Intro to Threads

Computer Operating Systems, Spring 2025

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Poll Everywhere

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- How are you doing? How do you like processes?

Administrivia

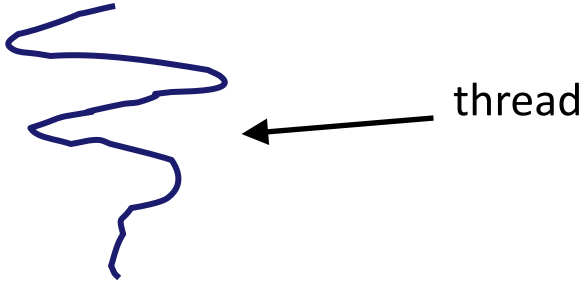
- Penn-shell is out (this shouldn't be news)!
  - ***Full thing is due (Fri, Feb 28) (1 more week!)***
  - ***Done in partners***
    - Everything was covered already that you would need…

Lecture Outline

- **Threads High Level**
- pthreads
- Processes vs threads
- Thread Interleaving & Sequential Consistency
- Benefits of Concurrency

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

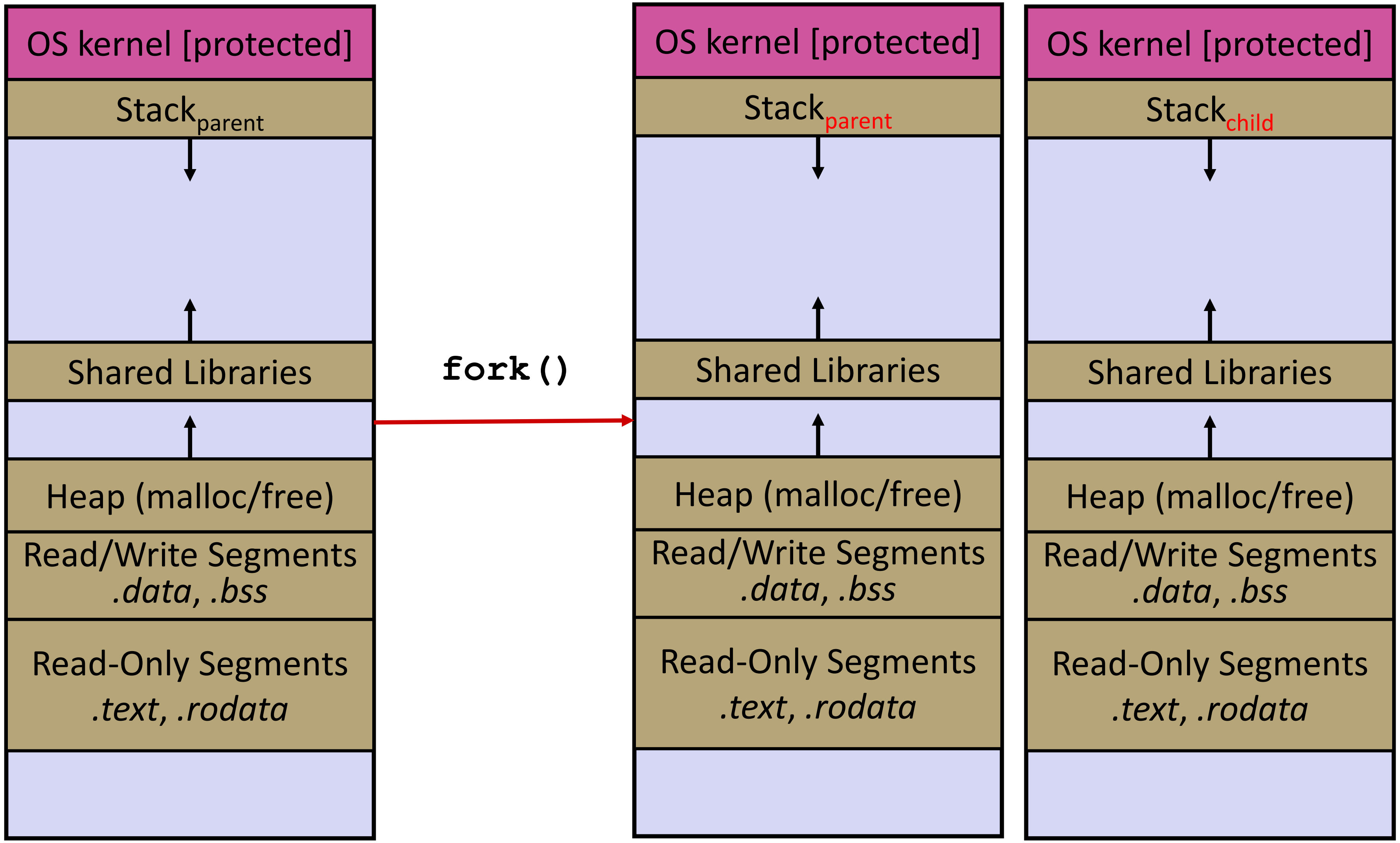


- In most modern OS's:
  - Threads are the *unit of scheduling.*

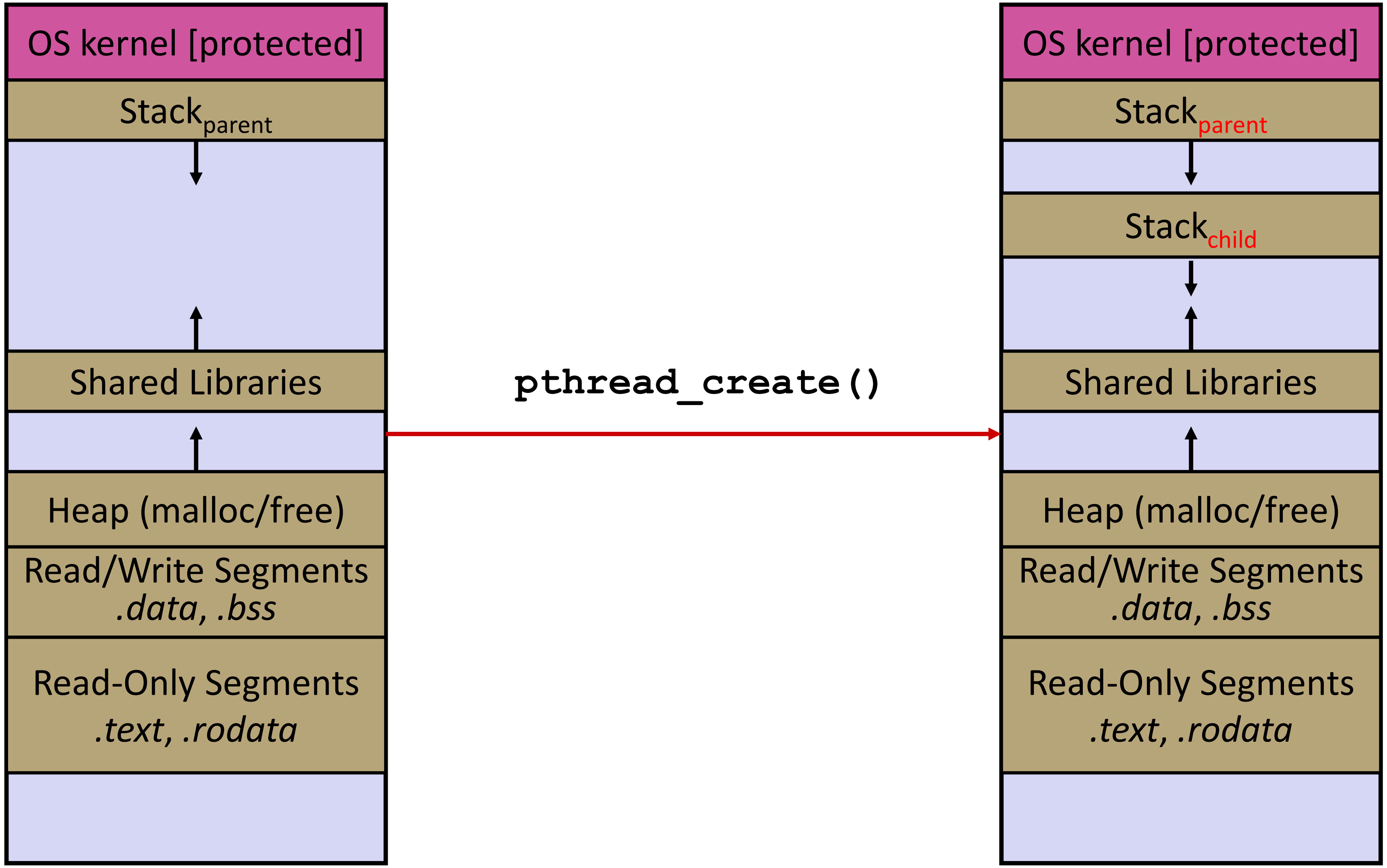
Threads vs. Processes

- 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

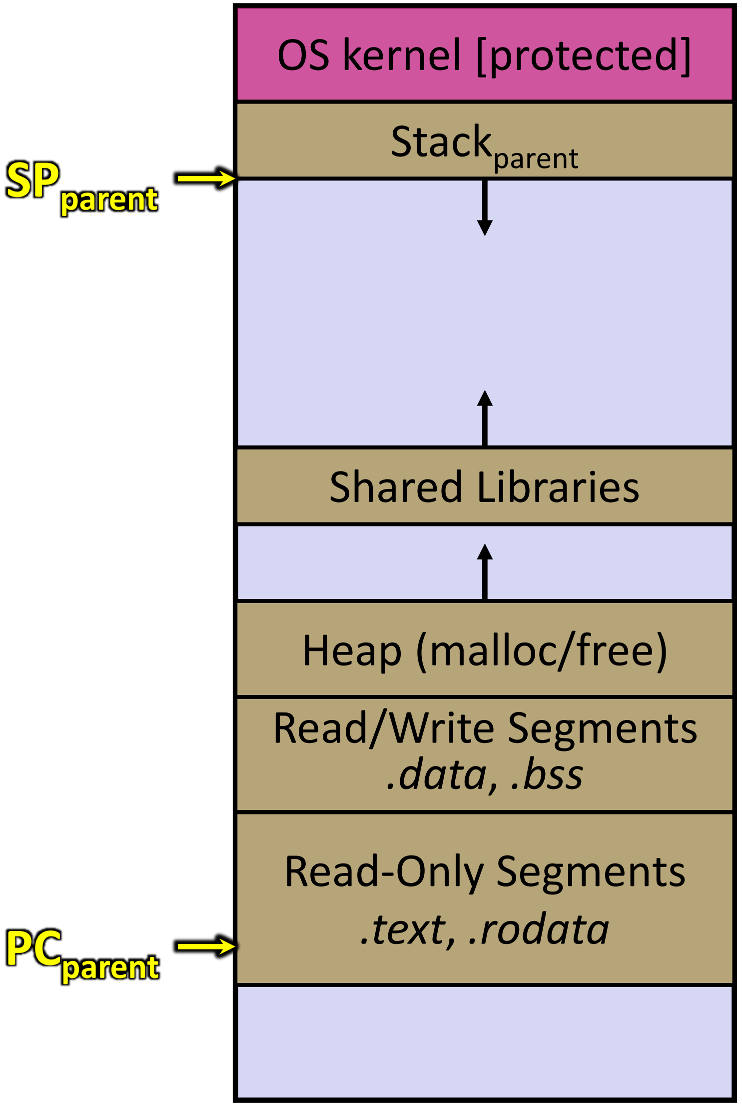


Threads

- 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

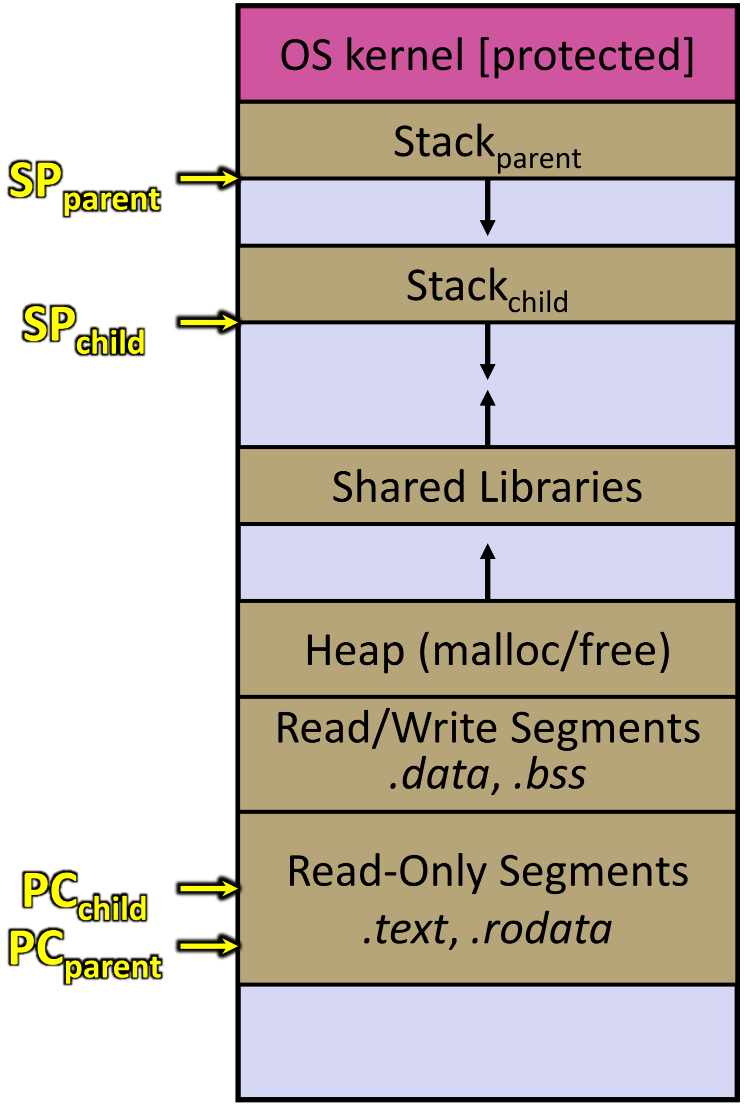
- Analogy: restaurant kitchen
  - Kitchen is process
  - Chefs are threads

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

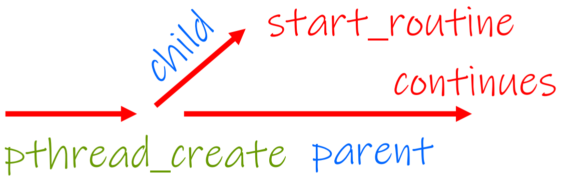
Output parameter.
Gives us a "thread_descriptor"

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

  Function pointer!
  Takes & returns void*
  to allow "generics" in C

  Argument for the thread function

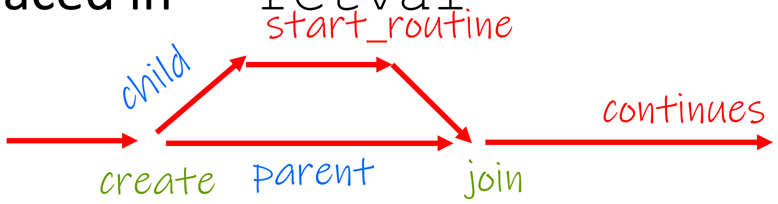
  - Creates a new thread into `*thread`, with attributes `*attr` (`NULL` means default attributes)
  - Returns **0** on success and an error number on error (can check against error constants)
  - The new thread runs **`start_routine`**`(arg)`



