



Network Programming: Part I

18-213/18-613: Introduction to Computer Systems
20th Lecture, Spring 2026

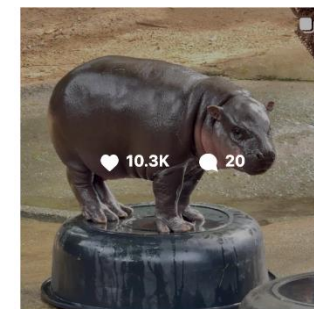
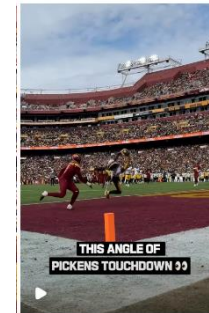
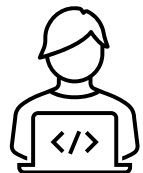
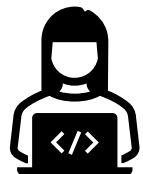
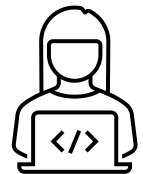
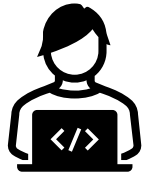
Today

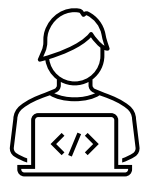
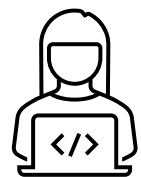
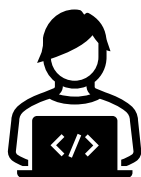
- **Networking Overview**
- **Global IP Internet**
- **Sockets Interface**

CSAPP 11.3

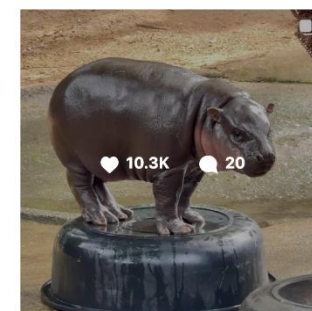
CSAPP 11.4

This lecture may be boring, let me check IG for cool reelz!

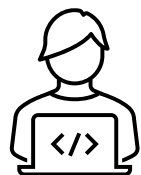
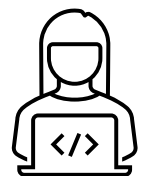




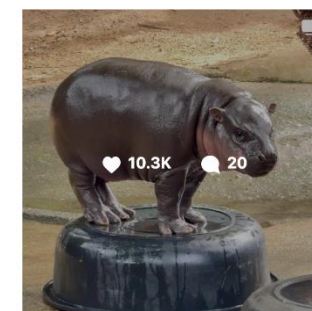
Wait, how does the
“Internet”
actually work to
watch reelz?



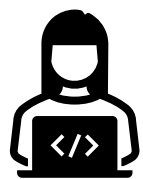
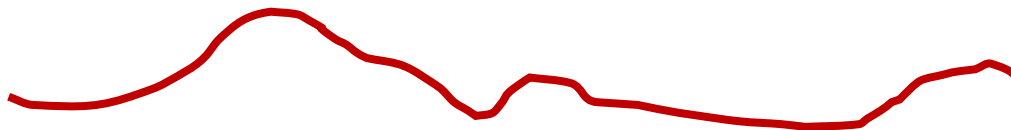
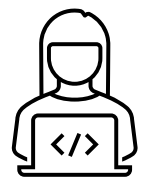
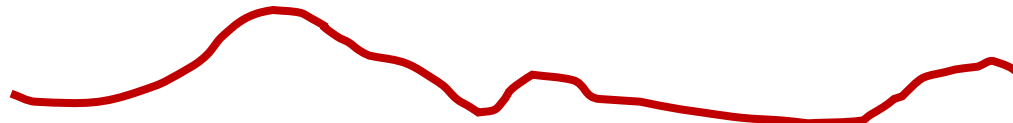
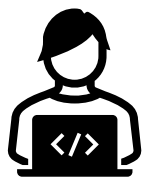
How does my app/browser know?



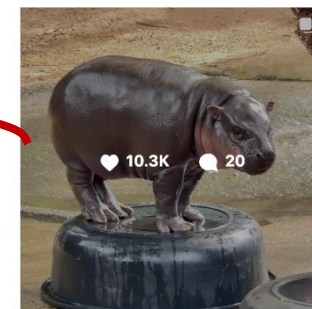
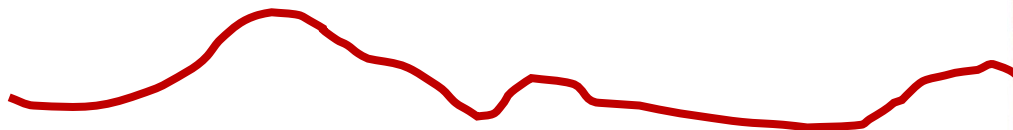
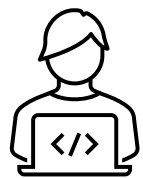
- Who is IG?
- Where is IG?
- How do I get to IG?
- Get bytes from IG?
- “Stream” from IG?
- Not mix up things?
-



A First Thought Experiment for Design: “Internet is a Series of (Dedicated) Tubes”



Let me pay attention 😊
Greg/Swarun are more entertaining



Series of Tubes Doesn't Work 😊

■ Deployment

- Every “App” needs to install “copper” “fiber” end to end to its users

■ Heterogeneity of Users

- IG needs to worry about “pipe” inside CMU, my home, airport, SBUX, ...

■ Geography/Society/Politics

- What about users in India, China, UK, how do I get pipes?

■ Scale/Cost

- More users come in? More devices come in?

■ Efficiency

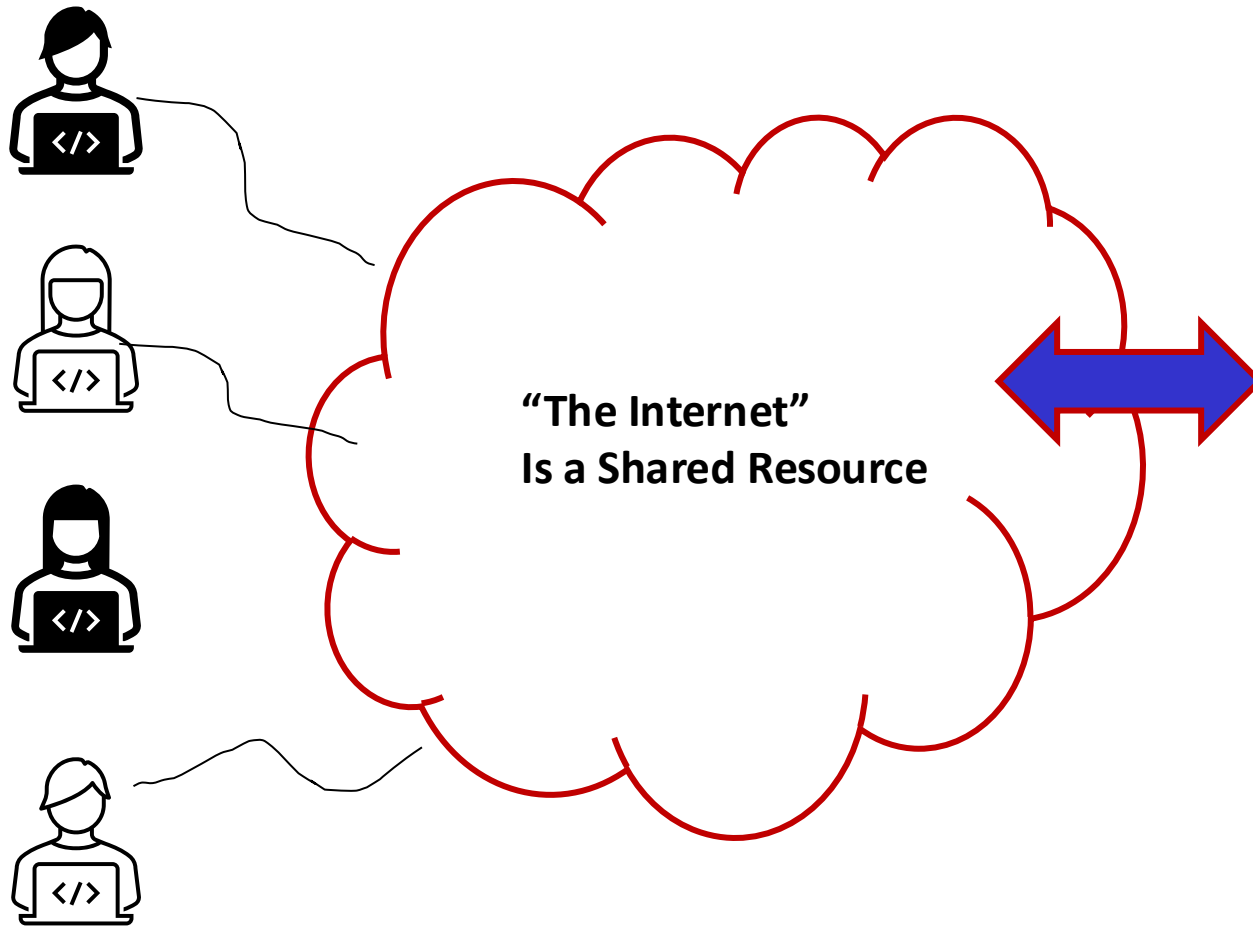
- I paused to listen to lecture, but pipe is still costing me!

■ Fault Tolerance

- What if pipe bursts 😊 insta fails

■

Great Ideas in Networking: Statistical Multiplexing not Dedicated Tubes



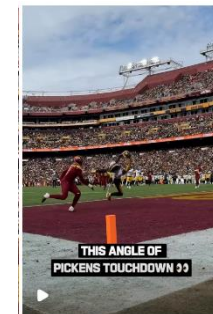
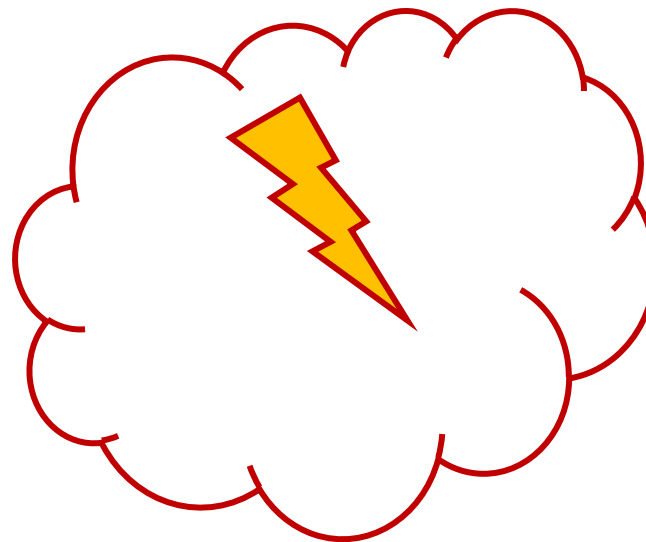
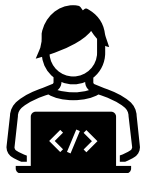
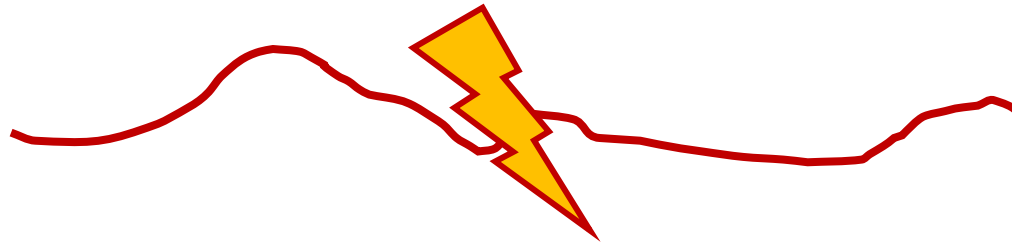
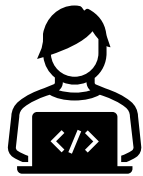
Most popular apps worldwide
2022, by category (million downloads)



