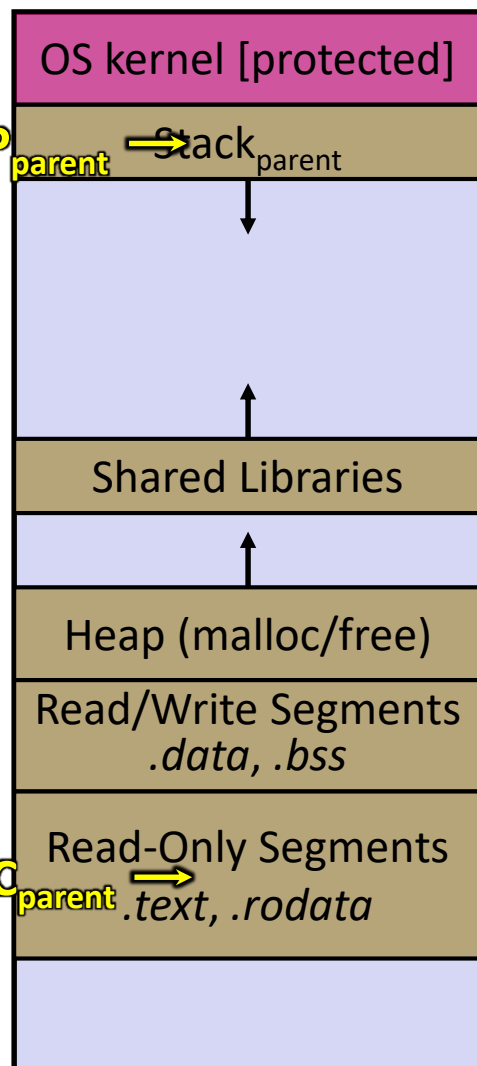
❖ Disadvantages:

- 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

Alternative: Processes

- ❖ What if we forked processes instead of threads?
- ❖ Advantages:
 - No shared memory between processes
 - No need for language support; OS provides “fork”
- ❖ Disadvantages:
 - More overhead than threads during creation and context switching
 - Cannot easily share memory between processes – typically communicate through the file system

