CSE 333

Lecture 17 -- network programming intro

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Today

Network programming

- dive into the Berkeley / POSIX sockets API

Files and file descriptors

Remember open, read, write, and close?

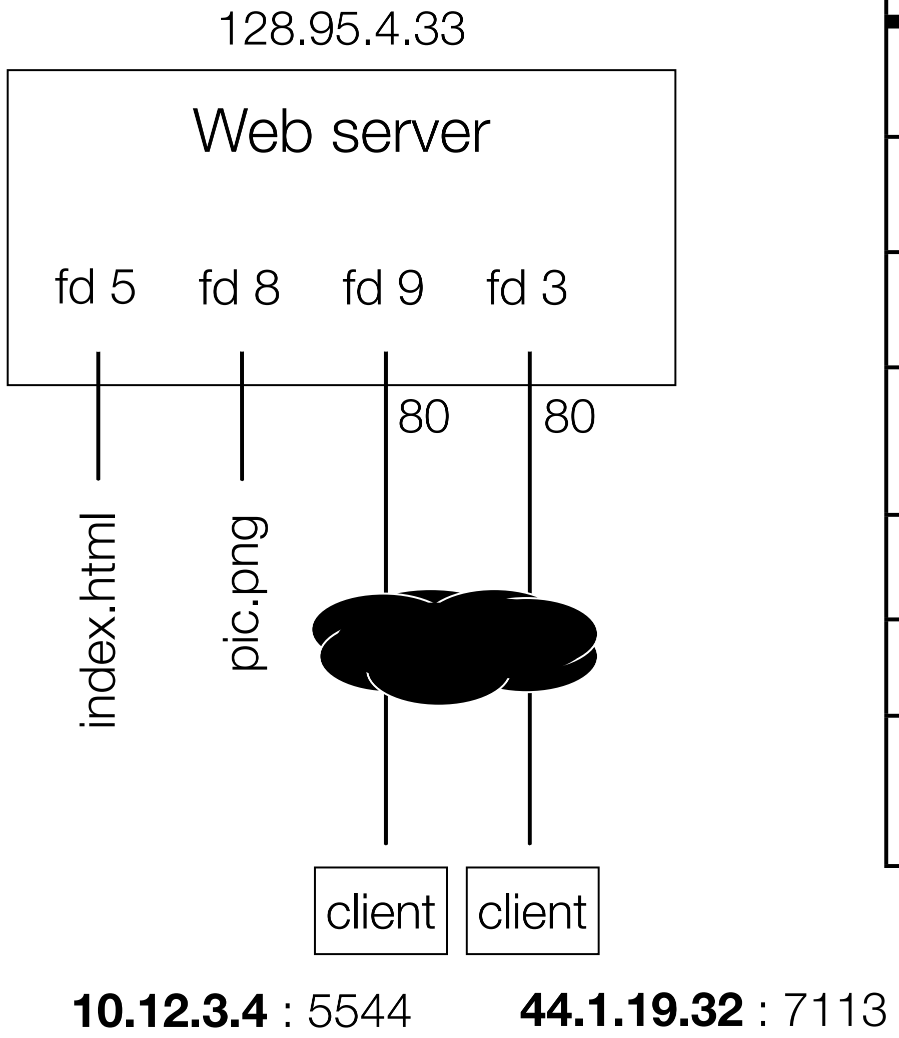
- POSIX system calls for interacting with files
- open( ) returns a *file descriptor*
  - an integer that represents an open file
  - inside the OS, it's an index into a table that keeps track of any state associated with your interactions, such as the file position
  - you pass the file descriptor into read, write, and close

Networks and sockets

UNIX likes to make all I/O look like file I/O

- the good news is that you can use read( ) and write( ) to interact with remote computers over a network!
- just like with files....
    - your program can have multiple network channels open at once
    - you need to pass read( ) and write( ) a ***file descriptor*** to let the OS know which network channel you want to write to or read from
- a file descriptor used for network communications is a **socket**

