CSE 333

Lecture 21 -- fork, pthread_create

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Administrivia

pthreads exercise due Monday morning

HW4 is due Thursday night

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

Final exam Wed., Dec. 13, 2:30 pm

- Some review in section next week; last-minute review Q&A Tue. 12/12, 4:30 pm, EEB 045 (bring questions!)
- Topic list and old exams on web now

Administrivia (Monday)

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Please fill out course evals this week

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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 a 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, disks

fork( )

`pid_t fork(void);`

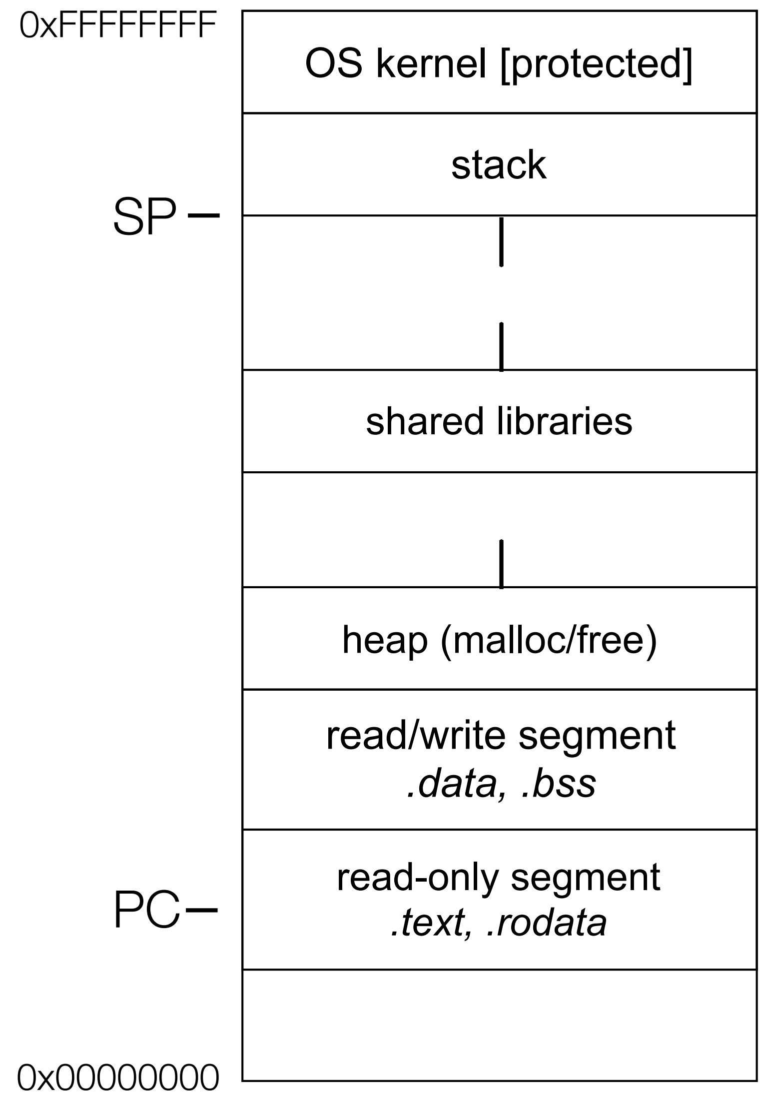
Fork is used to create a new process (the "child") that is an exact clone of the current process (the "parent")

- 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...?

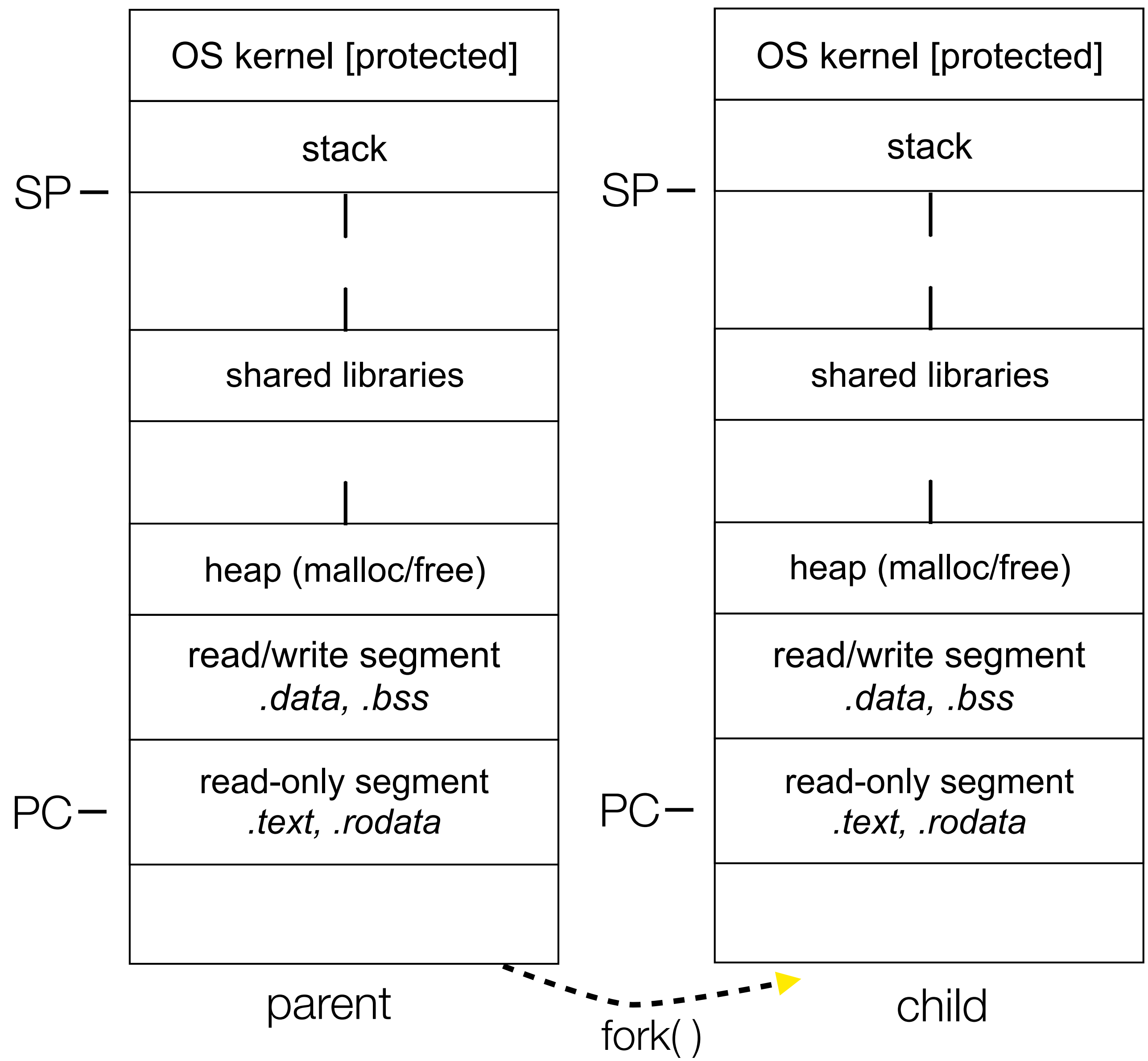
- a process executes within an ***address space***
- the address space includes:
  - a stack (for stack frames)
  - heap (for dynamically allocated data)
  - text segment (containing code)
  - etc.



