CSE 333

Lecture 22 -- fork, pthread_create, select

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Administrivia

HW4 out on Monday

- you're gonna love it

Final exam

- Wednesday, June 8th, 2:30-4:20pm, in this room
- will not be offering it early or late

Last time

We implemented a simple server, 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 four versions of the 'echo' server

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

Sequential

pseudocode:

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

*look at **echo_sequential.cc***

Whither sequential?

Benefits

- super simple to build

Disadvantages

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

Concurrency with processes

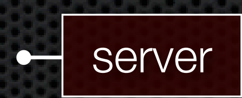
The ***parent*** process blocks on **accept( )**, waiting for a new client to connect

- 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

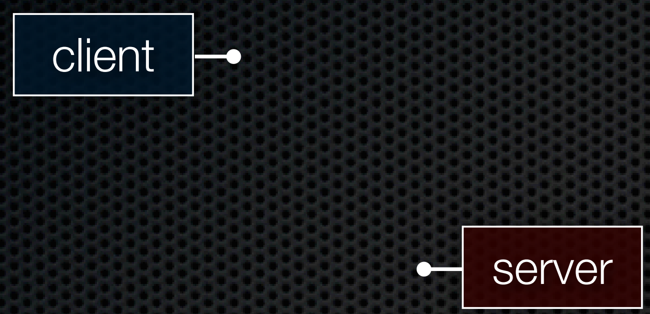
Remember that children become “zombies” after death

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

Graphically



Graphically



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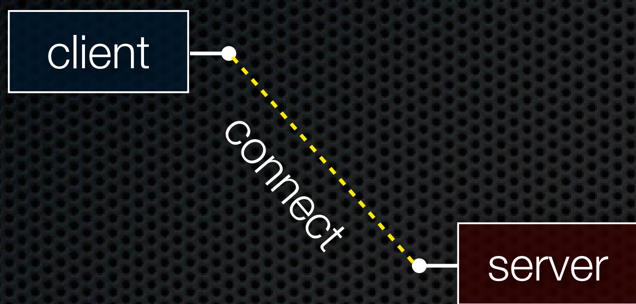

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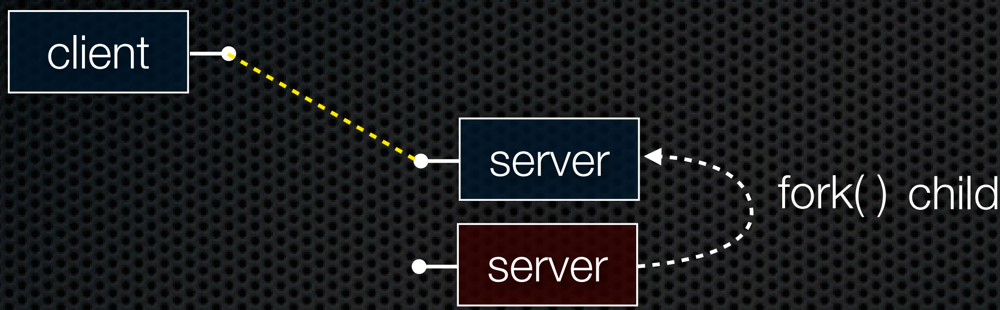

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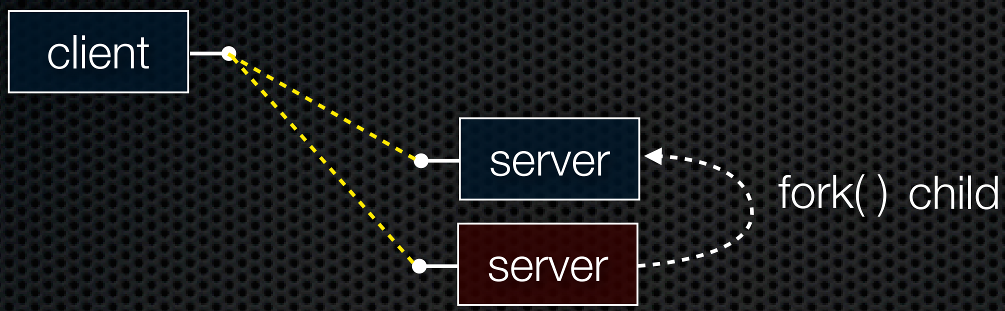

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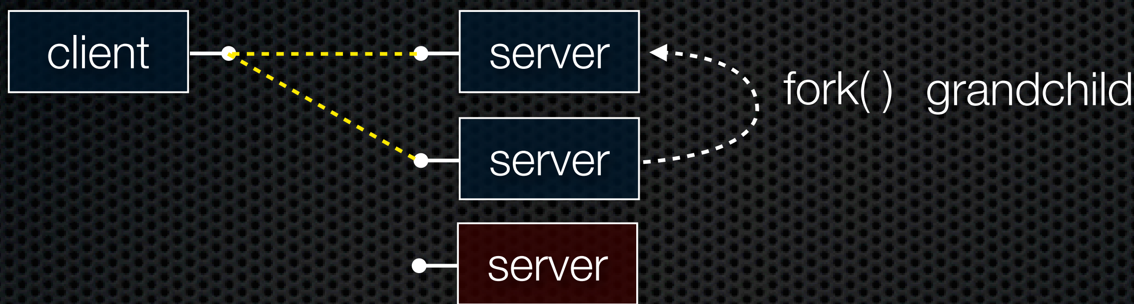

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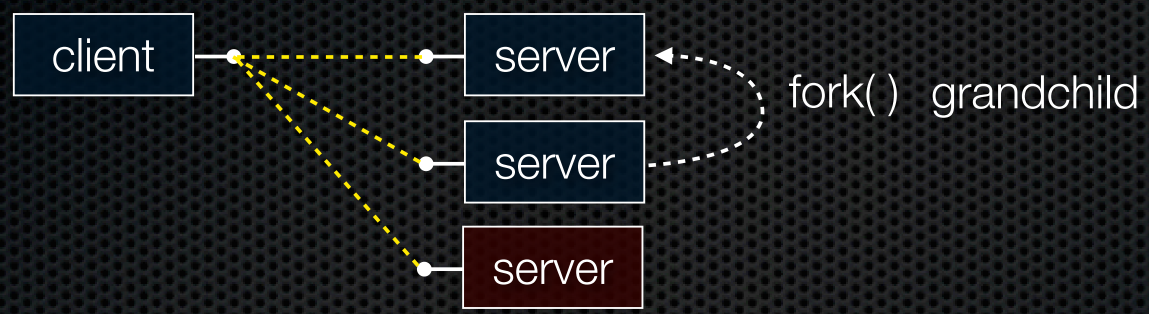

