CSE 333

Lecture 20 - intro to concurrency

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Administrivia

HW4 due in a week, 11 pm Thur. w/usual late days

- How's it going?
- Remember: no changes allowed in header files, Makefile, or specifications.

Reminder: watch your late days! (4 max per quarter, 2 max per hw assignment, none for exercises)

- Check the "late days remaining" entry in the gradebook

Section tomorrow: pthreads tutorial

- Last exercise posted tomorrow, due next Monday: pthreads

Goals

Understand concurrency

- why it is useful
- why it is hard

Exposure to concurrent programming styles

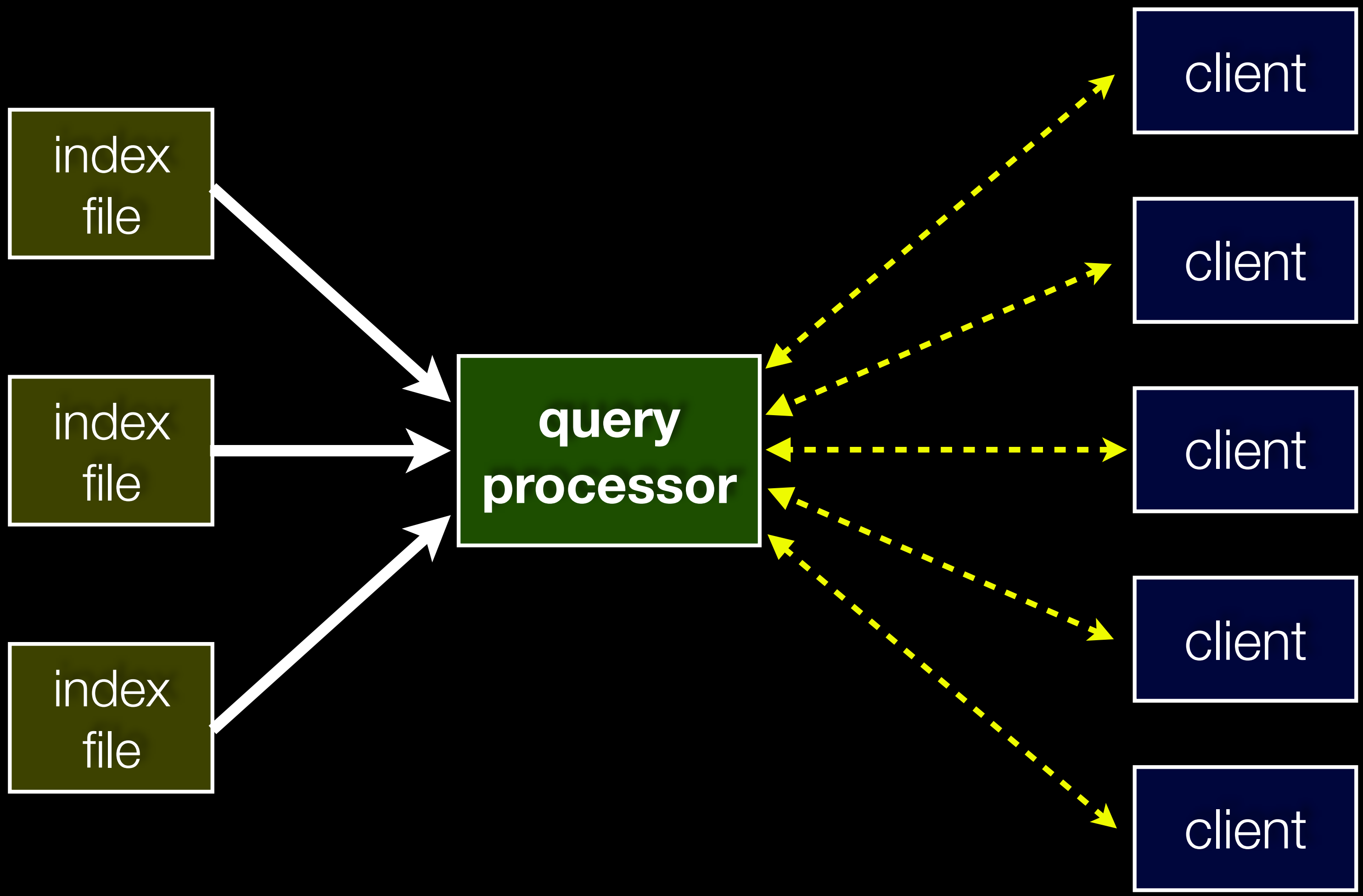
- using multiple threads or multiple processes
- using asynchronous or non-blocking I/O
    - “event-driven programming”