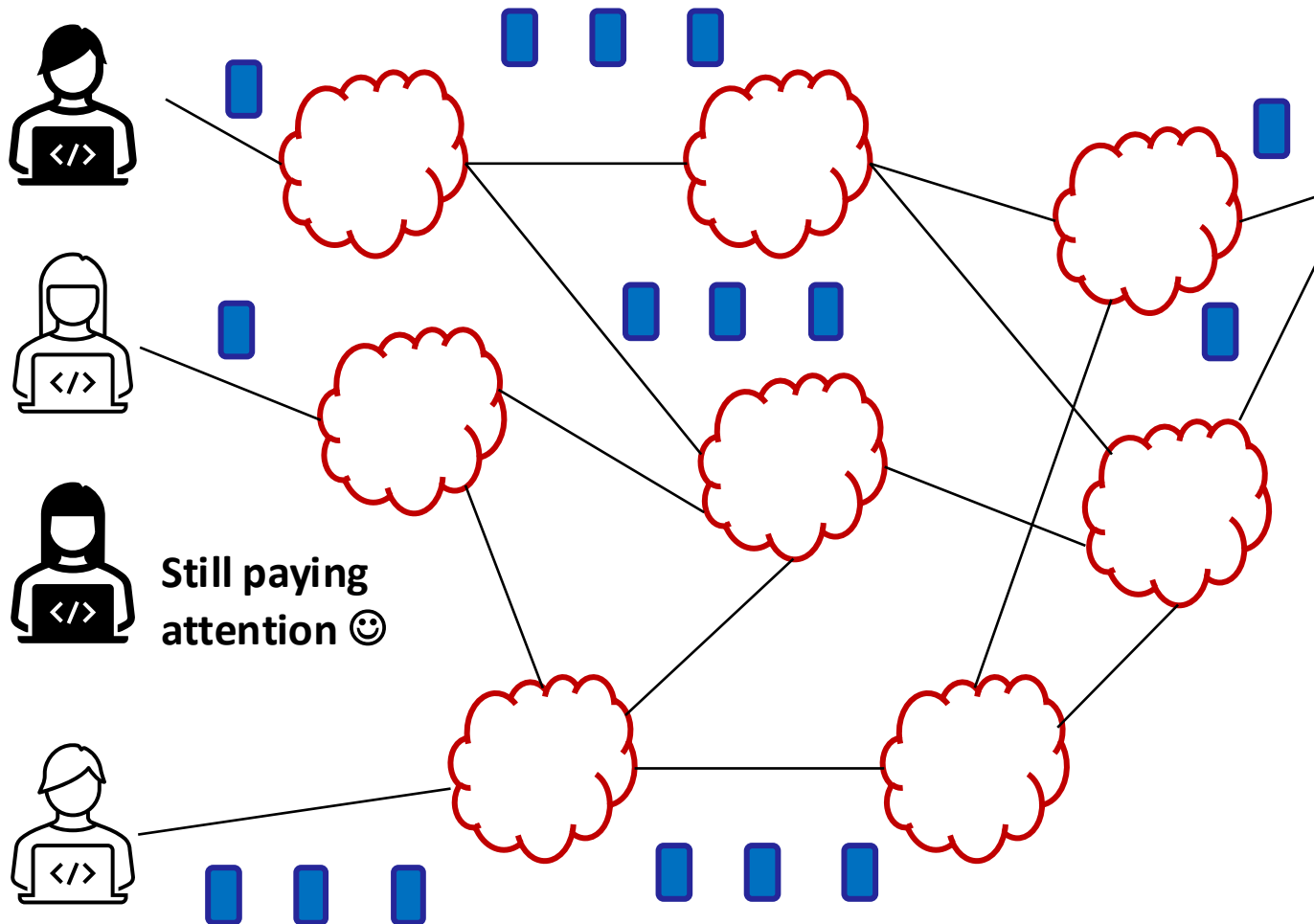
Source: BusinessOfApps
Created by genuine impact

More charts: genuineimpact.substack.com

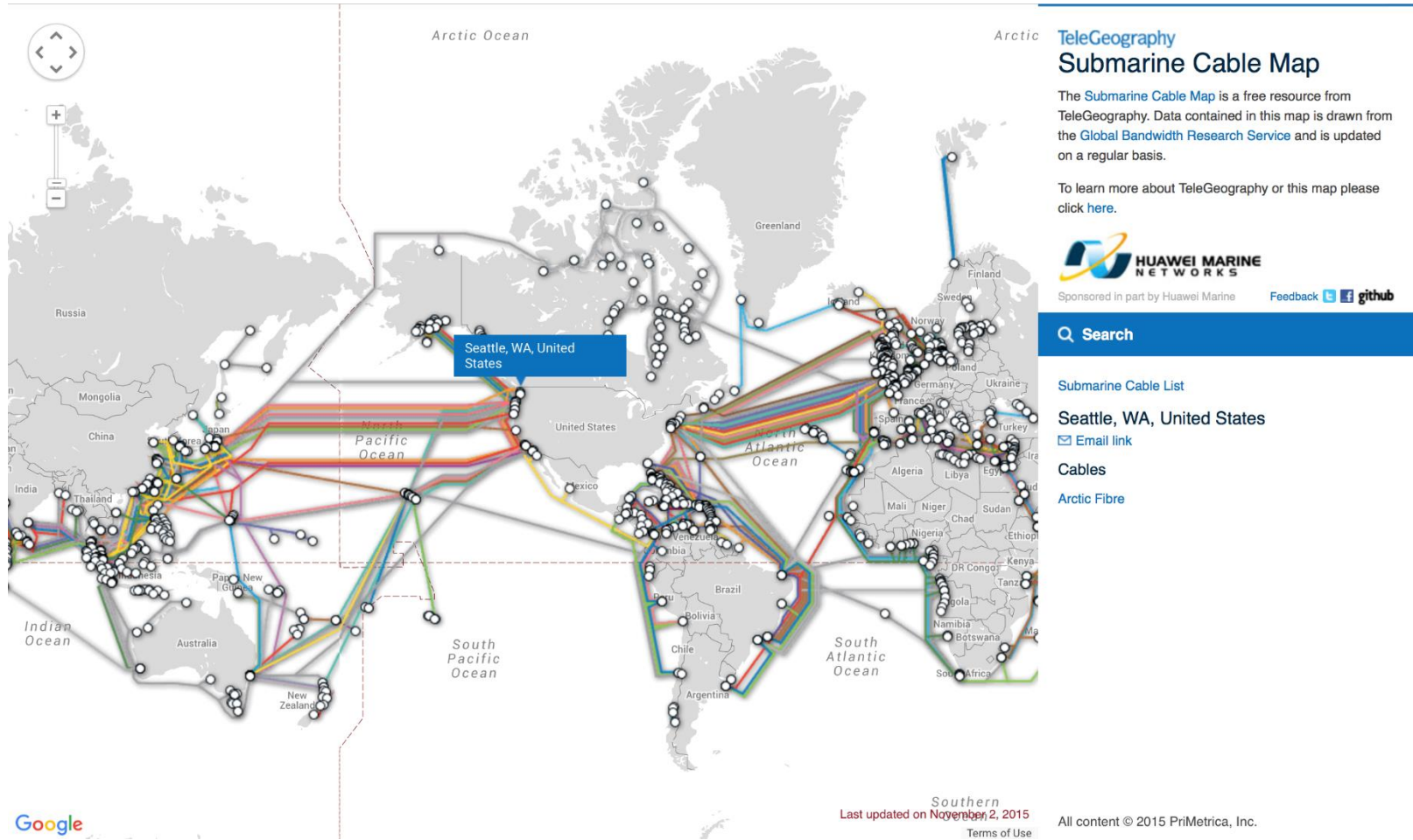
Great Ideas in Networking: Datagrams/Packet-Switched Networks



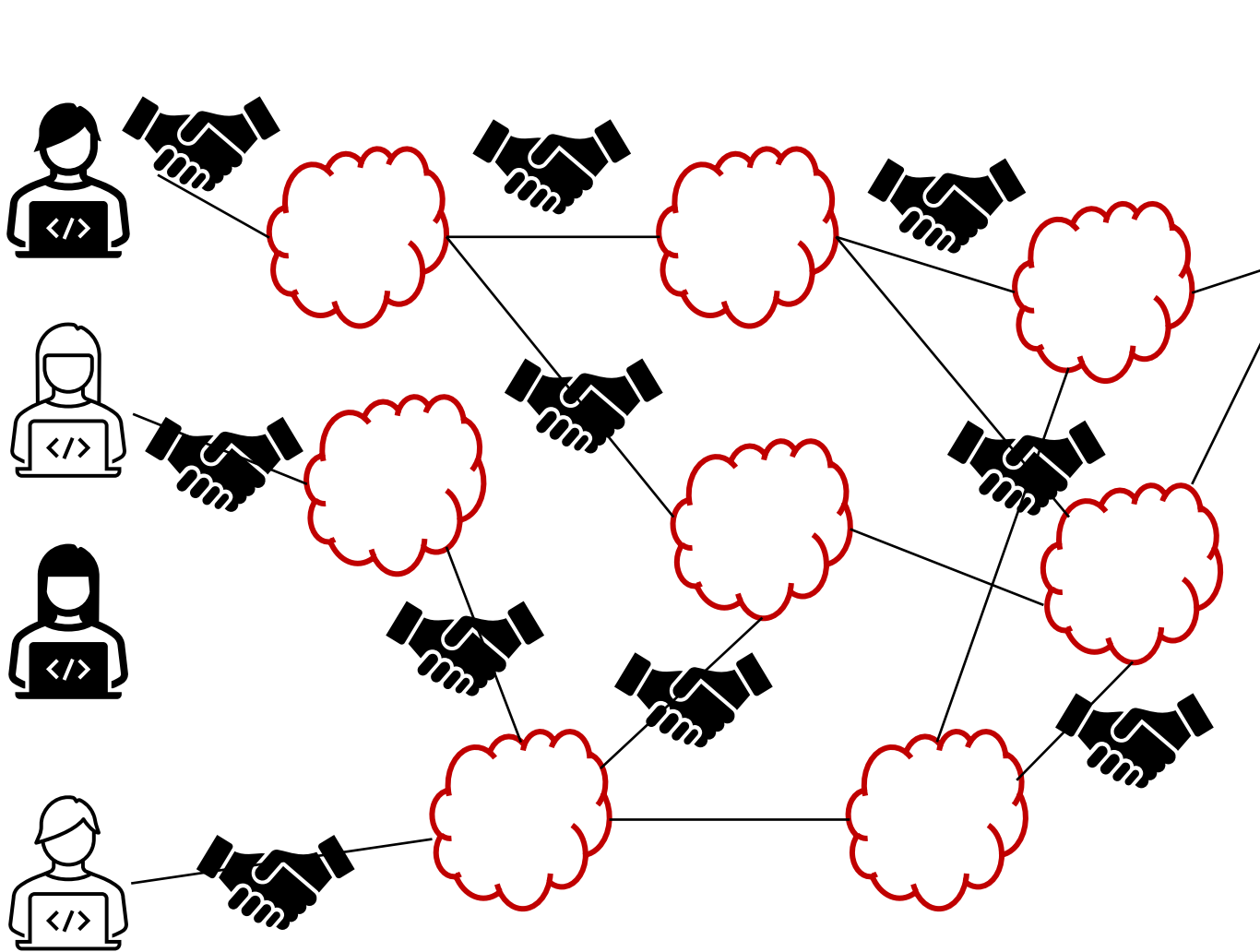
Great Ideas in Networking: Federation



Well, the Internet does actually have tubes at physical level 😊



Great Ideas in Networking: Protocols



Most popular apps worldwide
2022, by category (mill on downloads)

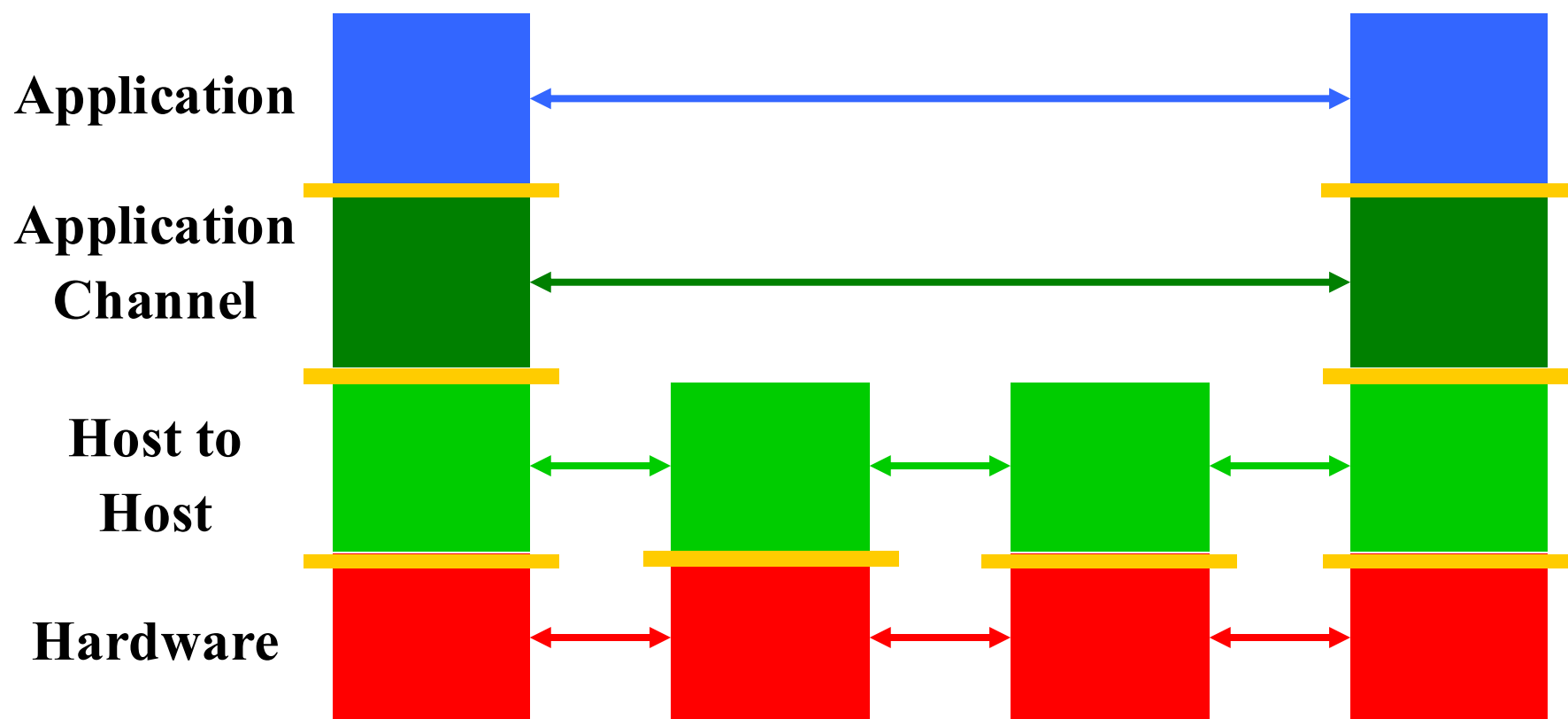


Source: Statista.com
Created by @genieimpact

More charts: genieimpact.substack.com



Great Ideas in Networking: Layering



Physical Layer: Establishes the Channel

- **Medium? Light? Radio frequency? Electrical signals?**
 - What color(s) of light? How bright?
 - What RF frequencies? How powerful?
 - What signals represent what values?
 - What shape are the connectors?
 - How far can cables run?
 - Etc.

