IP Addresses, DNS

CSE 333

Instructor: Alex Sanchez-Stern

Teaching Assistants:

Justin Tysdal

Sayuj Shahi

Nicholas Batchelder

Leanna Mi Nguyen

Administrivia

- HW3 due tomorrow night, 11pm
  - (plus late days if needed and you have them remaining – be sure to check "late days remaining" number on canvas)
  - (any last-minute questions? observations?)

- Exercise 15 due Monday
  - Client-side TCP connection

Lecture Outline

- **Sockets API**
  - **Sockets Overview**
  - Network Addresses
  - API Functions
- DNS
- Client-side Programming

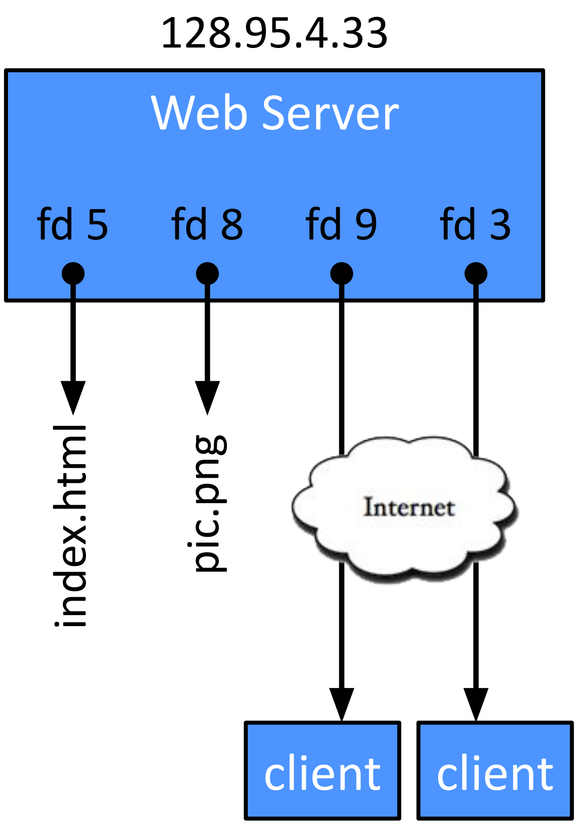
Files and File Descriptors

- 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

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 communication (raw IP packet manipulation)

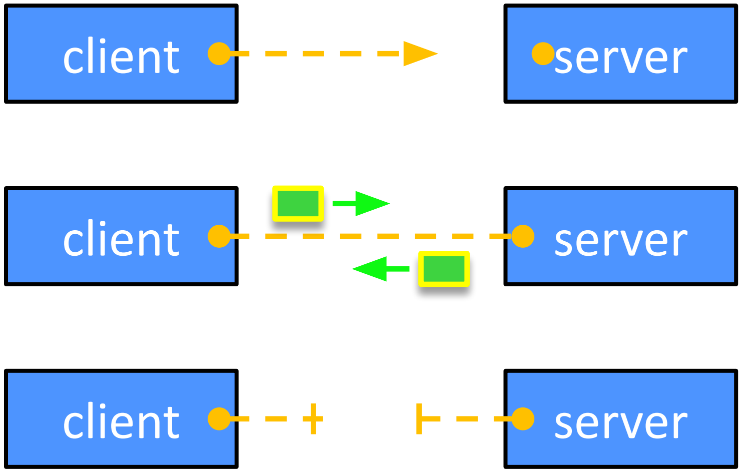
Stream Sockets

- 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:

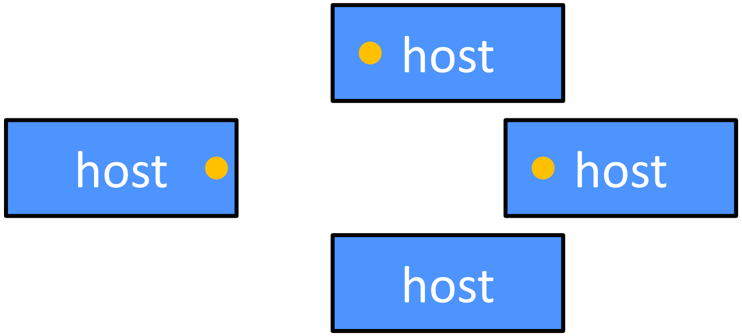
3) Close connection:



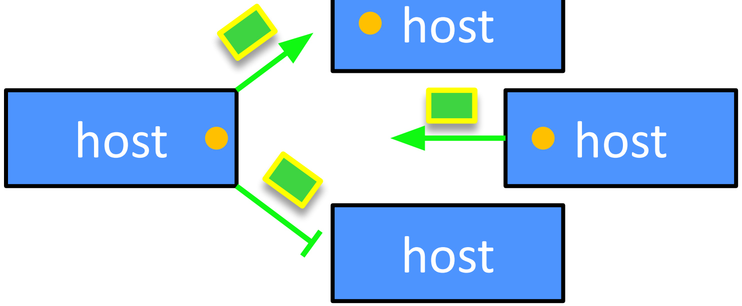
Datagram Sockets

- 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

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Step 1: Figure Out IP Address and Port

- Several parts:
  - Network addresses
  - Data structures for address info
  - DNS - Doman Name System – finding IP addresses

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)

- IPv4 address exhaustion
  - There are $2^{32} \approx$ 4.3 billion IPv4 addresses
  - There are ≈ 8 billion people in the world (July 2024)
  - Last unassigned IPv4 addresses allocated during 2011 to 2019 in various parts of the world

IPv6 Network Addresses

- An IPv6 address is a **16-byte** tuple
  - *e.g.* `2d01:0db8:f188:0000:0000:0000:0000:1f33`
  - 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:db8:f188::1f33`
  - Transition 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 ☹

IPv4 Address Structures

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

// 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	2–4	4–8	8–16

Working with Socket Addresses

- 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

```
// IPv4 4-byte address
struct in_addr {
  uint32_t s_addr;
};

// An IPv4 address structure
struct sockaddr_in {
  sa_family_t    sin_family;
  in_port_t      sin_port;
  struct in_addr sin_addr;
  unsigned char  sin_zero[8];
};
```

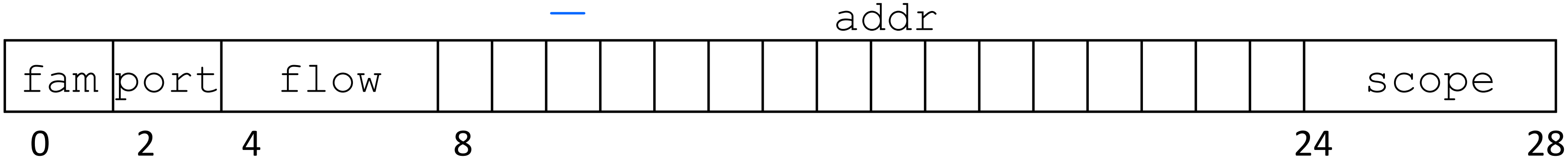
```
// IPv6 16-byte address
struct in6_addr {
  uint8_t s6_addr[16]
};

// An IPv6 address structure
struct sockaddr_in6 {
  sa_family_t     sin6_family;
  in_port_t       sin6_port;
  uint32_t        sin6_flowinfo;
  struct in6_addr sin6_addr;
  uint32_t        sin6_scope_id;
};
```

