Socket Programming

Computer Systems Programming, Spring 2025

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Administrivia

- HW09 – Threads “Grep”
  - Posted☺
  - Due Friday 4/11 at midnight, leaving open till Sunday night tho
  - AG posted soon
  - Some hints gone over in Recitation this week
  - We will check your submissions manually

- Final Project Details Coming soon-ish

- Check-in to be posted soon

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- Which layer handles this problem?

- Host A tries to send a long message to Host B in another city, broken up into many packets. A packet in the middle does not arrive, so Host A sends it again.

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- Which layer handles this problem?

- Host A tries to send a message to Host B, but Host C and Host D are also trying to communicate on the same network, so Host A has to avoid interfering

Lecture Outline

- **IP Addresses**
- Sockets
- Socket API
  - DNS
  - Client Side Socket Programming

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- Approximately how many internet connected devices do you own?

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

Can still use these in C++ code
You'll see some C-idioms and design practices.

- 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

IPv4 Network Addresses

- An IPv4 address is a **4-byte** tuple (2^{32} addresses)
  - 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 (April 2025)

How many internet connected devices do each of us have?

IPv6 Network Addresses

- An IPv6 address is a **16-byte** tuple

  (2^{128} addresses ~about 3.4×10^{38})

  - Typically written in "hextets" (groups of 4 hex digits)

    2 rules for human readability

    - 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

First field in a struct is always an ID

"AF" = Address Family

(other types of sockets exist, not just ipv4 & ipv6)

IPv4 Address Structures

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

// An IPv4-specific address structure
struct sockaddr_in {                          should always be AF_INET
  sa_family_t    sin_family;    // Address family: AF_INET
  in_port_t      sin_port;      // Port in network byte order (2 bytes)
  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

"Practice Question"

- 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 (host)		sin_port (network)		sin_addr (network)				
0	02	00	00	50	C6	23	1A	60	
8	00	00	00	00	00	00	00	00	zeroes (host)

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 {                              should always be AF_INET6
  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`:

			addr																
fam	port	flow																	scope
0	2	4	8															24	28

Generic Address Structures

struct sockaddr*

```
// 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];
};
```

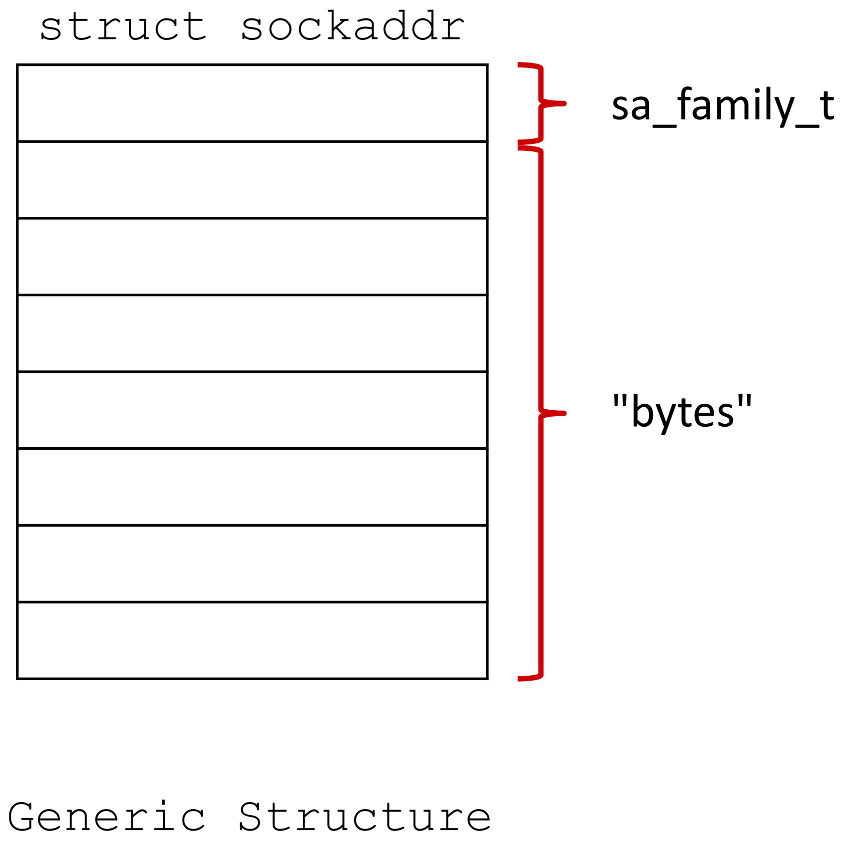
Family is always first to identify the socket type

struct sockaddr isn't big enough for ipv6

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

Explaining the weird struct relationship

- Does C have objects? Does C Have Inheritance?
- The Socket API was designed to support a bunch of different Socket Types



The struct stockaddr is designed to be the "Base class" or "generic" struct for a socket address.