Let’s imagine you want to...

...build a web search engine.

- you need a Web index
  - an inverted index (a map from “word” to “list of documents containing the word”)
  - 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

Architecturally

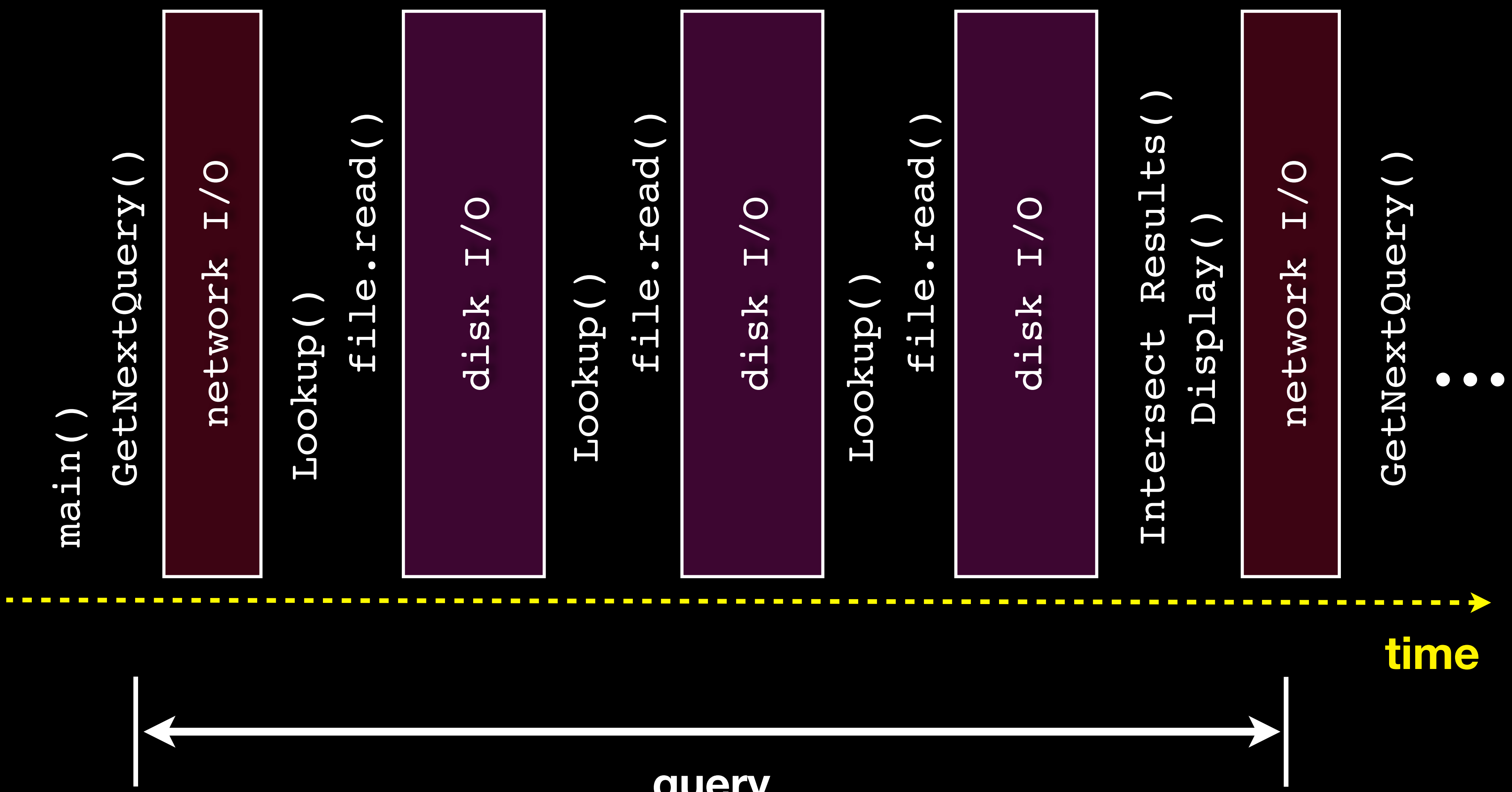


