Intro to Threads

Computer Operating Systems, Spring 2024

Instructor: Travis McGaha

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TAs:

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Administrivia

- PennOS:
  - To be done in groups of 4
  - Group signup to be released soon
    - Group signup due Tuesday next week
    - Those who do not form a group will be randomly assigned
    - Random assignment will prefer to keep people in pairs (unless you reach out and specify otherwise)
  - Specification to be released soon (over the weekend)

- Next Lecture (Tuesday 3/19) will be on Zoom only
- Thursday (3/21) will be in-person TA led PennOS overview
- Tuesday 3/26 & Thurs 3/28 will be on Zoom

Poll Everywhere

pollev.com/tqm

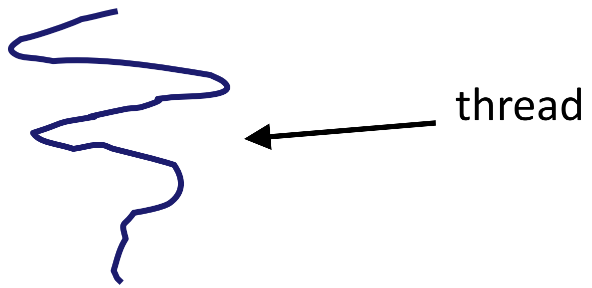
- Any questions, comments or concerns from last lecture?

Lecture Outline

- **Threads High Level**
- Pthreads
- Threads vs processes
- Threads & Blocking

Introducing Threads

- Separate the concept of a process from the "*thread of execution*"
  - Threads are contained within a process
  - Usually called a thread, this is a sequential execution stream within a process

