Threads & Scheduling

Computer Operating Systems, Fall 2023

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Administrivia

- Project 1 is out now
  - Project is due 11:59 pm on Wed, Oct 11 **(TOMORROW)**
    late deadline 11:59 pm on Sun, Oct 15
- For project 1 full submission, please do a group submission on gradescope (one of you submits but you add your partner to the submission)
- Recitation Today after lecture:
  - Some cool stuff ☺ and then Open Office Hours Afterwards
- Travis has Office hours 4:30 to 6:30
  - And will host more office hours tomorrow night

Administrivia

- Midterm is coming soon (1 week + 2 days from now!)
  - Meyerson B1 7:00 pm to 9:00pm Thursday 10/19
  - If you can't make the time, please send me an email **ASAP**
- Midterm Policies posted on the course website. Please read through them.
  - You are allowed 1 page of notes 8.5 x 11 double sided notes
  - Clobber policy: can show growth by doing better on the second midterm
- Recitation next week and lectures next week will contain midterm review
  - Tuesday lecture will warp up scheduling, not only review

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- Any questions, comments or concerns from last lecture?

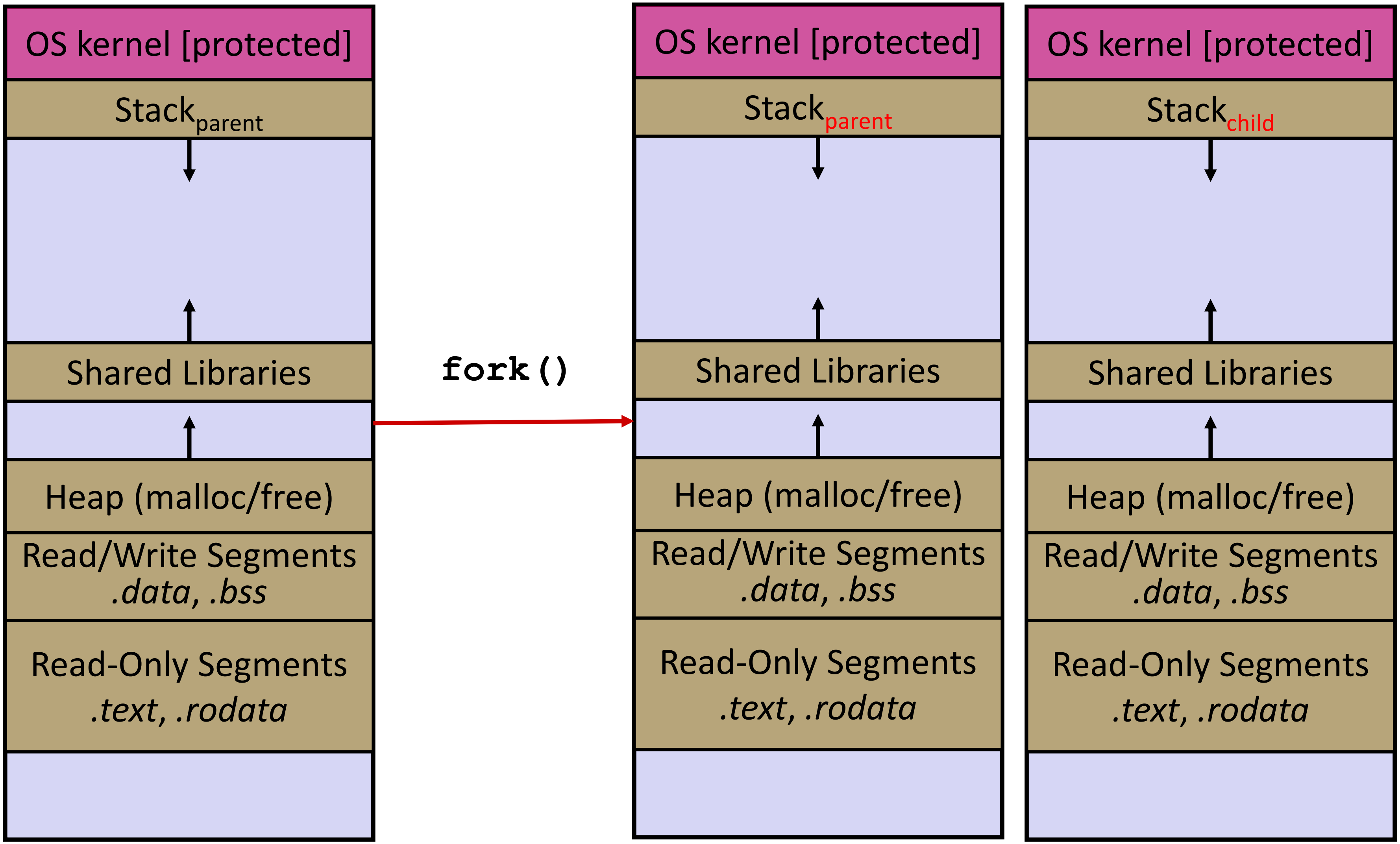
Lecture Outline

- **Threads vs processes**
- Threads & Blocking
- User Level Threads vs Kernel Level Threads
  - `ucontext`
- Scheduling

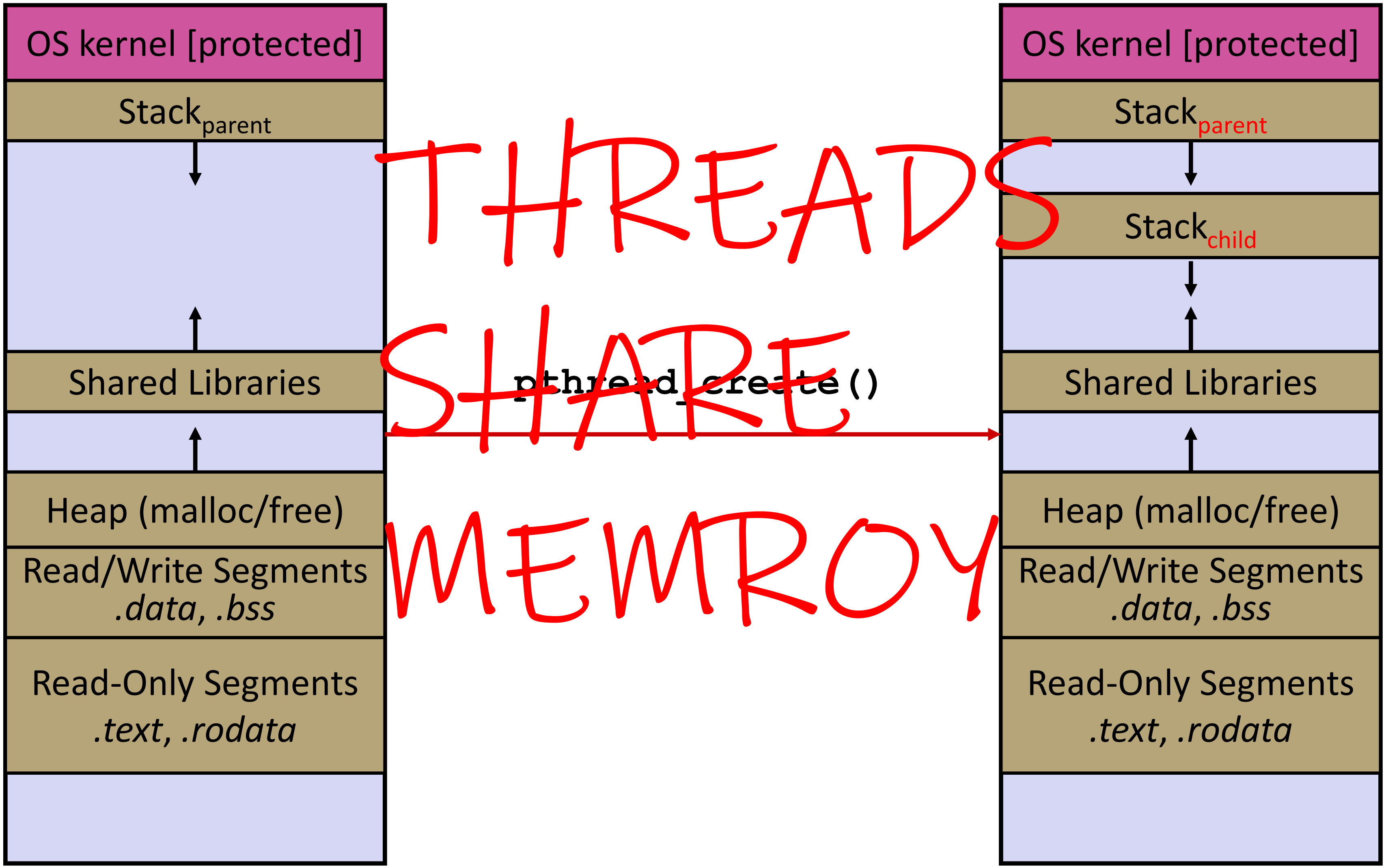
Threads vs. Processes

- In most modern OS's:
  - A Process has a unique: address space, OS resources, & security attributes
  - A Thread has a unique: 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 vs. Processes



Threads vs. Processes



Process Isolation

- Process Isolation is a set of mechanisms implemented to protect processes from each other and protect the kernel from user processes.
  - Processes have separate address spaces
  - Processes have privilege levels to restrict access to resources
  - If one process crashes, others will keep running

- Inter-Process Communication (IPC) is limited, but possible
  - Pipes via pipe()
  - Sockets via socketpair()
  - Shared Memory via shm_open()

How fast is fork()?

