Concurrency: Threads

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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/`

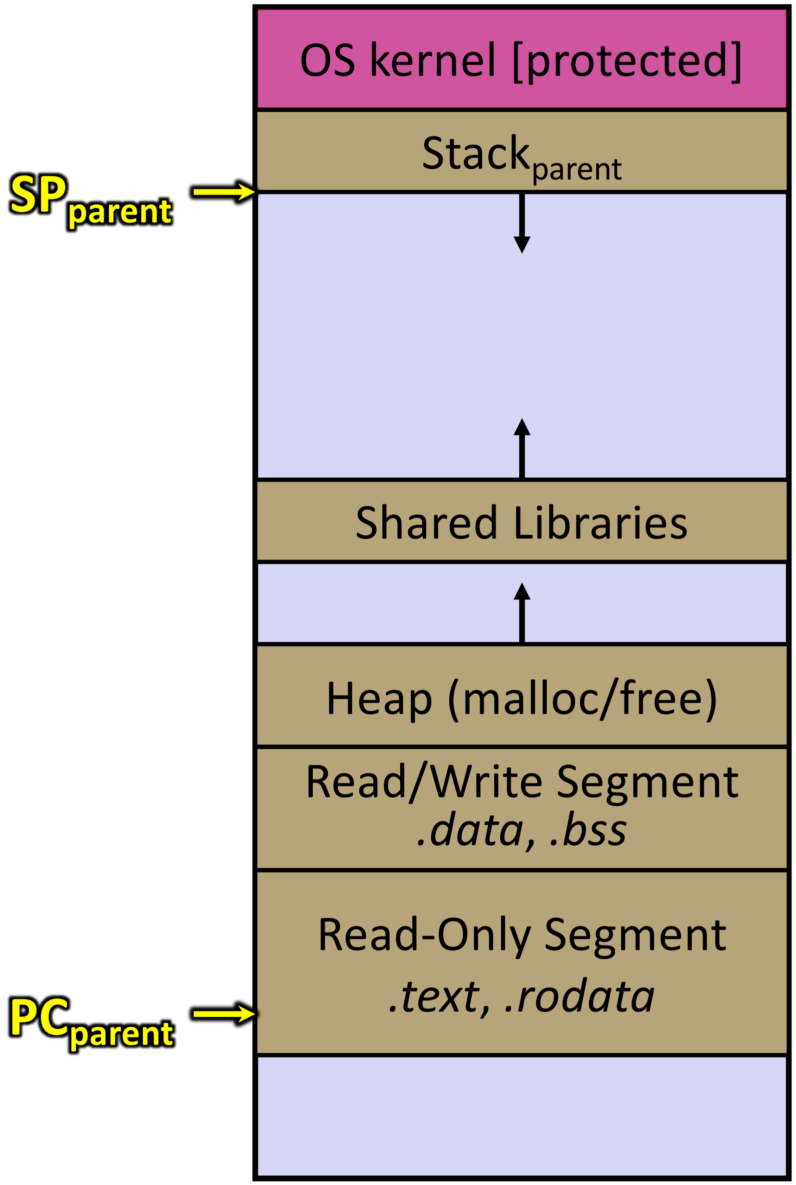
Whither Sequential?