First two bytes identify which type of socket address it is

The rest is generic "bytes" (14 of them) that don't have a clear meaning on their own

Explaining the weird struct relationship

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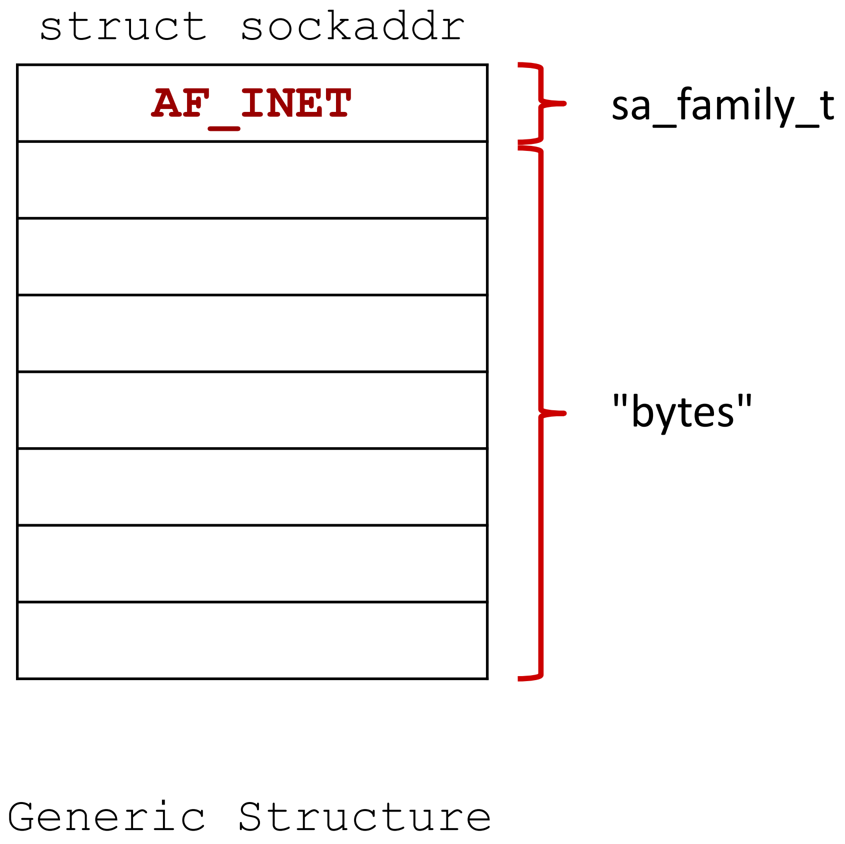
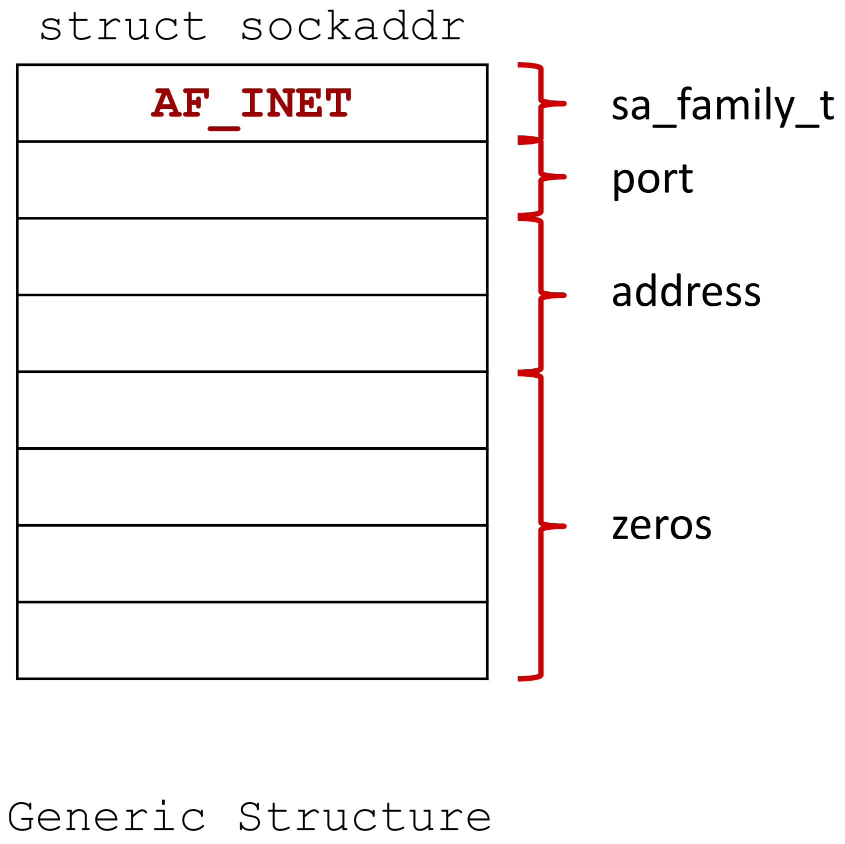