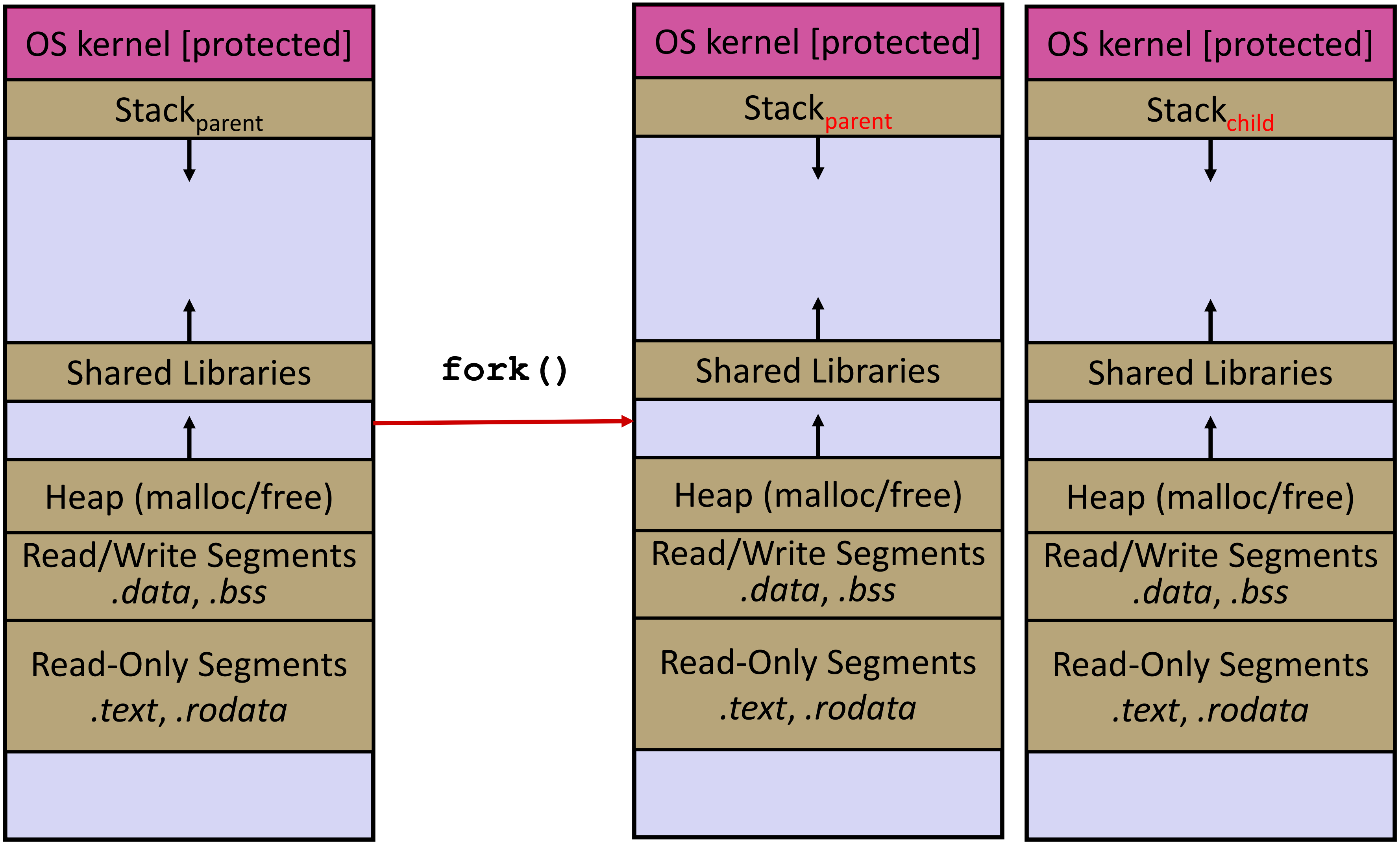


- In most modern OS's:
  - Threads are the *unit of scheduling.*

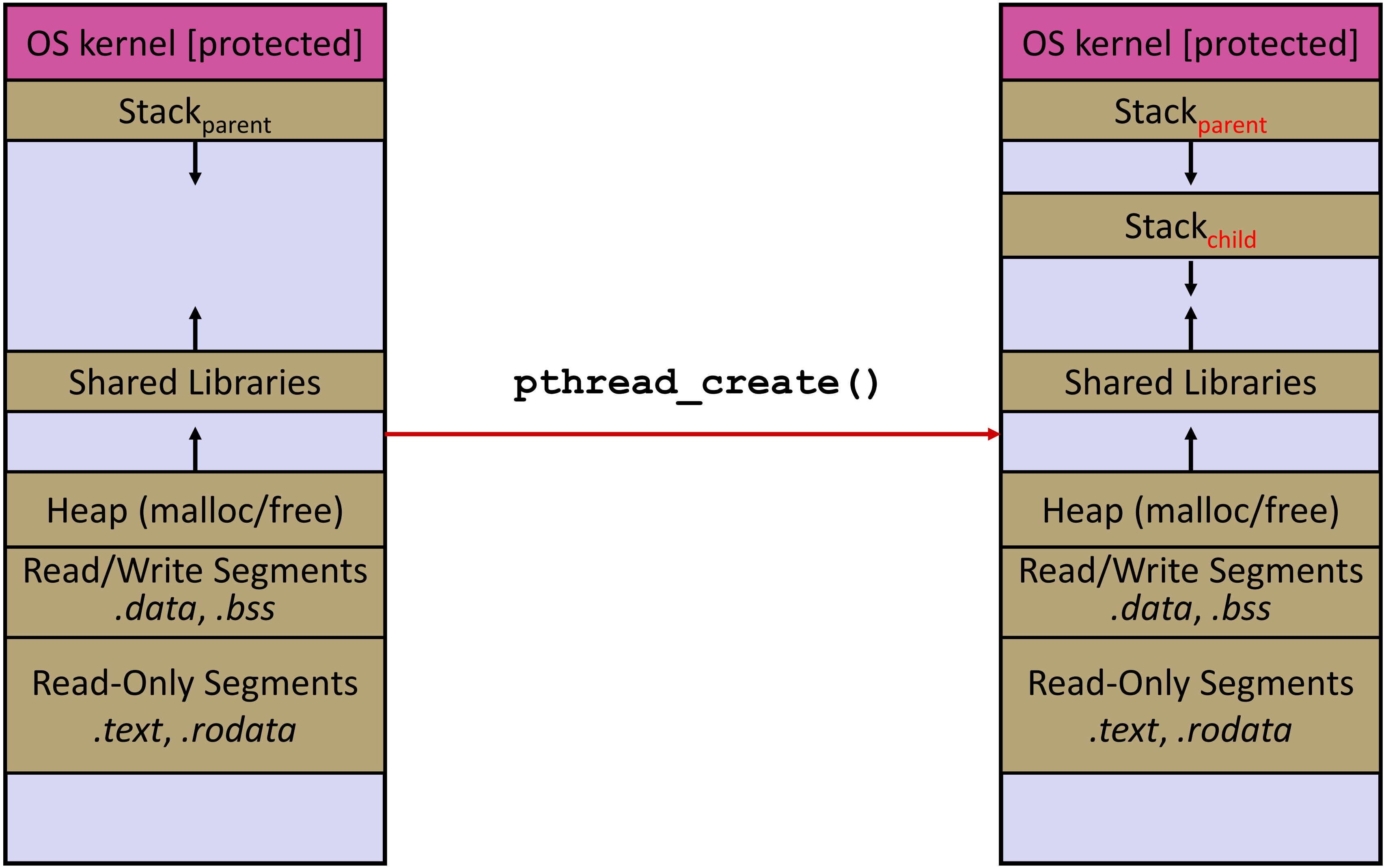
Threads vs. Processes

- 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

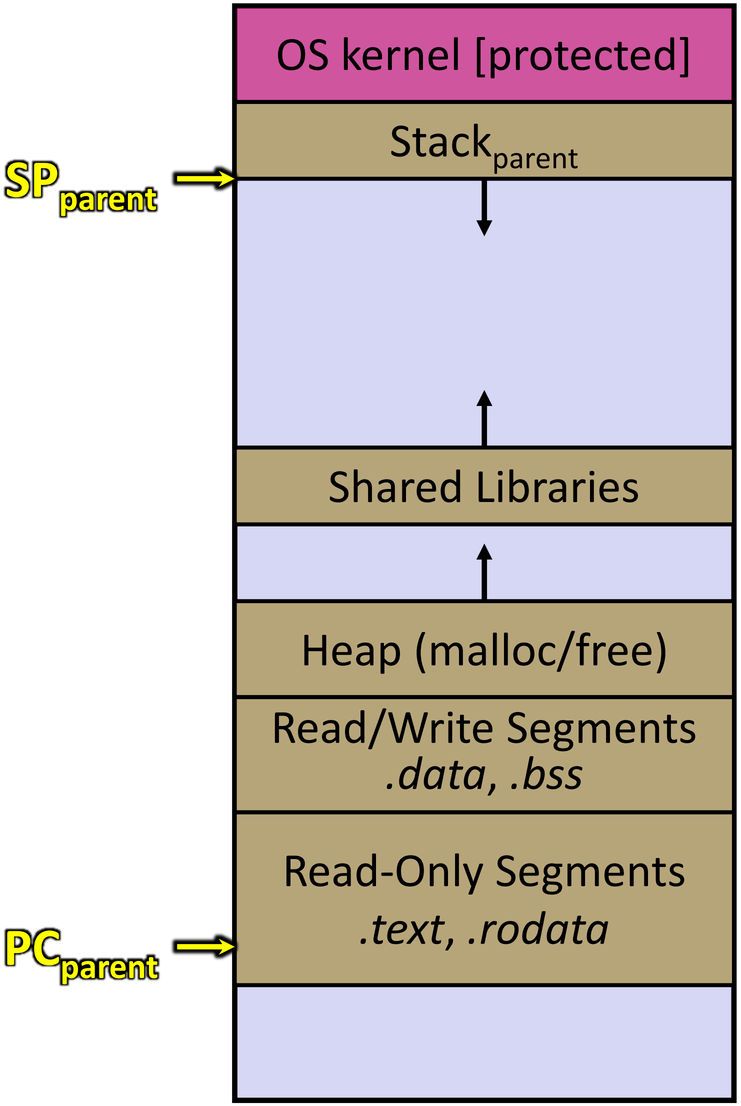


Threads

- Threads are like lightweight processes
  - **They execute concurrently like processes**
    - **Multiple threads can run simultaneously on multiple CPUs/cores**
  - Unlike processes, threads cohabitate 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, they can interfere with each other – need synchronization for shared resources
    - Each thread has its own stack

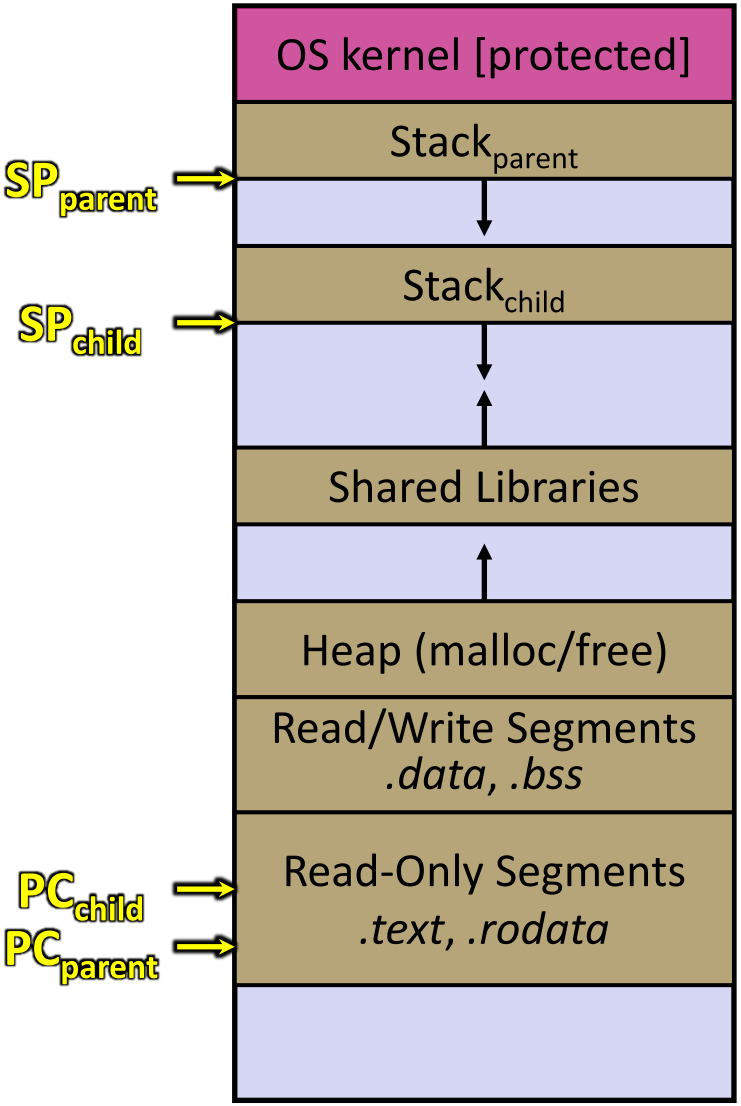
- Analogy: restaurant kitchen
  - Kitchen is process
  - Chefs are threads

Single-Threaded Address Spaces



- 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()`

Multi-threaded Address Spaces



- After creating a thread
  - *Two* threads of execution running in the address space
    - Original thread (parent) and new thread (child)
    - New stack created for child thread
    - Child thread has its own *values* of the PC and SP
  - Both threads share the other segments (code, heap, globals)
    - They can cooperatively modify shared data

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POSIX Threads (pthreads)

- The POSIX APIs for dealing with threads
  - Declared in `pthread.h`
    - Not part of the C/C++ language
  - To enable support for multithreading, must include `-pthread` flag when compiling and linking with `gcc` command
    - `gcc -g -Wall -pthread -o main main.c`
  - Implemented in C
    - Must deal with C programming practices and style

Creating and Terminating Threads

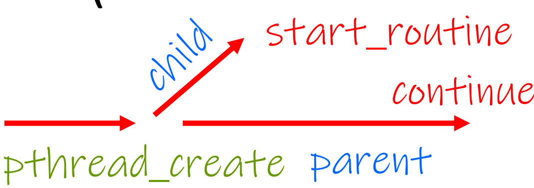
```
int pthread_create(
        pthread_t* thread,
        const pthread_attr_t* attr,
        void* (*start_routine)(void*),
        void* arg);
```

Output parameter. Gives us a "thread_descriptor" (→ `thread`)

Function pointer! Takes & returns void to allow "generics" in C* (→ `start_routine`)

Argument for the thread function (→ `arg`)

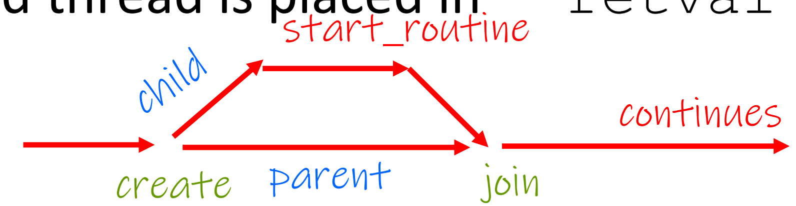
- Creates a new thread into `*thread`, with attributes `*attr` (`NULL` means default attributes)
- Returns **0** on success and an error number on error (can check against error constants)
- The new thread runs **`start_routine`**`(arg)`



What To Do After Forking Threads?

- `int pthread_join(pthread_t thread, void** retval);`
  - Waits for the thread specified by `thread` to terminate
  - The thread equivalent of **`waitpid`**`()`
  - The exit status of the terminated thread is placed in `**retval`

Parent thread waits for child thread to exit, gets the child's return value, and child thread is cleaned up



Thread Example

- See `cthreads.c`
  - How do you properly handle memory management?
    - Who allocates and deallocates memory?
    - How long do you want memory to stick around?
  - Threads execute in parallel

