Networking: IP Addresses and DNS

CSE 333 Autumn 2019

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Poll Everywhere

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About how long did Exercise 14b take?

A. 0-1 Hours
B. 1-2 Hours
C. 2-3 Hours
D. 3-4 Hours
E. 4+ Hours
F. I didn’t finish / I prefer not to say

Administrivia

- Canvas now has late days + HW1 & HW2 grades
  - Continue to use Gradescope for exercise grades

- Exercise 15 out today, due Monday
  - Still need some concepts from Friday, but sneak preview!

- HW3 due tomorrow!
  - Remember to use `hw3fsck` to check your index file
  - 1 late day = 8:59pm on Friday
  - 2 late days = 8:59pm on *Sunday*

Lecture Outline

- **Background: What is a Socket?**
- Client-side Networking
  - Roadmap
  - Step 1: Figure out the IP/Port
  - Step 2: Create a Socket
  - Step 3: Connect the Socket
  - Step 4: `read`() and `write`() Data
  - Step 5: Close the Socket

Review: Files and File Descriptors

- Remember `open()`, `read()`, `write()`, and `close()`?
  - POSIX system calls for interacting with files

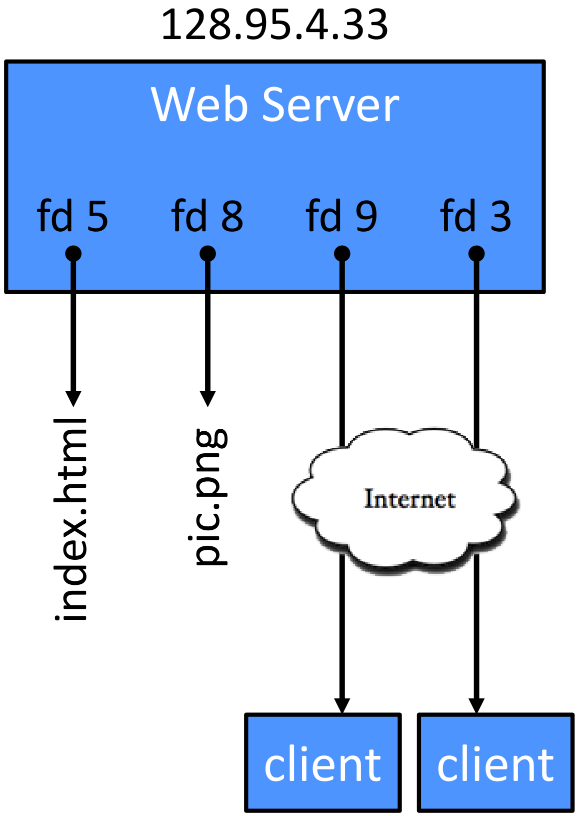
- `open()` returns a file descriptor
  - An integer that represents an open file
  - This file descriptor is then passed to `read()`, `write()`, and `close()`

- 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 used 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

★ all jumbled in the same table!

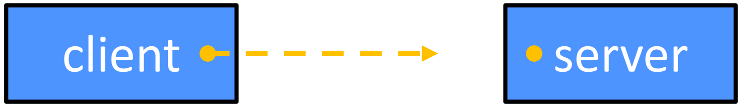
Types of Sockets

- Stream sockets
  - 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 (“network”) communication
  - Ie, raw IP packet manipulation

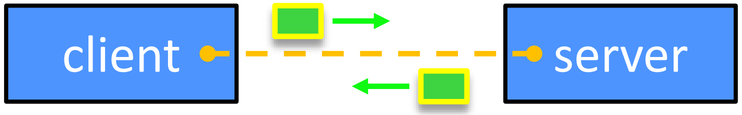
Stream Sockets

- 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

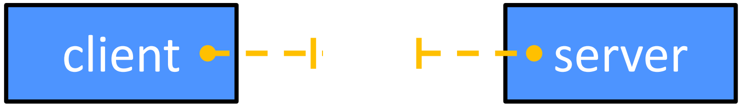
1) Establish connection:



2) Communicate:



