Introduction to Concurrency

CSE 333 Fall 2022

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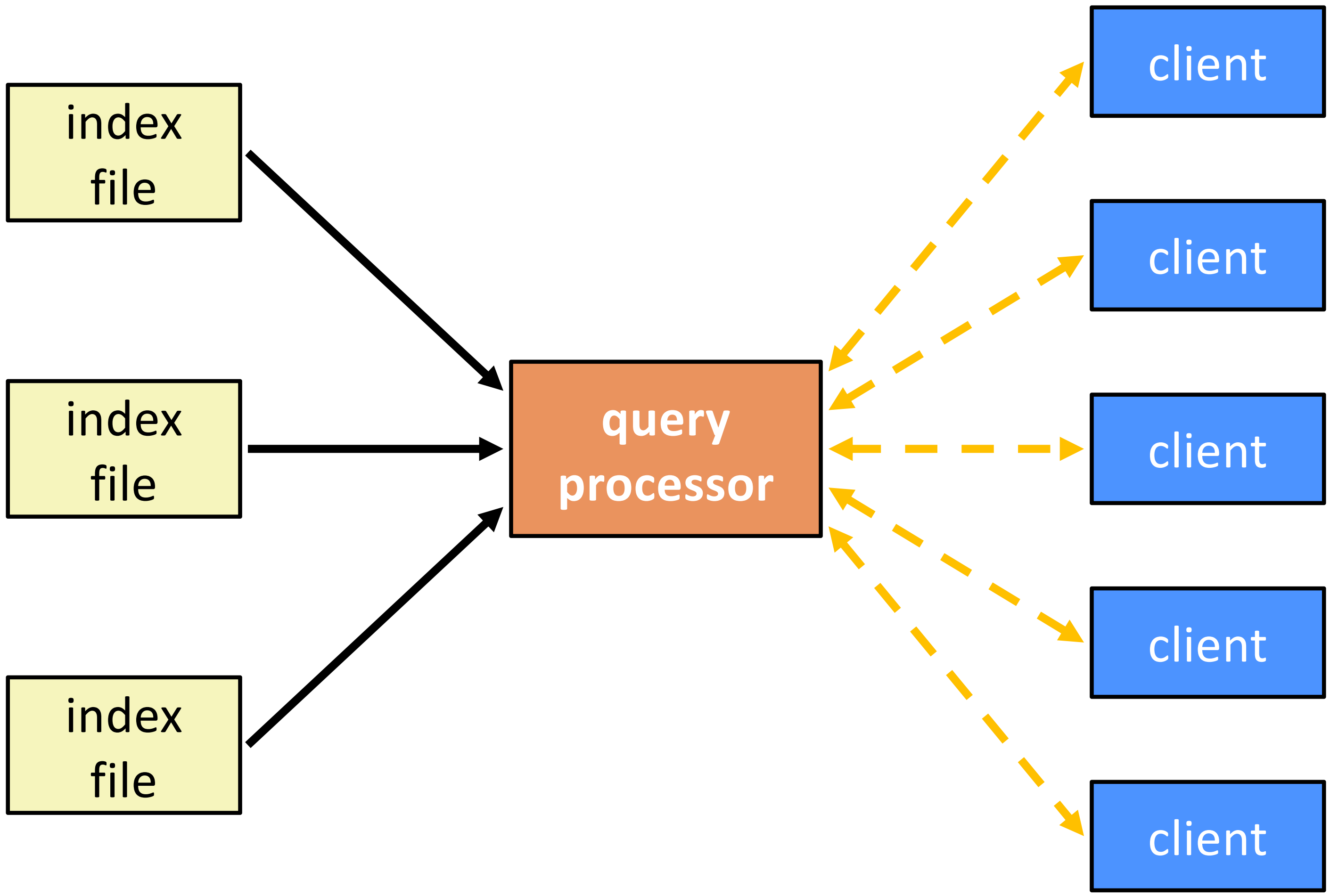
Outline

- Understanding Concurrency
  - Why is it useful
  - Why is it hard
- Concurrent Programming Styles
  - Threads vs. processes
  - Asynchronous or non-blocking I/O
    - "Event-driven programming"

