Concurrency: Threads

CSE 333 Summer 2023

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Relevant Course Information

- Exercise 12 released today, due Monday (8/14)
  - Concurrency via pthreads
- Homework 4 due next Wednesday (8/16)
  - Submissions accepted until Friday (8/18)
- Please fill out the course evaluations for lecture and your section next week!
- Quiz 4 (Wednesday, 8/16 – Friday, 8/18)
  - Same policies as previous quizzes
  - ex10-ex12, hw4, overall course questions!

Some Common HW4 Bugs

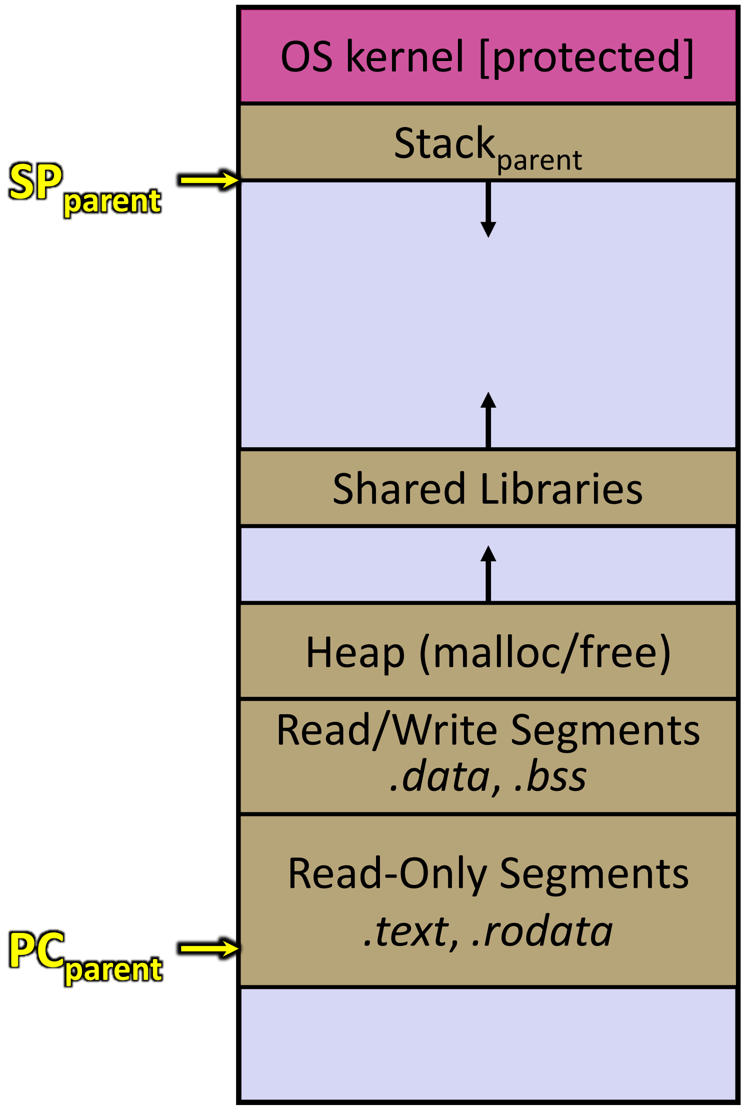
- Your server works, but is really, really slow
  - Check the 2nd argument to the `QueryProcessor` constructor
- Funny things happen after the first request
  - Make sure you're not destroying the `HTTPConnection` object too early (*e.g.*, falling out of scope in a while loop)
- Server crashes on a blank request
  - Make sure that you handle the case that **`read`**`()` (or **`WrappedRead`**`()`) returns `0`