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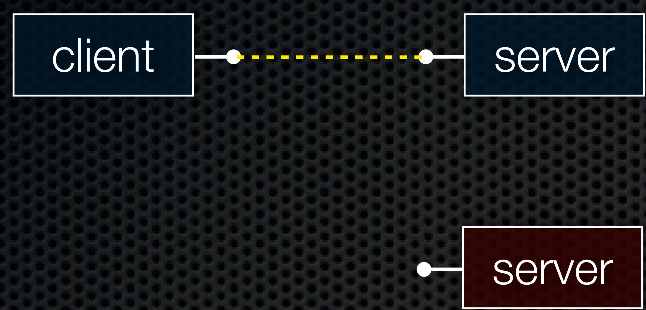
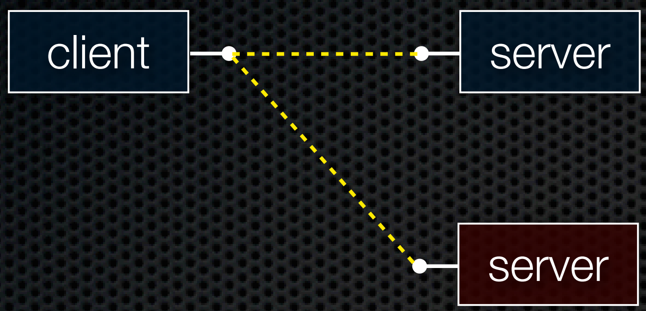


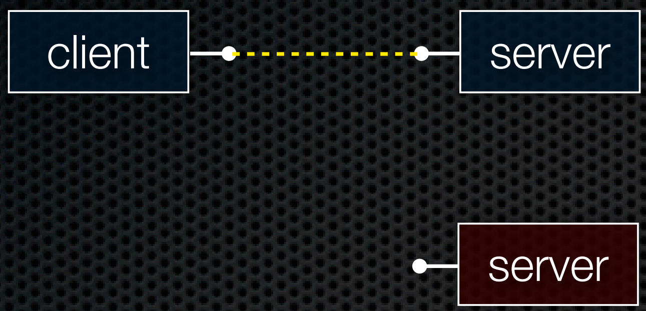
child exit( )'s / parent wait( )'s

Graphically



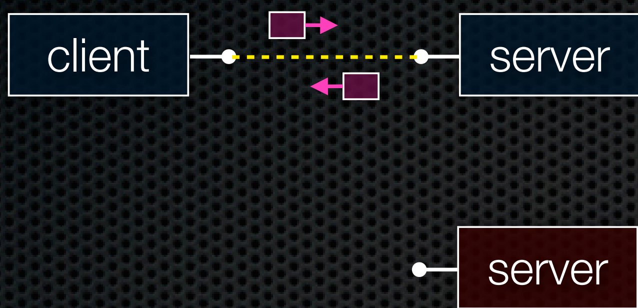
child exit( )'s / parent wait( )'s

Graphically



parent closes its
client connection

Graphically



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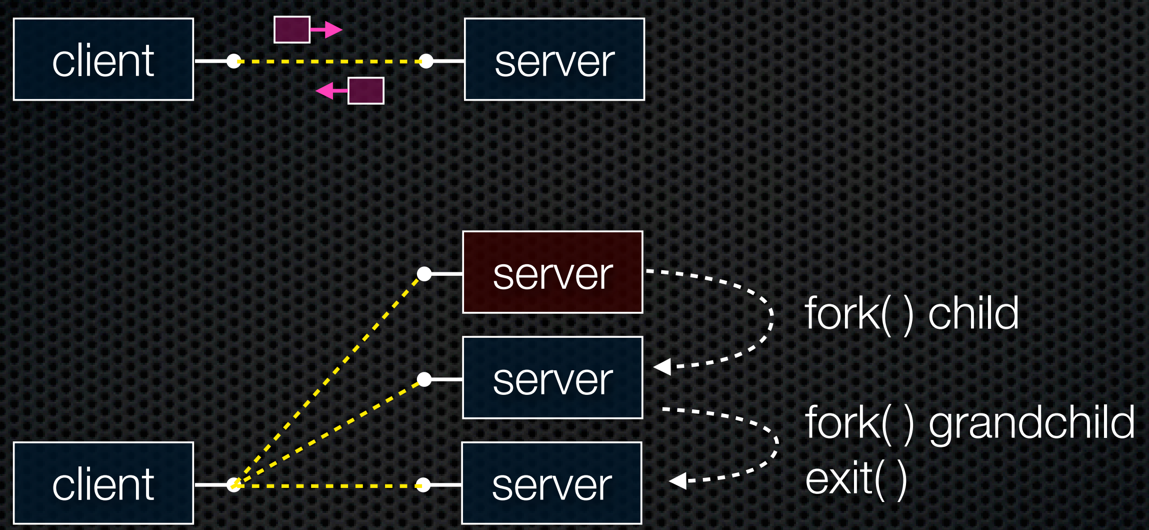

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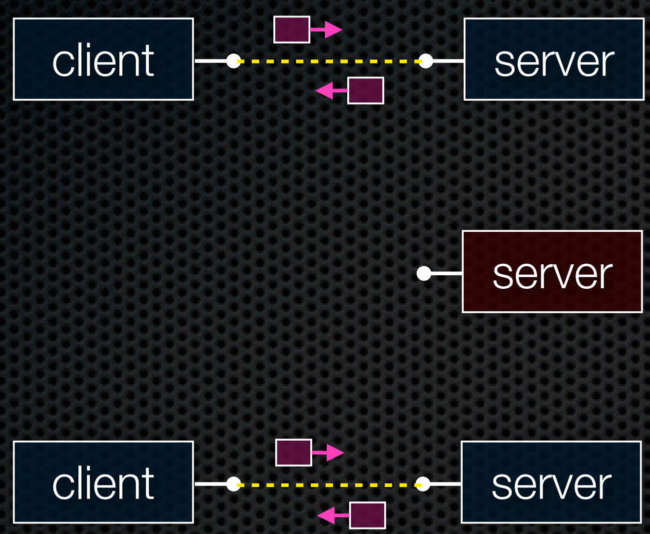

