CSE 333

Lecture 21 -- fork, pthread_create

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Administrivia

HW4 is due Thursday night

- **<panic>** if you haven't started yet **</panic>**
- Usual late days apply ***if*** you have any left

pthreads exercise due Wednesday before class

No class Monday - Memorial Day holiday

Please fill out course evals when they open next week

Final exam Wed. June 8, 2:30-4:20

- Overview/review in section next week
- Last-minute review Tue. June 7, 4:30, EEB 037
- Topic list and old exams on web now

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 blank request

- make sure you handle the case that read( ) [or WrappedRead] returns 0

Previously

We implemented hw3 searchserver, but it was sequential

- it processed requests one at a time, in spite of client interactions blocking for arbitrarily long periods of time
  - this led to terrible performance

Servers should be concurrent

- process multiple requests simultaneously
  - issue multiple I/O requests simultaneously
  - overlap the I/O of one request with computation of another
  - utilize multiple CPUs / cores

Today

We'll go over three versions of searchserver

- sequential
- concurrent
    - processes [**fork( )**]
    - threads [**pthread_create( )**]

Alternative (which we won't get to): non-blocking, event driven version

- non-blocking I/O [**select( )**]

Reference: *Computer Systems: A Programmer's Perspective*

- 351 textbook, good source for process/thread/OS concepts

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);
}
```

look at ***searchserver_sequential/***

Whither sequential?

Benefits

- super simple to build

Disadvantages

- incredibly poorly performing
  - one slow client causes **all** others to block
  - poor utilization of network, CPU

fork( )

