CS3281 / CS5281

Network Programming

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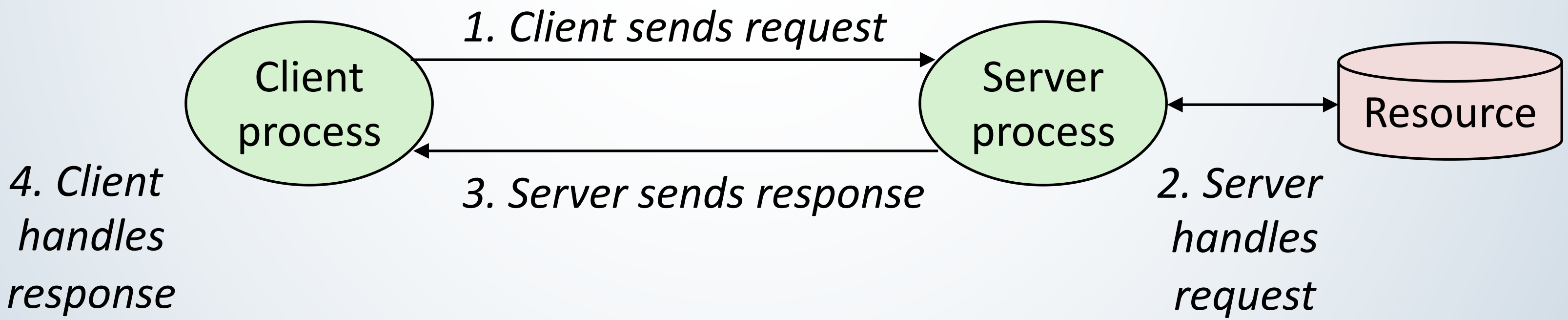
**Some lecture slides borrowed and adapted from CMU's "Computer Systems: A Programmer's Perspective"*

A Client-Server Transaction

- Most network applications are based on the client-server model:
  - A ***server*** process and one or more ***client*** processes
  - Server manages some ***resource***
  - Server provides ***service*** by manipulating resource for clients
  - Server activated by request from client (vending machine analogy)

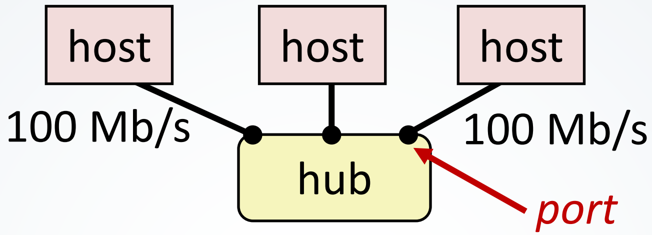


Note: clients and servers are processes running on hosts (can be the same or different hosts)

Computer Networks

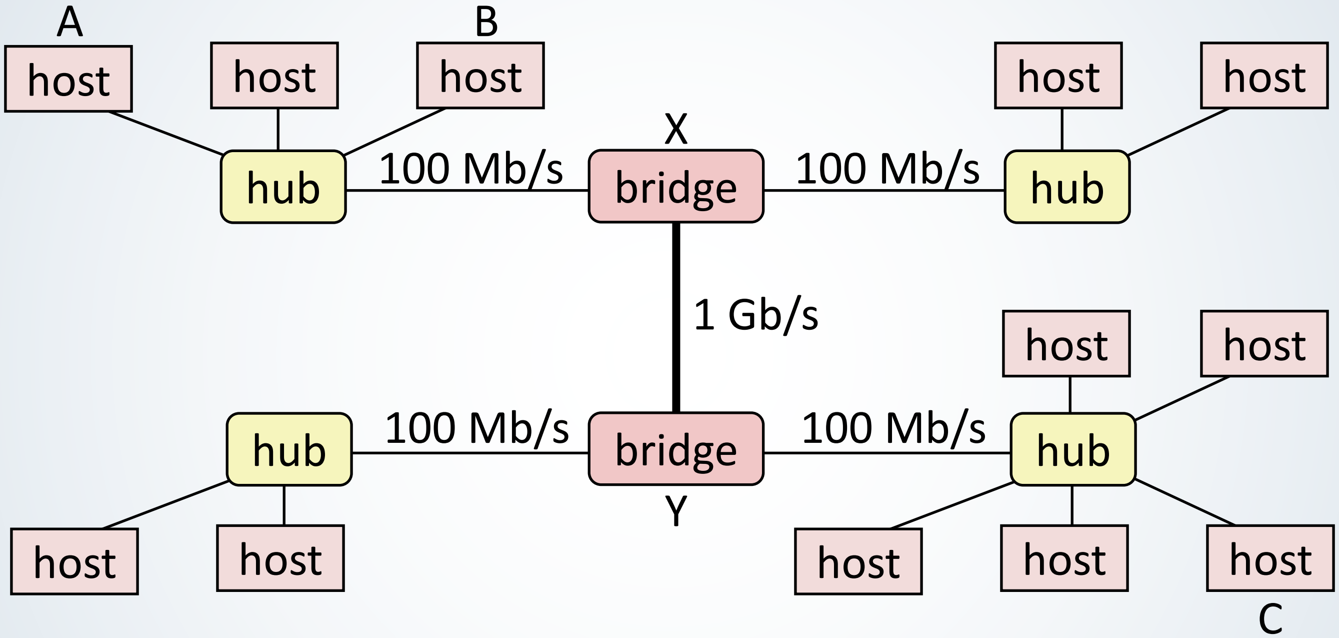
- A *network* is a hierarchical system of boxes and wires organized by geographical proximity
  - SAN (System Area Network) spans cluster or machine room
    - Switched Ethernet, Quadrics QSW, …
  - LAN (Local Area Network) spans a building or campus
    - Ethernet is most prominent example
  - WAN (Wide Area Network) spans country or world
    - Typically high-speed point-to-point phone lines
- An *internetwork (internet)* is an interconnected set of networks
  - The Global IP Internet (uppercase "I") is the most famous example of an internet (lowercase "i")
- Let's see how an internet is built from the ground up

Lowest Level: Ethernet Segment



- Ethernet segment consists of a collection of *hosts* connected by wires (twisted pairs) to a *hub*
- Spans room or floor in a building
- Operation
  - Each Ethernet adapter has a unique 48-bit address (MAC address)
    - E.g., 00:16:ea:e3:54:e6
  - Hosts send bits to any other host in chunks called ***frames***
  - Hub copies each bit from each port to every other port
    - Every host sees every bit
    - Note: Hubs are on their way out. Bridges (switches, routers) became cheap enough to replace them

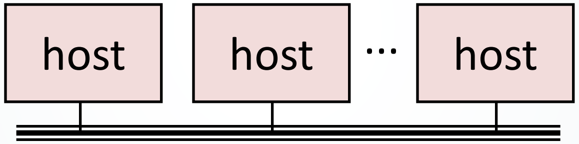
Next Level: Bridged Ethernet Segment



- Spans building or campus
- Bridges cleverly learn which hosts are reachable from which ports and then selectively copy frames from port to port

Conceptual View of LANs

- For simplicity, hubs, bridges, and wires are often shown as a collection of hosts attached to a single wire:



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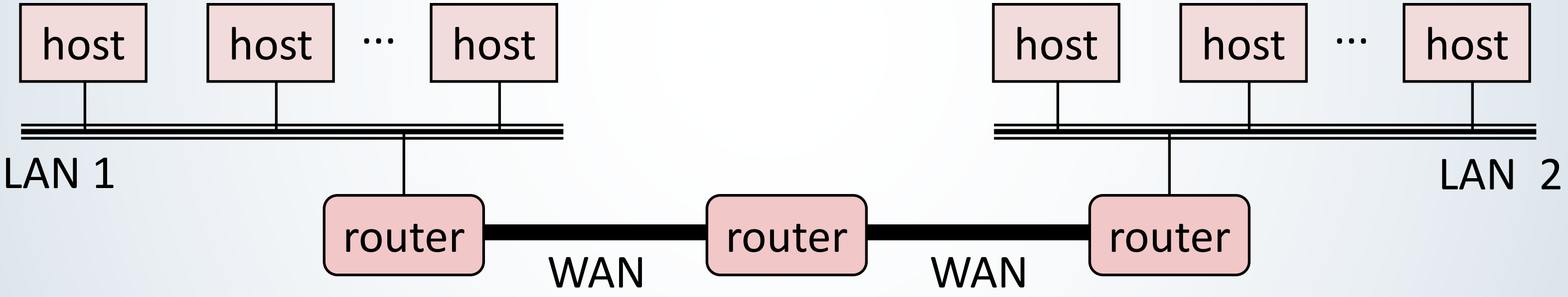
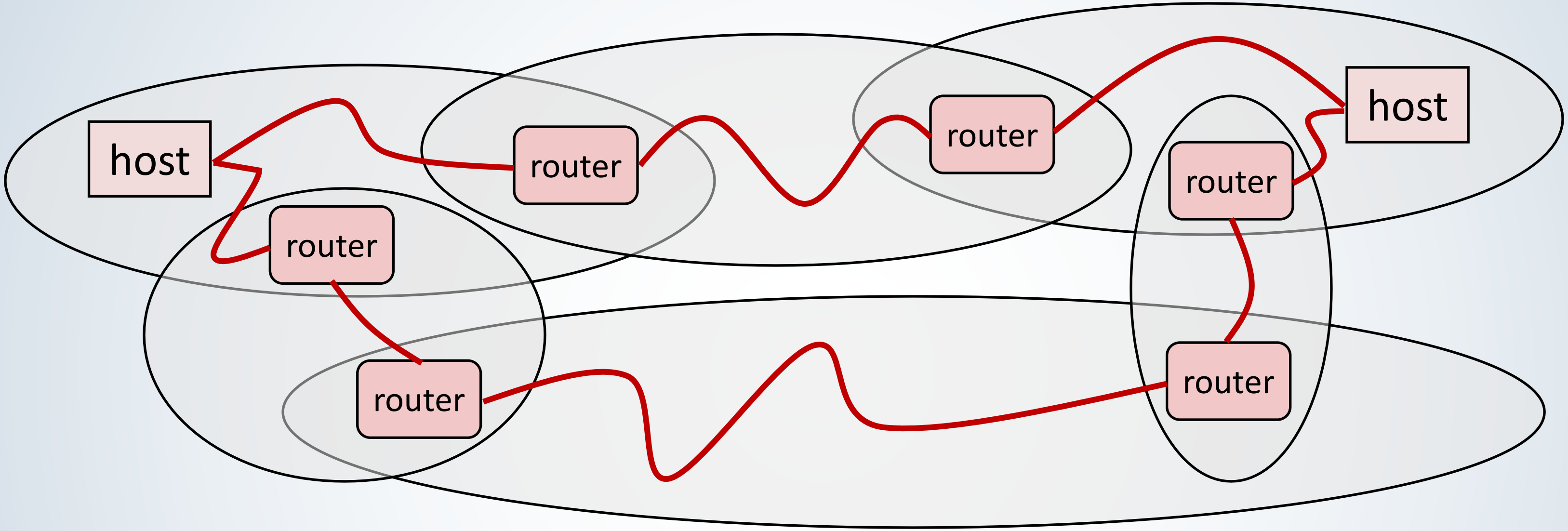
Next Level: Internets

- Multiple incompatible LANs can be physically connected by specialized computers called *routers*
- The connected networks are called an *internet* (lower case)



LAN 1 and LAN 2 might be completely different, totally incompatible (e.g., Ethernet, Fibre Channel, 802.11, T1-links, DSL, …)*

Logical Structure of an Internet



- Ad hoc interconnection of networks
  - No particular topology
  - Vastly different router & link capacities
- Send packets from source to destination by hopping through networks
  - Router forms bridge from one network to another
  - Different packets may take different routes

The Notion of an Internet Protocol

- How is it possible to send bits across incompatible LANs and WANs?

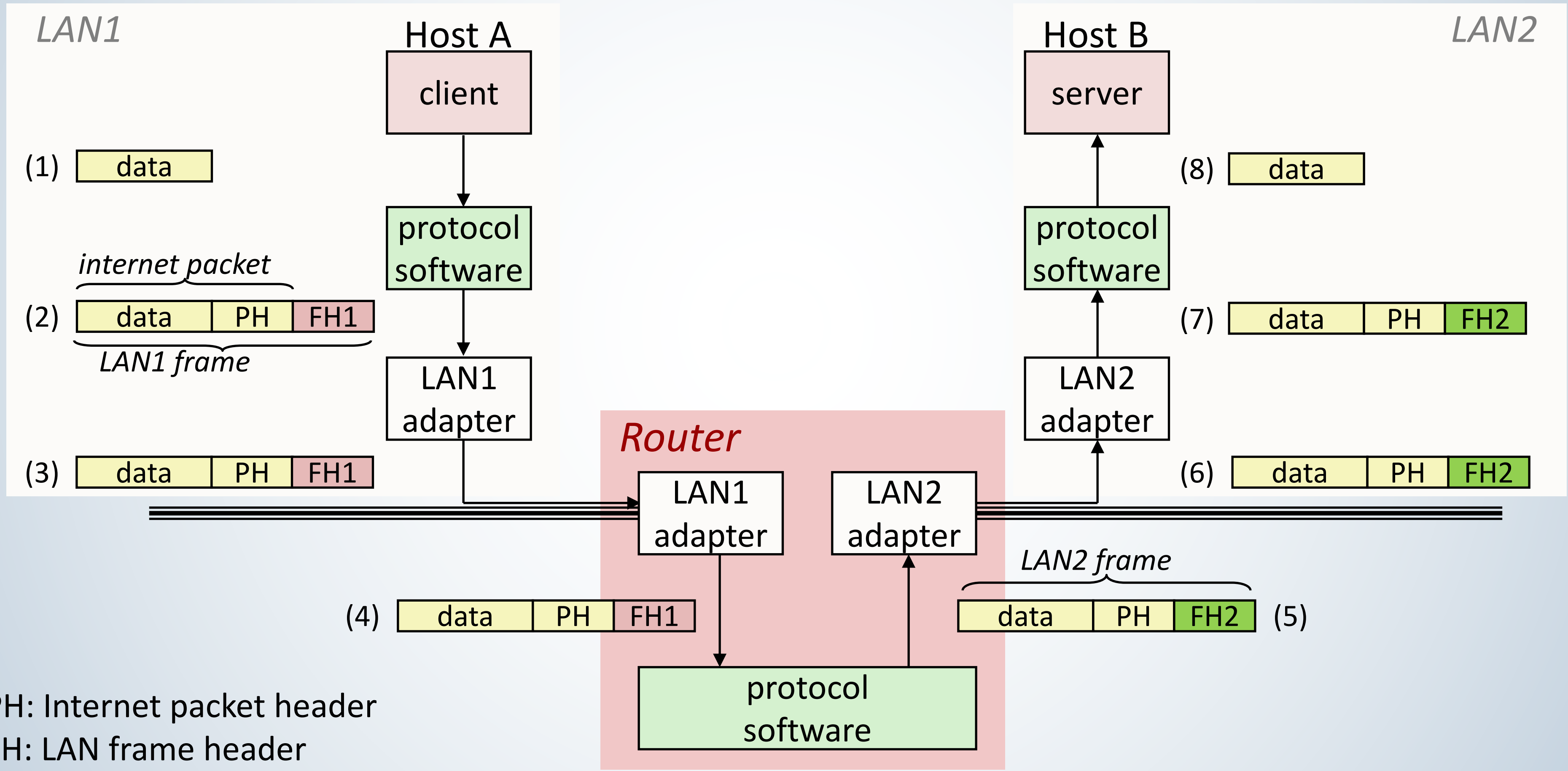
- Solution: *protocol* software running on each host and router
  – Protocol is a set of rules that governs how hosts and routers should cooperate when they transfer data from network to network.
  – Smooths out the differences between the different networks