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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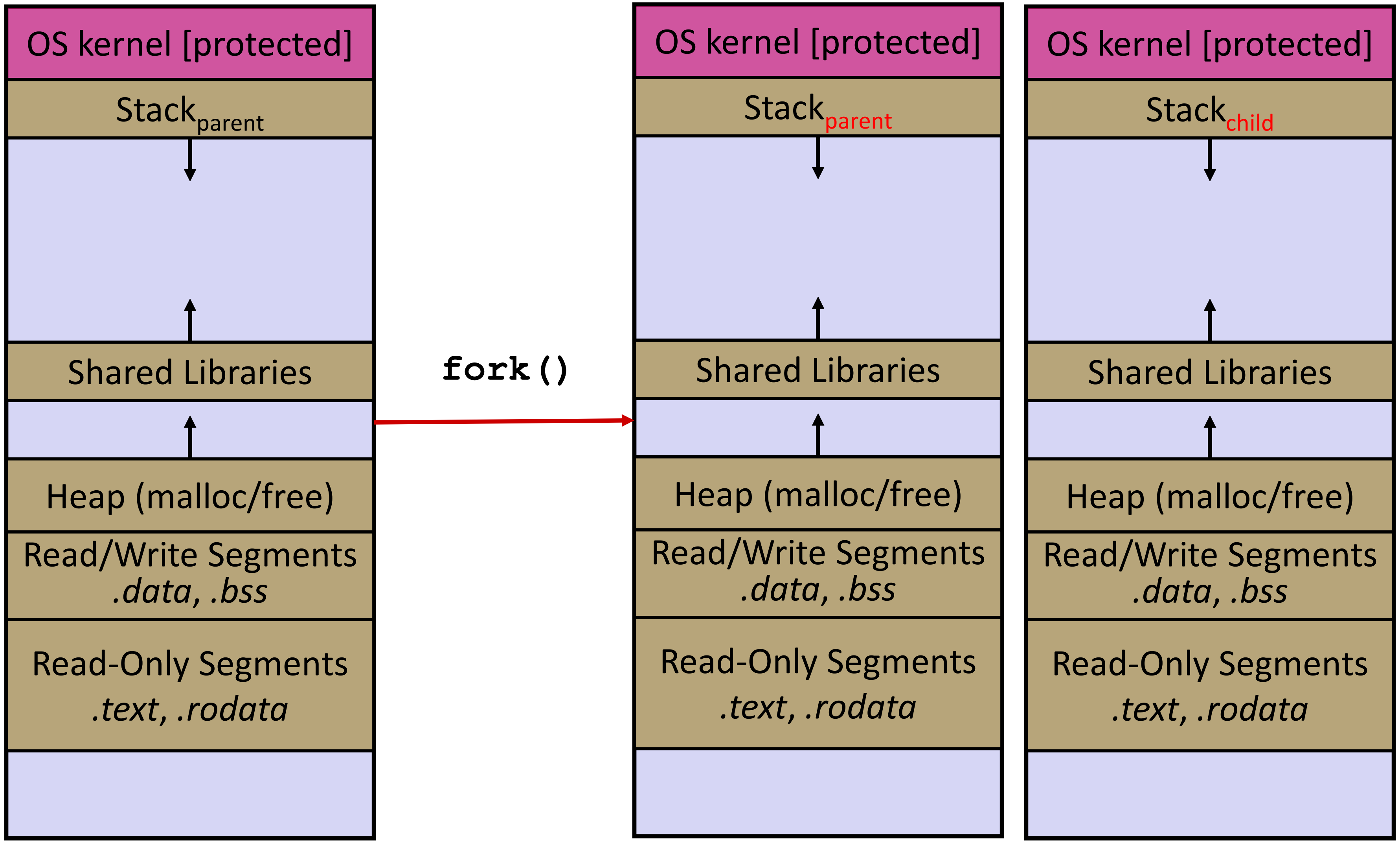
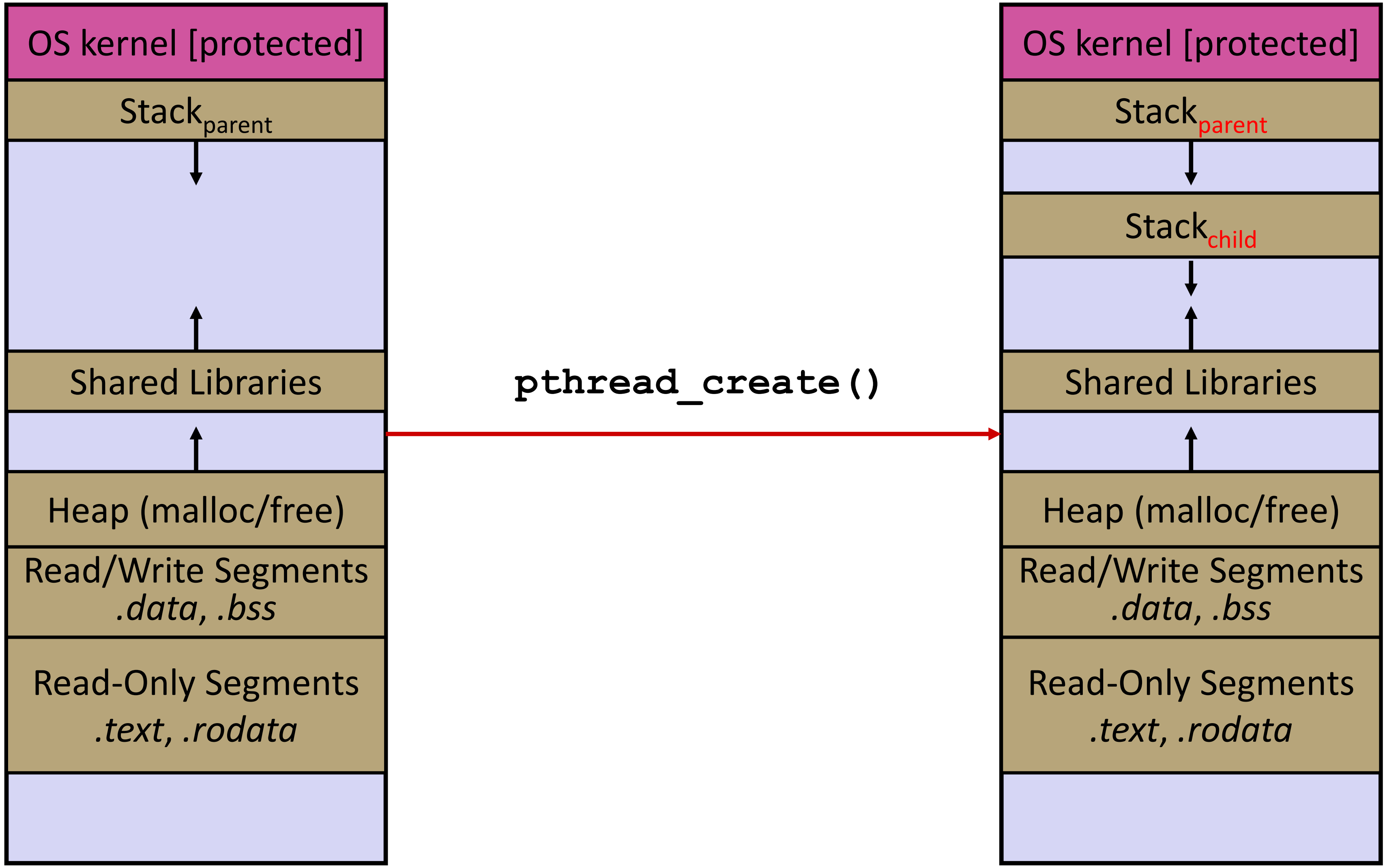
Threads vs. Processes



Threads vs. Processes



Poll Everywhere

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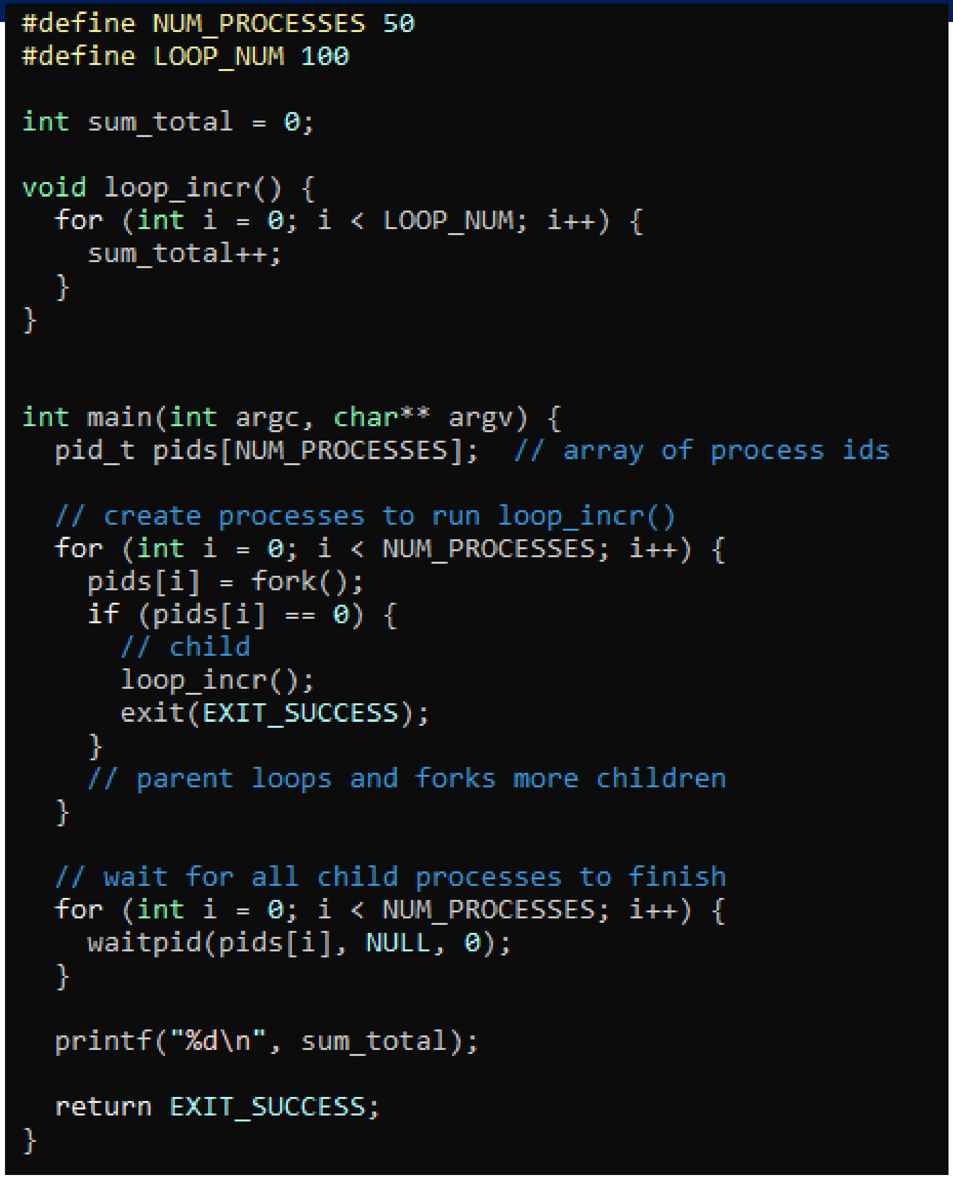
- What does this print?



```
#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;
}
```