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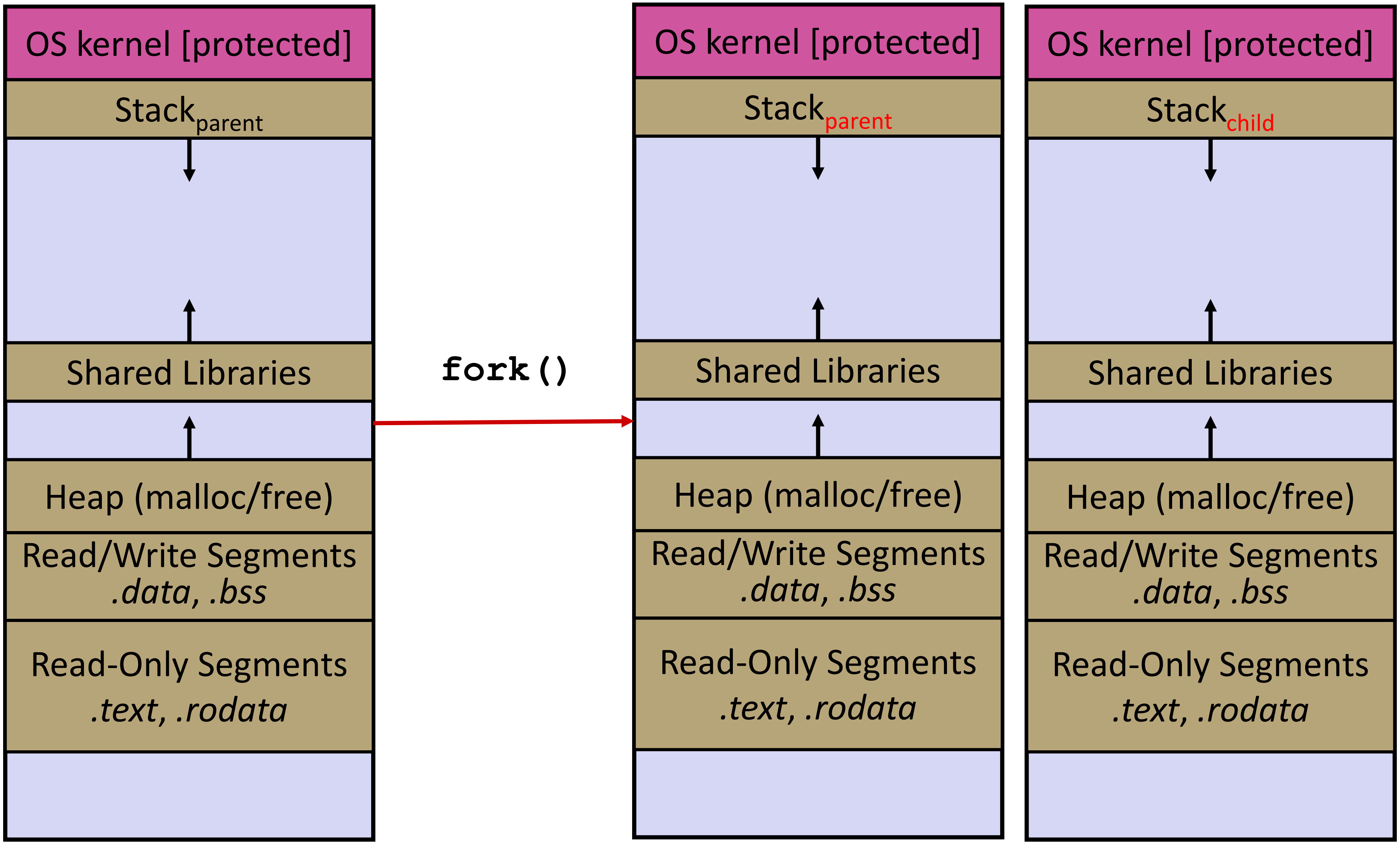
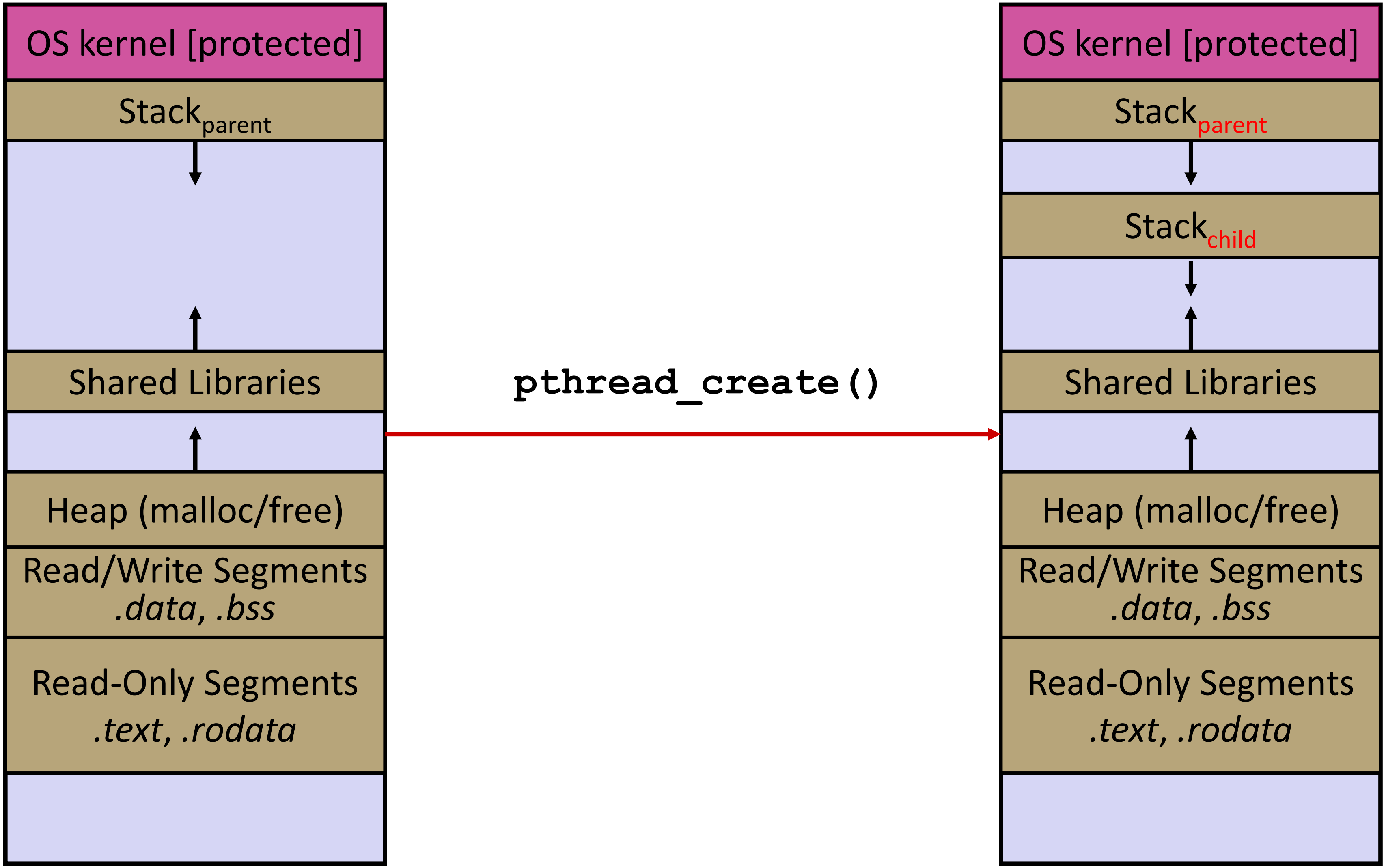
Threads vs. Processes



Threads vs. Processes



Discuss

- What does this print?

```
#define NUM_PROCESSES 50
#define LOOP_NUM 100

int sum_total = 0;

void loop_incr() {
  for (int i = 0; i < LOOP_NUM; i++) {
    sum_total++;
  }
}


int main(int argc, char** argv) {
  pid_t pids[NUM_PROCESSES];  // array of process ids

  // create processes to run loop_incr()
  for (int i = 0; i < NUM_PROCESSES; i++) {
    pids[i] = fork();
    if (pids[i] == 0) {
      // child
      loop_incr();
      exit(EXIT_SUCCESS);
    }
    // parent loops and forks more children
  }

  // wait for all child processes to finish
  for (int i = 0; i < NUM_PROCESSES; i++) {
    waitpid(pids[i], NULL, 0);
  }

  printf("%d\n", sum_total);

  return EXIT_SUCCESS;
}
```

Discuss

- What does this print?

```
#define NUM_THREADS 50
#define LOOP_NUM 100

int sum_total = 0;

// print out a sequence of LOOP_NUM numbers with thread identifying number
void* thread_main(void* arg) {
  for (int i = 0; i < LOOP_NUM; i++) {
    sum_total++;
  }
  return NULL;  // return type is a pointer
}


int main(int argc, char** argv) {
  pthread_t thds[NUM_THREADS];  // array of thread ids

  // create threads to run thread_main()
  for (int i = 0; i < NUM_THREADS; i++) {
    pthread_create(&thds[i], NULL, &thread_main, NULL);
  }

  // wait for all child threads to finish
  // (children may terminate out of order, but cleans up in order)
  for (int i = 0; i < NUM_THREADS; i++) {
    pthread_join(thds[i], NULL);
  }

  printf("%d\n", sum_total);

  return EXIT_SUCCESS;
}
```

Demos:

- See `total.c and total_processes.c`
  - Threads share an address space, if one thread increments a global, it is seen by other threads
  - Processes have separate address spaces, incrementing a global in one process does not increment it for other processes

- NOTE: sharing data between threads is actually kinda unsafe if done wrong (we are doing it wrong in this example), **more on this in the next couple lectures**

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()