What Does an Internet Protocol Do?

- Provides a *naming scheme*
  - An internet protocol defines a uniform format for ***host addresses***
  - Each host (and router) is assigned at least one of these internet addresses that uniquely identifies it

- Provides a *delivery mechanism*
  - An internet protocol defines a standard transfer unit (***packet***)
  - Packet consists of ***header*** and ***payload***
    - Header: contains info such as packet size, source and destination addresses
    - Payload: contains data bits sent from source host

Transferring Internet Data via Encapsulation



PH: Internet packet header
FH: LAN frame header

Other Issues

- We are glossing over a number of important questions:
  - What if different networks have different maximum frame sizes? (segmentation)
  - How do routers know where to forward frames?
  - How are routers informed when the network topology changes?
  - What if packets get lost?

- These (and other) questions are addressed by the area of systems known as *computer networking*

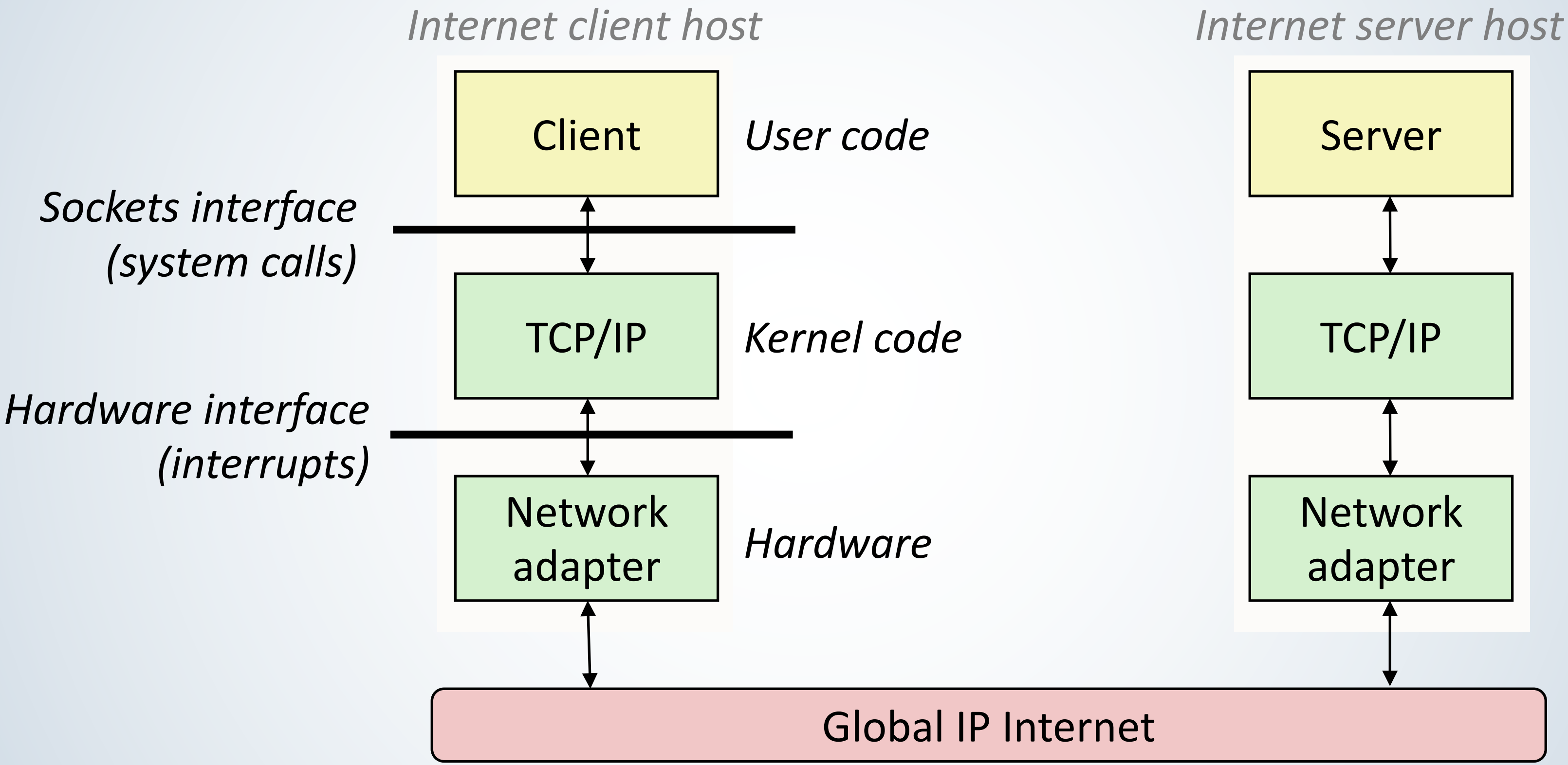
Global IP Internet (Upper Case)

- Most famous example of an internet

- Based on the TCP/IP protocol family
  - IP (Internet Protocol) :
    - Provides *basic naming scheme* and unreliable *delivery capability* of packets (datagrams) from *host-to-host*
  - UDP (Unreliable Datagram Protocol)
    - Uses IP to provide *unreliable* datagram delivery from *process-to-process*
  - TCP (Transmission Control Protocol)
    - Uses IP to provide *reliable* byte streams from *process-to-process* over *connections*

- Accessed via a mix of Unix file I/O and functions from the *sockets interface*

Organization of an Internet Application



A Programmer’s View of the Internet

1. Hosts are mapped to a set of 32-bit *IP addresses*
   – 128.2.203.179

2. The set of IP addresses is mapped to a set of identifiers called Internet *domain names*
   – 129.59.107.38 is mapped to www.isis.vanderbilt.edu