Building a Web Search Engine

- We need:
  - 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

Web Search Architecture



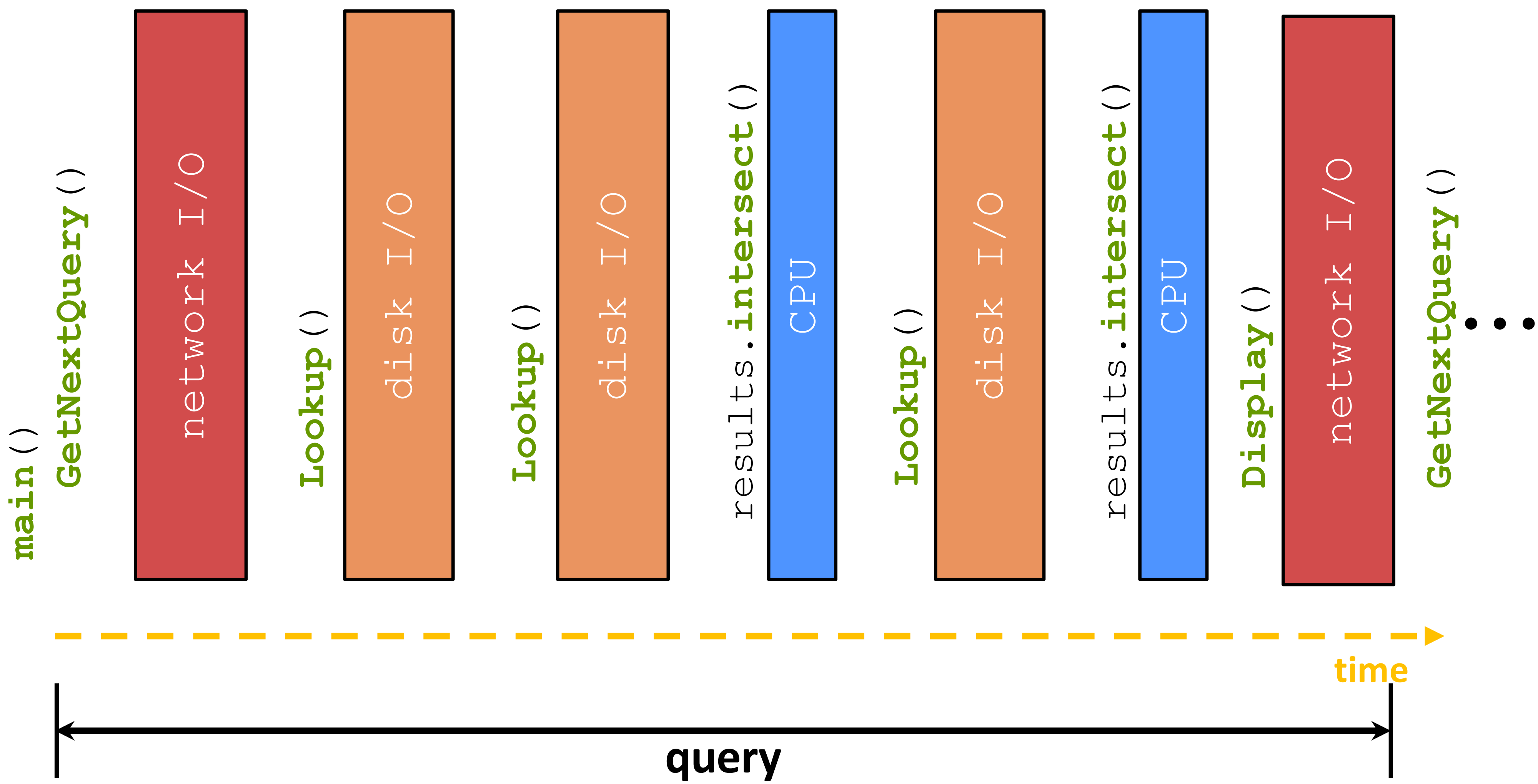
Sequential Implementation

- 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?

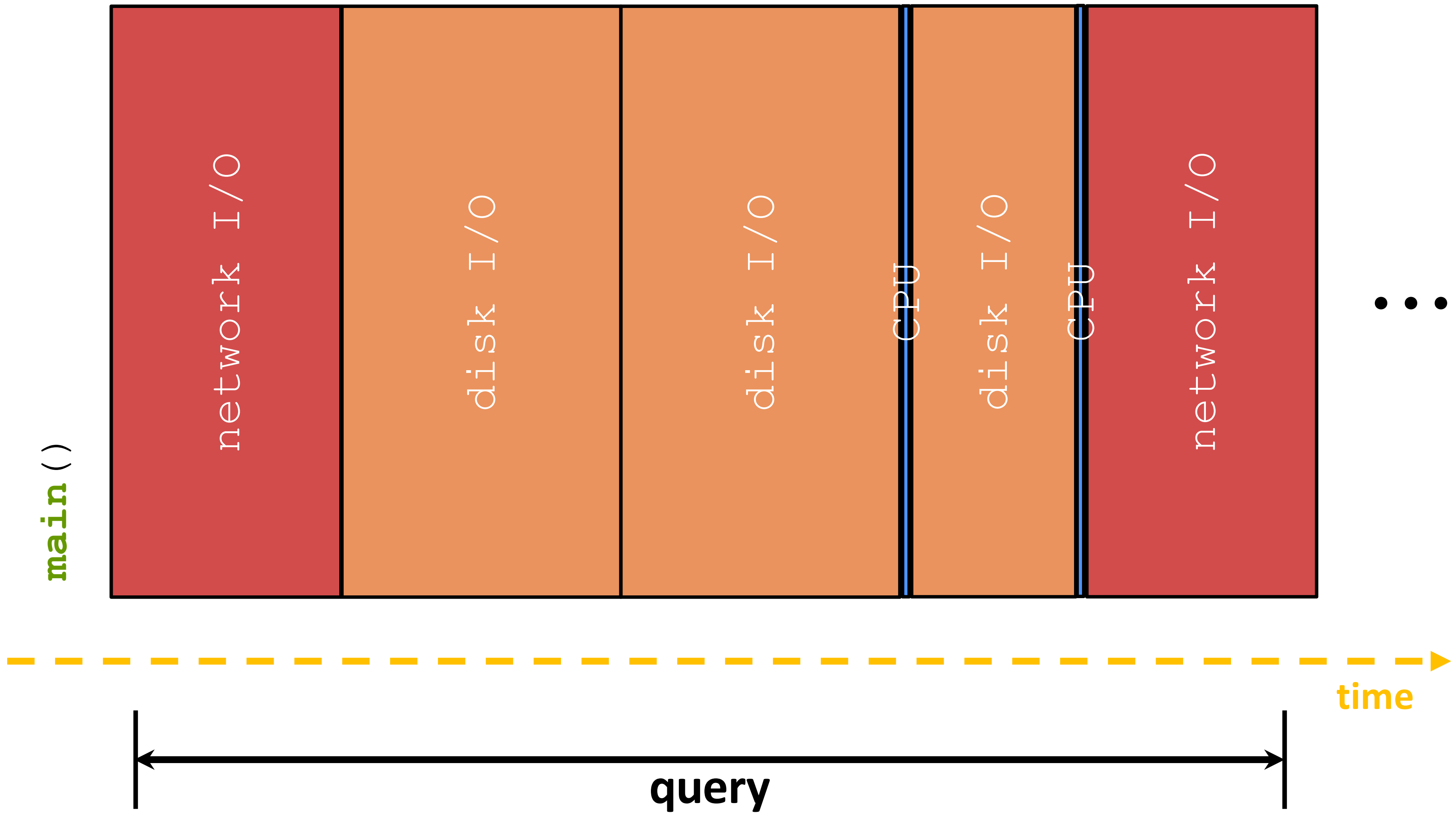
- Jeff Dean's "Numbers Everyone Should Know" (LADIS '09)