Pictorially



OS's descriptor table

file descriptor	type	connected to?
0	pipe	stdin (console)
1	pipe	stdout (console)
2	pipe	stderr (console)
3	TCP socket	local: 128.95.4.33:80 remote: 44.1.19.32:7113
5	file	index.html
8	file	pic.png
9	TCP socket	local: 128.95.4.33:80 remote: 102.12.3.4:5544

Types of sockets

Stream sockets

- for connection-oriented, point-to-point, reliable bytestreams
    - uses TCP, SCTP, or other stream transports

Datagram sockets

- for connection-less, one-to-many, unreliable packets
    - uses UDP or other packet transports

Raw sockets

- for layer-3 communication (raw IP packet manipulation)

Stream sockets

Typically used for client / server communications

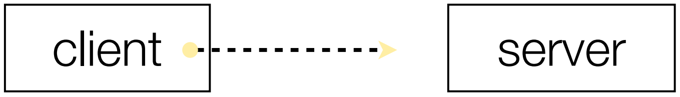
- but also for other architectures, like peer-to-peer

Client

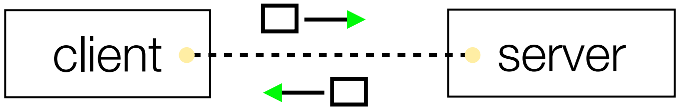
- an application that establishes a connection to a server