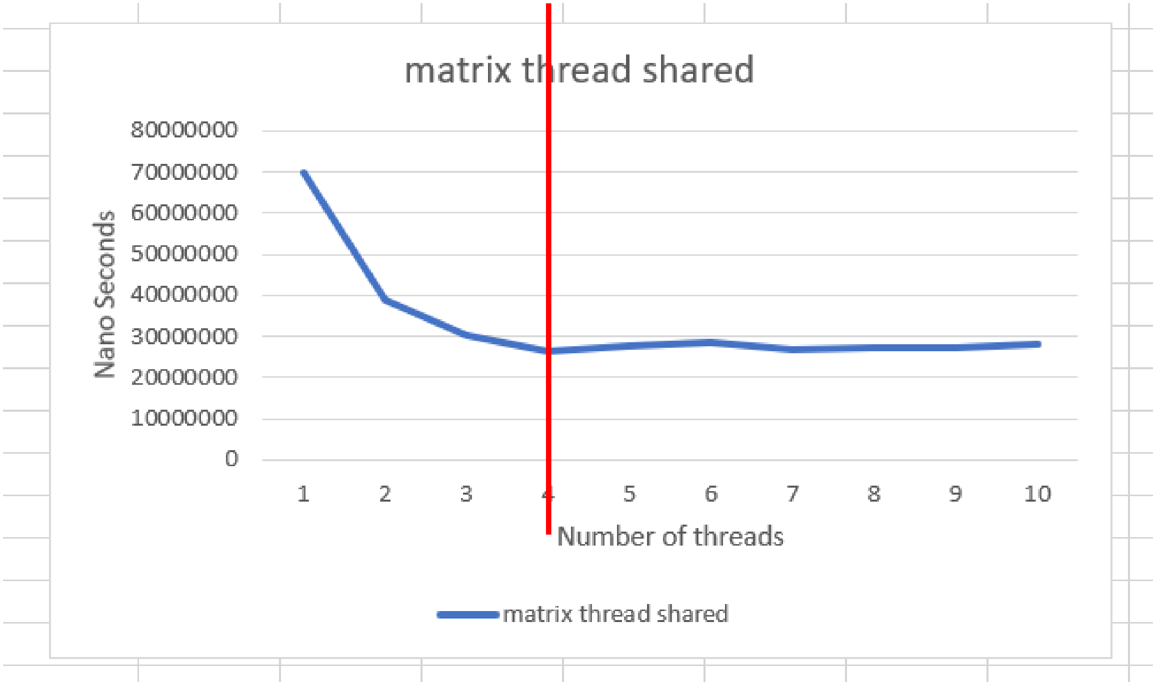
Parallelism

- 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

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

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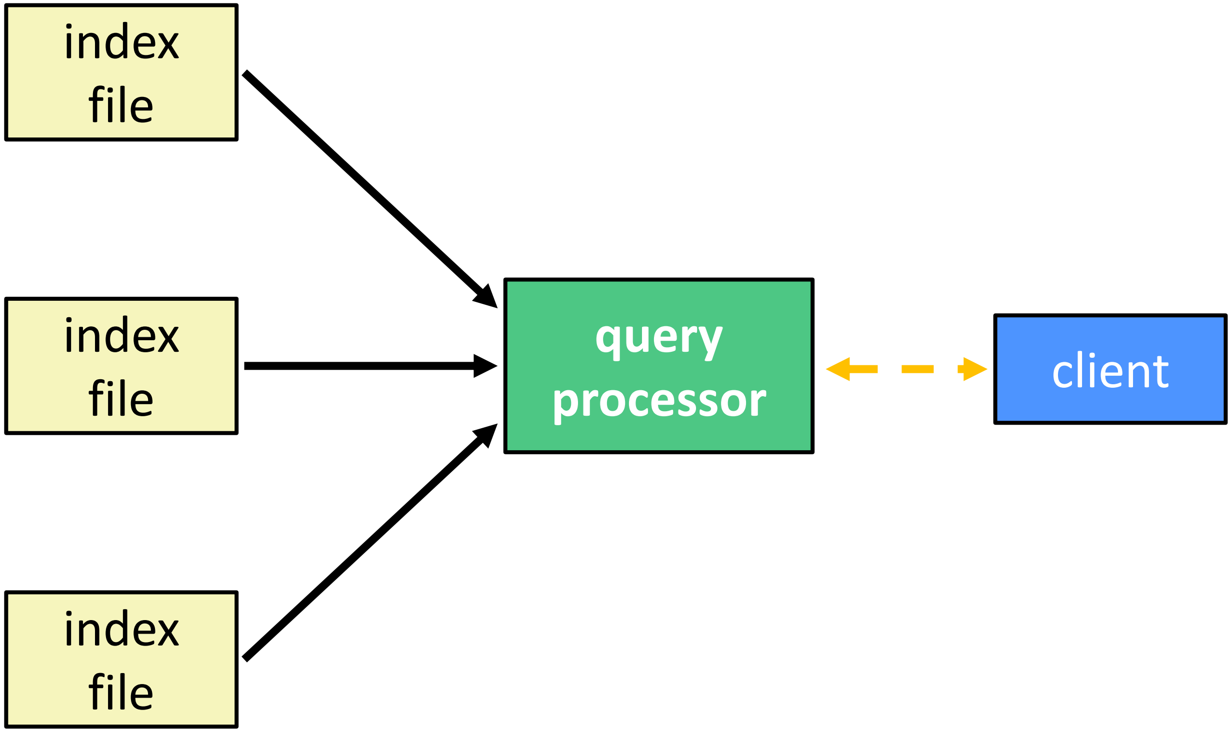
Building a Web Search Engine

