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About how long did Exercise 11 take you?

A. [0, 2) hours
B. [2, 4) hours
C. [4, 6) hours
D. [6, 8) hours
E. 8+ Hours
F. I didn’t submit / I prefer not to say

Concurrency: Threads

CSE 333 Spring 2023

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Relevant Course Information

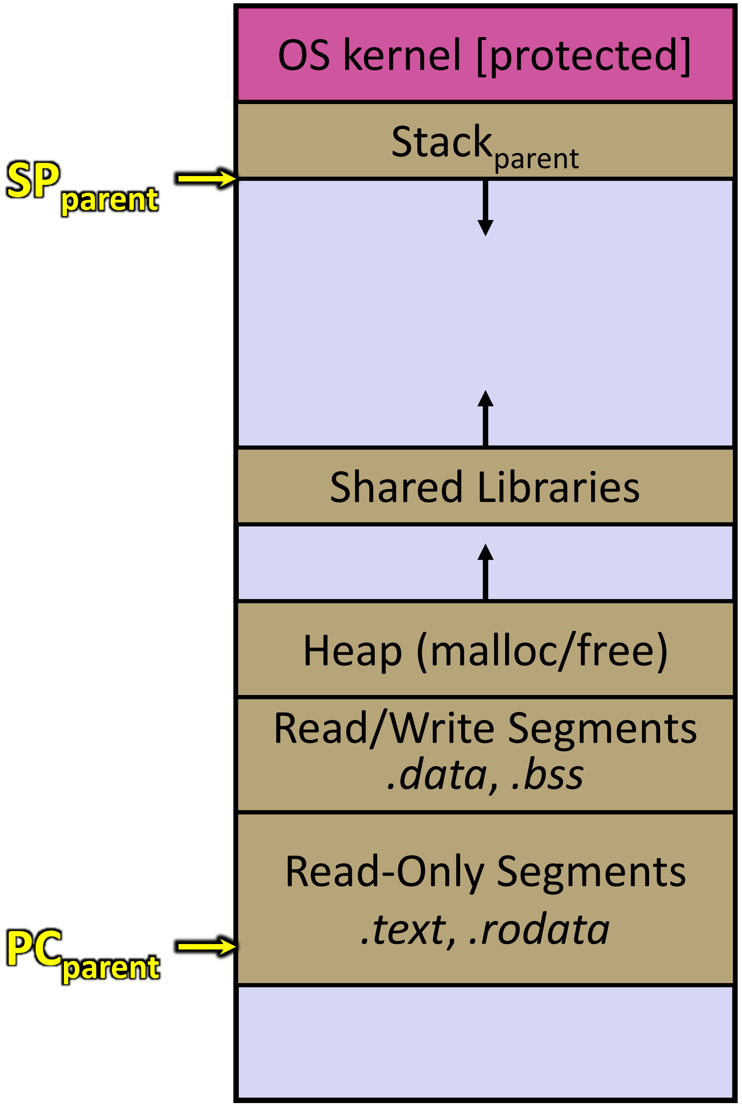
- No lecture on Monday (Memorial Day)
- Exercise 12 due next Wednesday (5/31)
- Homework 4 due next Thursday (6/1)
  - Submissions accepted until Sunday (6/4)
- Next lecture: Concurrency via multiprocessing
- Last lecture: *Writing highly performant C++*