```
pid_t fork(void);
```

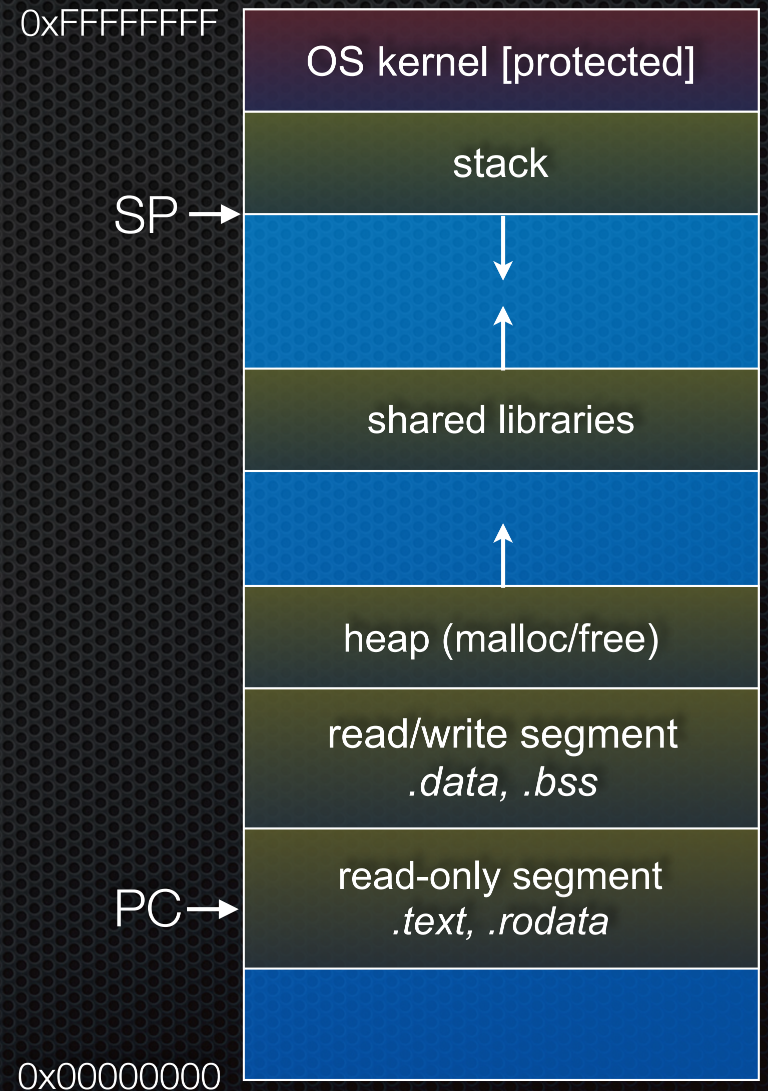
Fork is used to create a new process (the “child”) that is an exact clone of the current process (the “parent”)

- everything is cloned (except threads)
  - all variables, file descriptors, open sockets, etc.
  - the heap, the stack, etc.
- primarily used in two patterns
  - servers: fork a child to handle a connection
  - shells: fork a child, which then exec’s a new program

fork( ) and address spaces

Remember this picture...?

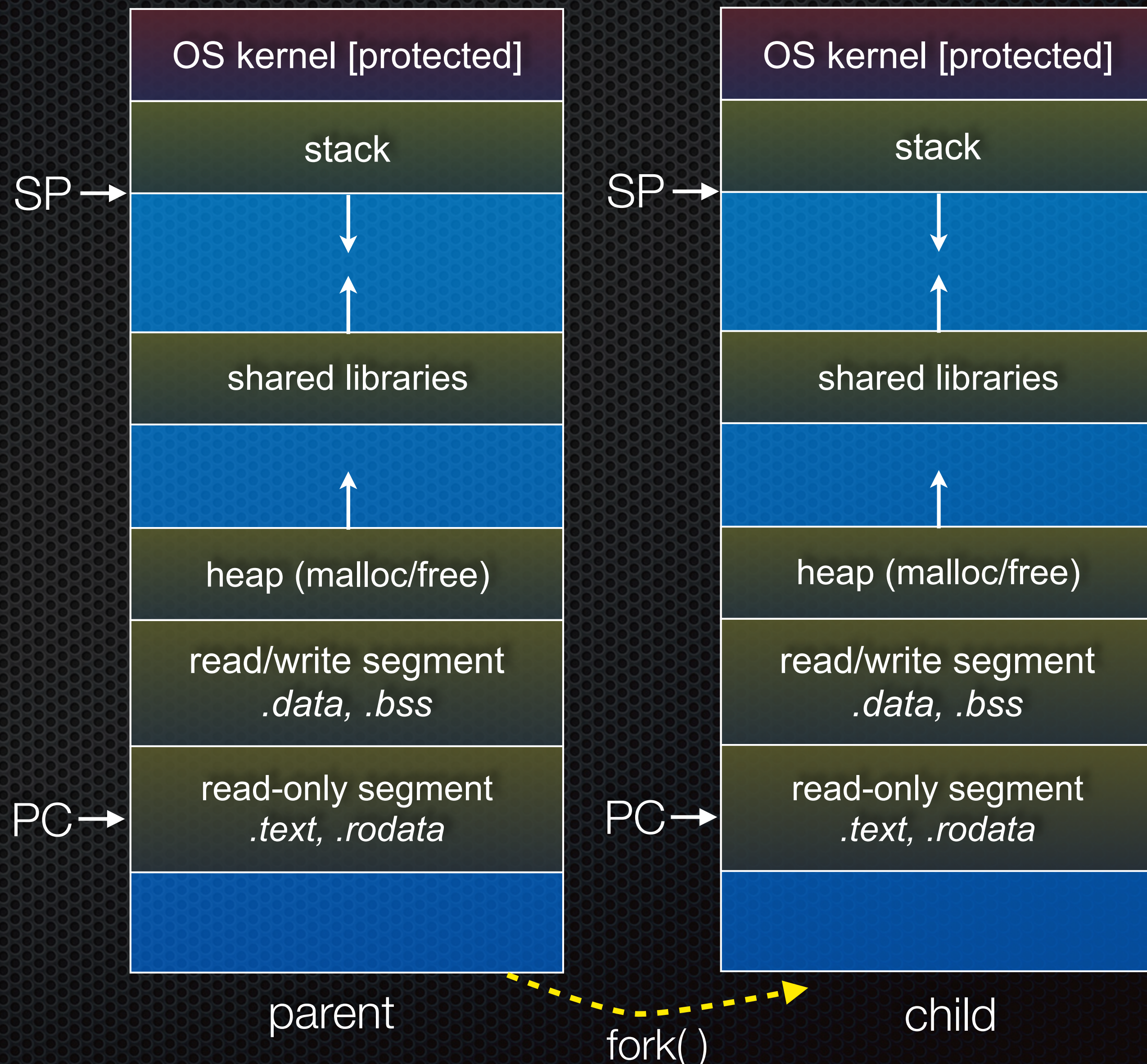
- a process executes within an ***address space***
- the address space includes:
  - a stack (for stack frames)
  - heap (for dynamically allocated data)
  - text segment (containing code)
  - etc.



fork( ) and address spaces

Fork causes the OS to clone the address space, creating a brand new process

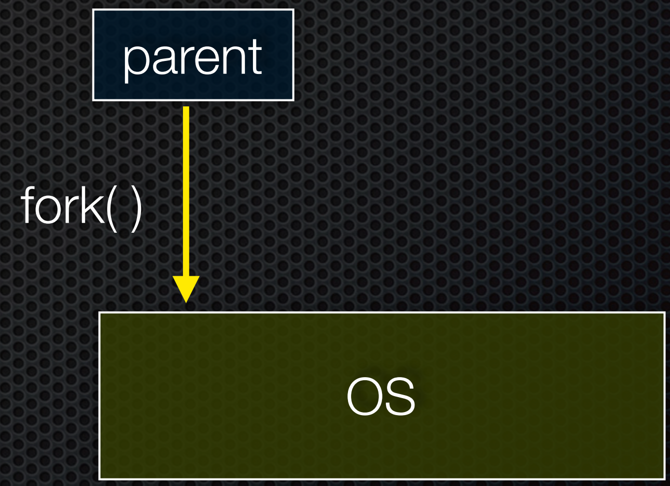
- the new process starts life as a **copy** the old process in (nearly) every way
- the **copies** of the heap, stack, text segment, etc. are (nearly) identical
- the new process has **copies** of the parent's data structures, stack-allocated variables, open file descriptors, and so on



fork( )

fork( ) has peculiar semantics

- the parent invokes fork( )