- ~ 0.5 milliseconds per fork*
- ~ 0.05 milliseconds per thread creation*
  - 10x faster than fork()

- *Past measurements are not indicative of future performance – depends on hardware, OS, software versions, …
  - Processes are known to be even slower on Windows

Context Switching

- Processes are considered "more expensive" than threads. There is more overhead to enforce isolation

- Advantages:
  - No shared memory between processes
  - Processes are isolated. If one crashes, other processes keep going

- Disadvantages:
  - More overhead than threads during creation and context switching
  - Cannot easily share memory between processes – typically communicate through the file system

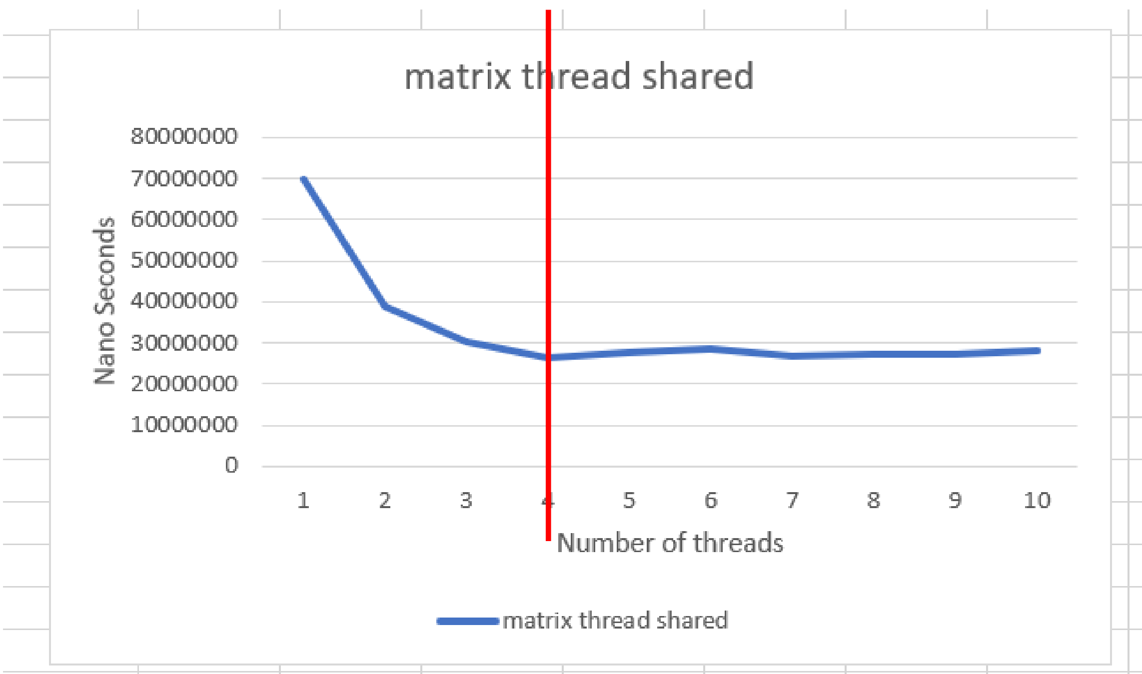
Parallelism

- You can gain performance by running things in parallel
  - Each thread can use another core

- I have a 3800 x 3800 integer matrix, and I want to count the number of odd integers in the matrix

Parallelism

- I have a 3800 x 3800 integer matrix, and I want to count the number of odd integers in the matrix
- I can speed this up by giving each thread a part of the matrix to check!
  - **Works with threads since they share memory**



Diminishing returns

After 4 threads, no gain in speed

why? Machine run on only has 4 cores

Other programs running, that may use the cores

Lecture Outline

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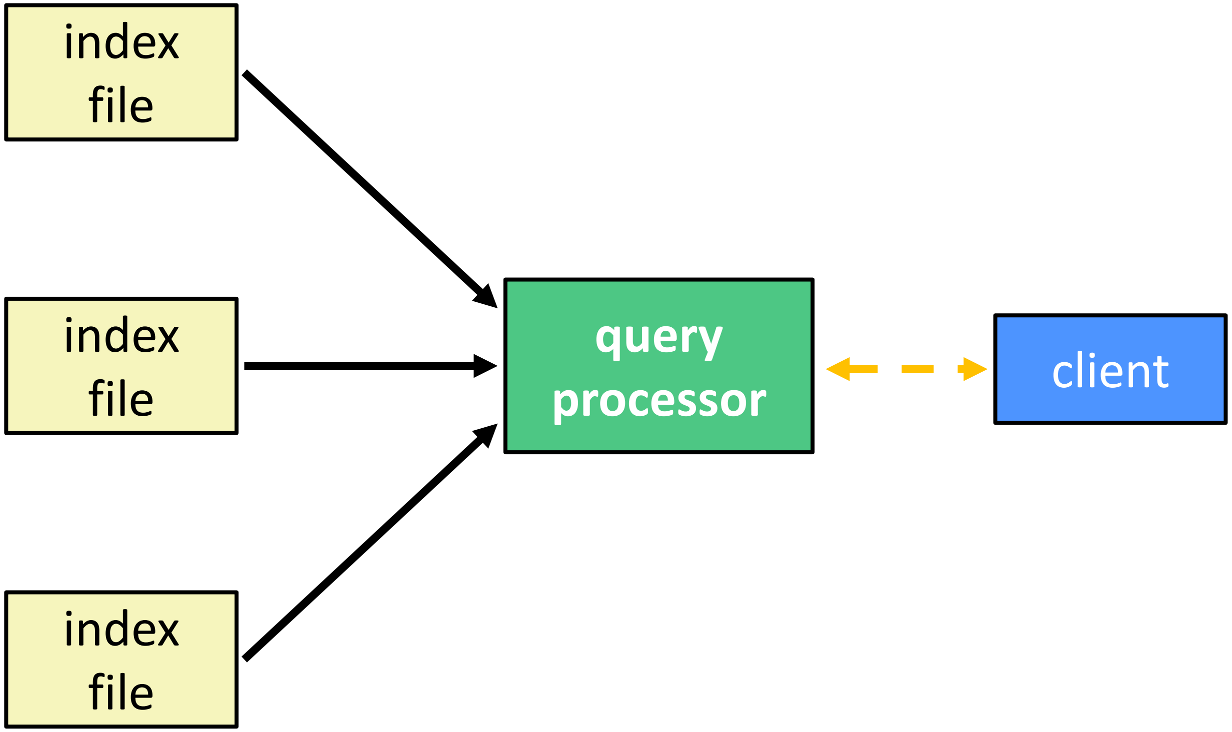
Building a Web Search Engine

