Poll Everywhere

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About how long did Exercise 9 take you?

A. [0, 2) hours
B. [2, 4) hours
C. [4, 6) hours
D. [6, 8) hours
E. 8+ Hours
F. I didn’t submit / I prefer not to say

Sockets & DNS

CSE 333 Summer 2023

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Relevant Course Information (1/2)

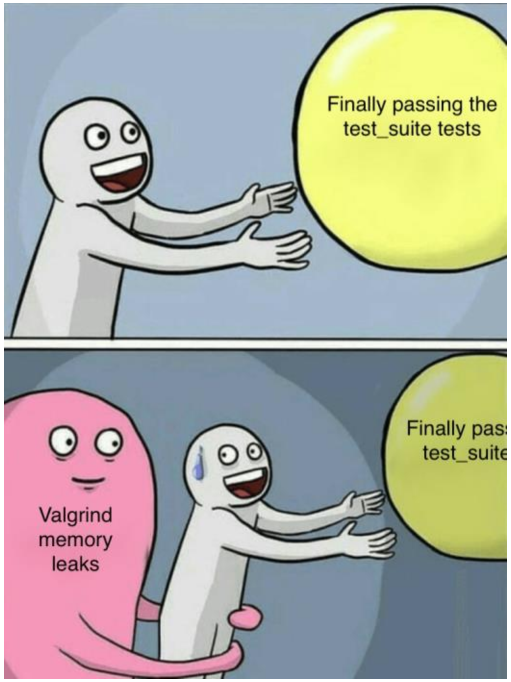
- Exercise 10 & 11 will be released on Wednesday
  - ex10 due next Monday (8/7), ex11 due next Thursday (8/10)
  - Primarily adapting existing network programming code

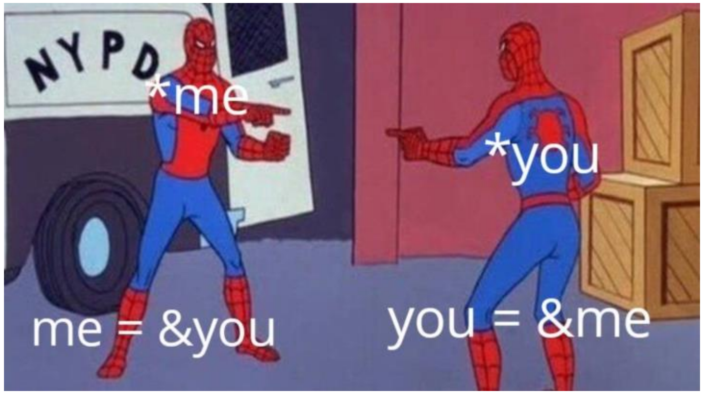
- Homework 3 is due Thursday (8/3)
  - Usual reminder: **don't forget to tag, clone elsewhere, and recompile** (will need to copy libhw1.a and libhw2.a)
- Homework 4 will be released on Friday (8/4)
  - Due Wednesday (8/16), late due date Friday (8/18)

Relevant Course Information (2/2)

- Quiz 2 open for edits/resubmission until (8/1)
  - Most submissions should be fine, some were partially/entirely wiped.
- Quiz 3 and 4 details soon (see Quizzes page for dates)

A couple of my favorite memes from Quiz 2 submissions:





Lecture Outline

- Network Programming
  - Sockets API
  - Network Addresses
  - DNS Lookup

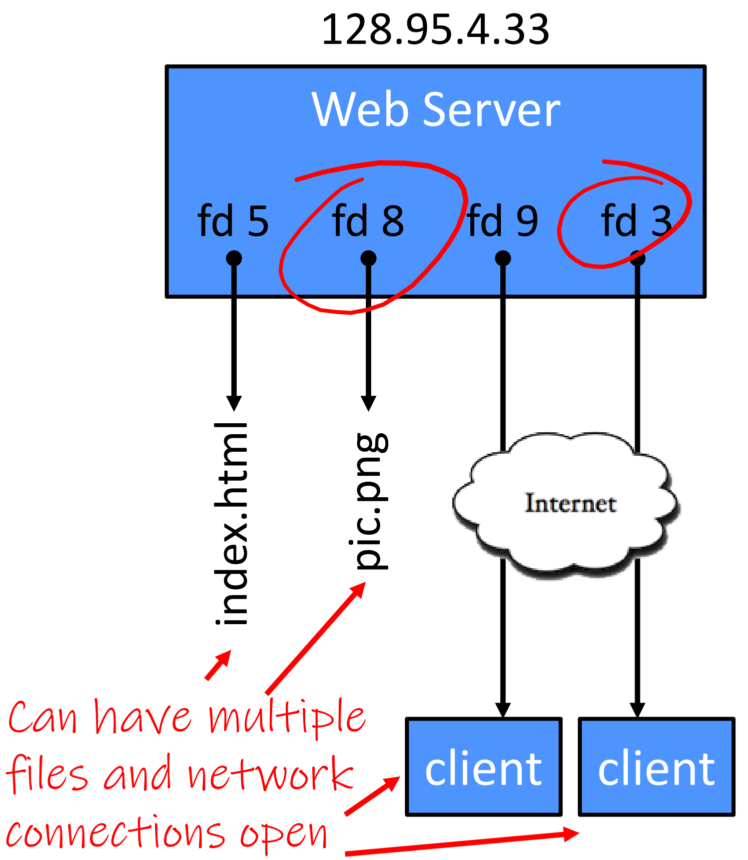
Files and File Descriptors

- 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
    - This file descriptor is then passed to `read()`, `write()`, and `close()`
  - Inside the OS, the file descriptor is used to index into a table that keeps track of any OS-level state associated with the file, such as the file position

Networks and Sockets

- UNIX likes to make *all* I/O look like file I/O
  - You use `read()` and `write()` to communicate with remote computers over the network!
  - A file descriptor use for network communications is called a socket
  - Just like with files:
    - Your program can have multiple network channels open at once
    - You need to pass a file descriptor to `read()` and `write()` to let the OS know which network channel to use

File Descriptor Table



OS's File Descriptor Table for the Process

File Descriptor	Type	Connection
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

0,1,2 always start as stdin, stdout & stderr.

Types of Sockets

- Stream sockets – used the most in 333 :)
  - For connection-oriented, point-to-point, reliable byte streams
    - Using TCP, SCTP, or other stream transports
- Datagram sockets
  - For connection-less, one-to-many, unreliable packets
    - Using UDP or other packet transports
- Raw sockets
  - For layer-3 communication (raw IP packet manipulation)

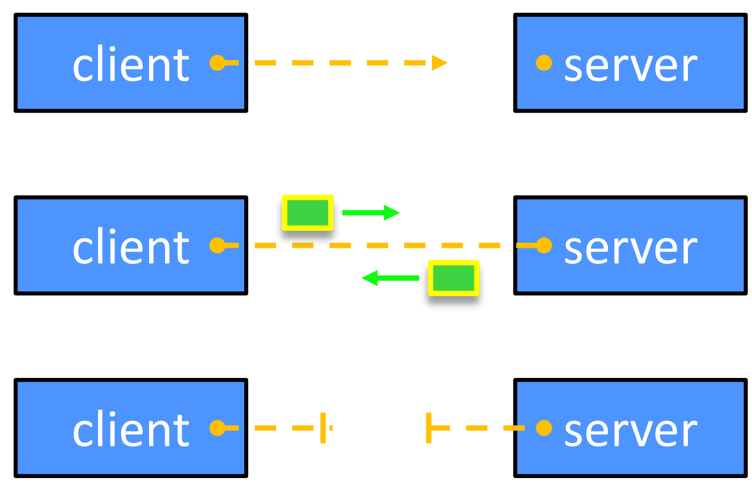
Stream Sockets

- Typically used for client-server communications
  - Client: An application that establishes a connection to a server
  - Server: An application that receives connections from clients
  - Can also be used for other forms of communication like peer-to-peer

1) Establish connection:

2) Communicate:

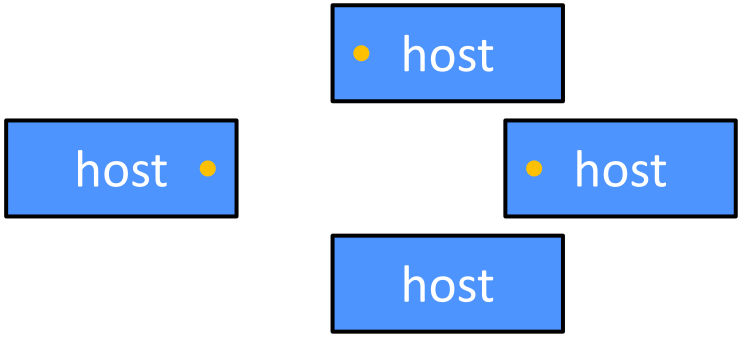
3) Close connection:



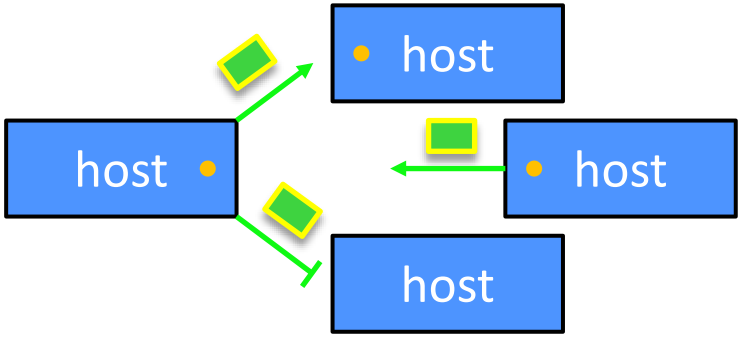
Datagram Sockets

- Often used as a building block
  - No flow control, ordering, or reliability, so used less frequently
  - *e.g.*, streaming media applications or DNS lookups

1) Create sockets:



2) Communicate:



The Sockets API

- Berkeley sockets originated in 4.2BSD Unix (1983)
  - It is the standard API for network programming
    - Available on most OSs
  - Written in C
- POSIX Socket API
  - A slight update of the Berkeley sockets API
    - A few functions were deprecated or replaced
    - Better support for multi-threading was added

Socket API: Client TCP Connection

- 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 IP 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

New!

Same as File I/O

Step 1: Figure Out IP Address and Port

- Several parts:
  - Network addresses
  - Data structures for address info   C data structures ☹
  - DNS (Domain Name System) – finding IP addresses

IPv4 Network Addresses

32 bits

- An IPv4 address is a **4-byte** tuple
  - For humans, written in "dotted-decimal notation"
  - *e.g.*, 128.95.4.1 (`80:5f:04:01` in hex)

- IPv4 address exhaustion
  - There are 2^{32} ≈ 4.3 billion IPv4 addresses
  - There are ≈ 8.01 billion people in the world (February 2023)

IPv6 Network Addresses

128 bits

- An IPv6 address is a **16-byte** tuple
  - Typically written in "hextets" (groups of 4 hex digits)
    - Can omit leading zeros in hextets
    - Double-colon replaces consecutive sections of zeros
  - *e.g.*, `2d01:0db8:f188:0000:0000:0000:0000:1f33`
    - Shorthand: `2d01:db8:f188::1f33`
  - Transition to IPv6 is still ongoing
    - IPv4-mapped IPv6 addresses
      - 128.95.4.1 mapped to `::ffff:`128.95.4.1 or `::ffff:805f:401`
    - This unfortunately makes network programming more of a headache ☹

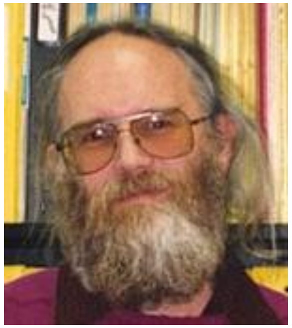
Aside: IP Address Allocation

- This map is outdated (2006), as all IPv4 addresses have been allocated, but what interesting observations can you make?
  - Geographic regions?
  - Companies?

https://xkcd.com/195/

Aside: IP Address Allocation

- Global IP address allocation (among other things) is overseen by the **Internet Assigned Numbers Authority (IANA)**
  - "Currently it is a function of ICANN, a nonprofit private American corporation established in 1998 primarily for this purpose under a United States Department of Commerce contract. Before it, IANA was administered principally by Jon Postel at [USC], under a contract… with the United States Department of Defense."



- Does this make sense? Is this fair?
  - Historically, it does (Internet "born" in the US)
  - Probably not entirely fair though – what values and priorities are encoded in this allocation?

