

# Sockets, addresses and hostnames

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# Administrivia

- ❖ HW3 due on Thursday
- ❖ Ex15 out today, due Friday
  - Uses material we'll learn throughout the week – start now and do in little chunks

# Lecture Outline

## ❖ Network Programming

- Sockets API
- Network Addresses
- DNS Lookup

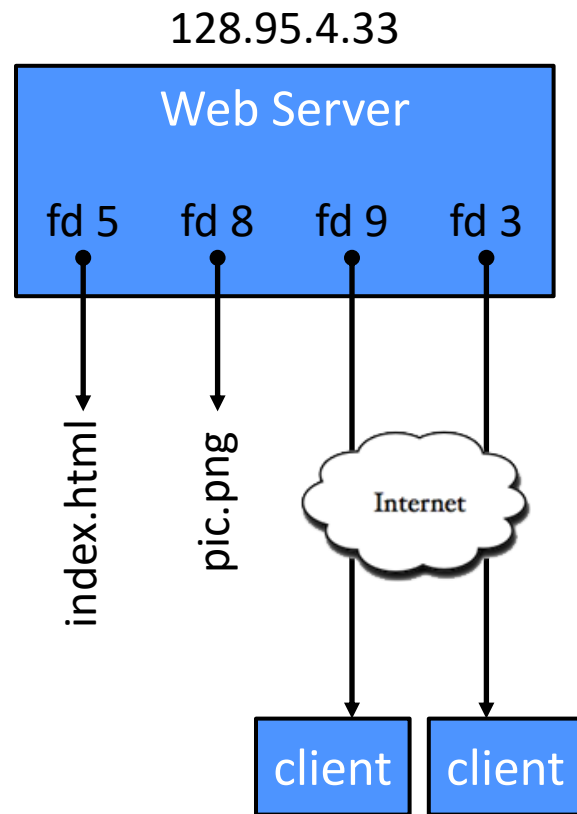
# Files and File Descriptors

- ❖ 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 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<br>remote: 44.1.19.32:7113 |
| 5               | file       | index.html                                       |
| 8               | file       | pic.png                                          |
| 9               | TCP socket | local: 128.95.4.33:80<br>remote: 102.12.3.4:5544 |

# Types of Sockets

## ❖ Stream sockets

- For connection-oriented, point-to-point, reliable byte streams
  - Using TCP, STCP, 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

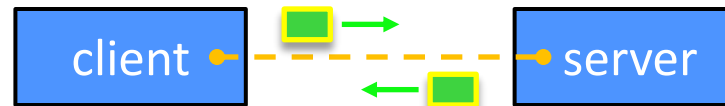
- ❖ Typically used for client-server communications
  - **Client**: An application that establishes a connection to a server
  - **Server**: An application that receives connections from clients
  - Can also be used for other forms of communication like peer-to-peer



1) Establish connection:



2) Communicate:



3) Close connection:

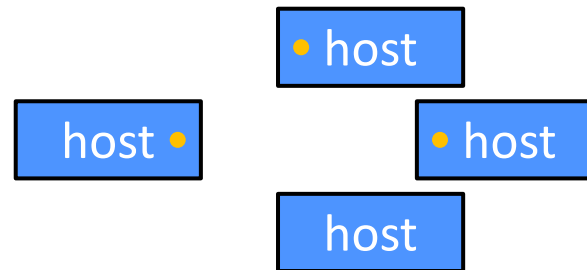




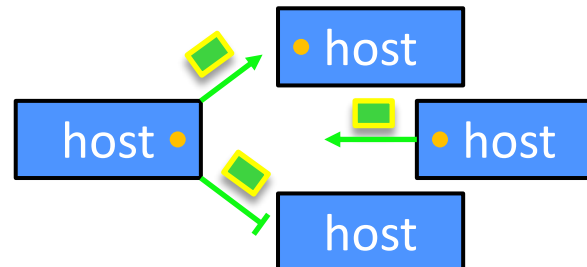
# Datagram Sockets

- ❖ 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

# Why is this all this way?



<https://computeradsfromthepast.substack.com/p/unix-review-interviews-sun-co-founder>