IPv6 Address Structures

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

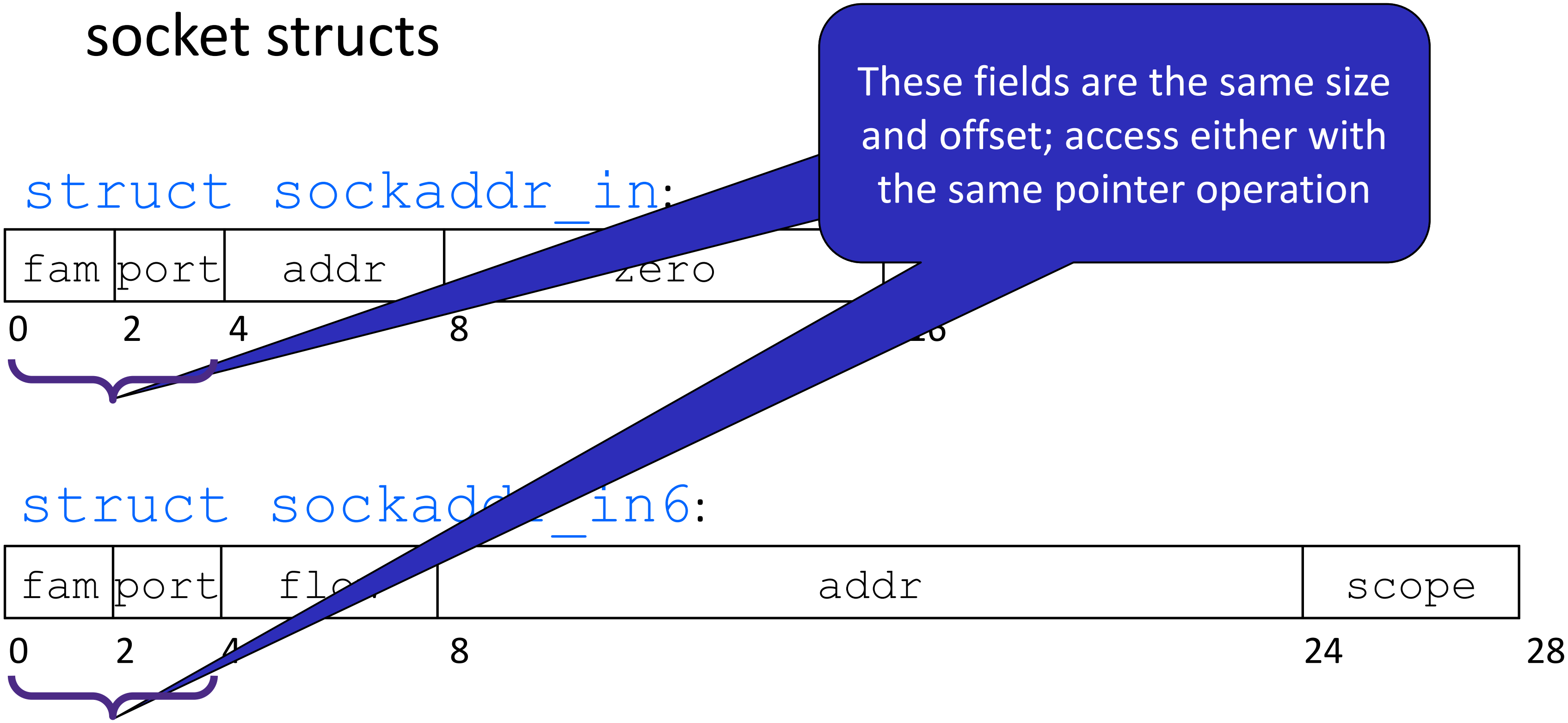
// An IPv6-specific address structure
struct sockaddr_in6 {
  sa_family_t     sin6_family;    // Address family: AF_INET6
  in_port_t       sin6_port;      // Port number
  uint32_t        sin6_flowinfo;  // IPv6 flow information
  struct in6_addr sin6_addr;      // IPv6 address
  uint32_t        sin6_scope_id;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

struct sockaddr_in6:



Address Structs: Generic?

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



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()`**

Lecture Outline

- **Sockets API**
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  - **API Functions**
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Working with 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)

Address Conversion

- `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

- ```
  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`

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;
}
```
```

Lecture Outline

- Sockets API
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  - API functions
- **DNS**
- Client-side Programming

Domain Name System

- People tend to use domain names, not IP addresses
  - The Sockets API lets you convert between the two
  - It's a complicated process, though:
    - A given domain name can have many IP addresses
    - Many different IP addresses can map to the same domain name
      - An IP address will reverse map into at most one domain 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 (optional)
    - `type`: `A` (IPv4), `AAAA` (IPv6), `ANY` (includes all types)

Dig example

A few other sections not important to this class

```
> dig www.google.com A
…
;; ANSWER SECTION:
www.google.com.     146 IN   A     142.250.217.68

