Concurrency: Threads

CSE 333

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Administrivia

- Ex17 due Monday - last exercise! 🎉
- HW4 due Wednesday night
- Final exam in class on Friday (1 hour)
  - Updated topic list and old exams on course web now
    - Some old finals are 1-hour summer exams, some are 2-hour regular quarters – don’t panic if you can’t finish those in 1 hour
  - Review Q&A in sections next week

Administrivia

- hw4 due Thursday night next week
  - <panic>If you haven't started yet</panic>
  - Usual late days (max 2) available if you have any left
  - Mime types (in server query replies): hw4 server only needs to have ones that match the files that it will actually send (including pictures)
  - Remember – don't modify Makefiles or header files
  - Please be careful about inappropriate copying of solution code from others or found on the web. (Let's not have problems this late in the quarter.) Sample code from class is fine – use it!

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)
  - Be sure to check for data in the buffer – might be an http request (or part of one) already there left over from a previous read
- Server crashes on a blank request
  - Make sure that you handle the case that **`read`**`()` (or **`WrappedRead`**`()`) returns `0`

Previously…

- We implemented a search server but it was sequential
  - Processes requests one at a time regardless of client delays
  - Terrible performance, resource utilization

- Servers should be concurrent
  - Different ways to process multiple queries simultaneously:
    - Issue multiple I/O requests simultaneously
    - Overlap the I/O of one request with computation of another
    - Utilize multiple CPUs or cores
    - Mix and match as desired

Outline (next two lectures)

- We'll look at different `searchserver` implementations
  - Sequential
  - Concurrent via dispatching threads: **`pthread_create`**`()`
  - Concurrent via forking processes: **`fork`**`()`
  - *Concurrent via non-blocking, event-driven I/O:* **`select`**`()`
    - *We won't get to this* ☹

- Reference: *Computer Systems: A Programmer's Perspective*, Chapter 12 (CSE 351 book)

Sequential

- Pseudocode:

```
listen_fd = Listen(port);

while (1) {
  client_fd = accept(listen_fd);
  buf = read(client_fd);
  resp = ProcessQuery(buf);
  write(client_fd, resp);
  close(client_fd);
}
```

- See `searchserver_sequential/`

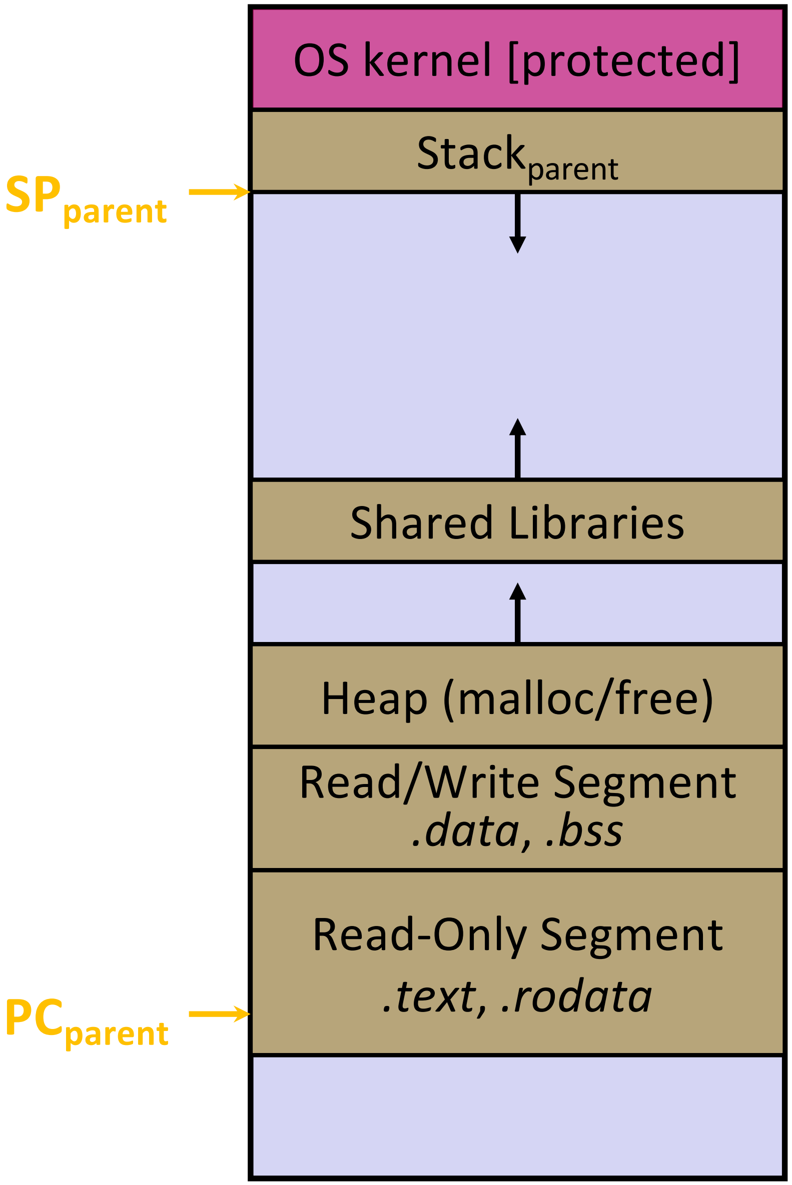
Wherefore Sequential?