- 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

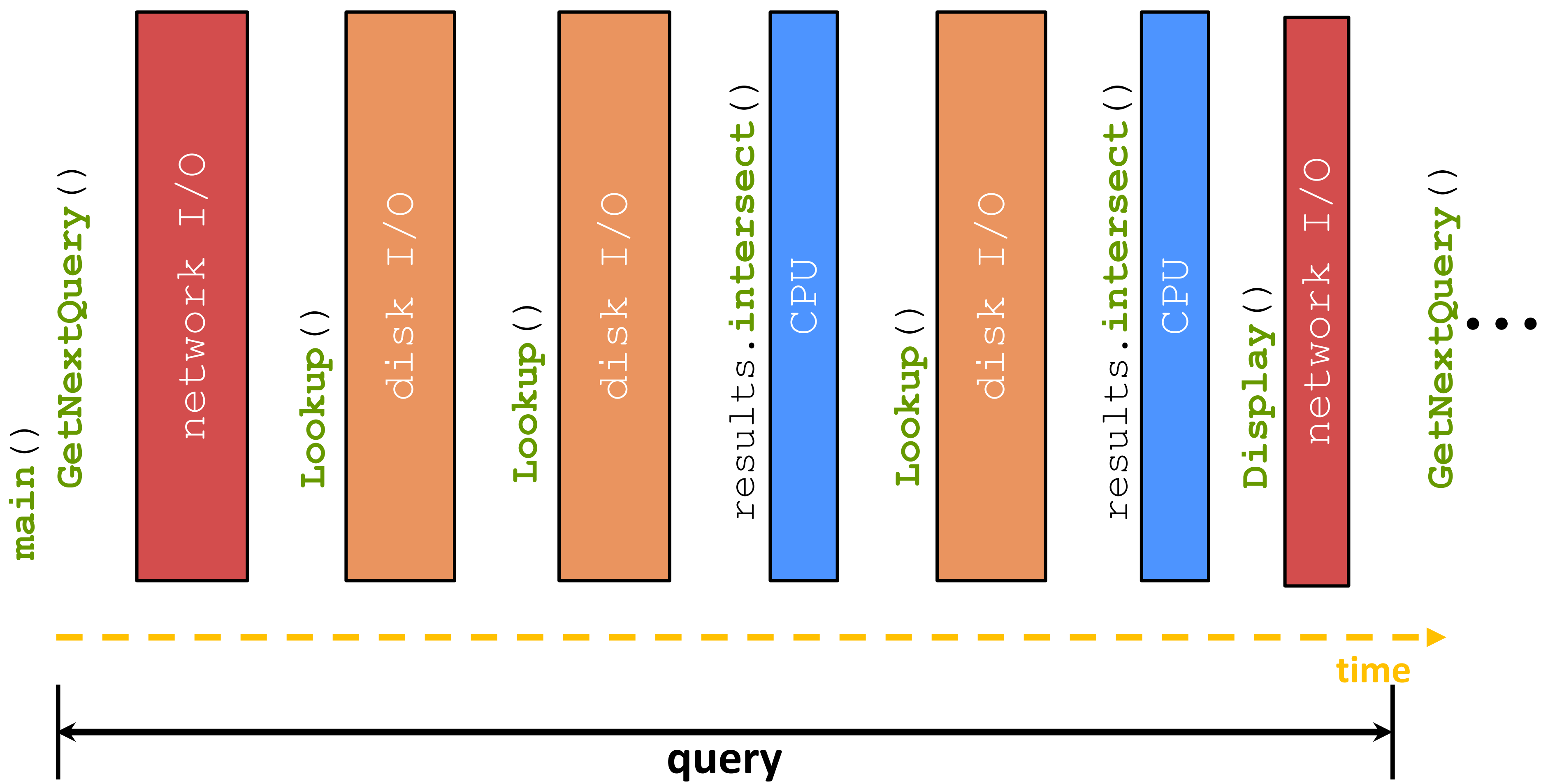


Search Engine (Pseudocode)

```
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)

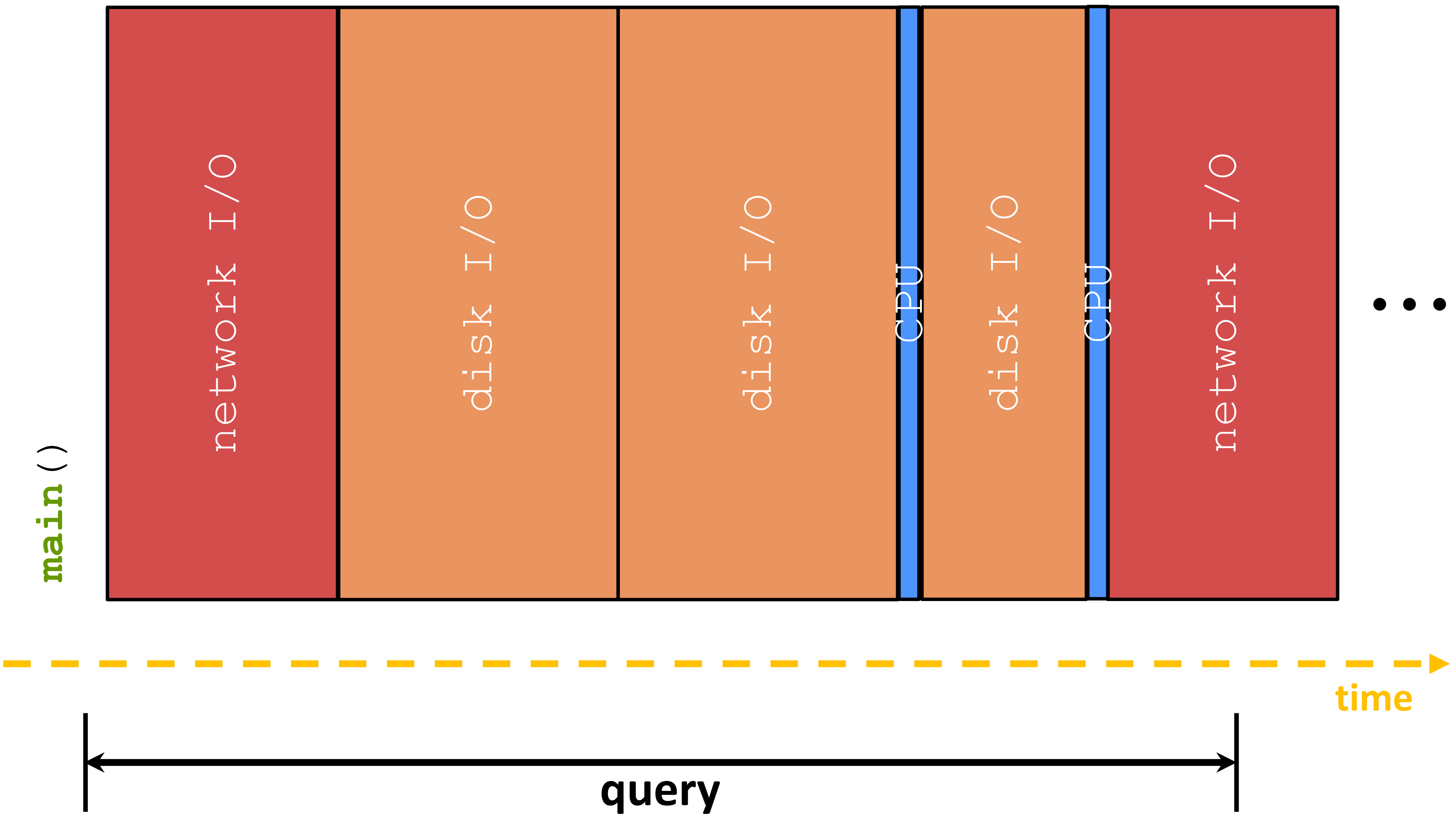
Numbers Everyone Should Know

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()`

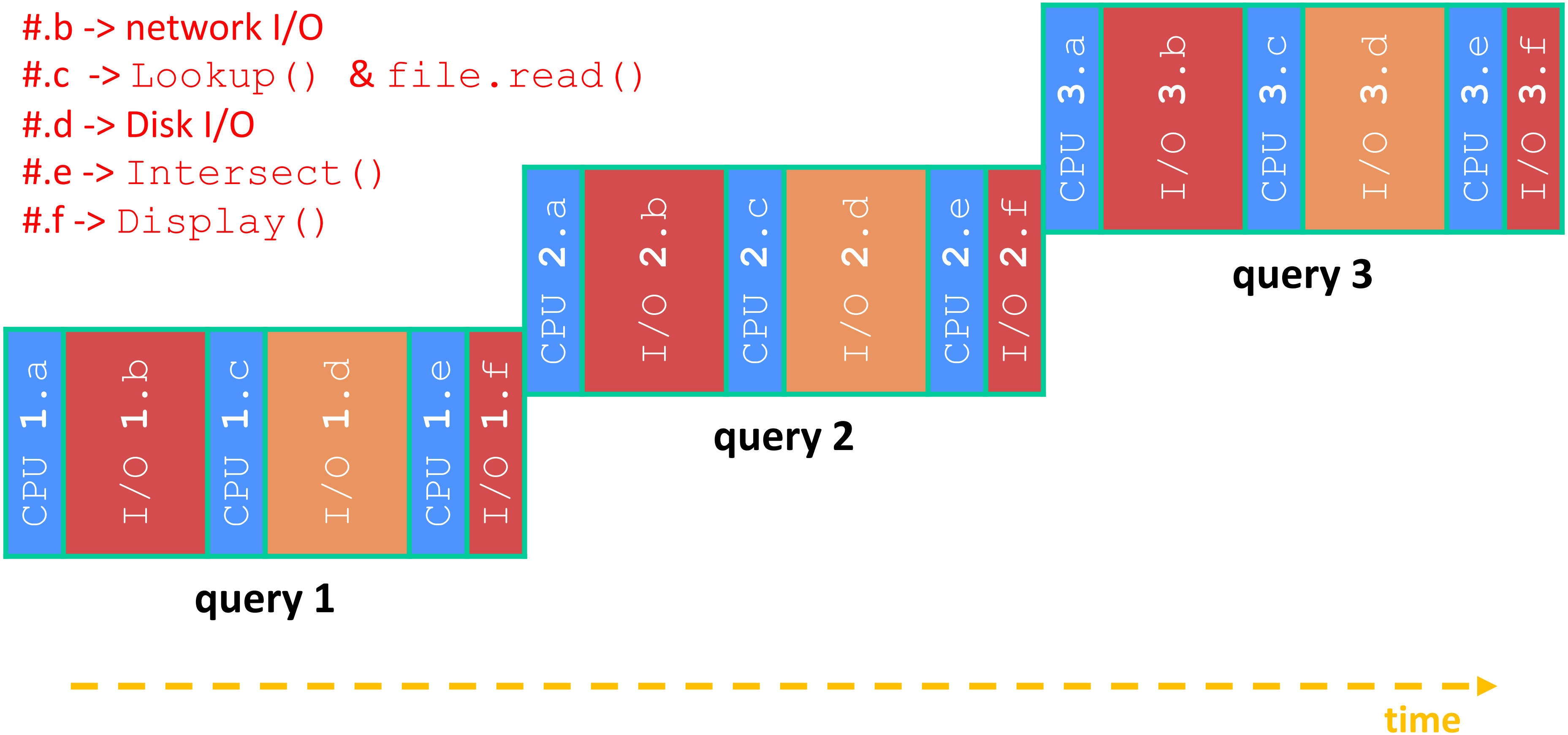
#.b -> network I/O

#.c -> `Lookup()` & `file.read()`

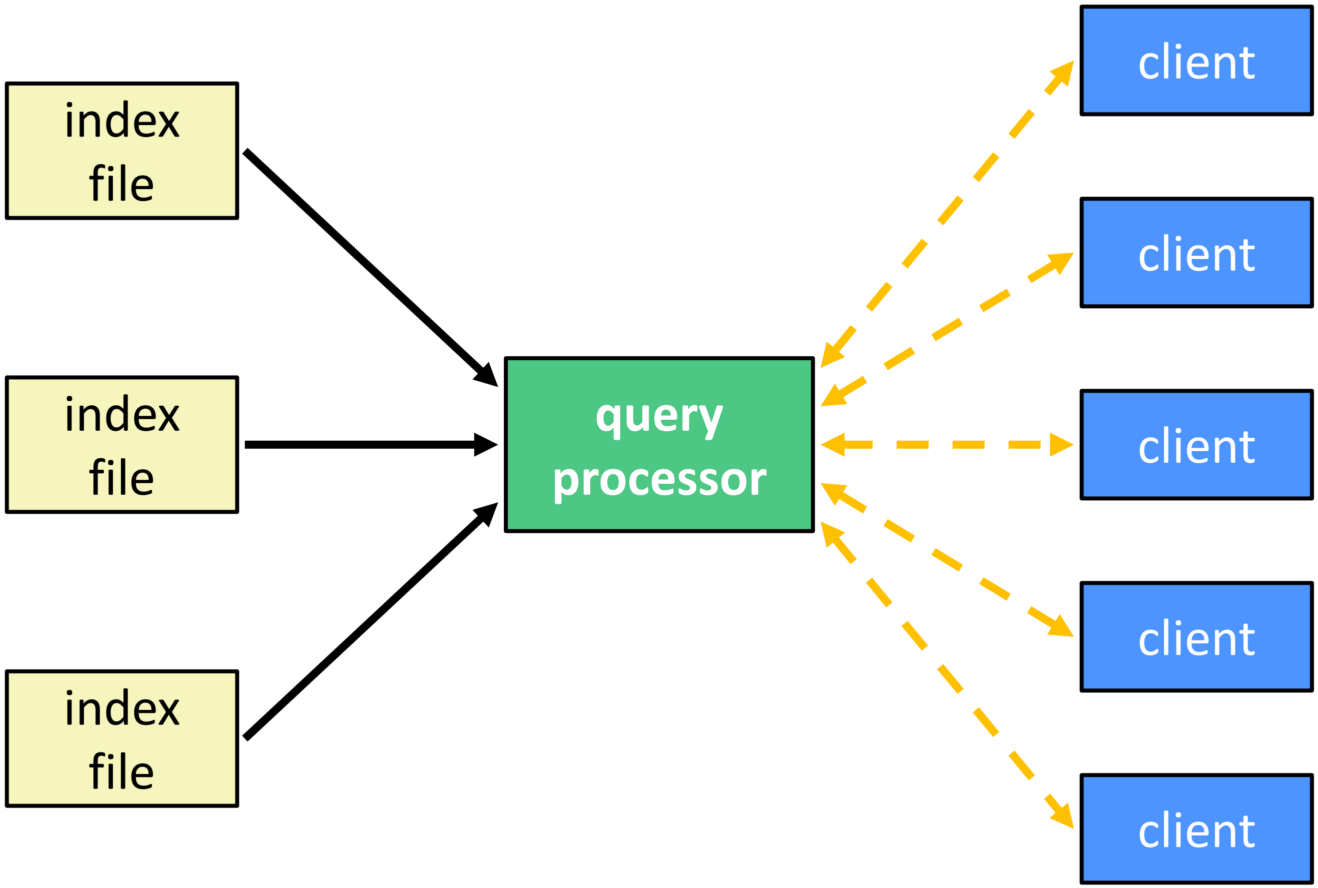