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

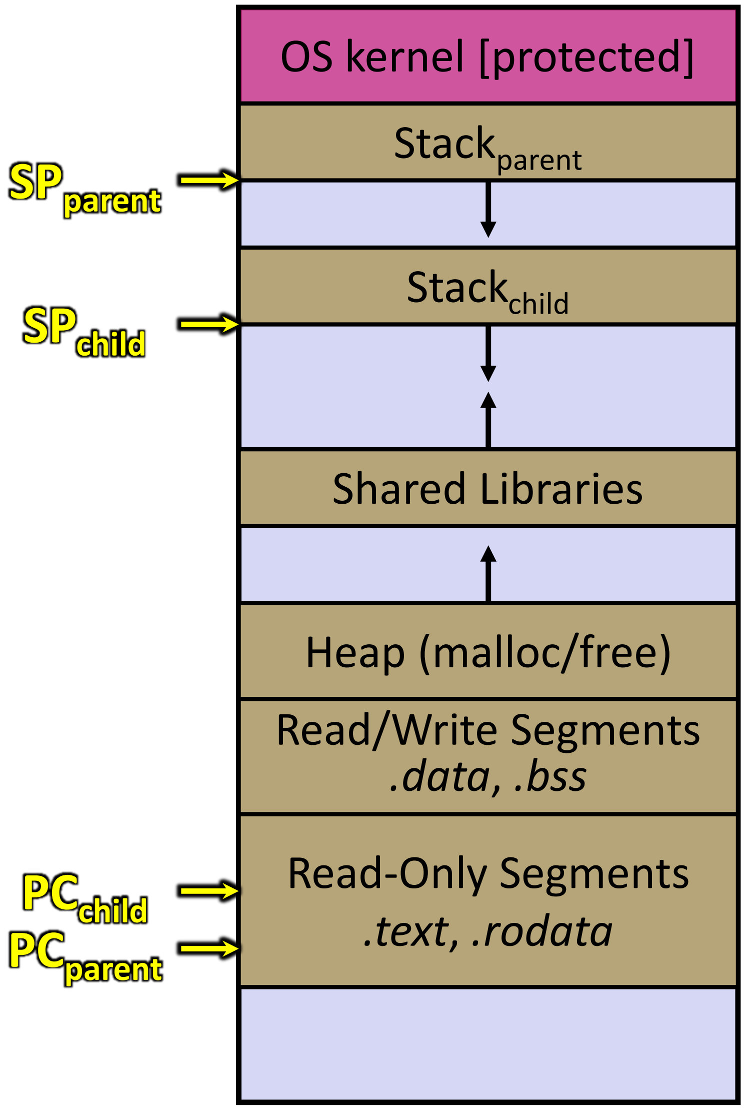
- Analogy: restaurant kitchen
  - Kitchen is process
  - Chefs are threads

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

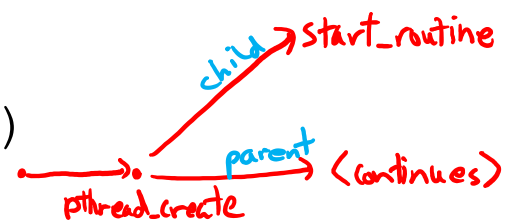
POSIX Threads (pthreads)

- The POSIX APIs for dealing with threads
  - Declared in `pthread.h`
    - Not part of the C/C++ language (*cf.*, Java)
  - To enable support for multithreading, must include `-pthread` flag when compiling and linking with `gcc` command
    - `gcc -g -Wall -std=c17 -pthread -o main main.c`

Creating and Terminating Threads

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




```
void pthread_exit(void* retval);
```

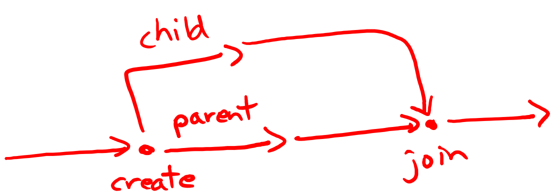
- Equivalent of **`exit`**`(retval);` for a thread instead of a process
- The thread will automatically exit once it returns from **`start_routine`**`()`

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`

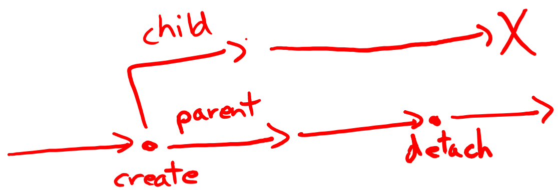
parent waits for child to finish and then receives its return value and cleans up