- **We have a functioning physical layer once we can send and receive signals.**

Physical Layer: Bandwidth vs. Latency

- **Bandwidth = bits/second**
 - Improved with parallelism or faster clock rate
- **Latency = Function of signal propagation speed**
 - Limited by speed of light
 - Major paradigm shift would be needed to make traffic to India or China less latent
- **Latency tends to be limiting at a global scale**
 - Speed of light over long distances
- **Bandwidth may be limited at local scale, e.g. data center**
 - How to divide up and recombine messages to utilize parallelism?
 - How to clock faster without losing signal to noise.

Physical

Link Layer: Manages the Channel

- When do we start transmitting? When do we stop?
- When do we start receiving? When do we stop?
- Who is sending? Who is receiving?
- How do we know if it is correct?
- What happens if there is contention for, or collision in, a shared channel?
- Key contributions: Framing, among others
- **We have a functioning link layer once we can build a functioning local area network (LAN) of at least two stations.**

Data link

Physical

Network layer: Scaling up

- **Passing messages among multiple networks**
 - For scale
 - Of different types (wired, wireless, fiber, infrared, etc)
 - Managed by different domains, etc.
- **Globally meaningful addressing: IPv4, IPv6**
- **Ability to choose paths among multiple options**
- **We have a functioning network layer once we can connect multiple networks, identify hosts among them, and messages can find their way across networks from source to destination.**

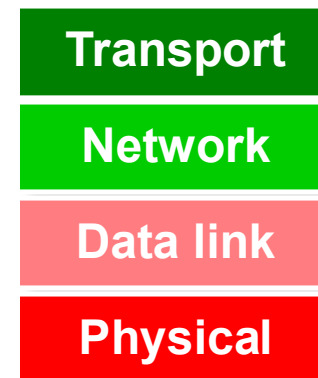
Network

Data link

Physical

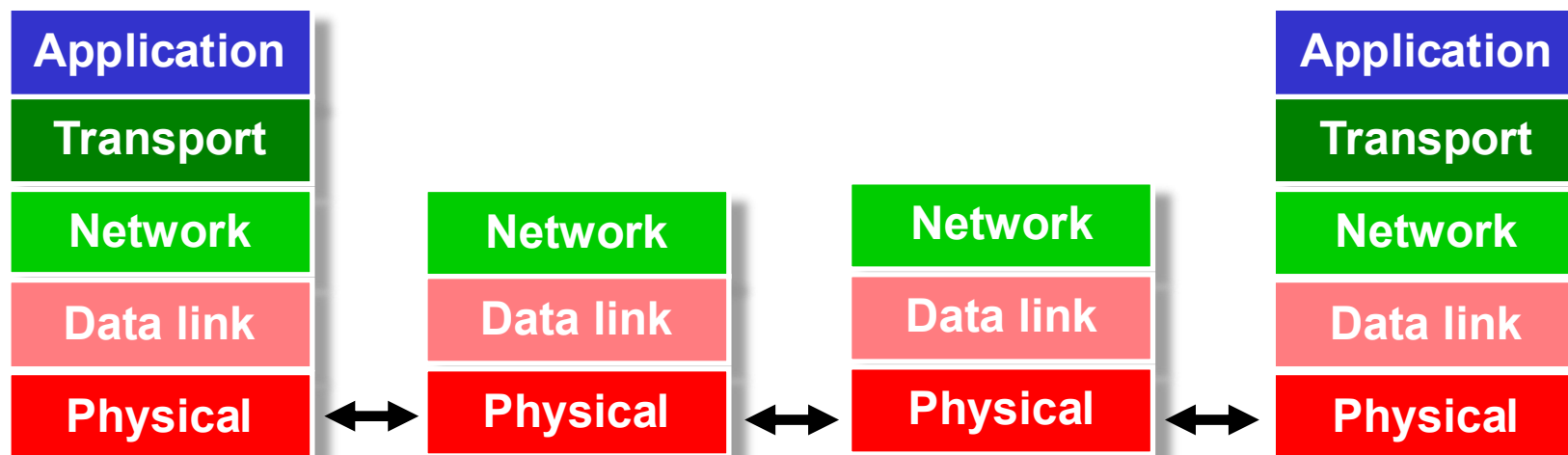
Transport Layer: Meaningful endpoints

- **Hosts don't do communication – various aspects of software systems do**
 - Consider how many different sessions your Web browser has with servers. Now add for your IM sessions, upgrades-in-progress, music streaming, etc.
- **Endpoints enable the establishment of sessions**
 - Classic model is <IPaddress:port>:<IPaddress:port>
 - Client: Ephemeral port. Host: Well-known port
- **Character of communication**
 - Reliable/session-oriented, e.g. TCP
 - Unreliable/datagram, e.g. UDP
 - Etc.
- **The transport layer exists once we have the ability to establish communication from end-point to end-point with well-understood properties.**

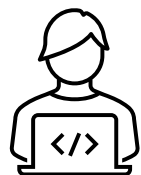
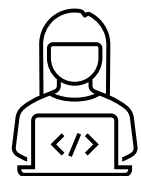


Application Layer: Purposeful Communication

- Defined by the messaging we, as programs, bake into our applications, shaped by our applications
 - e.g., client-server interactions, peer-to-peer interactions, etc.
- E.g., HTTP: PUT, GET, POST, etc.
- E.g., DNS: queries, responses, updates, etc.
- MIME, VOIP protocols, etc.
- Application protocols exist when applications can communicate

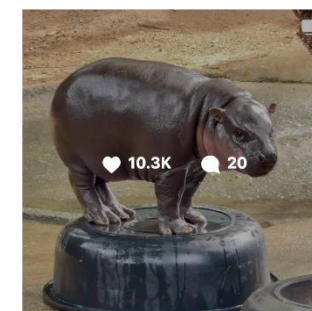


When connecting to Instagram, How does my app/browser know?



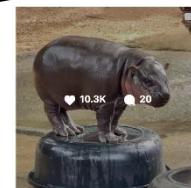
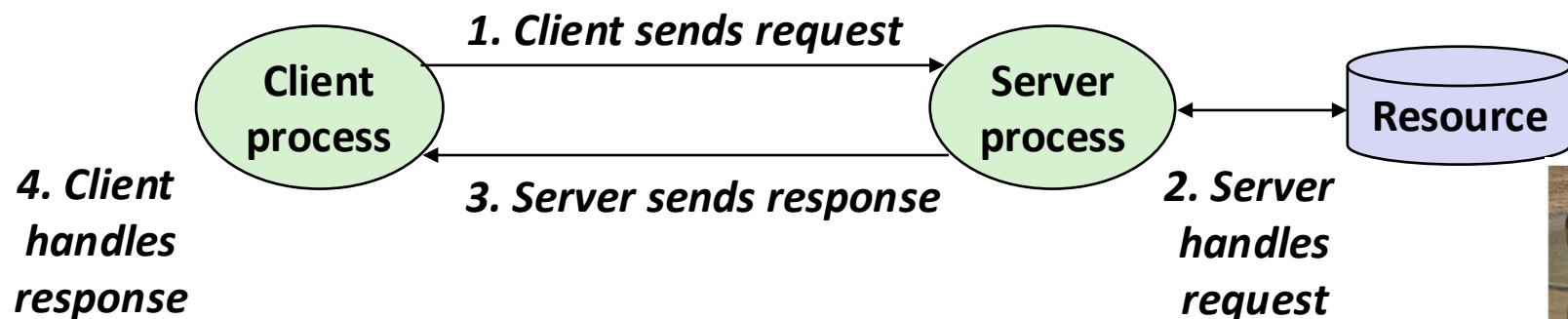
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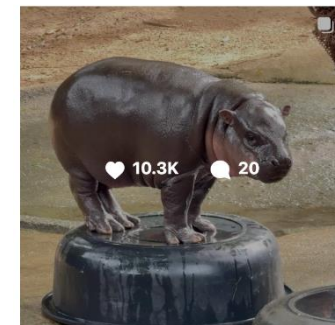
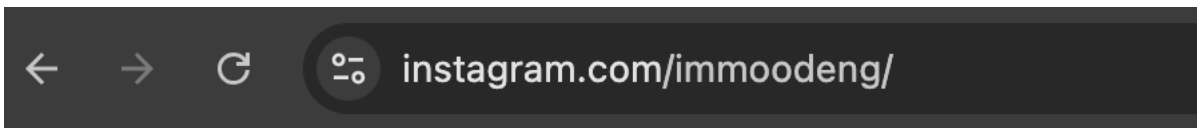
A Client-Server Transaction

- 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)

What is IG really?



```
$ sudo tcpdump -nn > insta_pcap
```

```
16:44:57.903130 IP 192.168.0.144.58340 > 157.240.229.174.443: quic, protected
16:44:57.903264 IP 192.168.0.144.58340 > 157.240.229.174.443: quic, protected
16:44:57.919207 IP 157.240.229.174.443 > 192.168.0.144.58340: quic, protected
16:44:57.923190 IP 192.168.0.144.58340 > 157.240.229.174.443: quic, protected
16:44:57.951425 IP 157.240.229.174.443 > 192.168.0.144.58340: quic, protected
16:44:57.981071 IP 157.240.229.174.443 > 192.168.0.144.58340: quic, protected
16:44:57.981077 IP 157.240.229.174.443 > 192.168.0.144.58340: quic, protected
16:44:57.986683 IP 192.168.0.144.58340 > 157.240.229.174.443: quic, protected
16:44:58.023664 IP 157.240.229.174.443 > 192.168.0.144.58340: quic, protected
16:44:58.901194 IP 192.168.0.144.58340 > 157.240.229.174.443: quic, protected
16:44:58.901414 IP 192.168.0.144.58340 > 157.240.229.174.443: quic, protected
16:44:58.929896 IP 157.240.229.174.443 > 192.168.0.144.58340: quic, protected
16:44:58.933695 IP 192.168.0.144.58340 > 157.240.229.174.443: quic, protected
16:44:58.960606 IP 157.240.229.174.443 > 192.168.0.144.58340: quic, protected
16:44:58.960726 IP 192.168.0.144.58340 > 157.240.229.174.443: quic, protected
16:44:58.986483 IP 157.240.229.174.443 > 192.168.0.144.58340: quic, protected
16:44:58.998233 IP 157.240.229.174.443 > 192.168.0.144.58340: quic, protected
16:44:59.003068 IP 192.168.0.144.58340 > 157.240.229.174.443: quic, protected
16:44:59.033298 IP 157.240.229.174.443 > 192.168.0.144.58340: quic, protected
16:44:59.905629 IP 192.168.0.144.58340 > 157.240.229.174.443: quic, protected
16:44:59.905828 IP 192.168.0.144.58340 > 157.240.229.174.443: quic, protected
16:44:59.930582 IP 157.240.229.174.443 > 192.168.0.144.58340: quic, protected
16:44:59.935577 IP 192.168.0.144.58340 > 157.240.229.174.443: quic, protected
16:44:59.965837 IP 192.168.0.144.58340 > 157.240.229.174.443: quic, protected
16:44:59.971363 IP 157.240.229.174.443 > 192.168.0.144.58340: quic, protected
16:44:59.992235 IP 157.240.229.174.443 > 192.168.0.144.58340: quic, protected
```