fork( ) and address spaces

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

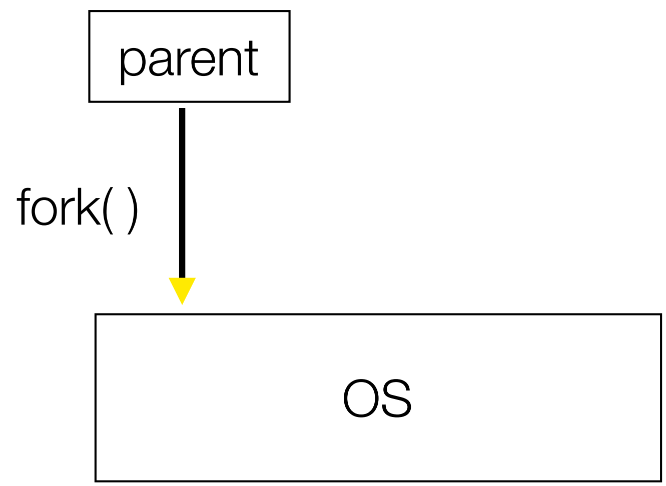
- the new process starts life as a **copy** the old process in (nearly) every way
- the **copies** of the heap, stack, text segment, etc. are (nearly) identical
- the new process has **copies** of the parent's data structures, stack-allocated variables, open file descriptors, and so on



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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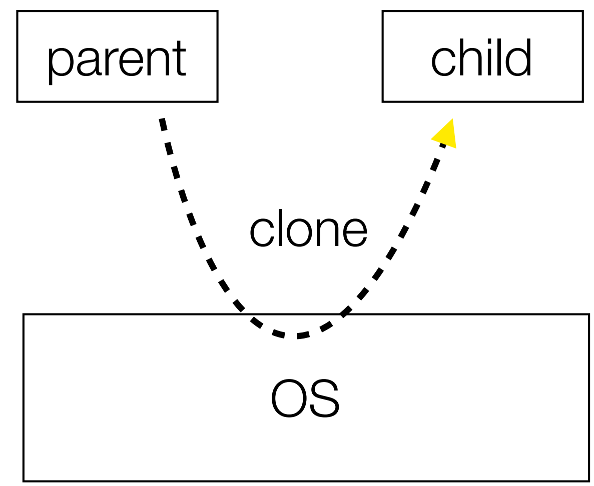

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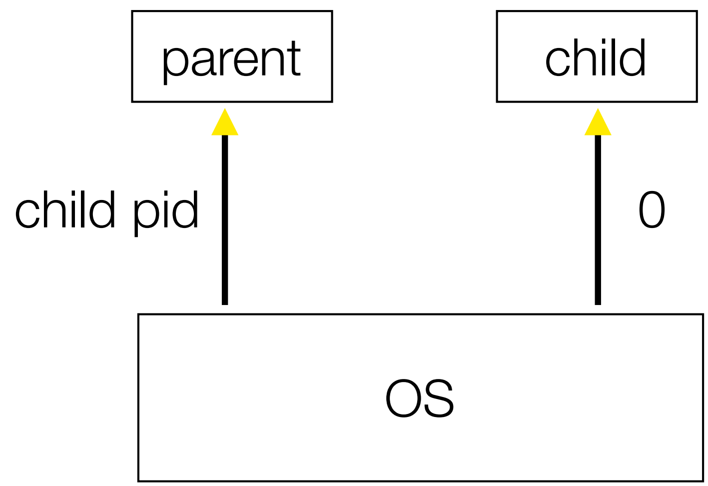


fork( )

fork_example.cc

Concurrency with processes

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

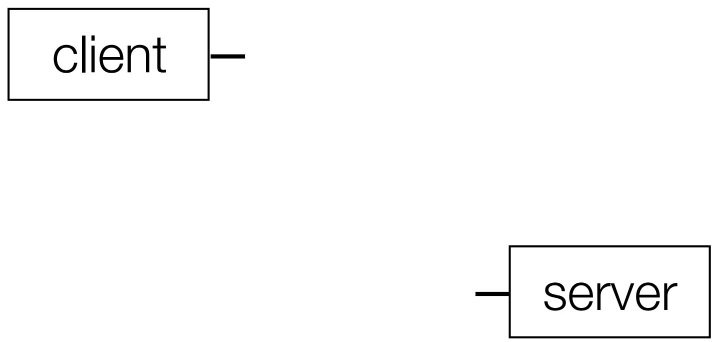
- when a new connection arrives, the parent calls **fork( )** to create a ***child*** process
- the child process handles that new connection, and **exit( )**'s when the connection terminates

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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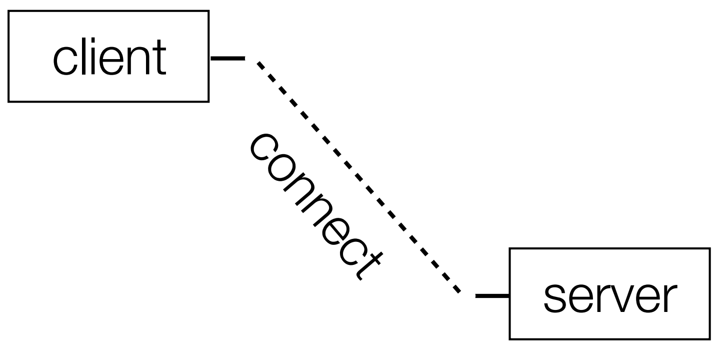

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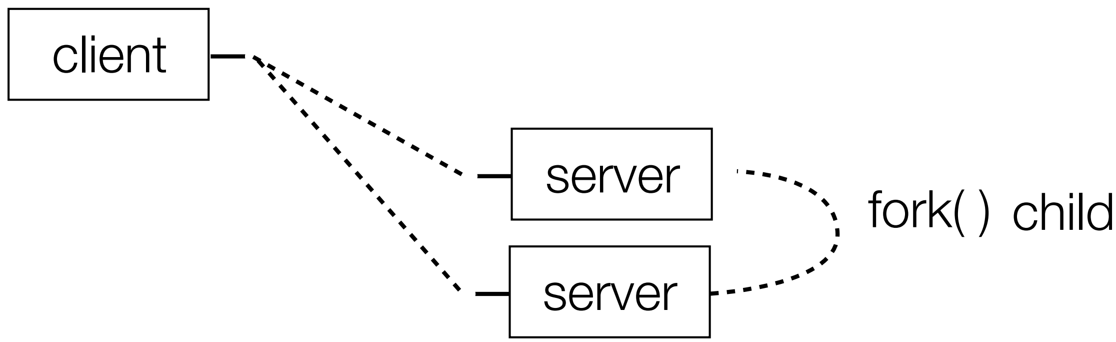