A sequential implementation

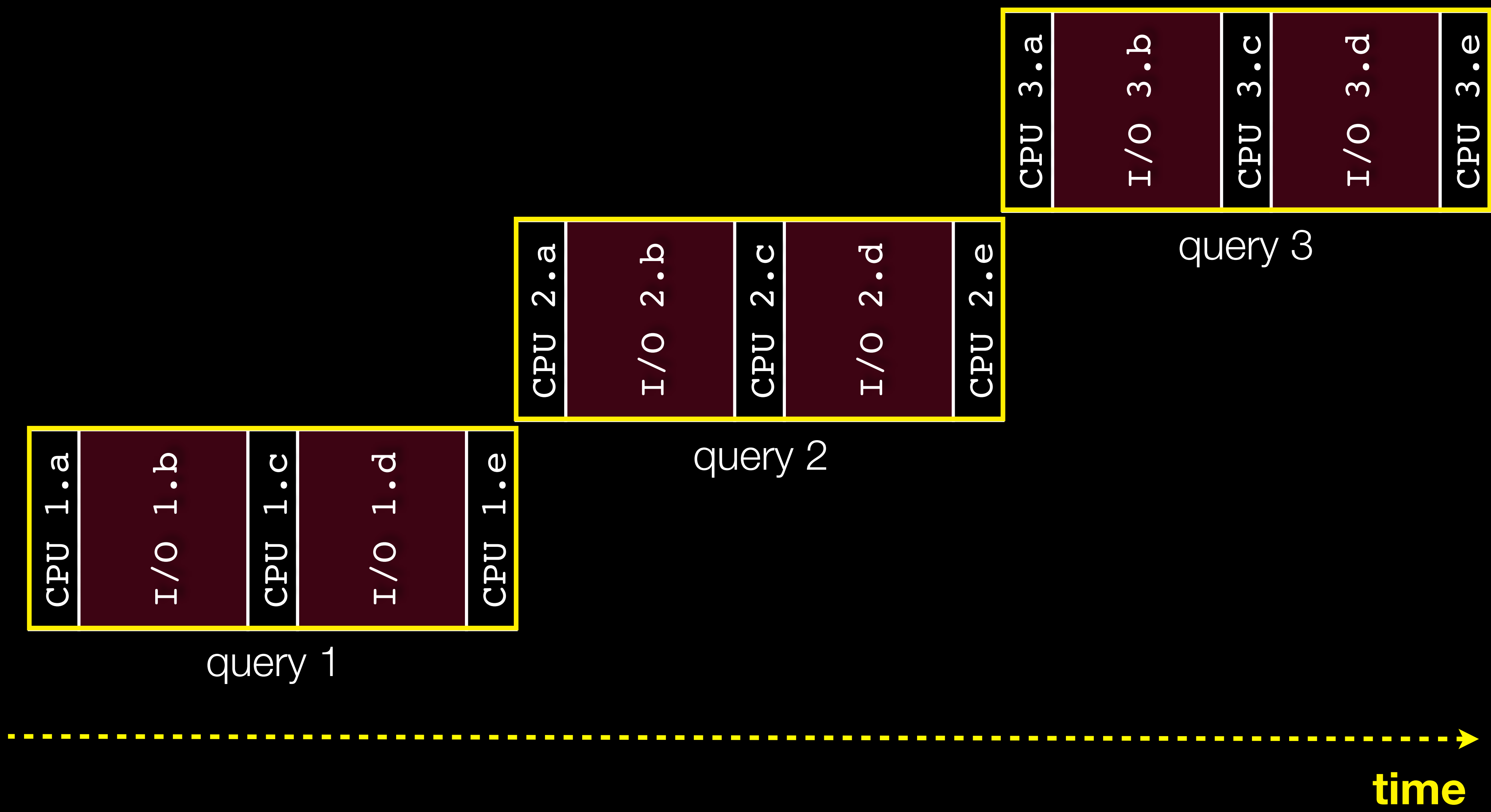
```
doclist Lookup(string word) {
  bucket = hash(word);
  hitlist = file.read(bucket);
  foreach hit in hitlist {
    doclist.append(file.read(hit));
  }
  return doclist;
}

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);
  }
}
```