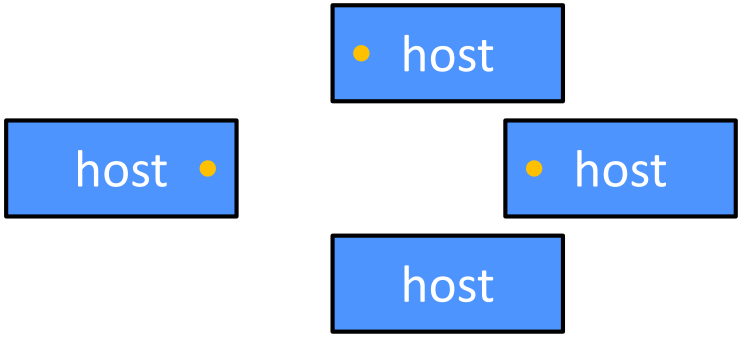
3) Close connection:



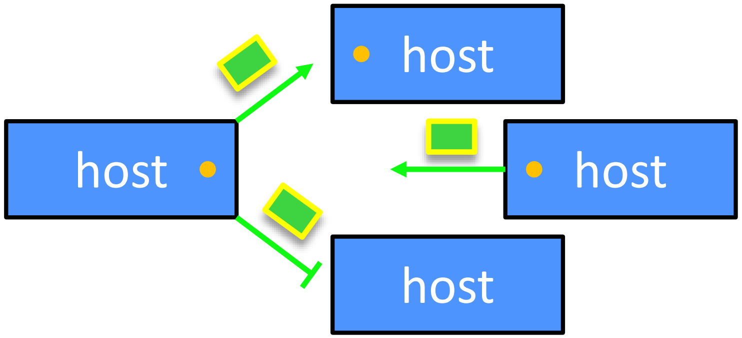
Datagram Sockets

- 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:



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- Background: What is a Socket?
- Client-side Networking
  - **Roadmap**
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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 (1988)
  - A slight update of the Berkeley sockets API
    - A few functions were deprecated or replaced
    - Better support for multi-threading was added

Sockets API: Client

- 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

Client Networking: Learning Objectives

- Understand how IP addresses are represented and how DNS is used to look them up

- Know what each of the 5 steps of client-side networking does and why it is important

- *Non-objective*: be able to write client-side networking code from scratch after this lecture
  - You'll have plenty of code to practice with at home ☺
  - Copy and paste is not necessarily a bad thing here – but make sure you *understand* it well enough to modify it if you have to

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… Actually …

- "Step 1: Figure Out IP Address and Port" has several parts:
  - What is a Network Address?
  - Data structures for address information
  - DNS (Domain Name System): finding IP addresses

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    - **What is a Network Address?**
    - Data structures for address information
    - DNS (Domain Name System): finding IP addresses
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IPv4 Network Addresses

- 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)
  - Designed in 1983

- IPv4 address exhaustion
  - There are 2^{32} ≈ 4.3 billion IPv4 addresses
  - There are ≈ 7.71 billion people in the world (February 2019)

IPv6 Network Addresses

- 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 a consecutive section of zeros (arbitrary length run of zeros)
  - *e.g.* `2d01:0db8:f188:0000:0000:0000:0000:1f33`
    - Shorthand: `2d01:db8:f188::1f33`

- Transition is still ongoing
  - IPv4 not compatible with IPv6
  - IPv4 addresses mapped into IPv6 address-space
    - 128.95.4.1 mapped to `::ffff:`128.95.4.1 or `::ffff:805f:401`
  - This unfortunately makes network programming more of a headache ☹

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    - **Data structures for address information**
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Socket API: Specifying Addresses (1 of 2)

- Structures, constants, and helper functions available in `#include <arpa/inet.h>`

- Address and port 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)

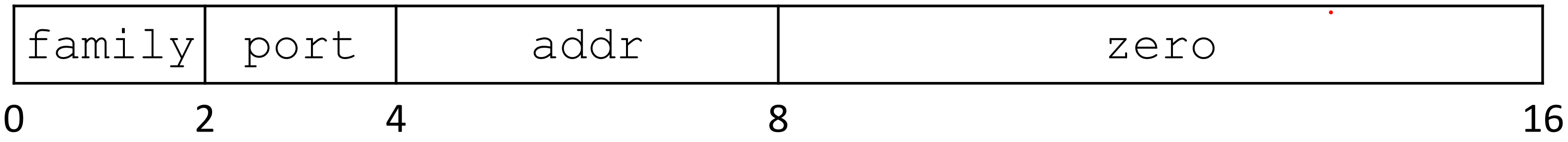
Socket API: Specifying Addresses (2 of 2)