Numbers Everyone Should Know

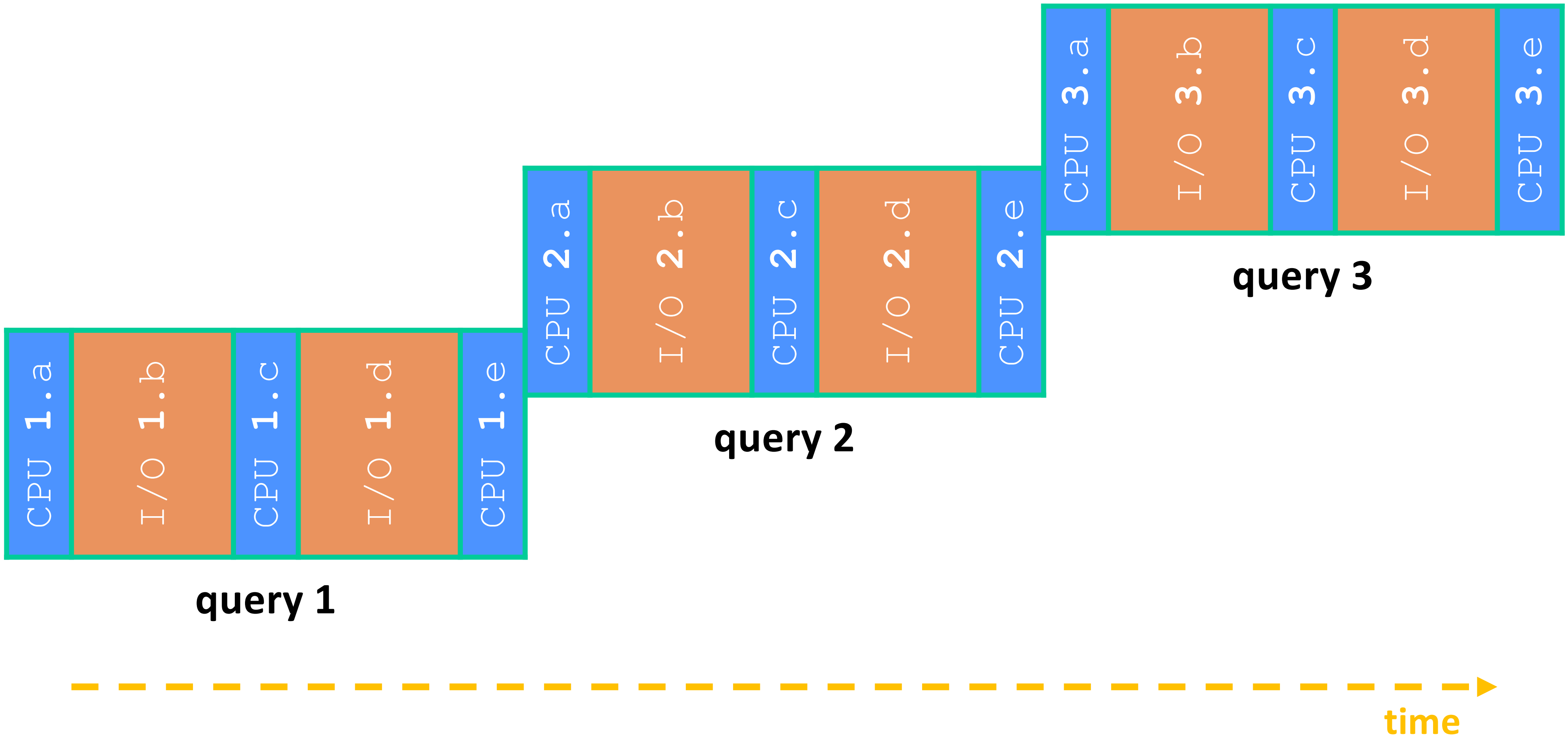
L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	100 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	10,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns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