- 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

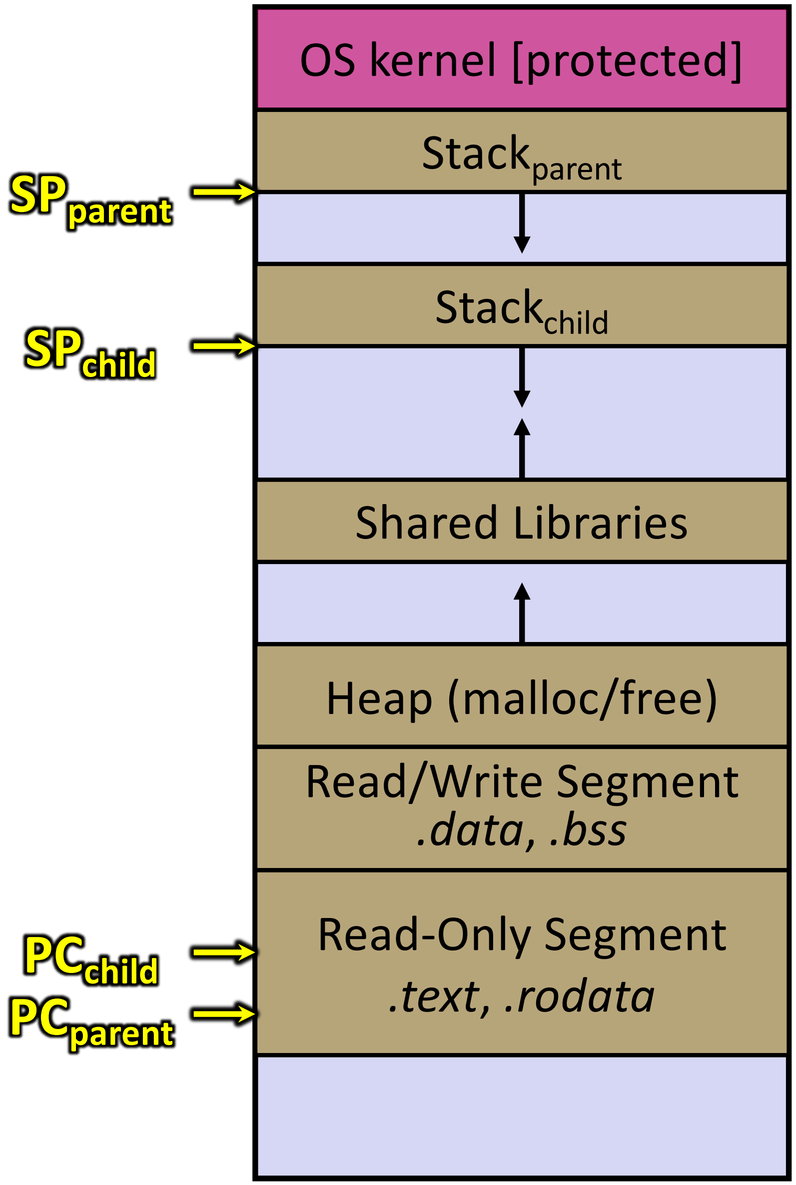
- Threads are like lightweight processes
  - They execute concurrently like processes
    - Multiple threads can run simultaneously on multiple CPUs/cores
  - Unlike processes, threads cohabitate the same address space