Poll Everywhere

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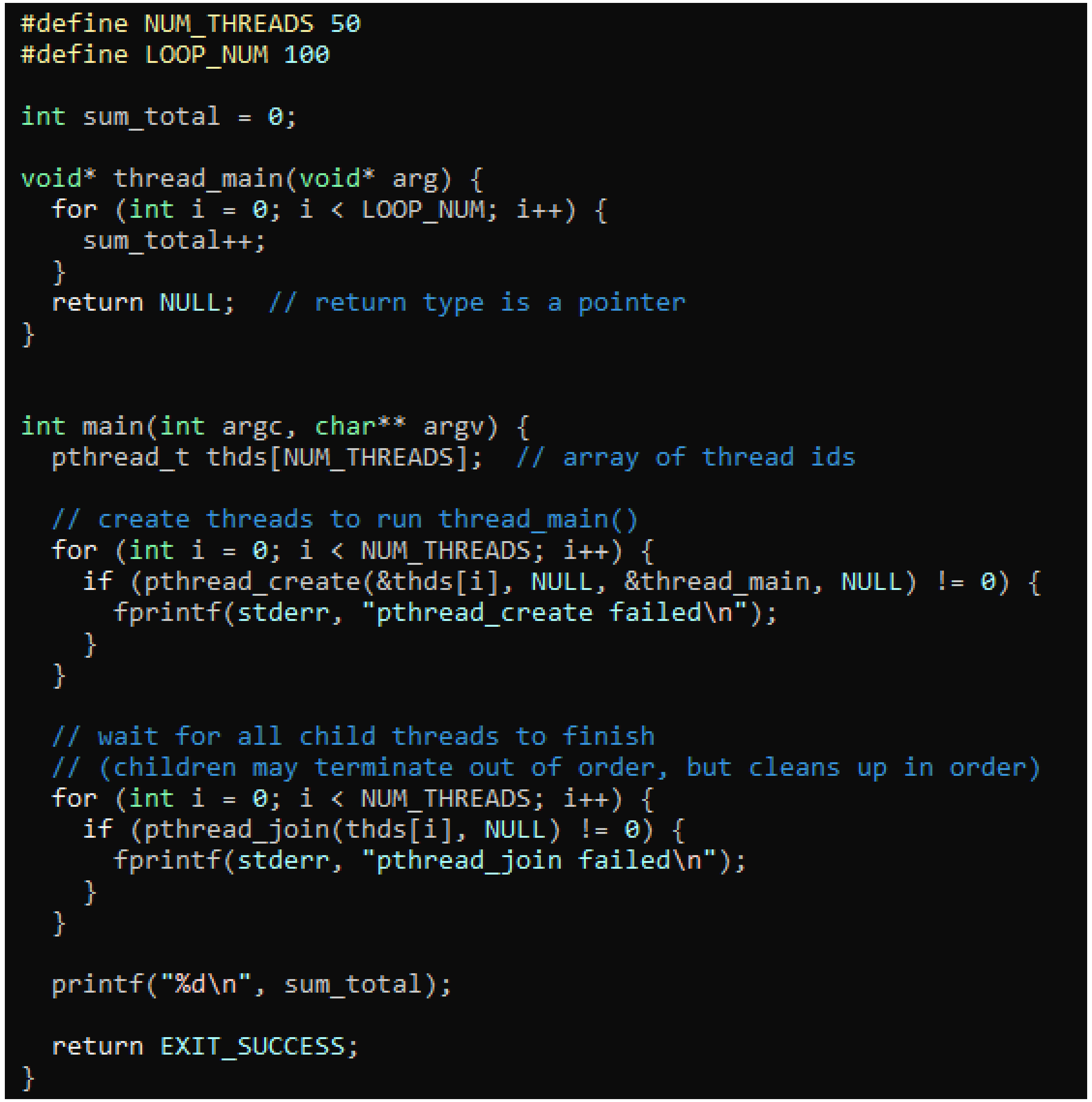
- What does this print?



```c
#define NUM_THREADS 50
#define LOOP_NUM 100

int sum_total = 0;

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++) {
    if (pthread_create(&thds[i], NULL, &thread_main, NULL) != 0) {
      fprintf(stderr, "pthread_create failed\n");
    }
  }

  // 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++) {
    if (pthread_join(thds[i], NULL) != 0) {
      fprintf(stderr, "pthread_join failed\n");
    }
  }

  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 next week**

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()

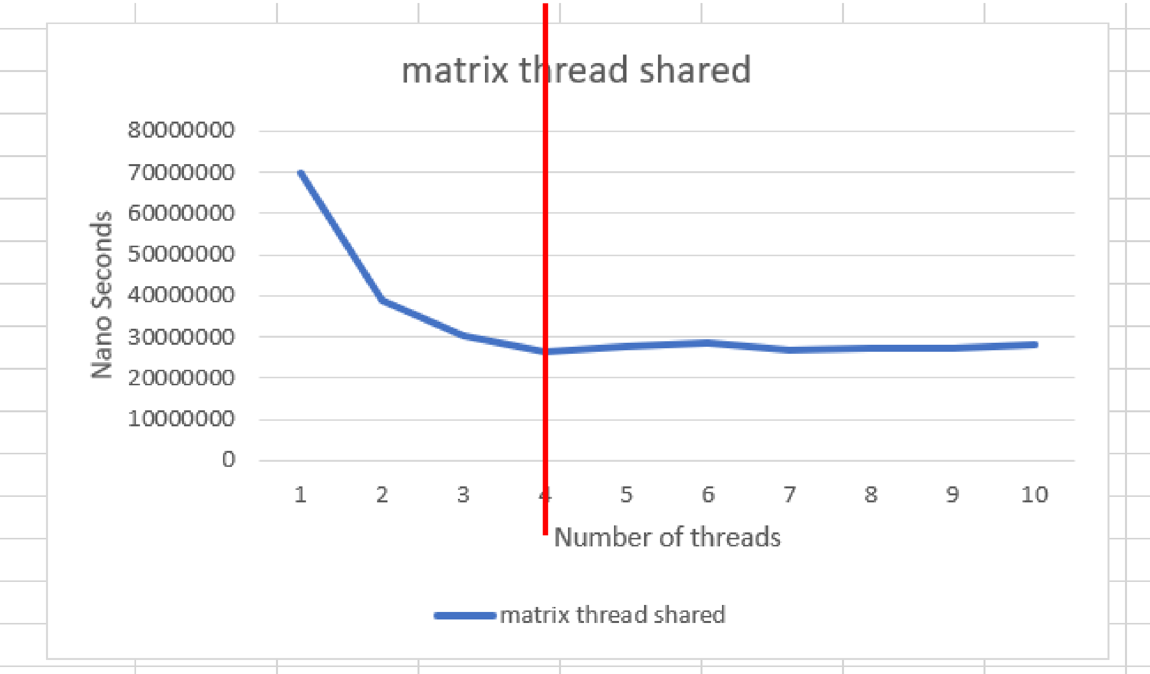
Parallelism

- 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

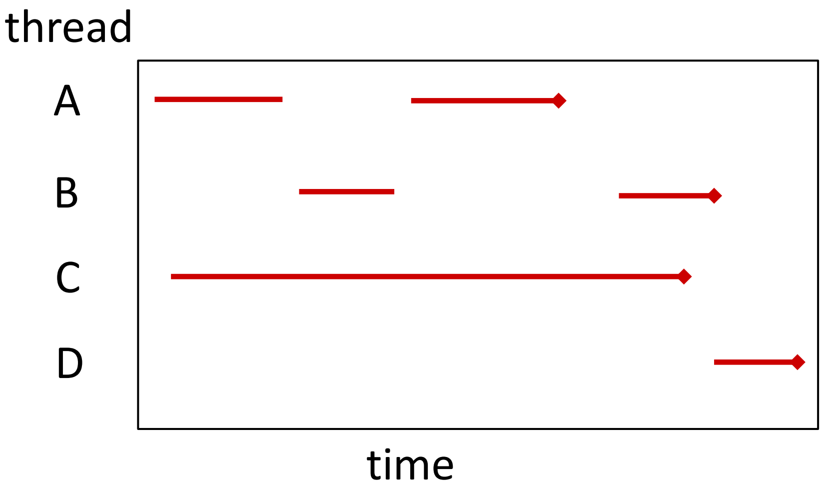
Parallelism vs Concurrency

- Two commonly used terms (often mistakenly used interchangeably).

- Concurrency: When there are one or more “tasks” that have overlapping lifetimes (between starting, running and terminating).
  - That these tasks are both running within the same **period**.

- Parallelism: when one or more “tasks” run at the same **instant** in time.

- Consider the lifetime of these threads. Which are concurrent with A? Which are parallel with A?



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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- Threads High Level
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- What are all possible outputs of this program?

```
void* thrd_fn(void* arg) {
  int* ptr = (int*) arg;
  printf("%d\n", *ptr);
  return NULL;
}

int main() {
  pthread_t thd1;
  pthread_t thd2;
  int x = 1;
  pthread_create(&thd1, NULL, thrd_fn, &x);
  x = 2;
  pthread_create(&thd2, NULL, thrd_fn, &x);

  pthread_join(thd1, NULL);
  pthread_join(thd2, NULL);
}
```

Are these output possible?

```
----------------------------
1
2
----------------------------
2
2
----------------------------
1
1
----------------------------
2
1
```

Visualization

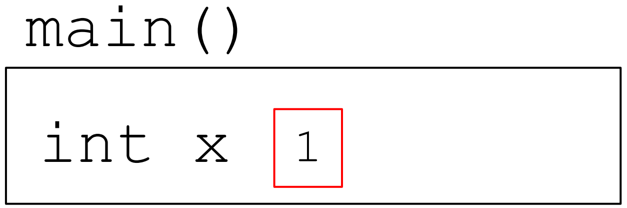
```
int main() {
  int x = 1;
  pthread_create(...);
  x = 2;
  pthread_create(...);

  pthread_join(...);
  pthread_join(...);
}
```

```
thrd_fn() {
  printf(*ptr);
  return NULL;
}
```

```
thrd_fn() {
  printf(*ptr);
  return NULL;
}
```

Visualization: Memory

- The variable x is shared across all threads.



```
int main() {
  int x = 1;
  pthread_create(thd1);
  x = 2;
  pthread_create(thd2);

  pthread_join(thd1);
  pthread_join(thd2);
}
```

Visualization: Memory

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int main() {
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Visualization: Memory

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Visualization: Memory

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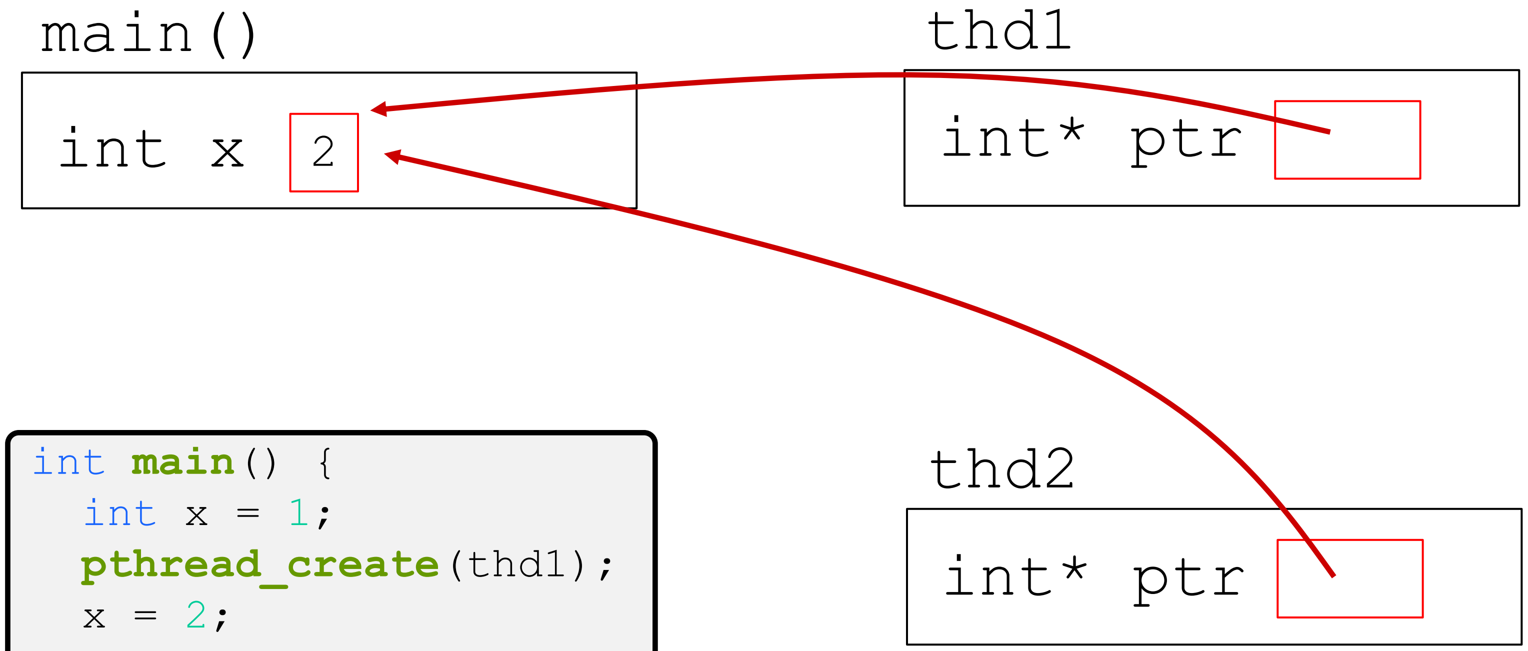


```
int main() {
  int x = 1;
  pthread_create(thd1);
  x = 2;
  pthread_create(thd2);

  pthread_join(thd1);
  pthread_join(thd2);
}
```

Sequential Consistency

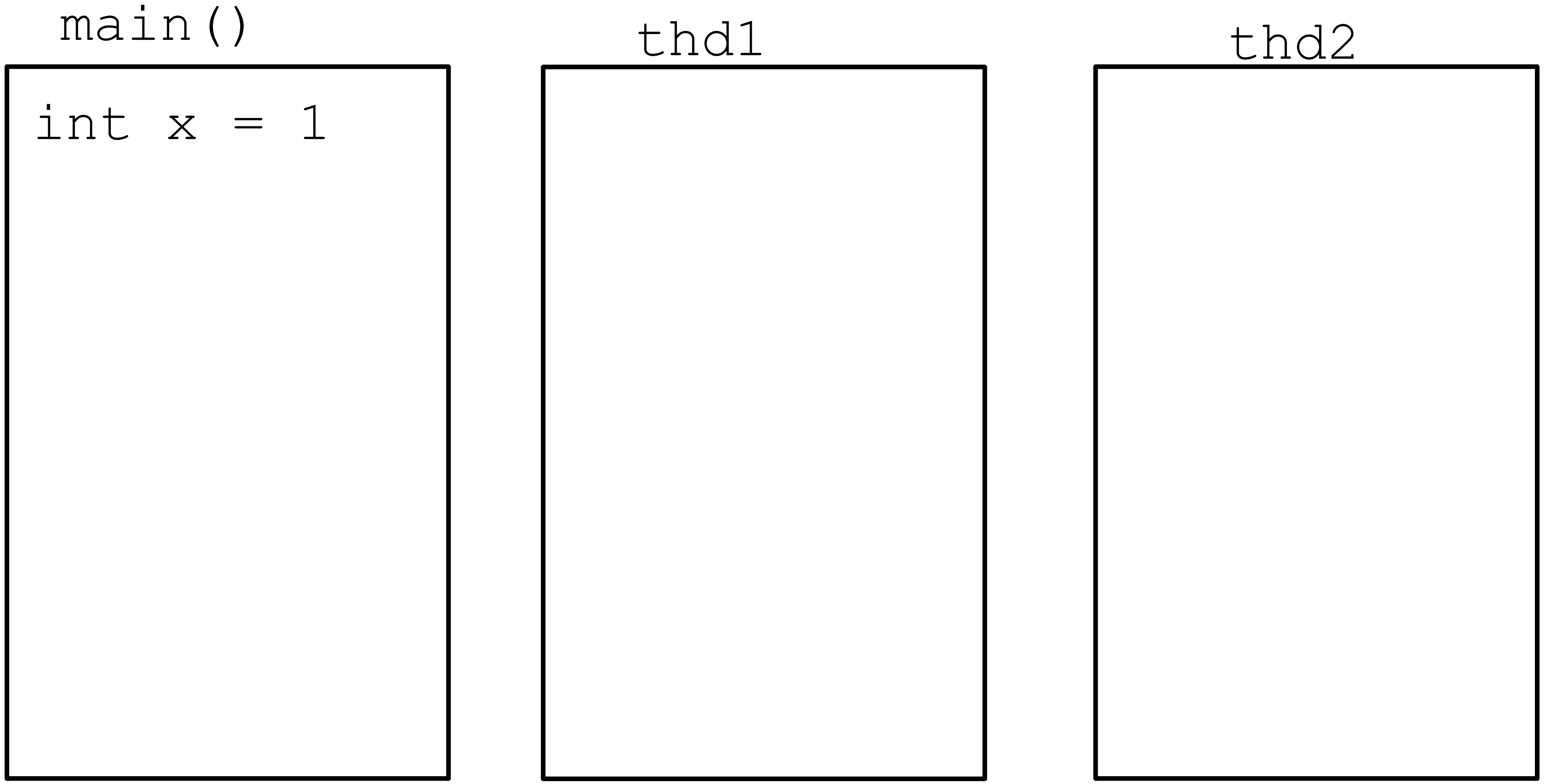
- Within a single thread, we assume* that there is sequential consistency. That the order of operations within a single thread are the same as the program order.