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

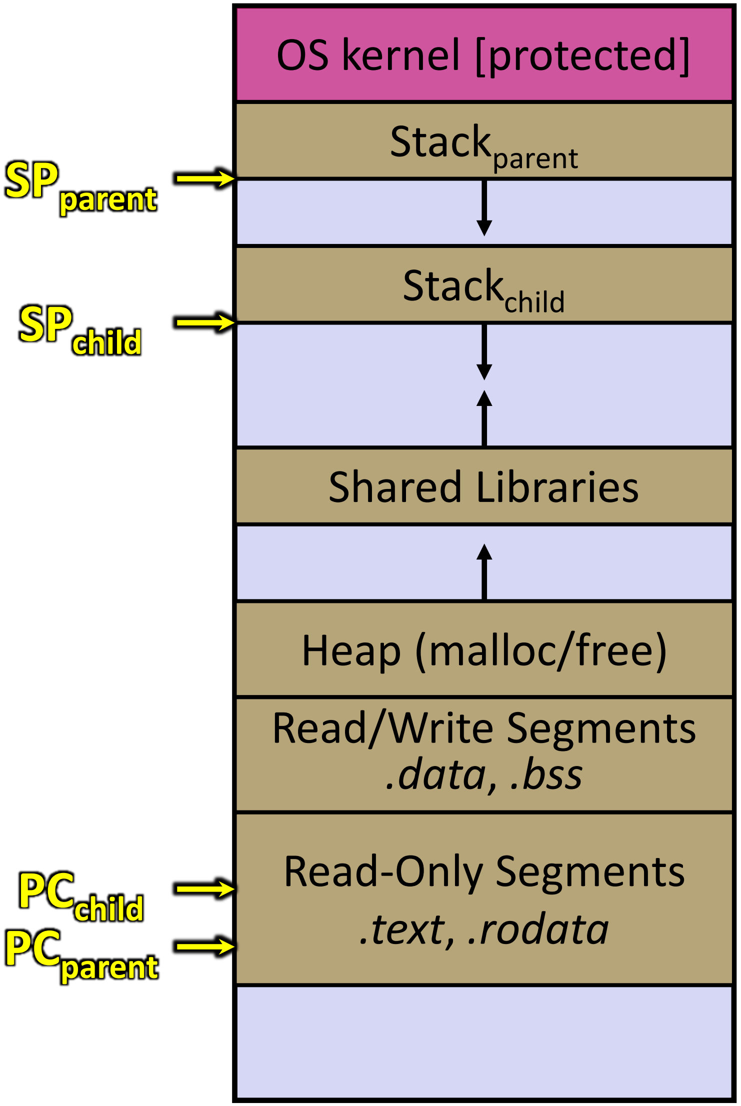
- Analogy: restaurant kitchen
  - Kitchen is process
  - Chefs are threads

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`

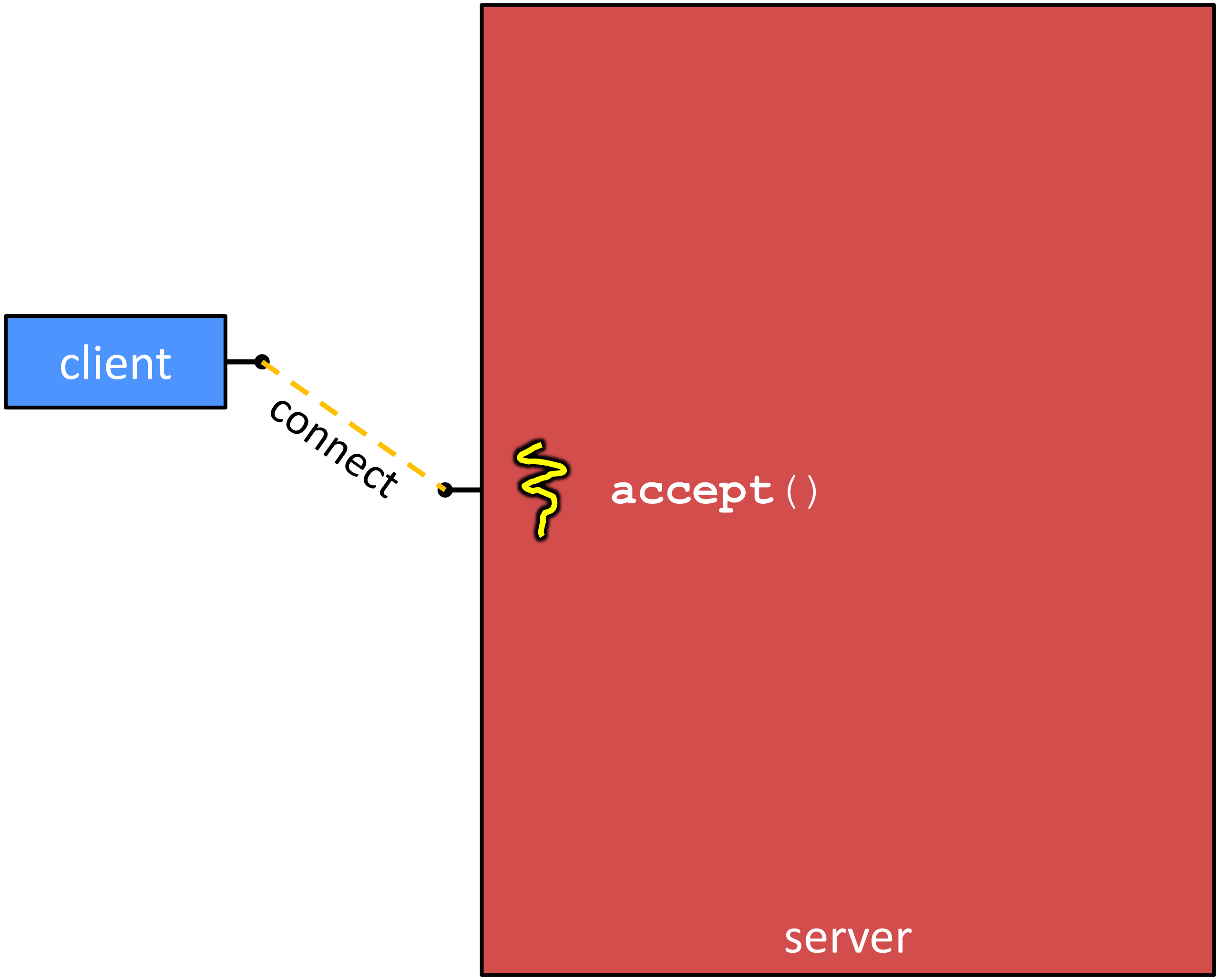
- `int pthread_detach(pthread_t thread);`
  - Mark thread specified by `thread` as detached – it will clean up its resources as soon as it terminates