- Advantages:
  - Super(?) simple to build/write
- Disadvantages:
  - Incredibly poor performance
    - One slow client will cause *all* others to block
    - Poor utilization of resources (CPU, network, disk)

Threads

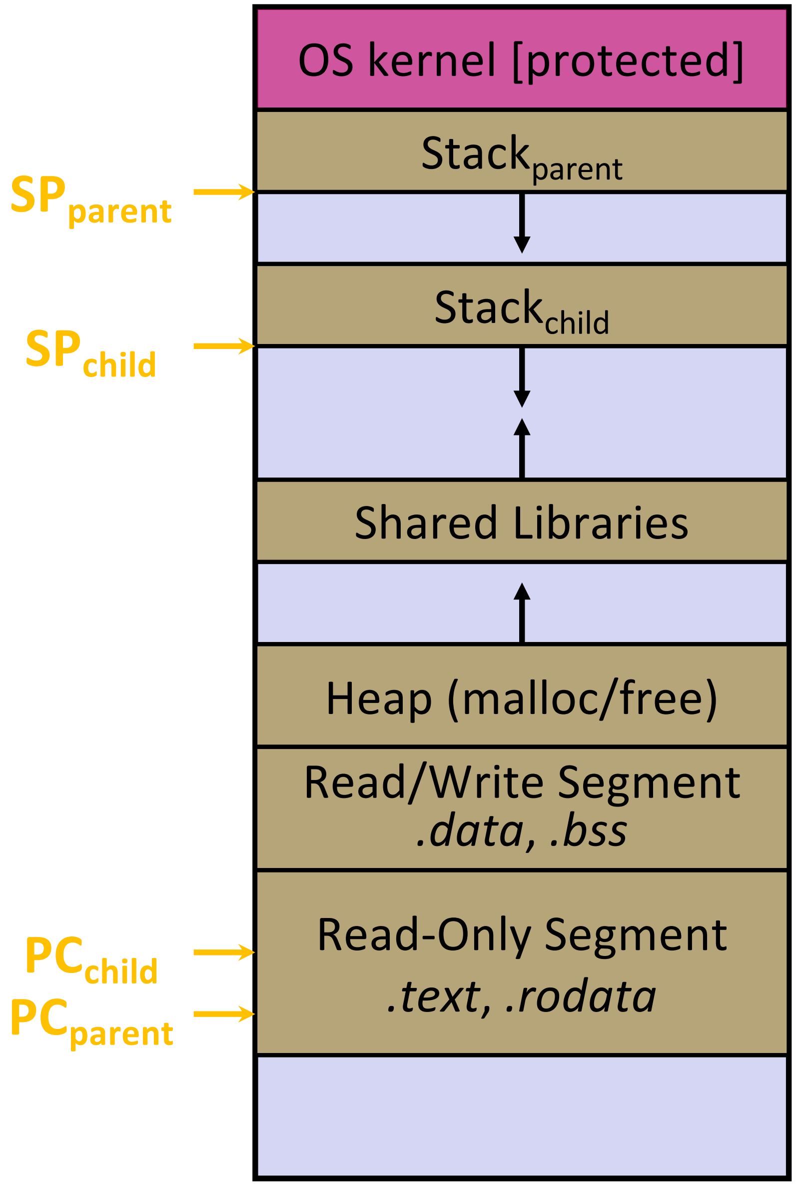
- Threads are like lightweight processes
  - They execute concurrently like processes
    - Multiple threads can run simultaneously on multiple CPUs/cores
  - Unlike processes, threads cohabitate the same address space
    - Threads within a process see the same heap and globals and can communicate with each other through variables and memory
      - But, they can interfere with each other – need synchronization for shared resources
    - Each thread has its own stack