```
main()

int x = 1
create thd1
x = 2
create thd2
```

Within main(), x is set to 1 before thread 1 is created
then thread 1 is created
then x is set to 2
then thread 2 is created

Visualization: Ordering

- Threads run concurrently; we can’t be sure of the ordering of things across threads.



`main()`

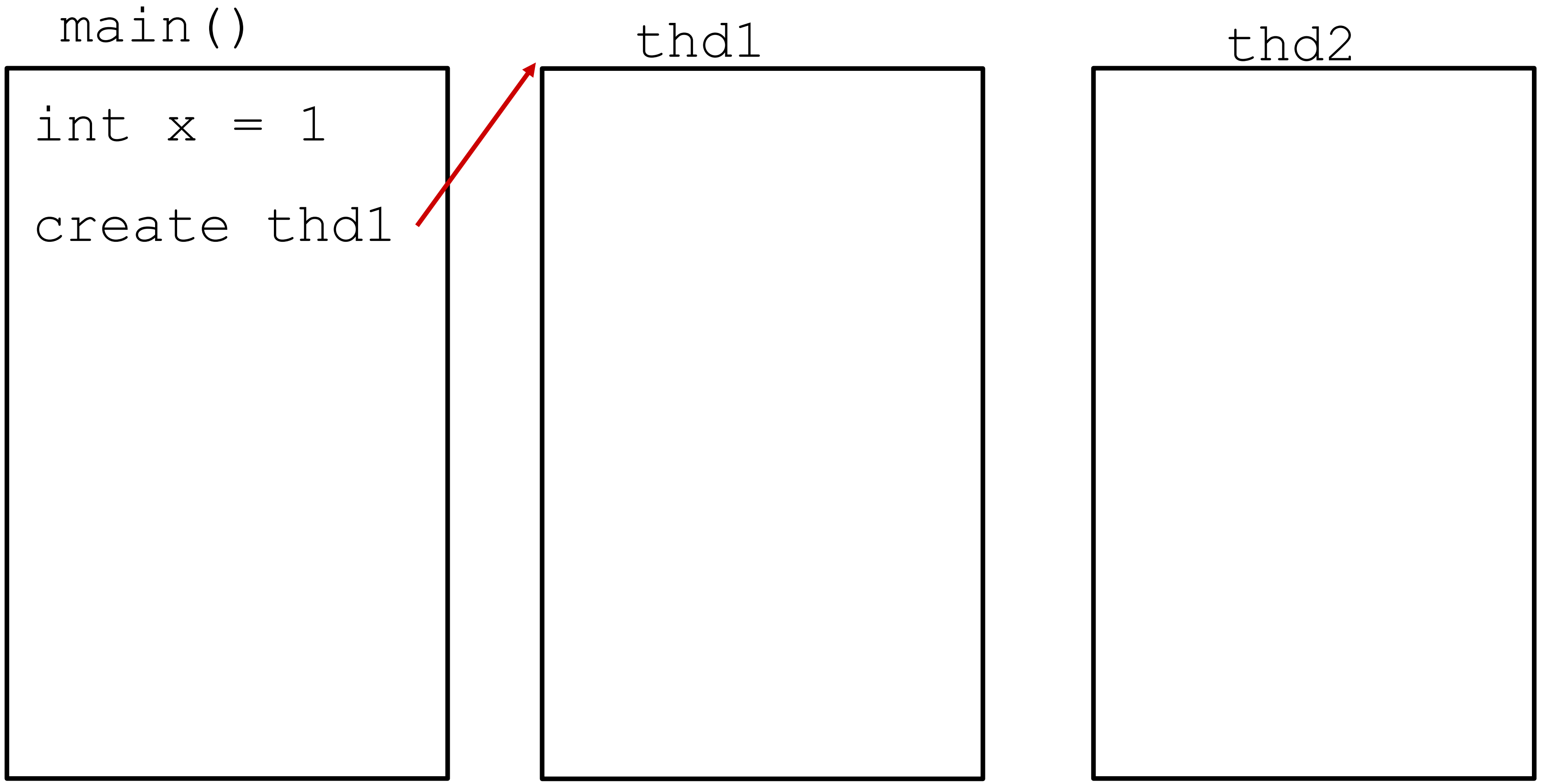
`int x = 1`

`thd1`

`thd2`

Visualization: Ordering

- Threads run concurrently; we can't be sure of the ordering of things across threads.



main()

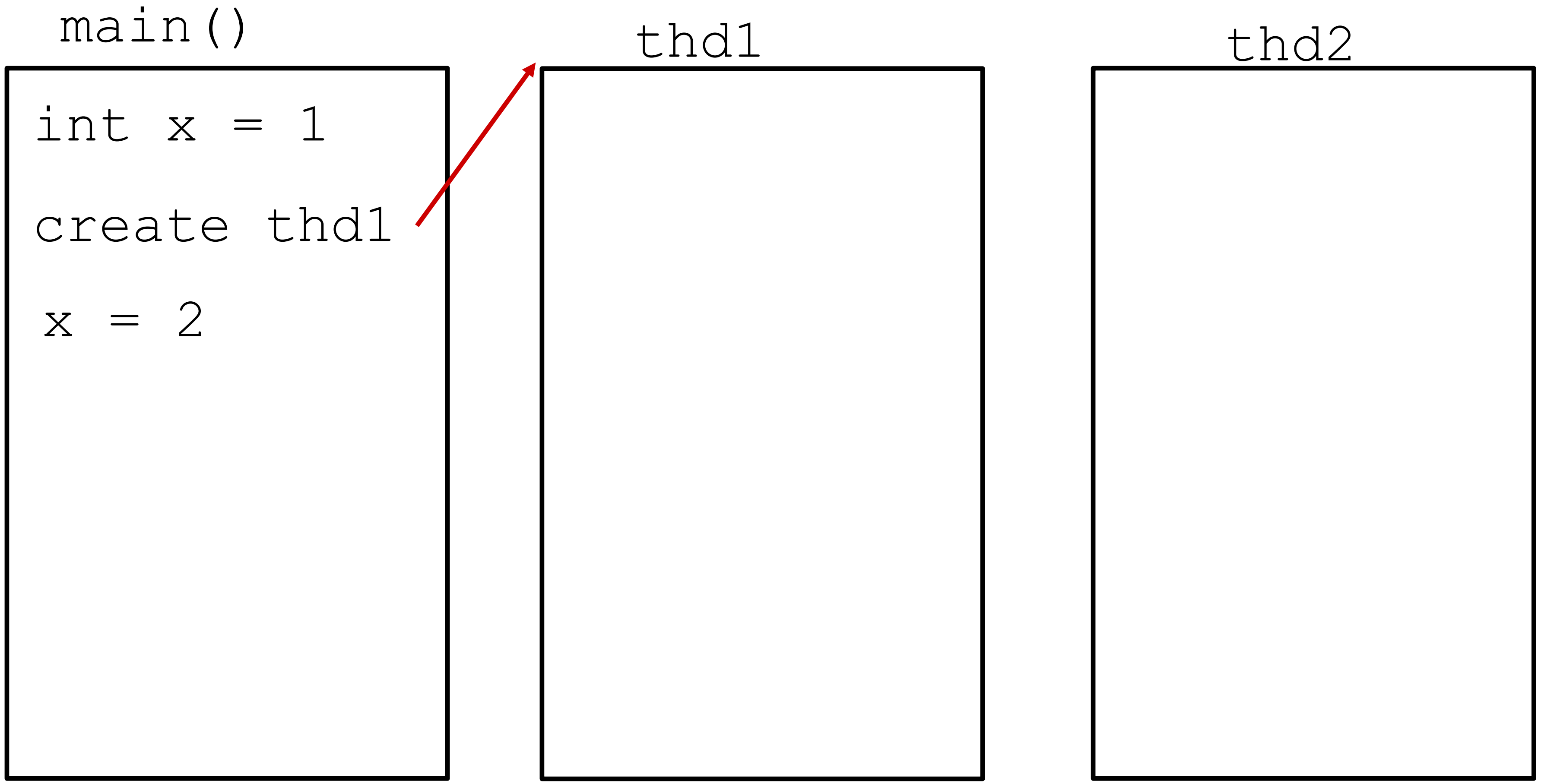
```
int x = 1

create thd1
```

thd1

thd2

Visualization: Ordering

- Threads run concurrently; we can't be sure of the ordering of things across threads.



main()

```
int x = 1

create thd1

x = 2
```

thd1

thd2

Visualization: Ordering

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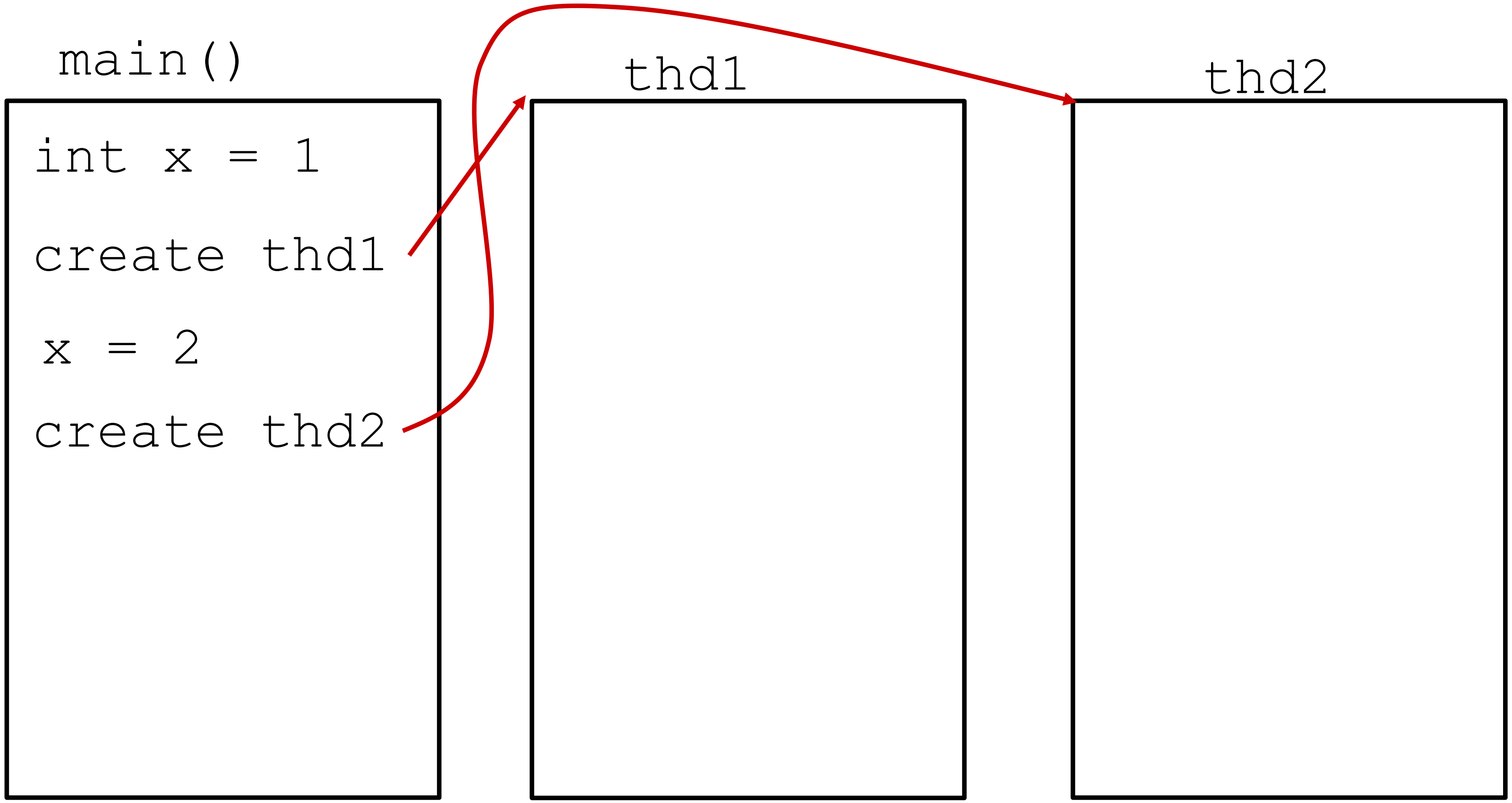

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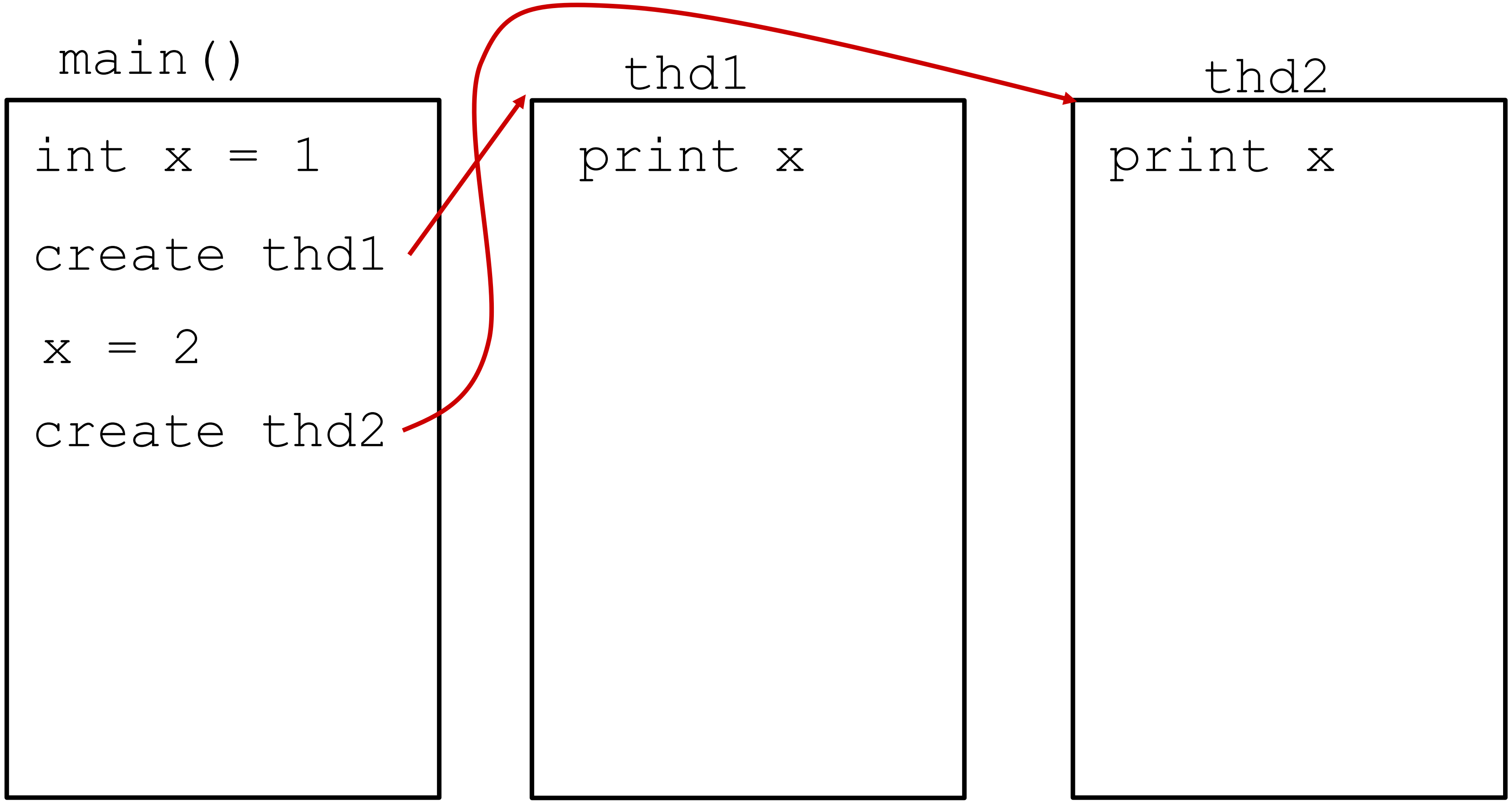
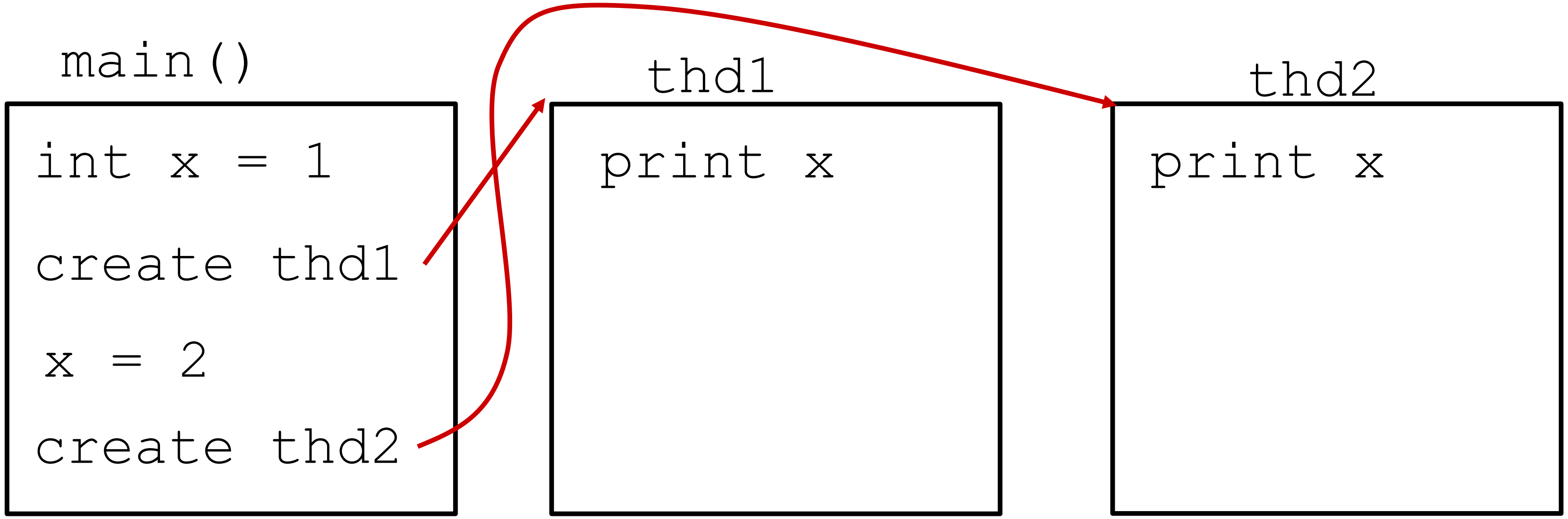


Visualization: Ordering

This is also why total.c malloc'd individual integers for each thread.
Though it could have also just made an array on the stack

- Threads run concurrently; we can't be sure of the ordering of things across threads.



main()