Server

- an application that receives connections from clients



1. establish connection

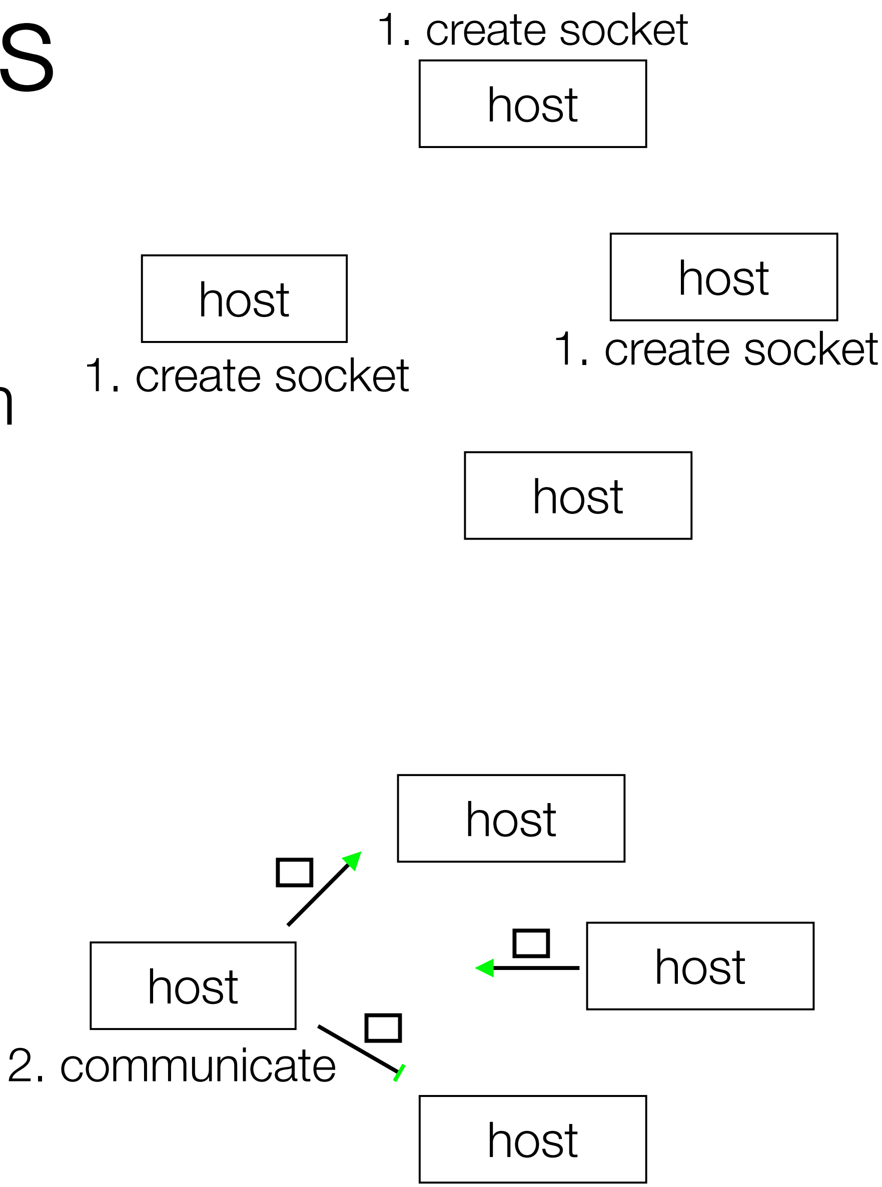


2. communicate

client
server

3. close connection

Datagram sockets



Used less frequently than stream sockets

- they provide no flow control, ordering, or reliability

Often used as a building block

- streaming media applications
- sometimes, DNS lookups

The sockets API

Berkeley sockets originated in 4.2 BSD Unix circa 1983

- it is the standard API for network programming
    - available on most OSs

POSIX socket API

- a slight updating of the Berkeley sockets API
    - a few functions were deprecated or replaced
    - better support for multi-threading was added

Let’s dive into it!

We’ll start by looking at the API from the point of view of a client connecting to a server over TCP

- there are five steps:
  1. figure out the address and port to which to connect
  2. create a socket
  3. connect the socket to the remote server
  4. read( ) and write( ) data using the socket
  5. close the socket

Connecting from a client to a server.

Step 1. Figure out the address and port to which to connect.

Network addresses

For IPv4, an IP address is a 4-byte tuple

- e.g., 128.95.4.1 (80:5f:04:01 in hex)

For IPv6, an IP address is a 16-byte tuple

- e.g., 2d01:0db8:f188:0000:0000:0000:0000:1f33
  - 2d01:0db8:f188::1f33 in shorthand

IPv4 address structures

```
// Port numbers and addresses are in *network order*.

// A mostly-protocol-independent address structure.
struct sockaddr {
    short int     sa_family;    // Address family; AF_INET, AF_INET6
    char          sa_data[14];  // 14 bytes of protocol address
};

// An IPv4 specific address structure.
struct sockaddr_in {
    short int          sin_family;  // Address family, AF_INET == IPv4
    unsigned short int sin_port;    // Port number
    struct in_addr     sin_addr;    // Internet address
    unsigned char      sin_zero[8]; // Same size as struct sockaddr
};

struct in_addr {
    uint32_t s_addr;  // IPv4 address
};
```

IPv6 address structures

```
// A structure big enough to hold either IPv4 or IPv6 structures.
struct sockaddr_storage {
    sa_family_t  ss_family;     // address family

    // a bunch of padding; safe to ignore it.
    char        __ss_pad1[_SS_PAD1SIZE];
    int64_t     __ss_align;
    char        __ss_pad2[_SS_PAD2SIZE];
};

// An IPv6 specific address structure.
struct sockaddr_in6 {
    u_int16_t       sin6_family;   // address family, AF_INET6
    u_int16_t       sin6_port;     // Port number
    u_int32_t       sin6_flowinfo; // IPv6 flow information
    struct in6_addr sin6_addr;     // IPv6 address
    u_int32_t       sin6_scope_id; // Scope ID
};

struct in6_addr {
    unsigned char   s6_addr[16];   // IPv6 address
};
```

Generating these structures

Often you have a string representation of an address

- how do you generate one of the address structures?

genaddr.cc

```
#include <stdlib.h>
#include <arpa/inet.h>

int main(int argc, char **argv) {
  struct sockaddr_in sa; // IPv4
  struct sockaddr_in6 sa6; // IPv6

  // IPv4 string to sockaddr_in.
  inet_pton(AF_INET, "192.0.2.1", &(sa.sin_addr));

  // IPv6 string to sockaddr_in6.
  inet_pton(AF_INET6, "2001:db8:63b3:1::3490", &(sa6.sin6_addr));

  return EXIT_SUCCESS;
}
```