Threads and 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()`

Threads and Address Spaces



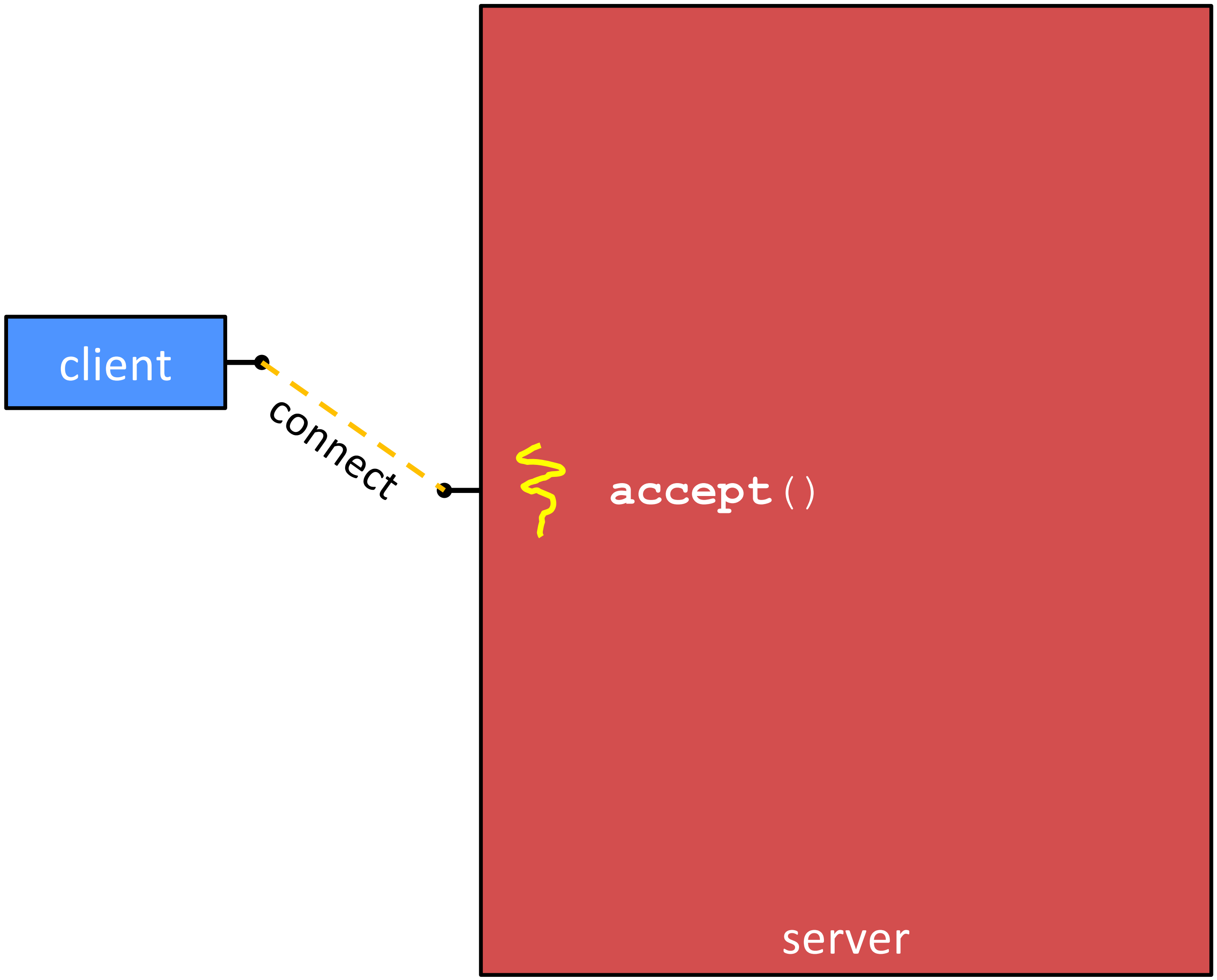
- After creating a thread
  - *Two* threads of execution running in the address space
    - Original thread (parent) and new thread (child)
    - New stack created for child thread
    - Child thread has its own PC, SP
  - Both threads share the other segments (code, heap, globals)
    - They can cooperatively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