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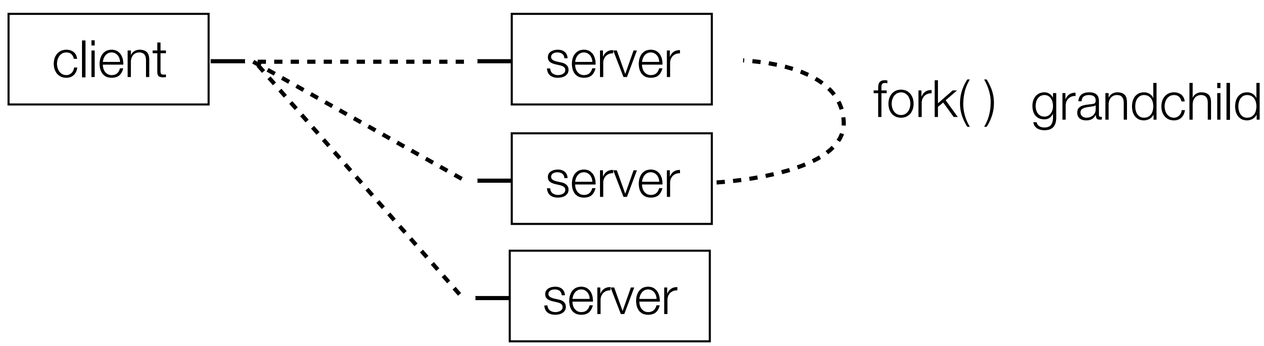

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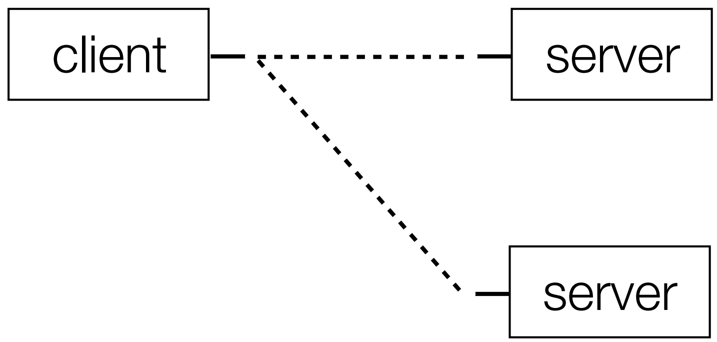
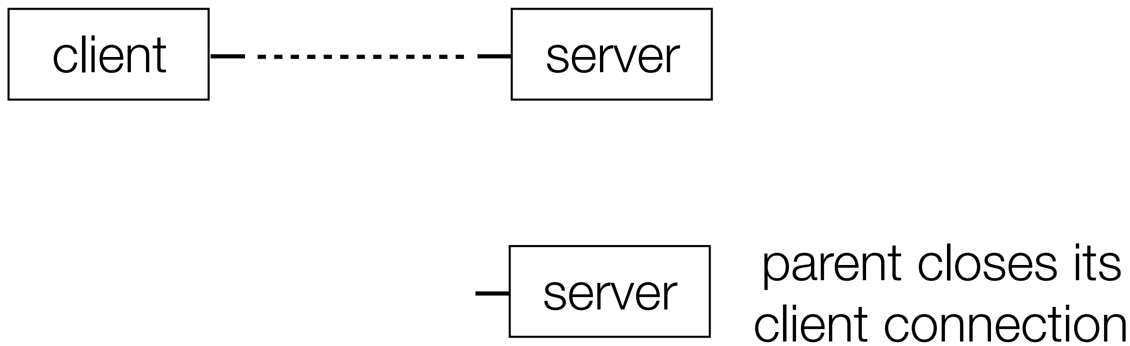


child exit( )'s / parent wait( )'s

Graphically



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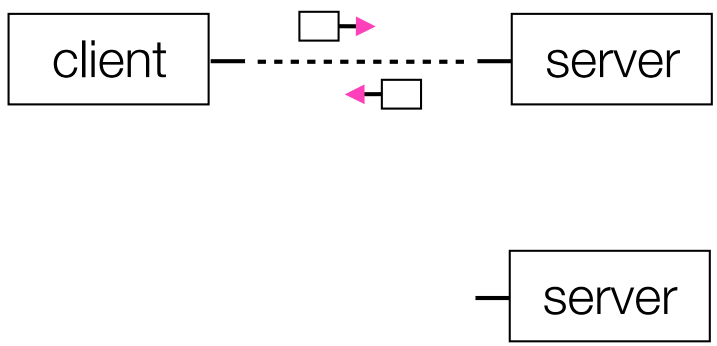

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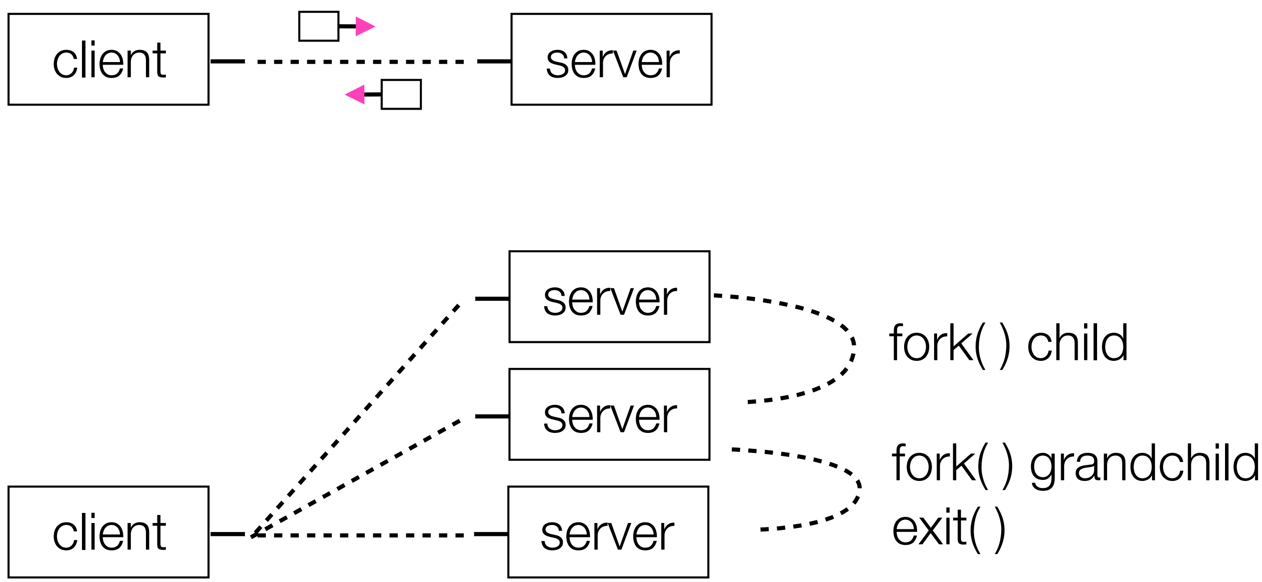