```
int x = 1
create thd1
x = 2
create thd2
```

thd1

```
print x
```

thd2

```
print x
```

We know that x is initialized to 1 before thd1 is created
We know that x is set to 2 and thd1 is created before thd2 is created

Anything else that we know? **No**. Beyond those statements, we do not know the ordering of main and the threads running.

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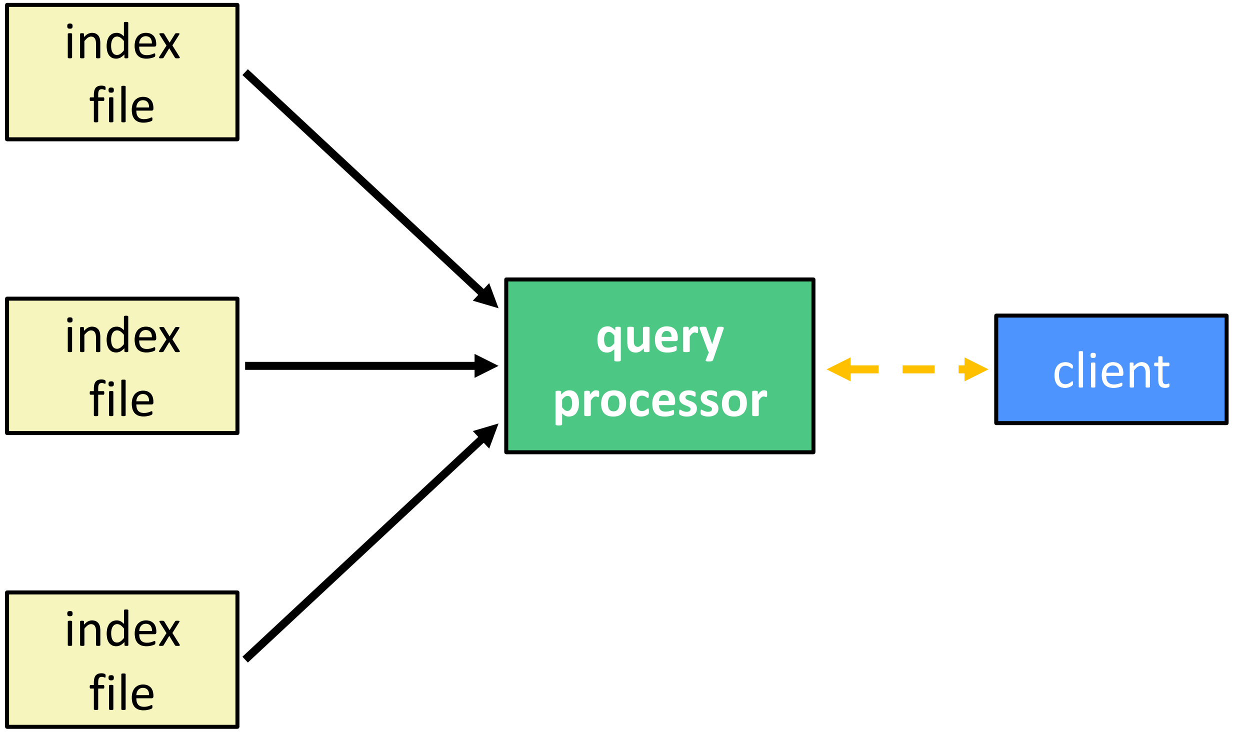
- **Benefits of Concurrency**

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

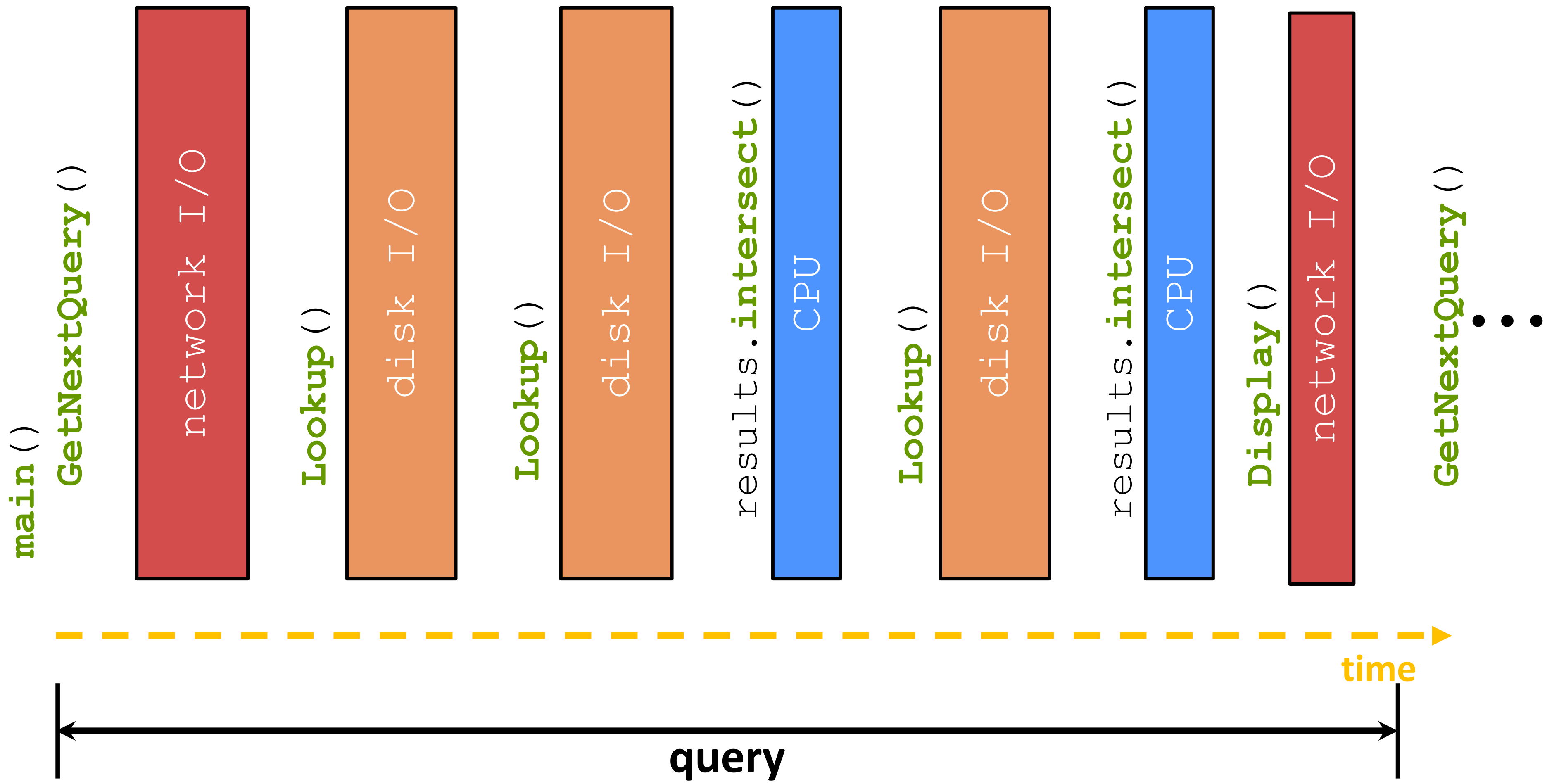
Search Engine Architecture



Search Engine (Pseudocode)

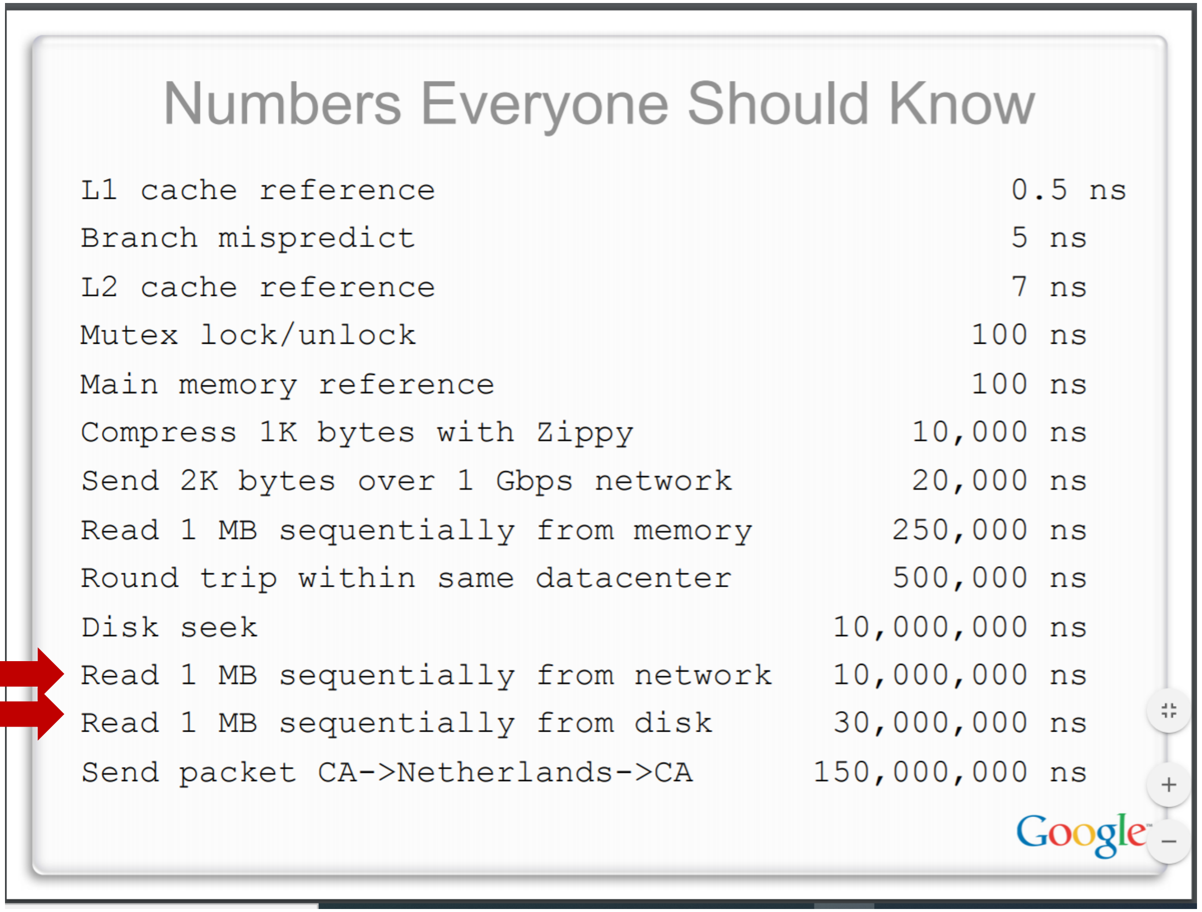
```
doclist Lookup(string word) {
  bucket = hash(word);
  hitlist = file.read(bucket);  ← Disk I/O
  foreach hit in hitlist {
    doclist.append(file.read(hit));
  }
  return doclist;
}

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)