Computing Standards and Protocols

- We've seen tons of these! Many more exist!
  - ASCII, IEEE 754, POSIX, IP, TCP/UDP, HTTP, etc.
  - These have *profound* and *long-lasting* effects

- **Standards always encode the priorities of their creators into data**
  - *e.g.*, ASCII prioritizes English and memory efficiency
  - *e.g.*, IP addresses allocated with a very US-centric view, often granting larger-than-necessary swaths to the "big players" of the time

- Who was in the room when it happened? (*i.e.*, creation)
- Who has a seat at the table? (*i.e.*, maintenance)

Linux Socket Addresses

- Structures, constants, and helper functions available in `#include <arpa/inet.h>`
- Addresses stored in network byte order (big endian)
- Converting between host and network byte orders:
  - `uint32_t htonl(uint32_t hostlong);`
  - `uint32_t ntohl(uint32_t netlong);`
    - '`h`' for host byte order and '`n`' for network byte order
    - Also versions with '`s`' for short (`uint16_t` instead)
- How to handle both IPv4 and IPv6?
  - Use C structs for each, but make them somewhat similar
  - Use defined constants to differentiate when to use each: `AF_INET` for IPv4 and `AF_INET6` for IPv6

Address Family

IPv4 Address Structures

```
// IPv4 4-byte address
struct in_addr {
  uint32_t s_addr;                // Address in network byte order
};

// An IPv4-specific address structure
struct sockaddr_in {
  sa_family_t    sin_family;    // Address family: AF_INET
  in_port_t      sin_port;      // Port in network byte order
  struct in_addr sin_addr;      // IPv4 address
  unsigned char  sin_zero[8];   // Pad out to 16 bytes
};
```

`struct sockaddr_in`:

family	port	addr	zero

0 2 4 8 16

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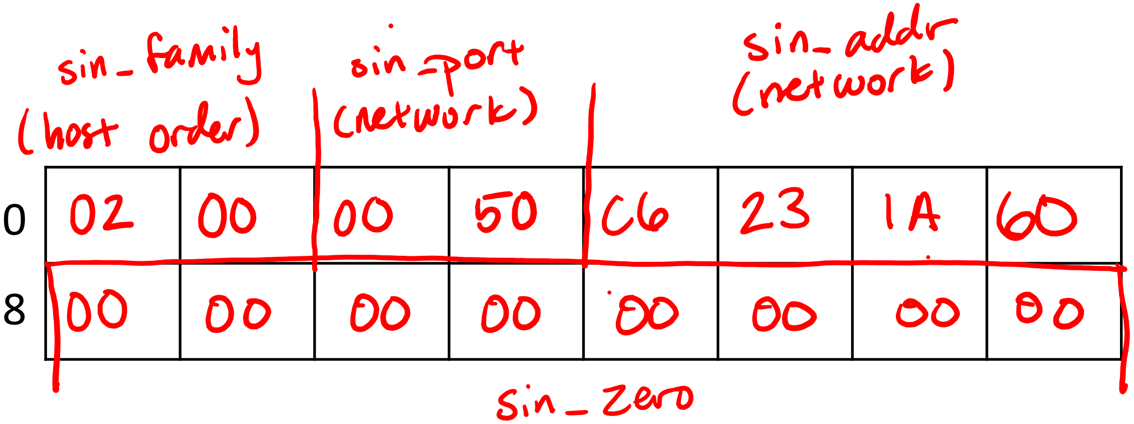
What will the first 4 bytes of the `struct sockaddr_in` be?

- Represents a socket connected to 198.35.26.96 (c6:23:1a:60) on port 80 (0x50) stored on a little-endian machine
  ↳ 0x0050
  - `AF_INET = 2`
    ↳ 0x0002



A. 0x 00 02 00 50
B. 0x 00 02 50 00
C. 0x 02 00 00 50
D. 0x 02 00 50 00
E. We're lost...

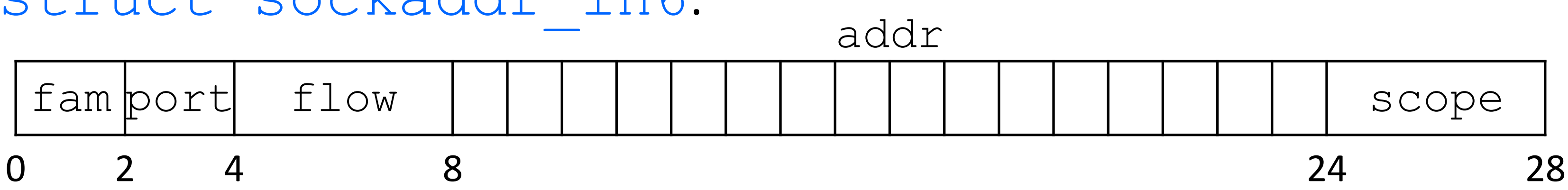
IPv6 Address Structures

```c
// IPv6 16-byte address
struct in6_addr {
  uint8_t s6_addr[16];          // Address in network byte order
};

// An IPv6-specific address structure
struct sockaddr_in6 {
  sa_family_t     sin6_family;   // Address family: AF_INET6
  in_port_t       sin6_port;     // Port number
  uint32_t        sin6_flowinfo; // IPv6 flow information
  struct in6_addr sin6_addr;     // IPv6 address
  uint32_t        sin6_scope_id; // Scope ID
};
```

can ignore

`struct sockaddr_in6`:



Generic Address Structures

```
// A mostly-protocol-independent address structure.
// Pointer to this is parameter type for socket system calls.
struct sockaddr {
  sa_family_t sa_family;    // Address family (AF_* constants)
  char        sa_data[14];  // Socket address (size varies
                            // according to socket domain)
};

// A structure big enough to hold either IPv4 or IPv6 structs
struct sockaddr_storage {
  sa_family_t ss_family;    // Address family

  // padding and alignment; don't worry about the details
  char __ss_pad1[_SS_PAD1SIZE];
  int64_t __ss_align;
  char __ss_pad2[_SS_PAD2SIZE];
};
```

- Commonly create `struct sockaddr_storage`, then pass pointer cast as `struct sockaddr*` to **`connect`**`()`

Address Conversion

addr. family → string representation → output param

- `int inet_pton(int af, const char* src, void* dst);`
  - Converts human-readable string representation ("**p**resentation") to **n**etwork byte ordered address
  - Returns 1 (success), 0 (bad `src`), or -1 (error)

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 (192.0.2.1 = C0:00:02:01).
  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;
}
```

Address Conversion

Address Family

address in network-byte order

- `const char* inet_ntop(int af, const void* src, char* dst, socklen_t size);`
  - Converts network addr in `src` into buffer `dst` of size `size`
  - Returns `dst` on success; `NULL` on error

genstring.cc

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

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, "2001:0db8:63b3:1::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;
}
```