❖
```
int pthread_detach(pthread_t thread);
```

- Mark thread specified by `thread` as detached – it will clean up its resources as soon as it terminates

detach child from parent
↳ child cleans up after it finishes

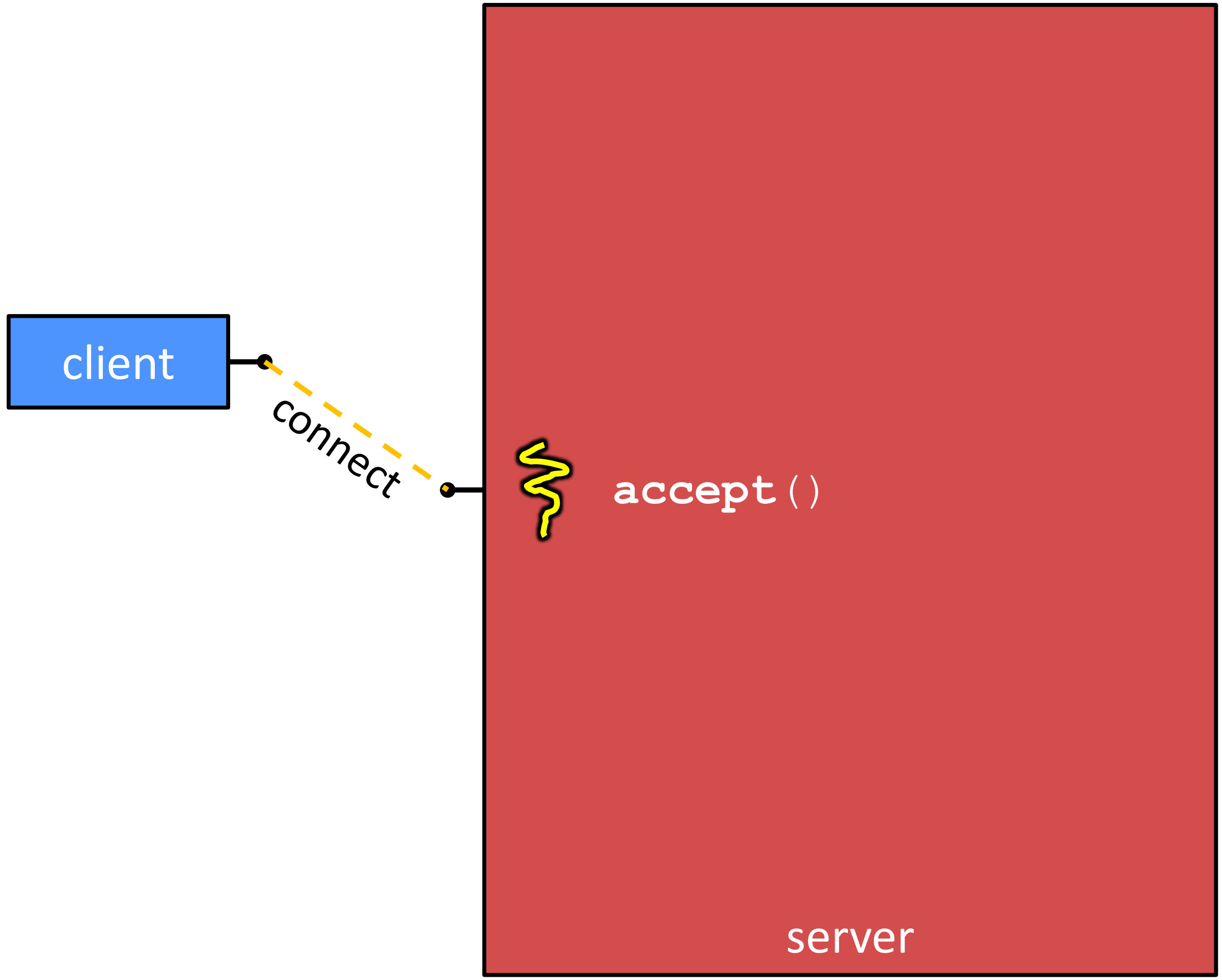


Concurrent Server with Threads