3. A process on one Internet host can communicate with a process on another Internet host over a *connection*

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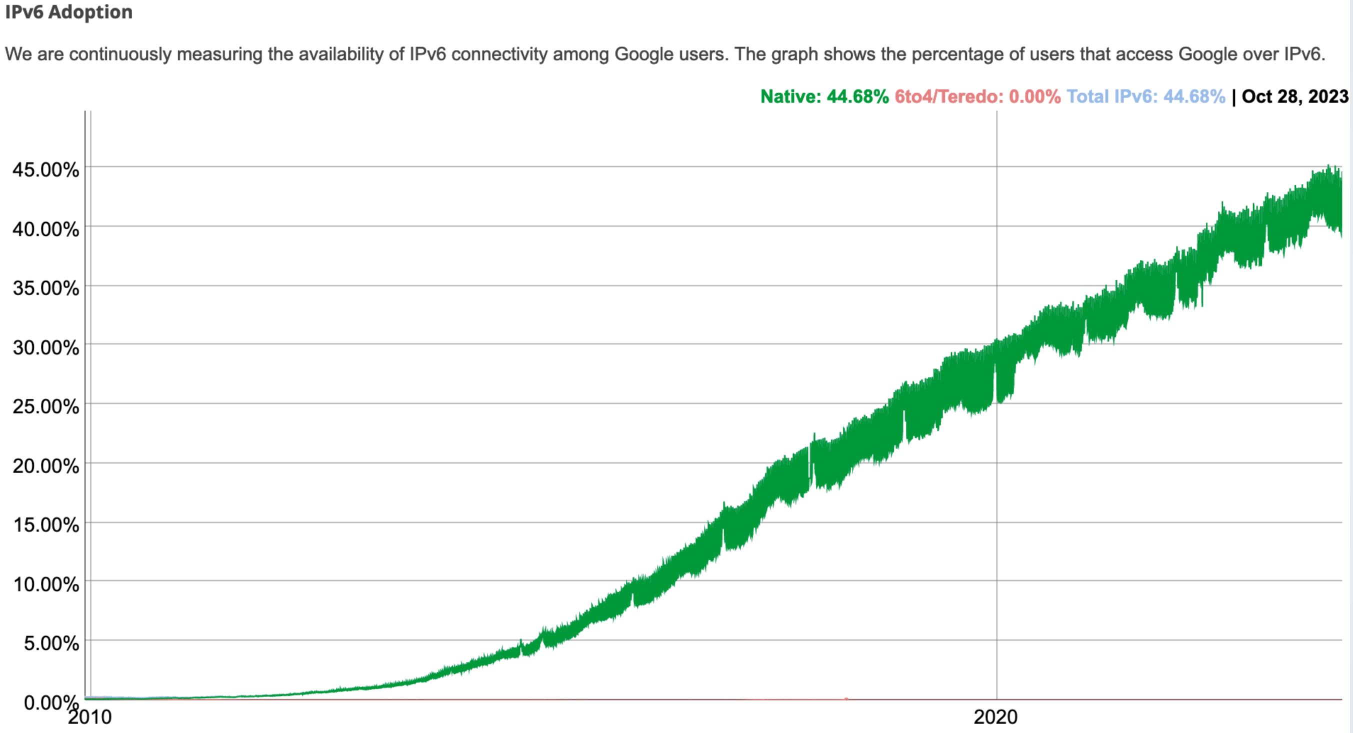
Aside: IPv4 and IPv6

- The original Internet Protocol, with its 32-bit addresses, is known as *Internet Protocol Version 4* (IPv4)
  - IPv4 *only* has 2^{32} = 4,294,967,296 address
  - … we ran out in 2011… whoops
- 1996: Internet Engineering Task Force (IETF) introduced *Internet Protocol Version 6* (IPv6) with 128-bit addresses
  - Intended as the successor to IPv4
- IPv6 traffic is increasing, but is still a minority of internet traffic
- We will focus on IPv4, but will show how to write networking code that is protocol independent



https://www.google.com/intl/en/ipv6/statistics.html#tab=ipv6-adoption

IP Addresses

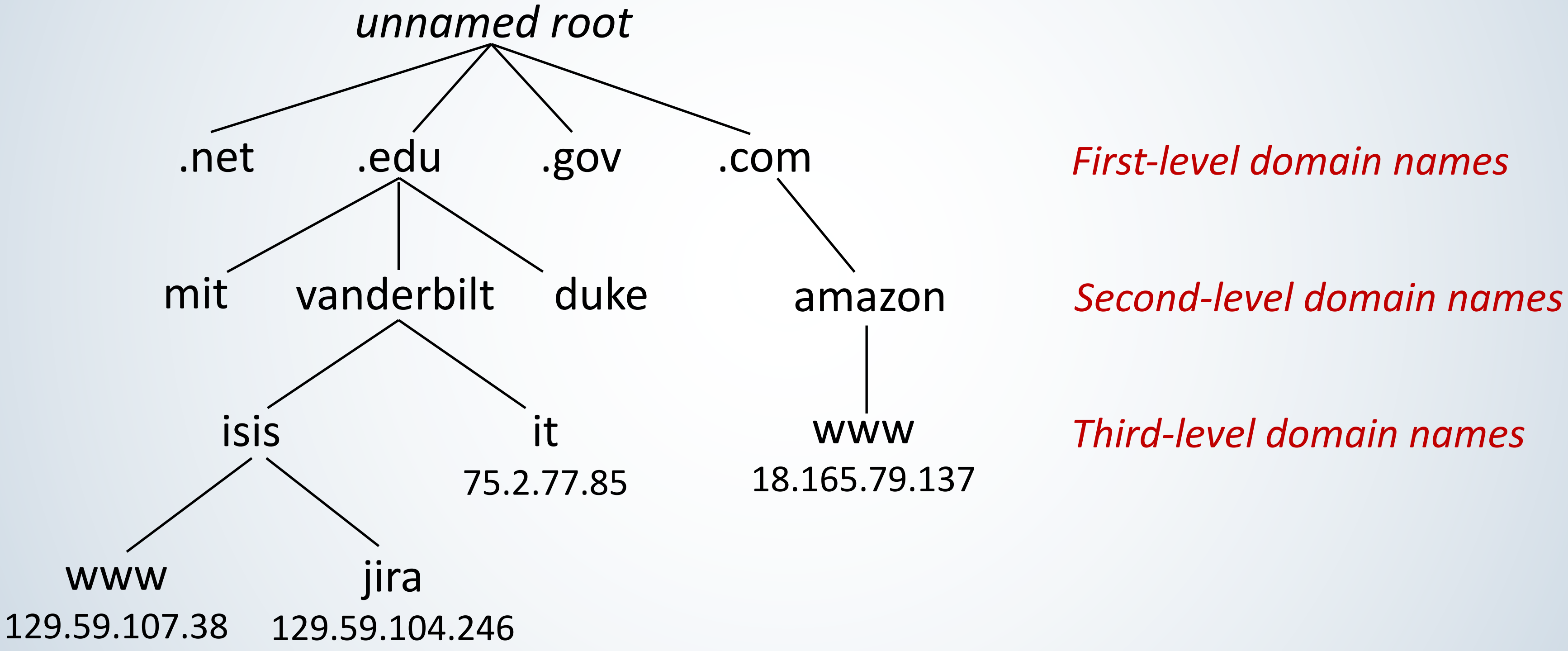
- 32-bit IP addresses are stored in an *IP address struct*
  - IP addresses are always stored in memory in *network byte order* (big-endian byte order)
    - x86, ARM, risc-v all little endian
  - True in general for any integer transferred in a packet header from one machine to another
    - E.g., the port number used to identify an Internet connection

```
/* Internet address structure */
struct in_addr {
    uint32_t  s_addr; /* network byte order (big-endian) */
};
```

Dotted-Decimal Notation

- By convention, each byte in a 32-bit IP address is represented by its decimal value and separated by a period
  - IP address: `0x8002C2F2 = 128.2.194.242`
- Use `getaddrinfo` and `getnameinfo` functions (described later) to convert between IP addresses and dotted decimal format.