- ❖ DARPA wanted Unix systems to be able to connect to their internet
  - Hired a contractor to write the C code
  - Hired a UC Berkeley student, Bill Joy, to “make the API”
  - Bill didn’t know much about networking at the time, but he figured it out (and then wrote all the C code himself anyway)
- ❖ After this experience, Bill rage quit academia and founded Sun Microsystems
  - Read the full story: <https://klarasystems.com/articles/history-of-freebsd-part-4-bsd-and-tcp-ip/>

# (as an aside, thank your historians)

- ❖ In this case, Kirk McKusick and our very own Hal Perkins :3



# Our mission this week: send bytes over TCP using sockets

- ❖ 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

# 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)
- ❖ Each of those bytes has information about “which part” of the network the machine is on
  - Read left to right, the machine’s location gets more “network local”
  - IPs with the same prefix are on the same “subnet,” which represents ***some abstract form of locality***

# 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 consecutive sections of zeros
  - *e.g.* `2d01:0db8:f188:0000:0000:0000:0000:1f33`
    - Shorthand: `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 ☹



# 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`)

- ❖ How to handle both IPv4 and IPv6?

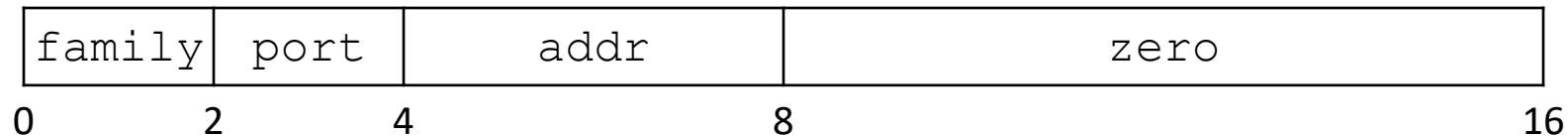
- Use C structs for each, but make them somewhat similar
- Use defined constants to differentiate when to use each: `AF_INET` for IPv4 and `AF_INET6` for IPv6
  - (Crude way to fake inheritance-like behavior in languages without it)

# 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:

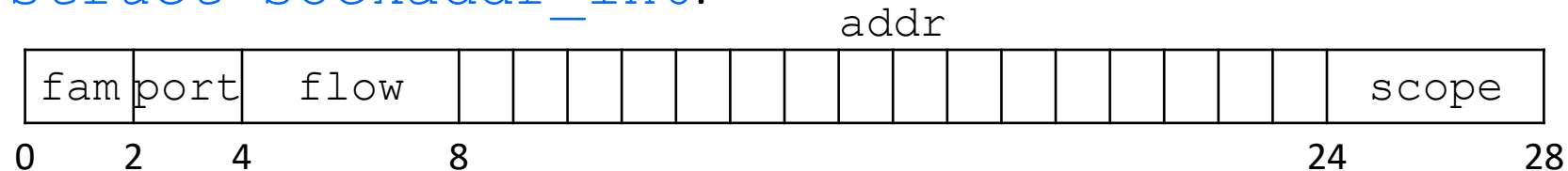


# IPv6 Address Structures

```
// 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:



# 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

- ❖ `int inet_pton(int af, const char* src, void* dst);`
  - Converts human-readable string representation (“presentation”) to network byte ordered address
  - Returns 1 (success), 0 (bad `src`), or -1 (error)

```
#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;
}
```

genaddr.cc

# 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`

```
#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;