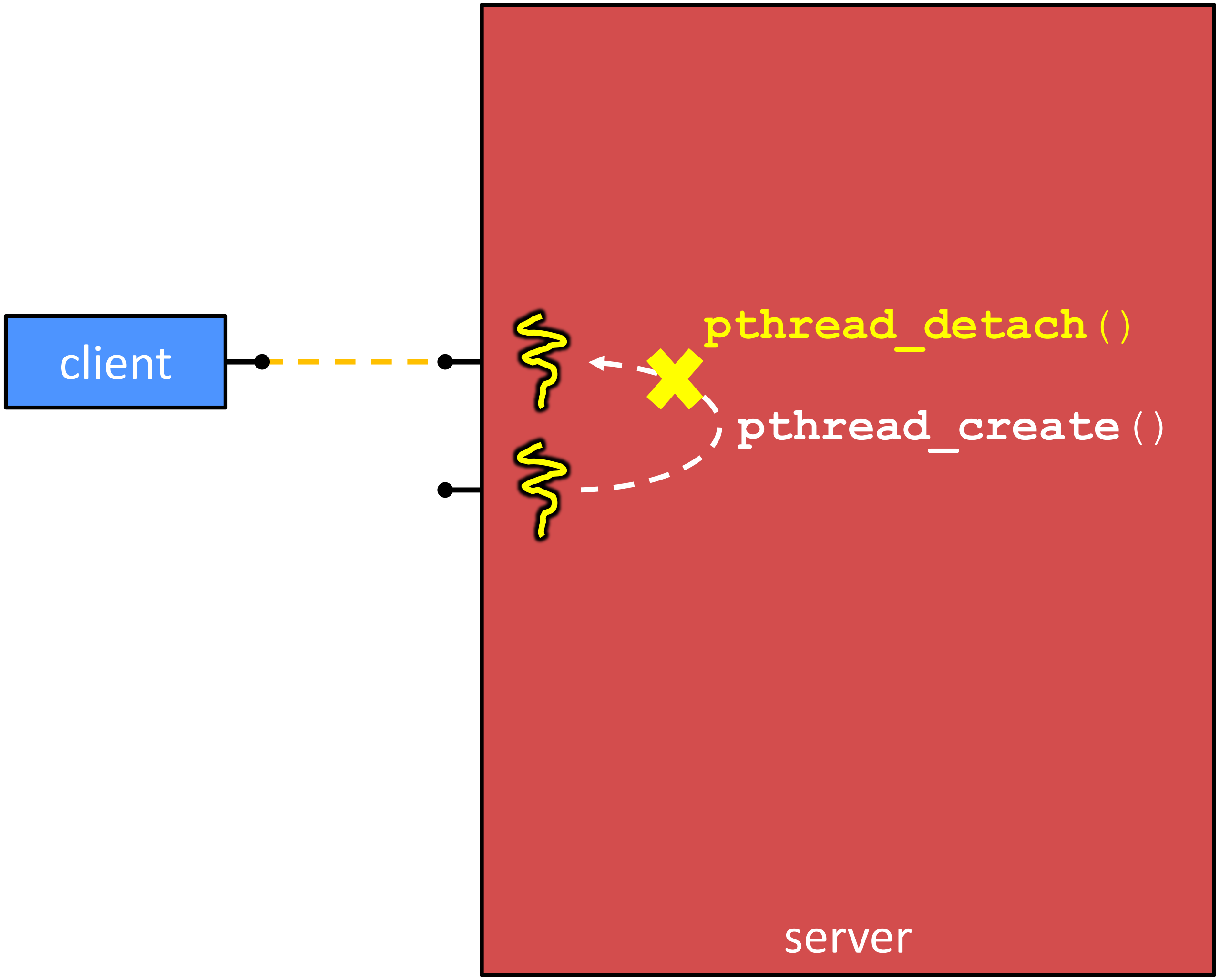
- A single *process* handles all of the connections, but a parent *thread* dispatches (creates) a new thread to handle each connection
  - The child thread handles the new connection and then exits when the connection terminates