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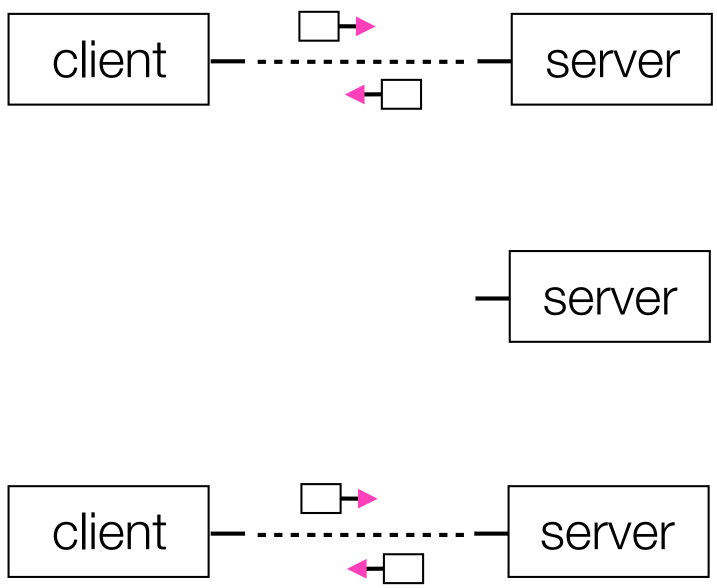

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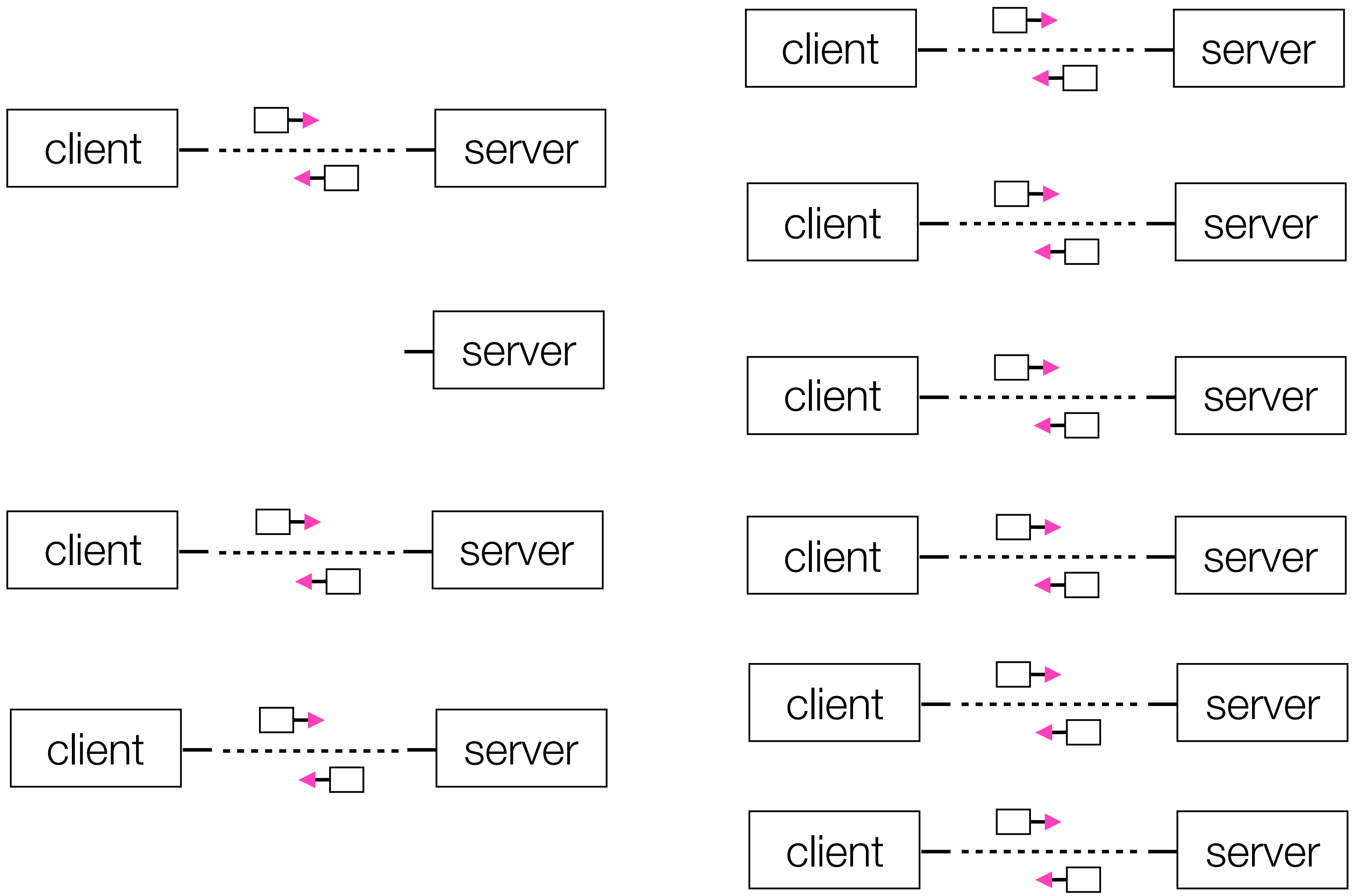


Concurrent with processes

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 served *O*(750 billion) page views per day 4 years ago!

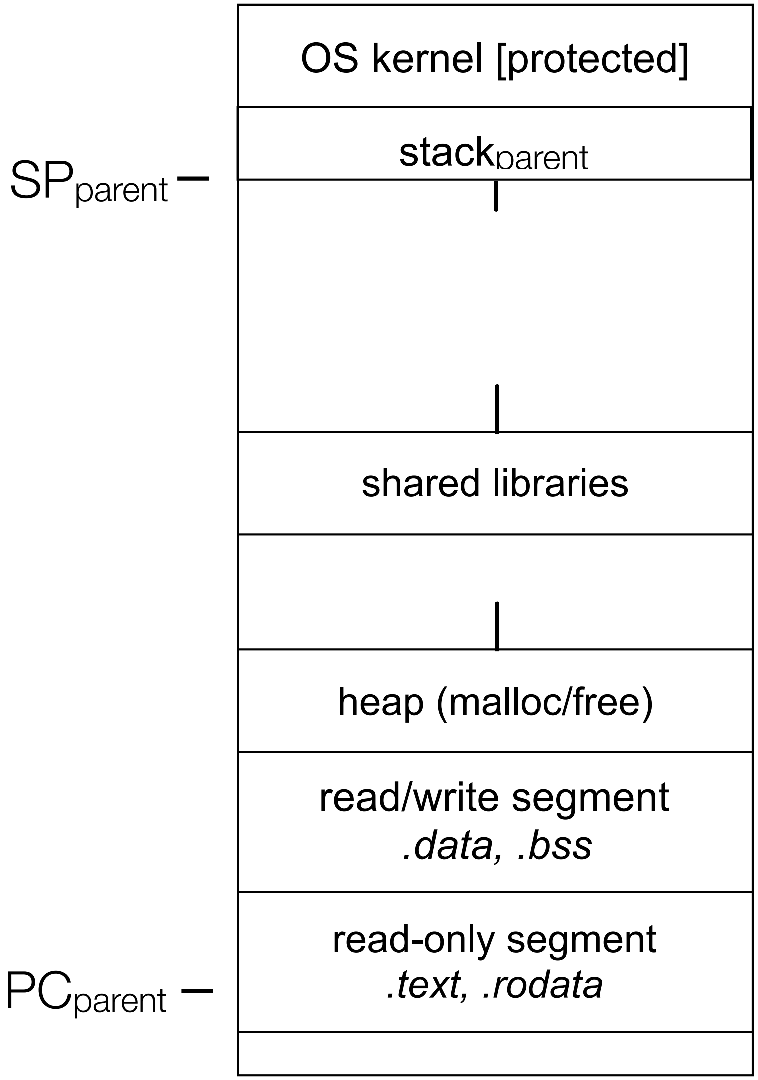
would need 3,000 -- 6,000 cores just to handle fork( ),
i.e., without doing any work for each connection!