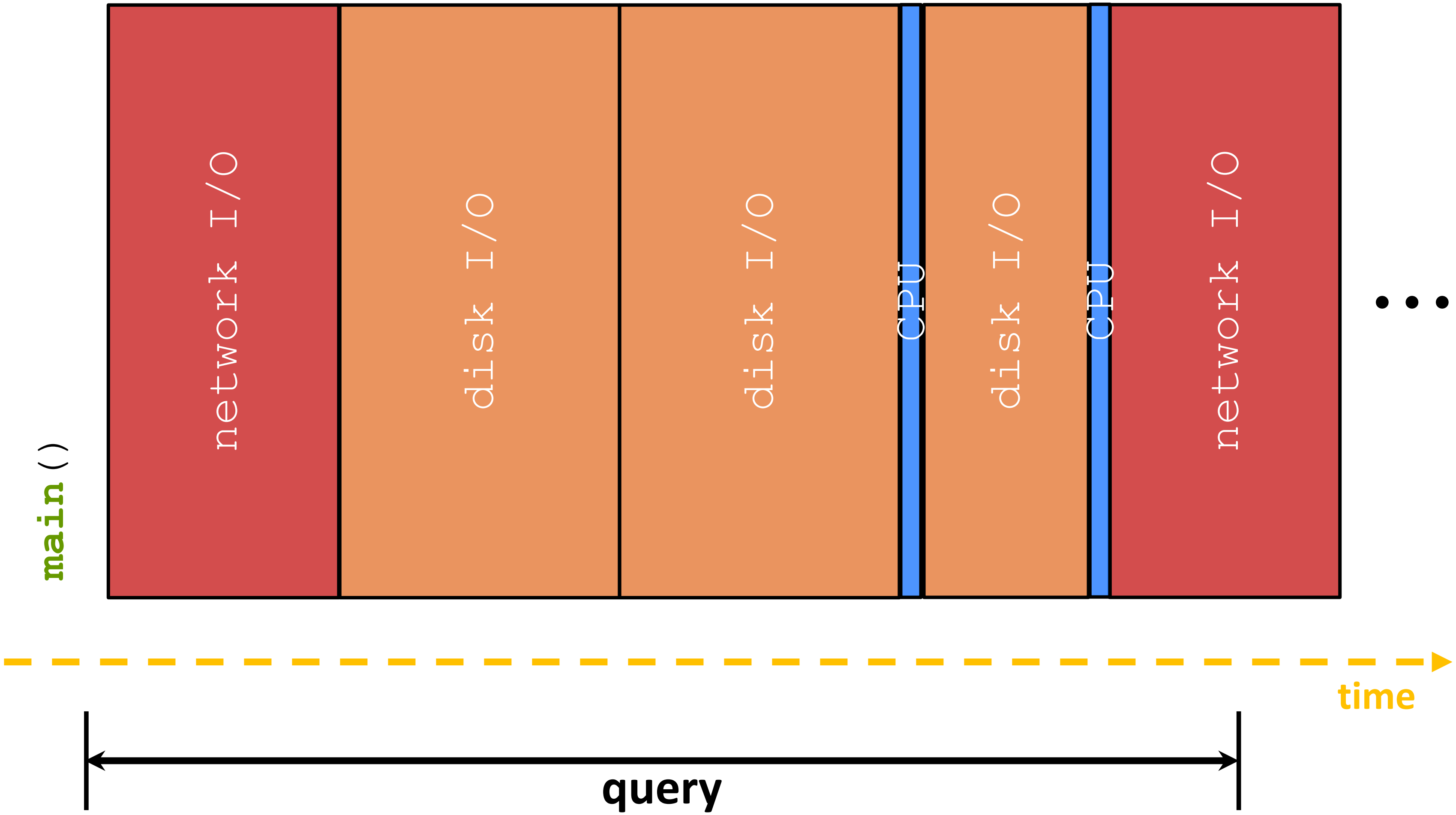


Numbers Everyone Should Know

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

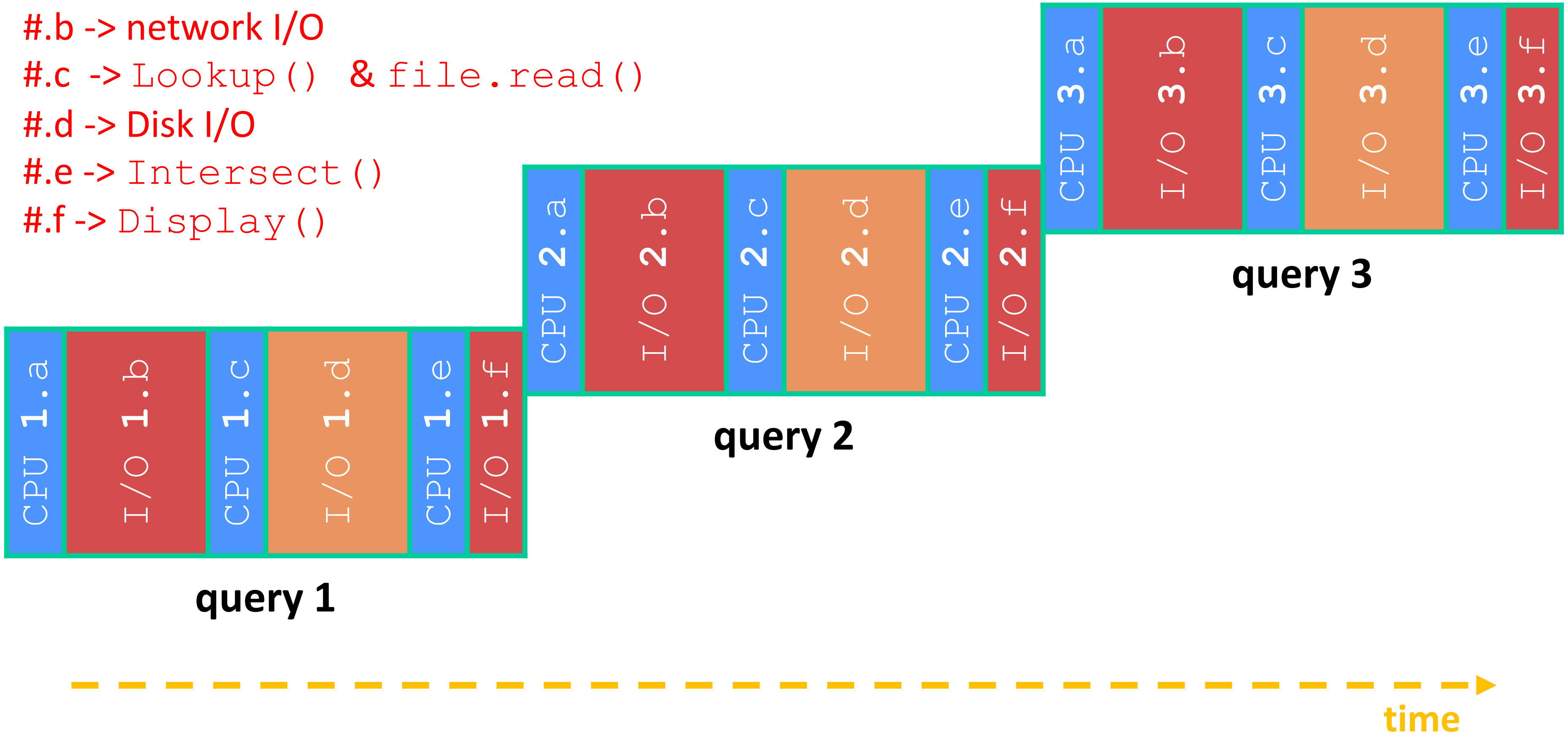
Execution Timeline: To Scale

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

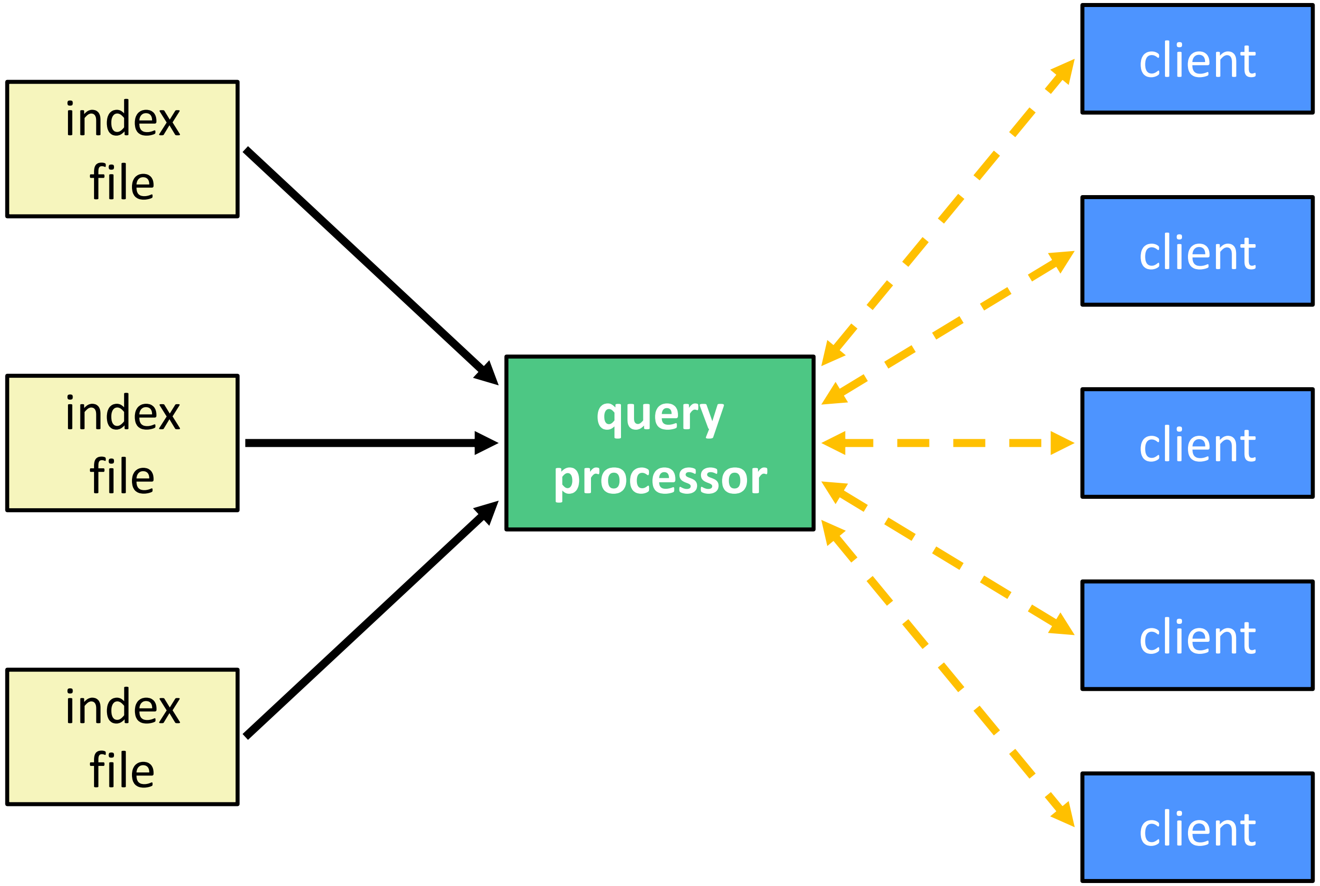


Multiple (Single-Word) Queries

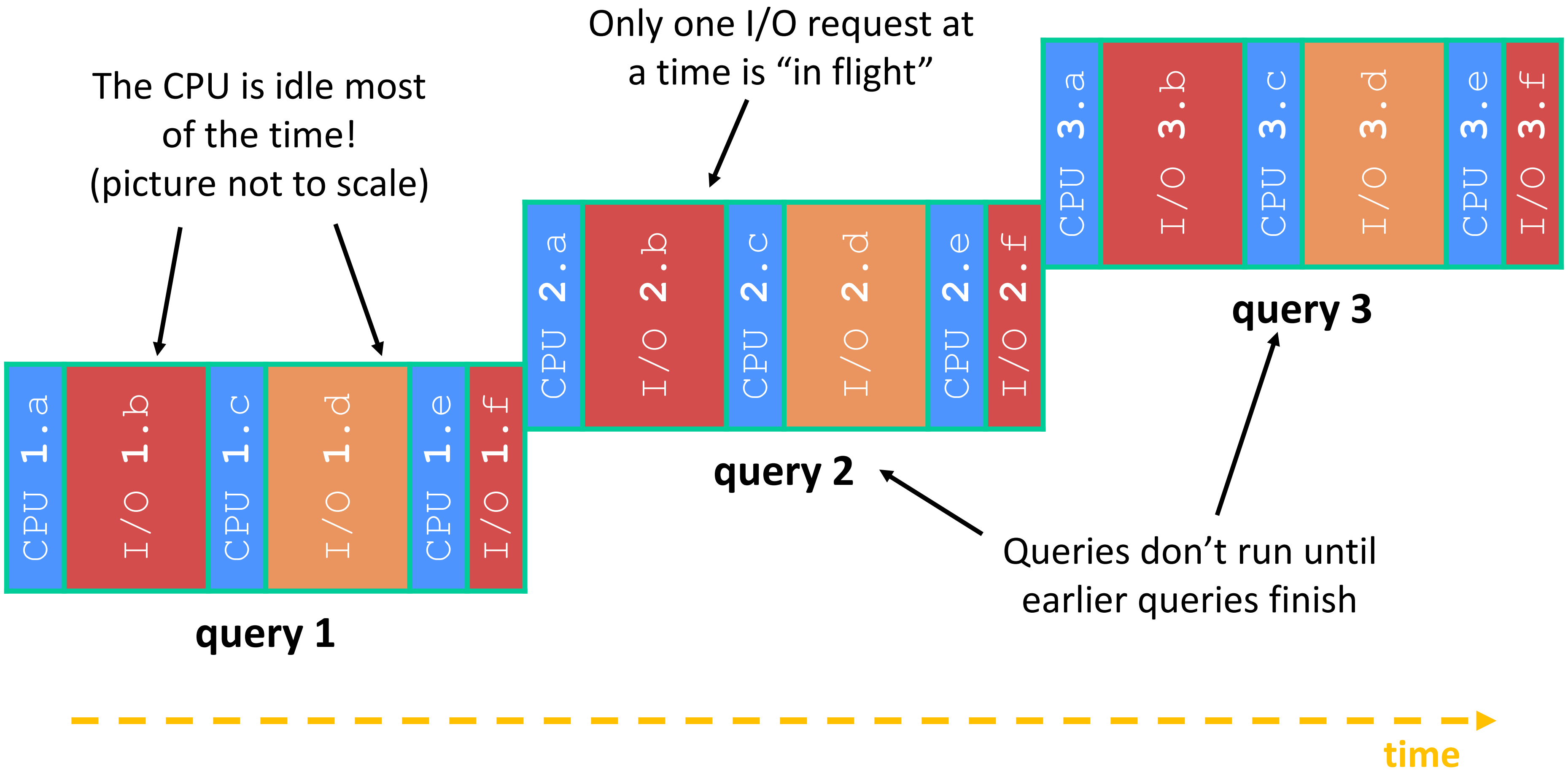
is the Query Number
#.a -> `GetNextQuery()`
#.b -> network I/O
#.c -> `Lookup()` & `file.read()`
#.d -> Disk I/O
#.e -> `Intersect()`
#.f -> `Display()`



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"

Queries don't run until earlier queries finish

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 …)