Generating these structures

How about going in reverse?

genstring.cc

```
#include <stdlib.h>
#include <arpa/inet.h>
#include <iostream>

int main(int argc, char **argv) {
  struct sockaddr_in6 sa6;         // IPv6
  char astring[INET6_ADDRSTRLEN];  // IPv6

  // IPv6 string to sockaddr_in6.
  inet_pton(AF_INET6, "2001:db8:63b3:1::3490", &(sa6.sin6_addr));

  // sockaddr_in6 to IPv6 string.
  inet_ntop(AF_INET6, &(sa6.sin6_addr), astring, INET6_ADDRSTRLEN);
  std::cout << astring << std::endl;

  return EXIT_SUCCESS;
}
```

DNS

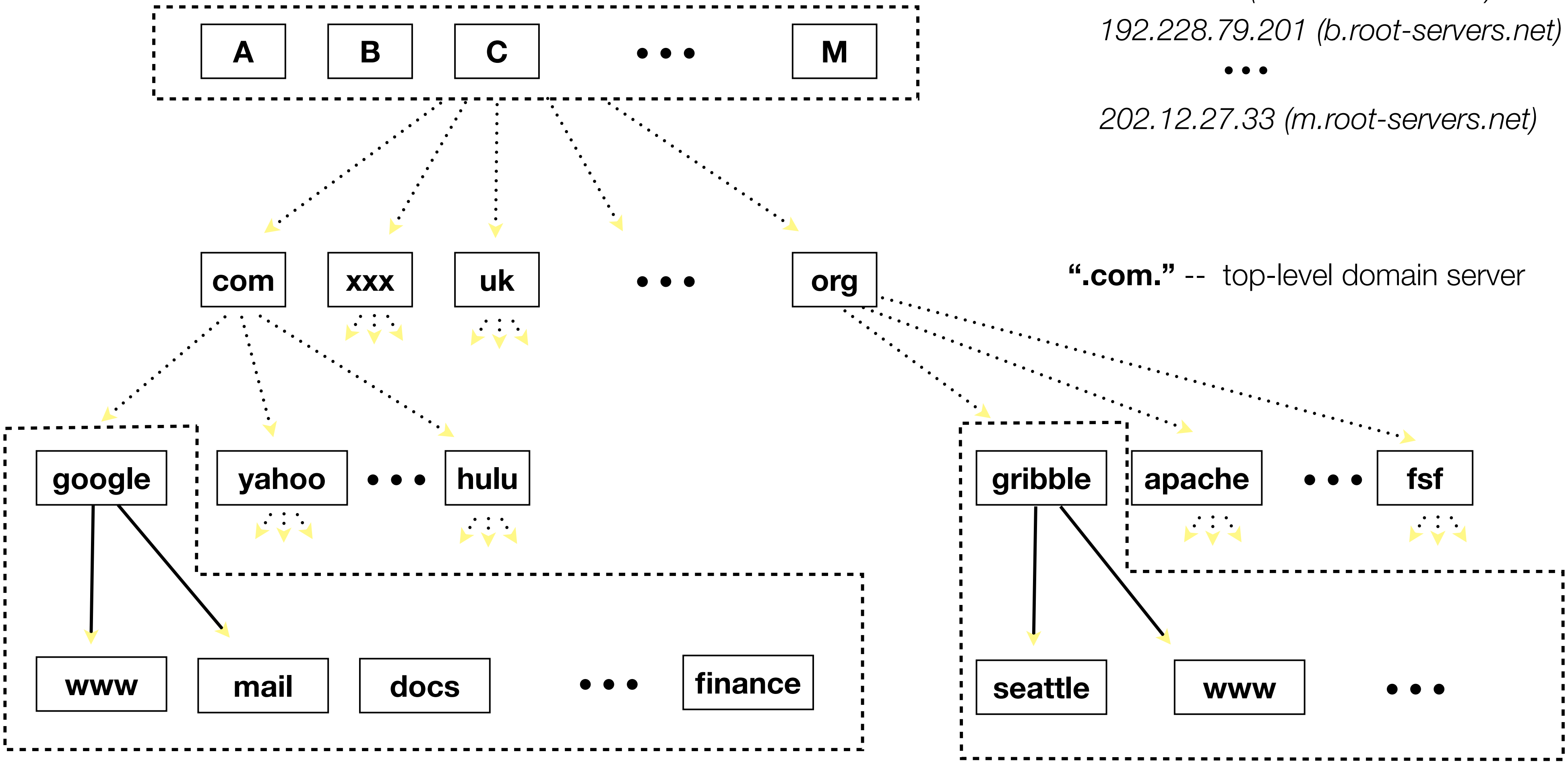
People tend to use DNS names, not IP addresses