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

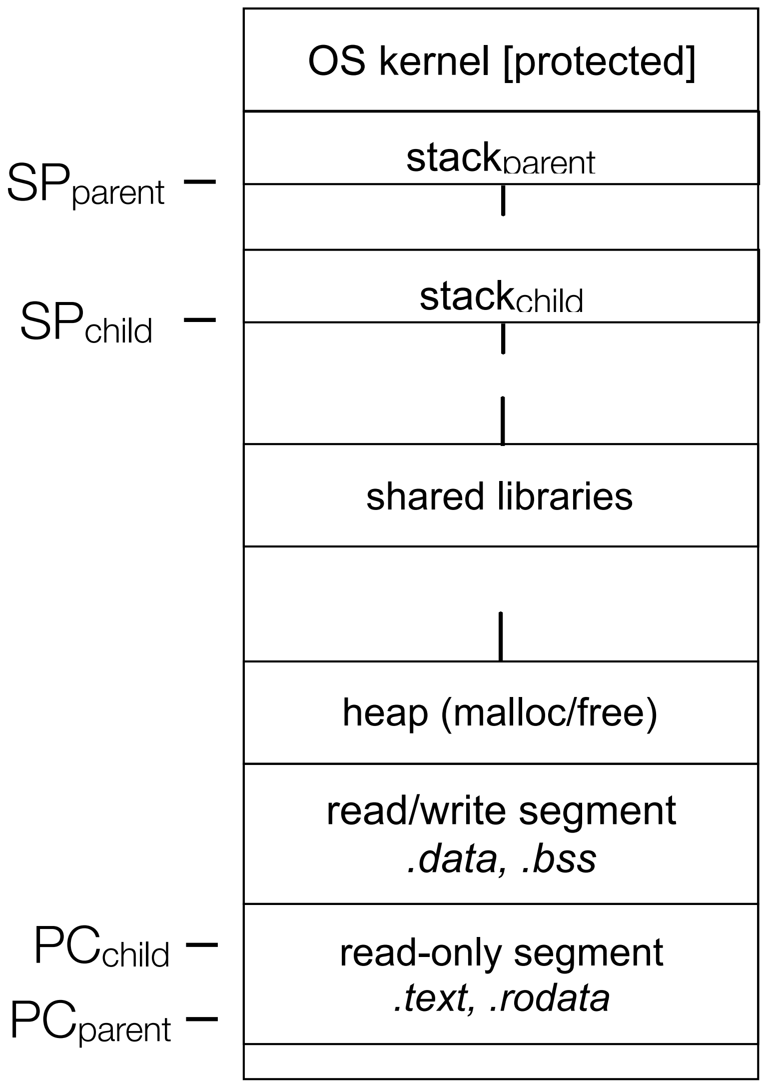
threads and the address space



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

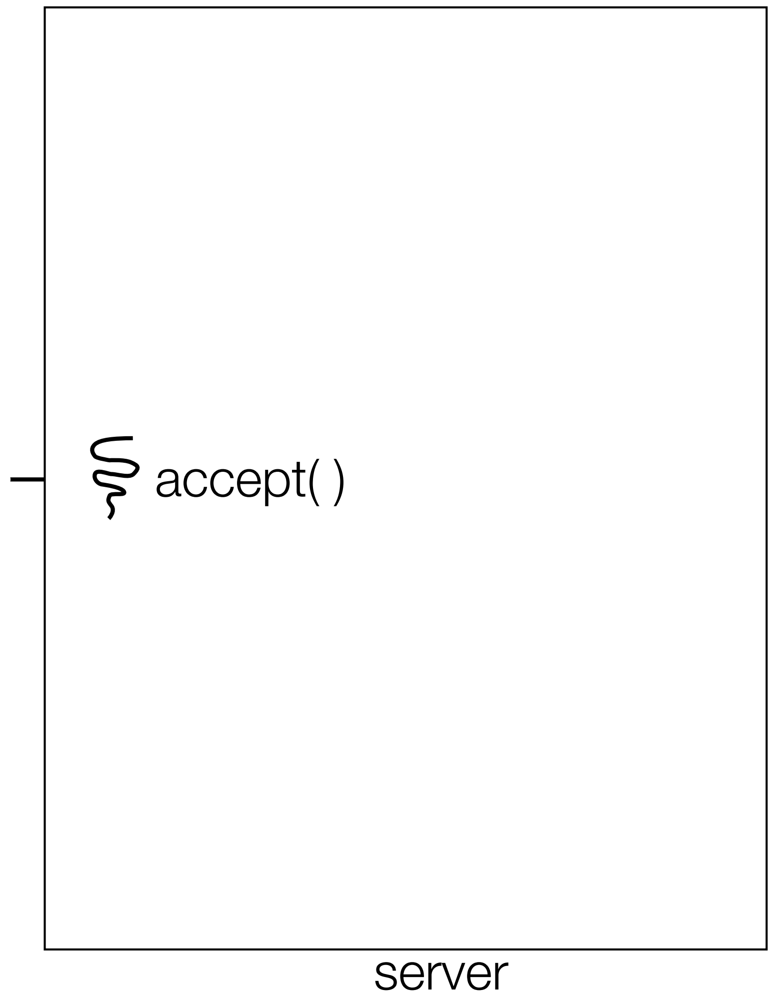
see thread_example.cc