- 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

Search Engine Architecture

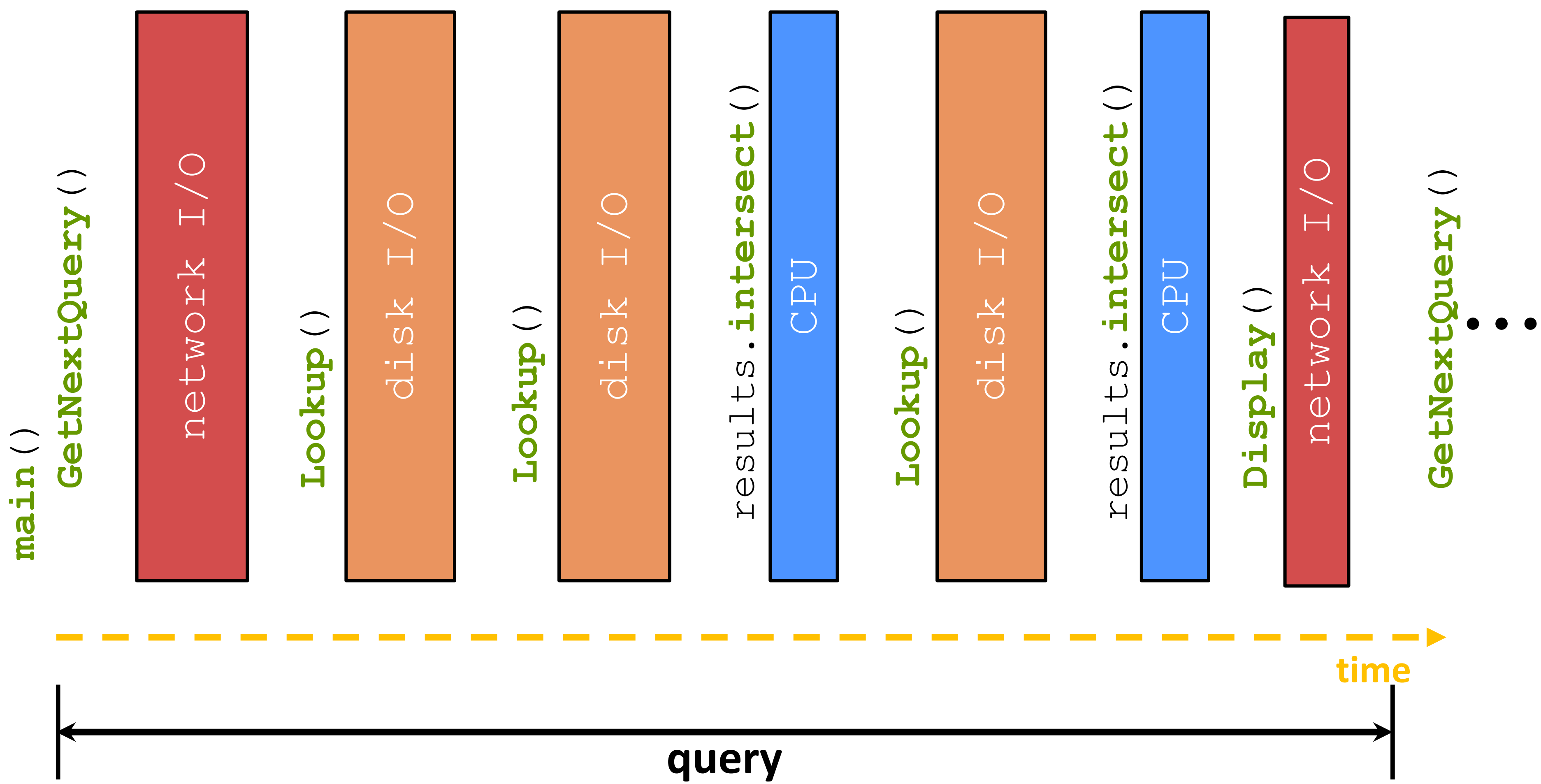


Search Engine (Pseudocode)

```
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
  }
}
```

Execution Timeline: a Multi-Word Query



What About I/O-caused Latency?

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

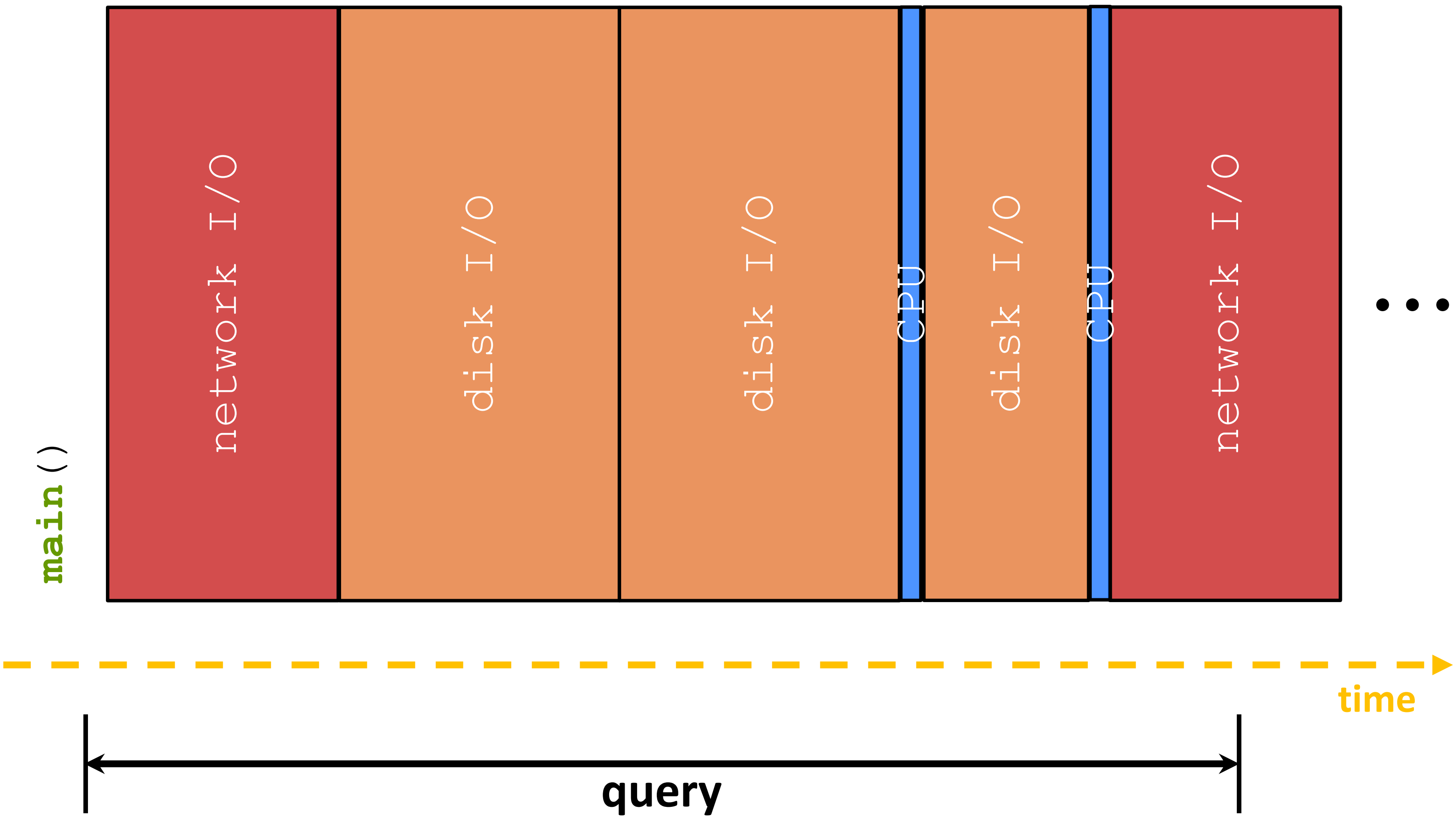
Numbers Everyone Should Know

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

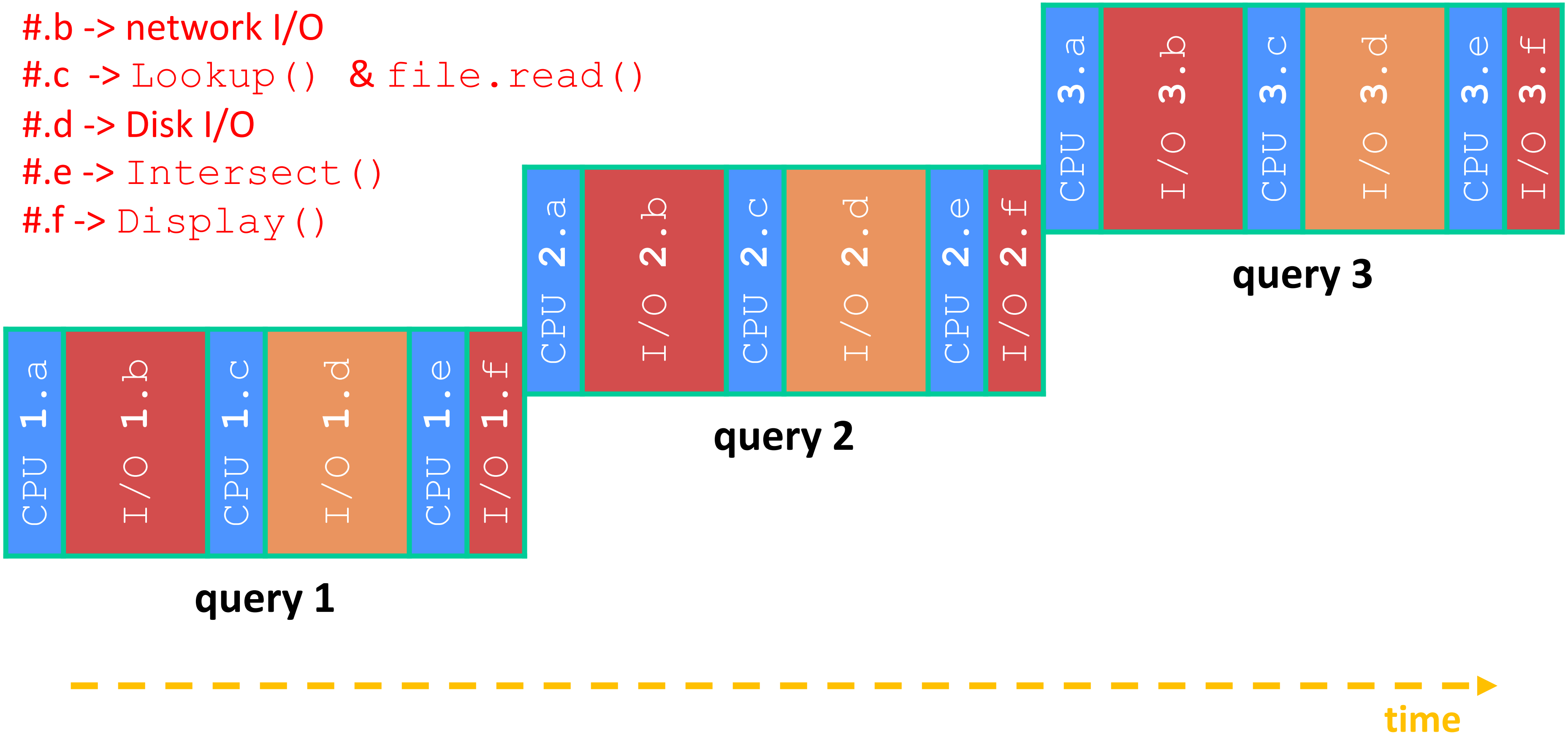
Execution Timeline: To Scale

Model isn't perfect:
Technically also some cpu usage to setup I/O.
Network output also (probably) won't block program .....