Concurrent Server with Threads

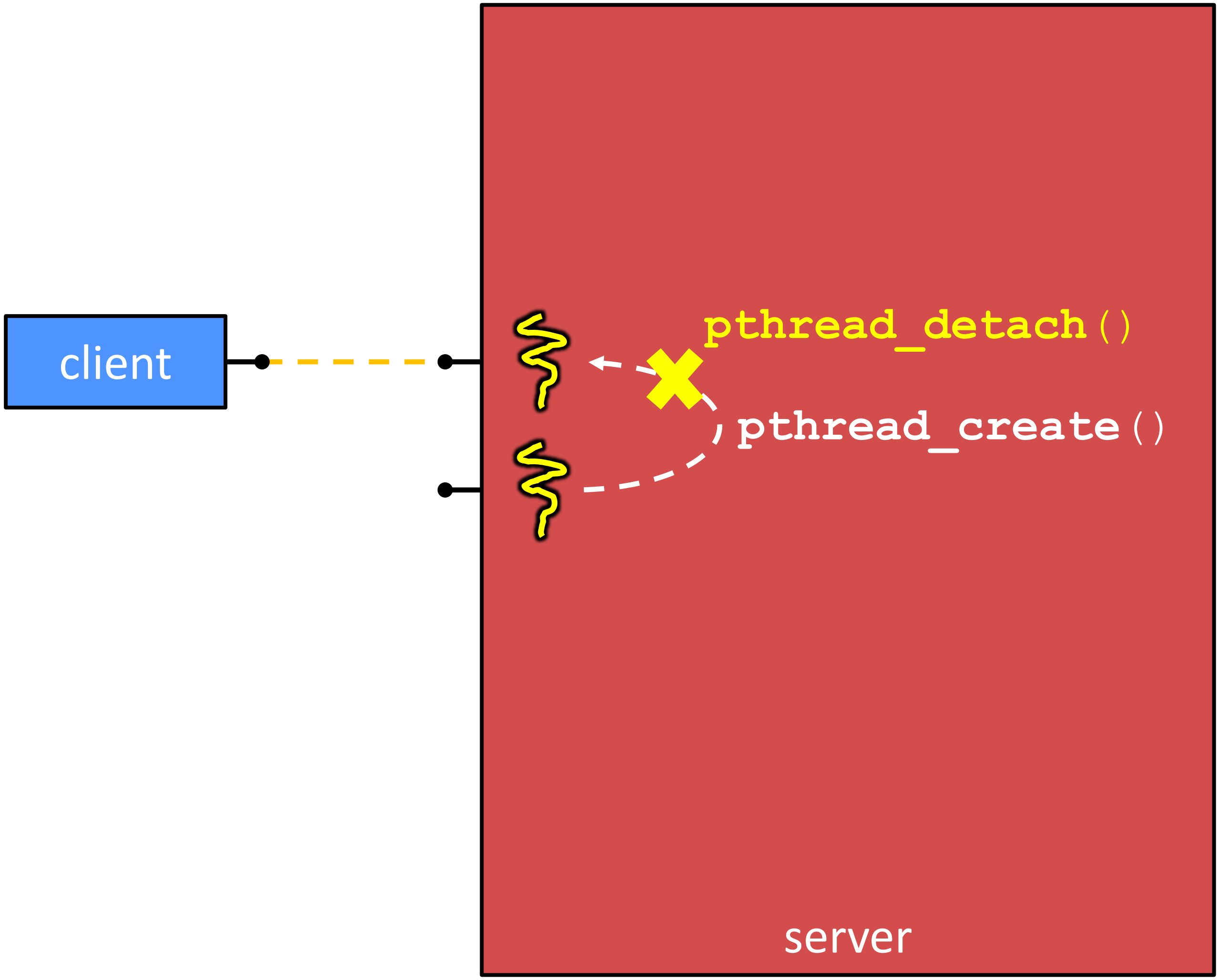
- A single *process* handles all of the connections, but a parent *thread* dispatches (creates) a new thread to handle each connection
  - The child thread handles the new connection and then exits when the connection terminates