Multithreaded Server: Architecture

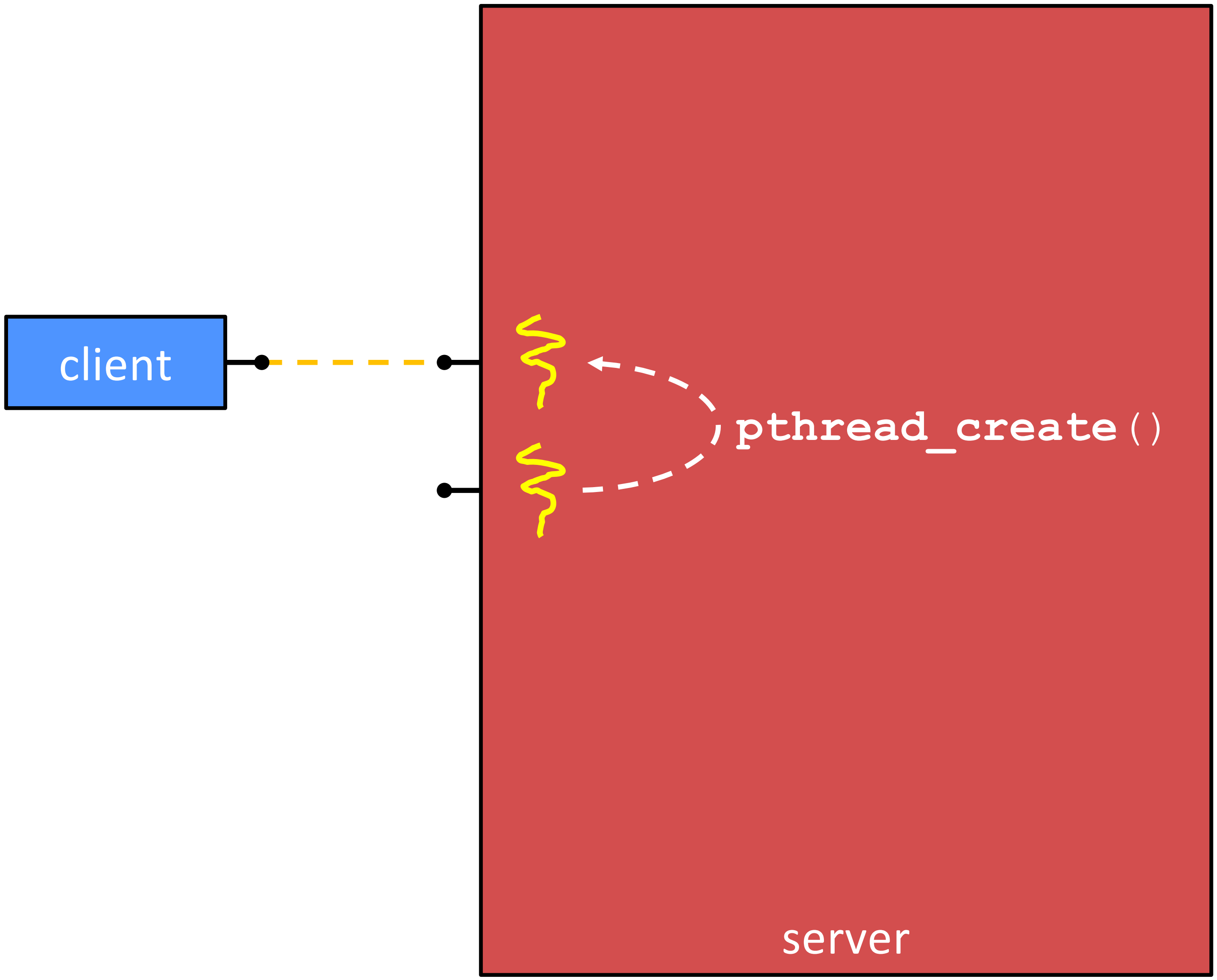
- A parent *thread* creates a new thread to handle each incoming connection
  - The child thread handles the new connection and subsequent I/O, then exits when the connection terminates