Internet Domain Names



Domain Naming System (DNS)

- The Internet maintains a mapping between IP addresses and domain names in a huge worldwide distributed database called *DNS*

- Conceptually, programmers can view the DNS database as a collection of millions of *host entries*
  - Each host entry defines the mapping between a set of domain names and IP addresses
  - In a mathematical sense, a host entry is an equivalence class of domain names and IP addresses

Properties of DNS Mappings

- Can explore properties of DNS mappings using `nslookup`
  - Output edited for brevity
- Each host has a locally defined domain name `localhost` which always maps to the *loopback address* `127.0.0.1`

```
linux> nslookup localhost
Address: 127.0.0.1
```

- Use `hostname` to determine real domain name of local host

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Properties of DNS Mappings (cont.)

- Simple case: one-to-one mapping between domain name and IP address:

```
linux> nslookup www.isis.vanderbilt.edu
Address: 129.59.107.38
```

- Multiple domain names can be mapped to the same IP address:

```
linux> nslookup amazon.com
Address: 54.239.28.85
linux> nslookup amzn.com
Address: 54.239.28.85
```

Properties of DNS Mappings (cont.)

- Multiple domain names mapped to multiple IP addresses:

```
linux> nslookup www.twitter.com
Address: 199.16.156.6
Address: 199.16.156.70
Address: 199.16.156.102
Address: 199.16.156.230

linux> nslookup twitter.com
Address: 199.16.156.102
Address: 199.16.156.230
Address: 199.16.156.6
Address: 199.16.156.70
```

Internet Connections

- Clients and servers communicate by sending streams of bytes over *connections*. Each connection is:
  - *Point-to-point*: connects a pair of processes.
  - *Full-duplex*: data can flow in both directions at the same time,
  - *Reliable*: stream of bytes sent by the source is eventually received by the destination in the same order it was sent.

- *A socket* is an endpoint of a connection
  - *Socket address* is an **`IPaddress:port`** pair

- A *port* is a 16-bit integer that identifies a process:
  - ***Ephemeral port*:** Assigned automatically by client kernel when client makes a connection request.
  - ***Well-known port:*** Associated with some *service* provided by a server (e.g., port 80 is associated with Web servers)

Well-Known Ports and Service Names

- Popular services have permanently assigned *well-known ports and* corresponding *well-known service names*:
  - echo server: 7/echo
  - ssh servers: 22/ssh
  - email server: 25/smtp
  - Web servers: 80/http, 443/https

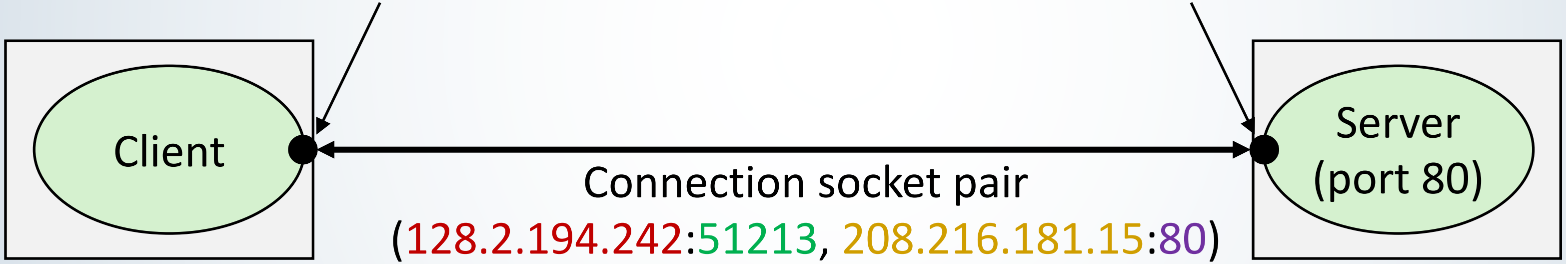
- Mappings between well-known ports and service names is contained in the file `/etc/services` on each Linux machine.

Anatomy of a Connection

- A connection is uniquely identified by the socket addresses of its endpoints (*socket pair*)
  - `(cliaddr:cliport, servaddr:servport)`