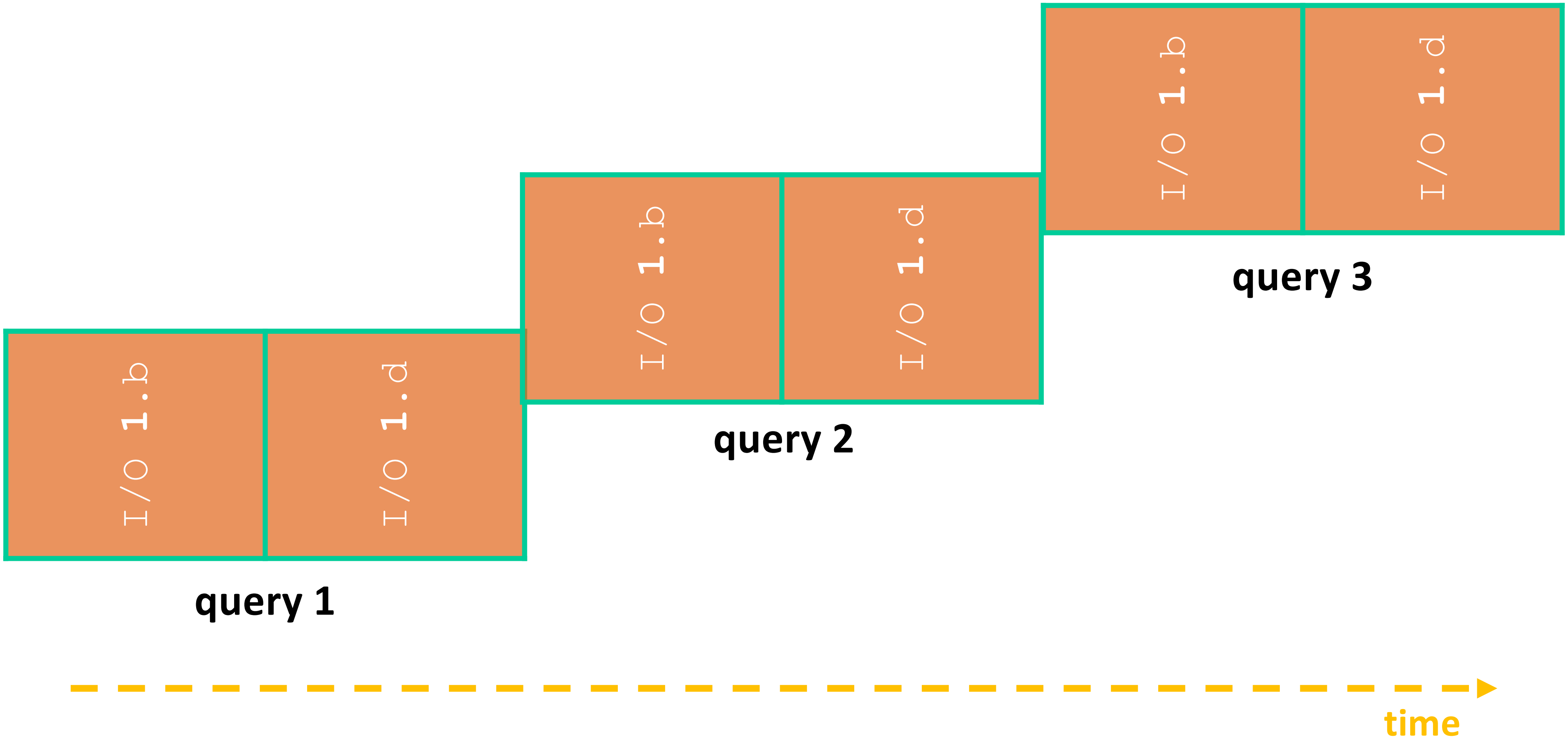
Execution Timeline: To Scale



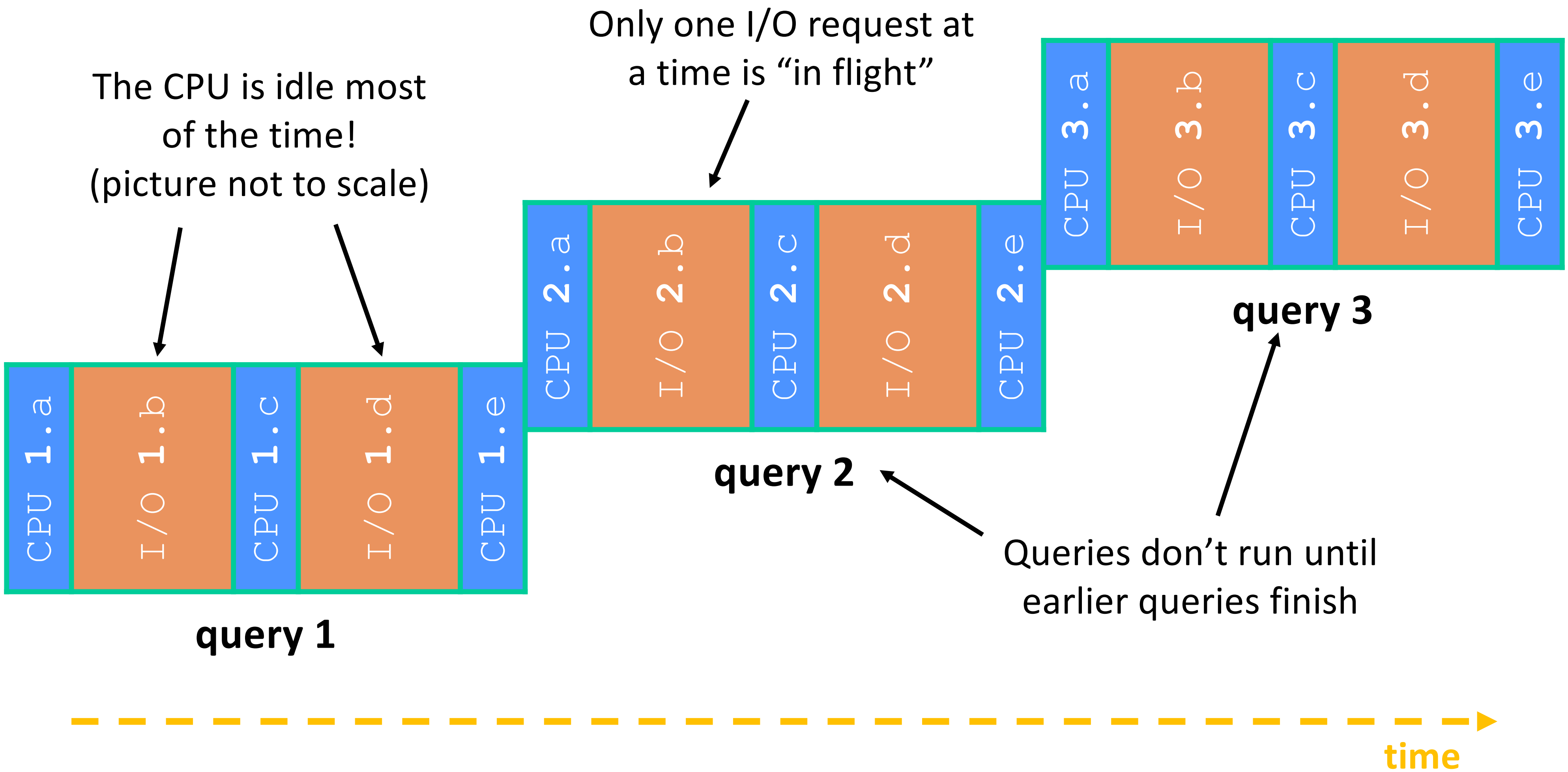
Sequential Queries – Simplified



Sequential Queries: To Scale



Multiple Clients – Simplified



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

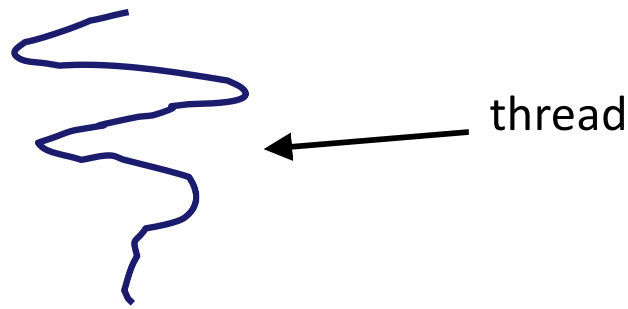
- A version of the program that executes multiple tasks simultaneously
  - Example: Our web server could execute multiple *queries* at the same time
    - While one is waiting for I/O, another can be executing on the CPU
  - Example: Execute queries one at a time, but issue *I/O requests* against different files/disks simultaneously
    - Could read from several index files at once, processing the I/O results as they arrive
- Concurrency != parallelism
  - Parallelism is executing multiple CPU instructions simultaneously