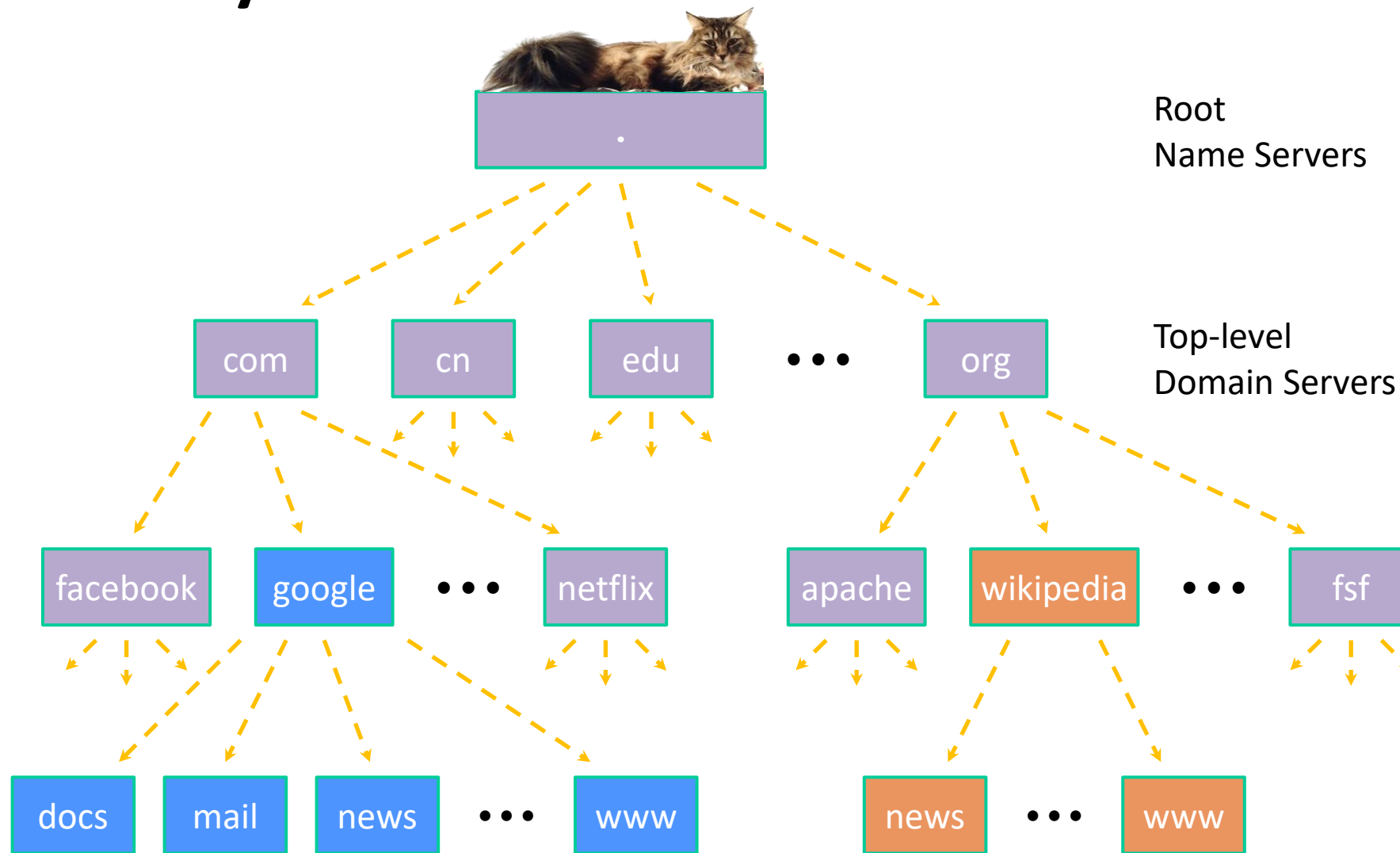
    return EXIT_SUCCESS;
}
```

genstring.cc

# 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>`

- Basic idea: 

```
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

## ❖ **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`