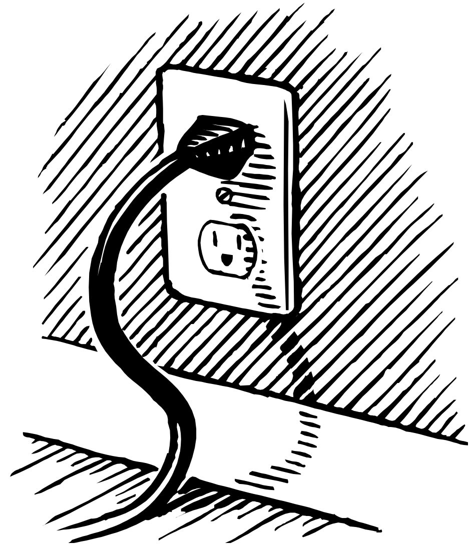

Layering & UNIX Sockets

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Note: The slides are adapted from the materials from Prof. Richard Han at CU Boulder and Profs. Jennifer Rexford and Mike Freedman at Princeton University.

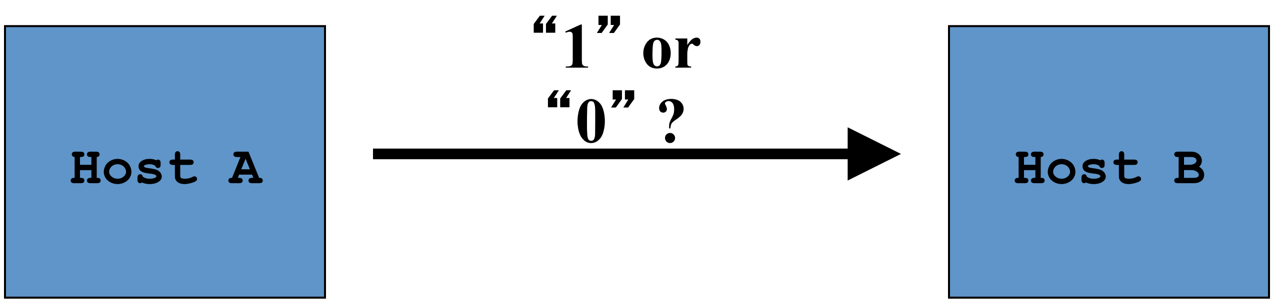
Network layering at a glance

Network Stack

Layer	Internet Stack	
5	Application Layer	Web (HTTP), email (SMTP), etc.
4	Transport Layer	End-to-end protocols over multiple hops (TCP, UDP)
3	Network Layer	Routing packets over multiple links/hops in a network (IP)
2	Data Link Layer	Sending packets over one link (Ethernet, WiFi, Bluetooth)
1	Physical Layer	Sending 1's and 0's over one link (CDMA, OFDM)

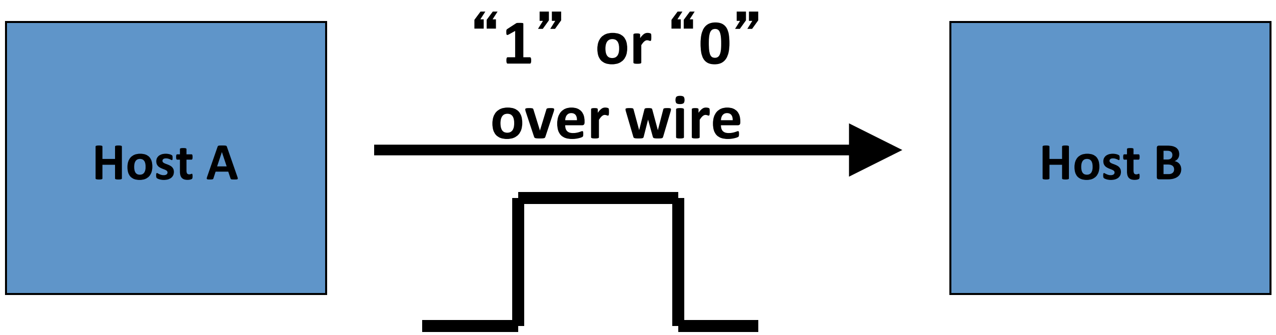
Network Layering – Starting from the Bottom Up

- Two hosts want to communicate with each other
- First, how do I send a "bit" from host A to host B?