Based on what the sa_family is set to, that's how the C functions interpret the rest of the bytes.

OH this is an AF_INET struct well then....

Explaining the weird struct relationship

- Does C have objects? Does C Have Inheritance?
- The Socket API was designed to support a bunch of different Socket Types



Based on what the sa_family is set to, that's how the C functions interpret the rest of the bytes.

OH this is an AF_INET struct well then....

Those 14 bytes should be read like this!

If it was a different sa_family then we would have read these 14 bytes differently

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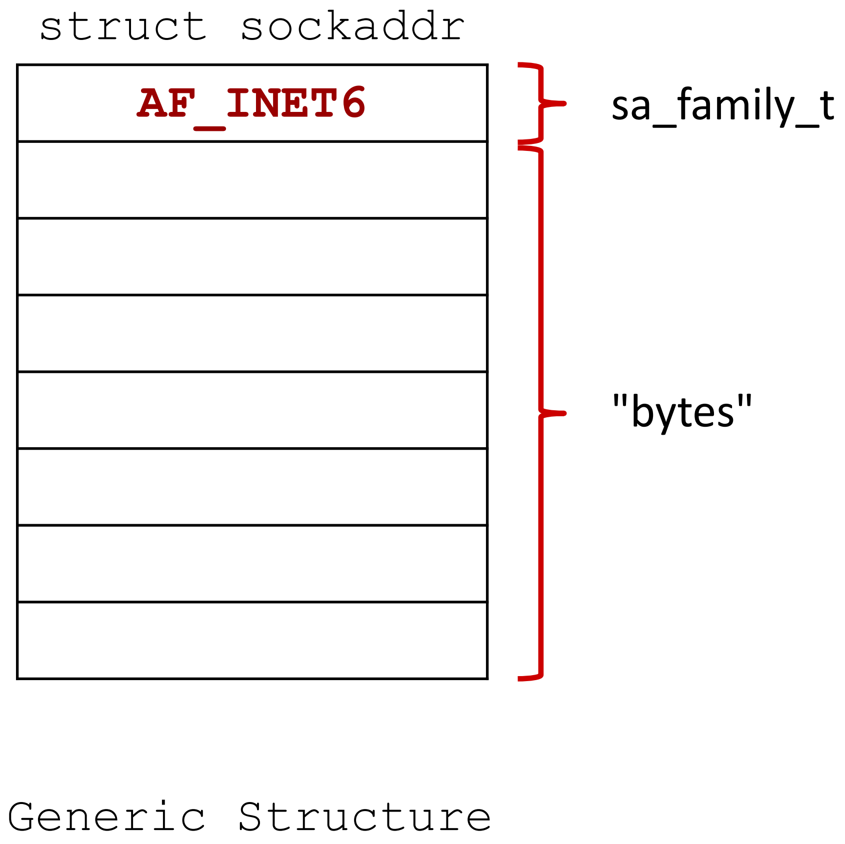
- Why do you think there are 8 bytes of zeroes in the sockaddr_in? (ipv4 struct)
  - Code says “Pad out to 16 bytes” why?