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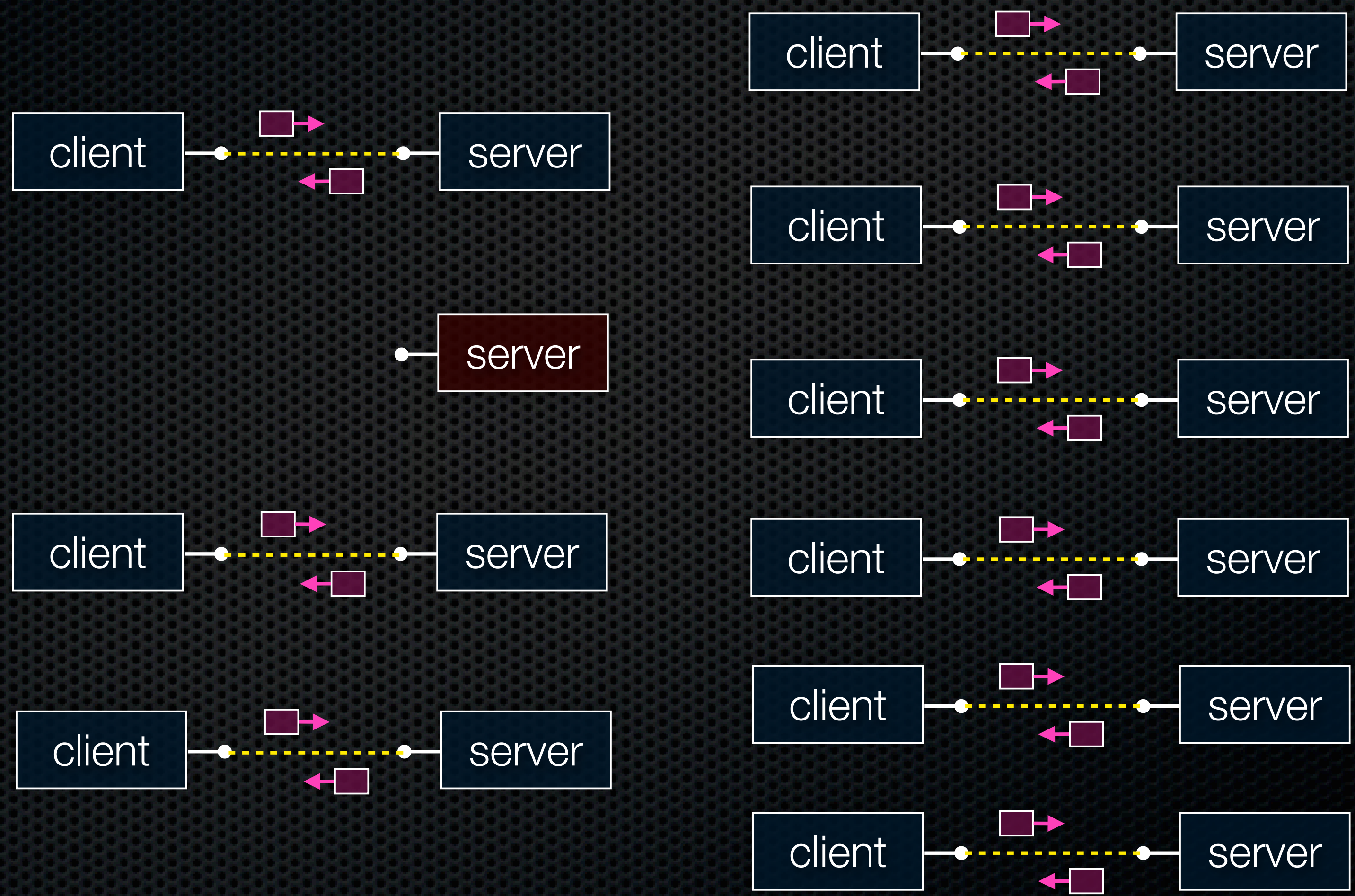


Concurrent with processes

look at ***echo_concurrent_processes.cc***

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?

0.18 ms per fork

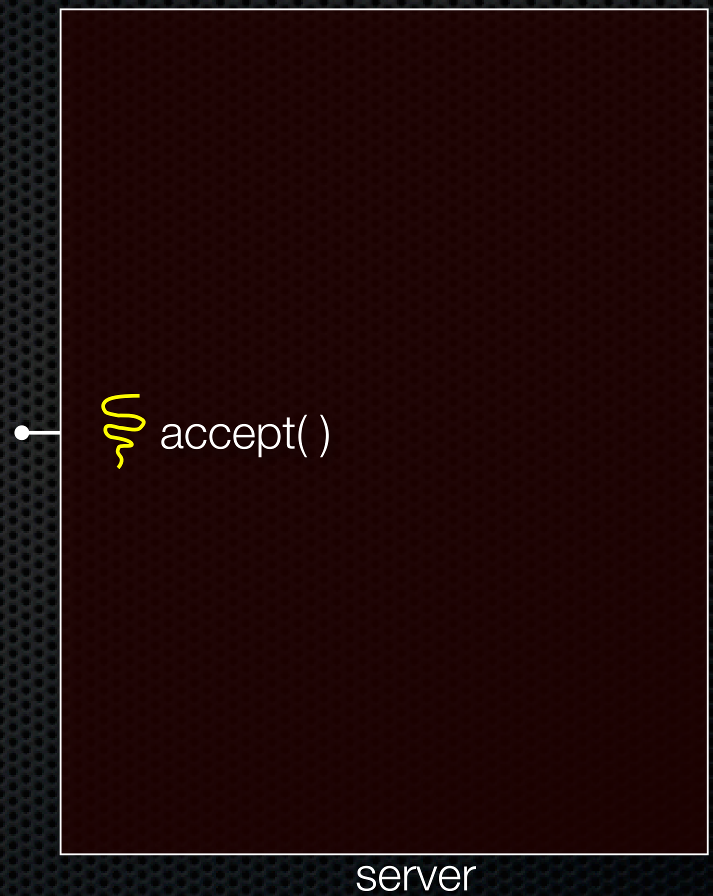
- maximum of (1000 / 0.18) = 5,555.5 connections per second
- 0.5 billion connections per day per machine
  - fine for most servers
  - too slow for a few super-high-traffic front-line web services
    - Facebook serves O(750 billion) page views per day
    - guess ~1-20 HTTP connections per page
    - would need 3,000 -- 60,000 machines just to handle fork( ), i.e., without doing any work for each connection!