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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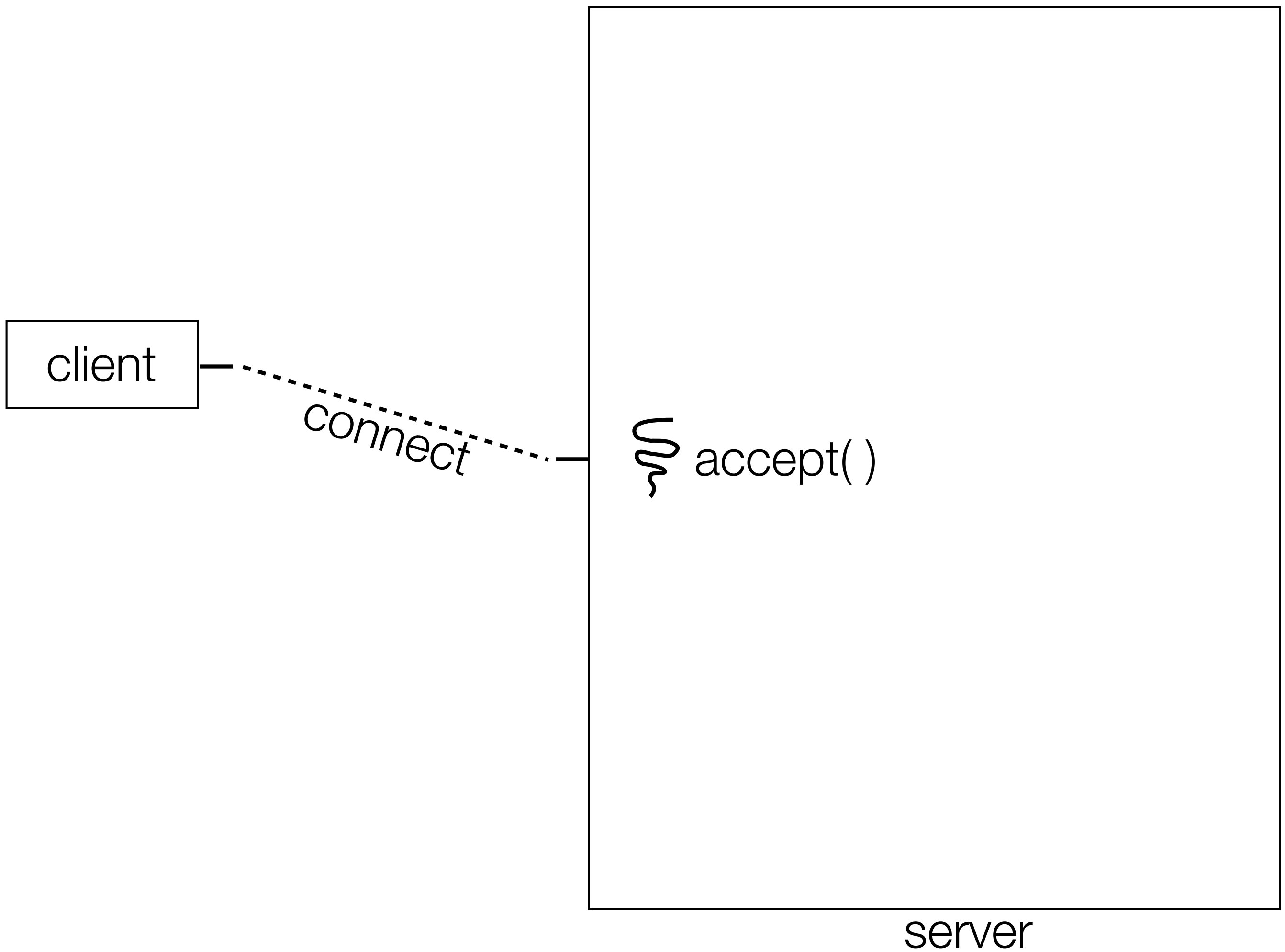

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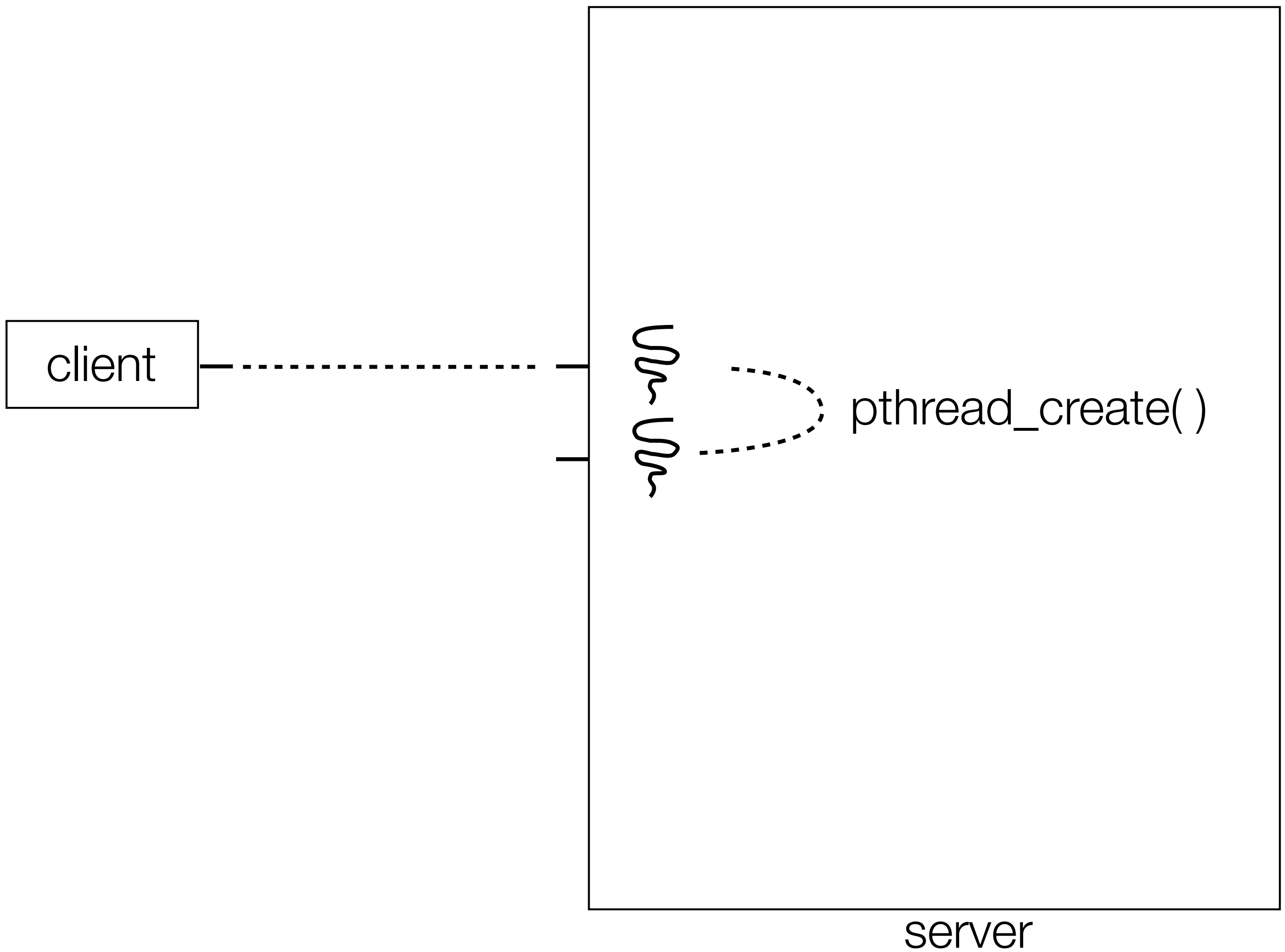