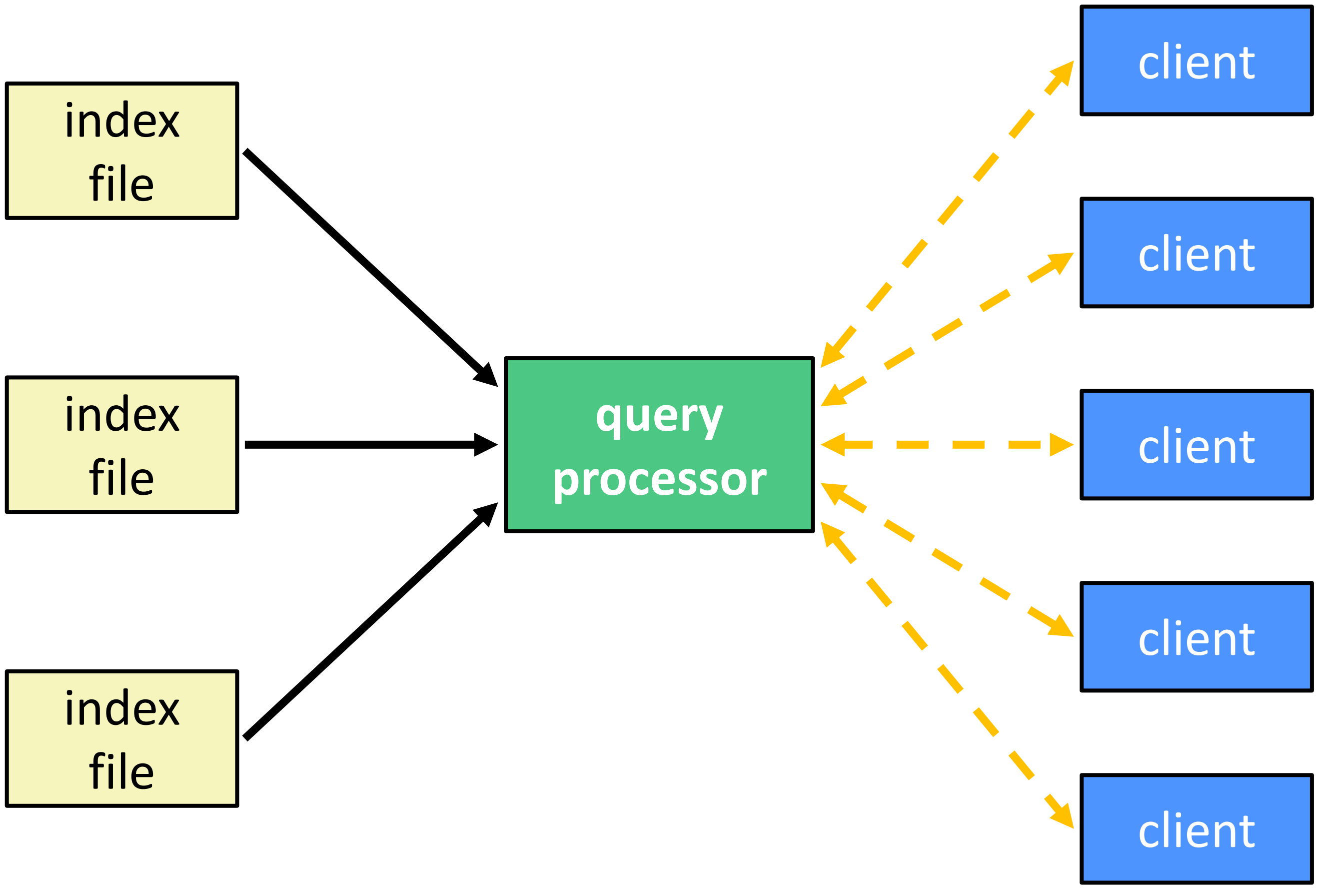


Multiple (Single-Word) Queries

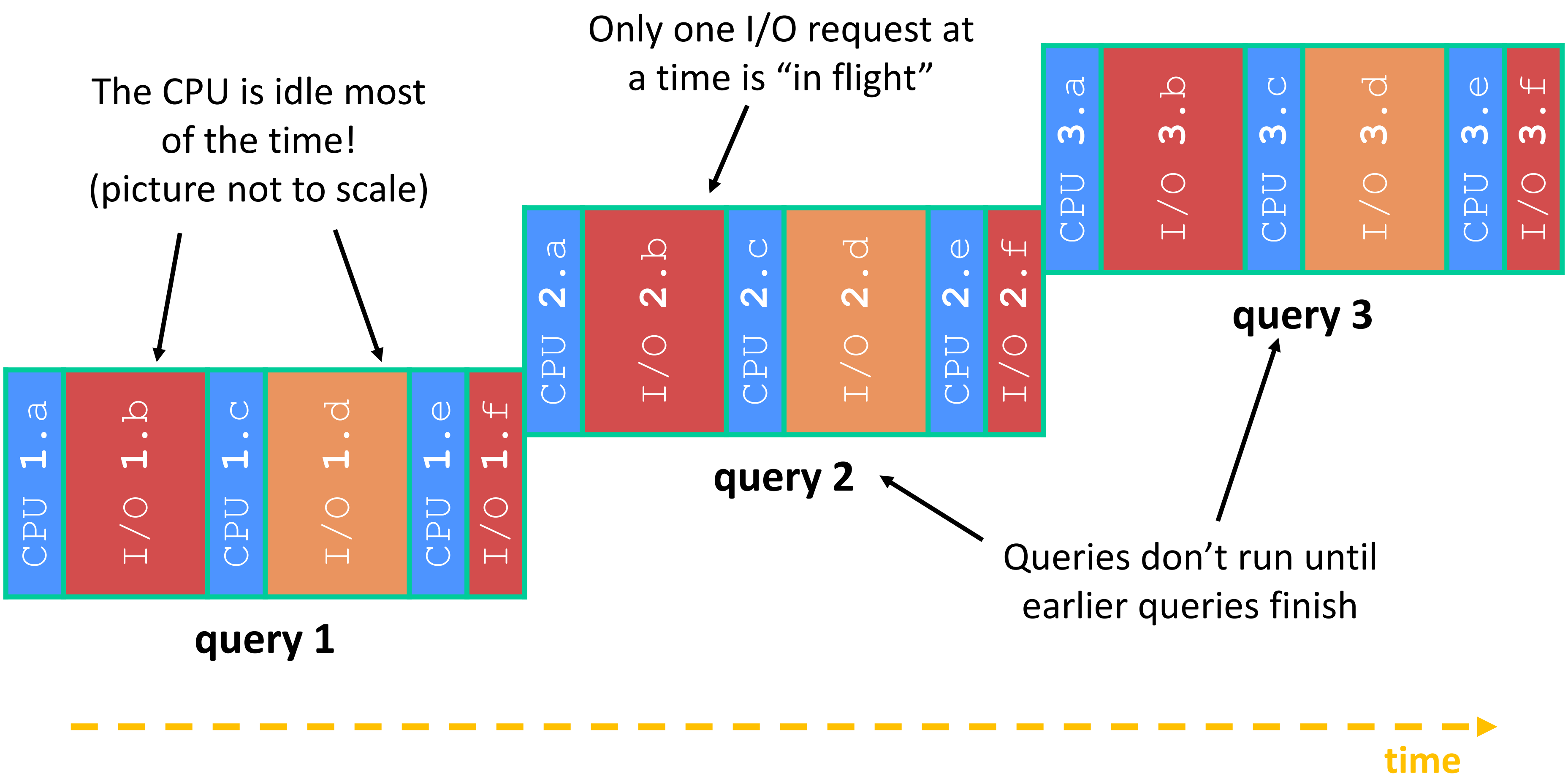
is the Query Number
#.a -> `GetNextQuery()`
#.b -> network I/O
#.c -> `Lookup()` & `file.read()`
#.d -> Disk I/O
#.e -> `Intersect()`
#.f -> `Display()`



Uh-Oh (1 of 2)


index
file
index
file
index
file
query
processor
client
client
client
client
client

Uh-Oh (2 of 2)


The CPU is idle most
of the time!
(picture not to scale)
Only one I/O request at
a time is "in flight"
CPU 1.a
I/O 1.b
CPU 1.c
I/O 1.d
CPU 1.e
I/O 1.f
query 1
CPU 2.a
I/O 2.b
CPU 2.c
I/O 2.d
CPU 2.e
I/O 2.f
query 2
CPU 3.a
I/O 3.b
CPU 3.c
I/O 3.d
CPU 3.e
I/O 3.f
query 3
Queries don't run until
earlier queries finish
time

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 …)