Concurrency 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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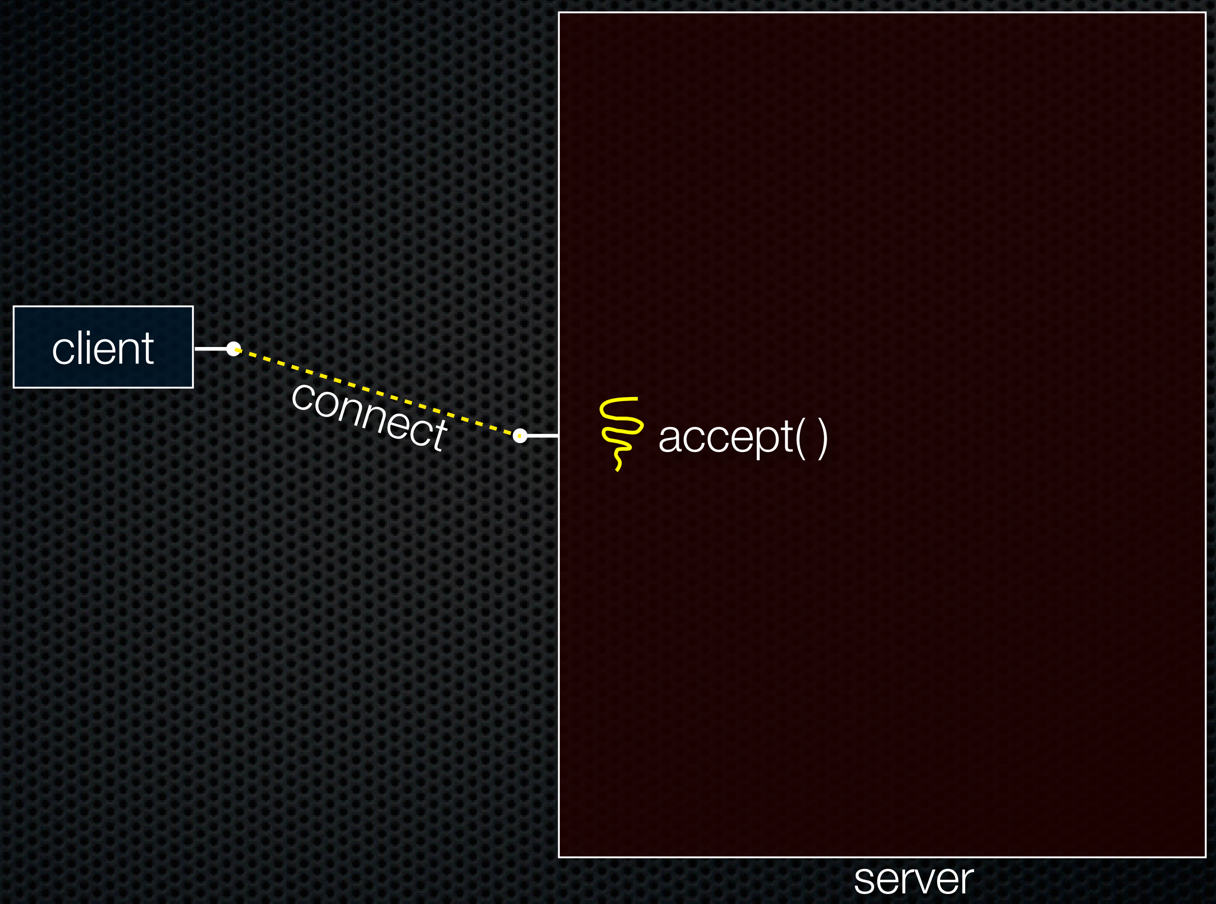

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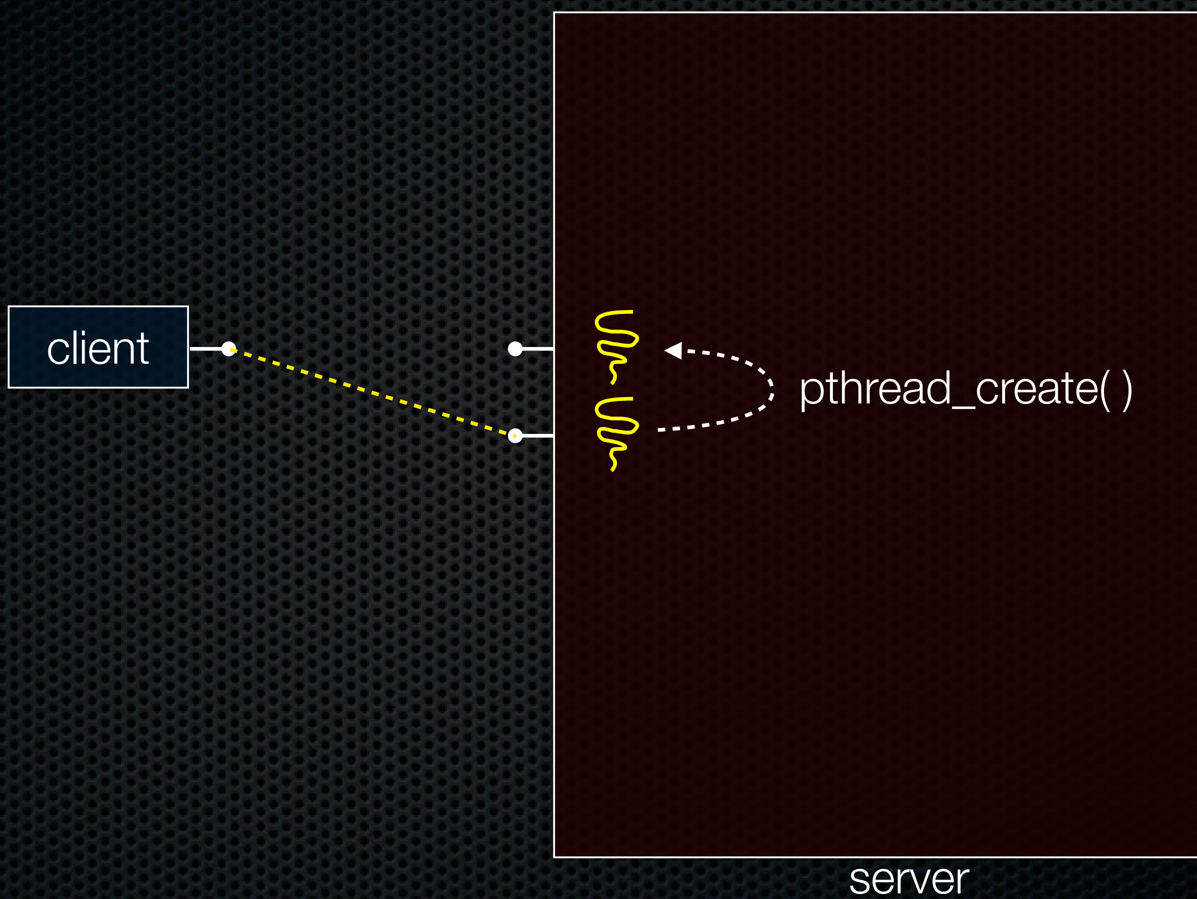