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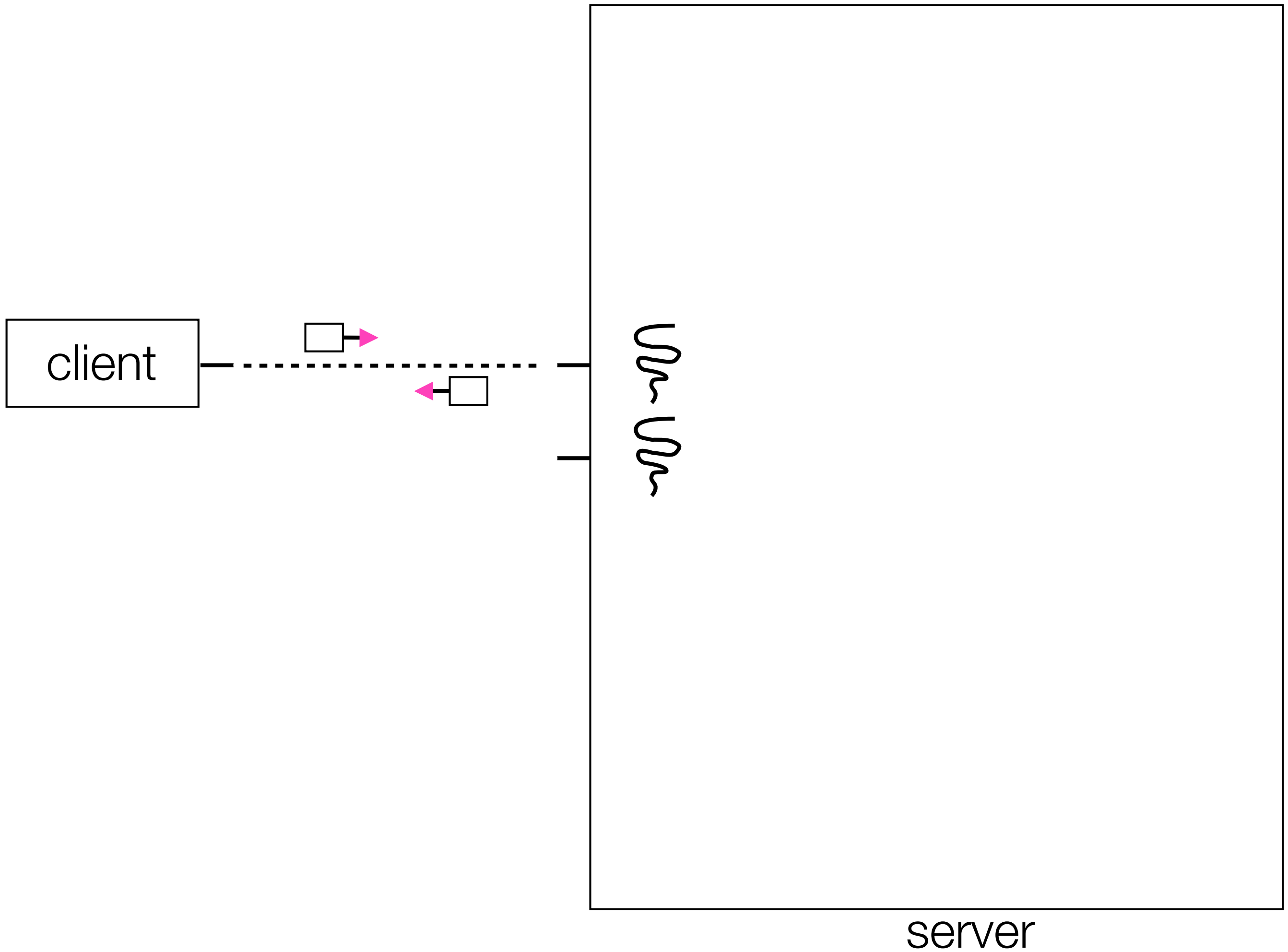

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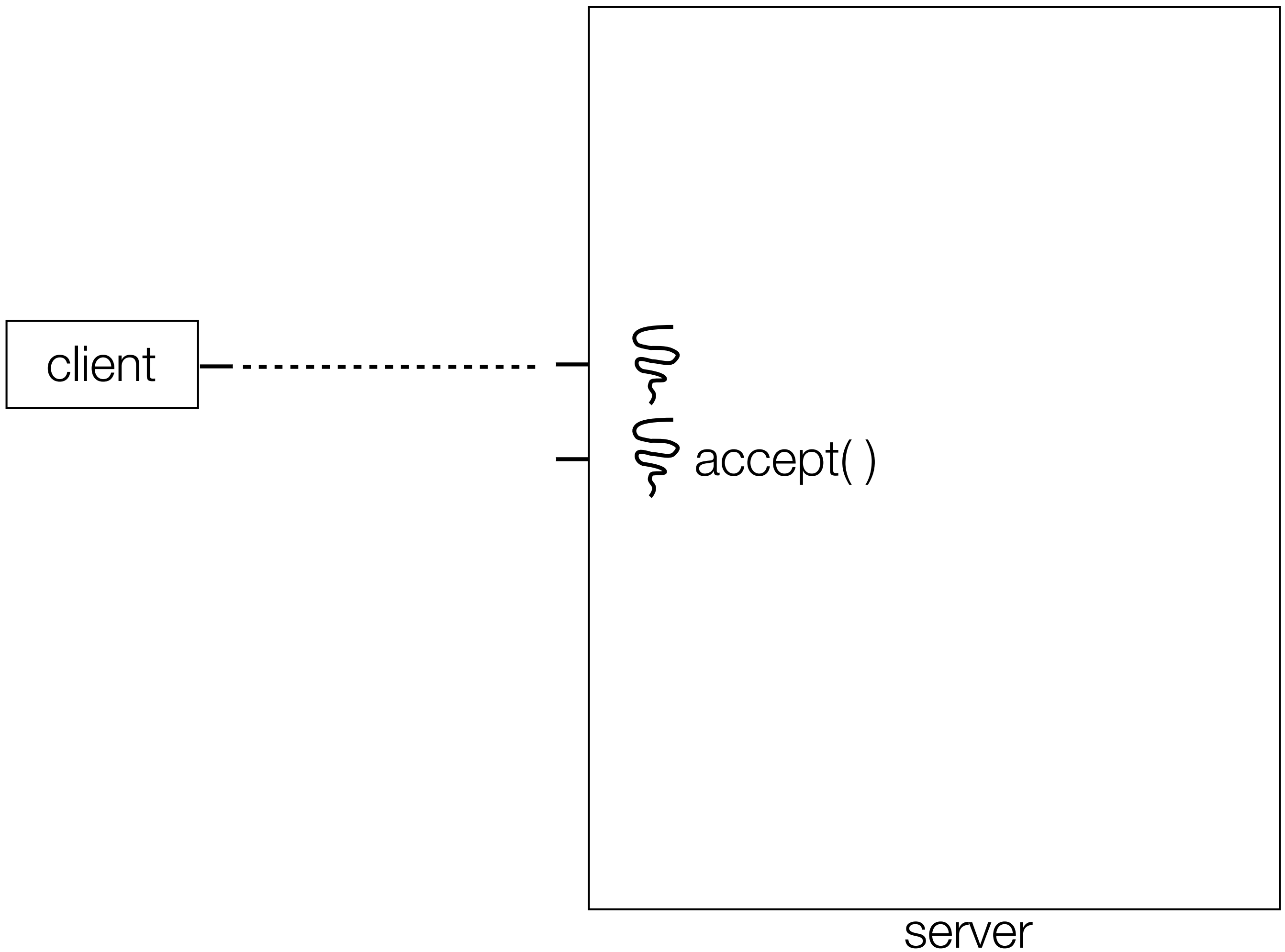