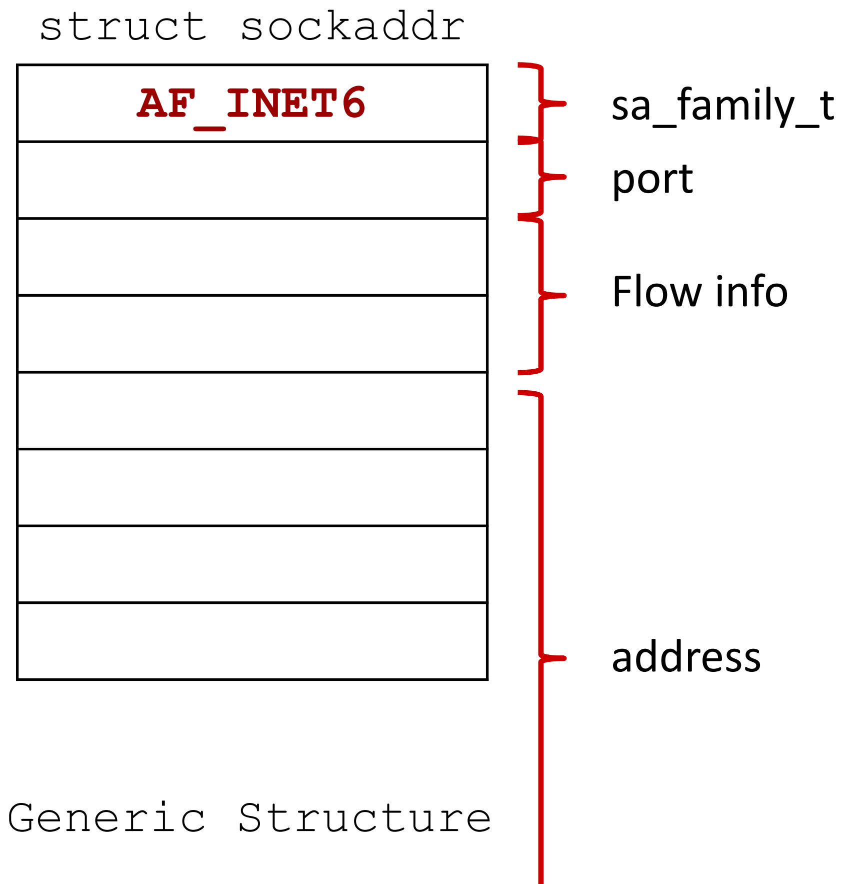
IPV6 & Storage Structs

- Whew, this worked really well. Ok, now we need to handle IPV6…



IPV6 & Storage Structs

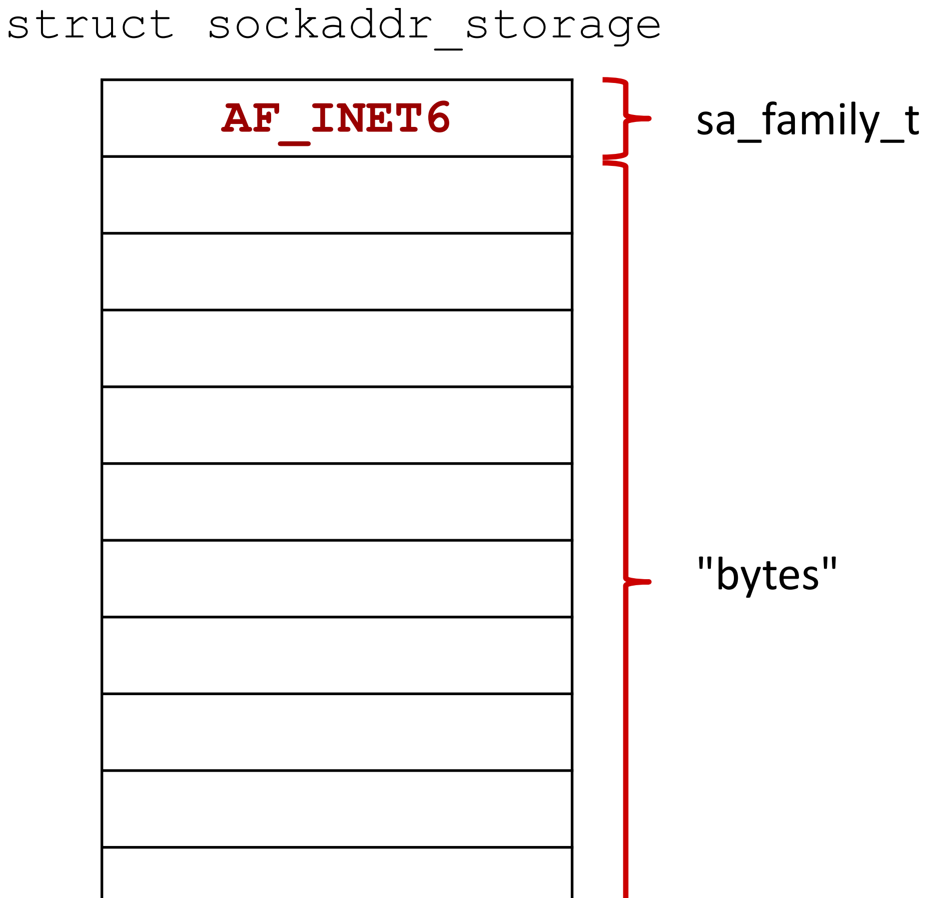
- Whew, this worked really well. Ok, now we need to handle IPV6…