- See `searchserver_threads/` for code if curious

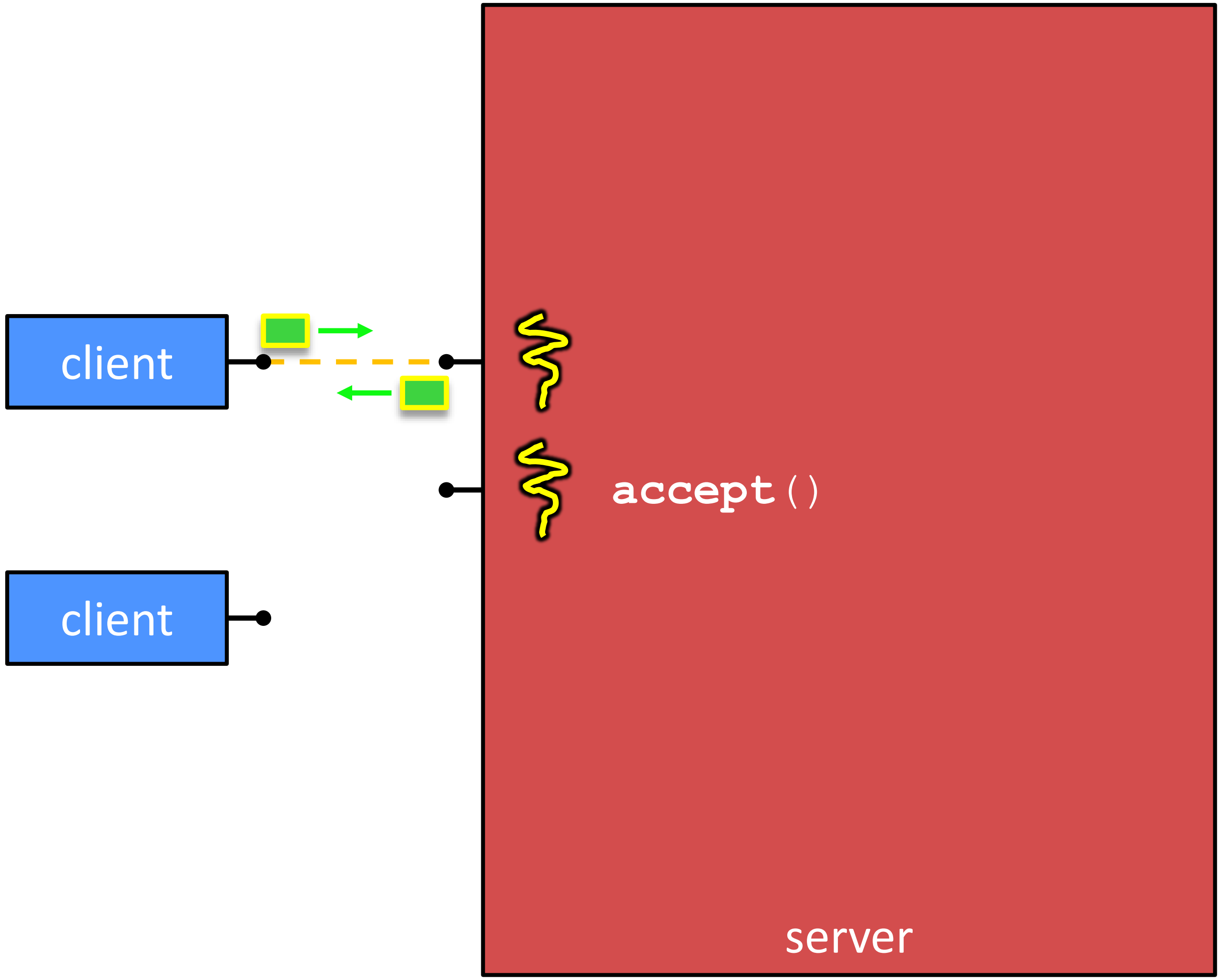
Multithreaded Server



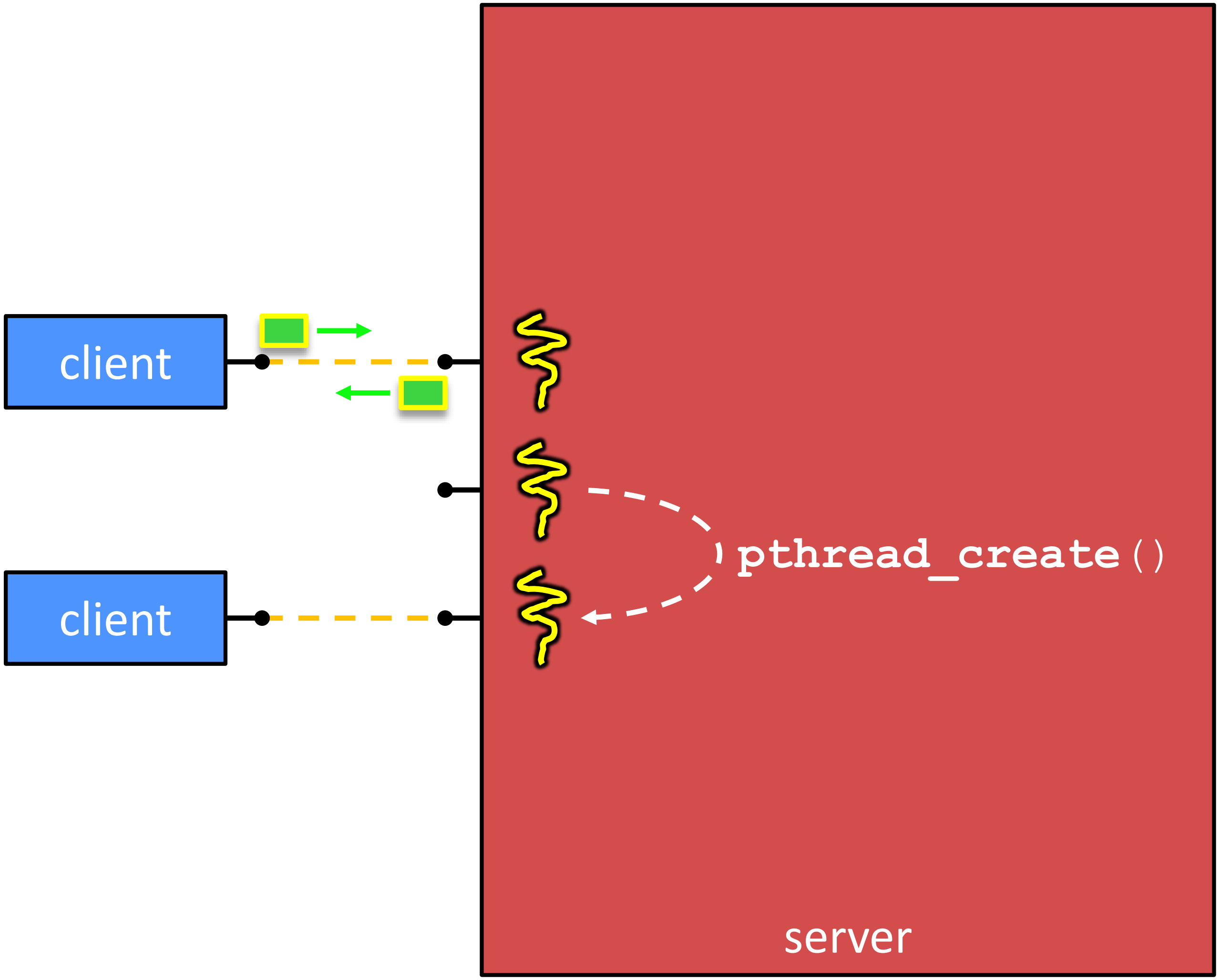
Multithreaded Server



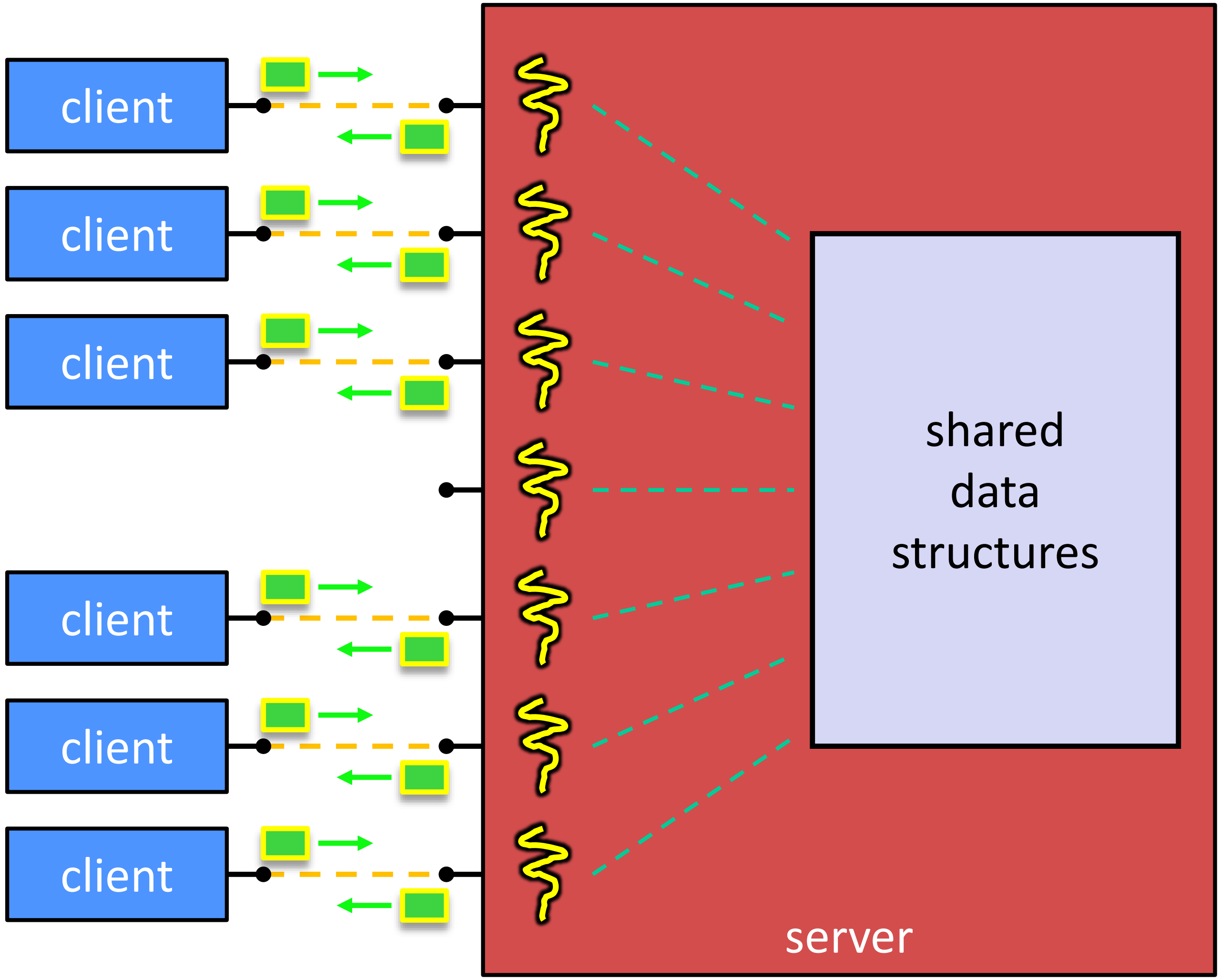
Multithreaded Server



Multithreaded Server



Multithreaded Server



Thread Examples

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

- See `pthreads.cc`
  - More instructions per thread = higher likelihood of interleaving

- See `searchserver_threads/searchserver.cc`
  - When calling **`pthread_create`**`()`, `start_routine` points to a function that takes only one argument (a `void*`)
    - To pass complex arguments into the thread, create a struct to bundle the necessary data