    - Threads within a process see the same heap and globals and can communicate with 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

pthreads Threads

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

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

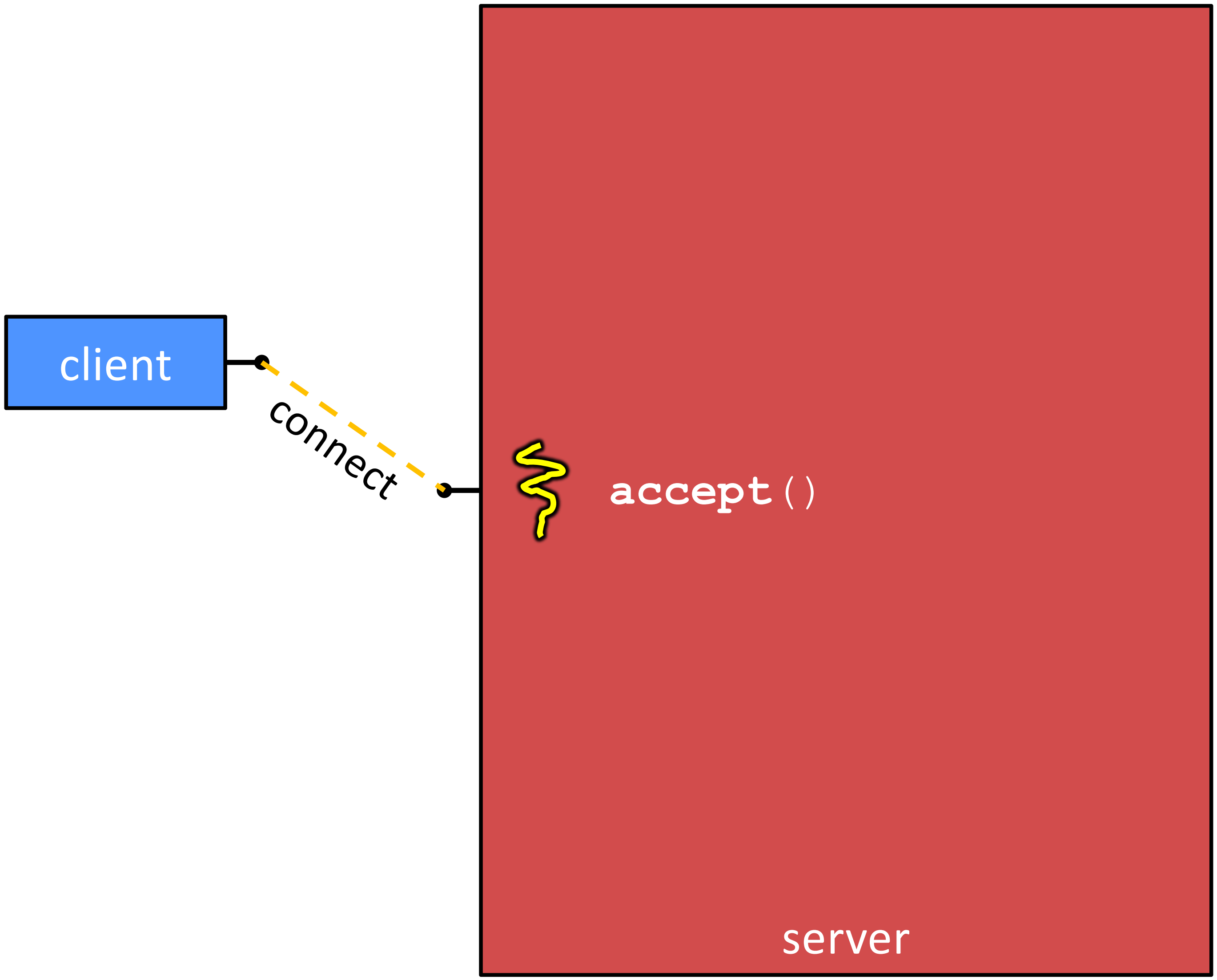
- ```
  int pthread_join(pthread_t thread,