Anything on
The Global Internet
is just an
“IP” address
e.g., 157.240.229.174

Who is IG = 157.240.229.174?

```
[vyass-mbp-2:Desktop vsekar$ whois 157.240.229.174
% IANA WHOIS server
% for more information on IANA, visit http://www.iana.org
% This query returned 1 object

refer:          whois.arin.net

inetnum:        157.0.0.0 - 157.255.255.255
organisation:   Administered by ARIN
status:         LEGACY

whois:          whois.arin.net

changed:        1993-05
source:         IANA

# whois.arin.net

NetRange:       157.240.0.0 - 157.240.255.255
CIDR:           157.240.0.0/16
NetName:        THEFA-3
NetHandle:      NET-157-240-0-0-1
Parent:         NET157 (NET-157-0-0-0-0)
NetType:        Direct Allocation
OriginAS:
Organization:   Facebook, Inc. (THEFA-3)
RegDate:        2015-05-14
Updated:        2021-12-14
Ref:            https://rdap.arin.net/registry/ip/157.240.0.0

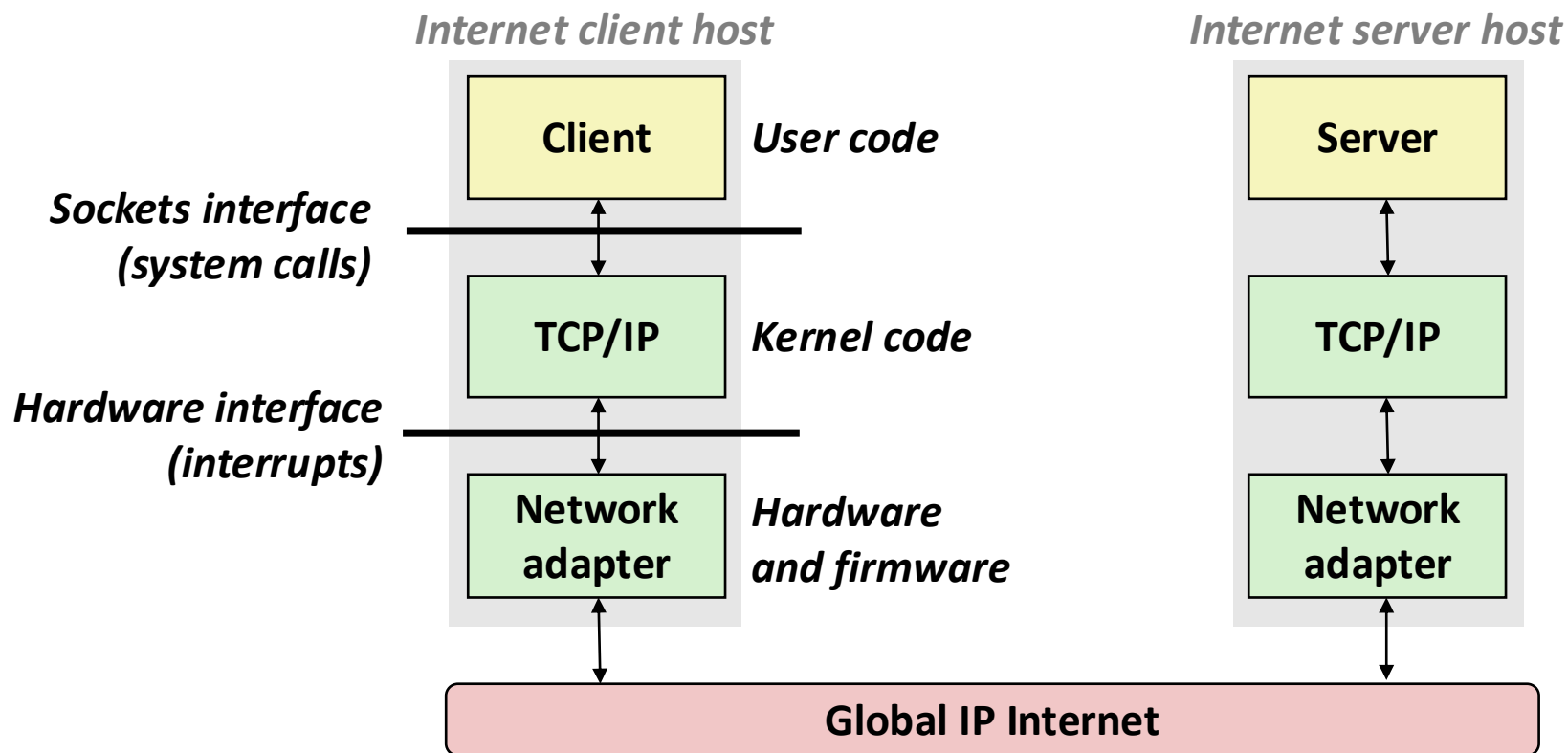
OrgName:        Facebook, Inc.
OrgId:          THEFA-3
Address:        1601 Willow Rd.
City:           Menlo Park
StateProv:      CA
```

“IP” addresses Assignment And ownership

Global IP 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***

Hardware and Software Organization of a Client-Server 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
- 127.0.0.1 (always *localhost*)

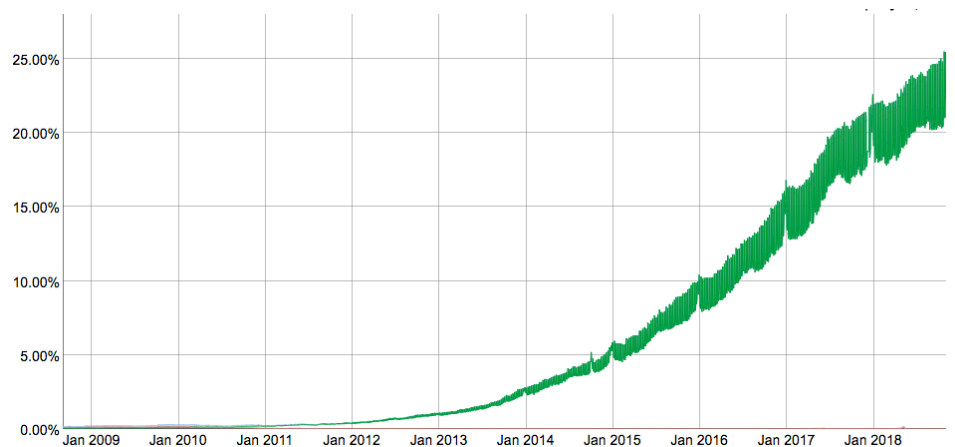
2. The set of IP addresses is mapped to a set of identifiers called Internet *domain names*

- 128.2.217.3 is mapped to `www.cs.cmu.edu`

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

Aside: IPv4 and IPv6

- The original Internet Protocol, with its 32-bit addresses, is known as *Internet Protocol Version 4 (IPv4)*
- 1996: Internet Engineering Task Force (IETF) introduced *Internet Protocol Version 6 (IPv6)* with 128-bit addresses
 - Intended as the successor to IPv4
- Majority of Internet traffic still carried by IPv4



IPv6 traffic at Google

- We will focus on IPv4, but will show you how to write networking code that is protocol-independent.

(1) 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)
 - 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.

How do I get to some IP (e.g., IG)?

Routing Protocols

```
[vyass-mbp-2:Desktop vsekar$ traceroute 8.8.8.8
traceroute to 8.8.8.8 (8.8.8.8), 64 hops max, 52 byte packets
 1  192.168.0.1 (192.168.0.1)  8.323 ms  1.644 ms  1.894 ms
 2  lo0-100.pitbpa-vfttp-308.verizon-gni.net (71.182.232.1)  1.891 ms  2.504 ms  1.952 ms
 3  * * *
 4  * * *
 5  google-com.customer.alter.net (204.148.170.134)  18.124 ms *  20.769 ms
 6  * * *
 7  dns.google (8.8.8.8)  16.032 ms  12.739 ms  8.139 ms
```

Why don't I need to know this IP thing?

```
[vyass-mbp-2:Desktop vsekar$ nslookup www.instagram.com
```

```
Server:          192.168.0.1
Address:         192.168.0.1#53
```

```
Non-authoritative answer:
```

```
www.instagram.com canonical name = z-p42-instagram.c10r.instagram.com.
```

```
Name:   z-p42-instagram.c10r.instagram.com
```

```
Address: 157.240.229.174
```

```
[vyass-mbp-2:Desktop vsekar$ nslookup www.google.com
```

```
Server:          192.168.0.1
Address:         192.168.0.1#53
```

```
Non-authoritative answer:
```

```
Name:   www.google.com
```

```
Address: 142.251.179.104
```

```
Name:   www.google.com
```

```
Address: 142.251.179.99
```

```
Name:   www.google.com
```

```
Address: 142.251.179.147
```

```
Name:   www.google.com
```

```
Address: 142.251.179.103
```

```
Name:   www.google.com
```

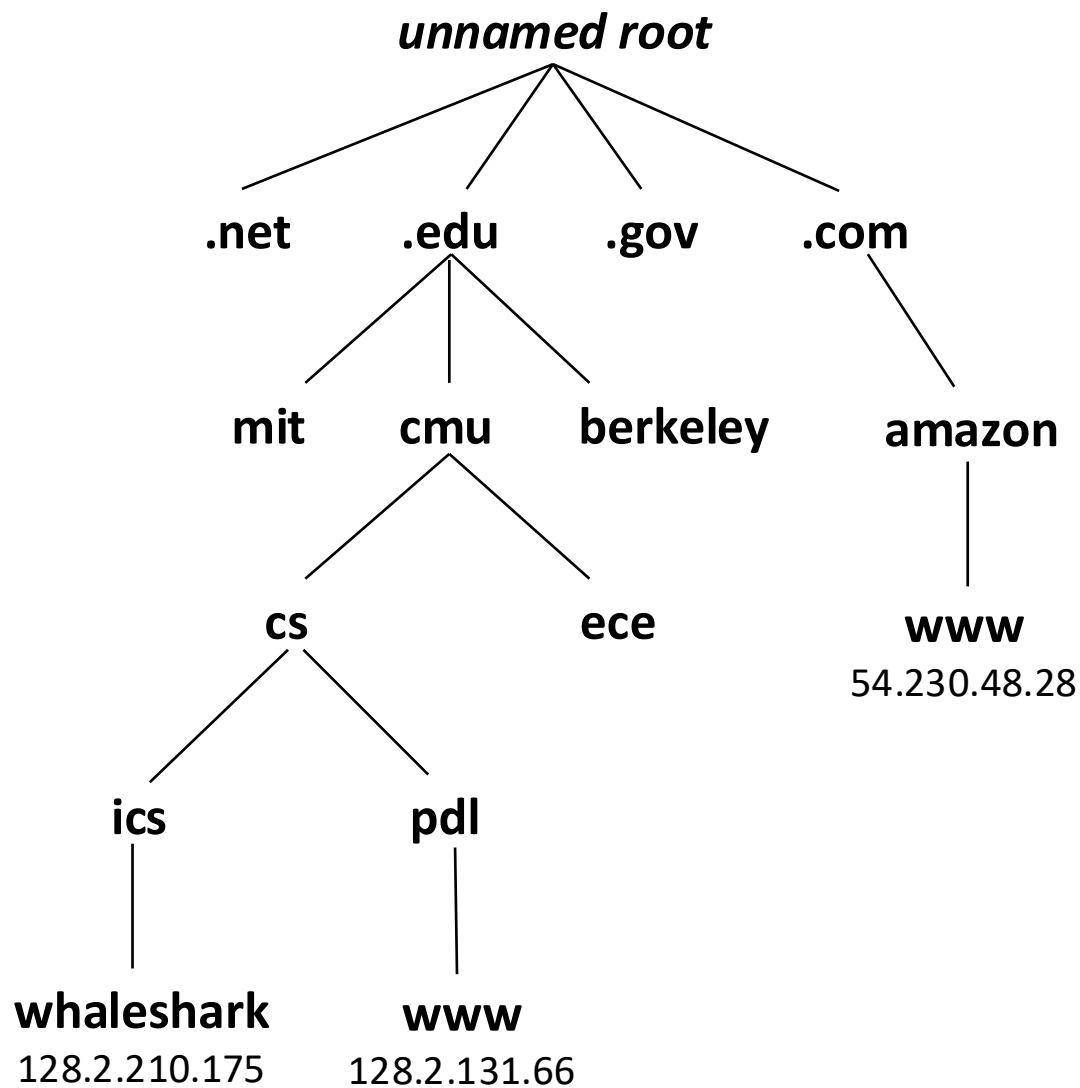
```
Address: 142.251.179.105
```

```
Name:   www.google.com
```

```
Address: 142.251.179.106
```

Domain Name System (DNS)
Names → “IP” addresses

(2) Internet Domain Names



First-level domain names

Second-level domain names

Third-level 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`
 - (In our examples, the output is 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:

```
linux> hostname  
whaleshark.ics.cs.cmu.edu
```

Properties of DNS Mappings (cont)

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

```
linux> nslookup whaleshark.ics.cs.cmu.edu  
Address: 128.2.210.175
```

- **Multiple domain names mapped to the same IP address:**

```
linux> nslookup cs.mit.edu  
Address: 18.62.1.6  
linux> nslookup eecs.mit.edu  
Address: 18.62.1.6
```

(3) Internet Connections

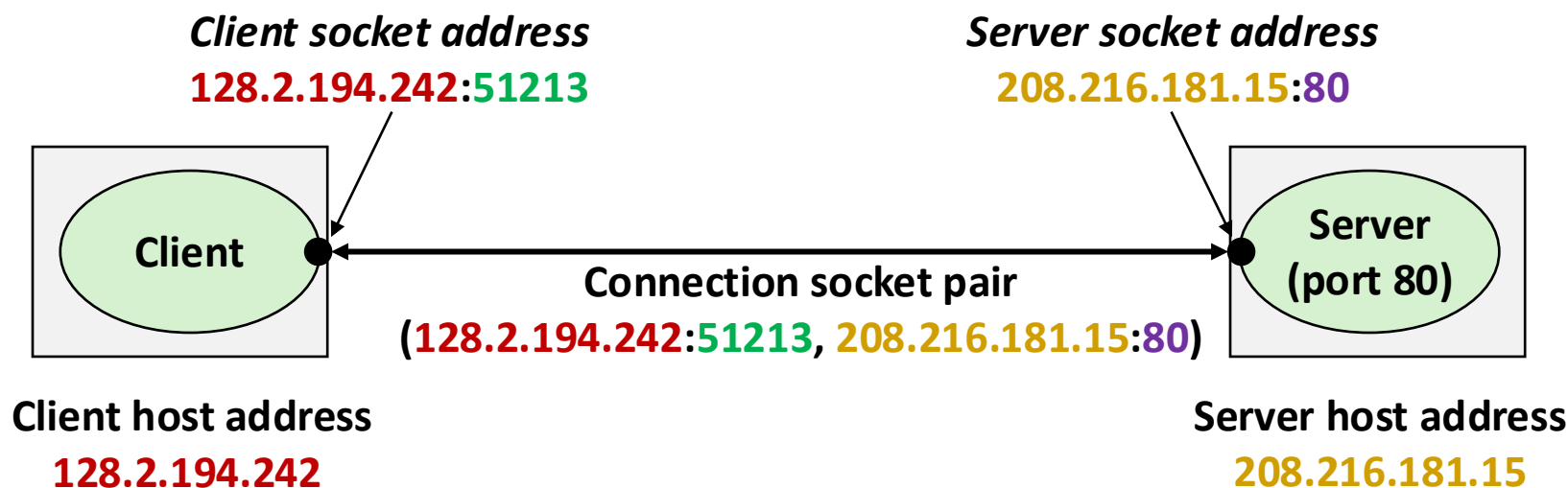
- Clients and servers communicate by sending streams of bytes over **connections**. Each connection is:
 - *Point-to-point*: connects a pair of processes.
 - *Full-duplex*: data can flow in both directions at the same time,
 - *Reliable*: stream of bytes sent by the source is eventually received by the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

- Popular services have permanently assigned *well-known ports* and corresponding *well-known service names*:
 - echo servers: echo 7
 - ftp servers: ftp 21
 - ssh servers: ssh 22
 - email servers: smtp 25
 - Web servers: http 80
- Mappings between well-known ports and service names is contained in the file `/etc/services` on each Linux machine.