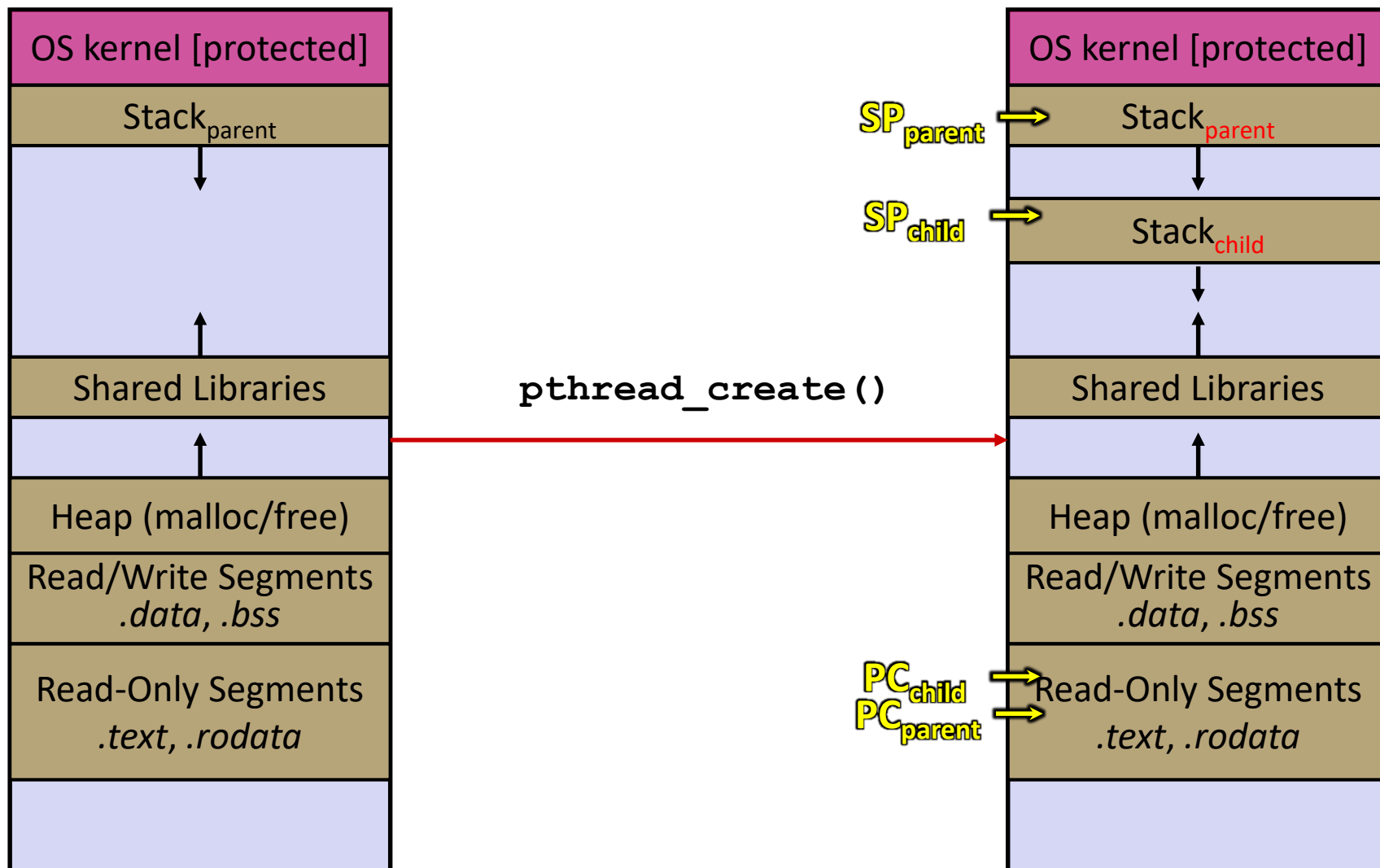
Threads vs. Processes



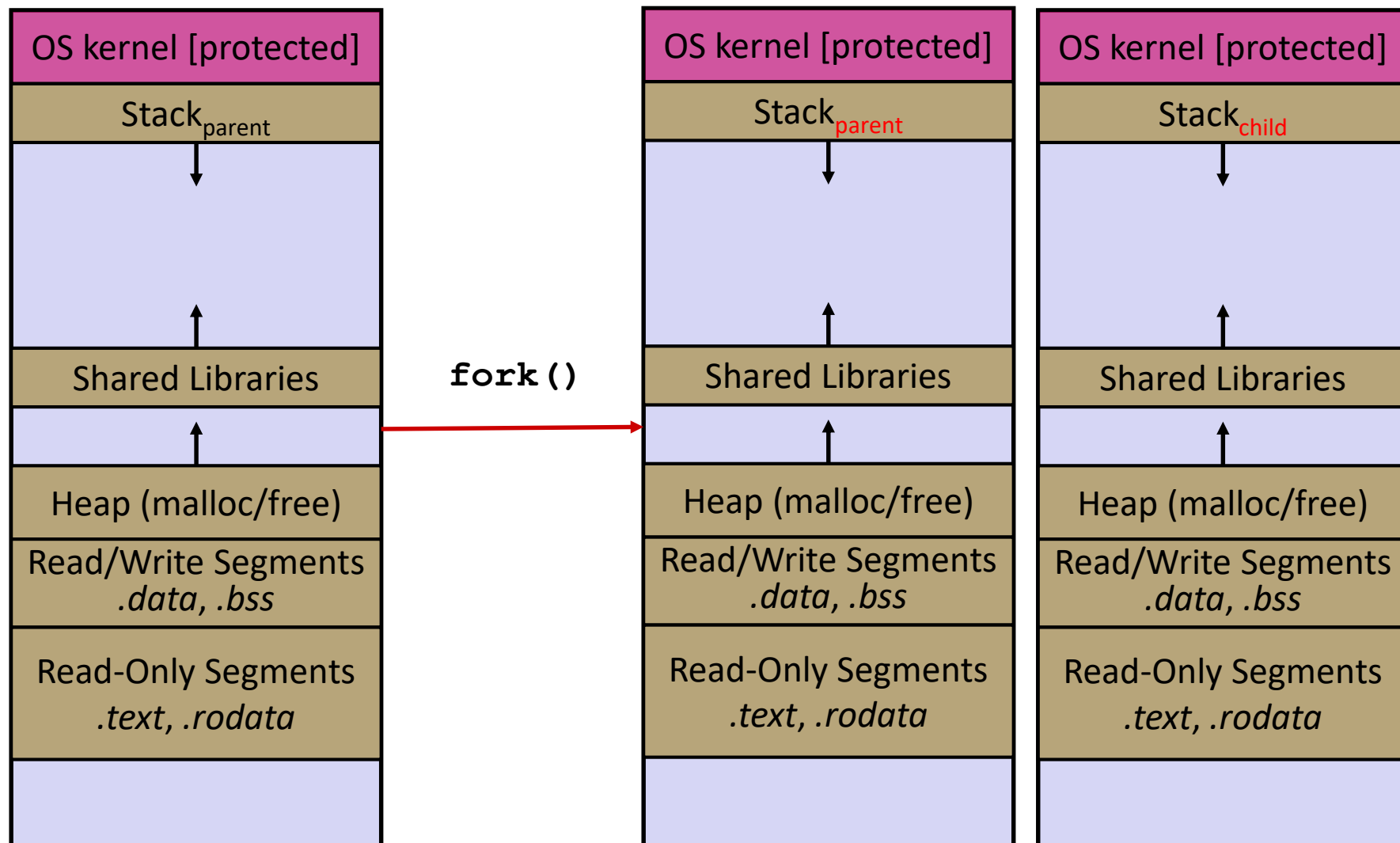
❖ Before creating a thread

- 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()`

Threads vs. Processes



Threads vs. Processes



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Alternate: Asynchronous I/O

- ❖ 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

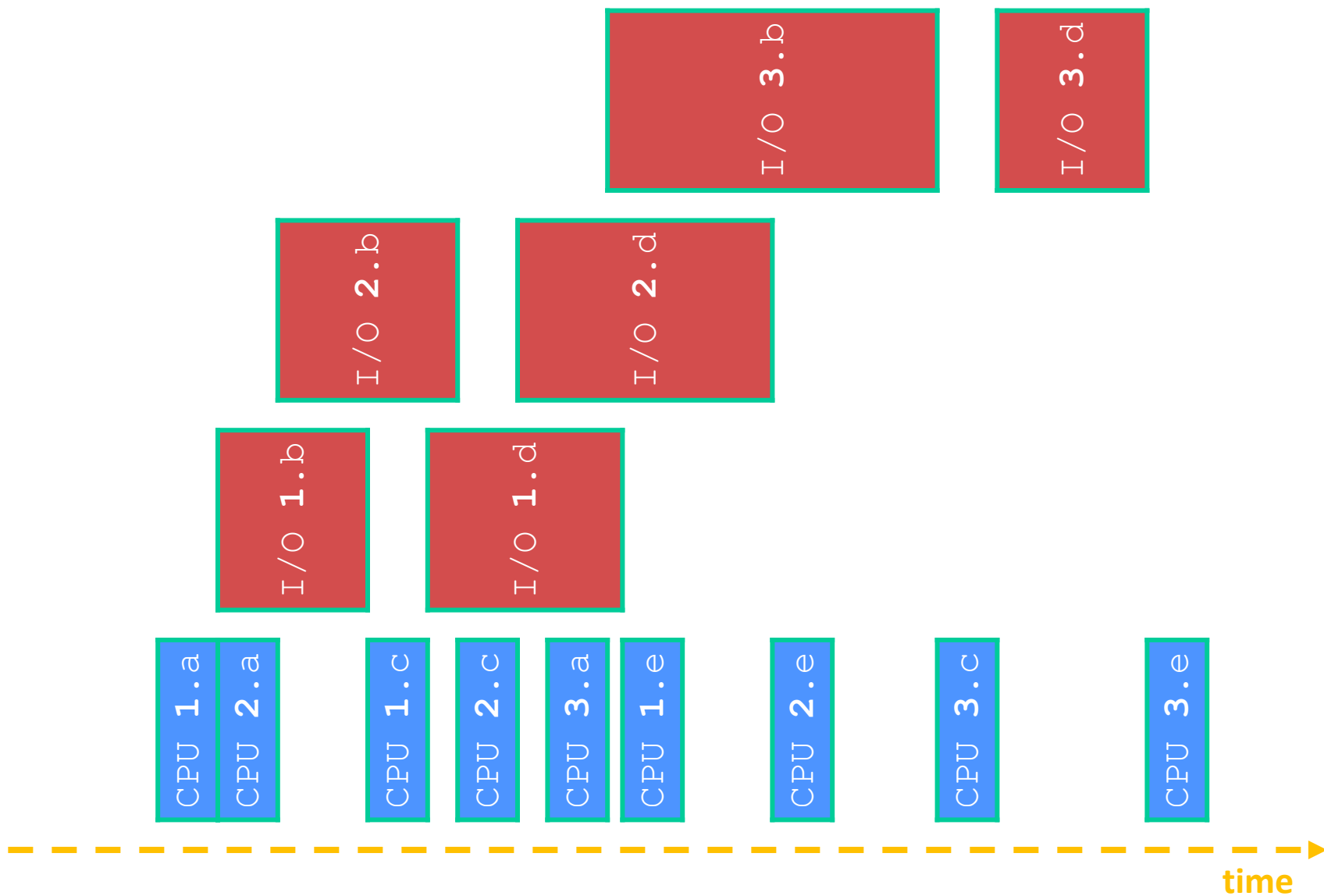
Event-Driven Programming

- ❖ 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);
}
```

Asynchronous, Event-Driven



Non-blocking vs. Asynchronous

- ❖ 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/writable
 - Program can choose to block while no file descriptors are ready

Non-blocking vs. Asynchronous

- ❖ Asynchronous I/O (disk)
 - Program tells the OS to begin reading/writing
 - The “begin_read” or “begin_write” returns immediately
 - When the I/O completes, OS delivers an event to the program
- ❖ According to the Linux specification, the disk never blocks your program (just delays it)
 - Asynchronous I/O is primarily used to hide disk latency
 - Asynchronous I/O system calls are messy and complicated 😞

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

One Way to Think About It

- ❖ Threaded code:
 - Each thread executes its task sequentially, and per-task state is naturally stored in the thread's stack
 - OS and thread scheduler switch between threads for you
- ❖ Event-driven code:
 - *You* are the scheduler
 - You have to bundle up task state into continuations (data structures describing what-to-do-next); tasks do not have their own stacks