#.d -> Disk I/O

#.e -> `Intersect()`

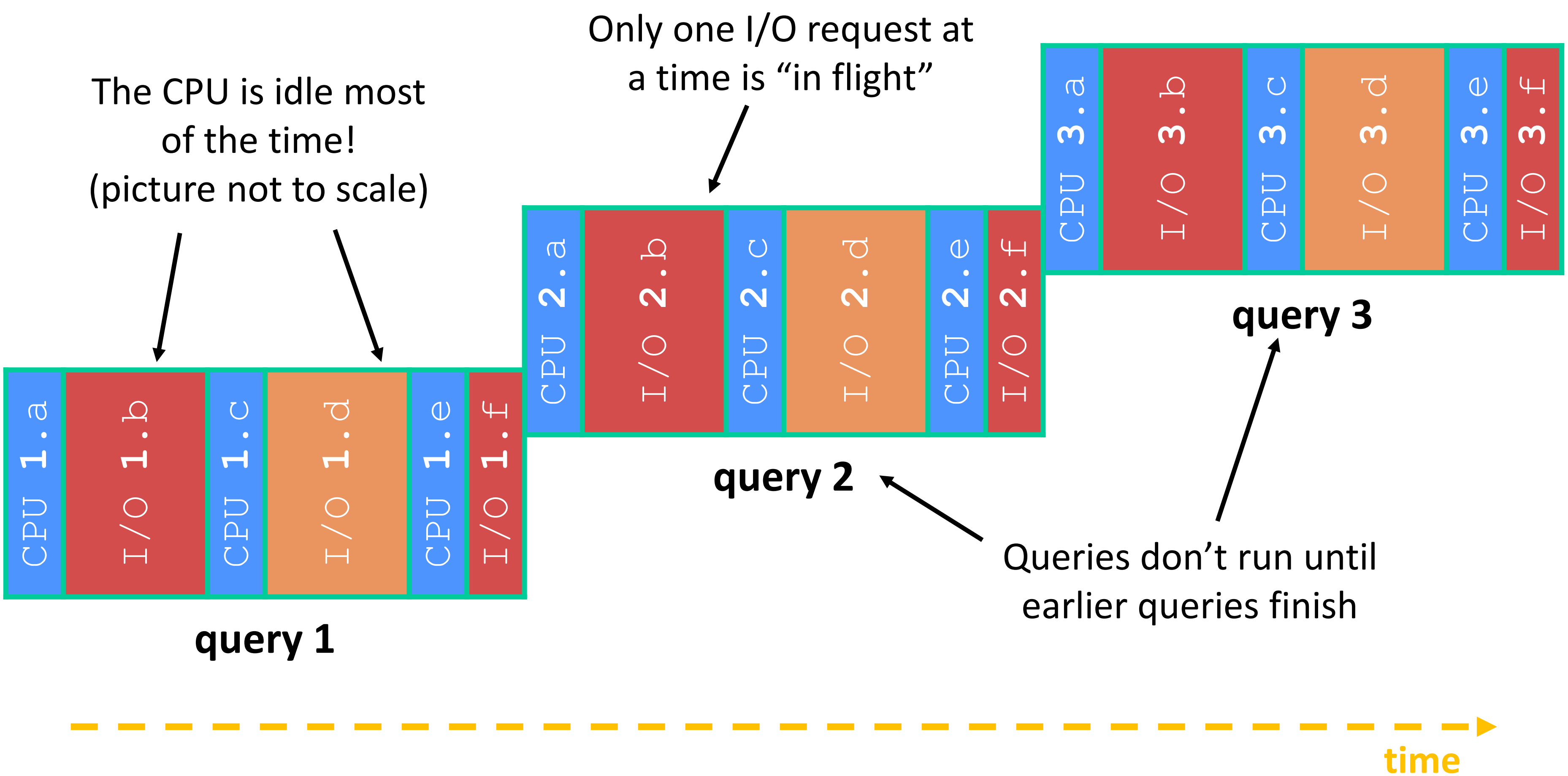
#.f -> `Display()`



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

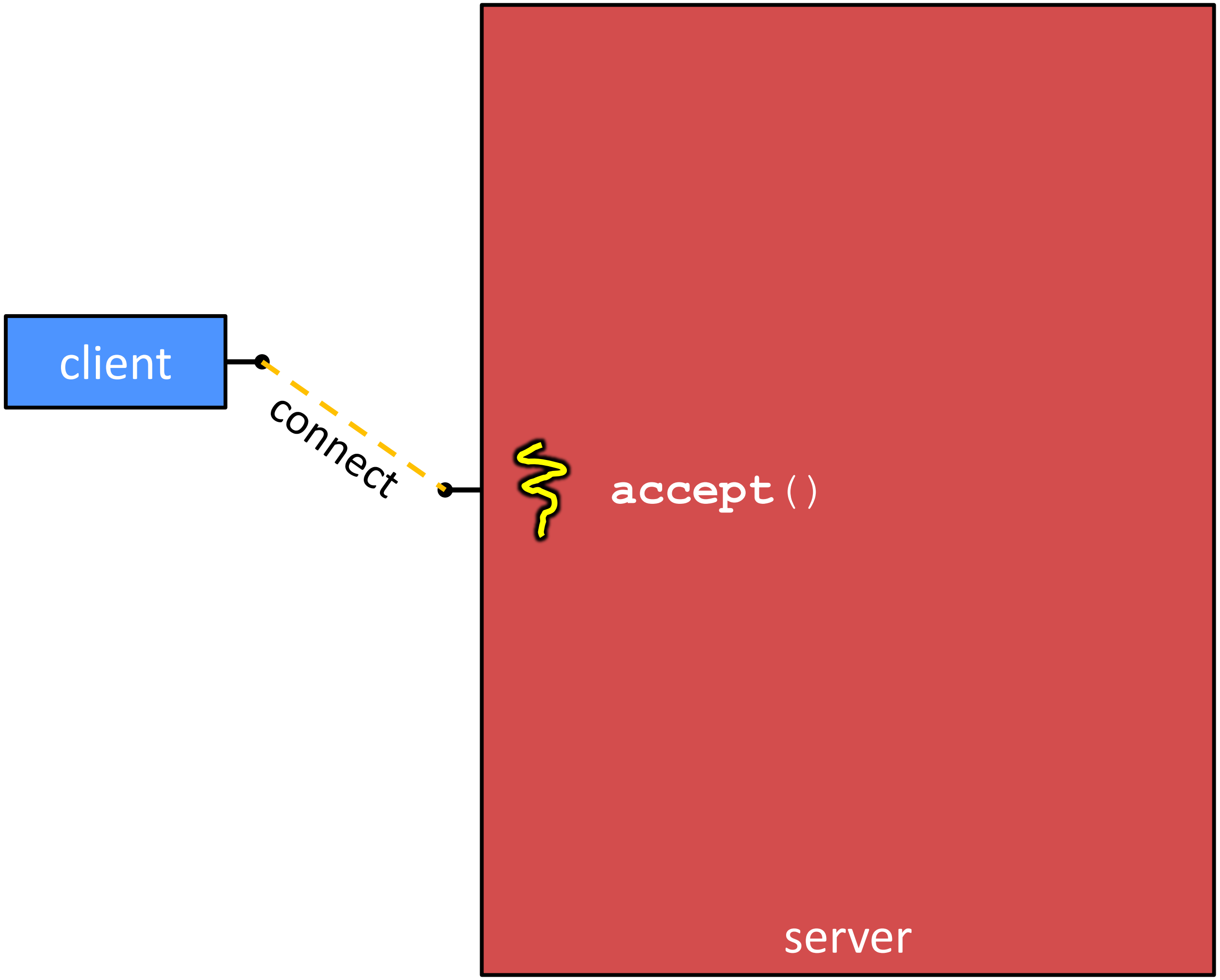
- Only one query is being processed at a time
  - All other queries queue up behind the first one
  - And clients queue up behind the queries …
- Even while processing one query, the CPU is idle the vast majority of the time