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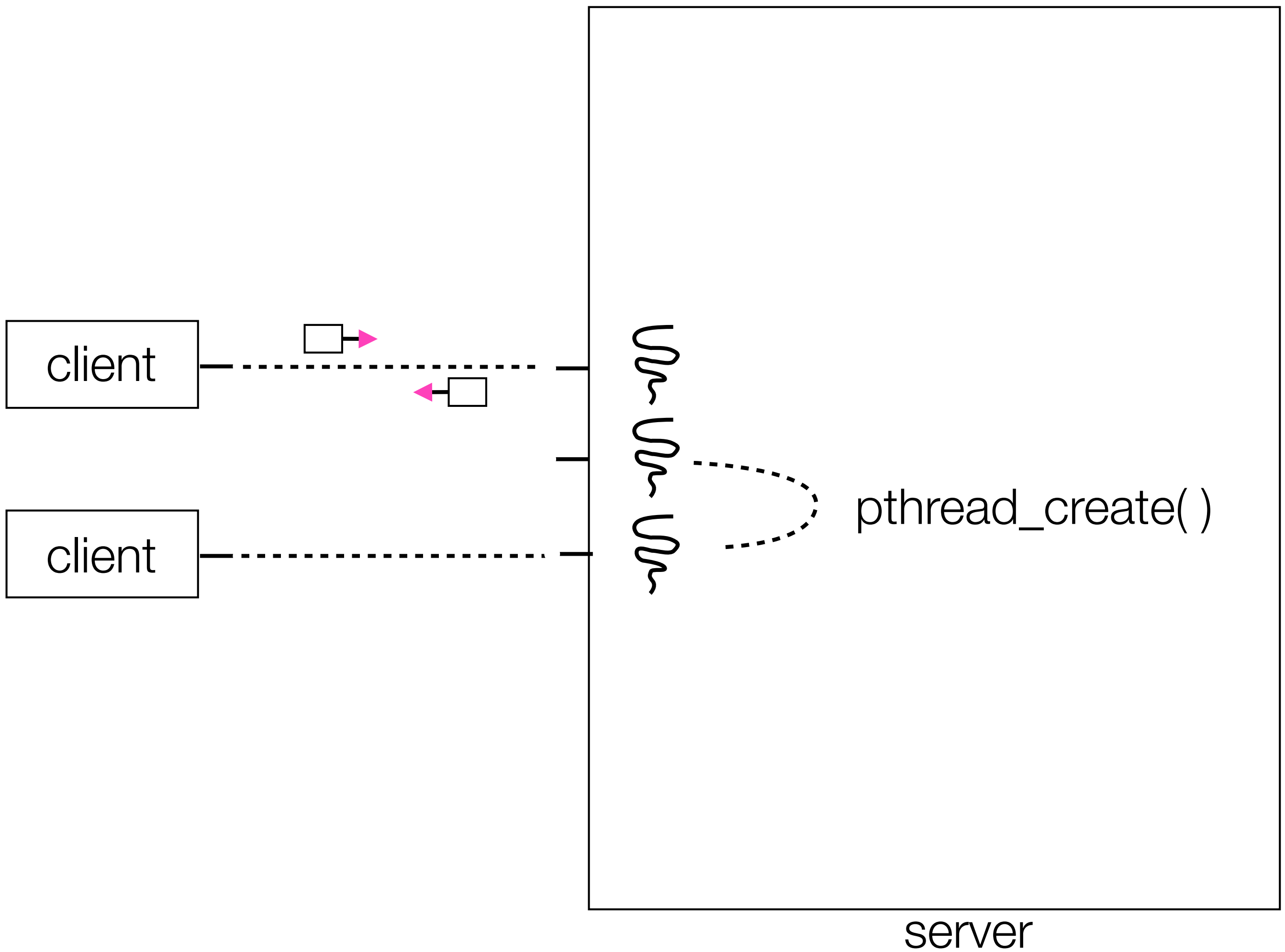

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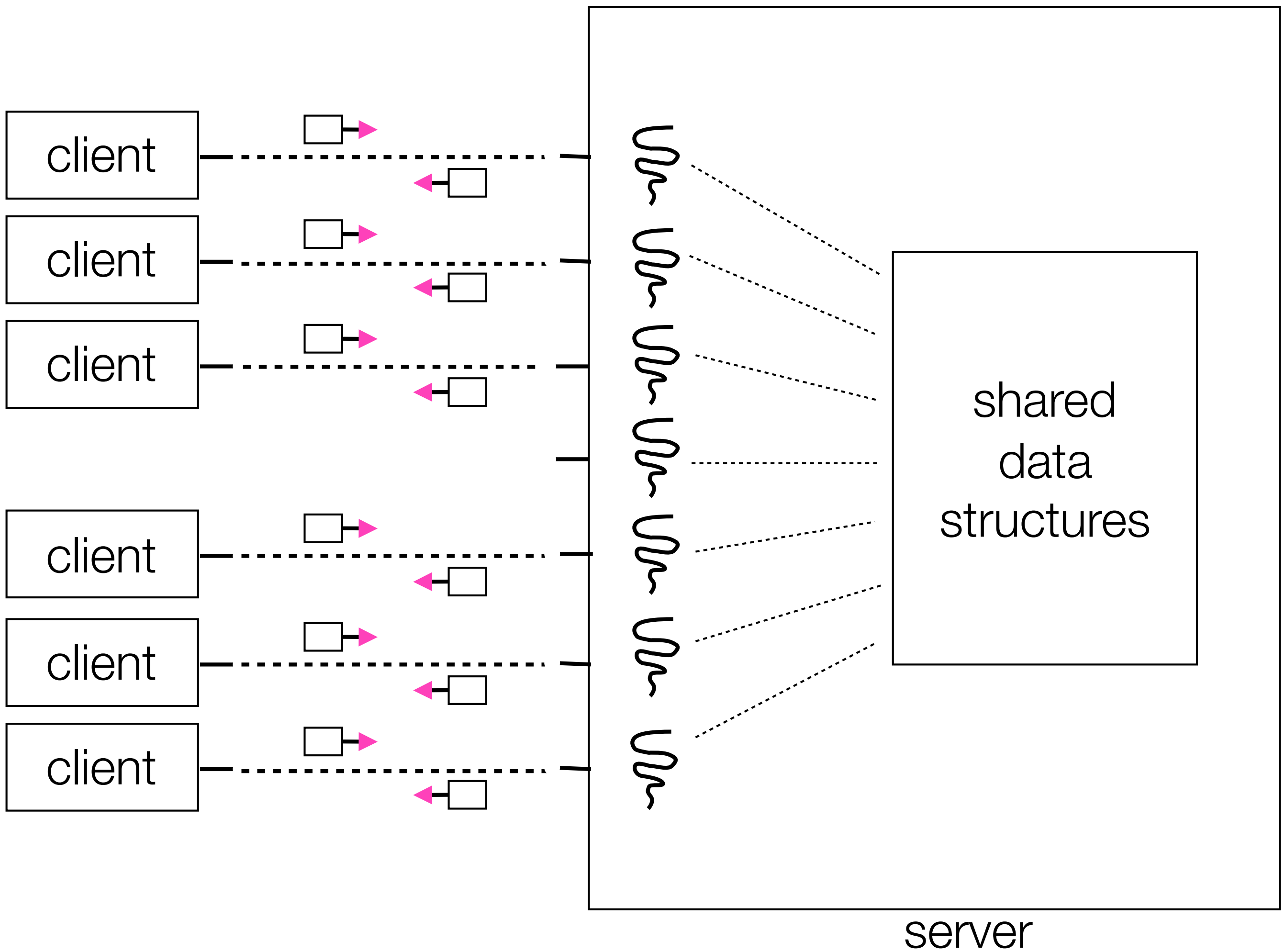

Concurrent with threads

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 pthreads will still be around for a long, long time (and use pthreads in current exercise)

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 Wednesday !