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

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

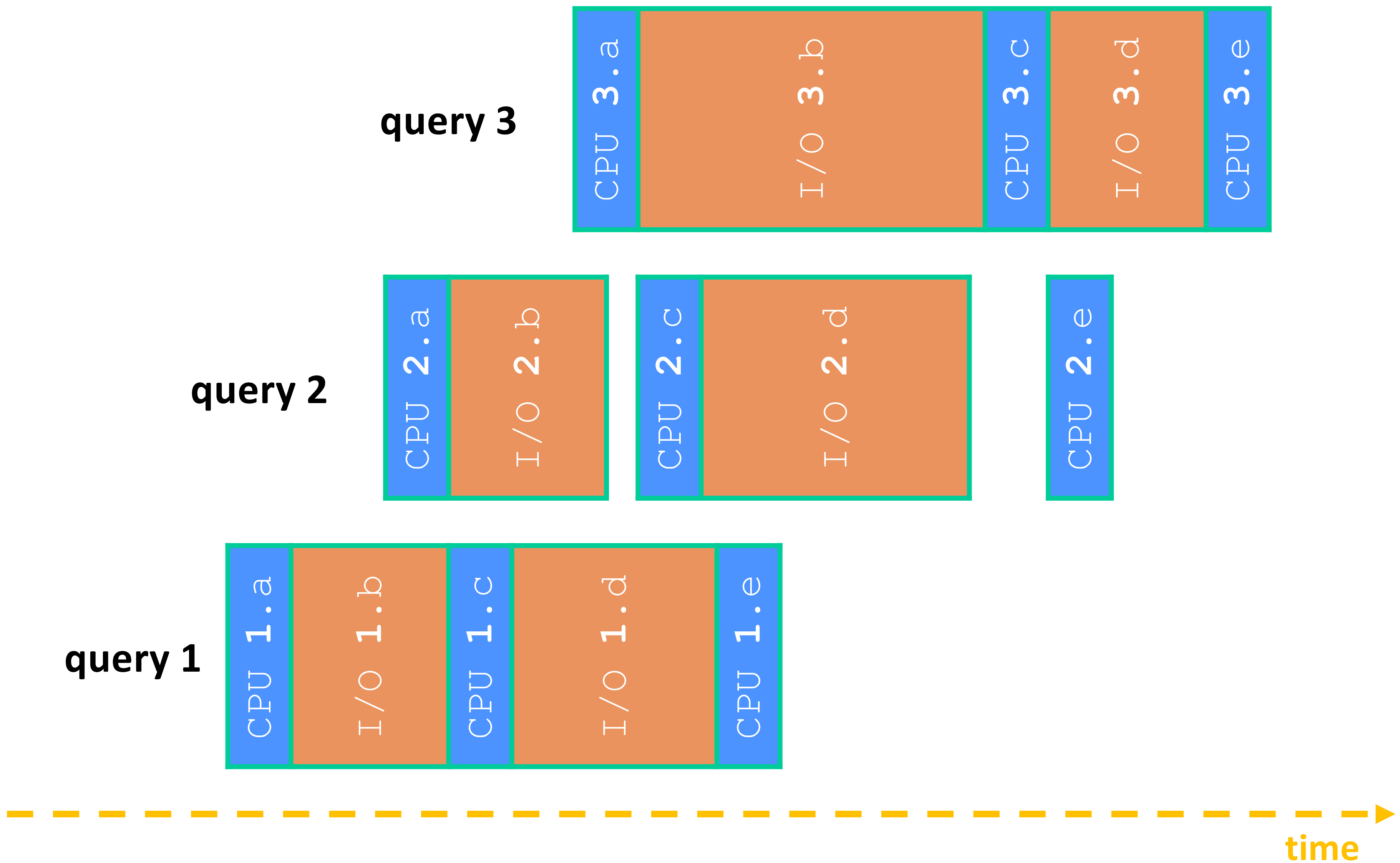
Multithreaded Pseudocode

```
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

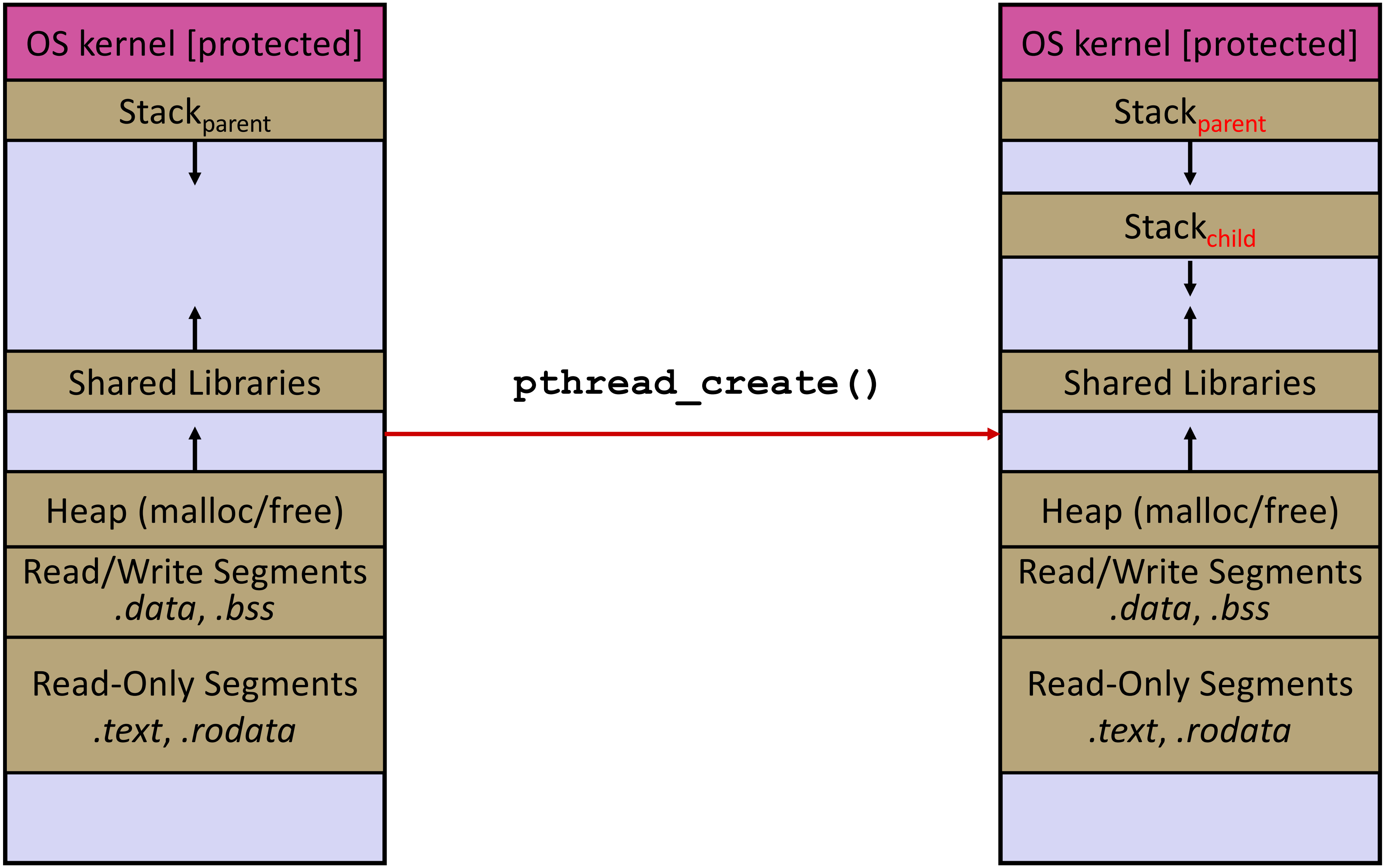
Alternative: Processes