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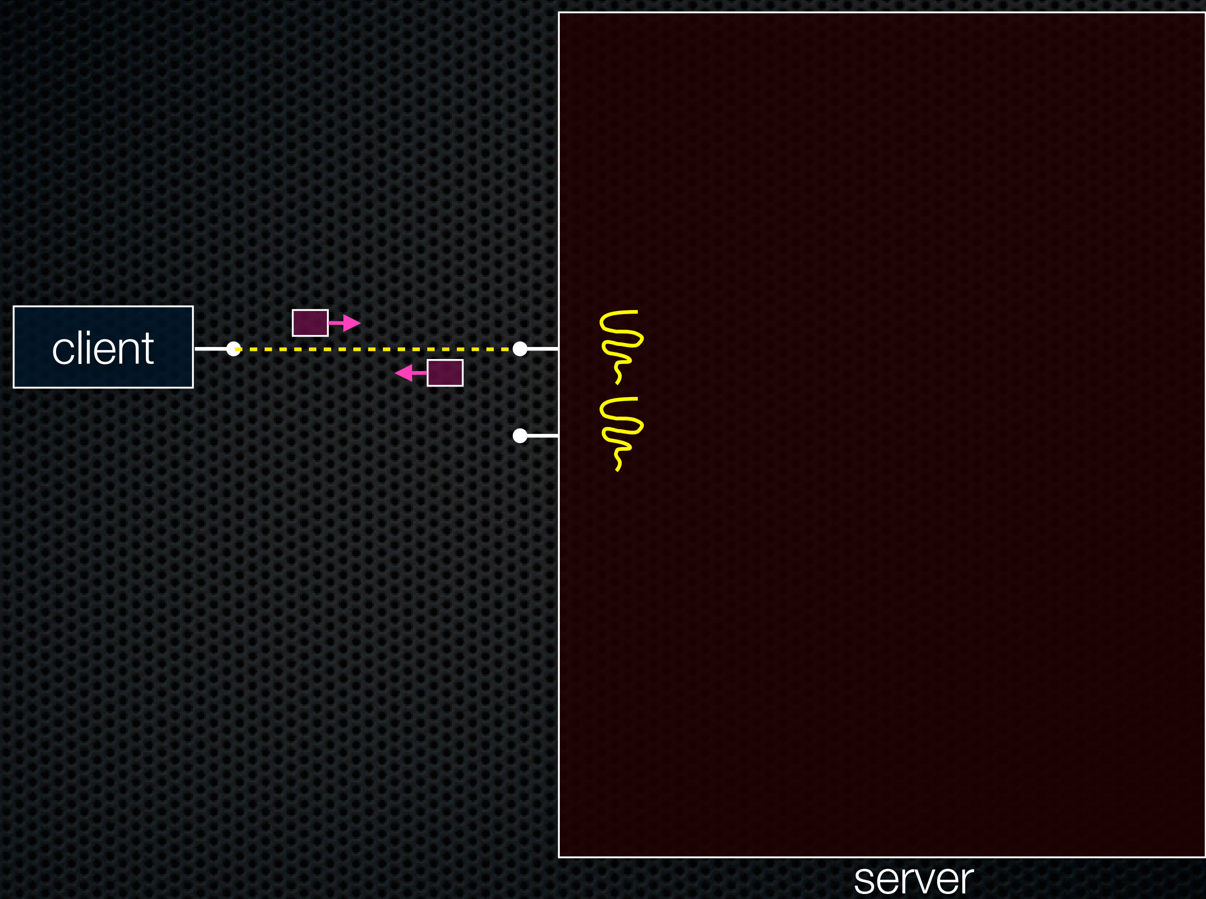