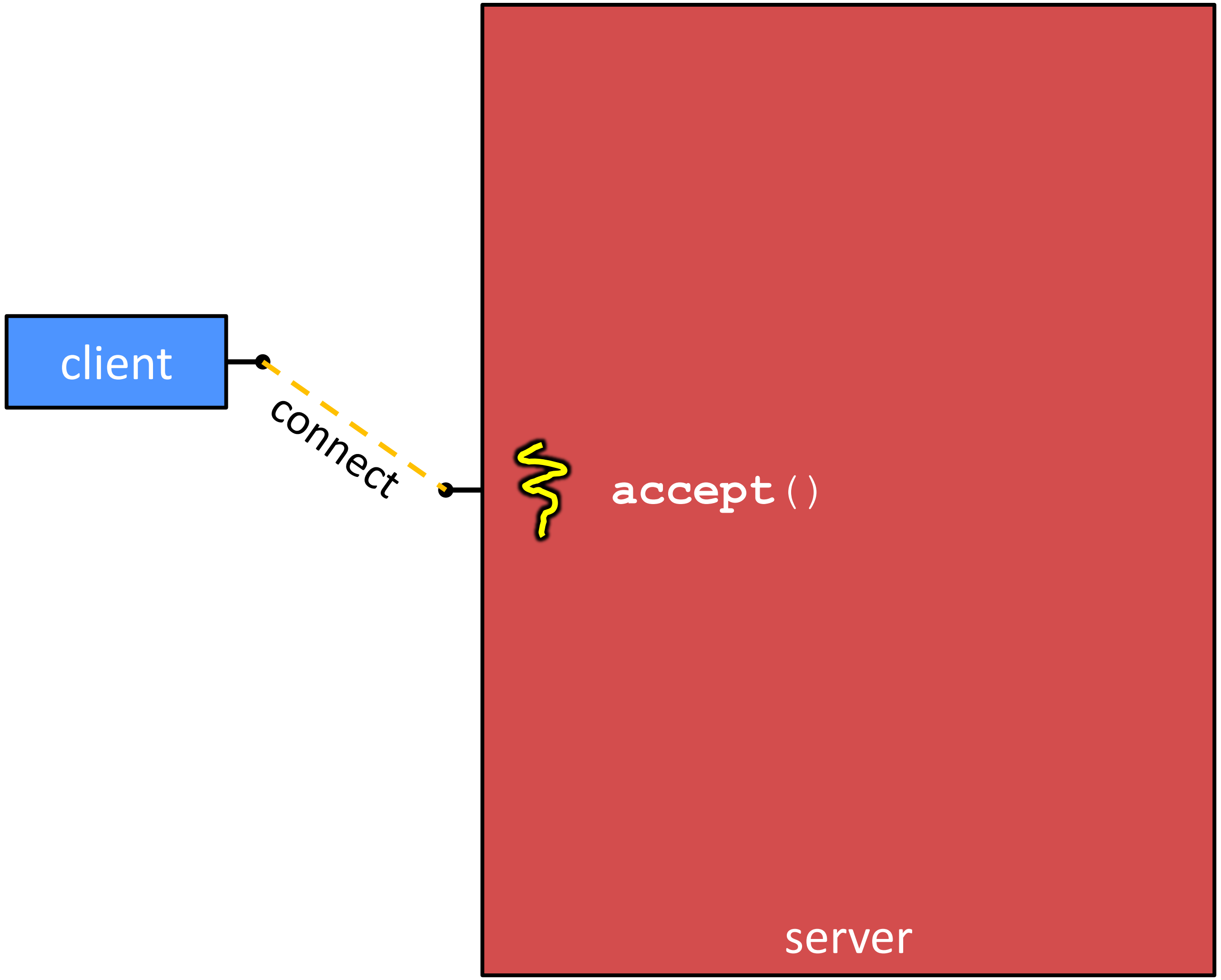
- At most one I/O operation is in flight at a time
  - Missed opportunities to speed I/O up
    - Separate devices in parallel, better scheduling of a single device, etc.

A Concurrent Implementation

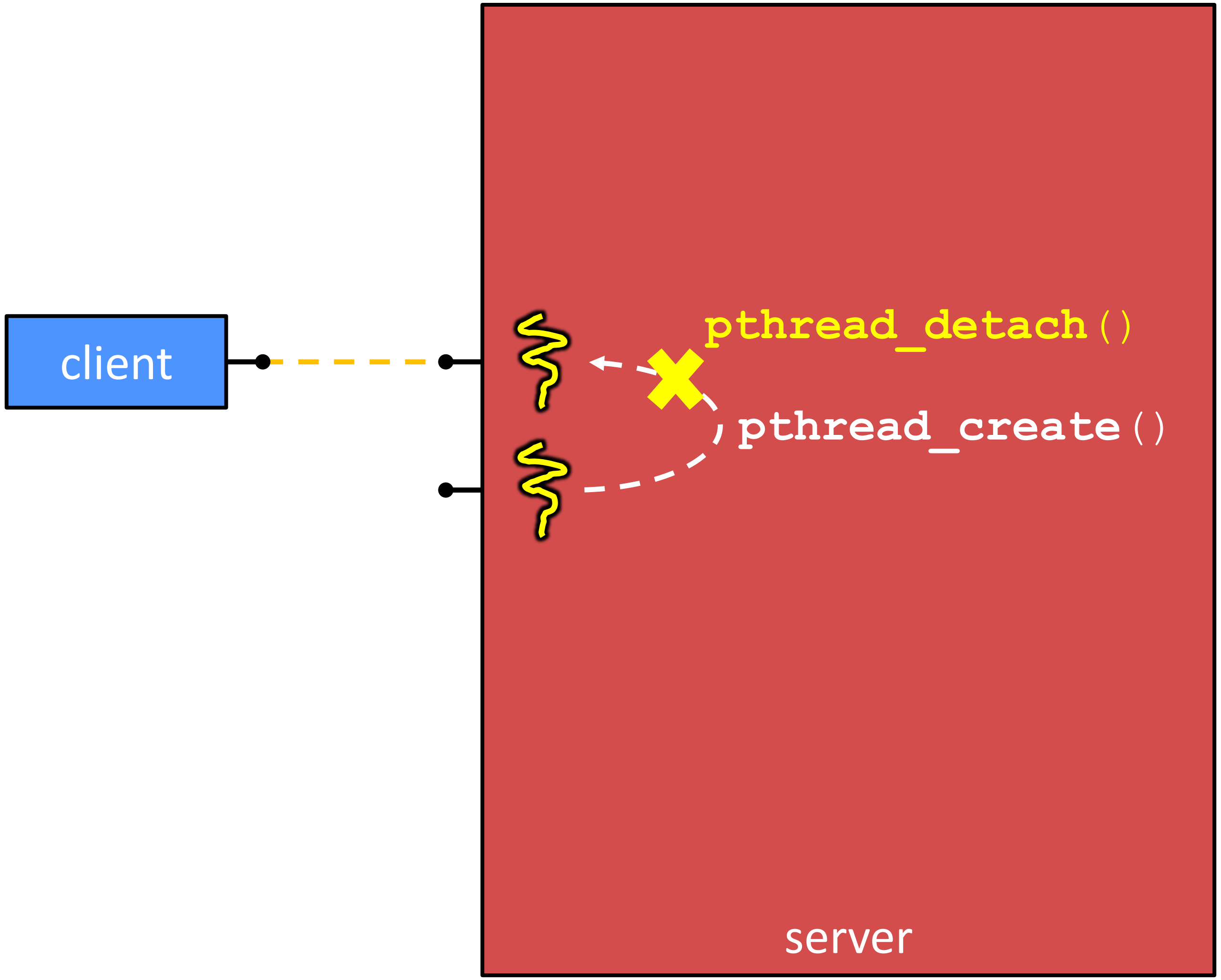
- Use multiple "workers"
  - As a query arrives, create a new "worker" to handle it
    - The "worker" reads the query from the network, issues read requests against files, assembles results and writes to the network
    - The "worker" uses blocking I/O; the "worker" alternates between consuming CPU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