Client socket address
128.2.194.242:51213

Server socket address
208.216.181.15:80



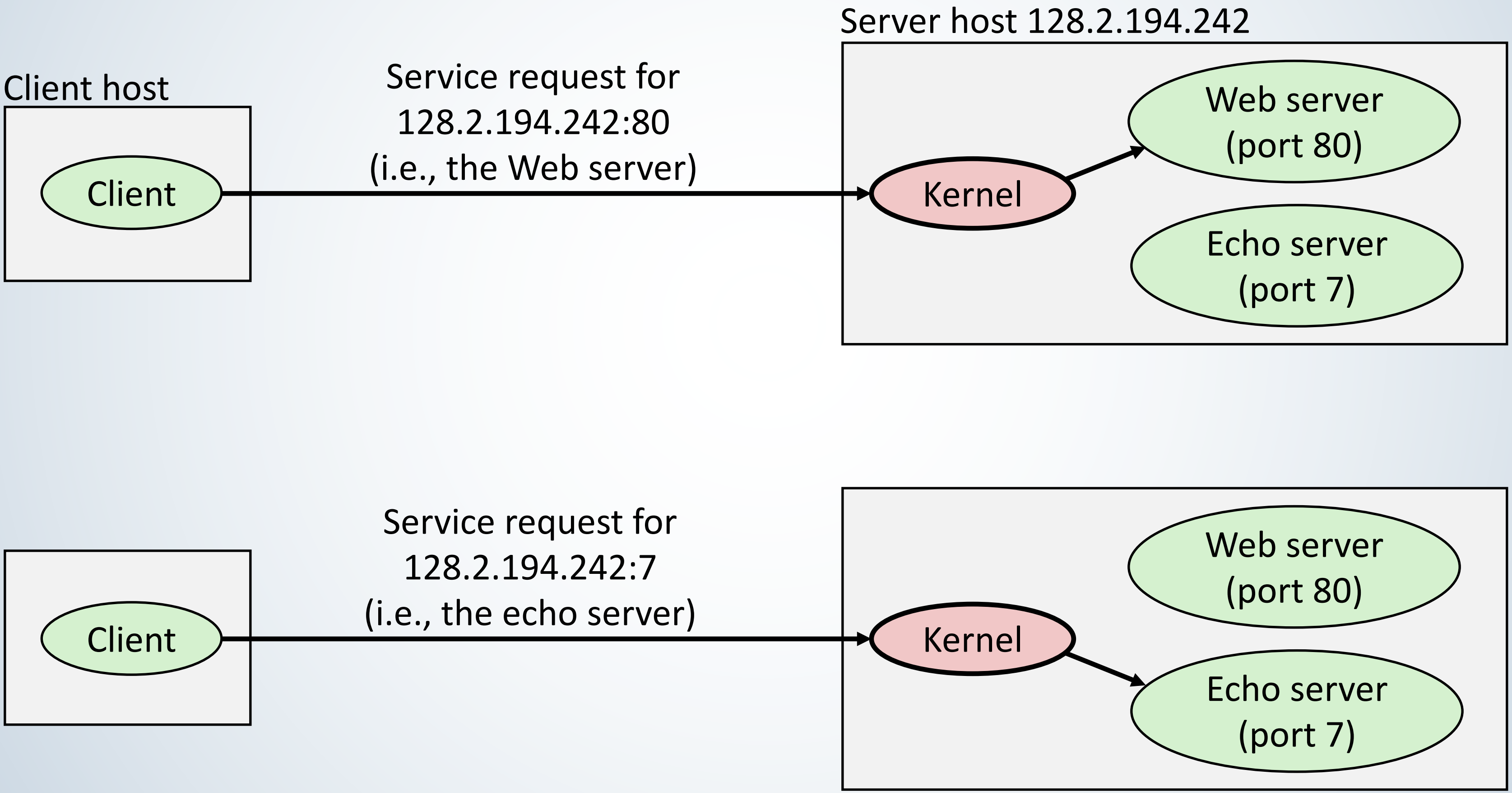
Client host address
128.2.194.242

Server host address
208.216.181.15

51213 is an ephemeral port allocated by the kernel

80 is a well-known port associated with Web servers

Using Ports to Identify Services



Sockets Interface

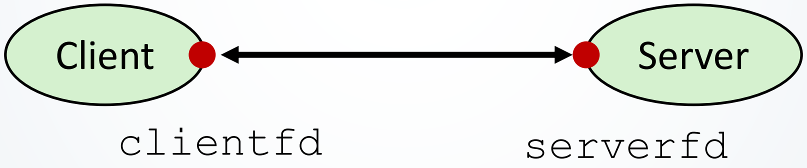
- Set of system-level functions used in conjunction with Unix I/O to build network applications.

- Created in the early 80's as part of the original Berkeley distribution of Unix that contained an early version of the Internet protocols.

- Available on all modern systems
  – Unix variants, Windows, OS X, IOS, Android, ARM

Sockets

- What is a socket?
  - To the kernel, a socket is an endpoint of communication
  - To an application, a socket is a file descriptor that lets the application read/write from/to the network
    - ***Remember:*** All Unix I/O devices, including networks, are modeled as files
- Clients and servers communicate with each other by reading from and writing to socket descriptors



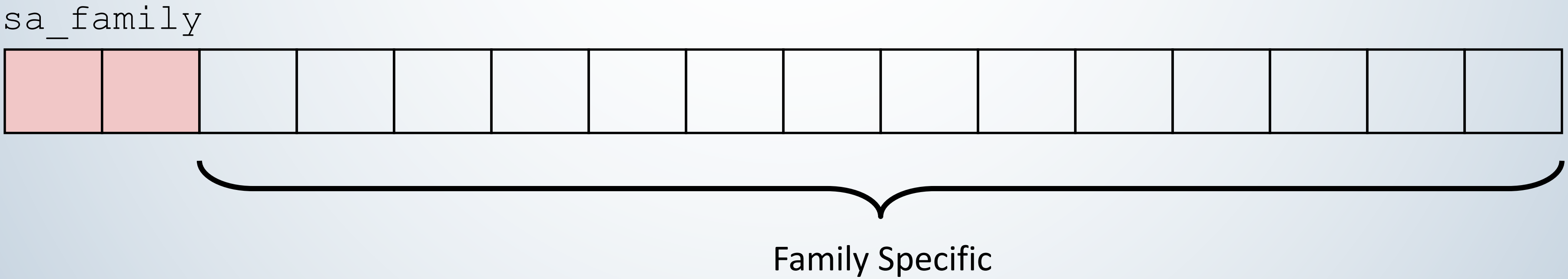
- The main distinction between regular file I/O and socket I/O is how the application "opens" the socket descriptors

Socket-Address Structures

- Generic socket address:
  - For address arguments to **`connect`**, **`bind`**, and **`accept`**
  - Necessary only because C did not have generic (**`void *`**) pointers when the sockets interface was designed
  - For casting convenience, we adopt the Stevens convention:

    `typedef struct sockaddr SA;`

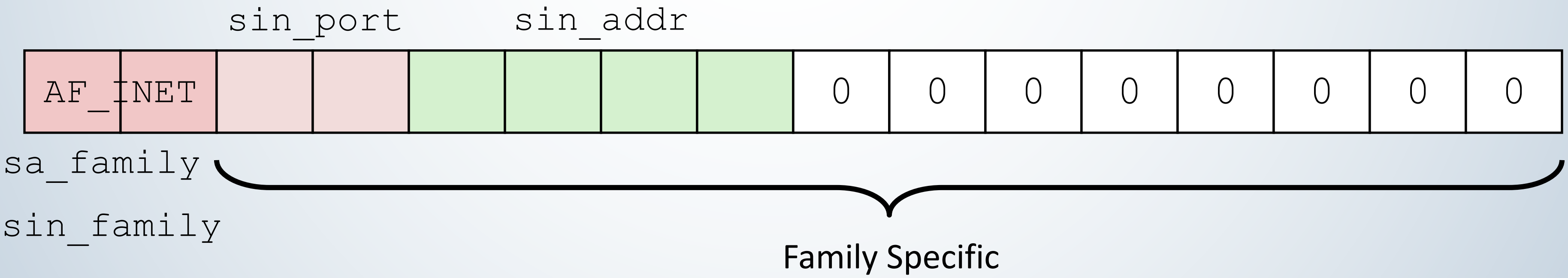
```
struct sockaddr {
  uint16_t  sa_family;    /* Protocol family */
  char      sa_data[14];  /* Address data.   */
};
```