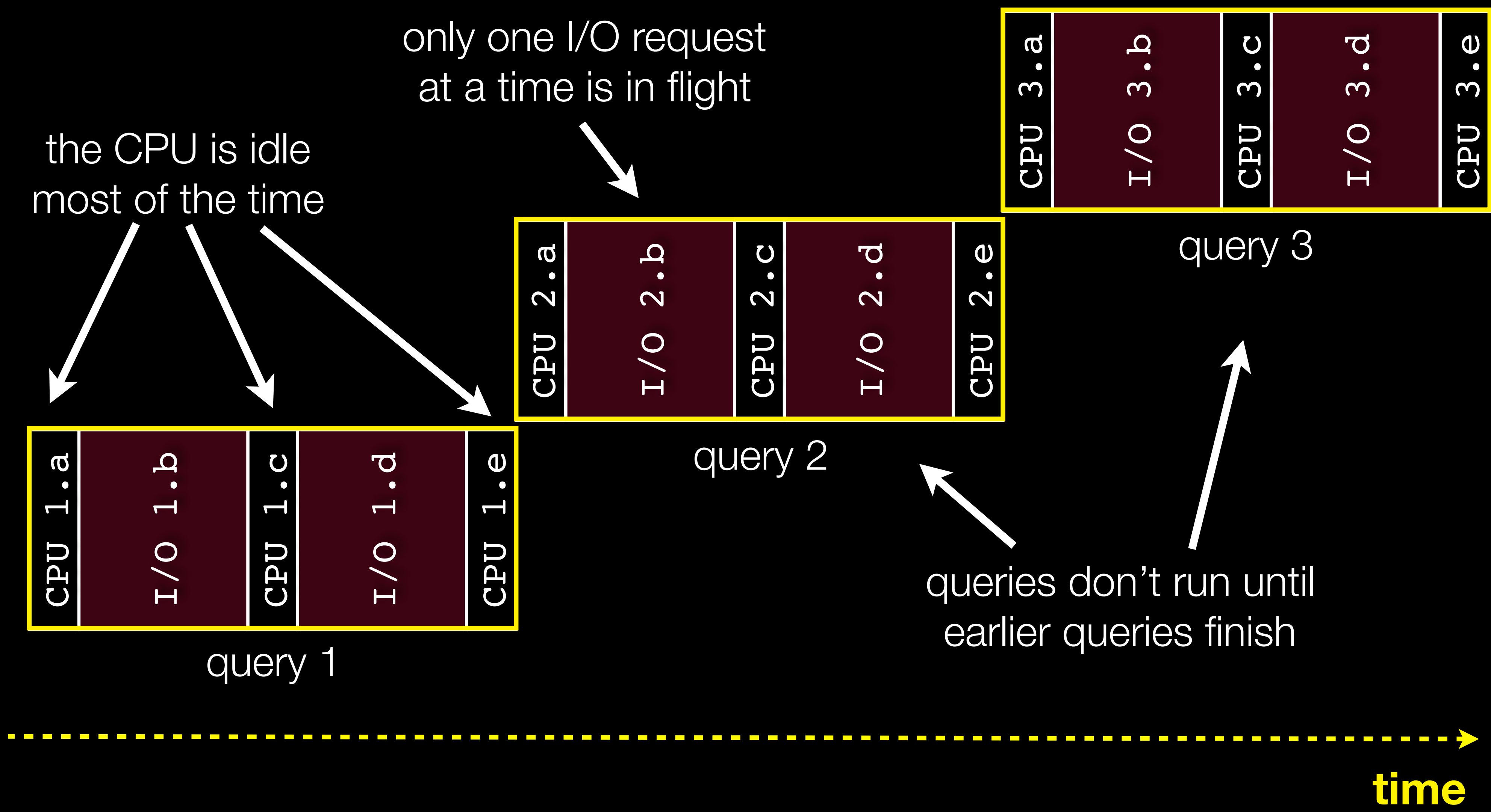
Visually


main()
GetNextQuery()
network I/O
Lookup()
file.read()
disk I/O
Lookup()
file.read()
disk I/O
Lookup()
file.read()
disk I/O
Intersect Results()
Display()
network I/O
GetNextQuery()
• • •
time
query

Simplifying



Simplifying



Sequentiality 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

- misses opportunities to speed I/O up
    - separate devices in parallel, better scheduling of single device, ...

What we want...concurrency

A version of the program that executes multiple **tasks** simultaneously

- it could execute multiple **queries** at the same time
  - while one is waiting for I/O, another can be executing on the CPU
- or, it could execute queries one at a time, but issue **I/O requests** against different files/disks simultaneously
  - it could read from several different index files at once, processing the I/O results as they arrive