Anatomy of a Connection

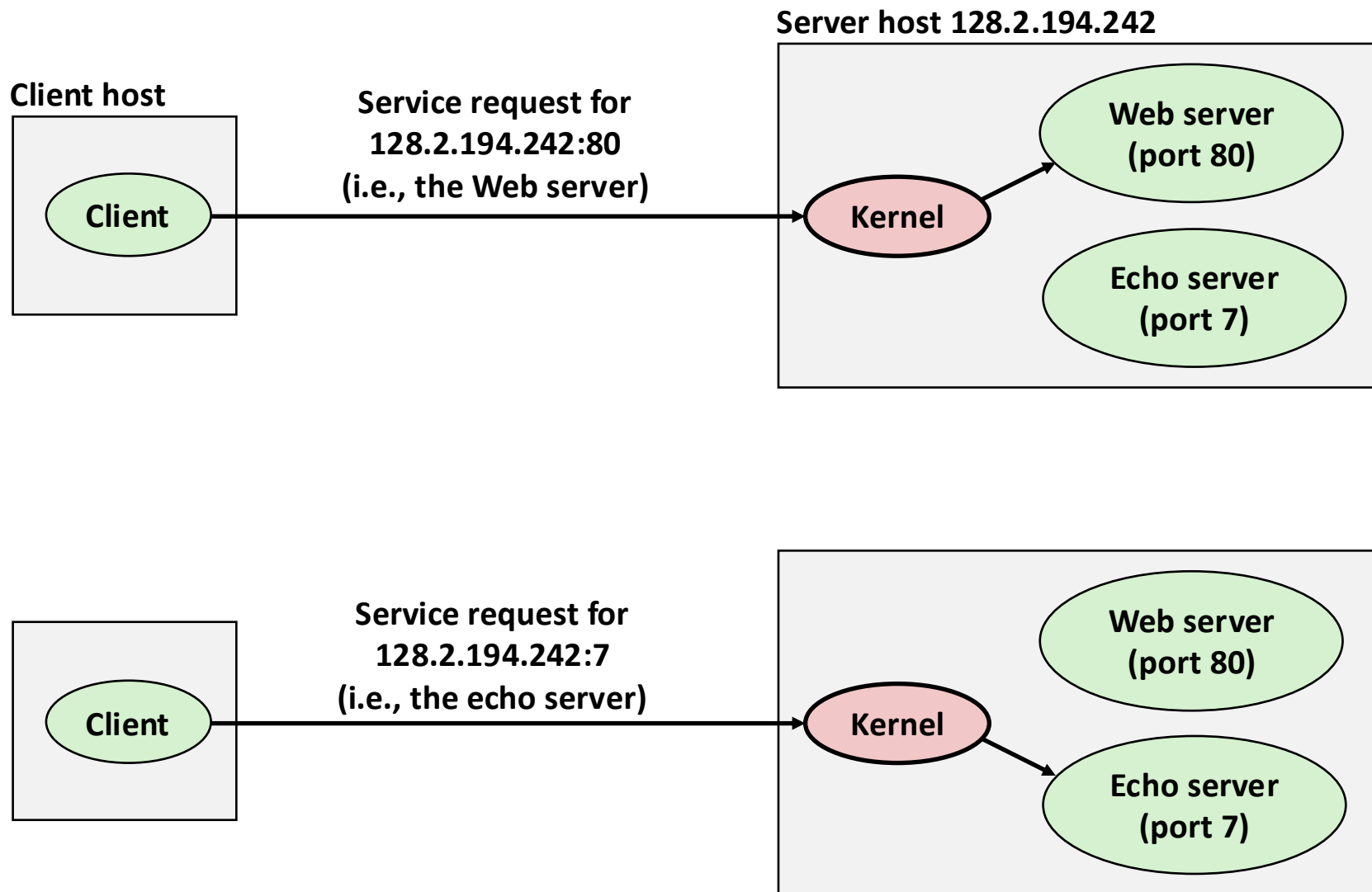
- A connection is uniquely identified by the socket addresses of its endpoints (*socket pair*)
 - (cliaddr:cliport, servaddr:servport)



51213 is an ephemeral port allocated by the kernel

80 is a well-known port associated with Web servers

Using Ports to Identify Services



Today

- Network Layers: Bird's Eye View
- Global IP Internet
- **Sockets Interface**

Sockets Interface

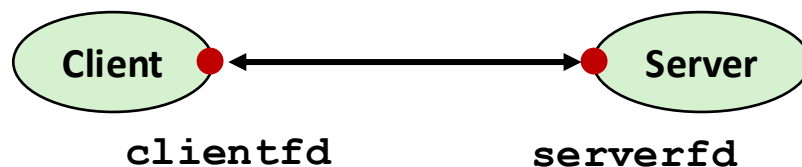
- **Set of system-level functions used in conjunction with Unix I/O to build network applications.**
- **Created in the early 80's as part of the original Berkeley distribution of Unix that contained an early version of the Internet protocols.**
- **Available on all modern systems**
 - Unix variants, 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 Programming Example

- **Echo server and client**
- **Server**
 - Accepts connection request
 - Repeats back lines as they are typed
- **Client**
 - Requests connection to server
 - Repeatedly:
 - Read line from terminal
 - Send to server
 - Read reply from server
 - Print line to terminal

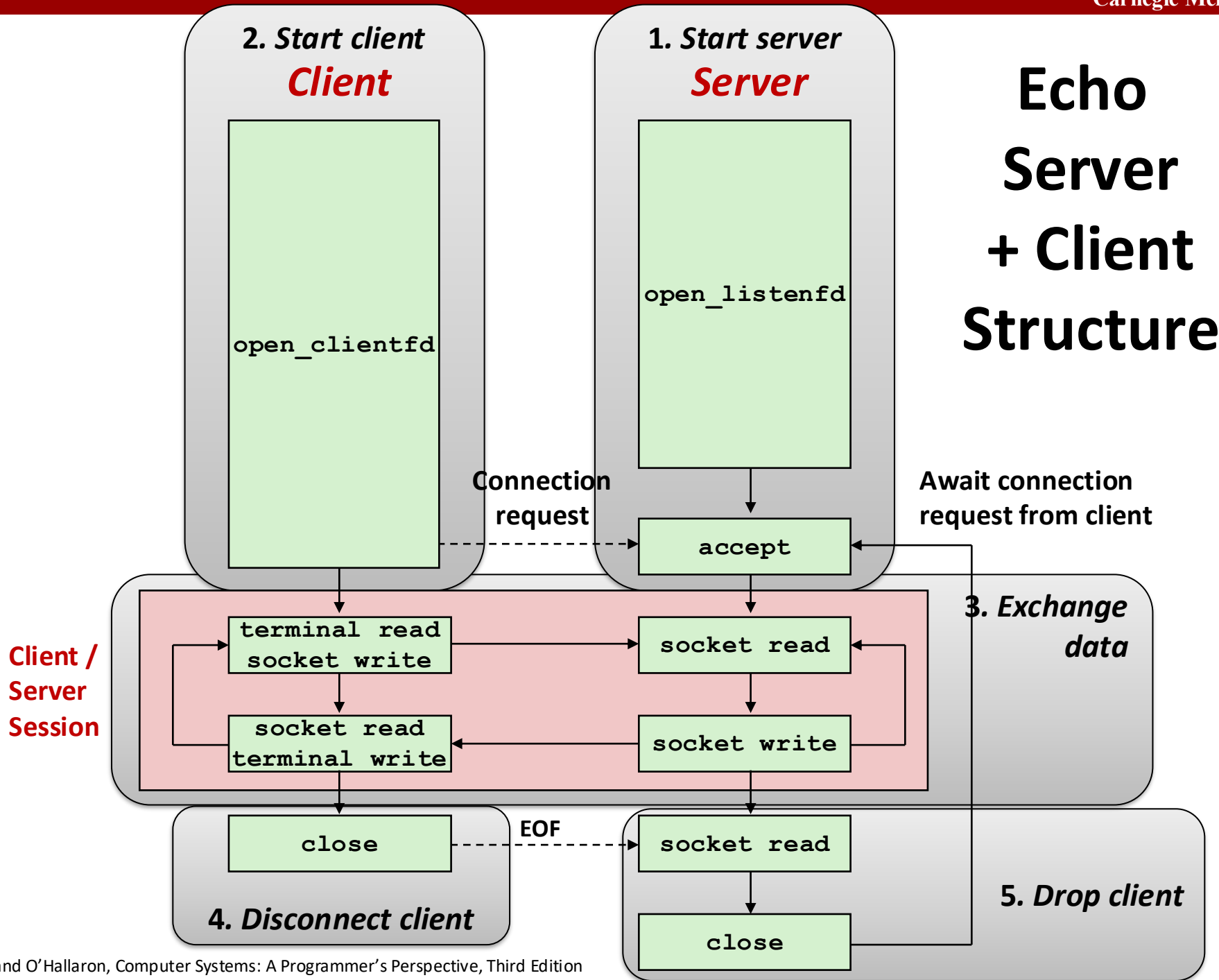
Echo Server/Client Session Example

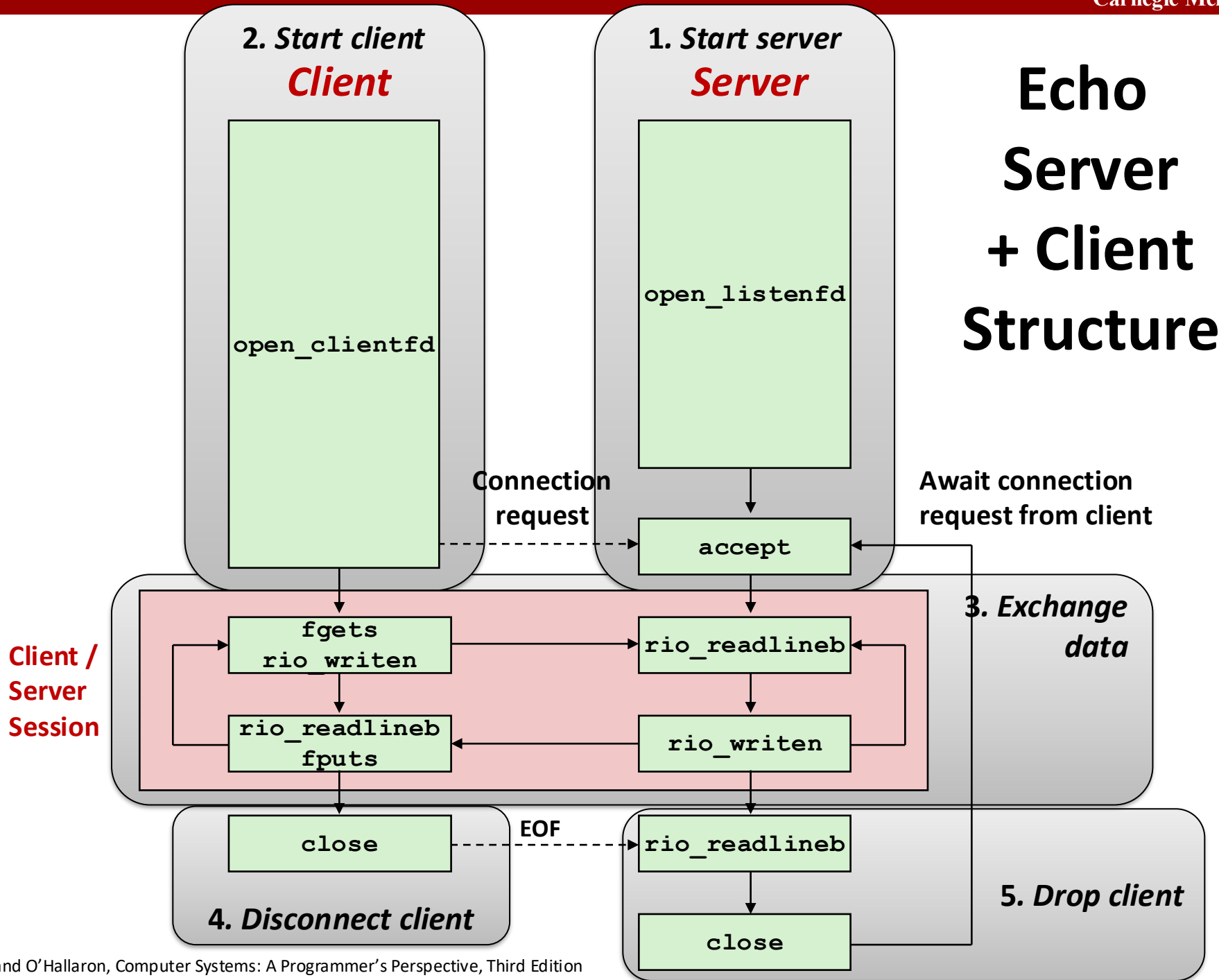
Client

```
bambooshark: ./echoclient whaleshark.ics.cs.cmu.edu 6616      (A)
This line is being echoed                                     (B)
This line is being echoed
This one is, too                                           (C)
This one is, too
^D
bambooshark: ./echoclient whaleshark.ics.cs.cmu.edu 6616      (D)
This one is a new connection                               (E)
This one is a new connection
^D
```