- See `searchserver_threads/` for code if curious

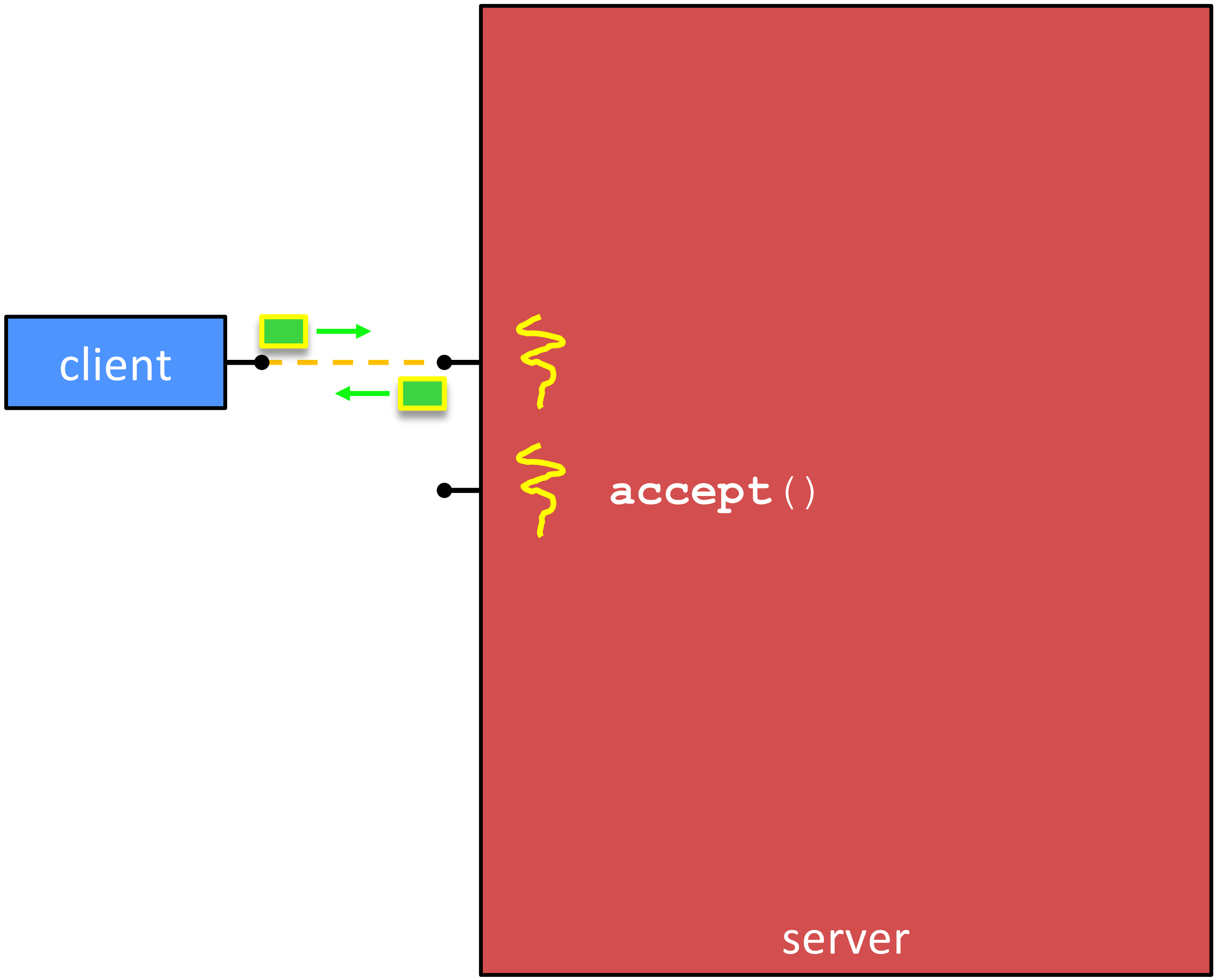
Multithreaded Server



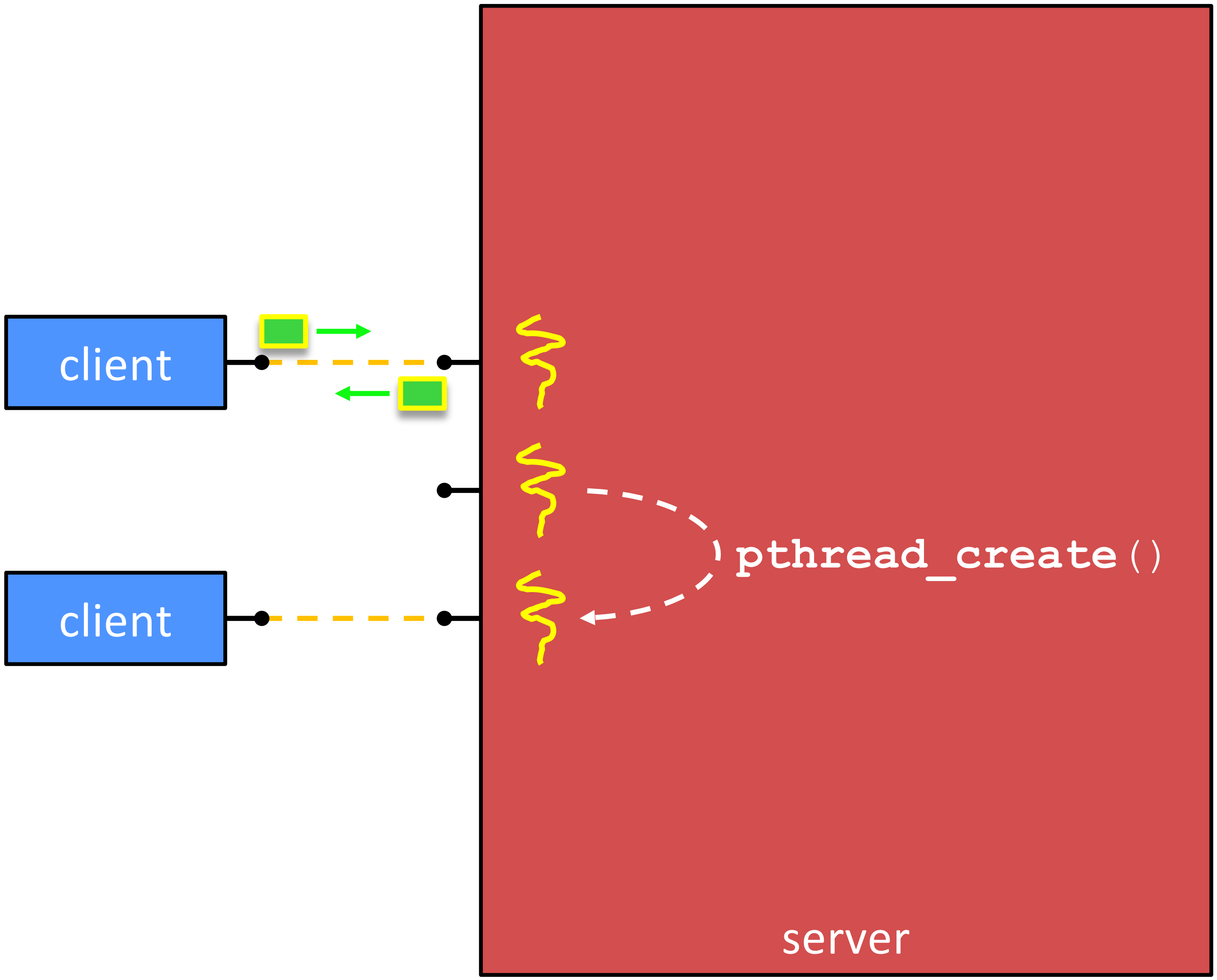
Multithreaded Server



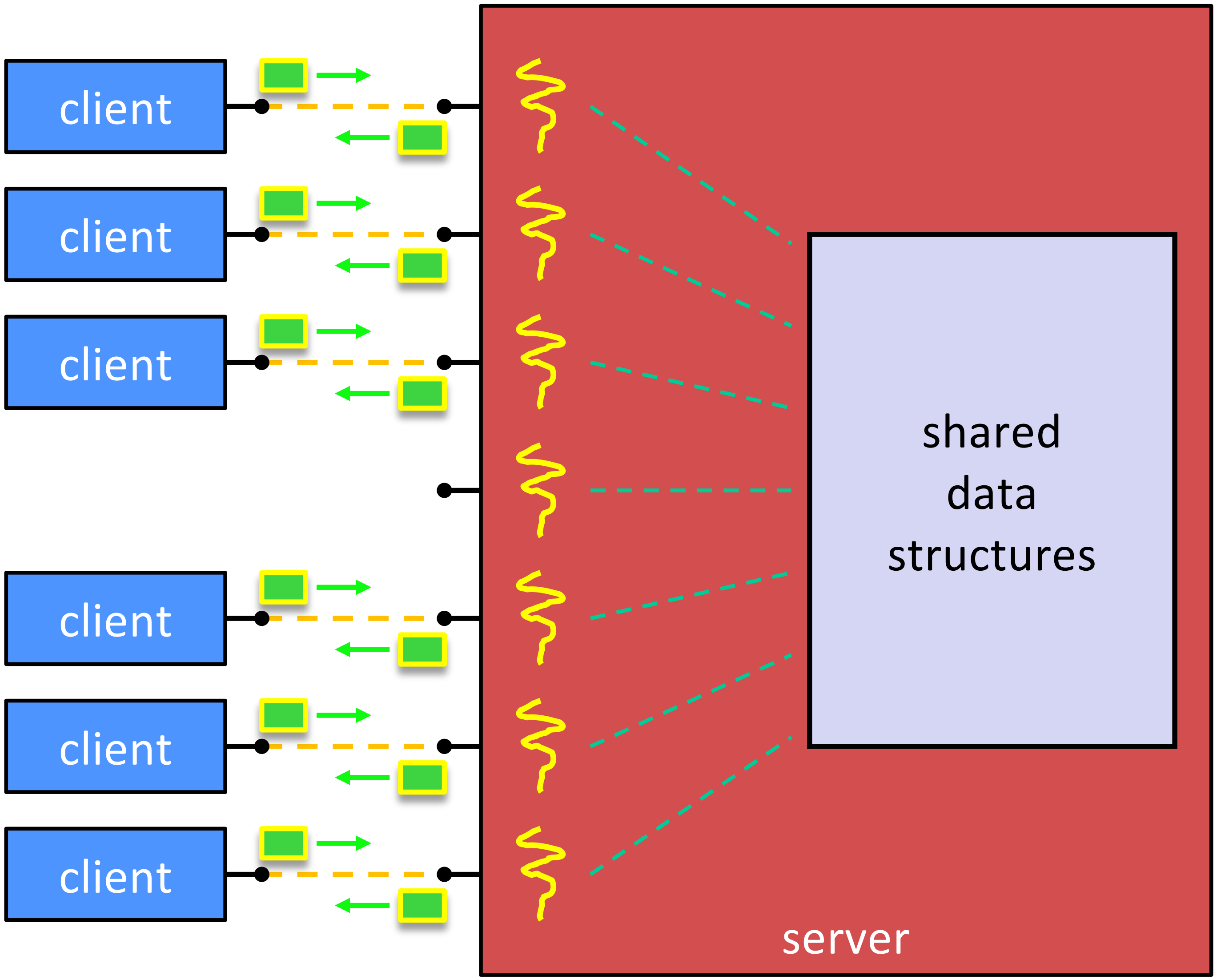
Multithreaded Server



Multithreaded Server



Multithreaded Server



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

pthreads Threads: Creation

- ```
  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`
  - Returns a status code (0 or an error number)
  - The new thread runs **`start_routine`**`(arg)`

- ```
  void pthread_exit(void* retval);
  ```
  - Equivalent of **`exit`**`(retval)` for a thread instead of a process
  - thread automatically exits when it returns from **`start_routine`**`()`

pthreads Threads: Afterwards

- ```
  int pthread_join(pthread_t thread,
                   void** retval);
  ```
  - Waits for thread to terminate (equivalent to waitpid, but for threads)
  - Exit status of the terminated thread is placed in `**retval`