- the sockets API lets you convert between the two
- it’s a complicated process, though:
  - a given DNS name can have many IP addresses
  - many different DNS names can map to the same IP address
    - an IP address will reverse map into at most one DNS names, and maybe none
  - a DNS lookup may require interacting with many DNS servers

You can use the “dig” Linux program to explore DNS

- “man dig”

DNS hierarchy



“.” -- root name servers

198.41.0.4 (a.root-servers.net)

192.228.79.201 (b.root-servers.net)

• • •

202.12.27.33 (m.root-servers.net)

“.com.” -- top-level domain server

A B C • • • M

com xxx uk • • • org

google yahoo • • • hulu

gribble apache • • • fsf

www mail docs • • • finance

seattle www • • •

Resolving DNS names

The POSIX way is to use **getaddrinfo( )**

- a pretty complicated system call; the basic idea...
    - set up a “hints” structure with constraints you want respected
        - e.g., IPv6, IPv4, or either
    - tell getaddrinfo( ) which host and port you want resolved
        - host: a string representation; DNS name or IP address
    - getaddrinfo( ) gives you a list of results packet in an “addrinfo” struct
    - free the addrinfo structure using freeaddrinfo( )

DNS lookup example

see dnsresolve.cc

Connecting from a client to a server.

Step 2. Create a socket.

Creating a socket

Use the **socket** system call

- creating a socket doesn’t yet bind it to a local address or port

socket.cc

```
#include <errno.h>
#include <stdlib.h>
#include <string.h>
#include <sys/socket.h>
#include <sys/types.h>
#include <iostream>

int main(int argc, char **argv) {
  int socket_fd = socket(PF_INET, SOCK_STREAM, 0);
  if (socket_fd == -1) {
     std::cerr << strerror(errno) << std::endl;
     return EXIT_FAILURE;
  }
  close(socket_fd);
  return EXIT_SUCCESS;
}
```

Connecting from a client to a server.

Step 3. Connect the socket to the remote server.

connect( )

The **connect( )** system call establishes a connection to a remote host

- you pass the following arguments to connect( ):
  - the socket file descriptor you created in step 2
  - one of the address structures you created in step 1
- connect may take some time to return
  - it is a **blocking** call by default
  - the network stack within the OS will communicate with the remote host to establish a TCP connection to it
  - this involves ~2 *round trips* across the network

connect example

see connect.cc

Connecting from a client to a server.

Step 4. read( ) and write( ) data using the socket.

read( )

By default, a blocking call

- if there is data that has already been received by the network stack, then read will return immediately with it
  - thus, read might return with less data than you asked for
- if there is no data waiting for you, by default read( ) will block until some arrives
  - pop quiz: how might this cause **deadlock**?

write( )

By default, a blocking call

- but, in a more sneaky way
- when write( ) returns, the receiver (i.e., the other end of the connection) probably has not yet received the data
    - in fact, the data might not have been send on the network yet!
    - write( ) enqueues your data in a send buffer in the OS, and then returns; the OS will transmit the data in the background
- if there is no more space left in the send buffer, by default write( ) will block
    - how might this cause **deadlock**?

read/write example

see sendreceive.cc

Connecting from a client to a server.

Step 5. close( ) the socket.

See you on Monday!

Exercise 1

Consider an input file of DNS names, one per line. Write a client that:

- reads from that file
- translates each name to an IP address
- prints out the IP address in string form to stdout, one per line