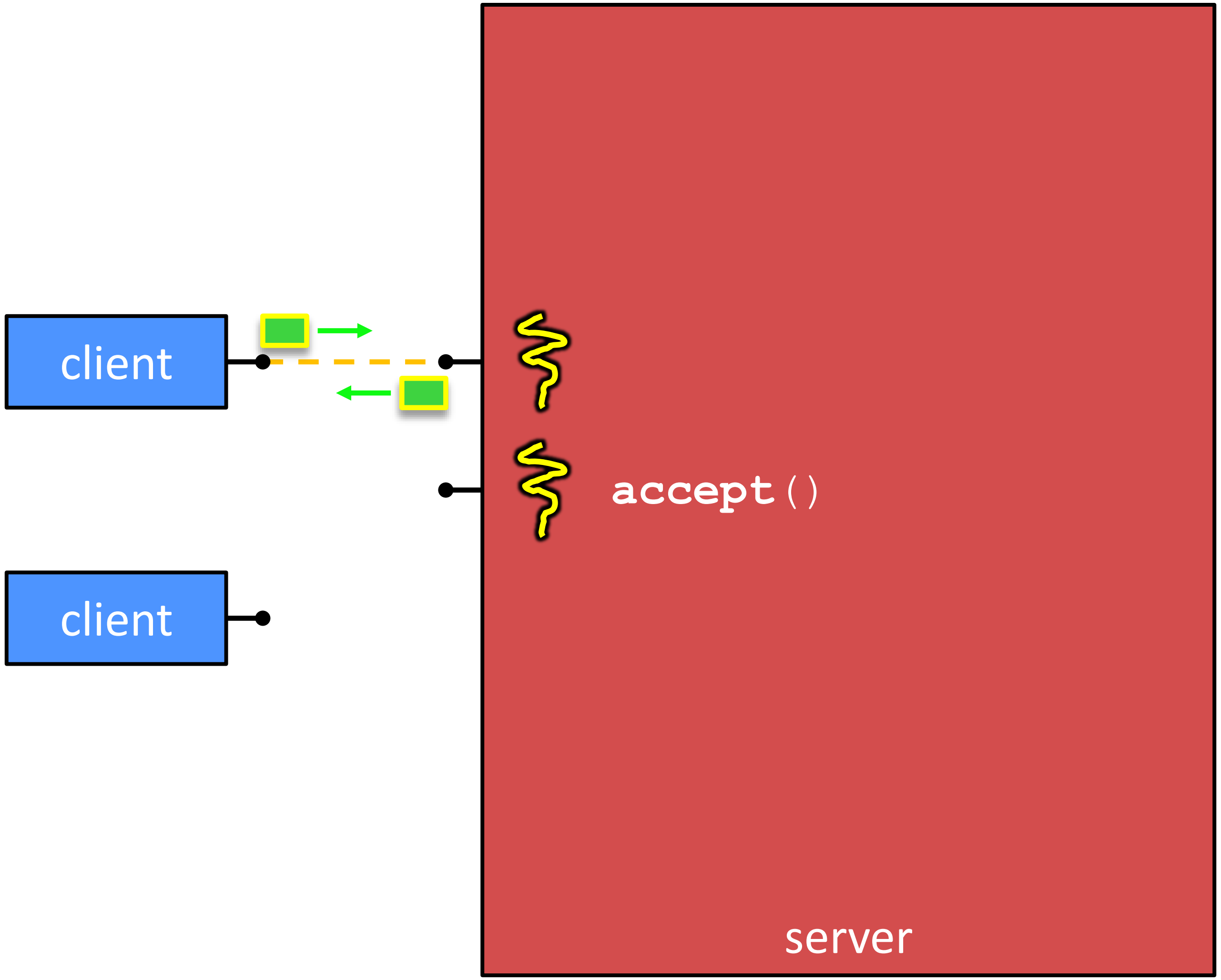
Multithreaded Server



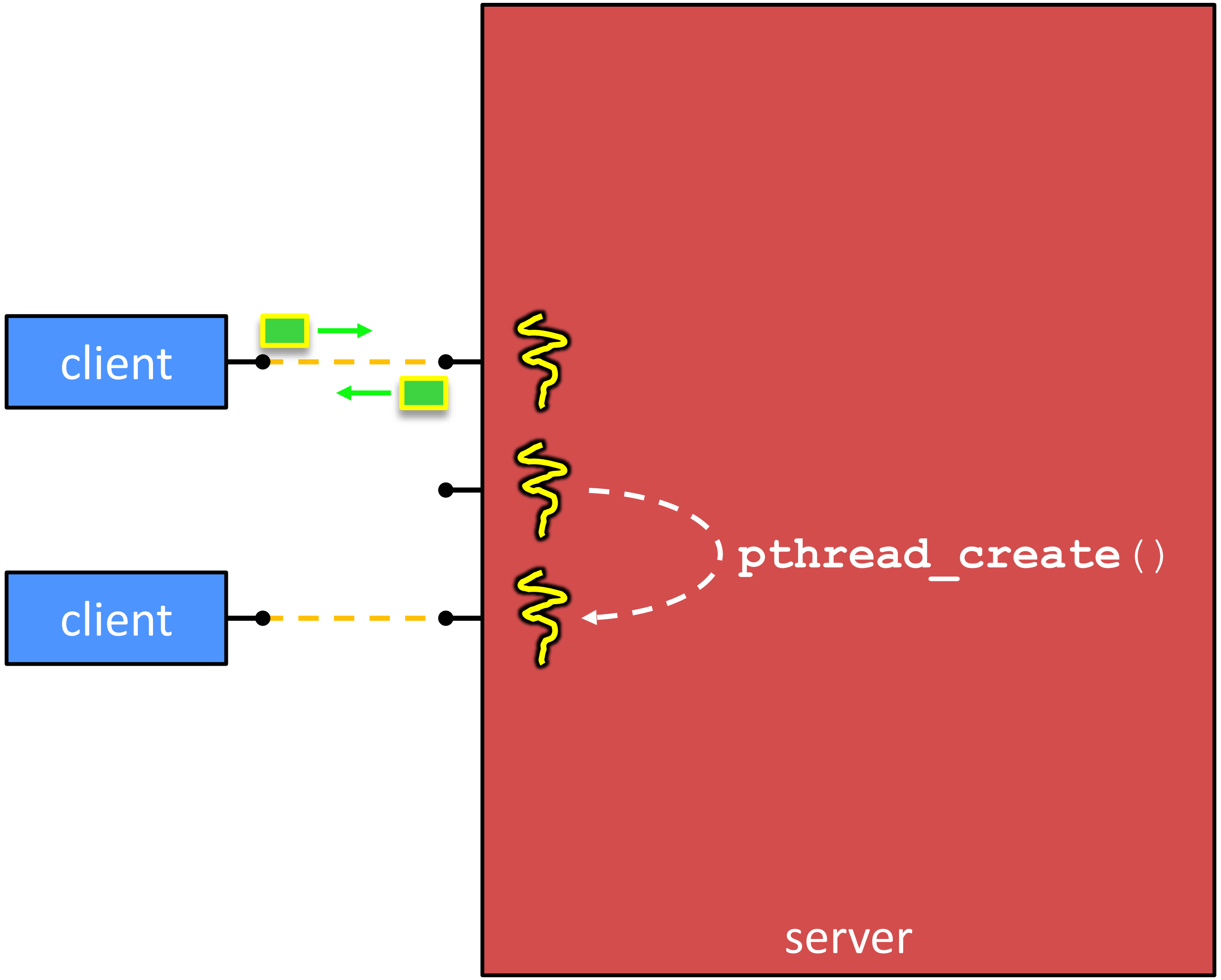
Multithreaded Server



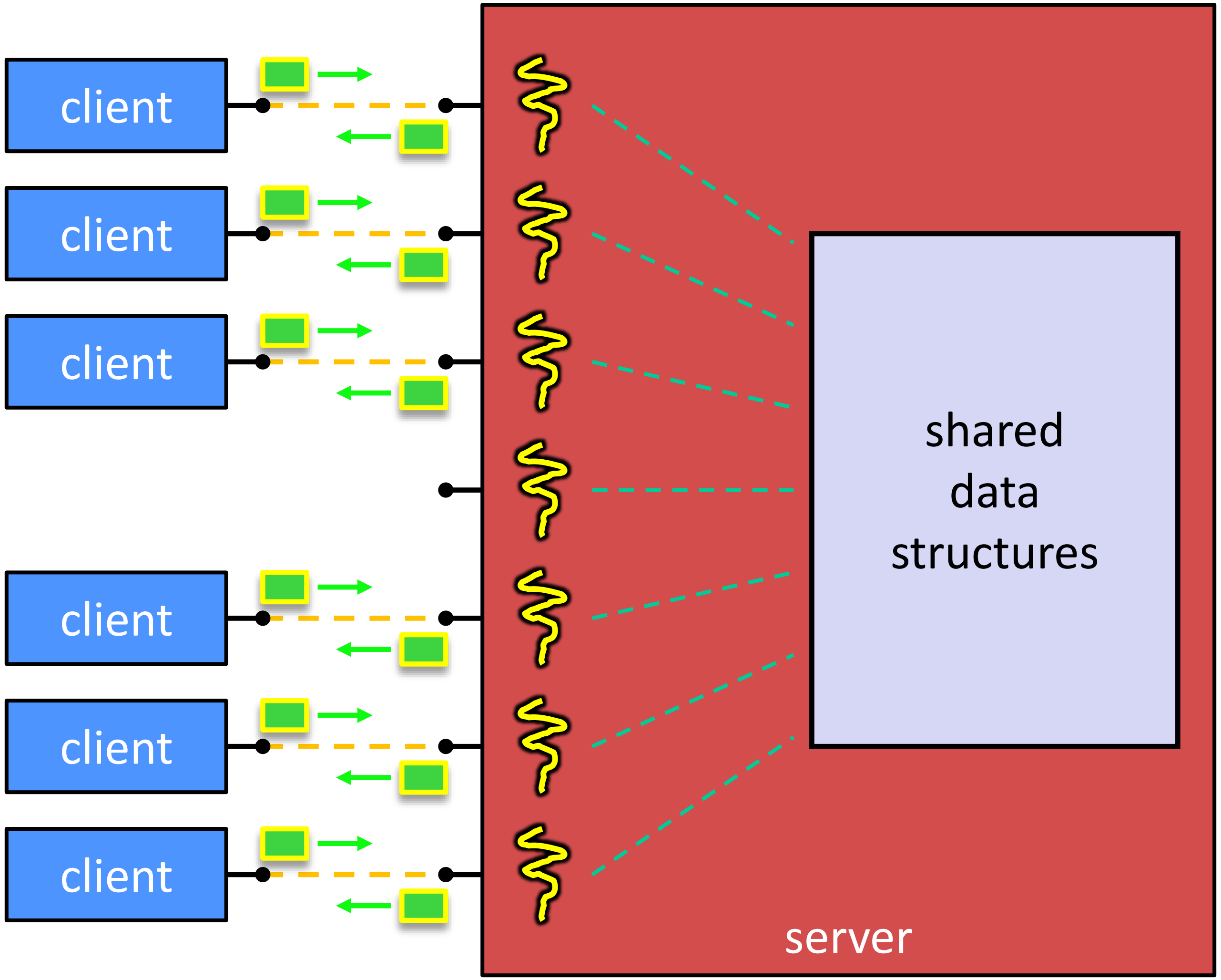
Multithreaded Server



Multithreaded Server

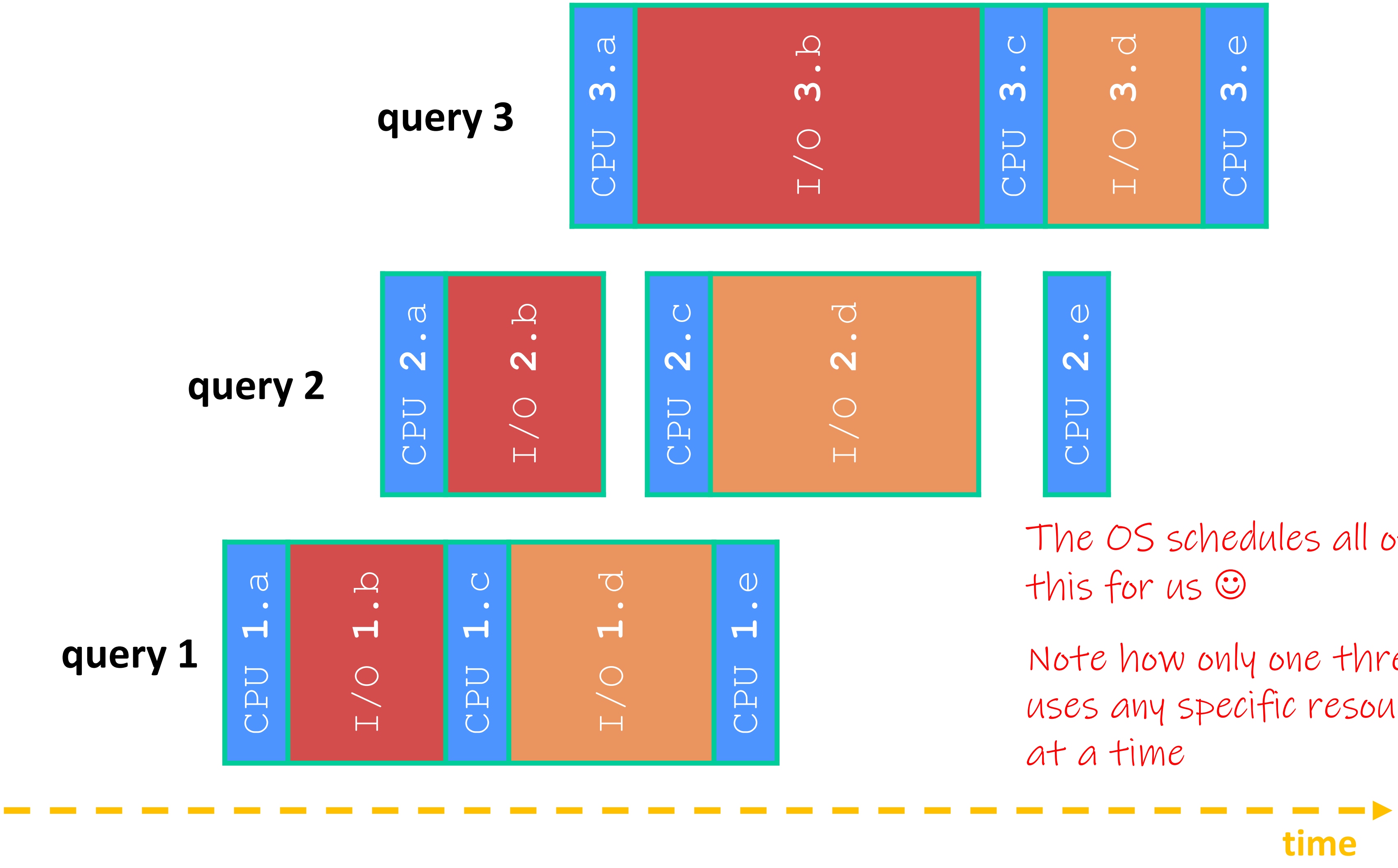


Multithreaded Server



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

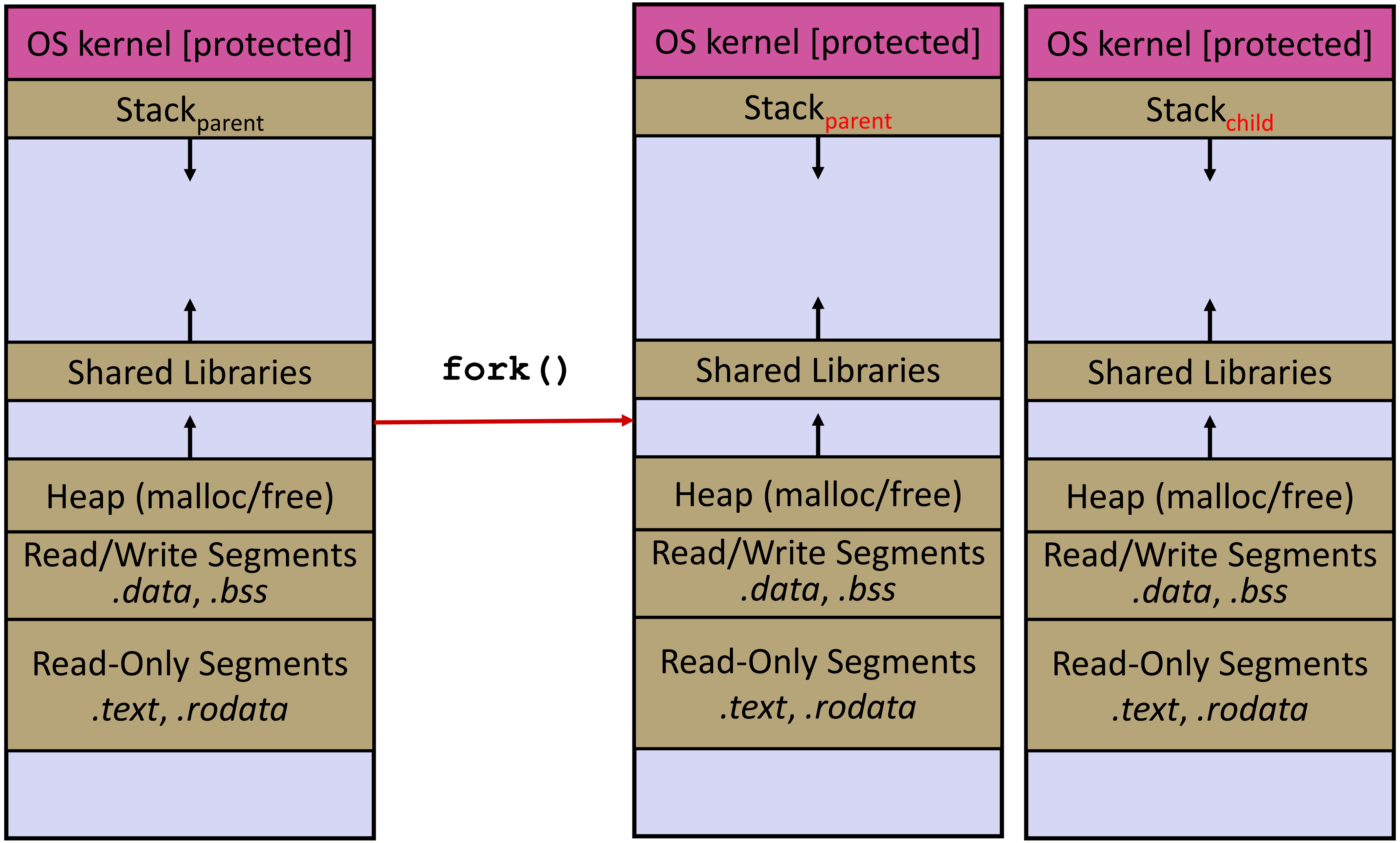
Why Threads?

- 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

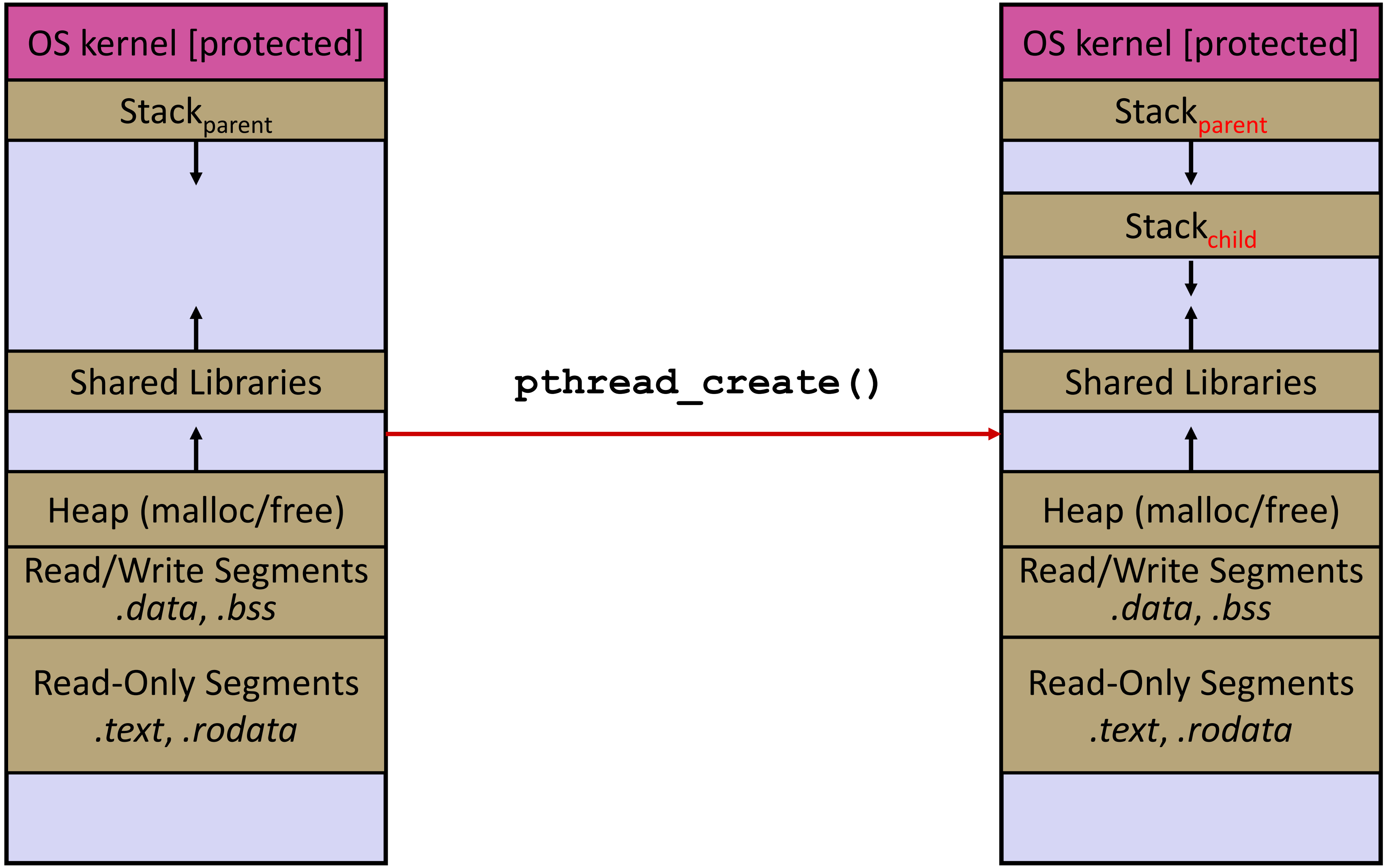
Threads vs. Processes

- 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



Alternative: Processes

- What if we forked processes instead of threads?

- Advantages:
  - No shared memory between processes
  - No need for language support; OS provides "fork"
  - Processes are isolated. If one crashes, other processes keep going

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

That’s all!

- See you next time!