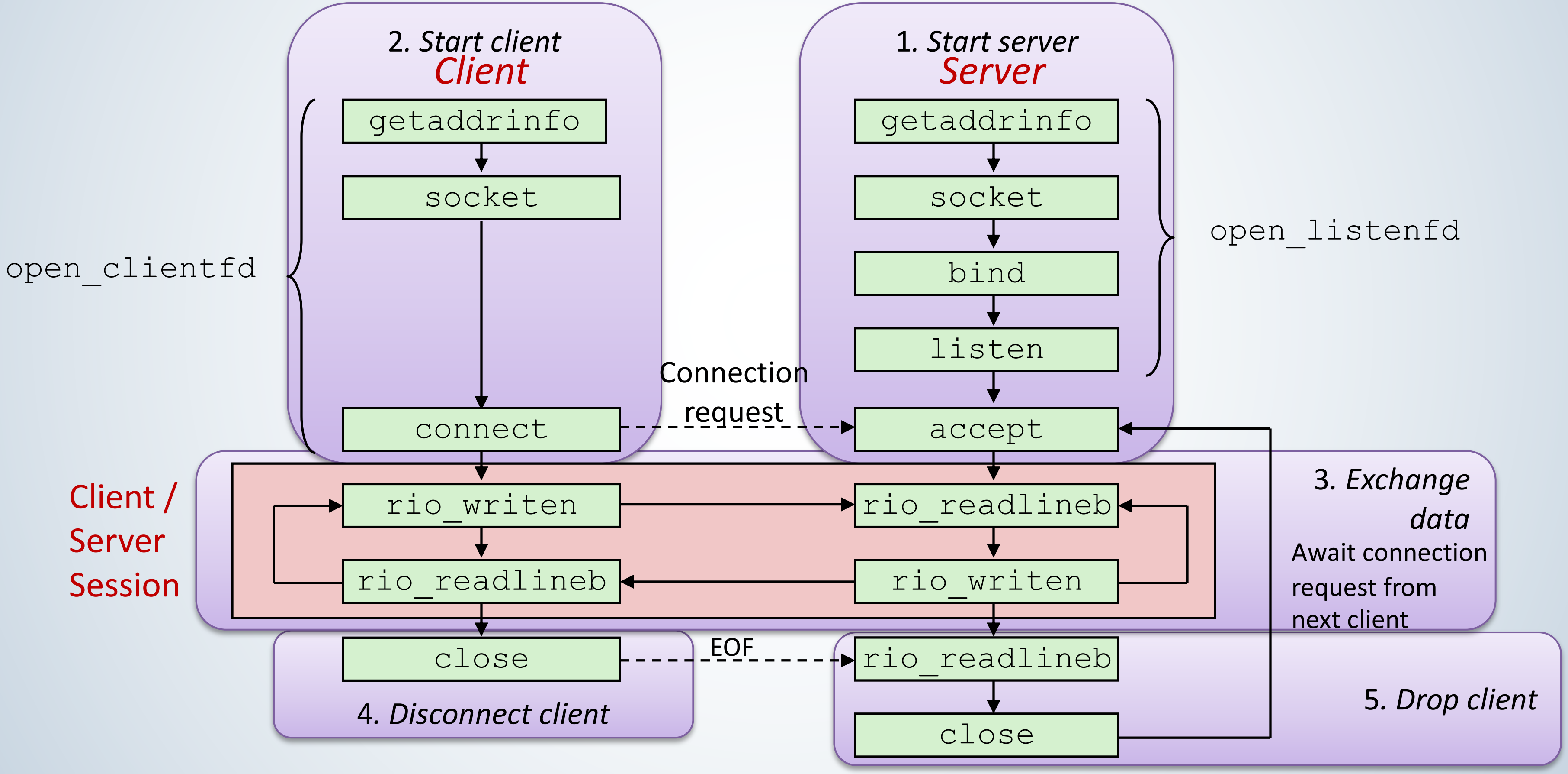
Socket Address Structures

- Internet-specific socket address:
  - Must cast (`struct sockaddr_in *`) to (`struct sockaddr *`) for functions that take socket address arguments.

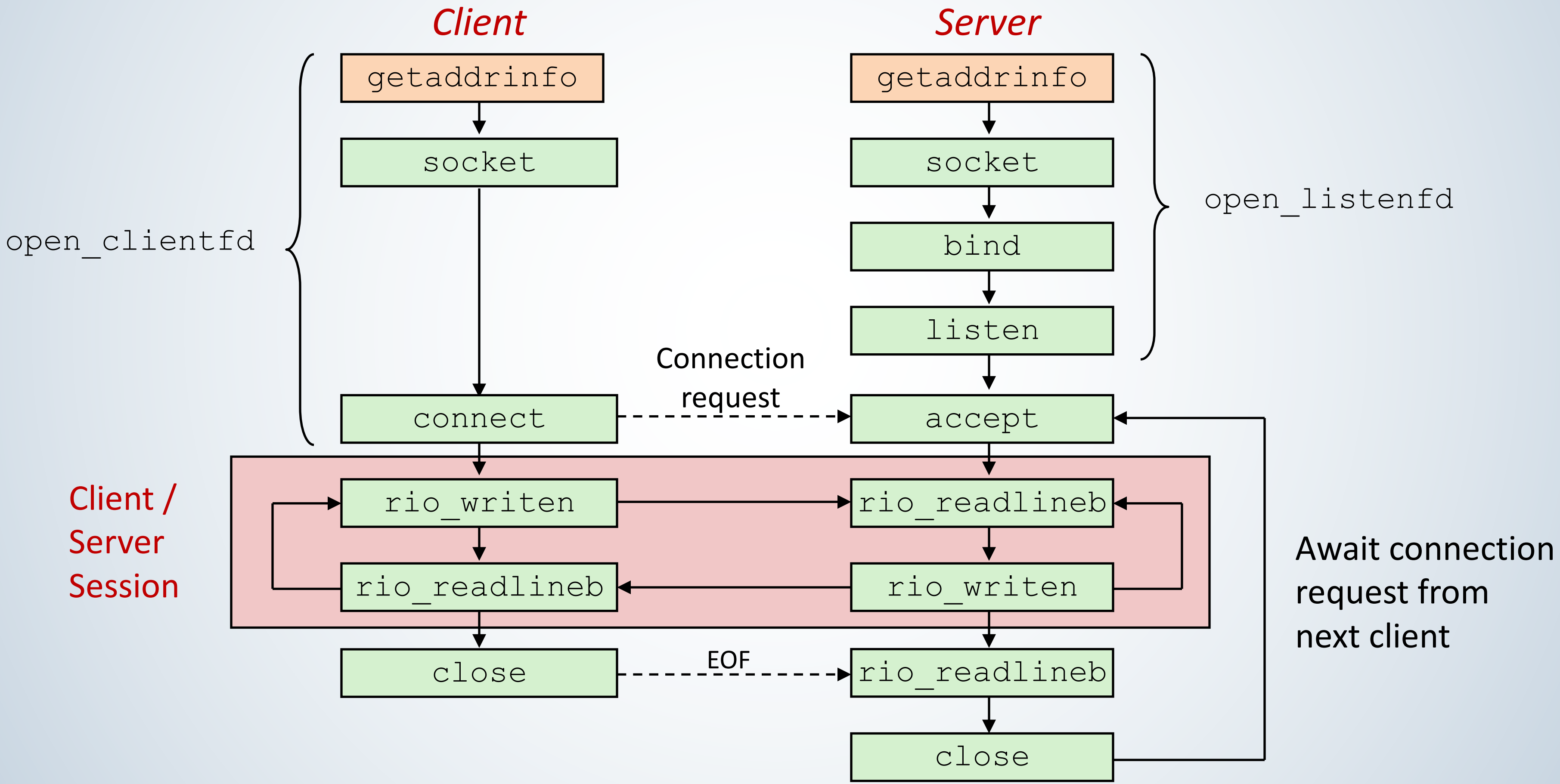
```
struct sockaddr_in  {
  uint16_t        sin_family;  /* Protocol family (always AF_INET) */
  uint16_t        sin_port;    /* Port num in network byte order */
  struct in_addr  sin_addr;    /* IP addr in network byte order */
  unsigned char   sin_zero[8]; /* Pad to sizeof(struct sockaddr) */
};
```



Sockets Interface



Sockets Interface



Host and Service Conversion: getaddrinfo()

- `getaddrinfo` is the modern way to convert string representations of hostnames, host addresses, ports, and service names to socket address structures.
  - Replaces obsolete `gethostbyname` and `getservbyname` funcs.