;; Query time: 19 msec
;; SERVER: 8.8.8.8#53(8.8.8.8) (UDP)
…

> dig www.google.com AAAA
…
;; ANSWER SECTION:
www.google.com.     34   IN   AAAA     2607:f8b0:400a:804::2004

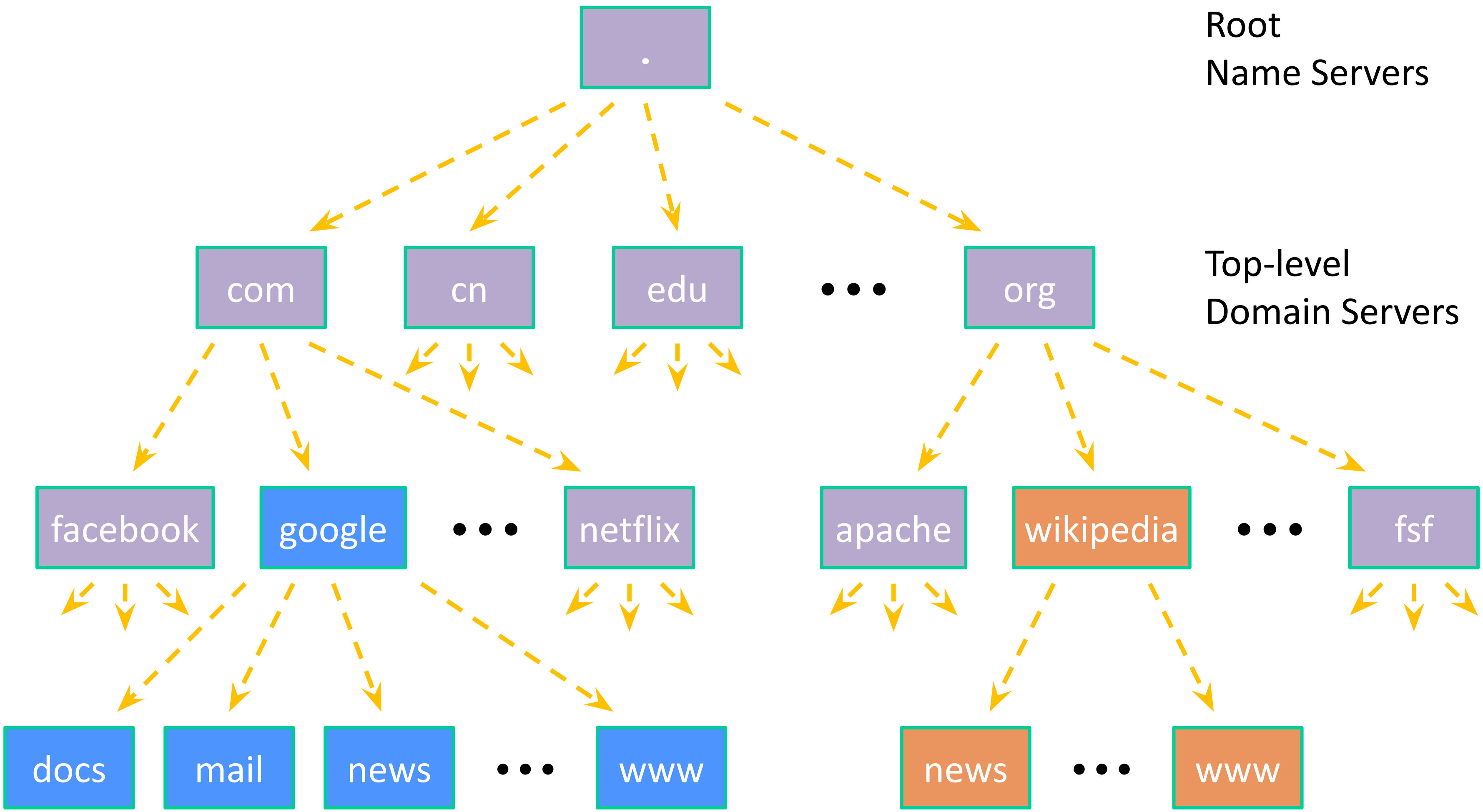
;; Query time: 23 msec
;; SERVER: 8.8.8.8#53(8.8.8.8) (UDP)
…
```

DNS Hierarchy

- The dots in a web address actually have a meaning!
  - Each web address component is a different "level" of DNS
  - Read from right to left

www.google.com

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,
                    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 list later using **freeaddrinfo**()

`getaddrinfo`

See `dnsresolve.cc`

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getaddrinfo

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

Socket API: Client TCP Connection

- There are five steps:
  1) Figure out the IP address and port to connect to
  2) Create a socket
  3) `connect()` the socket to the remote server
  4) `read()` and `write()` data using the socket
  5) Close the socket

Step 2: Creating a Socket

- `int socket(int domain, int type, int protocol);`
  - Creating a socket doesn't bind it to a local address or port yet
  - Returns file descriptor or -1 on error

socket.cc

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

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

Step 3: Connect to the Server

- The `connect()` system call establishes a connection to a remote host
  - ```
    int connect(int sockfd, const struct sockaddr* addr,
                socklen_t addrlen);
    ```
    - `sockfd`: Socket file description from Step 2
    - `addr` and `addrlen`: Usually from one of the address structures returned by `getaddrinfo` in Step 1 (DNS lookup)
    - Returns 0 on success and -1 on error
- `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
    ```

