

IP Addresses, DNS

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Lecture Outline

❖ Network Programming

- Sockets API
- Network Addresses
- DNS Lookup

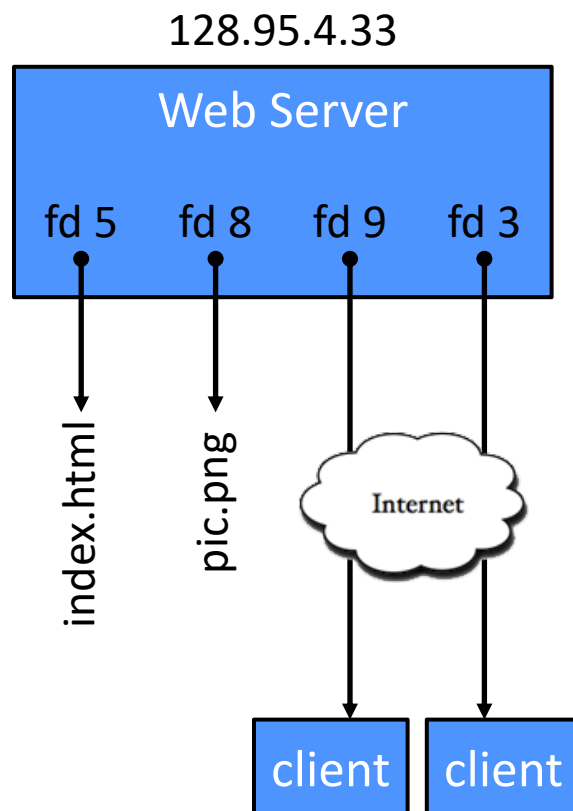
Files and File Descriptors

- ❖ 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

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)

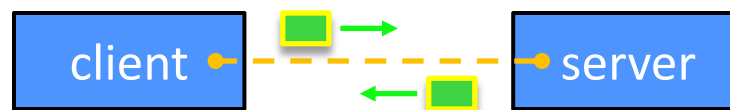
Stream Sockets

- ❖ 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:



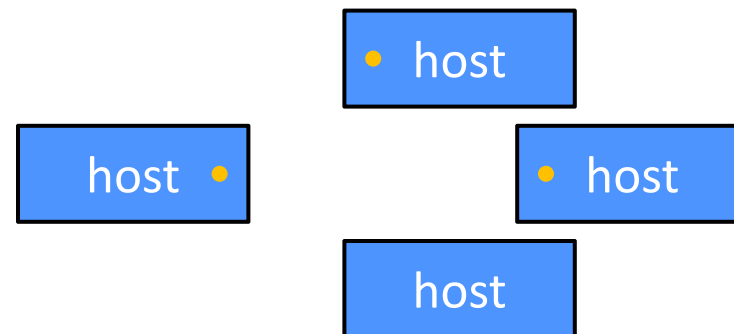
3) Close connection:



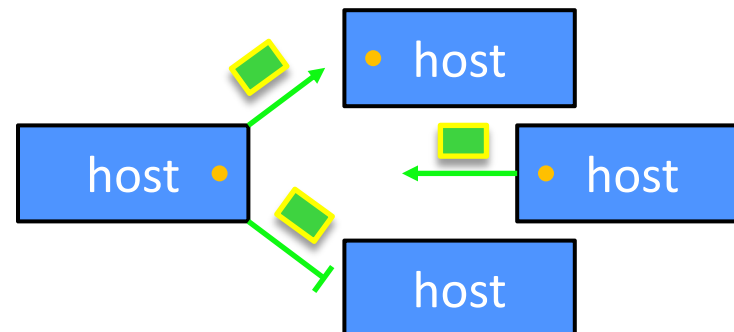
Datagram Sockets

- ❖ 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

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

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 ≈ 8.2 billion people in the world (2025)
 - 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
 - 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

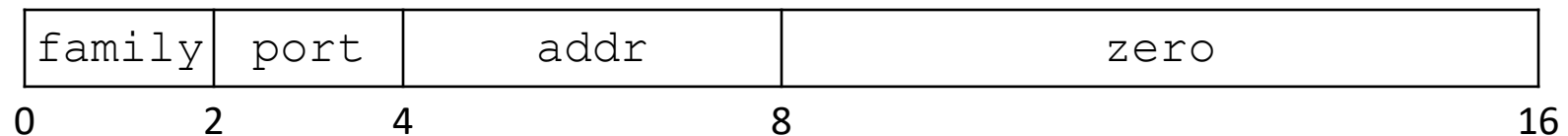
- ❖ Structures, constants, and helper functions available in `#include <arpa/inet.h>`
- ❖ Addresses stored in **network byte order** (big endian)
- ❖ Converting between host and network byte orders:
 - `uint32_t htonl(uint32_t hostlong);`
 - `uint32_t ntohl(uint32_t netlong);`
 - 'h' for host byte order and 'n' for network byte order
 - Also versions with 's' for short (`uint16_t` 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
 - (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:

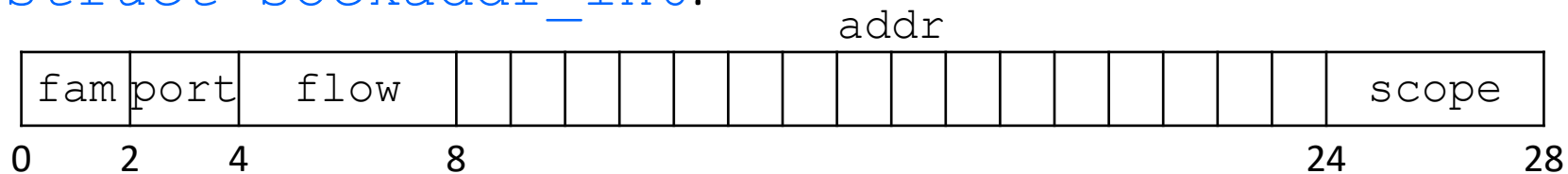


IPv6 Address Structures

```
// 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;

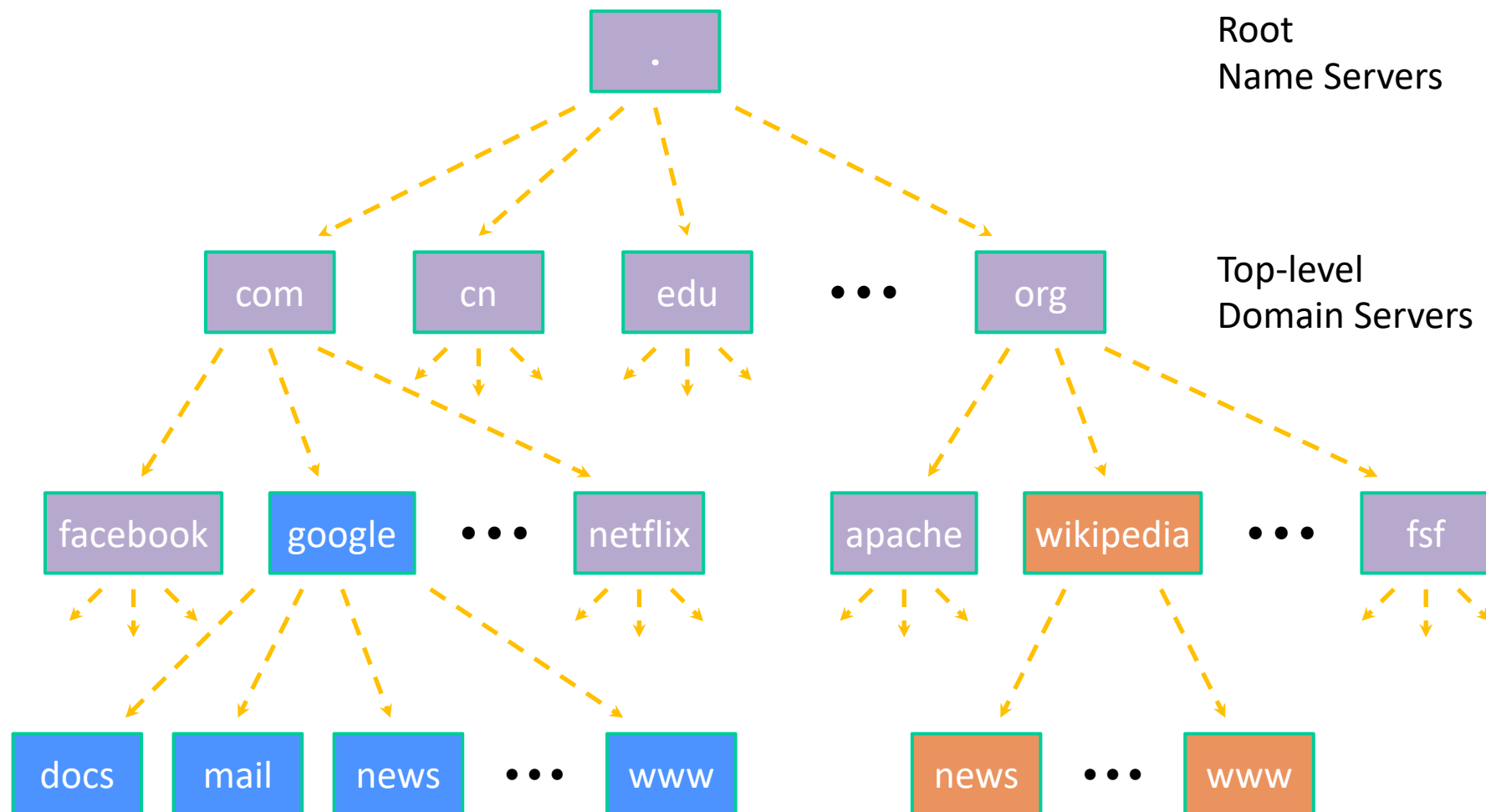
    return EXIT_SUCCESS;
}
```

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>`
 - ```
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`