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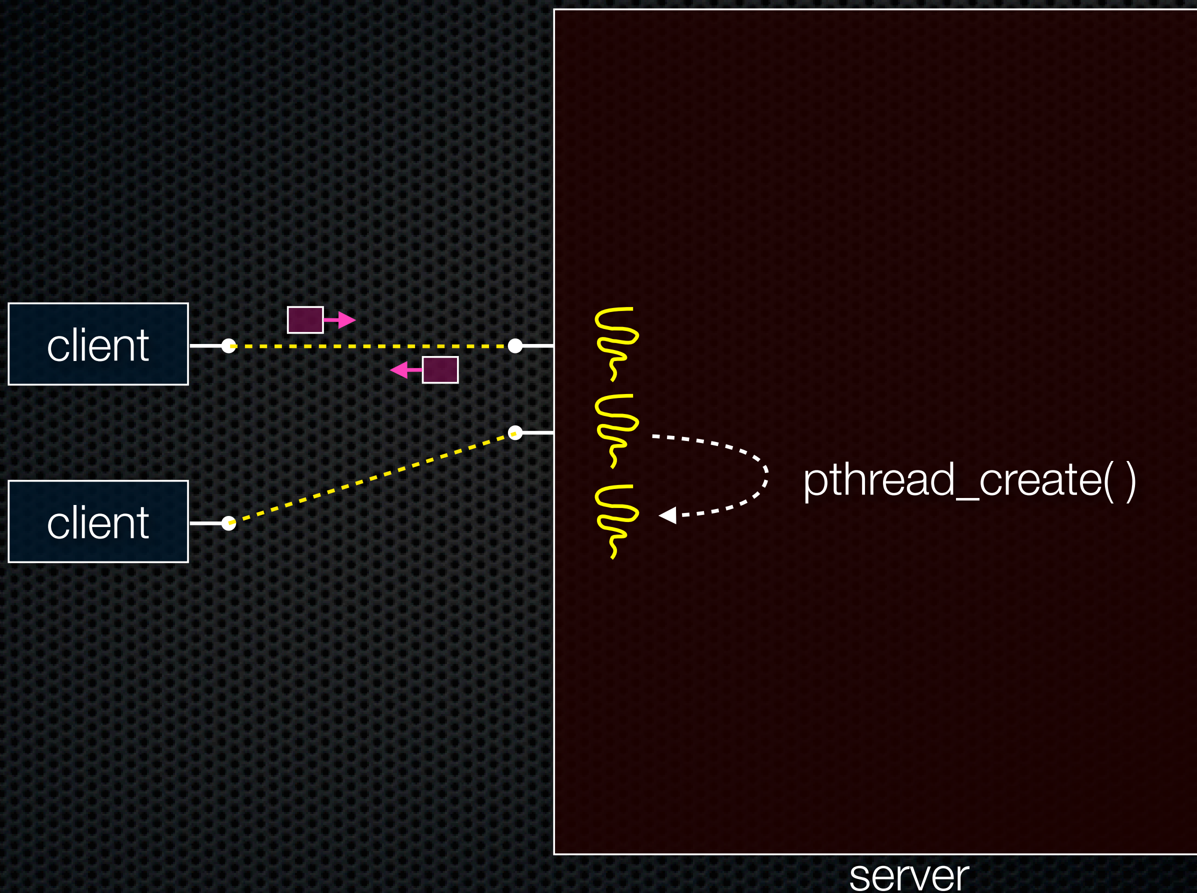

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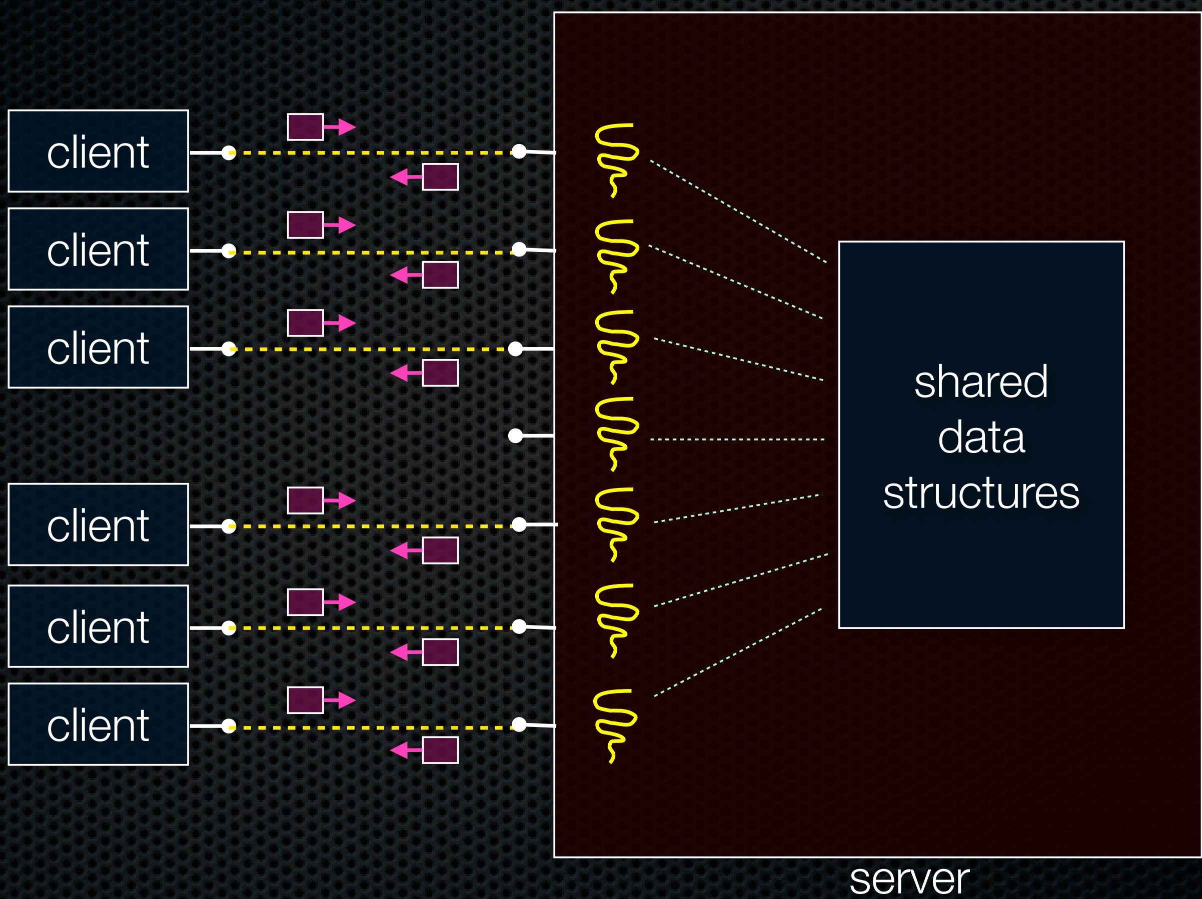


Concurrent with threads

look at ***echo_concurrent_threads.cc***

Whither concurrent threads?

Benefits

- straight-line code, line processes or sequential
  - still the case that much of the code is identical!
- 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?

0.021 ms per thread create; 10x faster than process forking

- maximum of (1000 / 0.021) = ~50,000 connections per second
- 4 billion connections per day per machine
  - much, much better

But, writing safe multithreaded code is serious voodoo

Non-blocking I/O

Warning: an unfamiliar and slightly non-intuitive topic...

Why did the sequential implementation do badly?