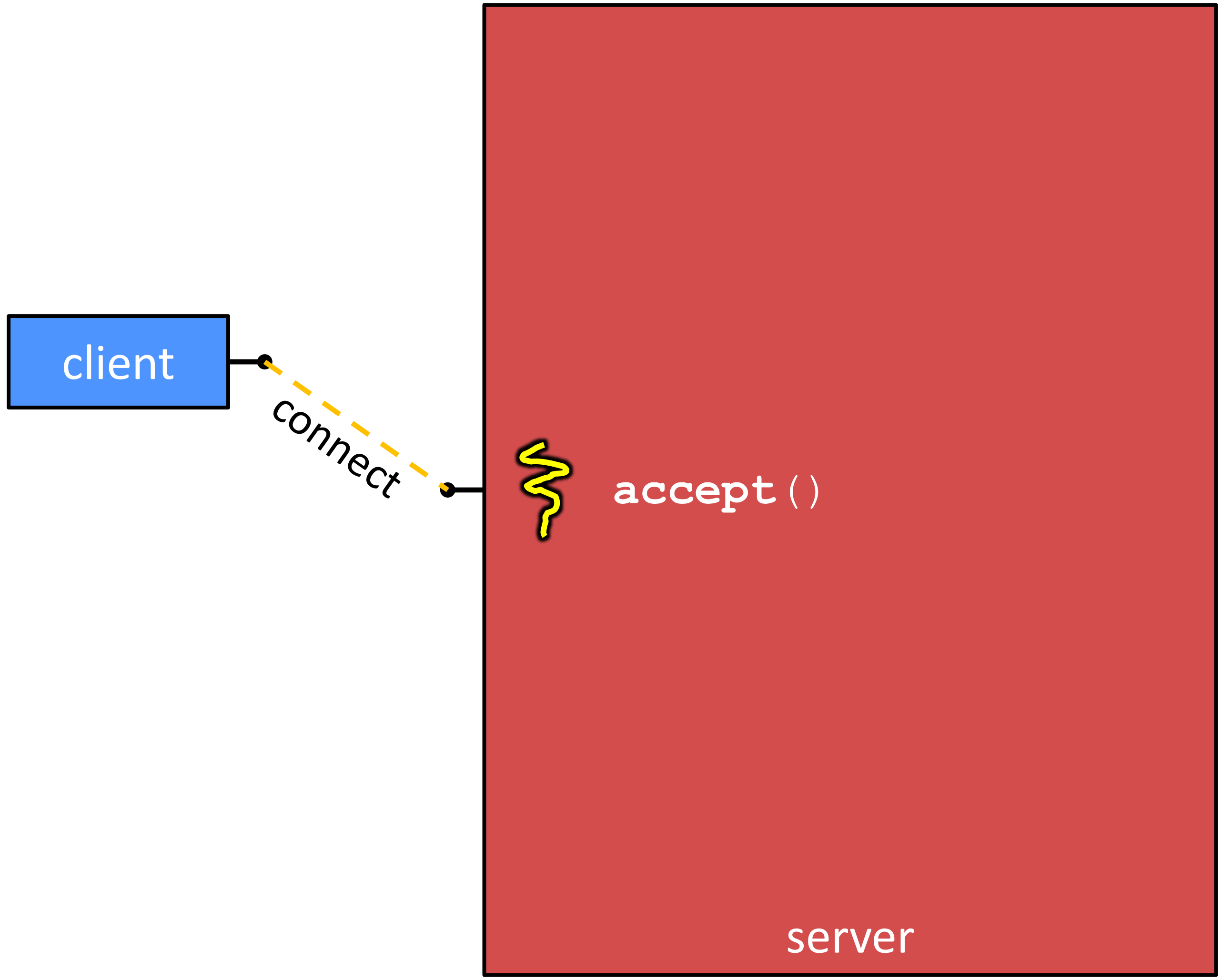
- At most one I/O operation is in flight at a time
  - Missed opportunities to speed I/O up
    - Separate devices in parallel, better scheduling of a single device, etc.

A Concurrent Implementation

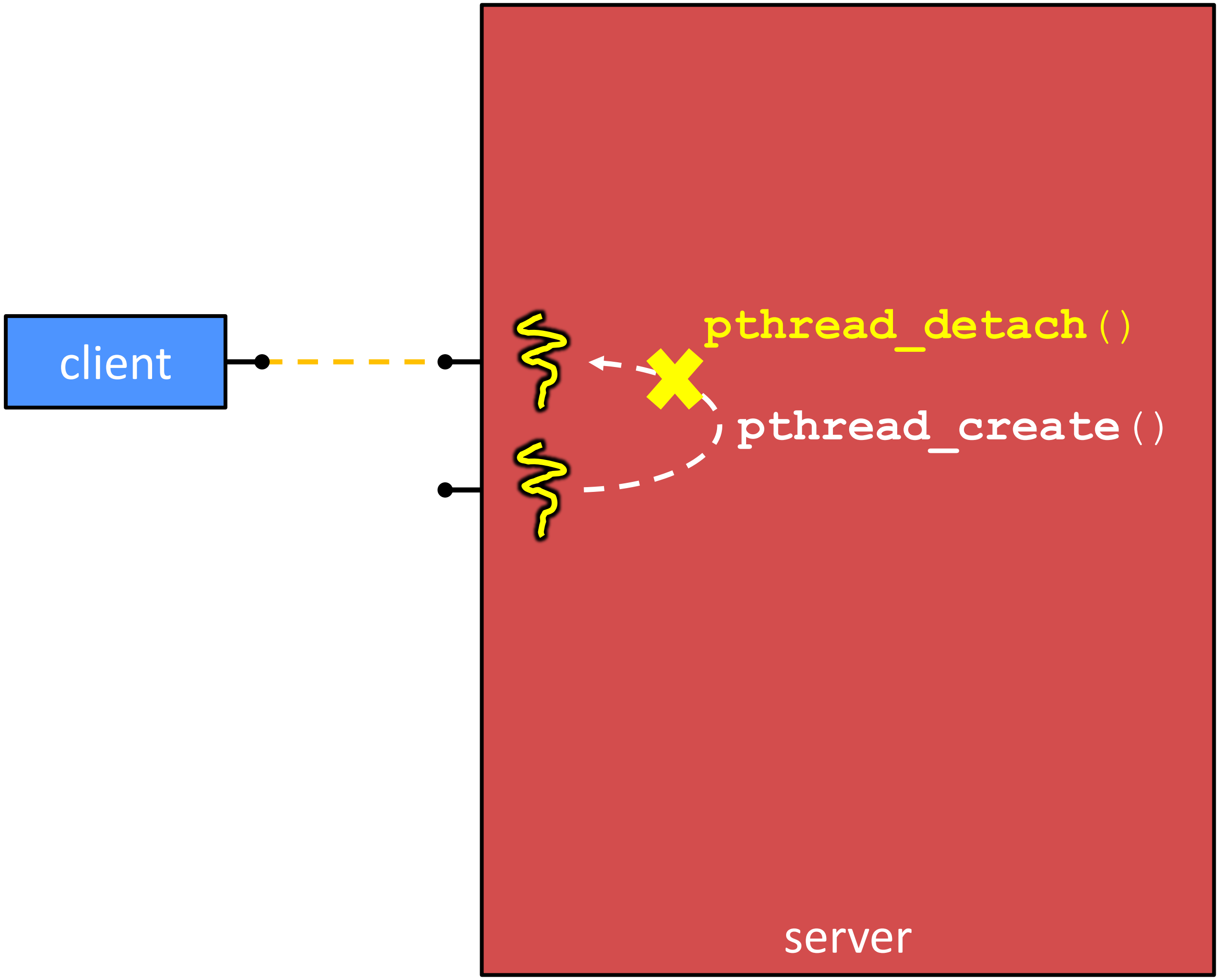
- Use multiple "workers"
  - As a query arrives, create a new "worker" to handle it
    - The "worker" reads the query from the network, issues read requests against files, assembles results and writes to the network
    - The "worker" uses blocking I/O; the "worker" alternates between consuming CPU 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"?

Threads!!!!