- What if we forked processes instead of threads?

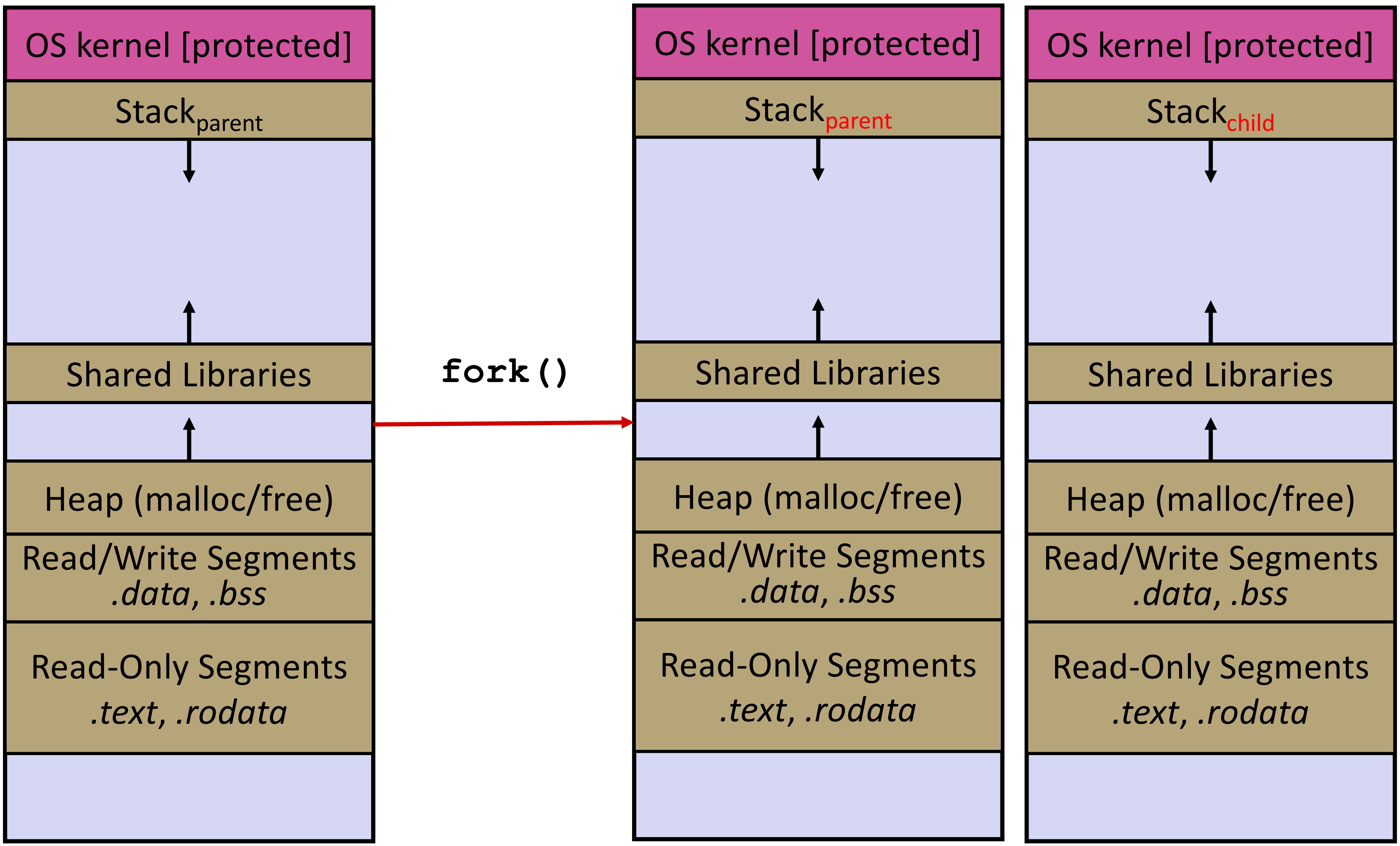
- Advantages:
  - No shared memory between processes
  - No need for language support; OS provides “fork”

- 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



Threads vs. Processes