Crap. Sockets were not designed to be this big!

IPV6 & Storage Structs

- Okay new plan, make a new sockaddr that is big enough to hold everything

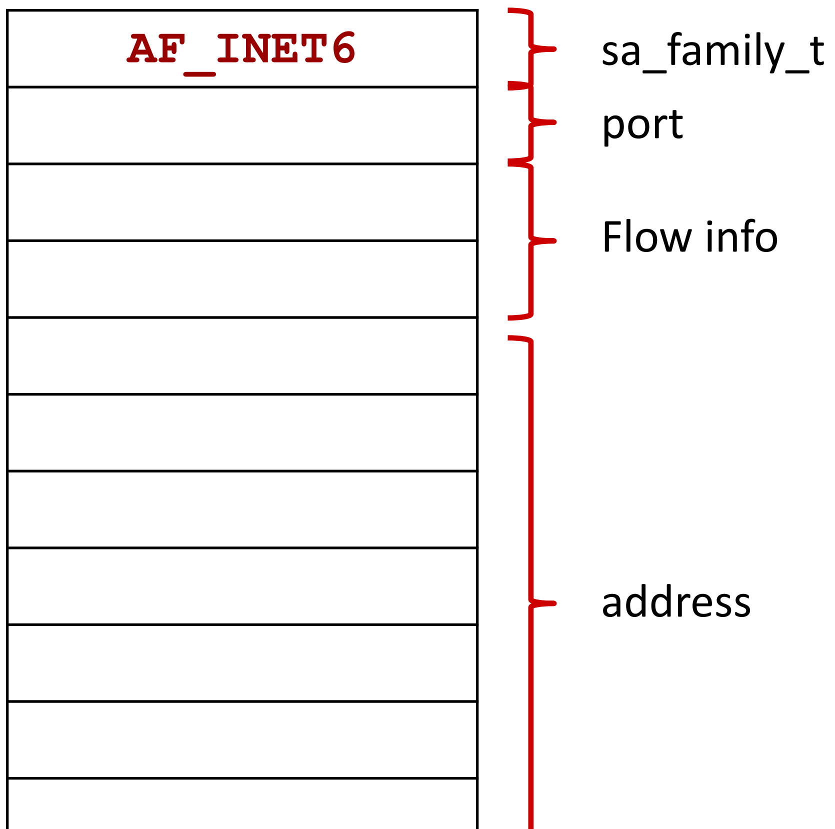


Crap. Sockets were not designed to be this big!

IPV6 & Storage Structs

- Okay new plan, make a new sockaddr that is big enough to hold everything

`struct sockaddr_storage`



Ok, now we have enough space!