- the operating system clones the parent
- **both** the parent and the child return from fork
    - parent receives child's pid
    - child receives a "0" as pid



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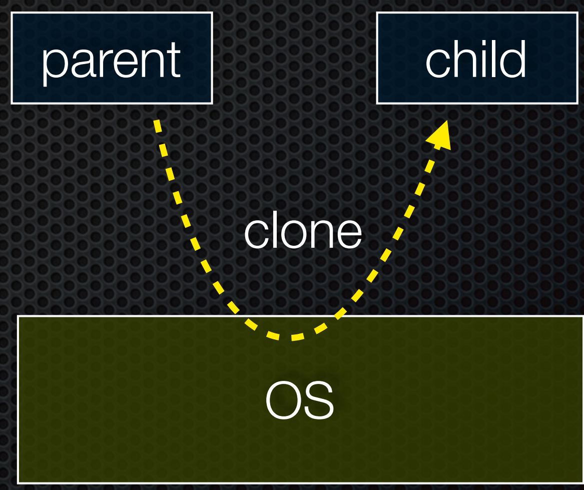

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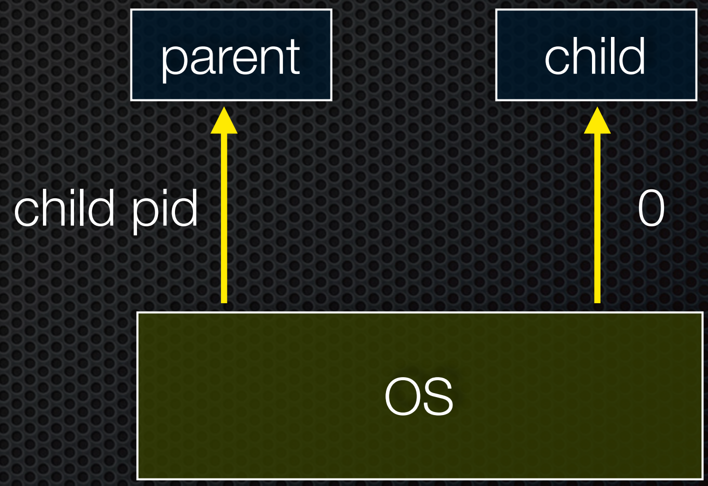


fork( )

fork_example.cc

Concurrency with processes

The ***parent*** process blocks on **accept( )**, waiting for a new client to connect

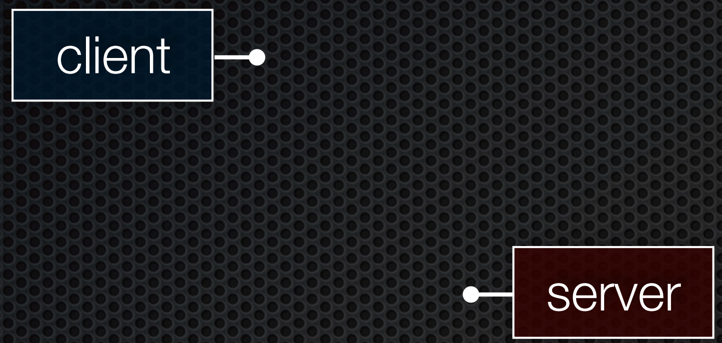
- when a new connection arrives, the parent calls **fork( )** to create a ***child*** process
- the child process handles that new connection, and **exit( )**’s when the connection terminates

Remember that children become “zombies” after death

- option a) parent calls wait( ) to “reap” children
- option b) use the double-fork trick

Graphically

Graphically



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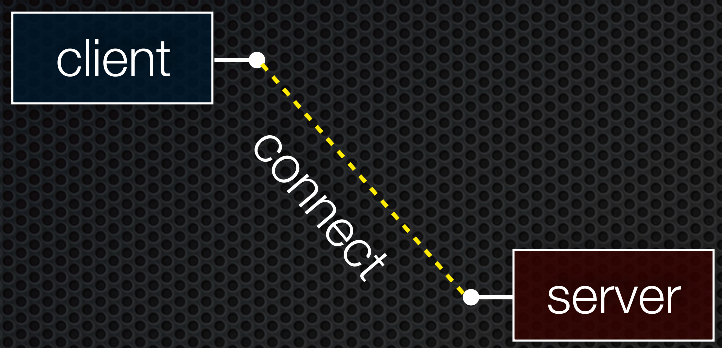

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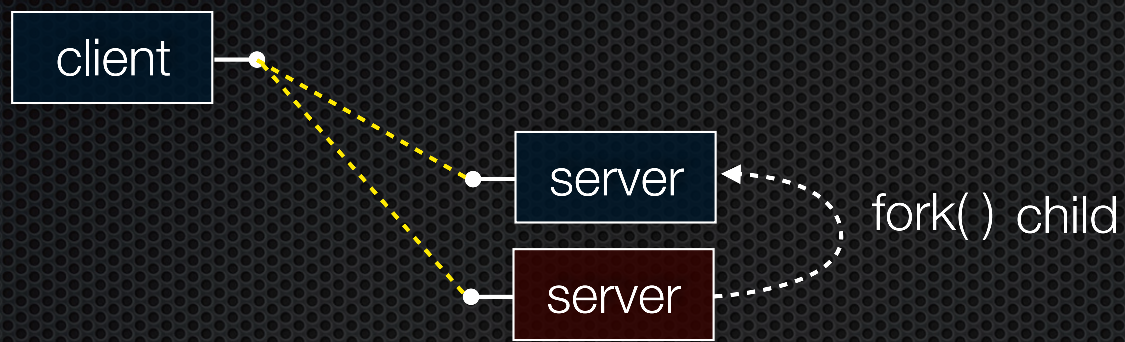

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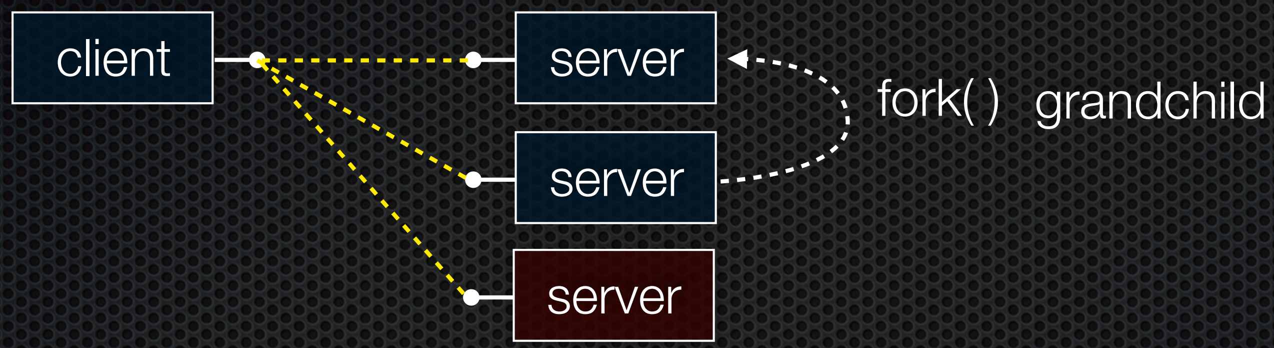

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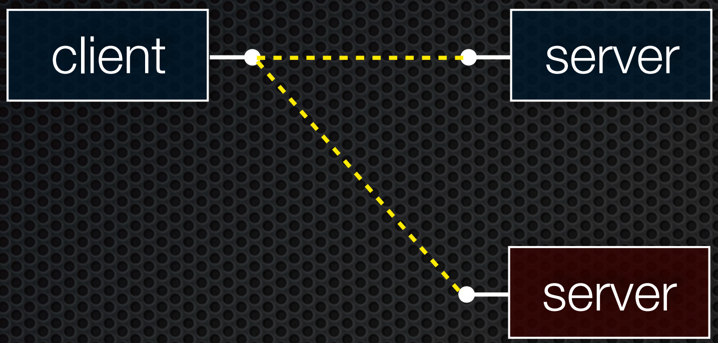