- it relied on **blocking** system calls
  - accept( ) blocked until a new connection arrived
  - read( ) blocked until new data arrived
  - write( ) potentially blocked until the write buffer had room
- nothing else could happen while the main thread blocks

Non-blocking I/O

An alternative: **non-blocking** system calls

- non-blocking accept( )
  - if a connection is waiting, accept( ) succeeds and returns it
  - if no connection is waiting, accept( ) fails and returns immediately
- non-blocking read( )
  - if data is waiting, read( ) succeeds and returns it
  - if no data is waiting, read( ) fails and returns immediately
- non-blocking write( )
  - if buffer space is available, write( ) deposits data and returns
  - if no buffer space is available, write( ) fails and returns immediately

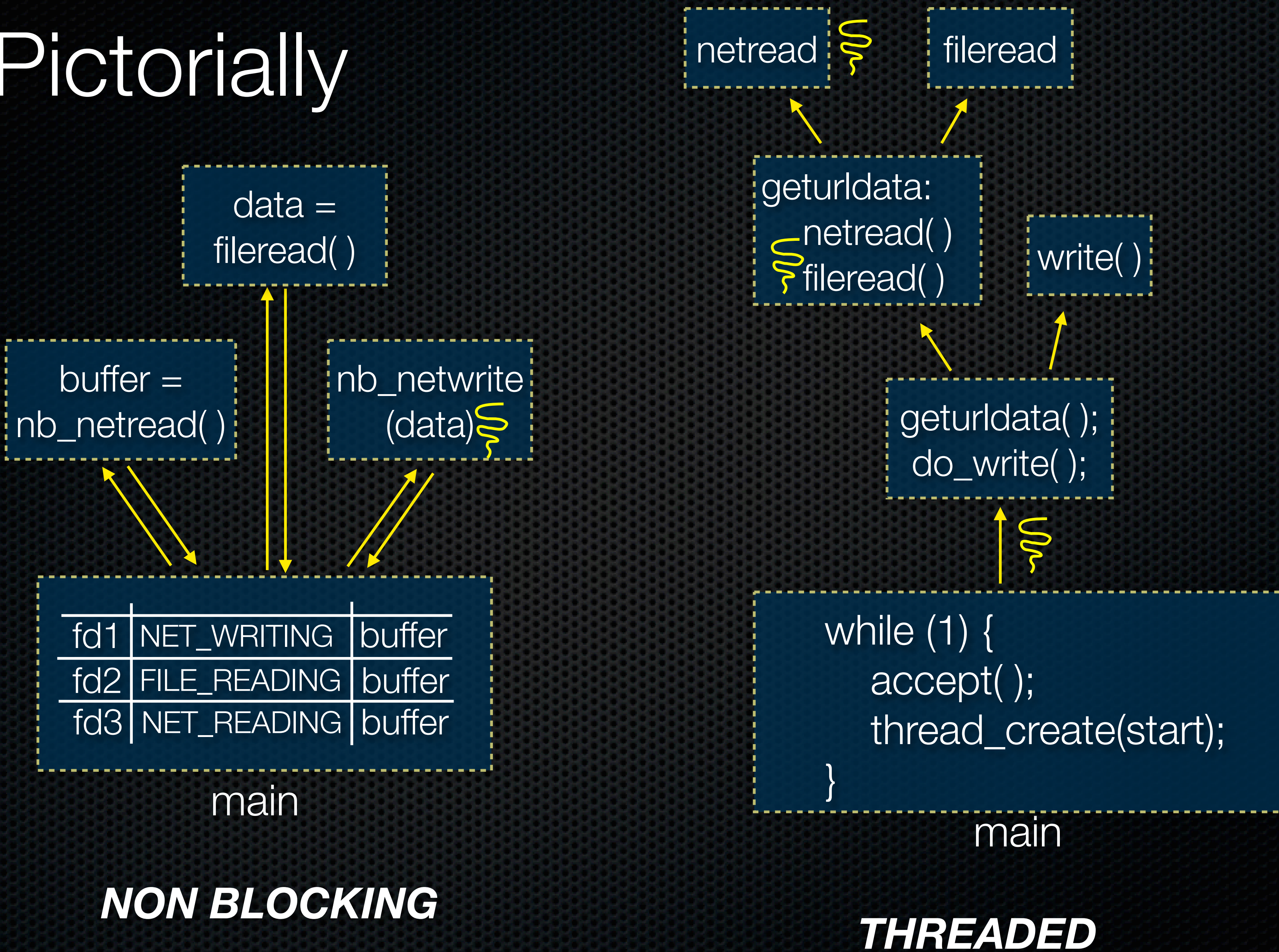
A (bad) first attempt [N clients]

```
state    s[N];              // clients' state field
int      fd[N], readfd[N];  // clients' file descriptors
char *data[N], *fdata[N];  // buffers holding clients' data

while (1) {
  for (int i = 0; i < N; i++) {

    if (s[i] == NET_READING) {
      if (nb_read(fd[i], data[i]))
        s[i] = FILE_READING;
    }

    if (s[i] == FILE_READING) {
      if (nb_read(getfd(data[i]), fdata[i]))
        s[i] = NET_WRITING;
    }

    if (s[i] == NET_WRITING) {
      if (nb_write(fd[i], fdata[i])
        s[i] = NET_READING;
    }
} }
```