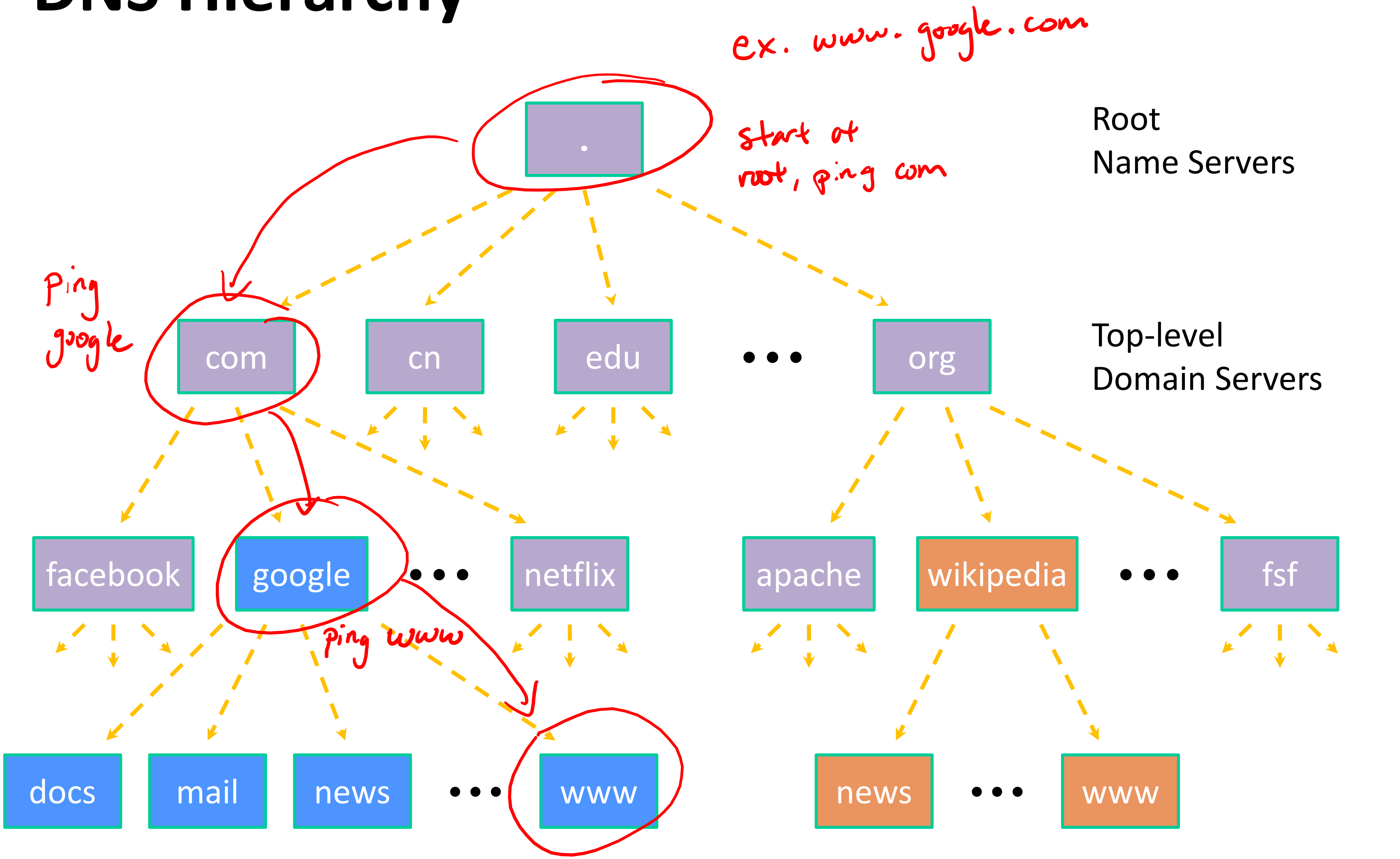
↳ if IPv4 INET_ADDRSTRLEN

Domain Name System

- 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 IP addresses can map to the same DNS name
      - An IP address will reverse map into at most one DNS name
    - A DNS lookup may require interacting with many DNS servers

- You can use the Linux program "`dig`" to explore DNS
  - `dig @server name type (+short)`
    - `server`: specific name server to query
    - `type`: `A` (IPv4), `AAAA` (IPv6), `ANY` (includes all types)

DNS Hierarchy



Resolving DNS Names

- The POSIX way is to use **getaddrinfo()**
  - A complicated system call found in #include <netdb.h>
  -
```
int getaddrinfo(const char* hostname,          ← e.g. "www.google.com"
                const char* service,           ← port num or service (ex. "www")
                const struct addrinfo* hints,
   output param → struct addrinfo** res);
```
    - Tell **getaddrinfo()** which host and port you want resolved
      - String representation for host: DNS name or IP address
    - Set up a "hints" structure with constraints you want respected (← filter results)
    - **getaddrinfo()** gives you a list of results packed into an "addrinfo" structure/linked list
      - Returns 0 on success; returns *negative number* on failure
  - Free the struct addrinfo later using **freeaddrinfo()** (← Don't lose your res pointer!)

getaddrinfo

0 "Don't care" options

- `getaddrinfo()` arguments:
  - `hostname` – domain name or IP address string
  - `service` – port # (*e.g.*, `"80"`) or service name (*e.g.*, `"www"`) or `NULL`/`nullptr`
  - `hints` – filter results

```
struct addrinfo {
  int     ai_flags;         // additional flags
  int     ai_family;        // AF_INET, AF_INET6, AF_UNSPEC
  int     ai_socktype;      // SOCK_STREAM, SOCK_DGRAM, 0
  int     ai_protocol;      // IPPROTO_TCP, IPPROTO_UDP, 0
  size_t  ai_addrlen;       // length of socket addr in bytes
  struct sockaddr* ai_addr; // pointer to socket addr
  char*   ai_canonname;     // canonical name
  struct addrinfo* ai_next; // can form a linked list
};
```

DNS Lookup Procedure

```
struct addrinfo {
  int      ai_flags;          // additional flags
  int      ai_family;         // AF_INET, AF_INET6, AF_UNSPEC
  int      ai_socktype;       // SOCK_STREAM, SOCK_DGRAM, 0
  int      ai_protocol;       // IPPROTO_TCP, IPPROTO_UDP, 0
  size_t   ai_addrlen;        // length of socket addr in bytes
  struct sockaddr* ai_addr;   // pointer to socket addr
  char*    ai_canonname;      // canonical name
  struct addrinfo* ai_next;   // can form a linked list
};
```

1) Create a `struct addrinfo hints`
2) Zero out `hints` for "defaults"
3) Set specific fields of `hints` as desired
4) Call **`getaddrinfo`**`()` using `&hints`
5) Resulting linked list `*res` will have all fields appropriately set

- See dnsresolve.cc