Concurrency != parallelism

- parallelism is when multiple CPUs work simultaneously on 1 job

One way to do this

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

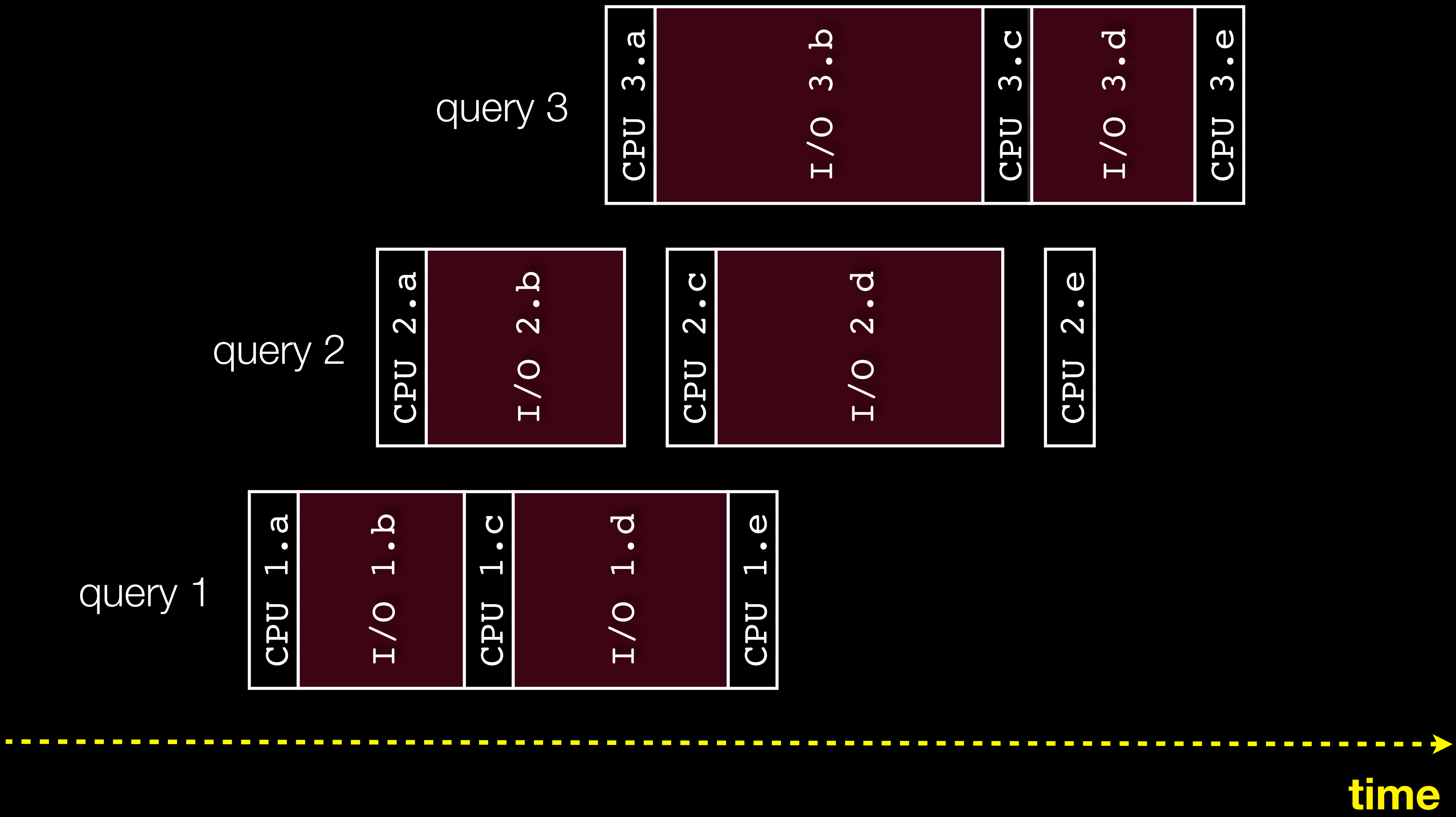
Multithreaded pseudocode

```
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, visually



Whither threads?

Advantages

- you (mostly) write sequential-looking code
- if you have multiple CPUs / cores, threads can run in **parallel**

Disadvantages

- if your threads share data, 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

One alternative

Fork **processes** instead of threads

- advantages:
  - no shared memory between processes, so no need to worry about concurrent accesses to shared variables / data structures
  - no need for language support; OS provides “fork”