- How to handle both IPv4 and IPv6?
  - Use different 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 Structs: IPv4

```
// 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`:



Your Turn!

- Assume we have a `struct sockaddr_in` that represents a socket connected to 198.35.26.96 (c6:23:1a:60) on port 80 (0x50) stored on a little-endian machine.
  - `AF_INET = 2`
  - Fill in the bytes in memory below (in hex):

sin_family
0x02 (host order)

sin_port
0x50 (network order)

sin_addr
0xc6231a60 (network)

0	02	00	00	50	c6	23	1a	60
8	00	00	00	00	00	00	00	00

sin_zero
(host order... but does it matter?)

Address Structs: IPv6

– not just "bigger address space"

```
// 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
};
```

new to IPv6

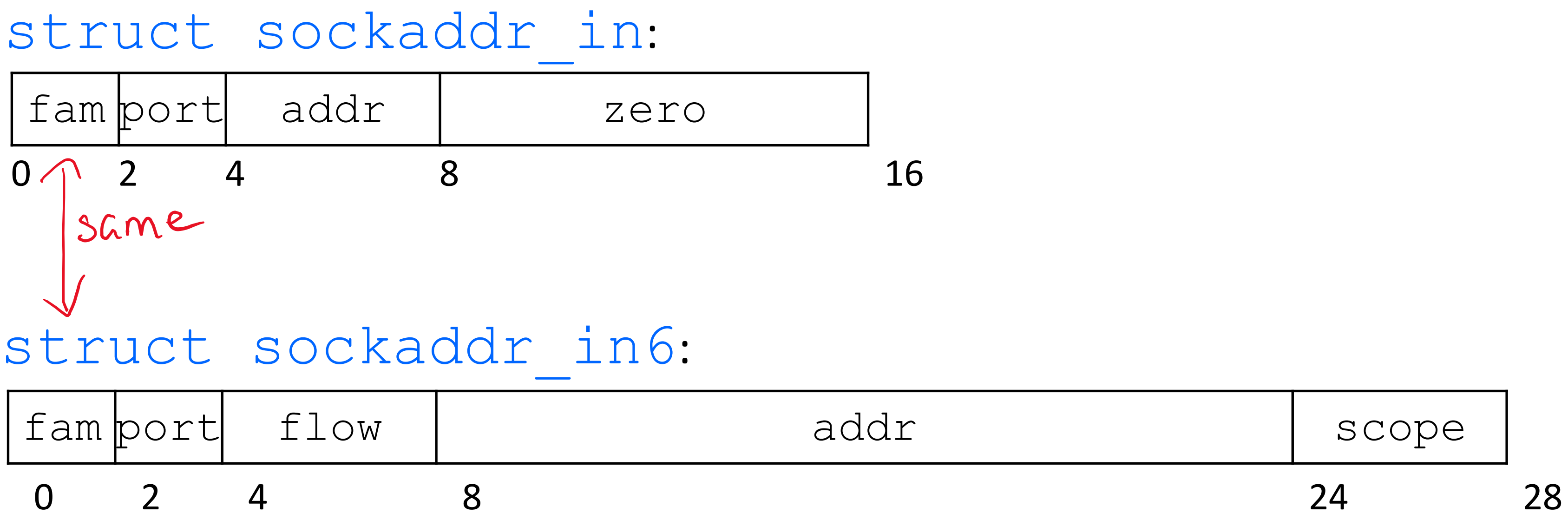
`struct sockaddr_in6`:

fam	port	flow	addr	scope

0 2 4 8 24 28

Address Structs: Generic?

- Let’s compare the memory layout of the IPv4 and IPv6 socket structs



struct sockaddr_in:

fam port addr zero

0 2 4 8 16

same

struct sockaddr_in6:

fam port flow addr scope

0 2 4 8 24 28

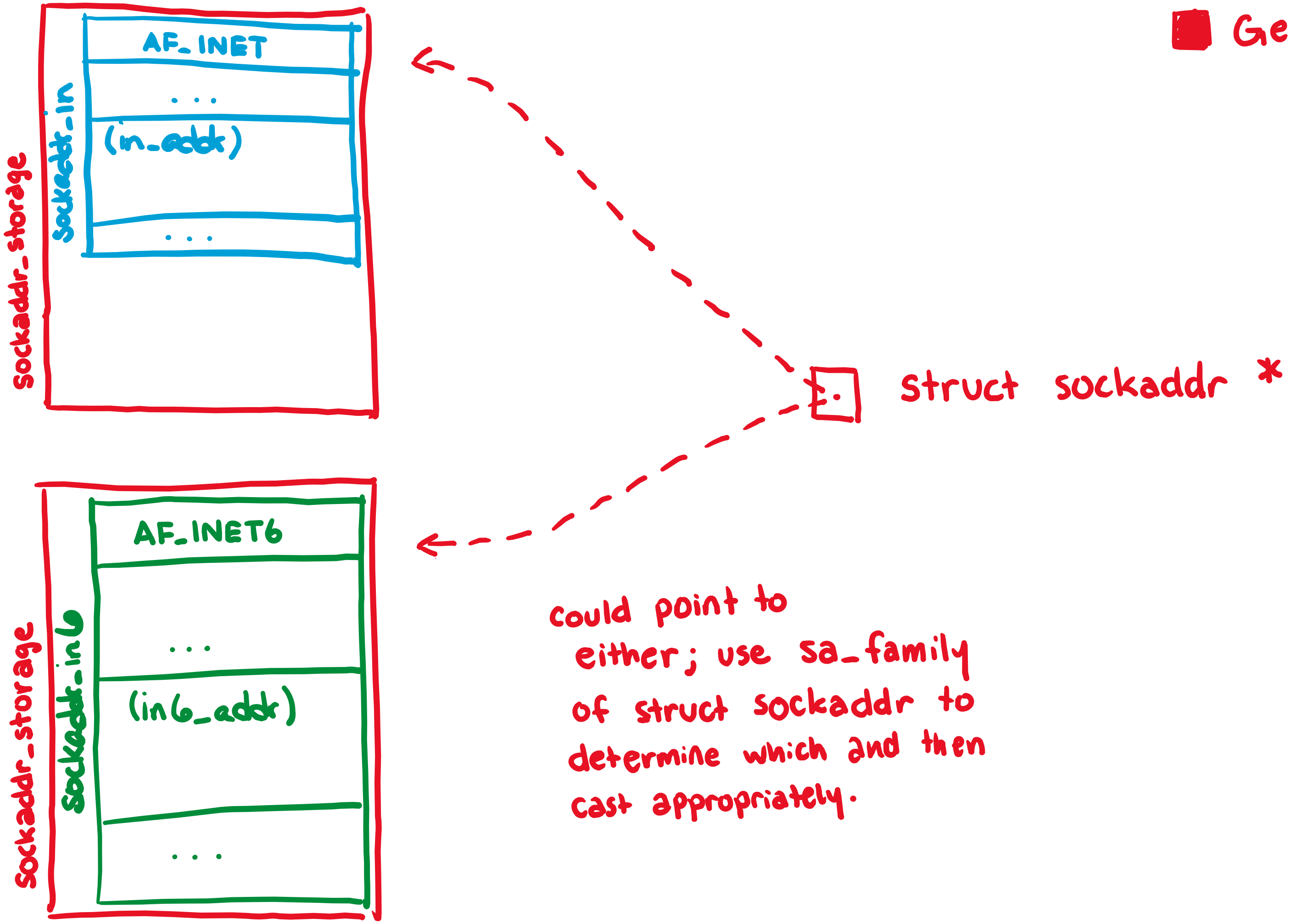
Address Structs: Generic!

```
// 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 its pointer cast as `struct sockaddr*` to **`connect()`**

Address Structs: Generic!

🟦 IPv4
🟩 IPv6
🟥 Generic



could point to either; use sa_family of struct sockaddr to determine which and then cast appropriately.