  - It is *blocked* waiting for I/O to complete
    - Disk I/O can be very, 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

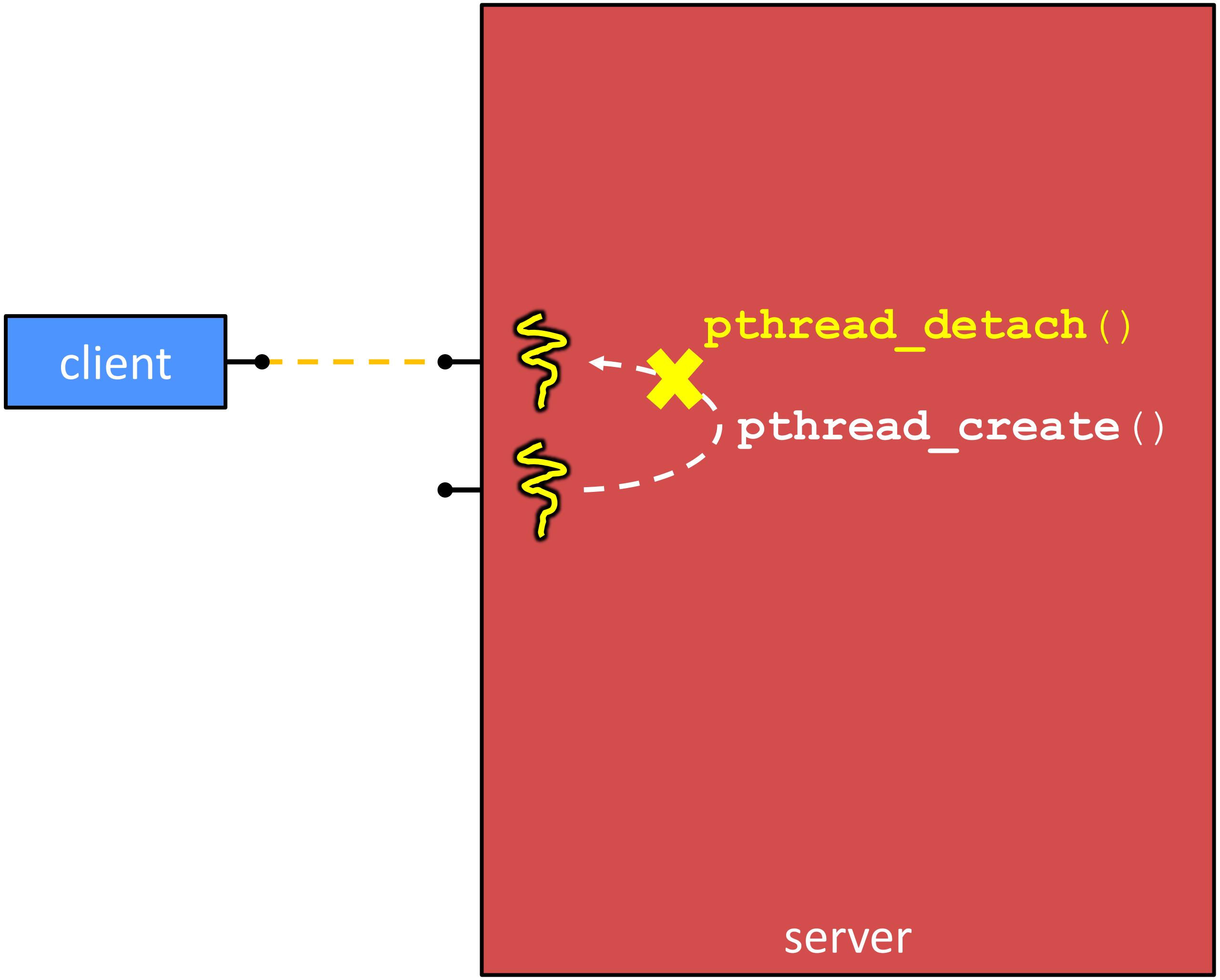
- Use multiple "workers"
  - As a query arrives, create a new "worker" to handle it
    - The "worker" reads the query from the network, issues read requests against files, assembles results and writes to the network