C functions still take pointers to sockadrr…

1. Create a sockaddr_storage
2. populate it with either an ipv4 or ipv6 addr
3. cast pointer it to a sockaddr* and pass it to the socket functions

Address Conversion

Addr destination:
```
struct in_addr*
// or
struct in_6addr*
```

Address family String representation

- `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

Addr src:
struct in_addr*
// or
struct in_6addr*

```
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; // 2001:0db8:63b3:1::3490

  return EXIT_SUCCESS;
}
```

If converting ipv4:
INET_ADDRSTRLEN

Lecture Outline

- IP Addresses
- **Sockets**
- Socket API
  - DNS
  - Client Side Socket Programming

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- Do you think we can have multiple connections on a computer to the same port?
  - Example Ports:
    - 80 for HTTP (web traffic)
    - 443 for HTTPS (Secure web traffic)

Socket

- A Socket is an endpoint for a specific connection
  - If we think of a connection like a wire, then it must "plug in" to each end of the connection. Sort of like how you plug a charger into an outlet/wall socket

- A connection is identified by four things:
  - Client IP address
  - Client Port Number
  - Server IP Address
  - Server Port Number

- Going back to our apartment and post office analogy. For real packages we don't just put an address and apartment number of the destination, we also include the address it came from.

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

Parameters to

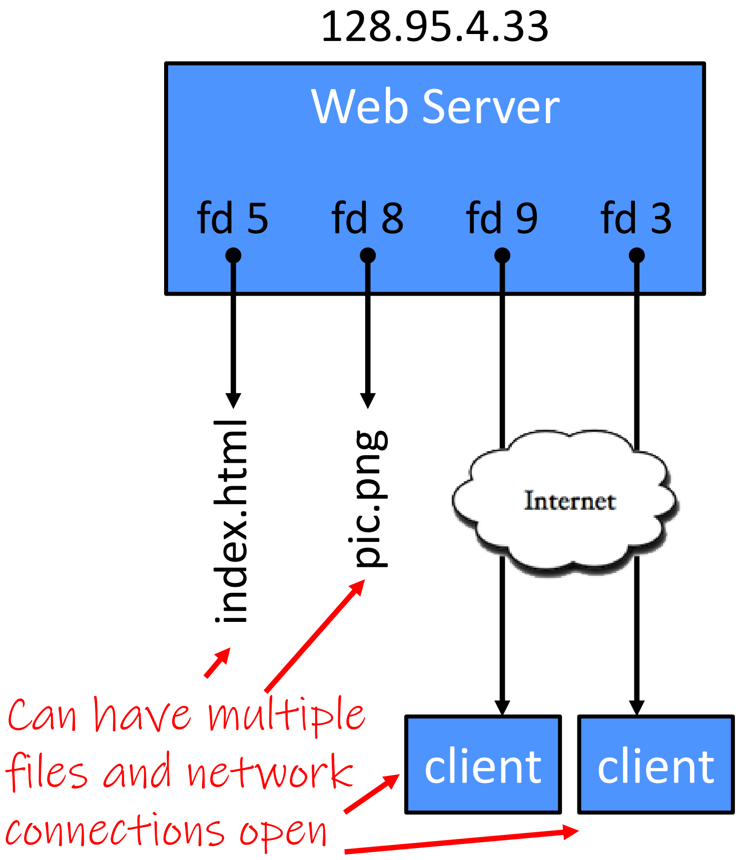
Can't be a pointer, don't want to give address to kernel

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

In other words, we
specify the socket
to read/write on

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 What we will focus on
  - 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)

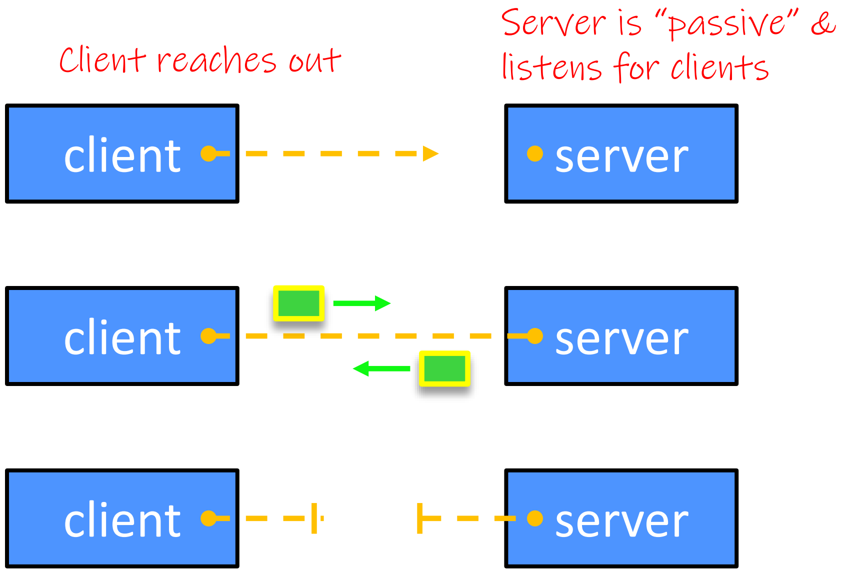
Stream Sockets

- 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:

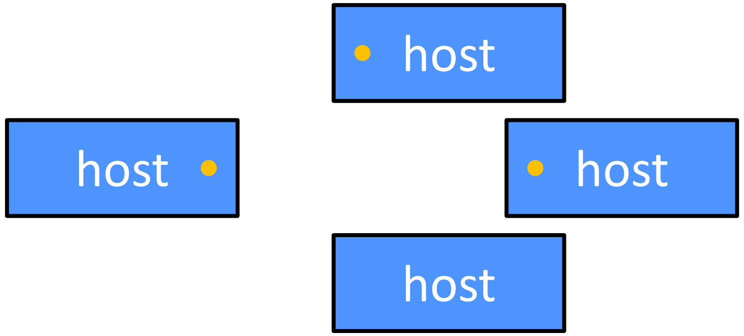
3) Close connection:



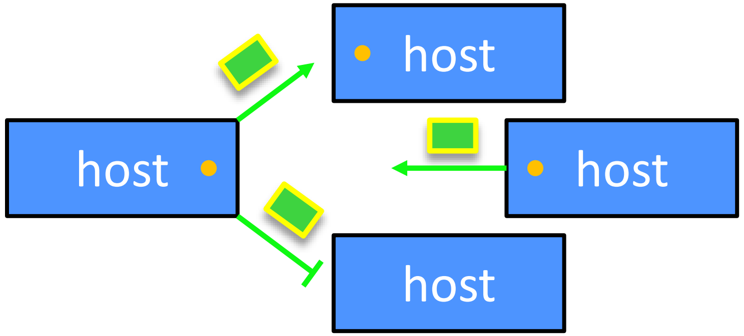
Datagram Sockets

- 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:



Lecture Outline

- IP Addresses
- Sockets
- **Socket API**
  - **DNS**
  - **Client Side Socket Programming**

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

Can still use these in C++ code
You'll see some C-idioms and design practices.

- 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:

** Today **

New stuff

1) Figure out the IP address and port to which to connect
2) Create a socket
3) Connect the socket to the remote server

Same as file I/O

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 (Domain Name System) – finding IP addresses