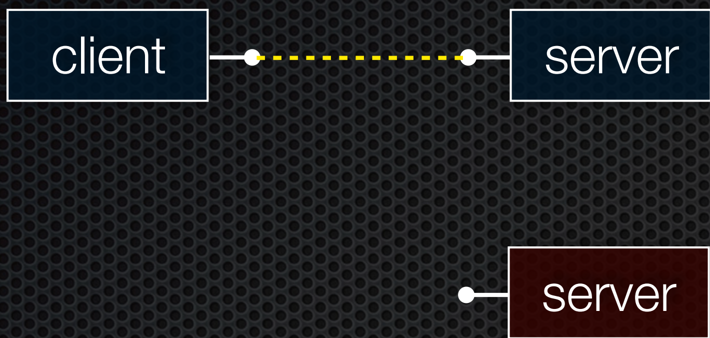


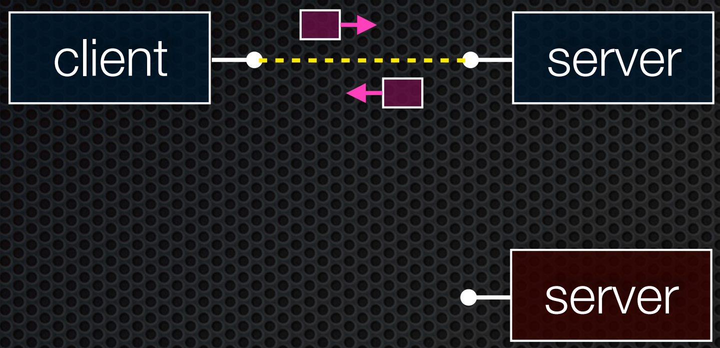
child exit( )'s / parent wait( )'s

Graphically



parent closes its client connection

Graphically



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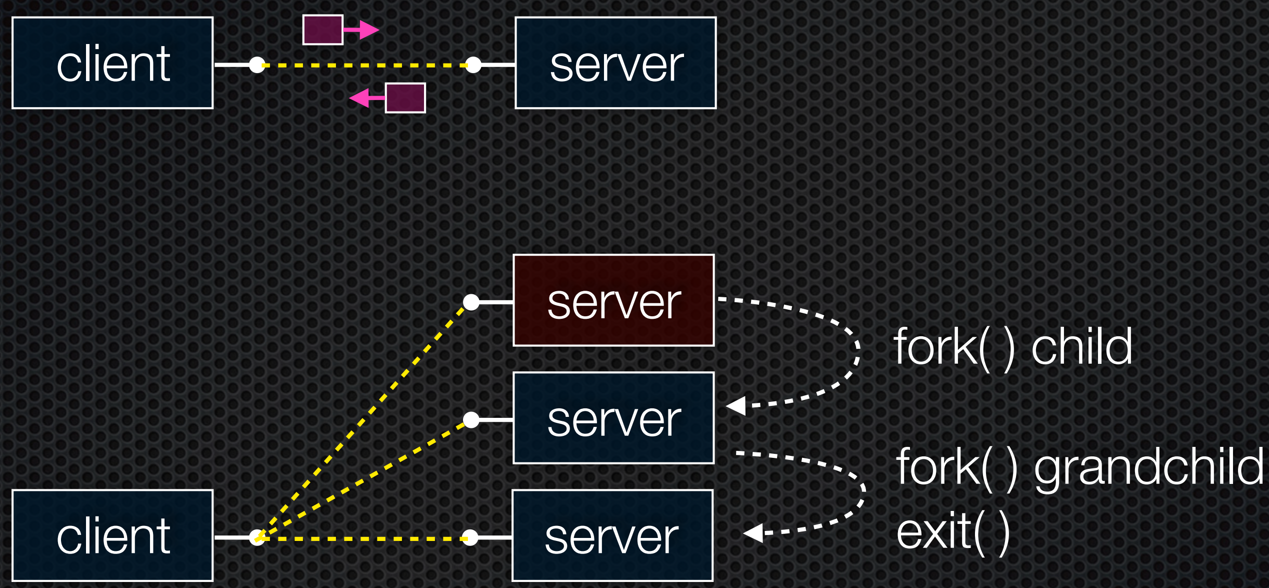

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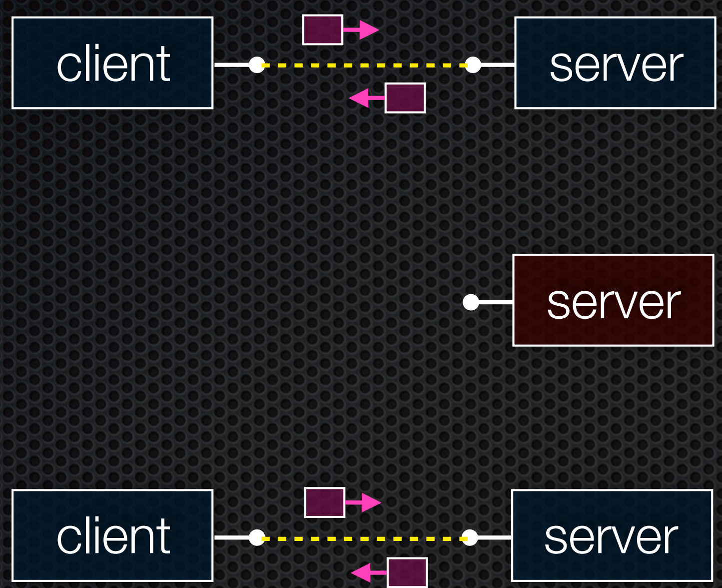

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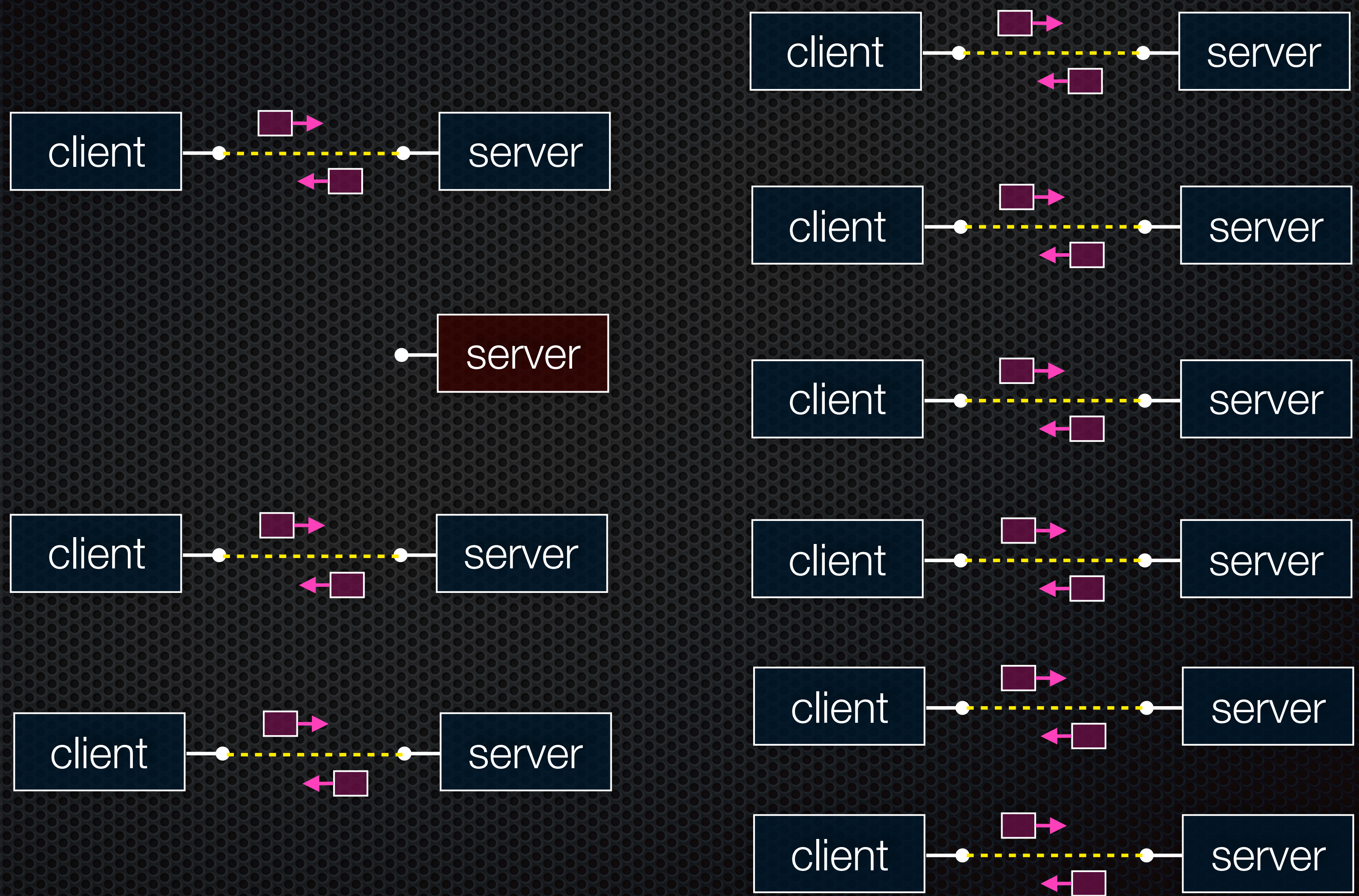


Concurrent with processes

look at ***searchserver_processes***

Whither concurrent processes?

Benefits

- almost as simple as sequential
  - in fact, most of the code is identical!
- parallel execution; good CPU, network utilization

Disadvantages

- processes are heavyweight
  - relatively slow to fork
  - context switching latency is high
- communication between processes is complicated

How slow is fork?

run ***forklatency.cc***

Implications?

0.25 ms per fork

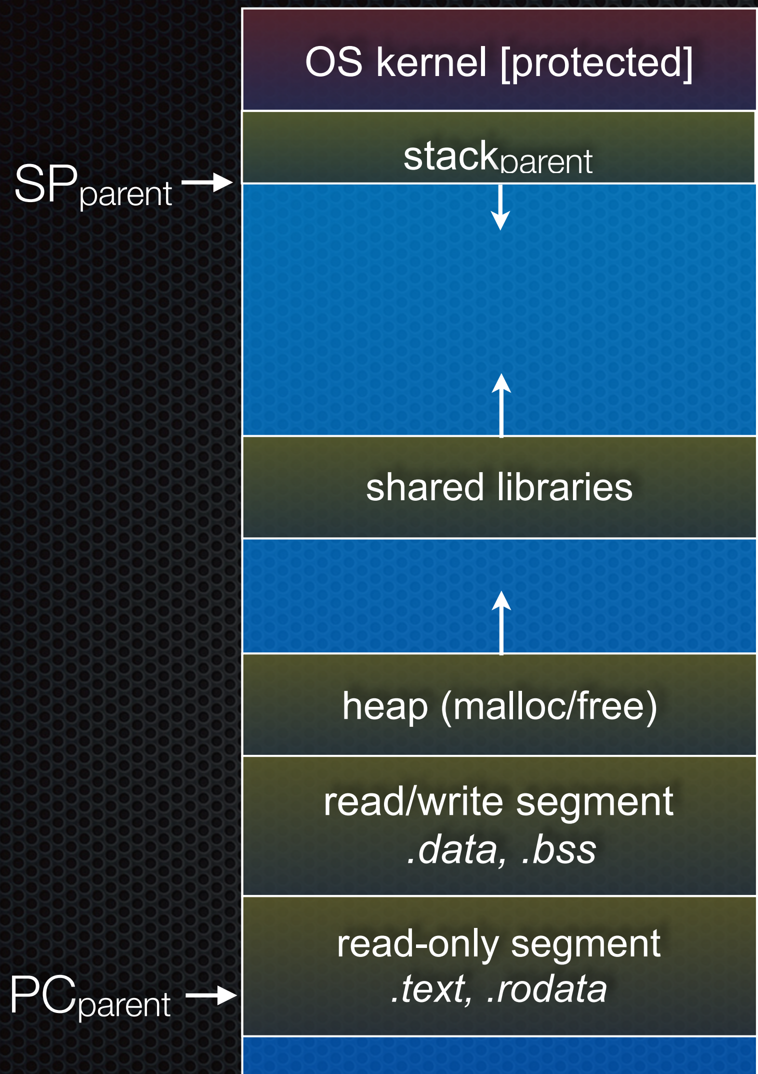
- maximum of (1000 / 0.25) = 4,000 connections per second per core
- ~0.5 billion connections per day per core
    - fine for most servers
    - too slow for a few super-high-traffic front-line web services
        - Facebook serves *O*(750 billion) page views per day