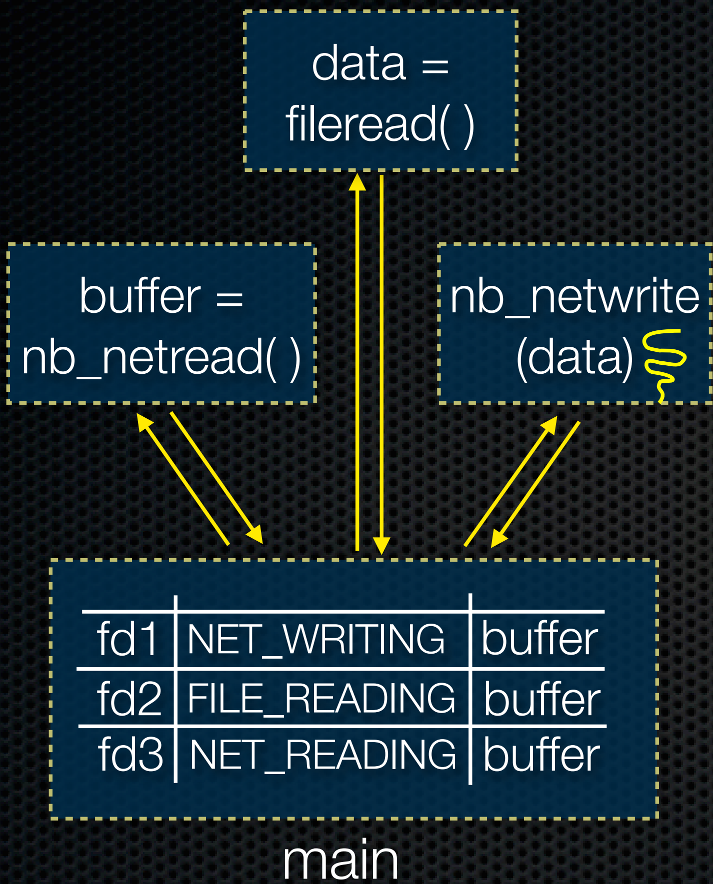
Compare with threaded

```
pthread_create(t1, handleclient, fd1);
pthread_create(t2, handleclient, fd2);

handleclient(int fd) {
  while (1) {
    data = geturldata(fd);
    do_netwrite(fd, filedata);   // NET_WRITING
  }
}

char *geturldata(int fd) {
  filename = read(fd);           // NET_READING
  return readfile(filename);     // FILE_READING
}

void do_write(int fd, char *data) {
  write(fd, data);
}

char *readfile(char *filename) {
  return do_read(fopen(filename));
}
```

Pictorially



NON BLOCKING



Task state

- kept in a table in the heap

Task concurrency, threads

- single thread dispatches "I/O is available" event
- program *is* task scheduler

Call graph

- only one "procedure" deep
- code path is **sliced** at what used to be blocking I/O

THREADED

Task state

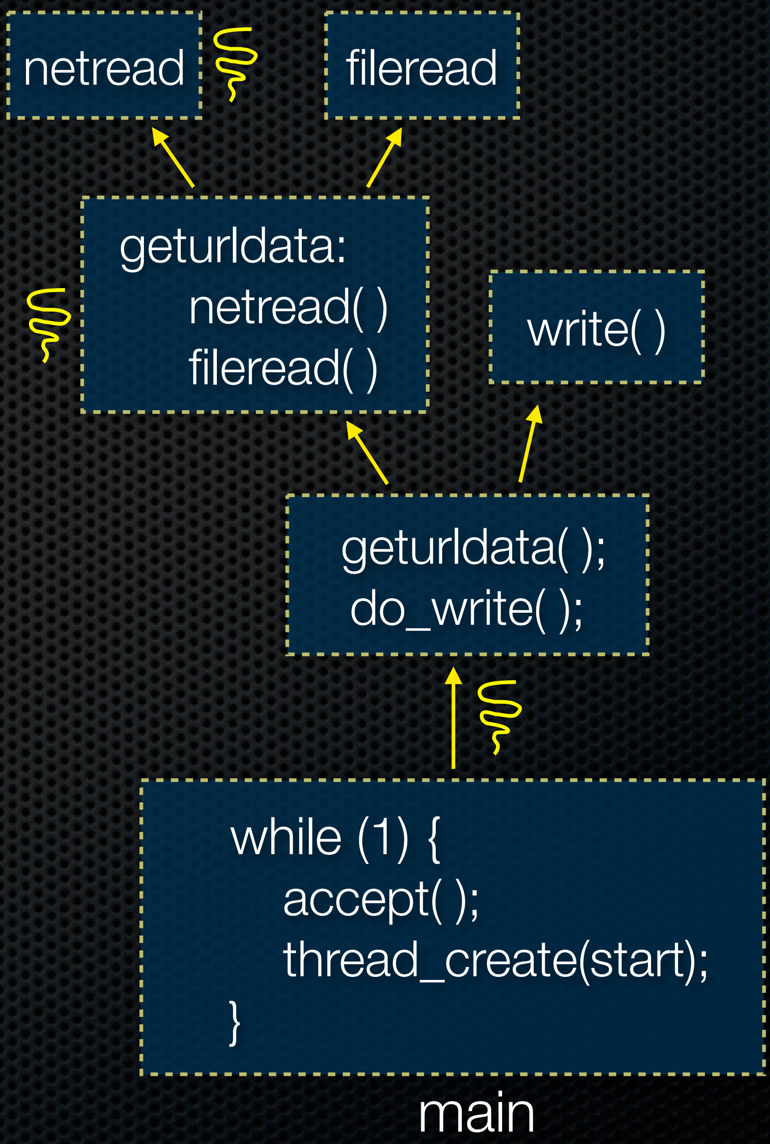
- kept in each thread's stack

Task concurrency, threads

- each thread spurts computation between long blocking IOs
- OS is the scheduler

Call graph

- many procedures deep; stack trace lines up with task progress



Problem with first attempt

It burns up the CPU, constantly looping

- testing each connection to see if it received an event
  - if so, dispatch the event
- which events?
  - fd is read'able
  - fd is write'able
  - *fd is accept'able*
  - *fd closed / in an error state*

```
while (1) {
  for (int i = 0; i < N; i++) {

    if (s[i] == NET_READING) {
      if (nb_read(fd[i], data[i]))
        s[i] = FILE_READING;
    }

    if (s[i] == FILE_READING) {
      if (nb_read( ... )
        s[i] = NET_WRITING;
    }

    if (s[i] == NET_WRITING) {
      if (nb_write( ... )
        s[i] = NET_READING;
    }
}
```

An idea

Instead of constantly polling each file descriptor, why not have one blocking call?

- "hey OS, please tell me when the next event arrives"

```
while (1) {
    (fd, event) = wait_for_next_event( fd_array );

    switch (event) {
       NET_WRITEABLE:
         do_netwrite(fd, lookup_state(fd));
         break;
       NET_READABLE:
         do_netread(fd, lookup_state(fd));
         break;
       FILE_READABLE:
         do_fileread(fd, lookup_state(fd));
         break;
       NET_CLOSED:
         close(fd);
         break;
   }
}
```

select( )

```
int select(int nfds,
           fd_set *read_fds,
           fd_set *write_fds,
           fd_set *error_fds,
           struct timeval *timeout);
```

Waits (up to timeout) for one or more of the following:

- readable events on (read_fds)
- writeable events on (write_fds)
- error events on (error_fds)

See you on Monday!

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