How long are two "round trips"?

- Remember this table?
  - Exact numbers change somewhat over time, but you should know the order-of-magnitudes here

Numbers Everyone Should Know

L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	25 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	3,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns
Disk seek	10,000,000 ns
Read 1 MB sequentially from disk	20,000,000 ns
Send packet CA->Netherlands->CA	150,000,000 ns

Connect Example

- See `connect.cc`

```
// Get an appropriate sockaddr structure.
struct sockaddr_storage addr;
size_t addrlen;
LookupName(argv[1], port, &addr, &addrlen);

// Create the socket.
int socket_fd = socket(addr.ss_family, SOCK_STREAM, 0);
if (socket_fd == -1) {
  cerr << "socket() failed: " << strerror(errno) << endl;
  return EXIT_FAILURE;
}

// Connect the socket to the remote host.
int res = connect(socket_fd,
                  reinterpret_cast<sockaddr*>(&addr),
                  addrlen);
if (res == -1) {
  cerr << "connect() failed: " << strerror(errno) << endl;
}
```

Step 4: `read()`

- If there is data that has already been received by the network stack, then read will return immediately with it
  - `read()` might return with *less* data than you asked for
- If there is no data waiting for you, by default `read()` will *block* until something arrives
  - This might cause *deadlock*!
  - Can `read()` return `0`?

Step 4: `read()`

- Assume we have:
  - `int socket_fd;       // fd of connected socket`
  - `char readbuf[BUF]; // read buffer`
  - `int res;             // to store read result`
- Write *C++* code to read in `BUF` characters from `socket_fd`
  - If error occurs, send error message to user and exit()

Step 4: `write()`

- `write()` enqueues your data in a send buffer in the OS and then returns
  - The OS transmits the data over the network in the background
  - When `write()` returns, the receiver probably has not yet received the data!

- If there is no more space left in the send buffer, by default `write()` will *block*

Read/Write Example

```
while (1) {
  int wres = write(socket_fd, readbuf, res);
  if (wres == 0) {
    cerr << "socket closed prematurely" << endl;
    close(socket_fd);
    return EXIT_FAILURE;
  }
  if (wres == -1) {
    if (errno == EINTR)
      continue;
    cerr << "socket write failure: " << strerror(errno) << endl;
    close(socket_fd);
    return EXIT_FAILURE;
  }
  break;
}
```

- See `sendreceive.cc`
  - Demo

Step 5: `close()`

- ```
  int close(int fd);
  ```
  - Nothing special here – it's the same function as with file I/O
  - Shuts down the socket and frees resources and file descriptors associated with it on both ends of the connection
  ```

Extra Exercise #1

- Write a program that:
  - Reads DNS names, one per line, from `stdin`
  - Translates each name to one or more IP addresses
  - Prints out each IP address to `stdout`, one per line