        - would need 3,000 -- 6,000 cores just to handle fork( ), i.e., without doing any work for each connection!

threads

Threads are like lightweight processes

- like processes, they execute concurrently
  - multiple threads can run simultaneously on multiple cores/CPUs
- unlike processes, threads cohabit the same address space
  - the threads within a process see the same heap and globals
    - threads can communicate with each other through variables
    - but, threads can interfere with each other: need synchronization
  - each thread has its own stack

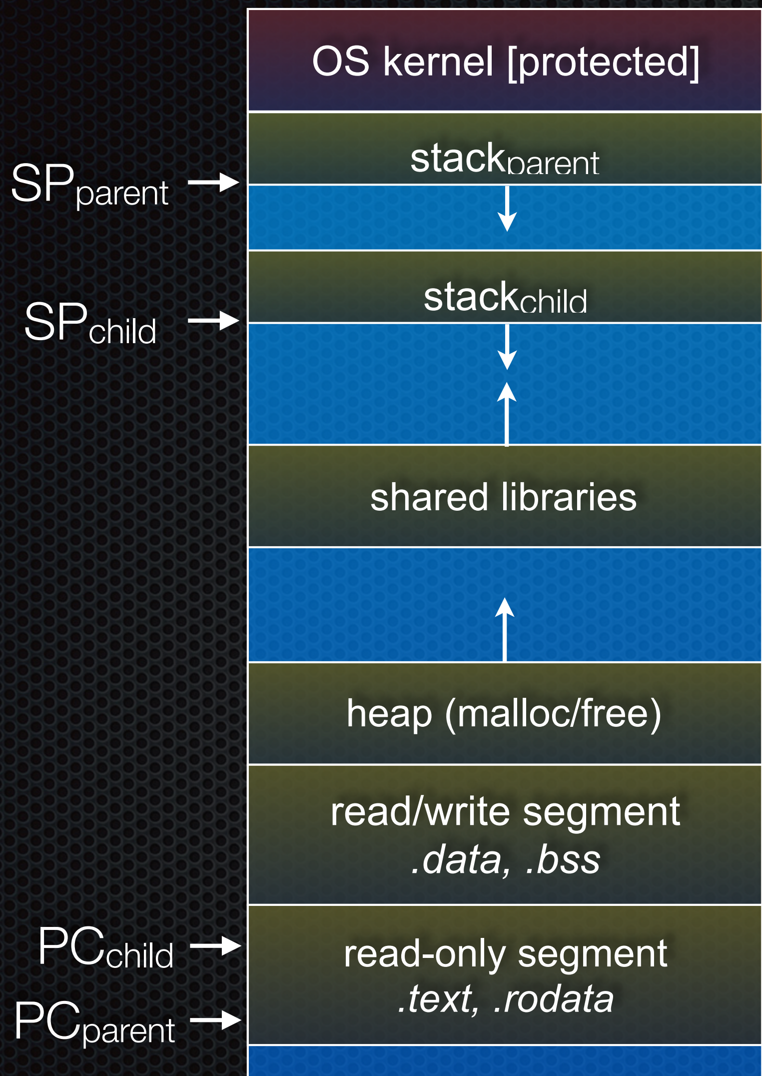
threads and the address space



Pre- thread create

- one thread of execution running in the address space
  - the “main” thread
  - therefore, one stack, SP, PC
- that main thread invokes a function to create a new thread
  - typically “pthread_create( )”

threads and the address space



Post- thread create

- two threads of execution running in the address space
  - the "main" thread (parent)
  - the child thread
  - thus, two stacks, SPs, PCs
- both threads share the heap and text segment (globals)
  - they can cooperatively modify shared data

threads

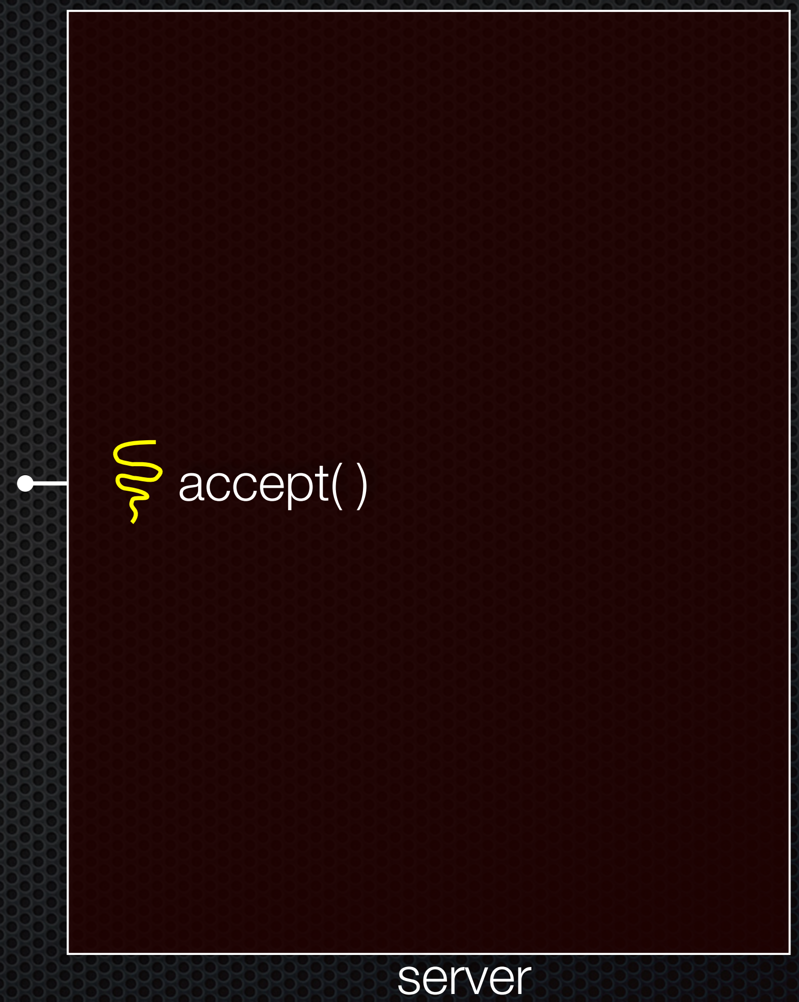
see thread_example.cc