Server

```
whaleshark: ./echoserveri 6616
Connected to (BAMBOOSHARK.ICS.CS.CMU.EDU, 33707)          (A)
server received 26 bytes                                    (B)
server received 17 bytes                                    (C)
Connected to (BAMBOOSHARK.ICS.CS.CMU.EDU, 33708)          (D)
server received 29 bytes                                    (E)
```





Recall: Unbuffered RIO Input/Output

- Same interface as Unix `read` and `write`
- Especially useful for transferring data on network sockets

```
#include "csapp.h"
```

```
ssize_t rio_readn(int fd, void *usrbuf, size_t n);  
ssize_t rio_writen(int fd, void *usrbuf, size_t n);
```

Return: num. bytes transferred if OK, 0 on EOF (`rio_readn` only), -1 on error

- `rio_readn` returns short count only if it encounters EOF
 - Only use it when you know how many bytes to read
- `rio_writen` never returns a short count
- Calls to `rio_readn` and `rio_writen` can be interleaved arbitrarily on the same descriptor

Recall: Buffered RIO Input Functions

- Efficiently read text lines and binary data from a file partially cached in an internal memory buffer

```
#include "csapp.h"

void rio_readinitb(rio_t *rp, int fd);

ssize_t rio_readlineb(rio_t *rp, void *usrbuf, size_t maxlen);
ssize_t rio_readnb(rio_t *rp, void *usrbuf, size_t n);
```

Return: num. bytes read if OK, 0 on EOF, -1 on error

- **rio_readlineb** reads a *text line* of up to **maxlen** bytes from file **fd** and stores the line in **usrbuf**
 - Especially useful for reading text lines from network sockets
- Stopping conditions
 - **maxlen** bytes read
 - EOF encountered
 - Newline ('\n') encountered

Echo Server: echo function

- The server uses RIO to read and echo text lines until EOF (end-of-file) condition is encountered.
 - EOF condition caused by client calling `close(clientfd)`

```
void echo(int connfd)
{
    size_t n;
    char buf[MAXLINE];
    rio_t rio;

    Rio_readinitb(&rio, connfd);
    while((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {
        printf("server received %d bytes\n", (int)n);
        Rio_writen(connfd, buf, n);
    }
}
```

echo.c

Echo Client: Main Routine

```
#include "csapp.h"

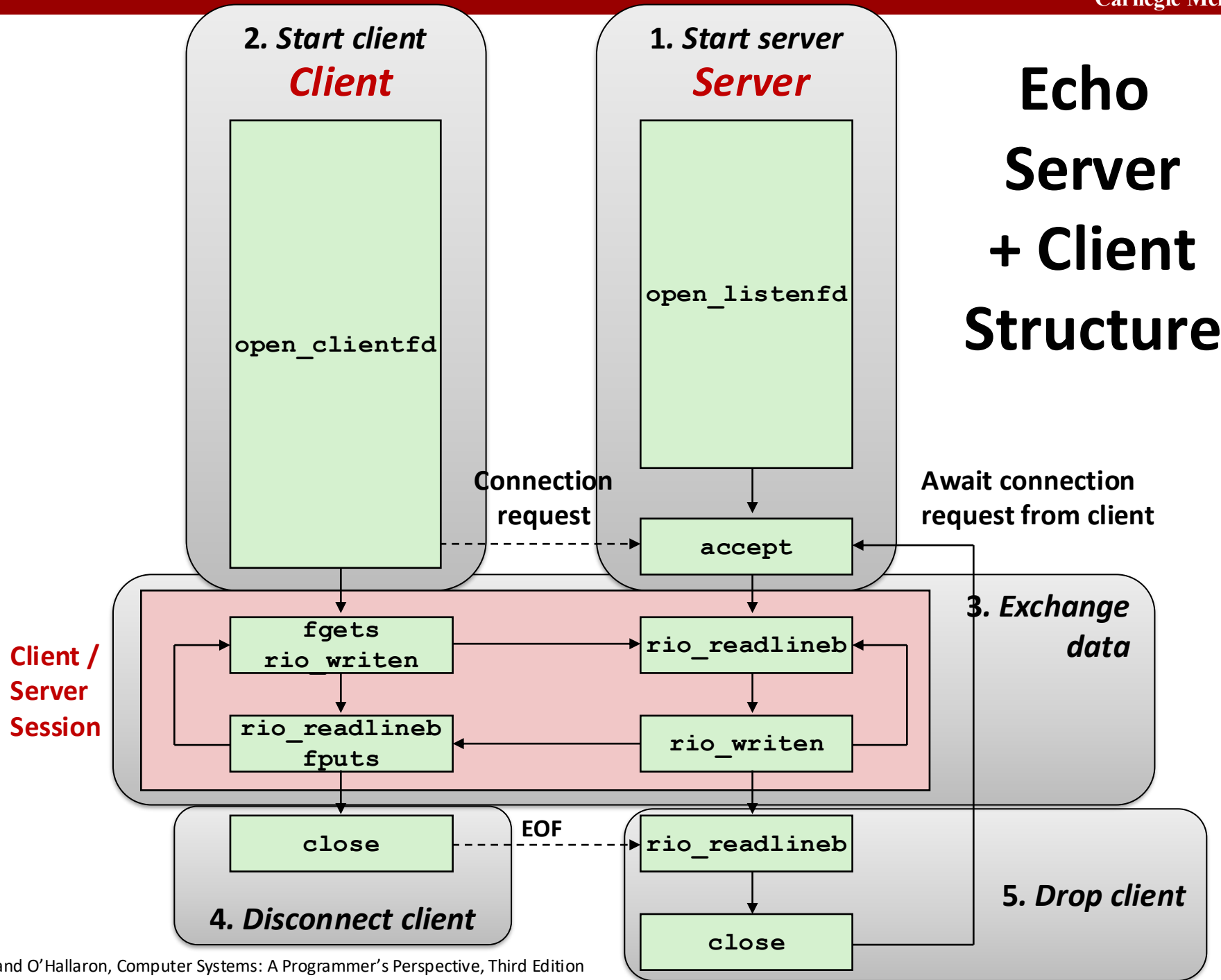
int main(int argc, char **argv)
{
    int clientfd;
    char *host, *port, buf[MAXLINE];
    rio_t rio;

    host = argv[1];
    port = argv[2];

    clientfd = Open_clientfd(host, port);
    Rio_readinitb(&rio, clientfd);

    while (Fgets(buf, MAXLINE, stdin) != NULL) {
        Rio_writen(clientfd, buf, strlen(buf));
        Rio_readlineb(&rio, buf, MAXLINE);
        Fputs(buf, stdout);
    }
    Close(clientfd);
    exit(0);
}
```

echoclient.c



Iterative Echo Server: Main Routine

```
#include "csapp.h"
void echo(int connfd);

int main(int argc, char **argv)
{
    int listenfd, connfd;
    socklen_t clientlen;
    struct sockaddr_storage clientaddr; /* Enough room for any addr */
    char client_hostname[MAXLINE], client_port[MAXLINE];

    listenfd = Open_listenfd(argv[1]);
    while (1) {
        clientlen = sizeof(struct sockaddr_storage); /* Important! */
        connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
        Getnameinfo((SA *)&clientaddr, clientlen,
                    client_hostname, MAXLINE, client_port, MAXLINE, 0);
        printf("Connected to (%s, %s)\n", client_hostname, client_port);
        echo(connfd);
        Close(connfd);
    }
    exit(0);
}
```

echoserveri.c

Socket Address Structures

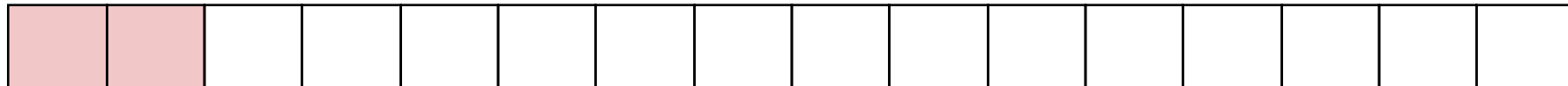
■ Generic socket address:

- For address arguments to **connect**, **bind**, and **accept** (*next lecture*)
- 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 */  
};
```

sa_family



Family Specific

Socket Address Structures

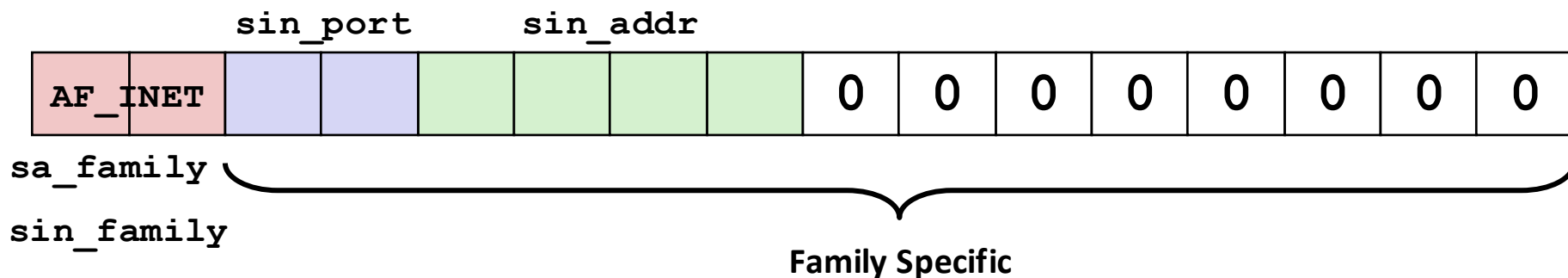
■ Internet (IPv4) specific socket address:

- 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) */
};

```



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`

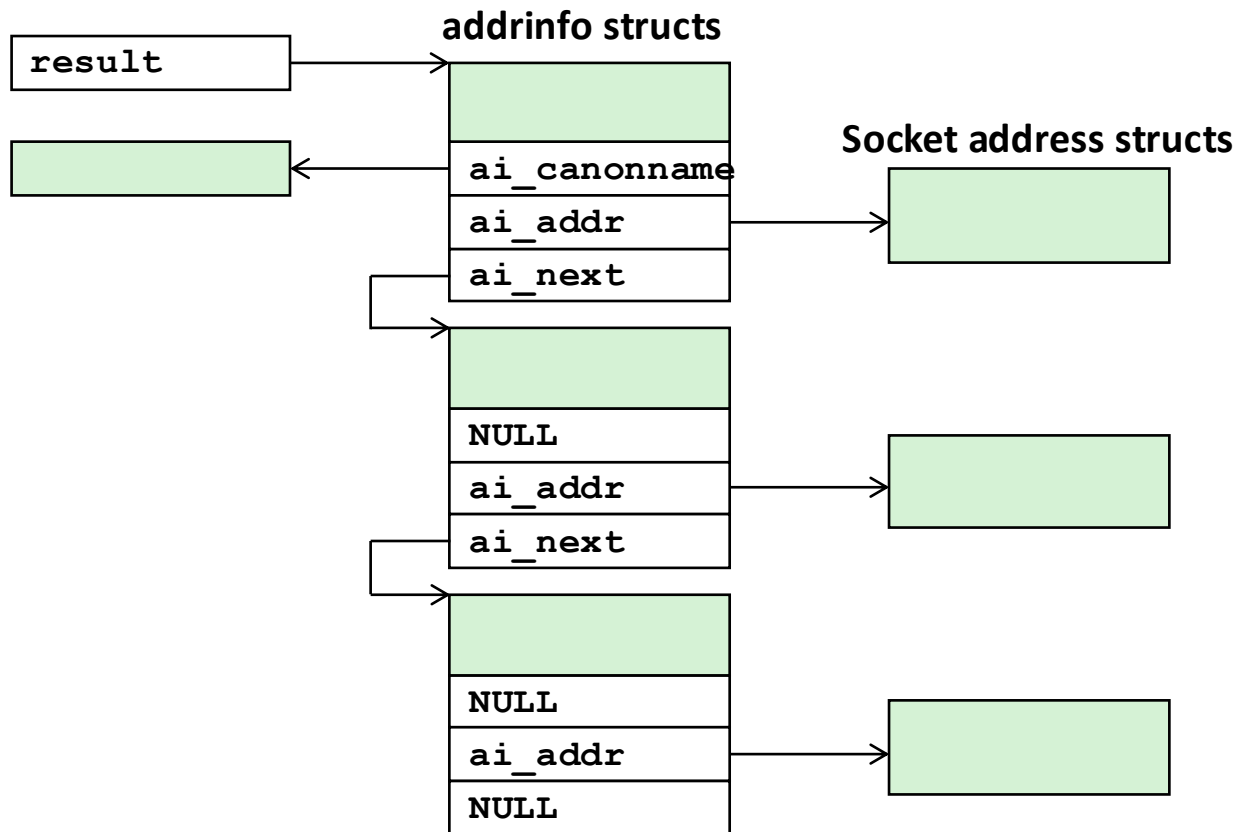
```
int getaddrinfo(const char *host,          /* Hostname or address */
               const char *service,      /* Port or service name */
               const struct addrinfo *hints, /* Input parameters */
               struct addrinfo **result); /* Output linked list */

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:**
 - `freeaddrinfo` frees the entire linked list.
 - `gai_strerror` converts error code to an error message.

Linked List Returned by `getaddrinfo`



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 .

(`socket`, `connect`, `bind` to be discussed next lecture)

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 */
```

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);
    }
}
```

hostinfo.c

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);
}
```

hostinfo.c

Running hostinfo

```
whaleshark> ./hostinfo localhost  
127.0.0.1
```

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

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

```
whaleshark> ./hostinfo google.com  
172.217.15.110  
2607:f8b0:4004:802::200e
```

Today

- Network Layers
- Global IP Internet
- Sockets Interface

Next time

- Using `getaddrinfo` for host and service conversion
- Writing clients and servers
- Writing Web servers!