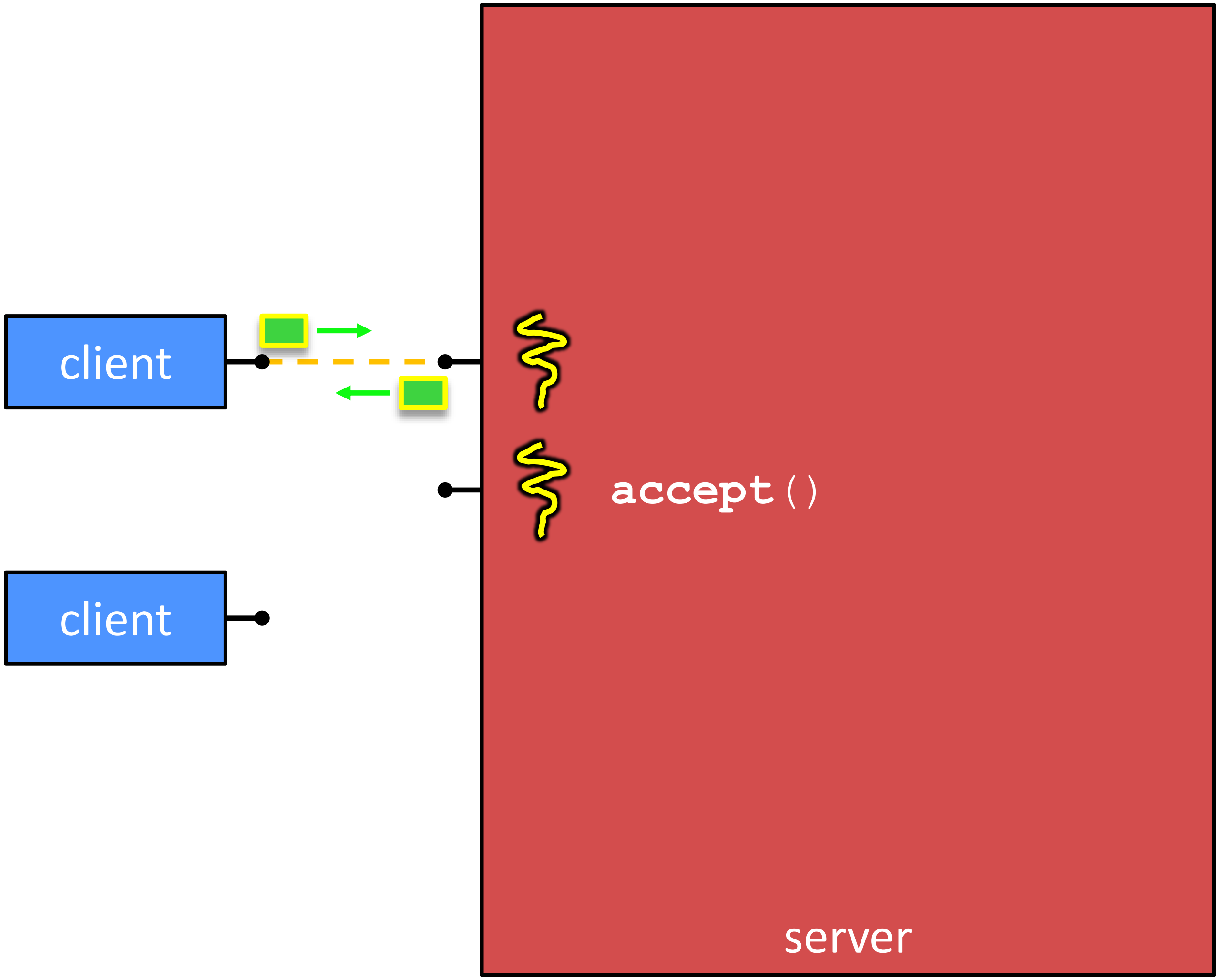
Multithreaded Server



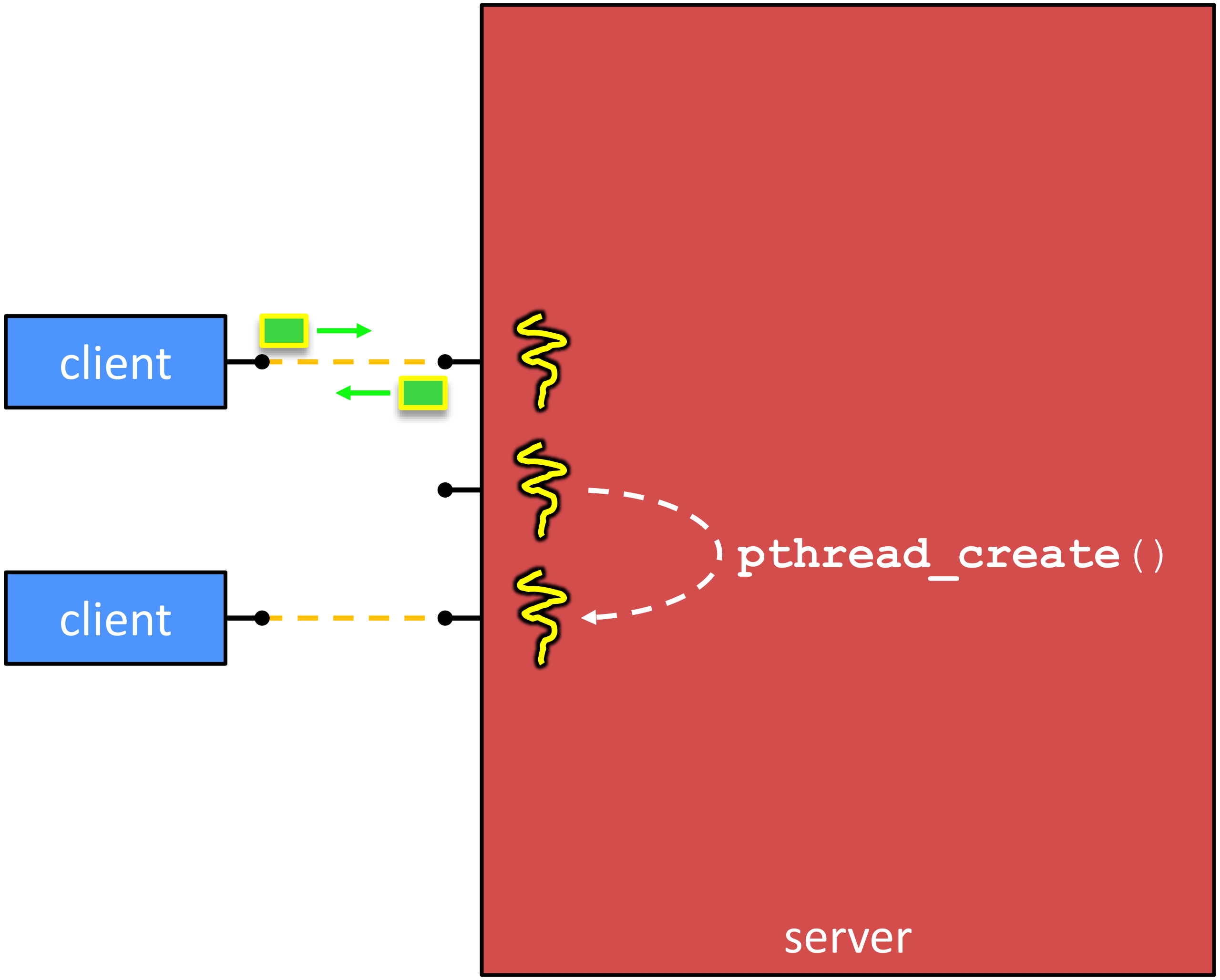
Multithreaded Server



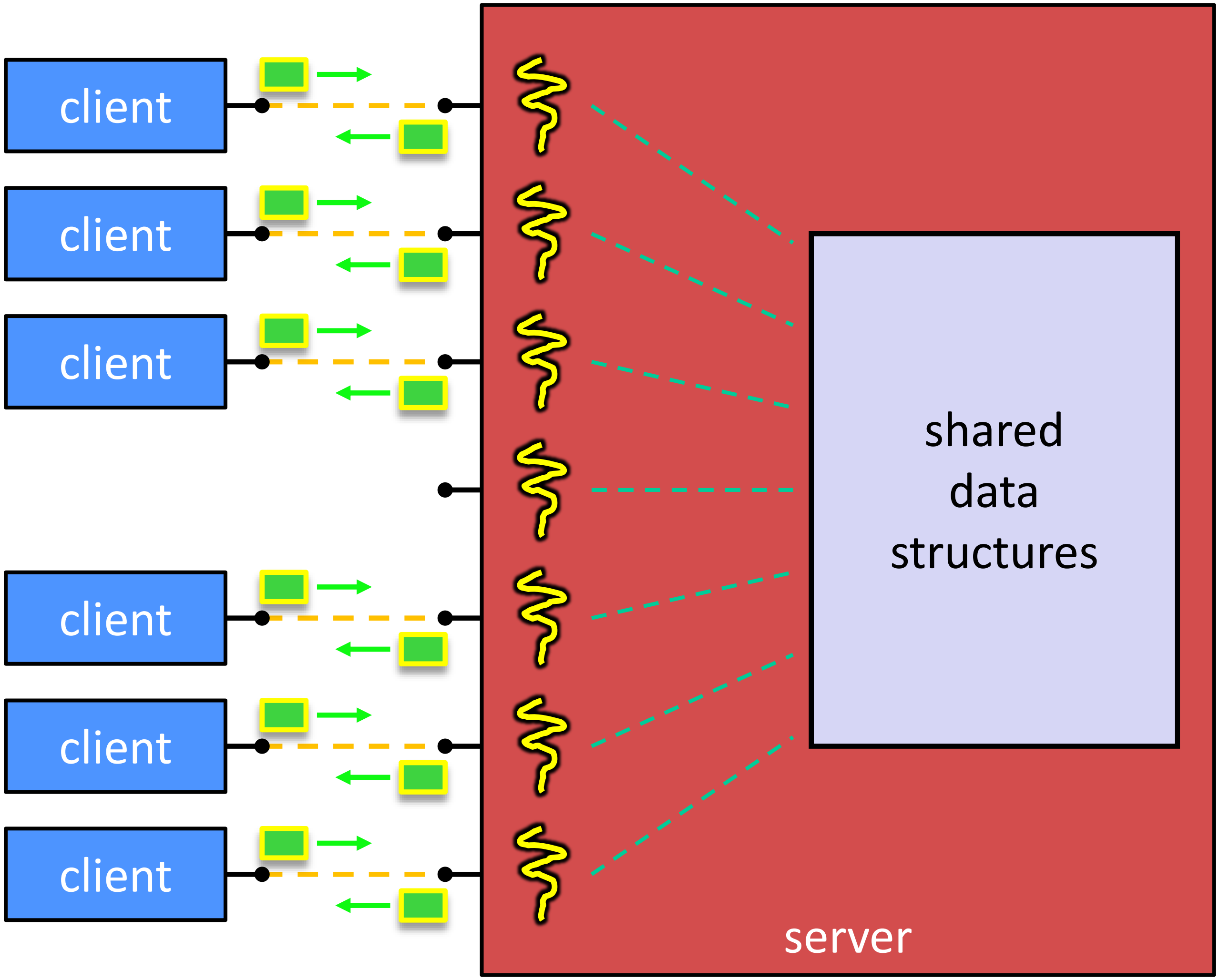
Multithreaded Server



Multithreaded Server

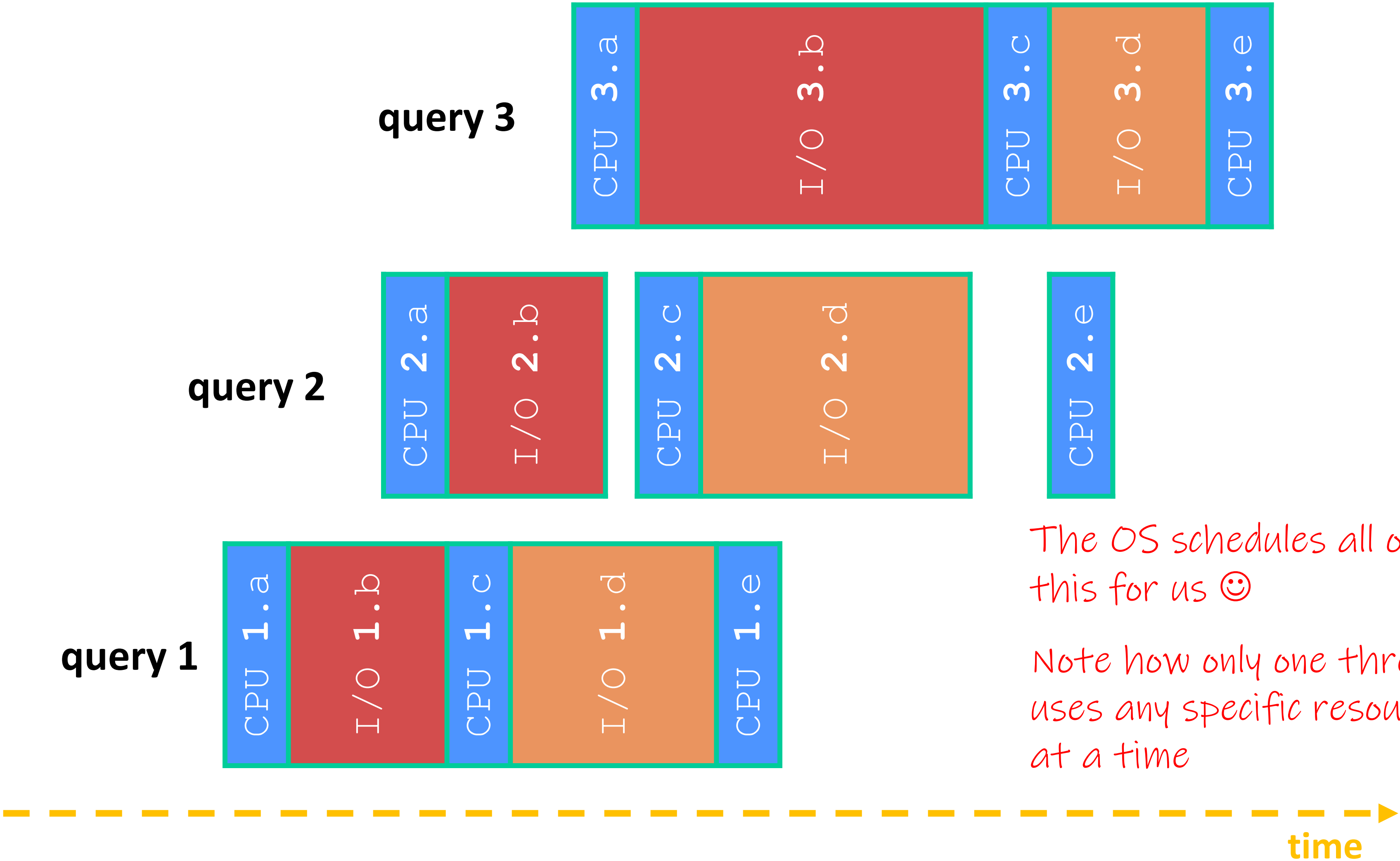


Multithreaded Server



Multi-threaded Search Engine (Execution)

*Running with 1 CPU



The OS schedules all of this for us ☺

Note how only one thread uses any specific resource at a time

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

MORE ON THE DISADVANTAGES LATER IN THE SEMESTER

Lecture Outline

- Threads vs processes
- Threads & Blocking
- **User Level Threads vs Kernel Level Threads**
  - **`ucontext`**
- Scheduling

Kernel Level Threads

- When the pthread library creates a new thread, it registers the new thread with the kernel
  - The new thread is stored similar to how a new process gets a new PCB
- The kernel knows about the new thread and schedules the thread for us
- Despite the name, the thread still runs in user space
- This is the default for pretty much every language

User Level Threads

- Instead of having the kernel manage threads and schedule them, we instead have the user program do this?
  - There is still a single OS thread, you can think of it as being "shared" among user level threads.