- disadvantages:
  - more overhead than threads to create, context switch
  - cannot easily share memory between processes, so typically share through the file system

Another alternative

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, 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

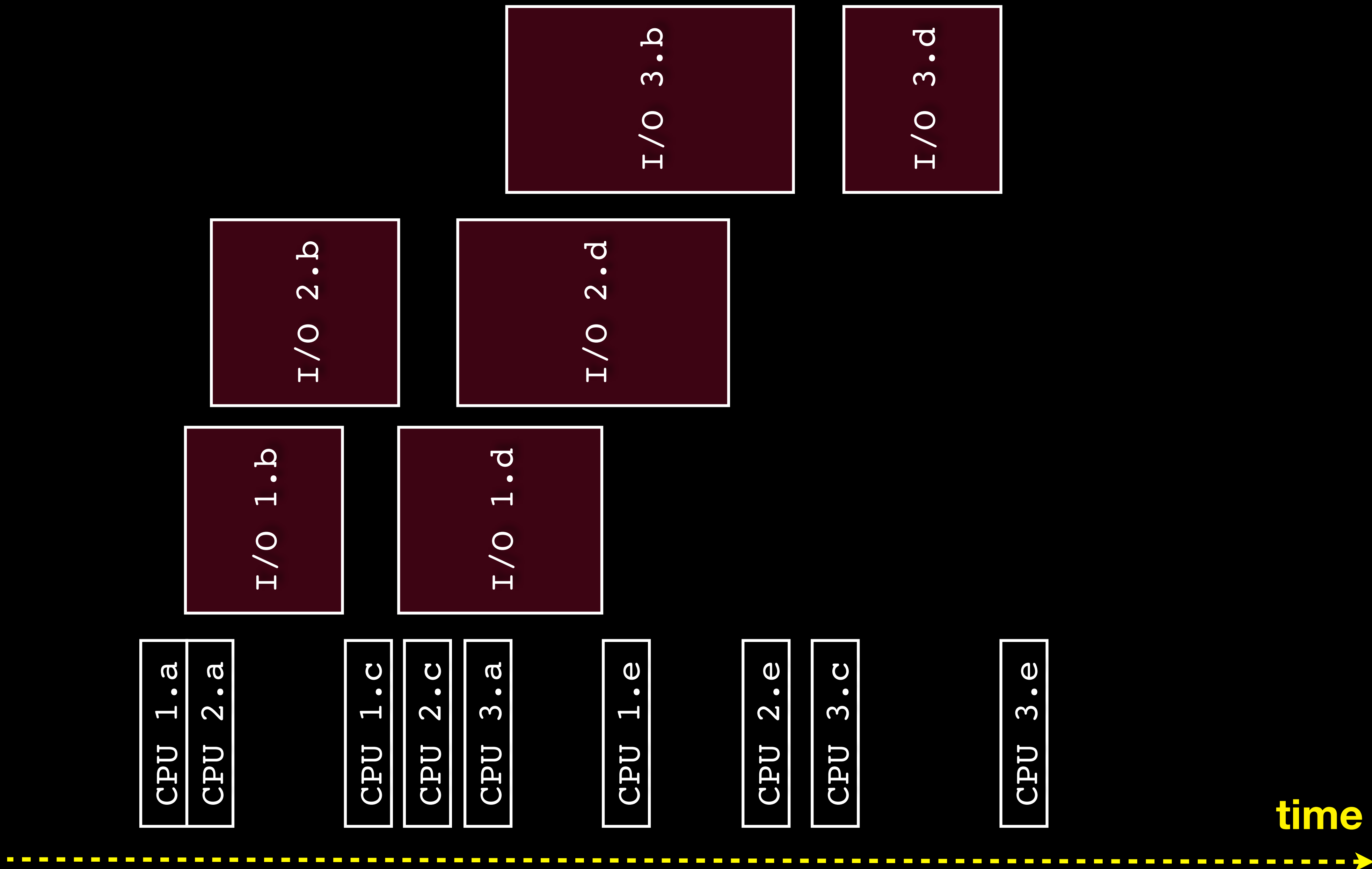
Event-driven programming

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:
      ...etc.
  }
}

while(1) {
  event = OS.GetNextEvent( );
  task = lookup(event);
  dispatch(task, event);
}
```

Asynchronous, event-driven



Non-blocking vs. asynchronous

Non-blocking I/O (network, console)

- your program enables non-blocking I/O on its fd's
- your program issues read( ), write( ) system calls
    - if the read/write would **block**, the system call returns immediately
- program can ask the OS which fd's are readable/writeable
    - program can choose to block while no fds are ready

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

Why the difference?

Non-blocking I/O is for networks

- according to Linux, the disk never **blocks** your program
  - it just delays it
- but, reading from the network can truly block your program
  - a remote computer may wait arbitrarily long before sending data

Asynchronous I/O is for files

- primarily used to hide disk latency
  - asynchronous I/O system calls are messy and complicated :(
  - instead, typically use a threadpool to emulate asynchronous I/O

Whither 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; tasks do not have their own stacks

See you on Friday!