Additional slides

Basic Internet Components

■ Internet backbone:

- collection of routers (nationwide or worldwide) connected by high-speed point-to-point networks

■ Internet Exchange Points (IXP):

- router that connects multiple backbones (often referred to as peers)
- Also called Network Access Points (NAP)

■ Regional networks:

- smaller backbones that cover smaller geographical areas (e.g., cities or states)

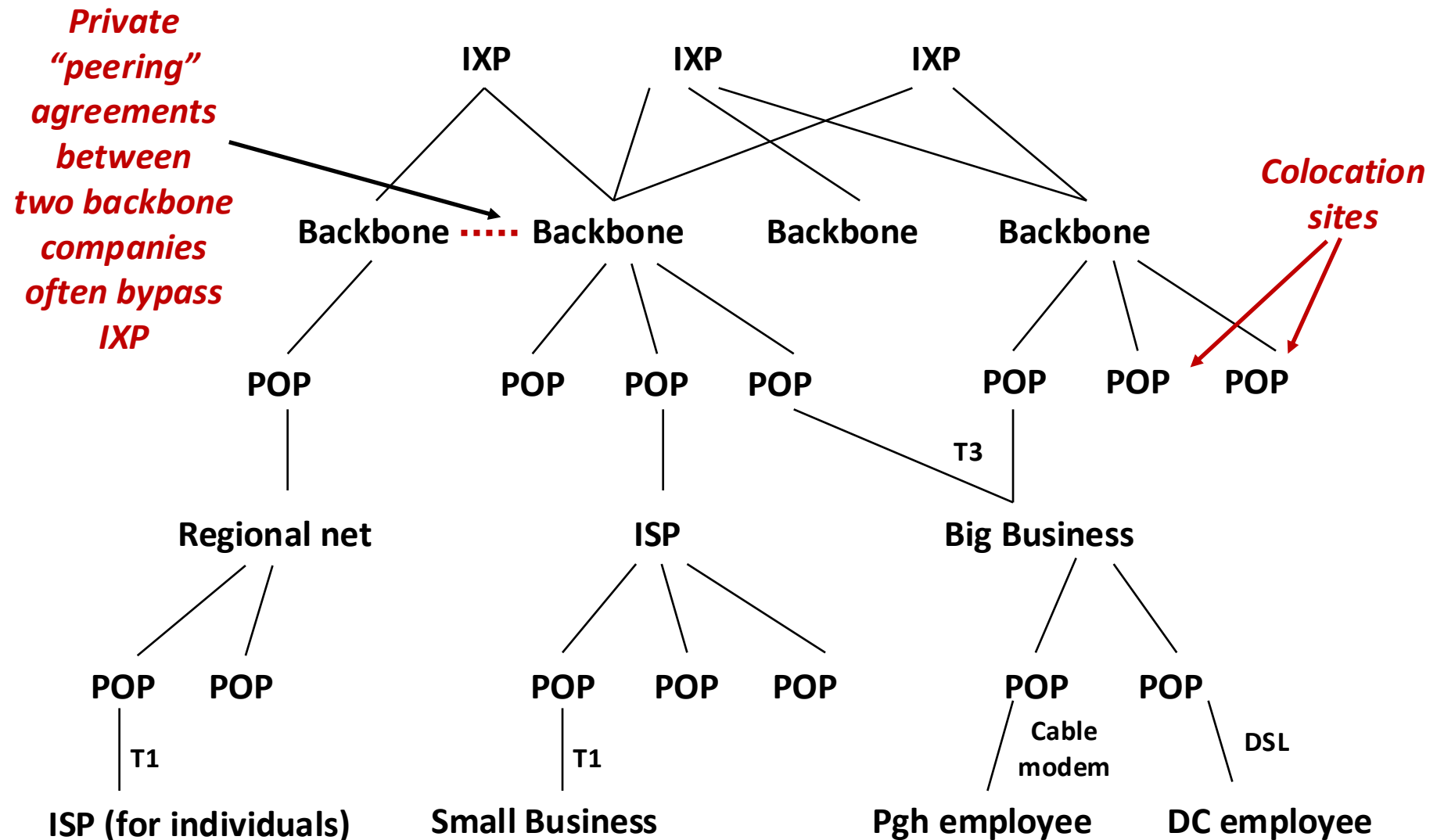
■ Point of presence (POP):

- machine that is connected to the Internet

■ Internet Service Providers (ISPs):

- provide dial-up or direct access to POPs

Internet Connection Hierarchy



IP Address Structure

■ IP (V4) Address space divided into classes:

	0	1	2	3	8	16	24	31	
Class A	0	Net ID				Host ID			
Class B	1	0	Net ID				Host ID		
Class C	1	1	0	Net ID				Host ID	
Class D	1	1	1	0	Multicast address				
Class E	1	1	1	1	Reserved for experiments				

■ Network ID Written in form w.x.y.z/n

- n = number of bits in host address
- E.g., CMU written as 128.2.0.0/16
 - Class B address

■ Unrouted (private) IP addresses:

10.0.0.0/8 172.16.0.0/12 192.168.0.0/16

Evolution of Internet

■ Original Idea

- Every node on Internet would have unique IP address
 - Everyone would be able to talk directly to everyone
- No secrecy or authentication
 - Messages visible to routers and hosts on same LAN
 - Possible to forge source field in packet header

■ Shortcomings

- There aren't enough IP addresses available
- Don't want everyone to have access or knowledge of all other hosts
- Security issues mandate secrecy & authentication

Evolution of Internet: Naming

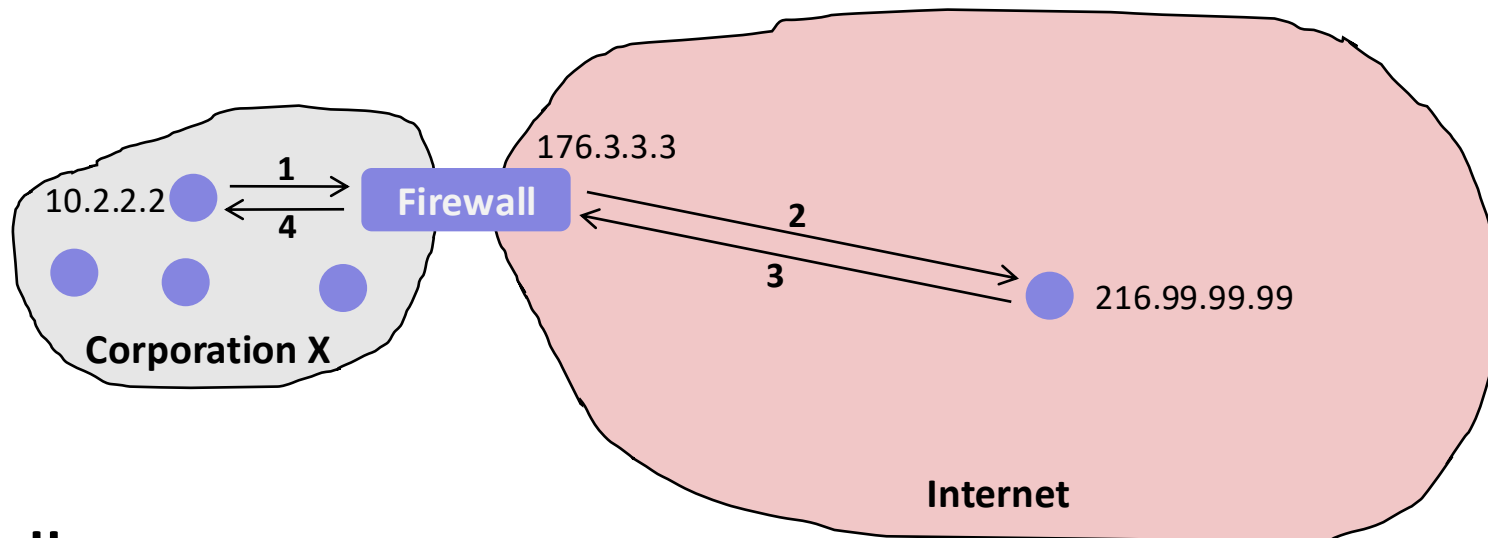
■ Dynamic address assignment

- Most hosts don't need to have known address
 - Only those functioning as servers
- DHCP (Dynamic Host Configuration Protocol)
 - Local ISP assigns address for temporary use

■ Example:

- Laptop at CMU (wired connection)
 - IP address 128.2.213.29 (**bryant-tp4 . cs . cmu . edu**)
 - Assigned statically
- Laptop at home
 - IP address 192.168.1.5
 - Only valid within home network

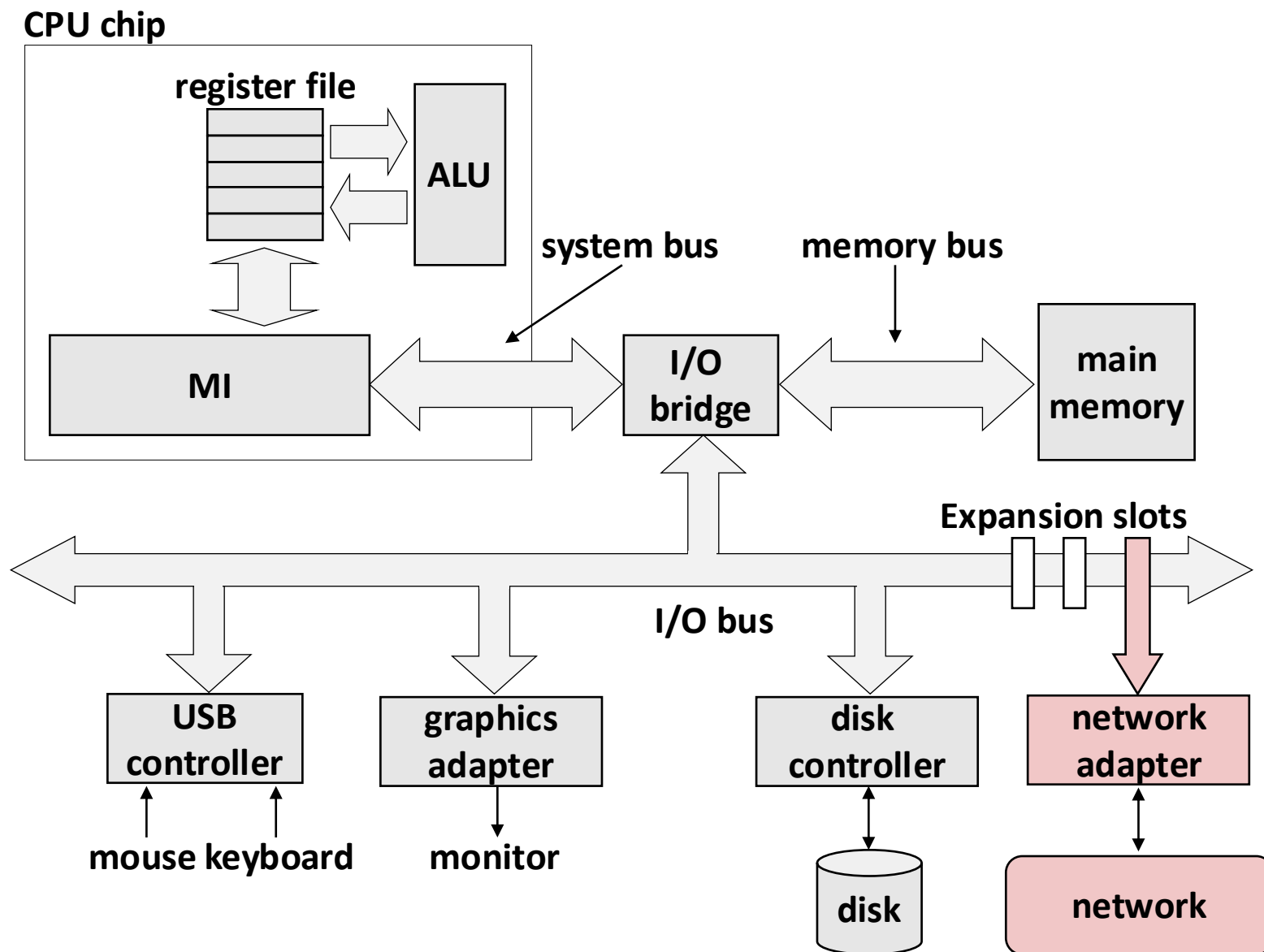
Evolution of Internet: Firewalls



■ Firewalls

- Hides organizations nodes from rest of Internet
- Use local IP addresses within organization
- For external service, provides proxy service
 1. Client request: src=10.2.2.2, dest=216.99.99.99
 2. Firewall forwards: src=176.3.3.3, dest=216.99.99.99
 3. Server responds: src=216.99.99.99, dest=176.3.3.3
 4. Firewall forwards response: src=216.99.99.99, dest=10.2.2.2