    - The "worker" uses blocking I/O; the "worker" alternates between consuming CPU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

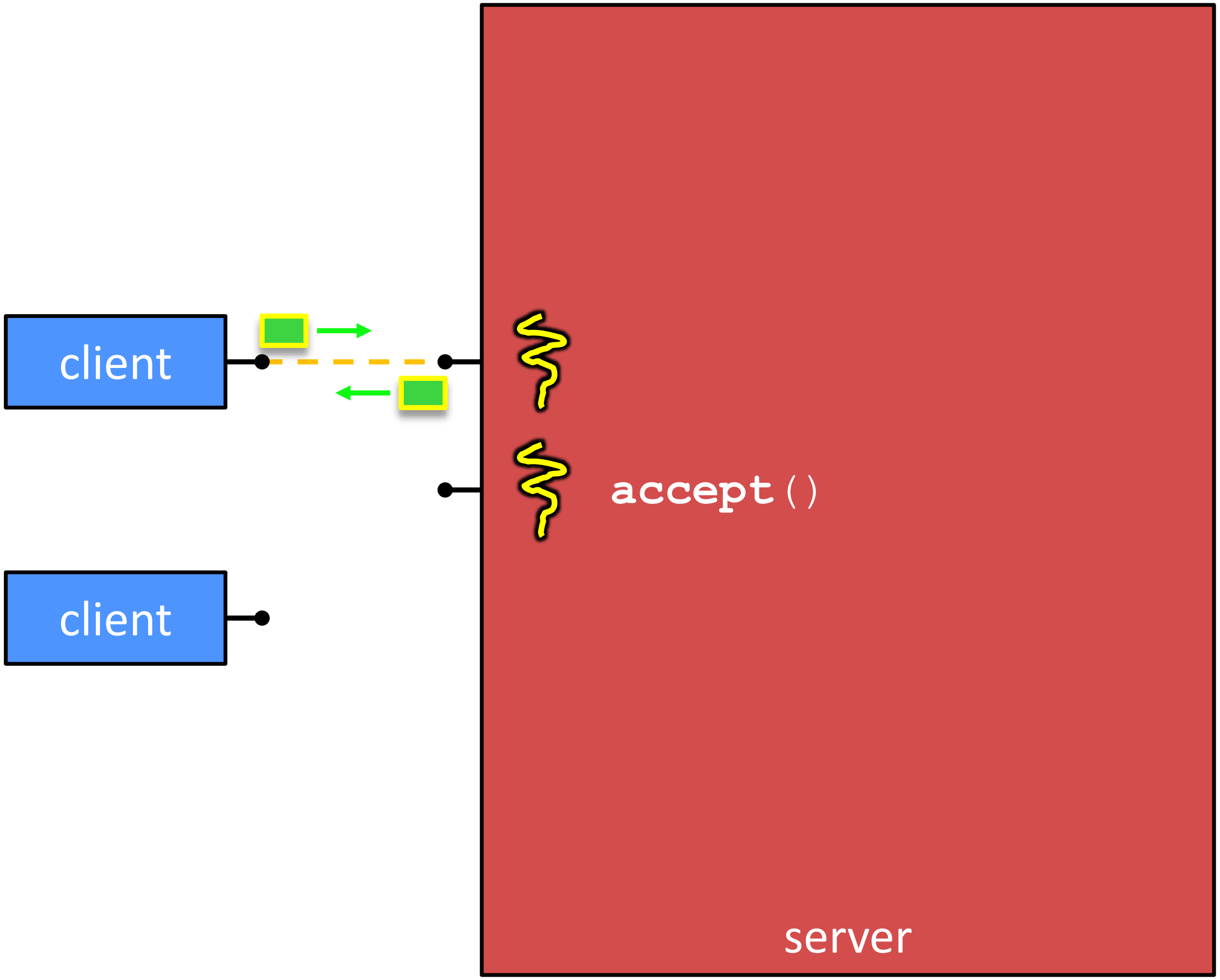
Multithreaded Server



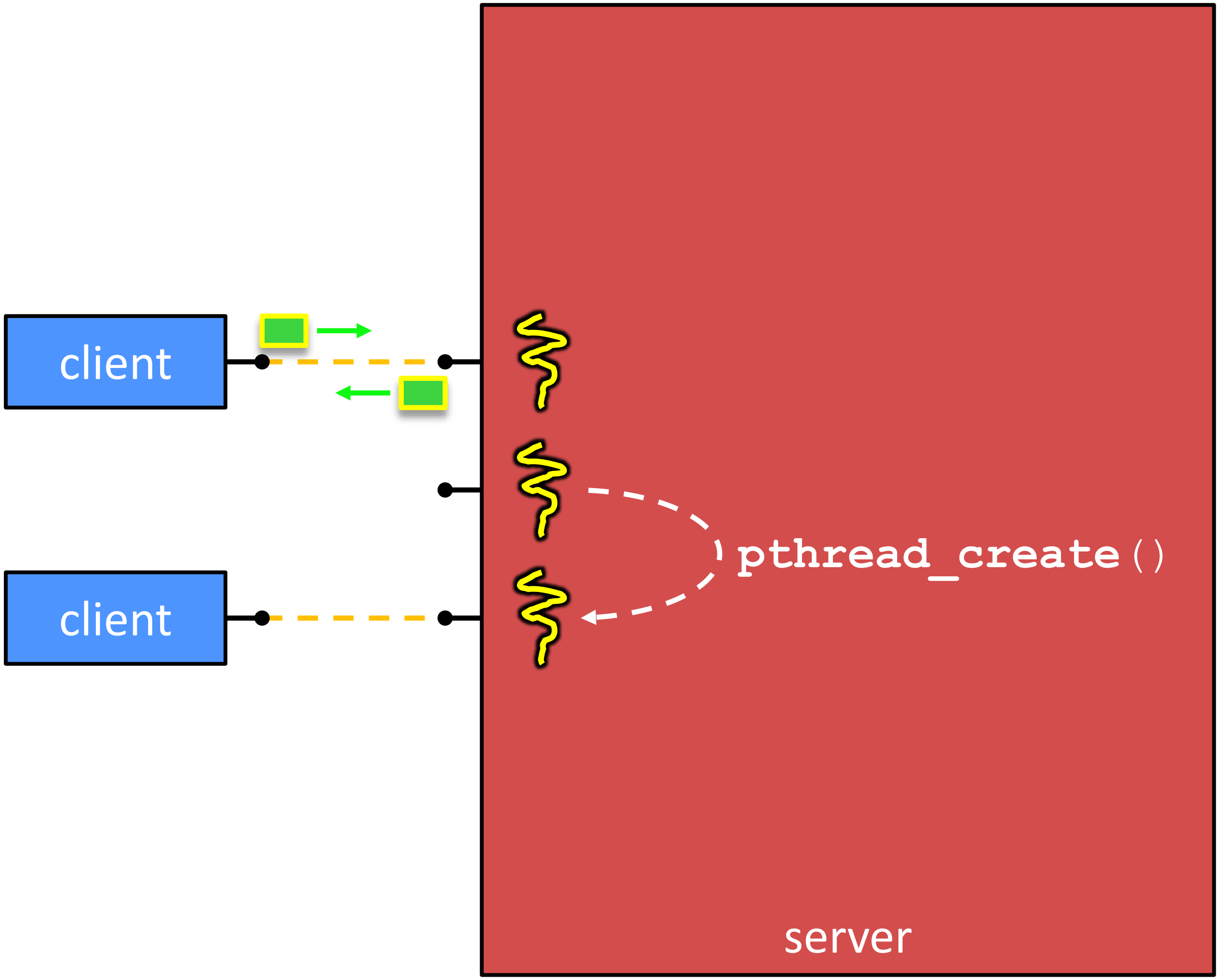
Multithreaded Server



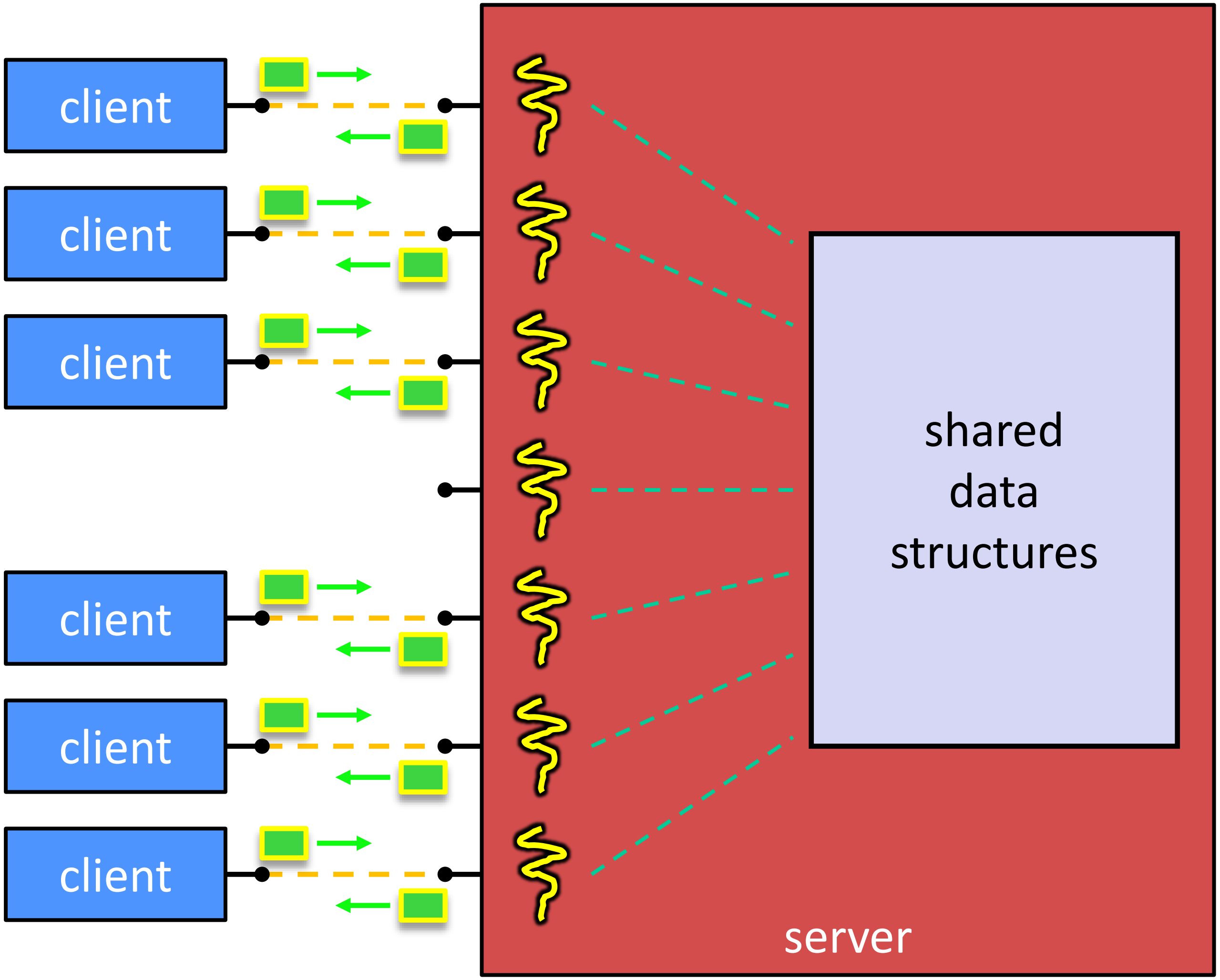
Multithreaded Server



Multithreaded Server

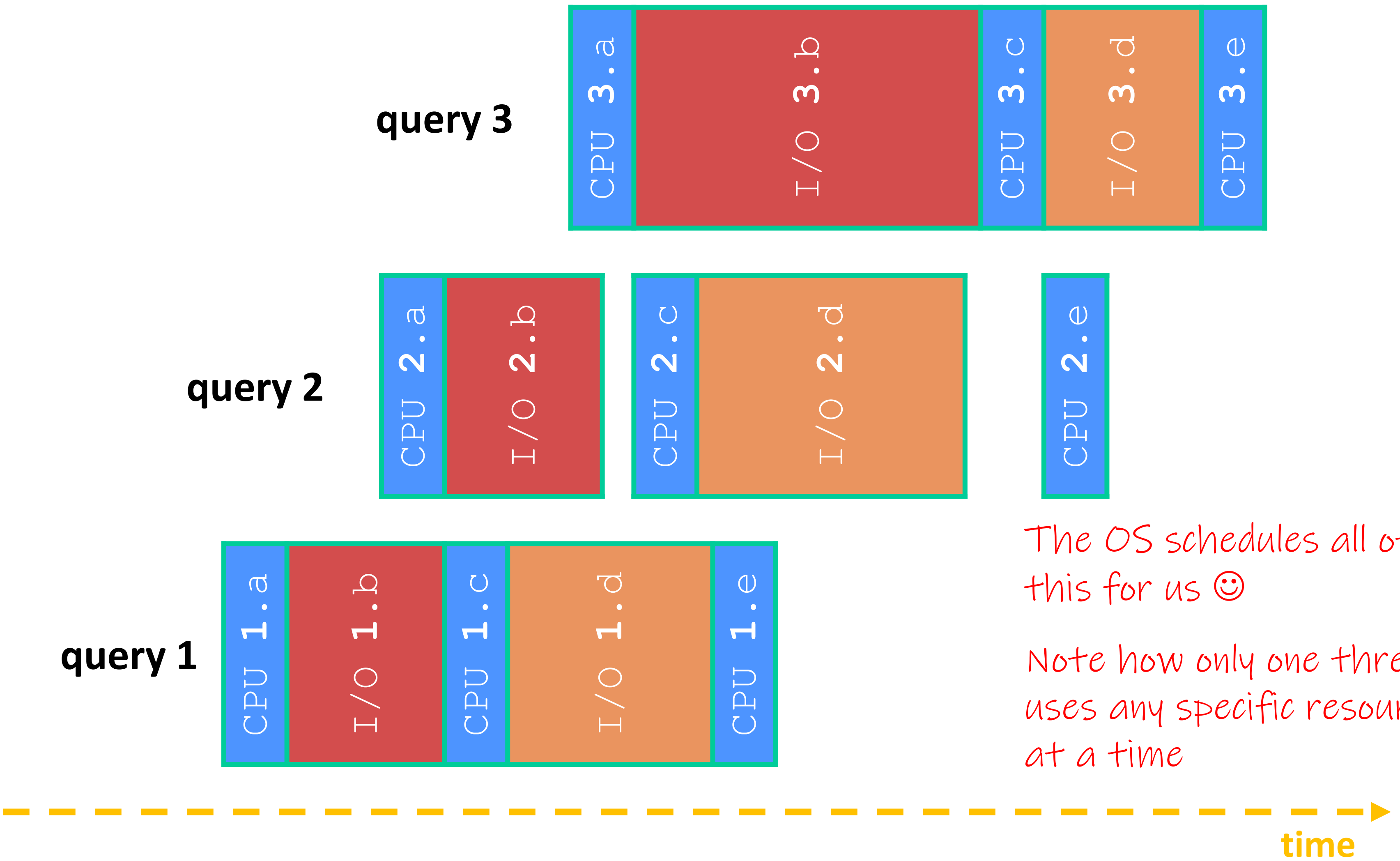


Multithreaded Server



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 IN THE NEXT FEW LECTURES