Human-Readable Addresses (1 of 2)

- `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;
}
```

Human-Readable Addresses (2 of 2)

-
  ```
  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;
}
```

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  - Step 1: Figure out the IP/Port
    - What is a Network Address?
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    - **DNS (Domain Name System): finding IP addresses**
  - Step 2: Create a Socket
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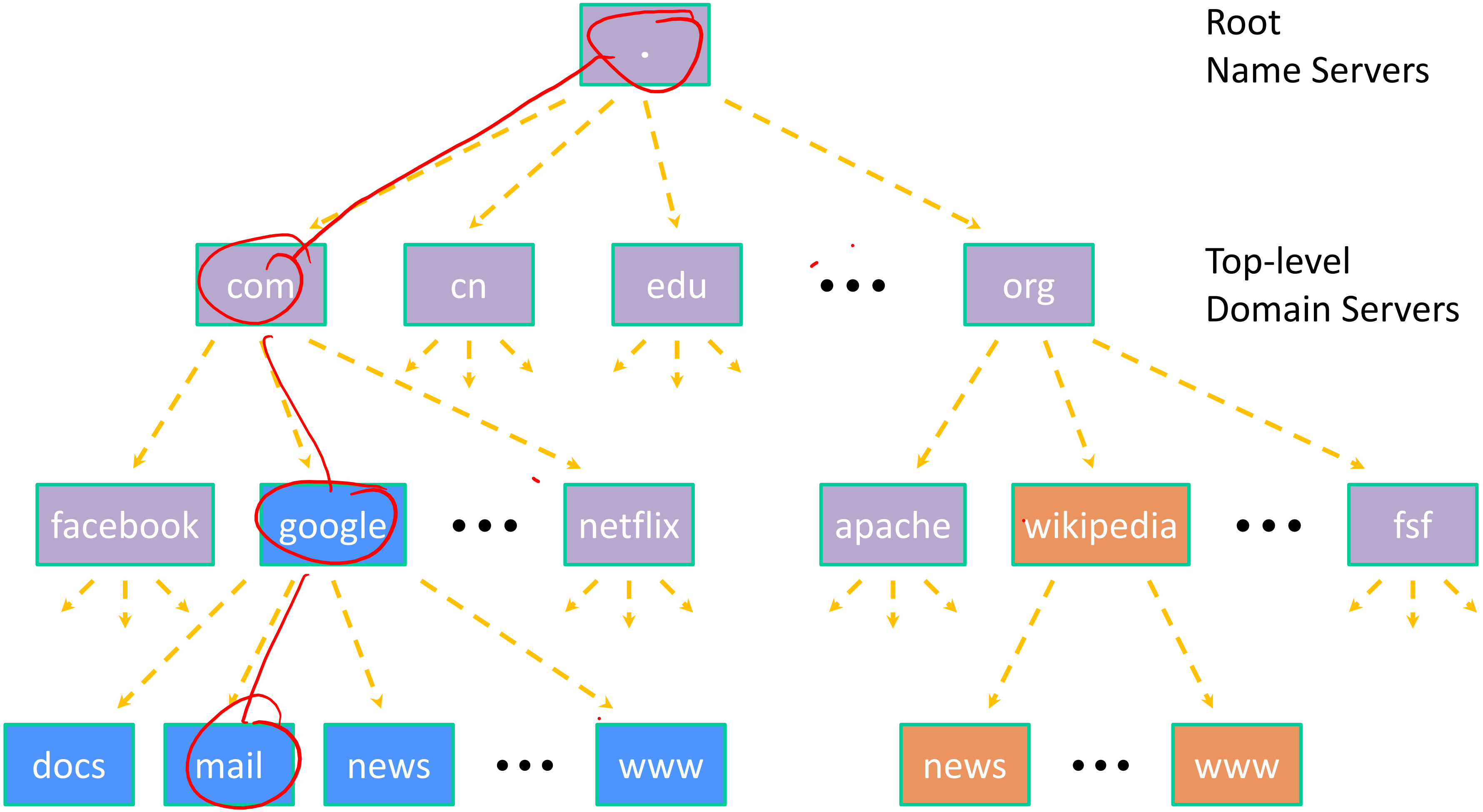
Domain Name System

- 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 DNS names can map to the same IP address 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

mail.google.com (uncached)



`getaddrinfo`: Resolving DNS Names

- The POSIX way is to use `getaddrinfo()`
  - A complicated system call found in `#include <netdb.h>`

  -
    ```
    int getaddrinfo(const char *hostname,
                    const char *service,
                    const struct addrinfo *hints,
                    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
    - `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()`

getaddrinfo: Args and Retvals

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

- Returns an addrinfo "linked list":

```
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