Hardware Organization of a Network Host

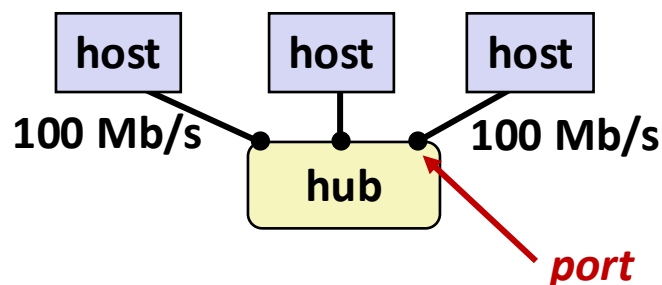


Computer Networks

- A ***network*** is a hierarchical system of boxes and wires organized by geographical proximity
 - BAN (Body Area Network) spans devices carried / worn on body
 - 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**

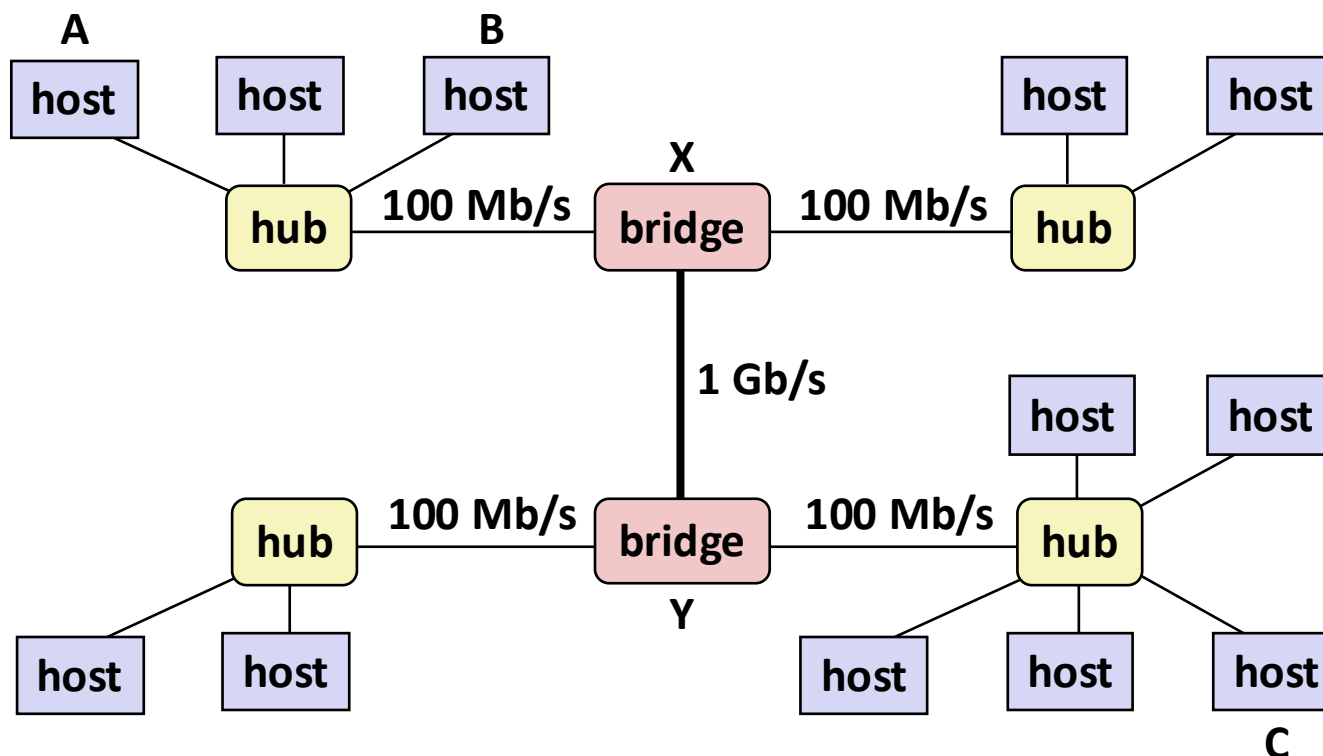
* Not to be confused with a Storage Area Network

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 slavishly copies each bit from each port to every other port
 - Every host sees every bit
- [Note: Hubs are obsolete. Bridges (switches, routers) became cheap enough to replace them]

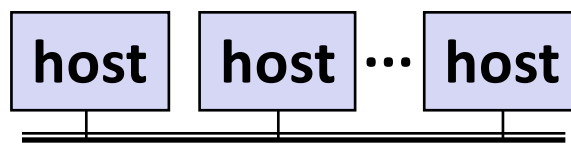
Next Level: Bridged Ethernet Segment



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

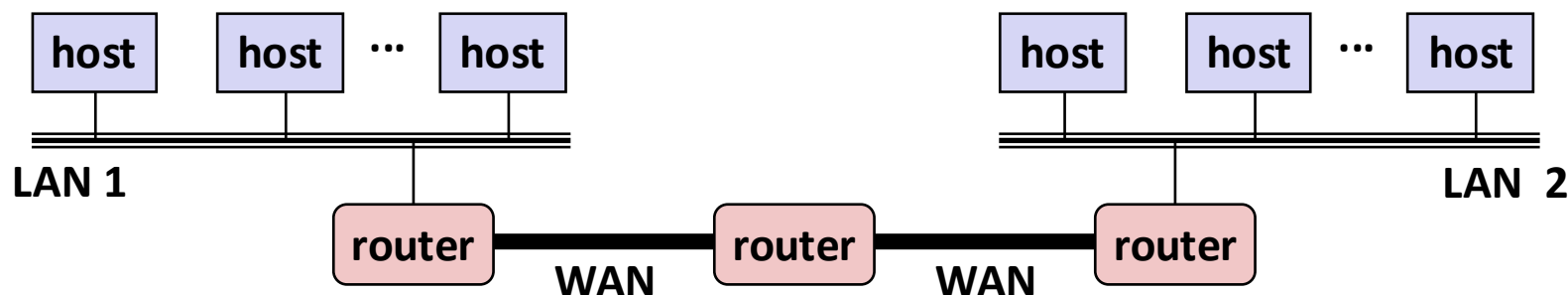
Conceptual View of LANs

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



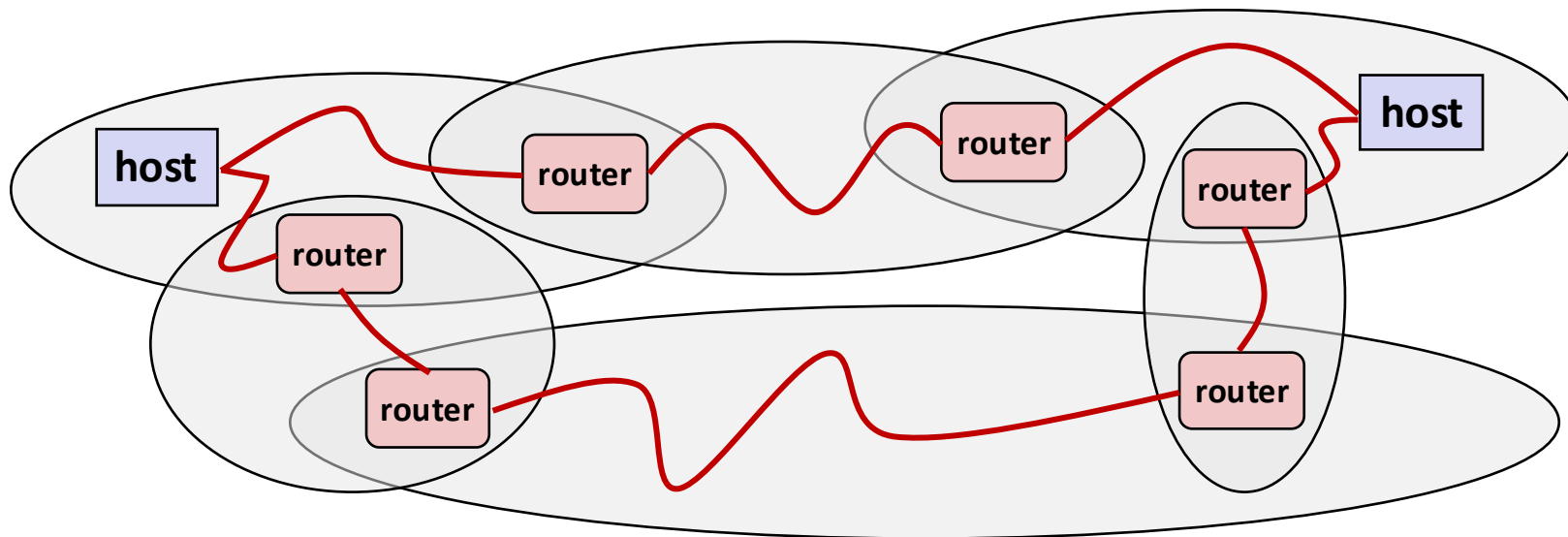
Next Level: internets

- 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?

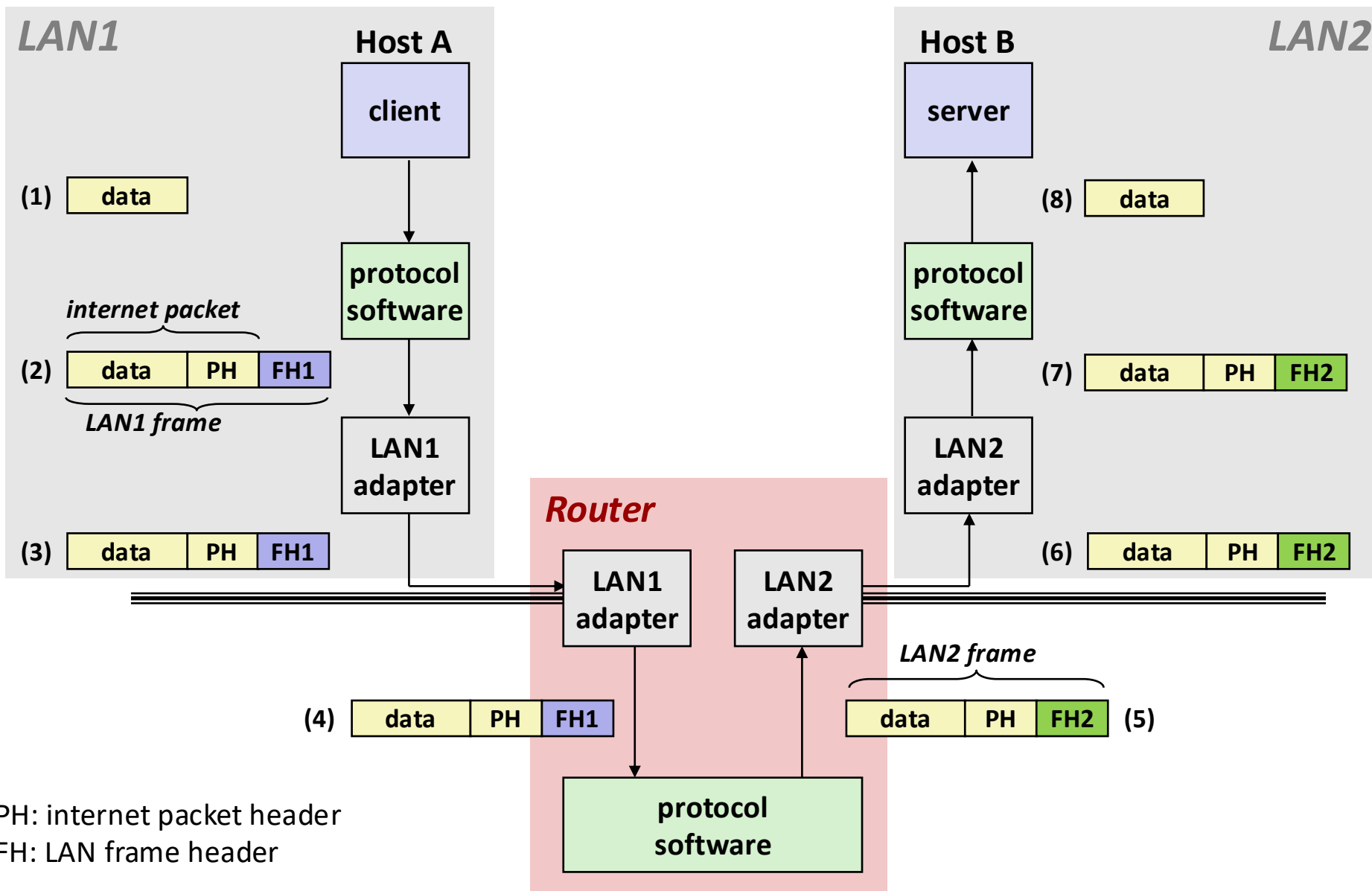
■ Provides a *naming scheme*

- 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



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***