- In languages with a runtime (like Java), the runtime environment can switch between threads for us
- In C, you must switch between threads manually if you want to manage them in user land
  - Or use some user level threading library
  - You will sort of be implementing PennOS using user-level threads

Threading Models

- The “kernel level threads” approach can be called 1:1
  - For each thread we create, it is backed by the operating system, is run & scheduled by the operating system, and can be run in parallel

- The “User level threads” approach can be called N:1
  - The kernel sees the process as containing a singular thread that is scheduled and run as normal.
  - The program decides which user level thread is the one running and when to swap to another user level thread
    - This all happens while the kernel is scheduling the “1 thread” as if it is any other thread

Hybrid Threading

- Can instead have a model that is M:N
  - Create M user level threads that share N threads of execution maintained by the operating system
  - Not too common
  - Rather complex to implement yourself
  - Neat Idea ☺

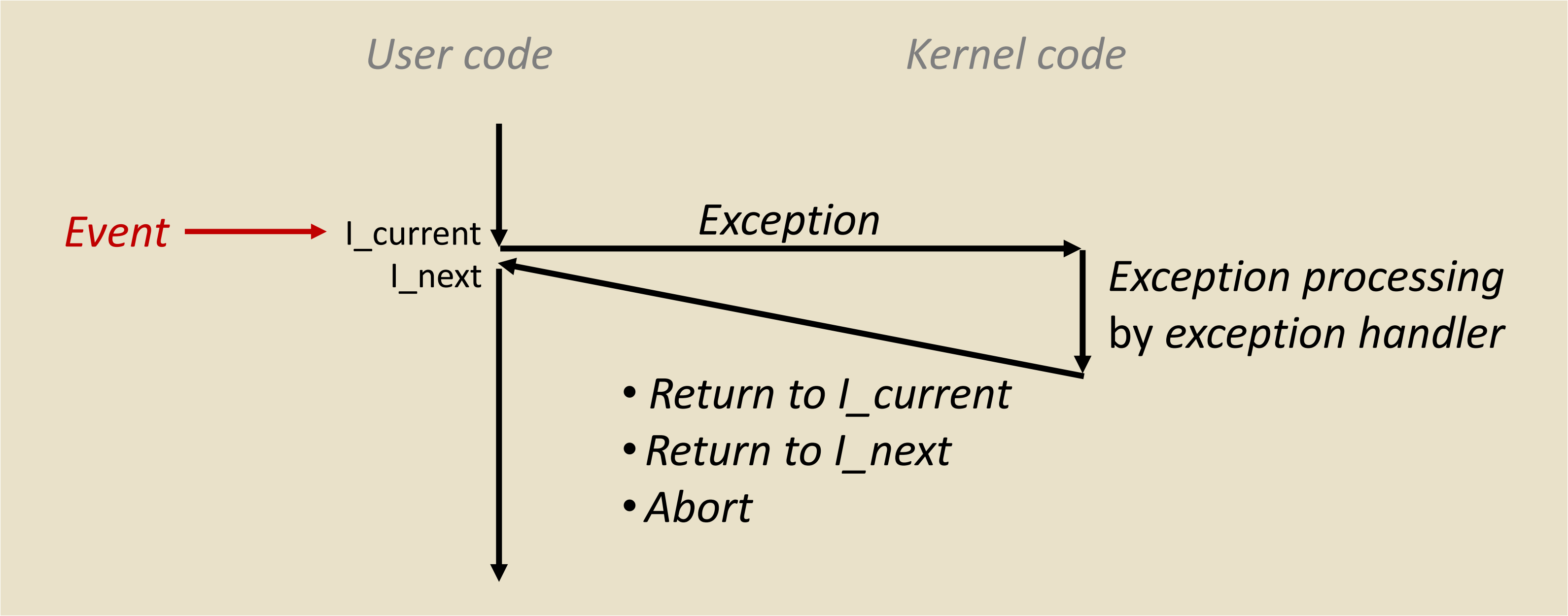
Pros & Cons of user level threads

- Pros
  - Less Operating System Overhead
  - Can customize scheduler more easily
  - If a system did not support multi threading, you can do this