- See `searchserver_threads/`

Multithreaded Server



Multithreaded Server



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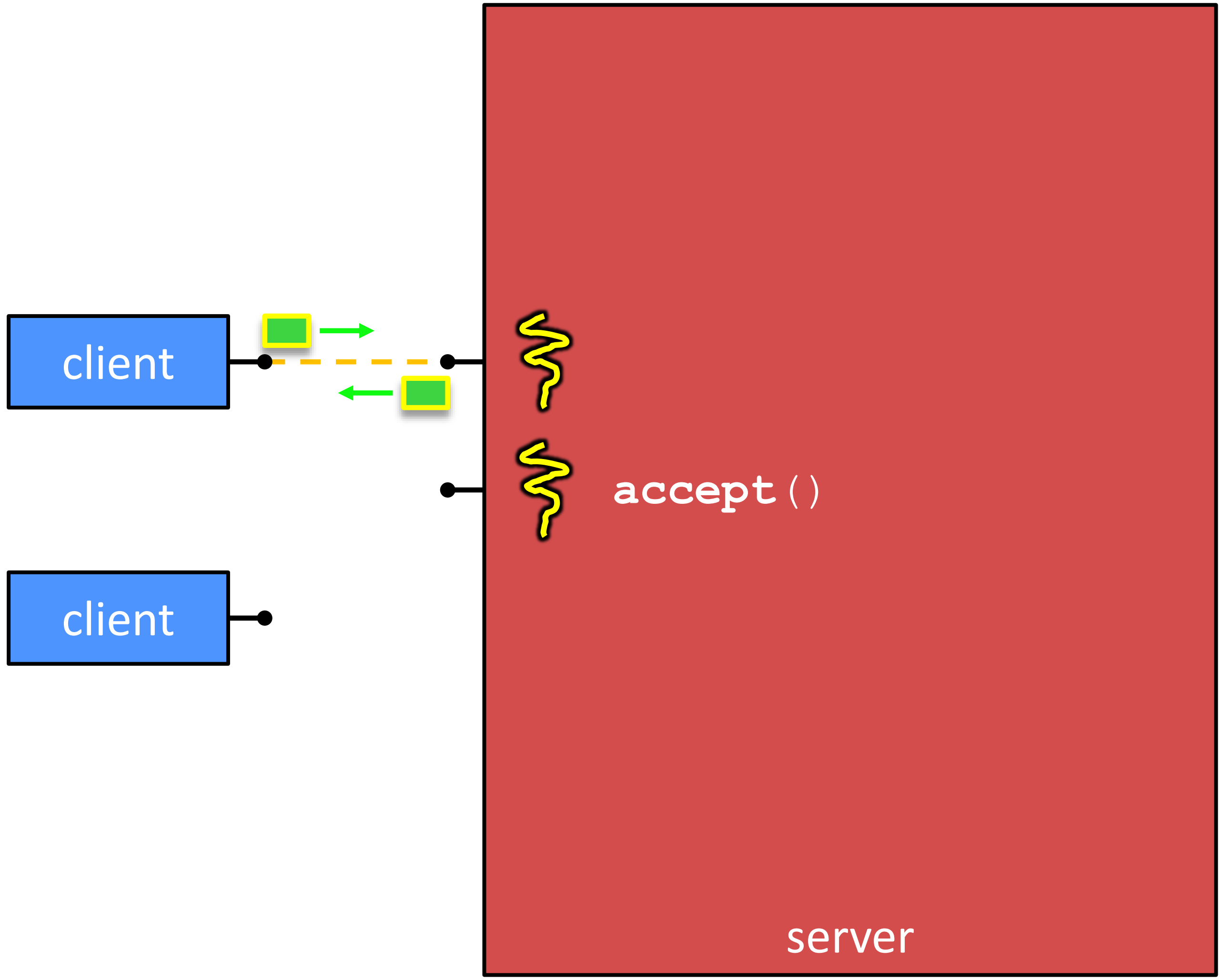
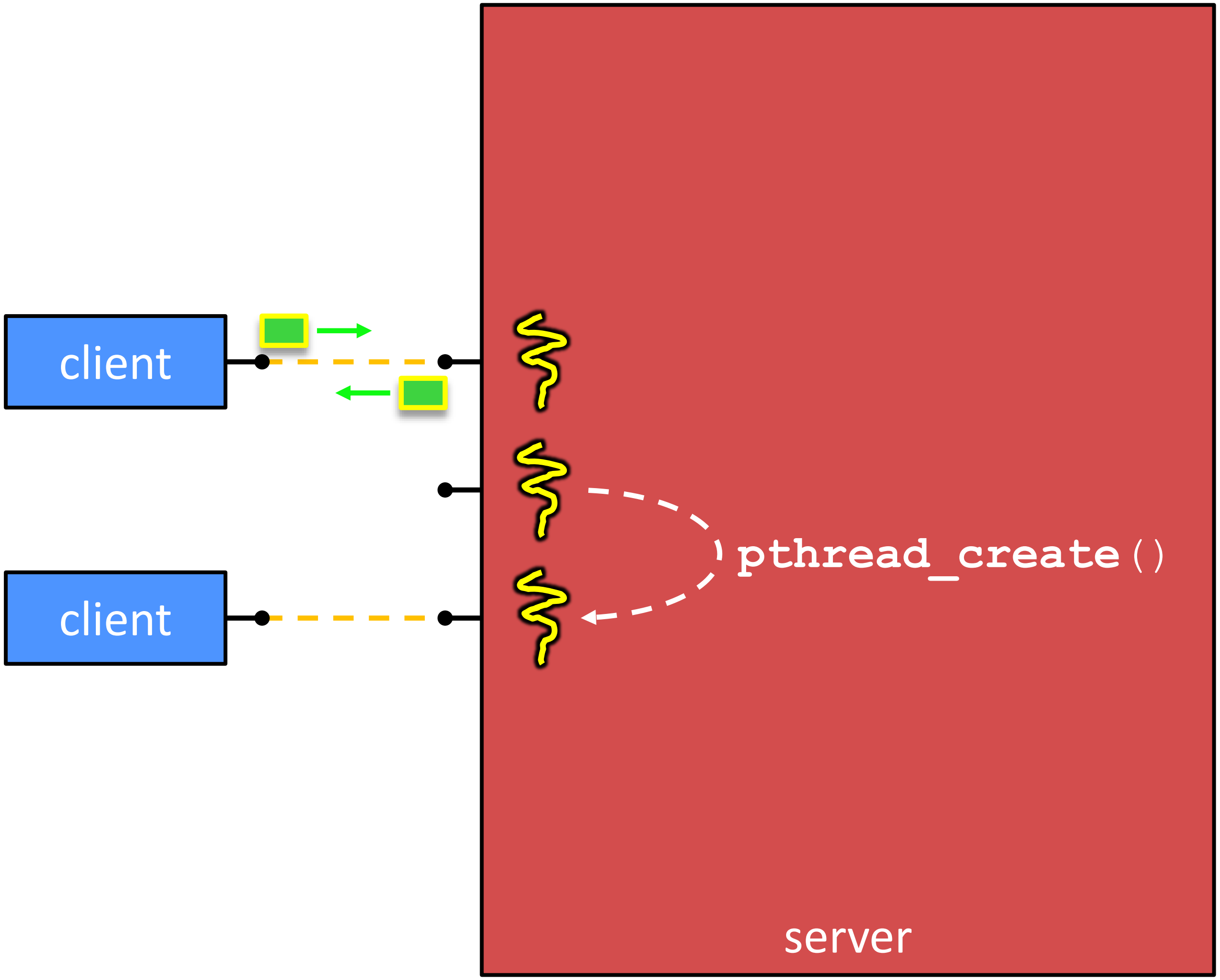
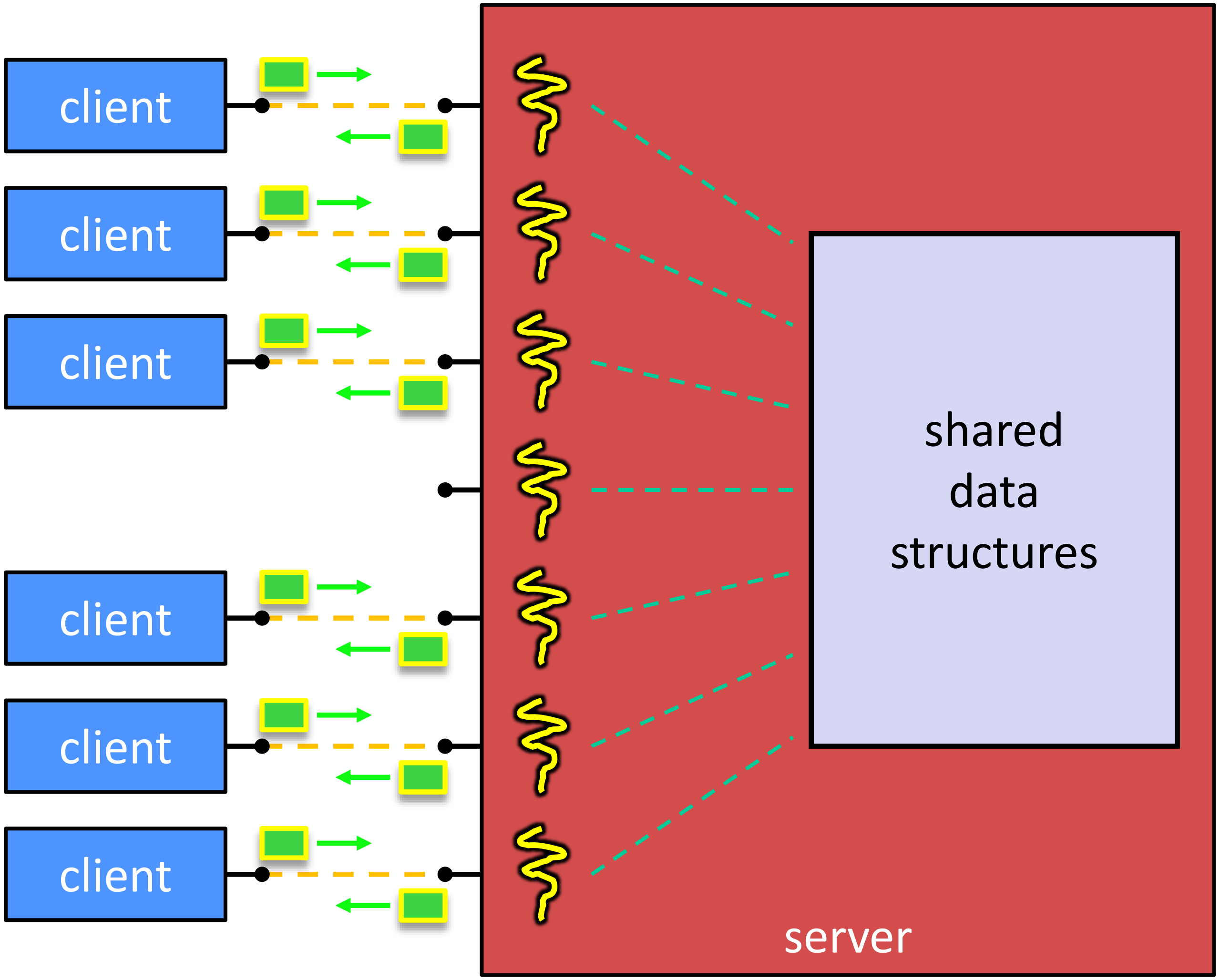


Multithreaded Server



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 (!milk) {

  buy milk

}
```

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

- If you live with a roommate:

Poll Everywhere

pollev.com/cse333

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

A. Yes, problem fixed

B. No, could end up with no milk

C. No, could still buy multiple milk

D. We're lost…

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

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
  - Could accidentally read old or intermediate (*i.e.*, invalid) value
  - One thread's work could get "lost"
- 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

- 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

- Pseudocode:

```
// non-critical code

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

// non-critical code
```

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?

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

↓

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

- 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)

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!

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 ex12, the boilerplate code uses C++ threads