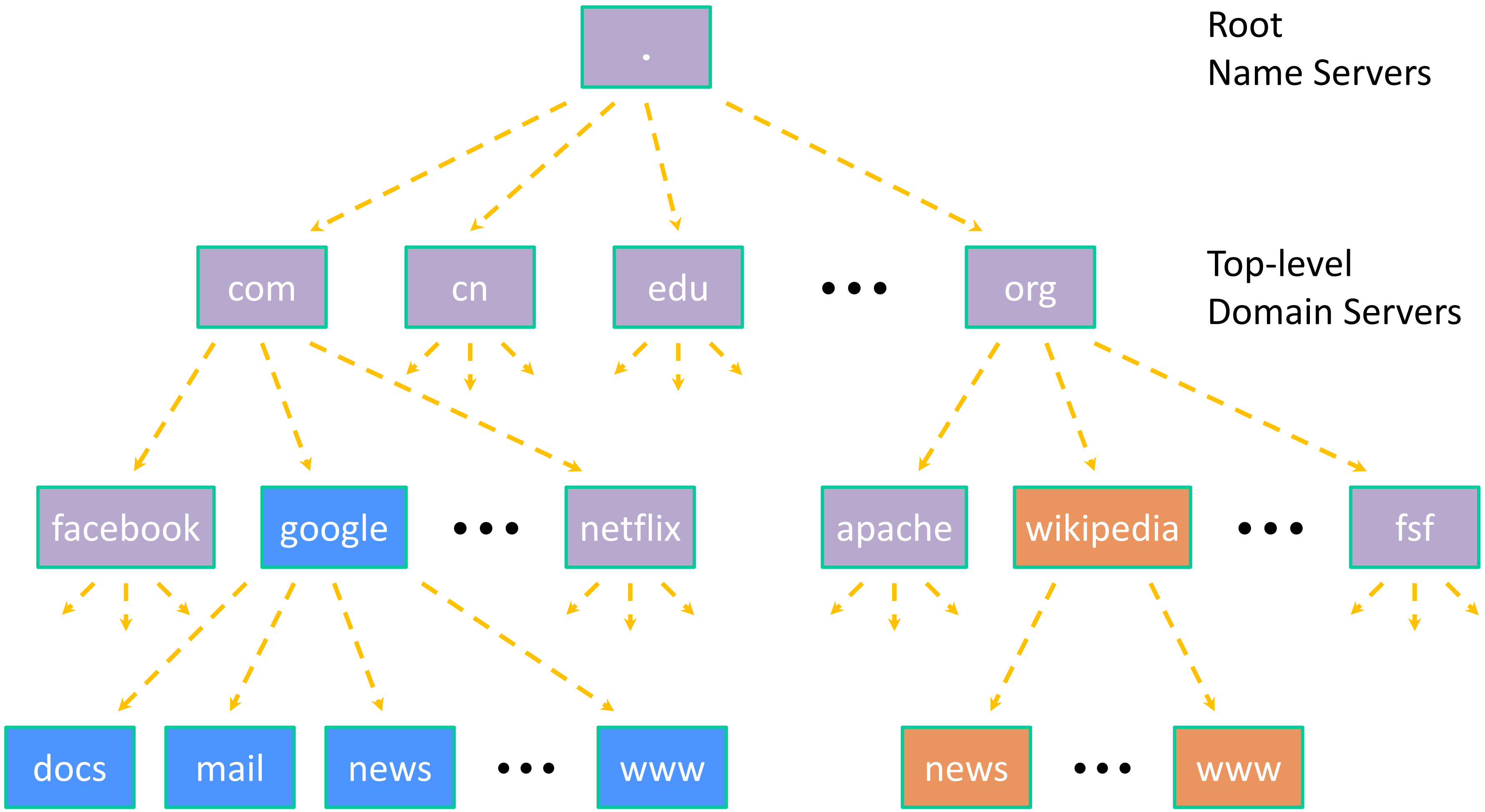
C data structures ☹

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);
```

Output param

- 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

Can use 0 or nullptr to indicate you don't want to filter results on that characteristic

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

```
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.cpp

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.cpp

```
#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) { // check for error
    std::cerr << strerror(errno) << std::endl;
    return EXIT_FAILURE;
  }
  close(socket_fd); // clean up
  return EXIT_SUCCESS;
}
```

Step 3: Connect to the Server

- The `connect()` system call establishes a connection to a remote host result from socket()
  - ```
    int connect(int sockfd, const struct sockaddr* addr,
                socklen_t addrlen);
    ```
    result from getaddrinfo()
    - `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 Waits on an event before returning
  - The network stack within the OS will communicate with the remote host to establish a TCP connection to it Performs a "Handshake" with the server
    - This involves ~2 *round trips* across the network
    ```

Connect Example

- See connect.cpp

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

// 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;
}
```

Sockets are sort of like files

- From this point it just turns into
  - Read/write
  - Close

- Looks like a file right?

- But this isn't a file, it's a network connection. It just looks like one
  - File
  - Terminal Input/Output
  - Pipe
  - Network Connection (More similar to reading/writing terminal or pipe than a file)

Sockets are sort of like files

- When dealing with stream sockets (TCP) Sockets, the TCP part is done for us. We can deal with the stream ABSTRACTION
  - Stream: That the bytes show up in order reliably

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- How do you think a network connection may behave differently from a file?
  - If it helps you can compare a file to reading/writing into a book and reading/writing a socket to texting/messaging a friend.

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

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  - How might this cause *deadlock*?
  - Can `read()` return `0`? (EOF)

Step 4: `write()`

- `write()` queues 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*

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- When we call `write()`, what data do we need to pass to it when writing over the network?

A. Any data our application needs to send

B. All of the above + TCP info (sequence number, port, …)

C. All of the above + IP info (source & dest IP addresses…)

D. All of the above + Ethernet info (source & dest MAC addresses)

E. We're lost…

Read/Write Example

- See sendreceive.cpp

```
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;
}
```

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
  ```

Next Lecture

- Server Side Socket Programming!