Concurrent server with threads

A single ***process*** handles all of the connections

- but, a parent ***thread*** forks (or dispatches) a new thread to handle each connection
- the child thread:
  - handles the new connection
  - exits when the connection terminates

Graphically



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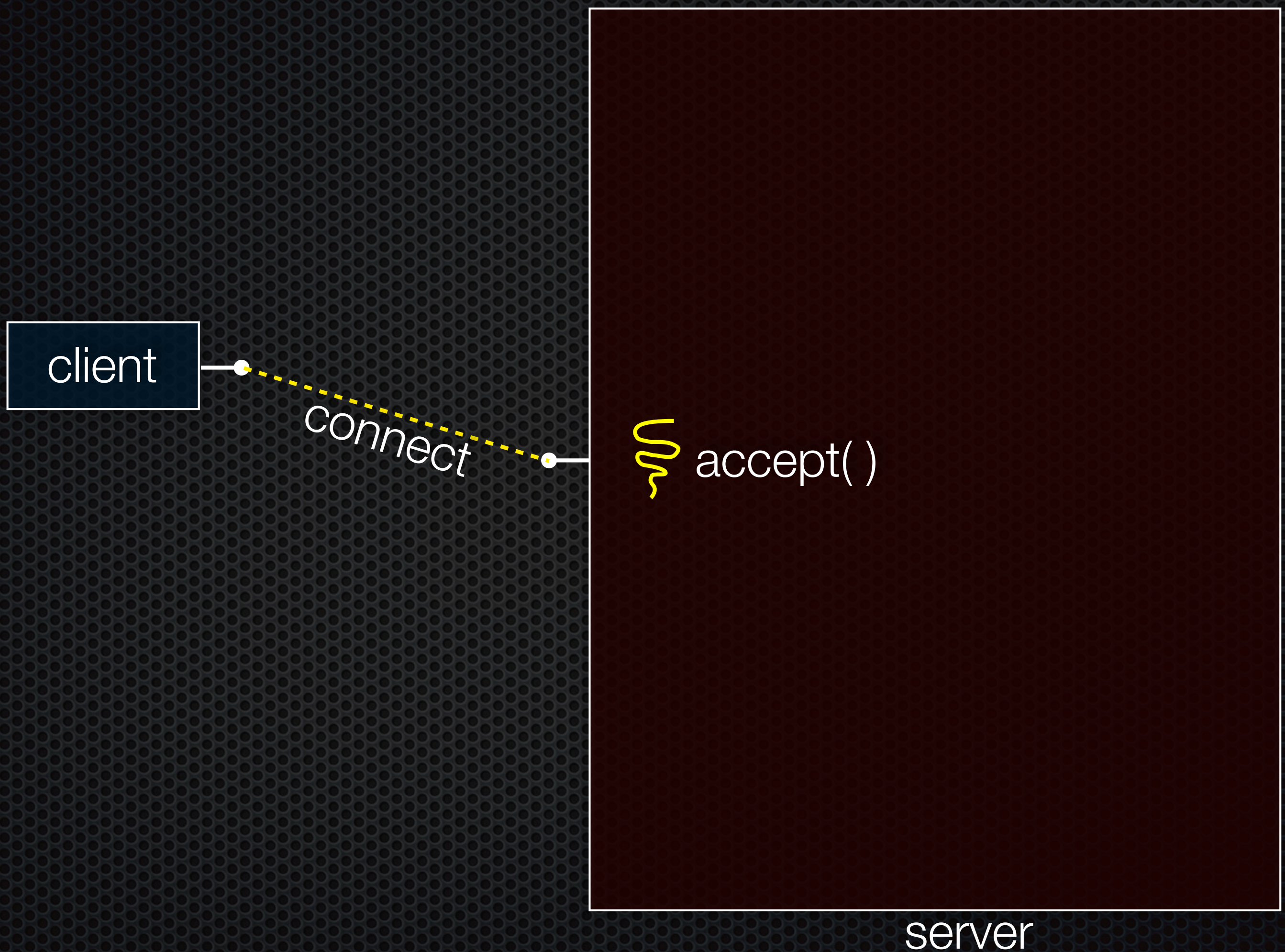

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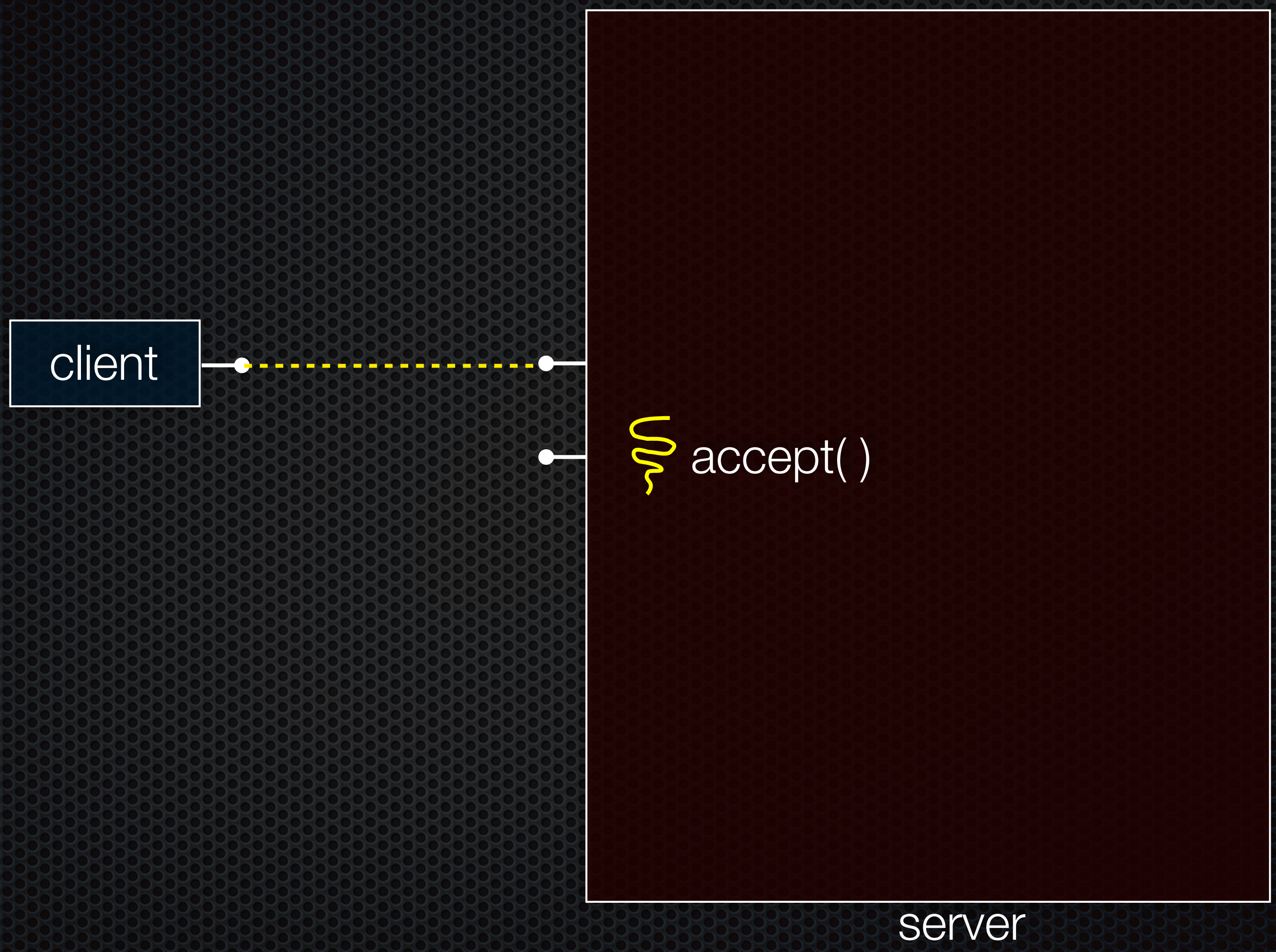

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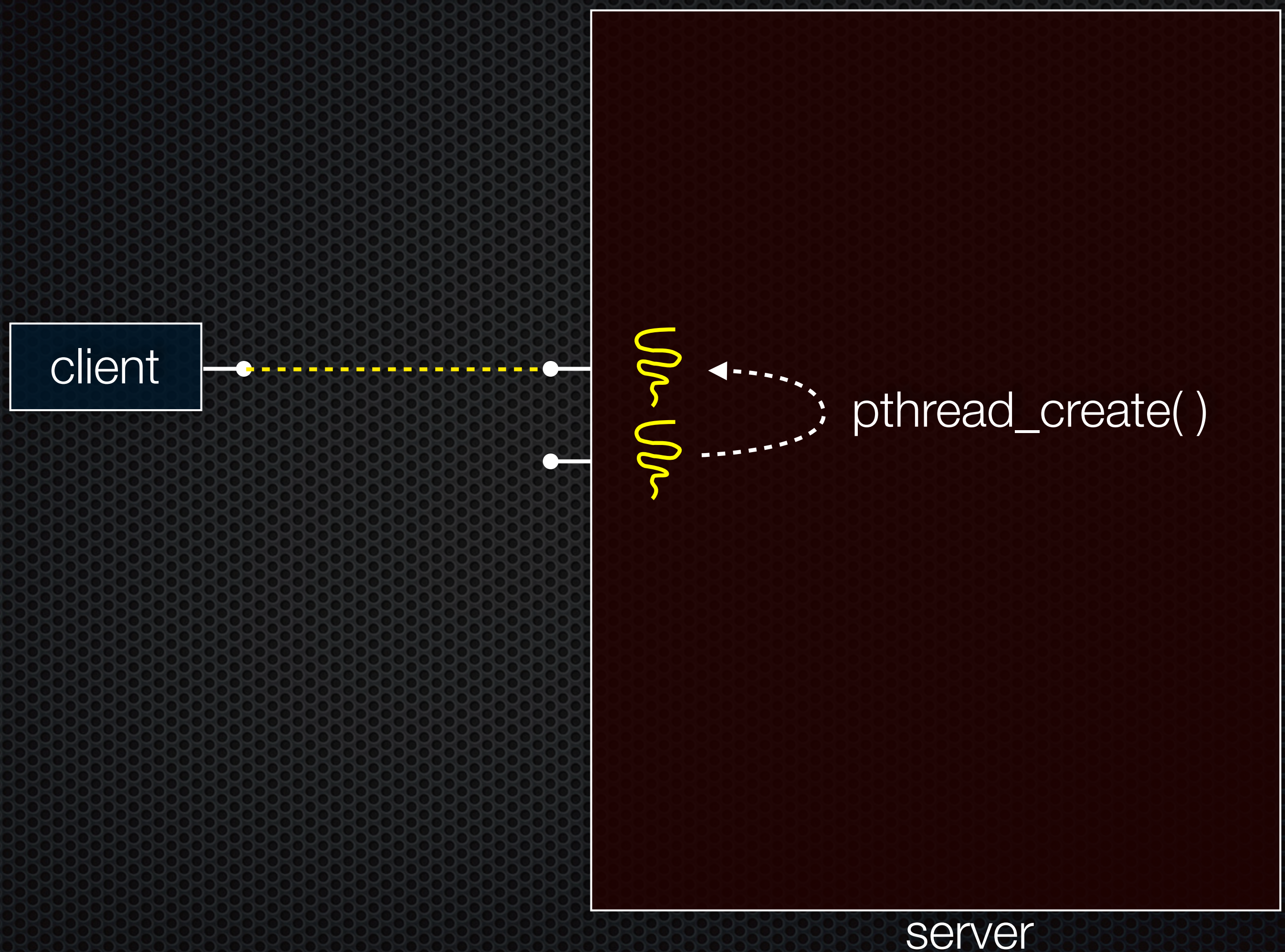

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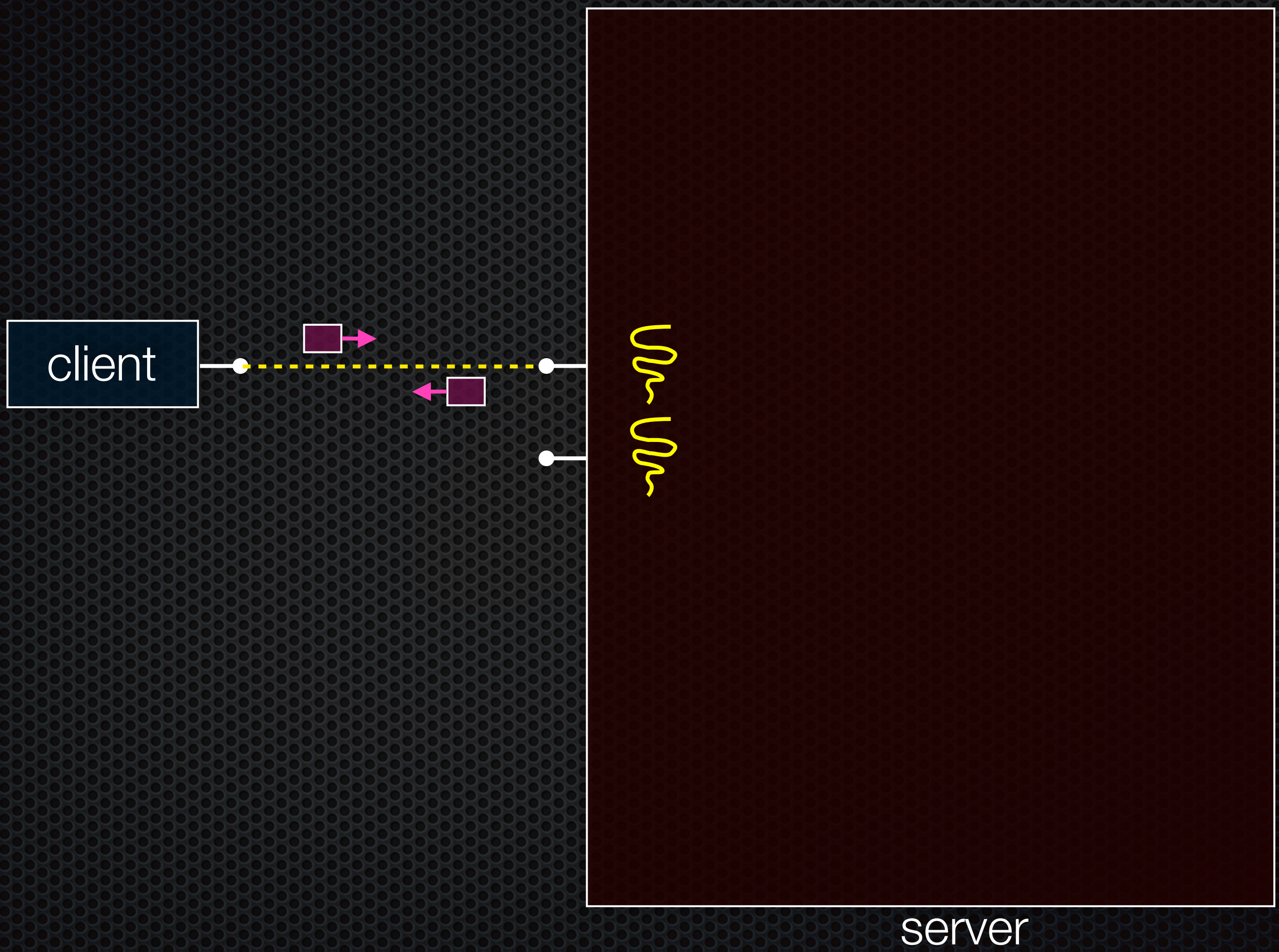

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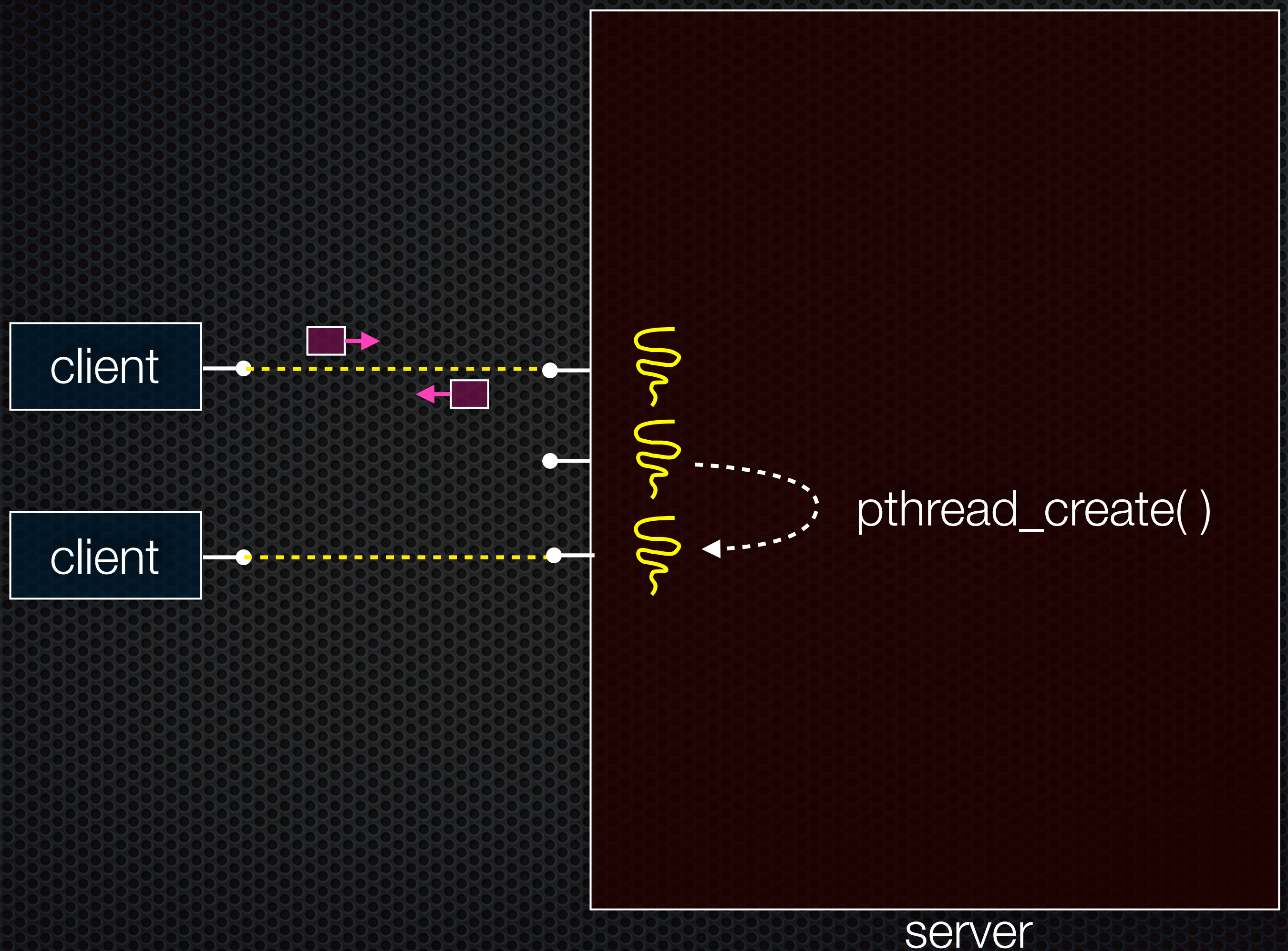

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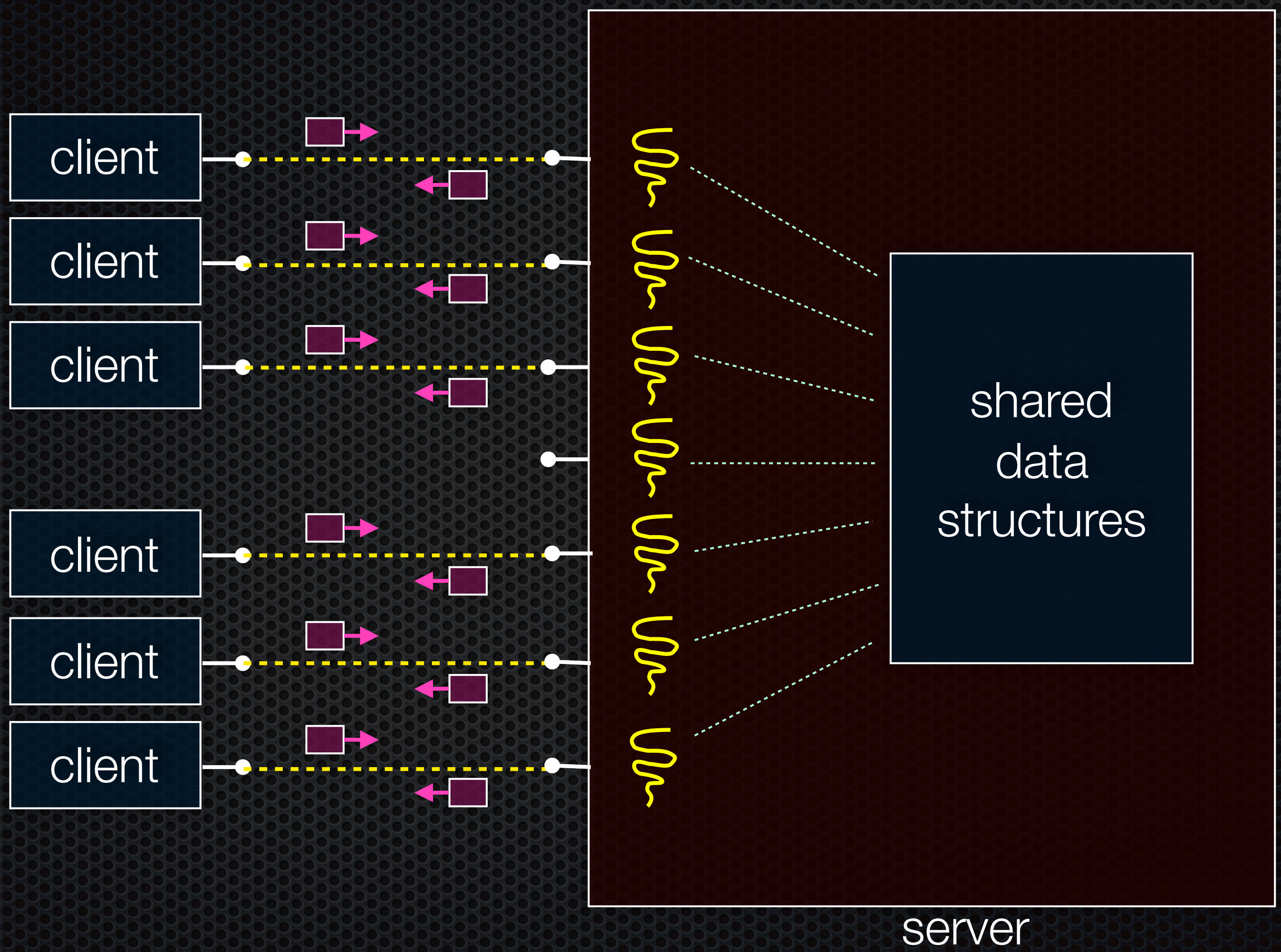

Concurrent with threads

look at ***searchserver_threads/***

Whither concurrent threads?

Benefits

- straight-line code
  - still the case that much of the code is identical to sequential!
- parallel execution; good CPU, network utilization
  - lower overhead than processes
- shared-memory communication is possible

Disadvantages

- ***synchronization*** is complicated
- shared fate within a process; one rogue thread can hurt you badly

How fast is pthread_create?

*run **threadlatency.cc***

Implications?

0.036 ms per thread create; ~10x faster than process forking

- maximum of (1000 / 0.018) = ~60,000 connections per second
- ~10 billion connections per day per core
    - much better

But, writing safe multithreaded code can be serious voodoo

Thread Pools

In real servers we'd like to avoid overhead needed to create a new thread or process for every request

Idea: thread pools

- Create a set of worker threads or processes on server startup, put them in a queue
- When a request arrives, remove the first worker thread from the queue and assign it to handle the request
- When a worker is done it places itself back on the queue and then sleeps until dequeued and handed a new request

Threads and 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
  - imagine if two threads try to push an item onto the head of the linked list at the same time
  - depending on how the threads interleave, you might end up with a correct answer, or you might break the data structure altogether

Simple “race” example

If no milk, buy some more

- liveness: if out, somebody buys
- safety: at most one person buys

What happens with multiple threads?