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

- See `thread_example.cc`

Concurrent Server via Threads

- See `searchserver_threads/`

- **Notes:**
  - 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
  - How do you properly handle memory management?
    - Who allocates and deallocates memory?
    - How long do you want memory to stick around?

Wherefore Concurrent Threads?

- 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

Threads and Data Races

- What happens if two threads try to mutate the same data structure?
  - They might interfere in painful, non-obvious ways, depending on the specifics of the data structure

- <u>Example</u>: two threads try to push an item onto the head of a linked list at the same time
  - Could get "correct" answer
  - Could get different ordering of items
  - Could break the data structure! ☠️
  - Likely *will* get different results each time you run the program – a debugging nightmare

Data Race Example

- If your fridge has no milk,
  then go out and buy some more

```
if (!milk) {

  buy milk

}
```

- What could go wrong?
- If you live alone:

- If you live with a roommate:

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()
```

- 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)

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

pthreads and Locks

- Another term for a lock is a mutex ("mutual exclusion")
  - pthreads (`#include <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

But I only want to read the data!

- Is a lock needed when reading shared data?
  - No if all threads *only* read the shared data
  - Yes if ***any*** thread could potentially write to the shared data!
- Why?
  - The C and C++ standards do not guarantee that writes of multi-byte data are indivisible when observed from other asynchronous threads
    - i.e., writing multiple bytes to memory might involve multiple updates to caches or backing stores
    - Which means a reading thread might be able to see the results of a partial, not-yet-finished update if it does not use locks

But I only am reading the data!

- Example. Suppose shared 32-bit int x is initially 0x0000FFFF
- Thread 1 properly updates x using locks:

```
acquire x_lock;
x = x + 1;
release x_lock;
```

- Thread 2 only reads x and outputs it without locking: print x
  - Might print 0x0000FFFF (old value)
  - Might print 0x00010000 (new value)
  - Might print 0x0001FFFF (partially updated value) !!!!!
- How to fix: Thread 2 must acquire x_lock before printing and release it afterwards
- Practicalities: On modern x86/arm/etc. processors this won't happen for things like aligned small ints that don't span cache boundaries, so you probably won't see the bug – but the C/C++ language does ***not*** guarantee this behavior! Use locks or atomics (see C/C++ refs for details) if there are any writers to a shared variable!!

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 our exercise