- Advantages:
  - Reentrant (can be safely used by threaded programs).
  - Allows us to write portable protocol-independent code
    - Works with both IPv4 and IPv6

- Disadvantages
  - Somewhat complex
  - Fortunately, a small number of usage patterns suffice in most cases

Host and Service Conversion: getaddrinfo()

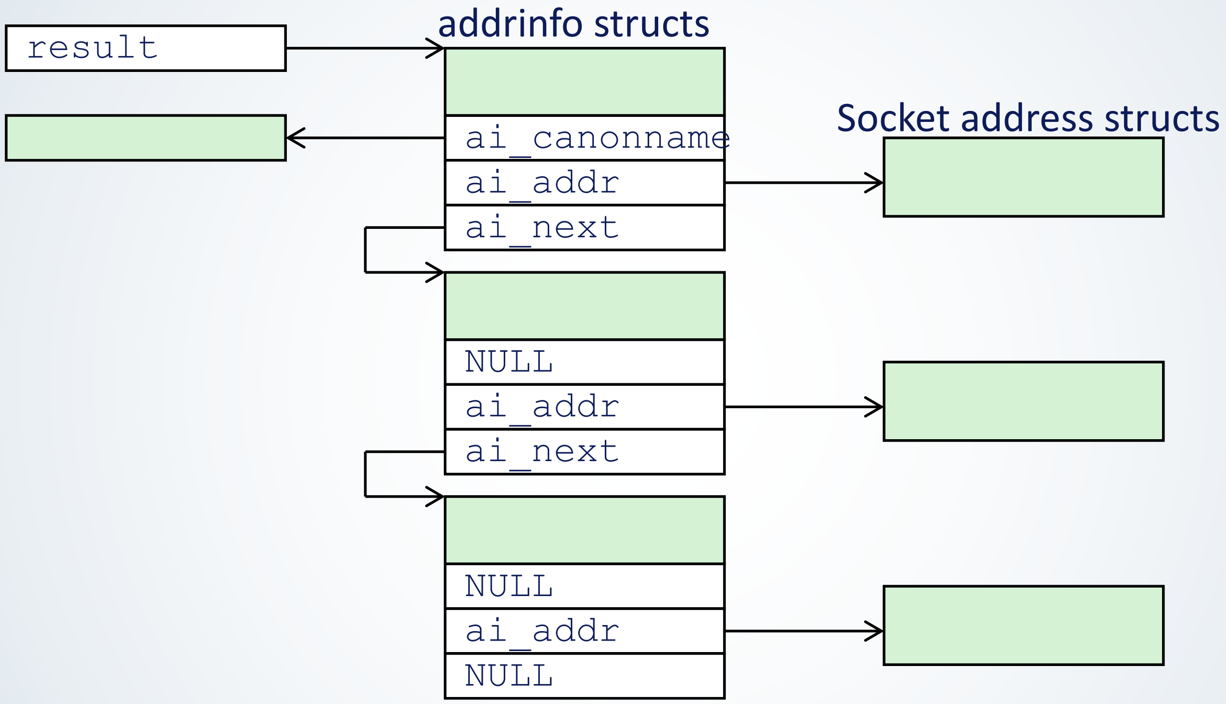
```
int getaddrinfo(const char *host,            /* Hostname or address */
                const char *service,         /* Port or service name */
                const struct addrinfo *hints,/* Input parameters */
                struct addrinfo **result);   /* Output linked list */

void freeaddrinfo(struct addrinfo *result);  /* Free linked list */

const char *gai_strerror(int errcode);       /* Return error msg */
```

- Given `host` and `service`, `getaddrinfo` returns `result` that points to a linked list of `addrinfo` structs, each of which points to a corresponding socket address struct, and which contains arguments for the sockets interface functions.
- Helper functions:
  - `freeadderinfo` frees the entire linked list.
  - `gai_strerror` converts error code to an error message.

Linked List Returned by getaddrinfo()



- Clients: walk this list, trying each socket address in turn, until the calls to `socket` and `connect` succeed.
- Servers: walk the list until calls to `socket` and `bind` succeed.

addrinfo Struct

```
struct addrinfo {
    int              ai_flags;     /* Hints argument flags */
    int              ai_family;    /* First arg to socket function */
    int              ai_socktype;  /* Second arg to socket function */
    int              ai_protocol;  /* Third arg to socket function  */
    char            *ai_canonname; /* Canonical host name */
    size_t           ai_addrlen;   /* Size of ai_addr struct */
    struct sockaddr *ai_addr;      /* Ptr to socket address structure */
    struct addrinfo *ai_next;      /* Ptr to next item in linked list */
};
```

- Each addrinfo struct returned by getaddrinfo contains arguments that can be passed directly to `socket` function.
- Also points to a socket address struct that can be passed directly to `connect` and `bind` functions.

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Host and Service Conversion: getnameinfo()

- `getnameinfo` is the inverse of getaddrinfo, converting a socket address to the corresponding host and service.
  - Replaces obsolete `gethostbyaddr` and `getservbyport` funcs.
  - Reentrant and protocol independent.

```
int getnameinfo(const SA *sa, socklen_t salen, /* In: socket addr */
                char *host, size_t hostlen,    /* Out: host */
                char *serv, size_t servlen,    /* Out: service */
                int flags);                    /* optional flags */
```

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Conversion Example

```
#include "csapp.h"

int main(int argc, char **argv)
{
    struct addrinfo *p, *listp, hints;
    char buf[MAXLINE];
    int rc, flags;

    /* Get a list of addrinfo records */
    memset(&hints, 0, sizeof(struct addrinfo));
    hints.ai_family = AF_INET;       /* IPv4 only */
    hints.ai_socktype = SOCK_STREAM; /* Connections only */
    if ((rc = getaddrinfo(argv[1], NULL, &hints, &listp)) != 0) {
        fprintf(stderr, "getaddrinfo error: %s\n", gai_strerror(rc));
        exit(1);
    }
```

Conversion Example (cont.)

```
    /* Walk the list and display each IP address */
    flags = NI_NUMERICHOST; /* Display address instead of name */
    for (p = listp; p; p = p->ai_next) {
        Getnameinfo(p->ai_addr, p->ai_addrlen,
                    buf, MAXLINE, NULL, 0, flags);
        printf("%s\n", buf);
    }

    /* Clean up */
    Freeaddrinfo(listp);

    exit(0);
}
```

Running hostinfo

```
whaleshark> ./hostinfo localhost
127.0.0.1

whaleshark> ./hostinfo whaleshark.ics.cs.cmu.edu
128.2.210.175

whaleshark> ./hostinfo twitter.com
199.16.156.230
199.16.156.38
199.16.156.102
199.16.156.198
```