```
if (!milk) {
  buy milk
}
```

Simple “race” example

Does this fix the problem?

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

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 go”
- many different coordination mechanisms have been invented
  - take cse451 for details

Locks

lock acquire

- wait until the lock is free, then take it

lock release

- release the lock
- if other threads are waiting for it
  - wake up exactly one of them
  - give it the lock

simplifies concurrent code

- prevents more than one thread from entering a *critical section*

```
... non-critical code ...

lock.acquire();
  critical section
lock.release();

... non-critical code ...
```

Simple “race” solution

What is the critical section?

- checking for milk
- buying more milk if out

These two steps must be uninterrupted, i.e., ***atomic***

- solution: protect the critical section with a lock

```
milk_lock.lock()

if (!milk) {
  buy milk
}

milk_lock.unlock()
```

pthreads and locks

pthread_mutex_init( )

- creates a mutex (a.k.a. a lock)

pthread_mutex_lock( )

- grabs the lock

pthread_mutex_unlock( )

- releases the lock

*see **lock_example.cc***

C++ 11 Threads

C++ 11 added threads and concurrency to the 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

Might be built on top of <pthread.h>, maybe not

Definitely use in C++ 11 code, but pthread will still be around for a long, long time

Exercise 1

Write a simple “proxy” server

- forks a process for each connection
- reads an HTTP request from the client
  - relays that request to www.cs.washington.edu
- reads the response from www.cs.washington.edu
  - relays the response to the client, closes the connection

Try visiting your proxy using a web browser :)

Exercise 2

Write a client program that:

- loops, doing “requests” in a loop. Each request must:
  - connect to one of the echo servers from the lecture
  - do a network exchange with the server
  - close the connection
- keeps track of the latency (time to do a request) distribution
- keeps track of the throughput (requests / s)
- prints these out

See you on Friday !