                   void** retval);
  ```

- See `thread_example.cc`
  ```

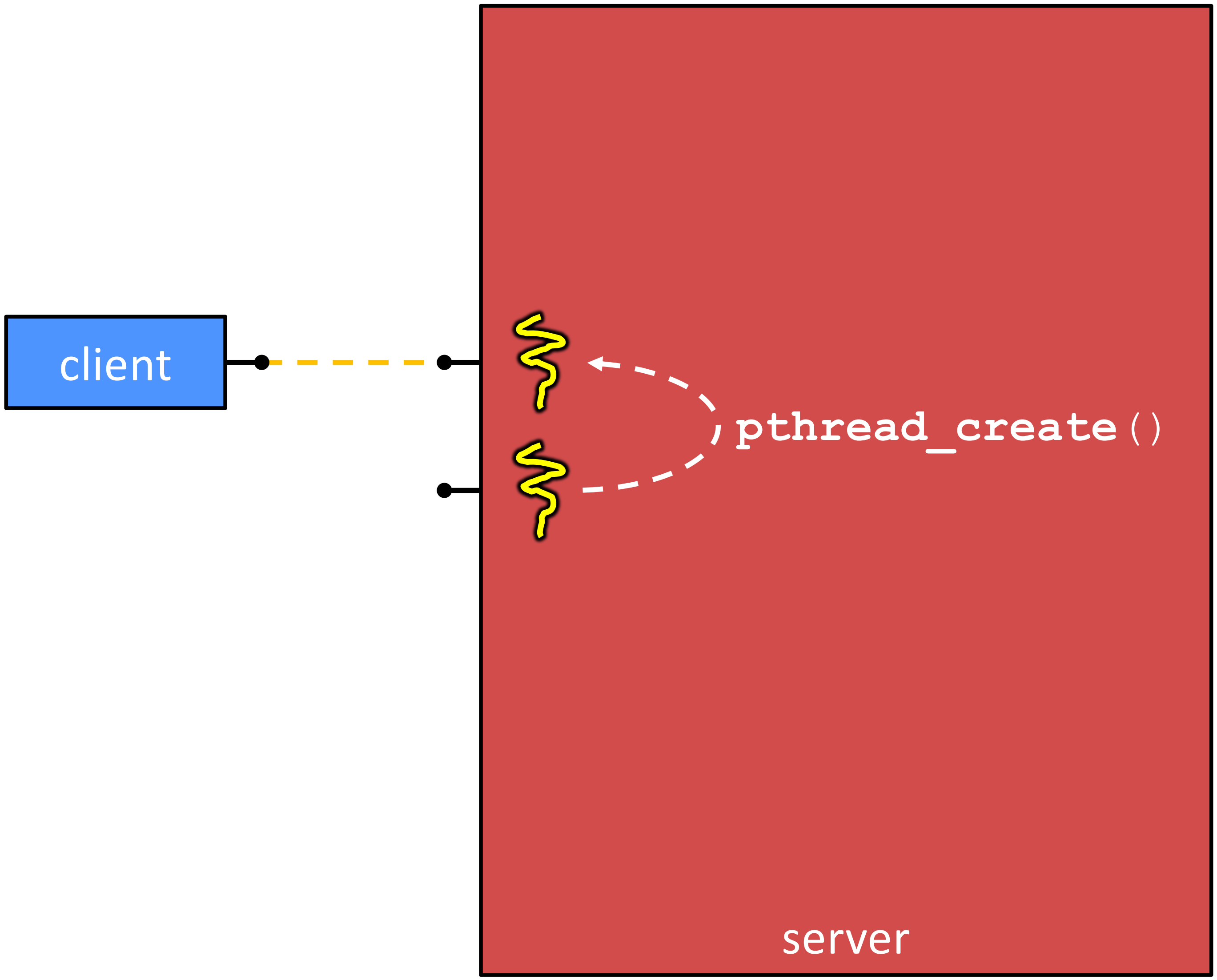
Concurrent Server with Threads

- 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

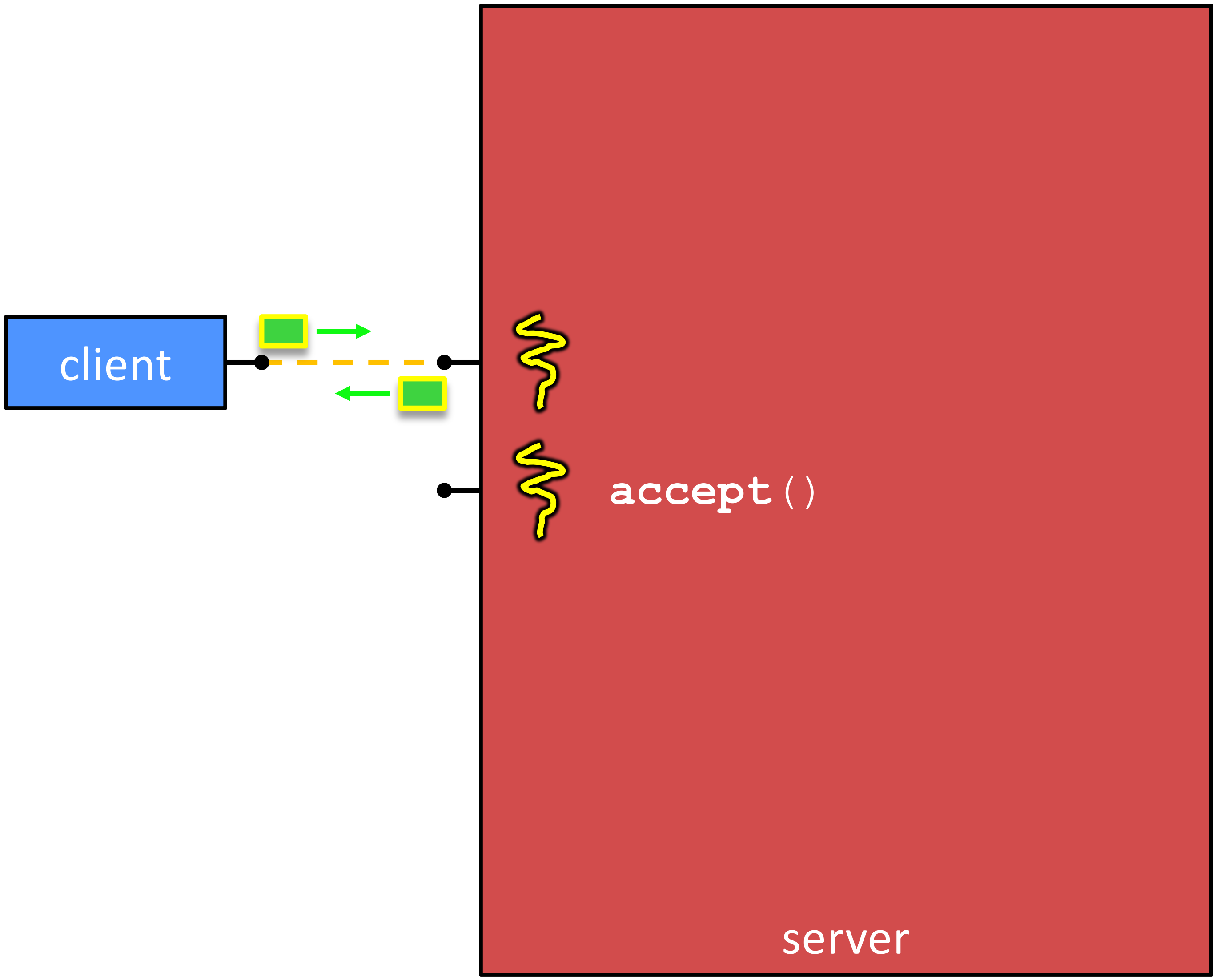
Multithreaded Server



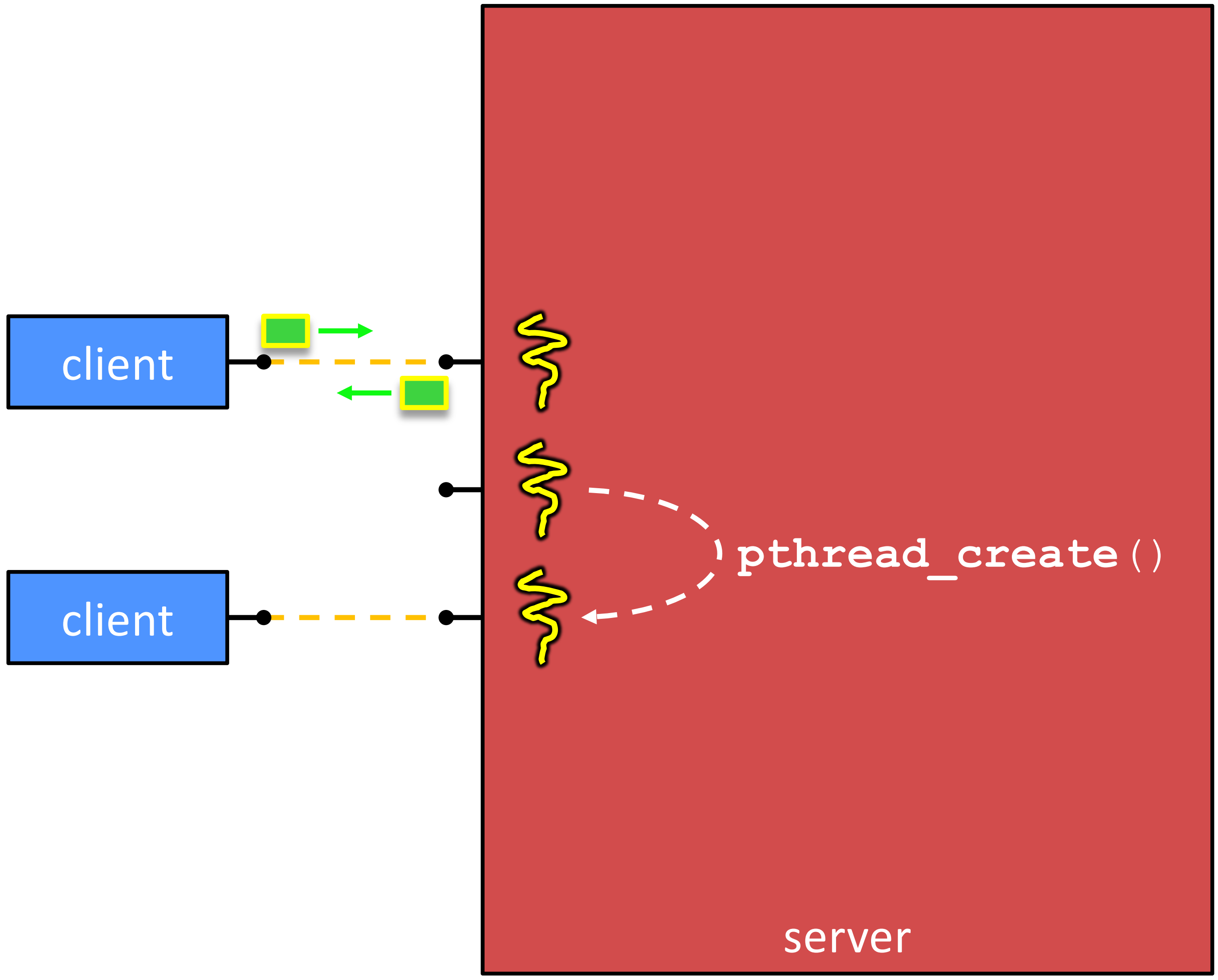
Multithreaded Server



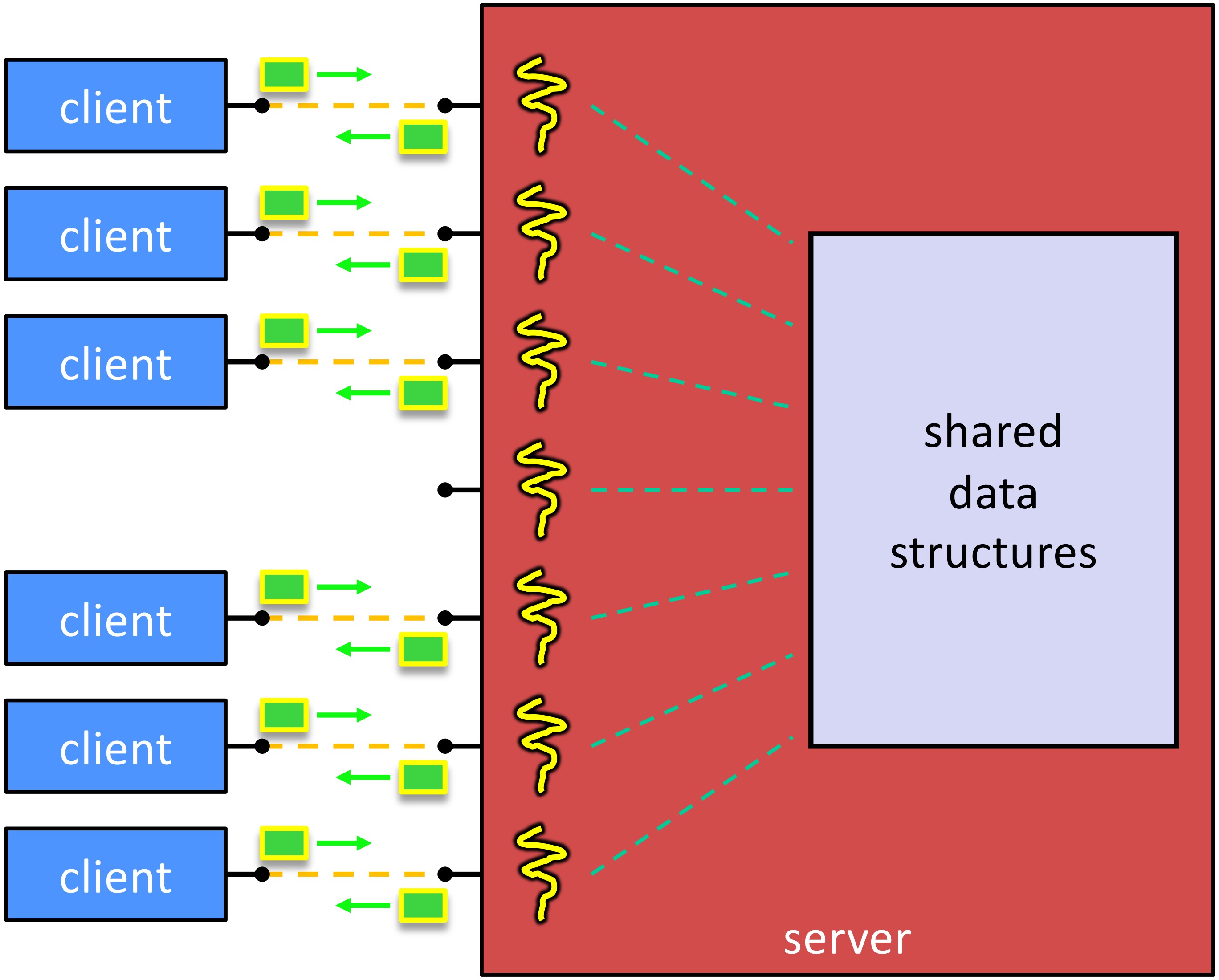
Multithreaded Server



Multithreaded Server



Multithreaded Server



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?

Whither 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

- Example: 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:

Data Race Example

- Idea: leave a note!
  - Does this fix the problem?

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

A. Yes, problem fixed

B. No, could end up with no milk

C. No, could still buy multiple milk

D. We're lost…

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")
  - 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
  ```

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