- Cons
  - If a thread blocks on I/O or page fault, all user level threads
  - If you need to make sure threads share time, hard to do this without pre-emption through the kernel or some time-based signal

Interrupts

- An *Interrupt* is a transfer of control to the OS *kernel* in response to some *event* (i.e., change in processor state)
  - Kernel is the memory-resident part of the OS
  - Examples of events: Divide by 0, arithmetic overflow, page fault, I/O request completes, typing Ctrl-C



Two ways of switching between “Threads”

- There are two main ways we switch between threads.
- The most common way is to be “pre-empted”, to be interrupted, which then switches threads on the interruption
- An alternative is “cooperative”, a thread willingly gives up execution to someone else.
  - ucontext does something like this, but in PennOS we will emulate pre-emption

ucontext

```
typedef struct ucontext_t {
  struct uctonext_t *uc_link;
  sigset_t           uc_sigmask;
  stack_t            uc_stack;
  // other machine specific stuff
} ucotnext_t;
```

- Stores information about an execution context.
  - uc_sigmask stores the signal mask of the context
  - uc_stack points to the stack used by that context
  - uc_link points to the context that will be resumed when the context represented by the struct returns. NULL if we just want the process to exit.
  - Stores some other information that is machine & architecture specific. E.g. registers and their values

Getcontext & setcontext

- ```c
  int getcontext(ucontext * ucp);
  ```
  - Initializes the ucontext_t struct pointed at by ucp to have the currently active context.
  - Specifically, the context of what the calling thread would look like right after getcontext returns

- ```c
  int setcontext(const context * ucp);
  ```
  - Sets the current executing context to the one specified by ucp
  - Does not return on success, sorta like exec

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- What does this code do?

```
#include <ucontext.h>
#include <stdio.h>
#include <stdlib.h>

int main() {
  ucontext_t context;
  getcontext(&context);

  printf("hello\n");

  setcontext(&context);

  printf("goodbye\n");

  exit(EXIT_SUCCESS);
}
```

Getcontext & setcontext

- ```
  int makecontext(ucontext * ucp, void (*func)(),
                          int argc, ...);
  ```
  - Modifies a context (which you got from getcontext)
    - Will now call the function specified by func when context is run
  - Need to allocate a new stack for the context beforehand
  - can set new signal mask and/or uc_link

  More on this in the PennOS Demo

- ```
  int swapcontext(ucontext_t *oucp, const context *ucp);
  ```
  - Like setcontext, but stores the context of the caller into oucp

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- What does this code do?

```c
#define STACKSIZE 4096

void funky_function() {
  printf("HOWDY :)\n");
}

int main(int argc, char * argv[]){
  ucontext_t uc;
  getcontext(&uc);

  void * stack;
  stack = malloc(STACKSIZE);

  uc.uc_stack.ss_sp = stack;
  uc.uc_stack.ss_size = STACKSIZE;
  uc.uc_stack.ss_flags = 0;

  ucontext_t ouc;
  uc.uc_link = &ouc;

  sigemptyset(&(uc.uc_sigmask));

  makecontext(&uc, funky_function, 0);

  if (swapcontext(&ouc, &uc) != 0) {
    perror("swapcontext");
  }

  printf("Well, how did I get here?\n");

  return EXIT_FAILURE;

}
```

Lecture Outline

- Threads vs processes
- Threads & Blocking
- User Level Threads vs Kernel Level Threads
  - `ucontext`
- **Scheduling**

OS as the Scheduler

- The scheduler is code that is part of the kernel (OS)
- The scheduler runs when a thread:
  - starts ("arrives to be scheduled"),
  - Finishes
  - Blocks (e.g., waiting on something, usually some form of I/O)
  - Has run for a certain amount of time
- It is responsible for scheduling threads
  - Choosing which one to run
  - Deciding how long to run it

Scheduler Terminology

- The scheduler has a scheduling algorithm to decide what runs next.

- Algorithms are designed to consider many factors:
  - Fairness: Every program gets to run
  - Liveness: That "something" will eventually happen
  - Throughput: amount of work completed over an interval of time
  - Wait time: Average time a "task" is "alive" but not running
  - Turnaround time: time between task being ready and completing
  - Response time: time it takes between task being ready and when it can take user input
  - Etc…

Goals

- The scheduler will have various things to prioritize
- Some examples:
- Minimizing wait time
  - Get threads started as soon as possible
- Minimizing latency
  - Quick response times and task completions are preferred
- Maximizing throughput
  - Do as much work as possible per unit of time
- Maximizing fairness
  - Make sure every thread can execute fairly

- These goals depend on the system and can conflict

Scheduling: Other Considerations

- It takes time to context switch between threads
  - Could get more work done if thread switching is minimized
- Scheduling takes resources
  - It takes time to decide which thread to run next
  - It takes space to hold the required data structures
- Different tasks have different priorities
  - Higher priority tasks should finish first

Types of Scheduling Algorithms

- **Non-Preemptive:** if a thread is running, it continues to run until it completes or until it gives up the CPU
  - First come first serve (FCFS)
  - Shortest Job First (SJF)

- **Preemptive:** the thread may be interrupted after a given time and/or if another thread becomes ready
  - Round Robin
  - Priority Round Robin
  - …

First Come First Serve (FCFS)

- Idea: Whenever a thread is ready, schedule it to run until it is finished (or blocks).
- Maintain a queue of ready threads
  - Threads go to the back of the queue when it arrives or becomes unblocked
  - The thread at the front of the queue is the next to run

Example of FCFS

1 CPU
Job 2 arrives slightly after job 1.
Job 3 arrives slightly after job 2

- Example workload with three “jobs”:
  Job 1: 24 time units; Job 2: 3 units; Job 3: 3 units

- FCFS schedule:

```
|   Job 1                          |   Job 2   |   Job 3   |
 0                                 24          27          30
```

- Total waiting time: 0 + 24 + 27 = 51
- Average waiting time: 51/3 = 17
- Total turnaround time: 24 + 27 + 30 = 81
- Average turnaround time: 81/3 = 27

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- What are the advantages/disadvantages/concerns with **First Come First Serve**

- Things a scheduler should prioritize:
  - Minimizing wait time
  - Minimizing Latency
  - Maximizing fairness
  - Maximizing throughput
  - Task priority
  - Cost to schedule things
  - Cost to context Switch

- Imagine we have 1 core, and tasks of various lengths…

Shortest Job First (SJF)

- Idea: variation on FCFS, but have the tasks with the smallest CPU-time requirement run first
  - Arriving jobs are instead put into the queue depending on their run time, shorter jobs being towards the front
  - Scheduler selects the shortest job (1st in queue) and runs till completion

Example of SJF

1 CPU
Job 2 arrives slightly after job 1.
Job 3 arrives slightly after job 2

- Same example workload with three "jobs":
  Job 1: 24 time units; Job 2: 3 units; Job 3: 3 units

- FCFS schedule:

```
| Job 2 | Job 3  |    Job 1                   |
0       3        6                            30
```

- Total waiting time: 6 + 0 + 3 = 9
- Average waiting time: 3
- Total turnaround time: 30 + 3 + 6 = 39
- Average turnaround time: 39/3 = 13

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- What are the advantages/disadvantages/concerns with **Shortest Job First**

- Things a scheduler should prioritize:
  - Minimizing wait time
  - Minimizing Latency
  - Maximizing fairness
  - Maximizing throughput
  - Task priority
  - Cost to schedule things
  - Cost to context Switch

- Imagine we have 1 core, and tasks of various lengths…

Types of Scheduling Algorithms

- **Non-Preemptive:** if a thread is running, it continues to run until it completes or until it gives up the CPU
  - First come first serve (FCFS)
  - Shortest Job First (SJF)

- **Preemptive:** the thread may be interrupted after a given time and/or if another thread becomes ready
  - Round Robin
  - Priority Round Robin
  - …

Round Robin

- Sort of a preemptive version of FCFS
  - Whenever a thread is ready, add it to the end of the queue.
  - Run whatever job is at the front of the queue

- BUT only led it run for a fixed amount of time (quantum).
  - If it finishes before the time is up, schedule another thread to run
  - If time is up, then send the running thread back to the end of the queue.

Example of Round Robin

- Same example workload:

  Job 1: 24 units, Job 2: 3 units, Job 3: 3 units
- RR schedule with time quantum=2:

```
|Job 1|Job 2|Job 3|Job 1|Jo2|Jo3|Job 1| …     |Job 1|
 0     2     4     6     8   9   10    12,14…       30
```

- Total waiting time: (0 + 4 + 2) + (2 + 4) + (4 + 3) = 19
  - Counting time spent waiting between each "turn" a job has with the CPU
- Average waiting time: 19/3 (~6.33)
- Total turnaround time: 30 + 9 + 10 = 49
- Average turnaround time: 49/3 (~16.33)

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- What are the advantages/disadvantages/concerns with **Round Robin**

- Things a scheduler should prioritize:
  - Minimizing wait time
  - Minimizing Latency
  - Maximizing fairness
  - Maximizing throughput
  - Task priority
  - Cost to schedule things
  - Cost to context Switch

- Imagine we have 1 core, and tasks of various lengths…

More

- More next lecture