Why Concurrent Threads? (Review)

- Advantages:
  - Almost as simple to code as sequential
    - In fact, most of the code is identical! (but a bit more complicated to dispatch a thread)
  - Concurrent execution with good CPU and network utilization
    - Some overhead, but less than processes
  - Shared-memory communication is possible

- Disadvantages:
  - Synchronization is complicated
  - Shared fate within a process
    - One “rogue” thread can hurt you badly

Data Races

- Two memory accesses form a data race if different threads access the same location, and at least one is a write, and they occur one after another
  - Means that the result of a program can vary depending on chance (which thread ran first?)

Data Race Example

- If your fridge has no milk, then go out and buy some more
  - What could go wrong?

```
if (!milk) {

  buy milk

}
```

- If you live alone:

- If you live with a roommate:

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Does leaving a note on the fridge fix our milk data race problem?

```
if (!note) {
  if (!milk) {
    leave note
    buy milk
    remove note
  }
}
```

only check at beginning

A. Yes, problem fixed

B. No, could end up with no milk

C. No, could still buy multiple milk

D. We're lost…

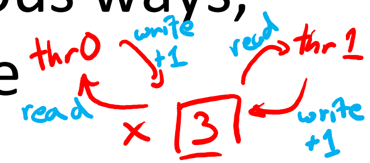
one possible scenario:

You	Roomate
check note check milk	
	check note check milk
leave note	
	leave note buy milk
buy milk	
⋮	⋮

time ↓

Threads and Data Races

- Data races might interfere in painful, non-obvious ways, depending on the specifics of the data structure



- Example: two threads try to read from and write to the same shared memory location
  - Could get "correct" answer   R0, W0, R1, W1 → 5 (3 4 4 5)
  - Could accidentally read old or intermediate (*i.e.*, invalid) value   R0, R1, W0, W1 → 4 (3 3 4 4)
  - One thread's work could get "lost"   R0, R1, W1, W0 → 4 (3 doesn't matter 4)
- Example: two threads try to push an item onto the head of the linked list at the same time
  - Could get "correct" answer
  - Could get different ordering of items
  - Could break the data structure! ☠

Synchronization

- Synchronization is the act of preventing two (or more) concurrently running threads from interfering with each other when operating on shared data
  - Need some mechanism to coordinate the threads
    - "Let me go first, then you can go"
  - Many different coordination mechanisms have been invented (see CSE 451)

- Goals of synchronization:
  - Liveness – ability to execute in a timely manner (informally, "something good happens")
  - Safety – avoid unintended interactions with shared data structures (informally, "nothing bad happens")

Lock Synchronization

- Use a "Lock" to grant access to a *critical section* so that only one thread can operate there at a time
  - Executed in an uninterruptible (*i.e.*, atomic) manner

- Pseudocode:

```
// non-critical code

lock.acquire();      loop/idle if locked
// critical section
lock.release();

// non-critical code
```

- Lock Acquire
  - Wait until the lock is free, then take it

- Lock Release
  - Release the lock
  - If other threads are waiting, wake exactly one up to pass lock to

Milk Example – What is the Critical Section?

- What if we use a lock on the refrigerator?
  - Probably overkill – what if roommate wanted to get eggs?
- For performance reasons, only put what is necessary in the critical section
  - Only lock the milk
  - But lock *all* steps that must run uninterrupted (*i.e.*, must run as an atomic unit)

```
fridge.lock()
if (!milk) {
  buy milk
}
fridge.unlock()
```

↓

```
milk_lock.lock()
if (!milk) {
  buy milk
}
milk_lock.unlock()
```

pthreads and Locks

- Another term for a lock is a mutex ("mutual exclusion")
  - `pthread.h` defines datatype `pthread_mutex_t`

- ```
  int pthread_mutex_init(pthread_mutex_t* mutex,
                         const pthread_mutexattr_t* attr);
  ```
  - Initializes a mutex with specified attributes

- ```
  int pthread_mutex_lock(pthread_mutex_t* mutex);
  ```
  - Acquire the lock – blocks if already locked

- ```
  int pthread_mutex_unlock(pthread_mutex_t* mutex);
  ```
  - Releases the lock

- ```
  int pthread_mutex_destroy(pthread_mutex_t* mutex);
  ```
  - "Uninitializes" a mutex – clean up when done

pthread Mutex Examples

- See `total.cc`
  - Data race between threads
- See `total_locking.cc`
  - Adding a mutex fixes our data race
- How does this compare to sequential code?
  - Likely *slower* – only 1 thread can increment at a time, but have to deal with checking the lock and switching between threads
  - One possible fix: each thread increments a local variable and then adds its value (once!) to the shared variable at the end

Your Turn! (pthread mutex)

- Rewrite `thread_main` from `total_locking.cc`:
  - It need to be passed an `int*` with the *address* of `sum_total` and an `int` with the number of times to loop (in that order)
  - Increment a local sum variable `NUM` times, then add it to `sum_total`
  - Handle synchronization properly!

see total_locking_better.cc

C++11 Threads

- C++11 added threads and concurrency to its libraries
  - `<thread>` – thread objects
  - `<mutex>` – locks to handle critical sections
  - `<condition_variable>` – used to block objects until notified to resume
  - `<atomic>` – indivisible, atomic operations
  - `<future>` – asynchronous access to data
  - These might be built on top of `<pthread.h>`, but also might not be

- Definitely use in C++11 code if local conventions allow, but pthreads will be around for a long, long time
  - Use pthreads in current exercise