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

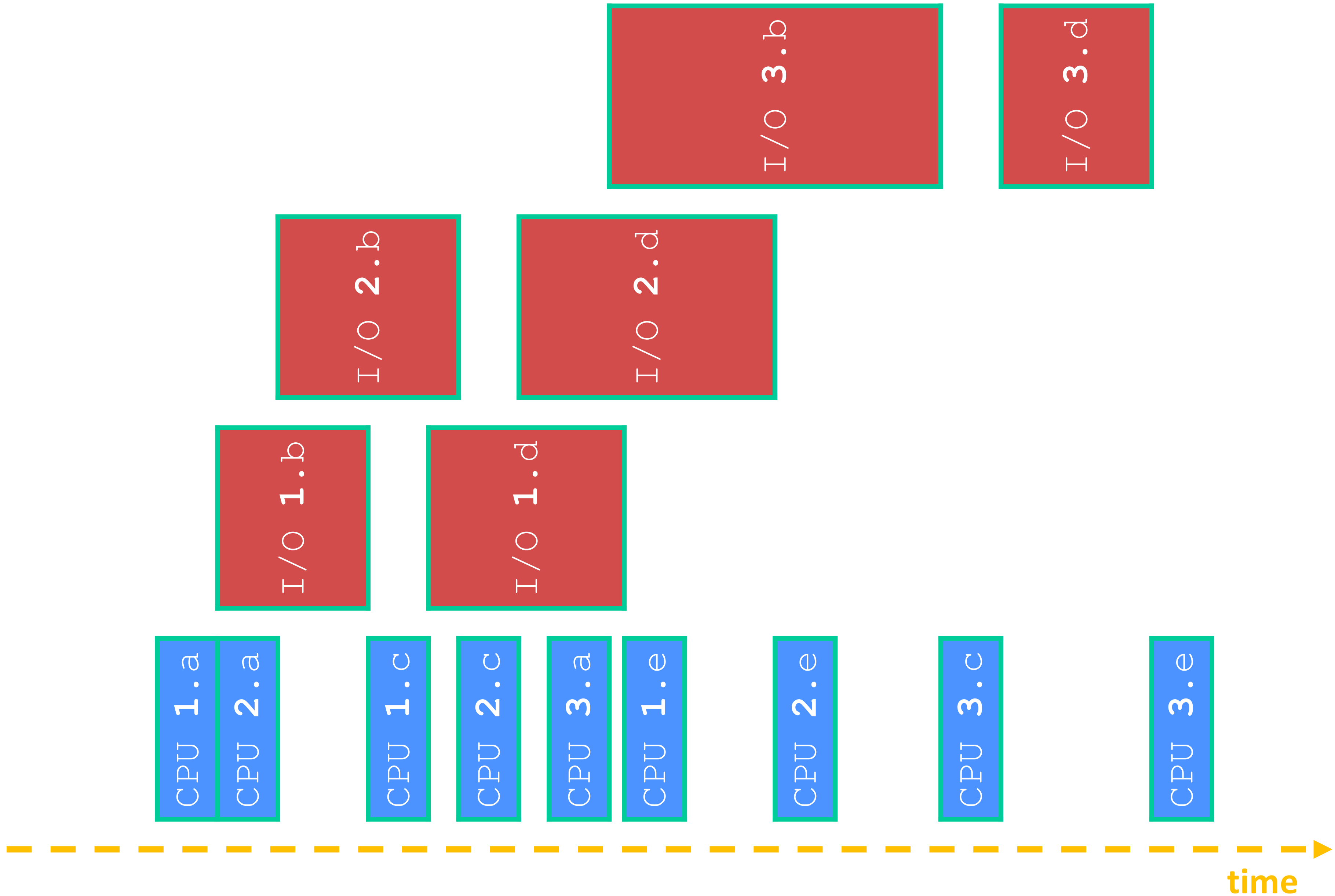
Event-Driven Programming

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

Non-blocking vs. Asynchronous

- Asynchronous I/O (disk)
  - Program tells the OS to being 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