Layer 1: The Physical Layer

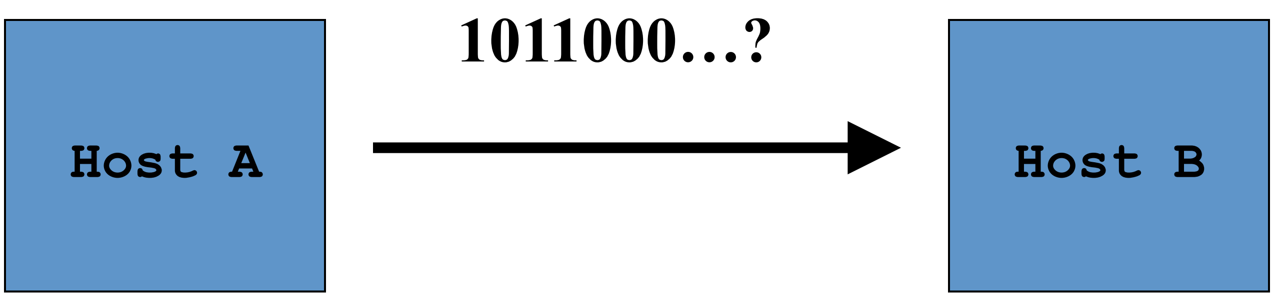
- Solution: Host A encodes the bit into an analog signal. Host B decodes the analog signal into a received bit.



- How would you encode a "1" and a "0"?
  - Amplitude, duration (telegraph & Morse code), tone, etc.
- *Physical Layer*, also called Layer 1, encodes & decodes a digital bit from its analog form
  - Modem has advanced DSP to achieve even 56 kbps

Layer 2: The Data Link Layer

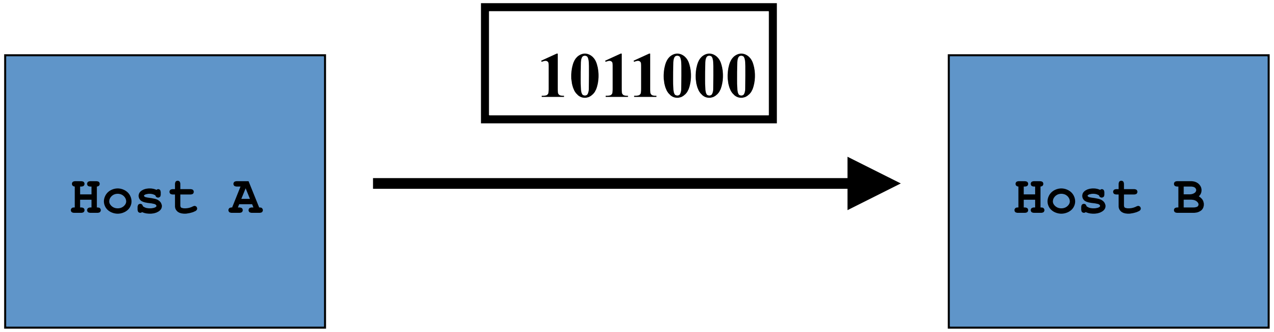
- Next Problem: How do I send a *message* from Host A to Host B?



- *Data Link Layer*, also called Layer 2, ensures that host B can decode a digital message from a stream of bits sent by host A

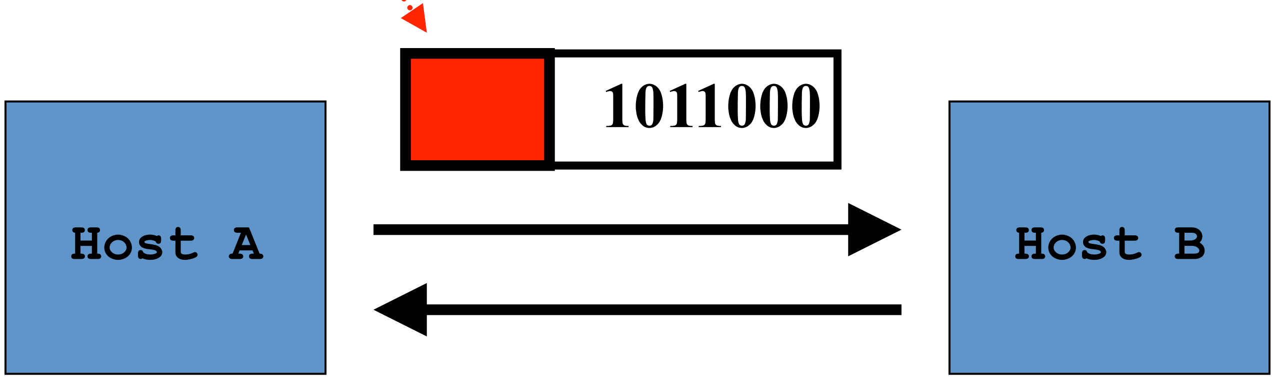
The Data Link Layer (cont.)

- A Data Link Layer *Protocol* implements:
  - Delimiting/framing of a message
  - Fragmenting of a long message
  - Retransmission of a lost message
  - …

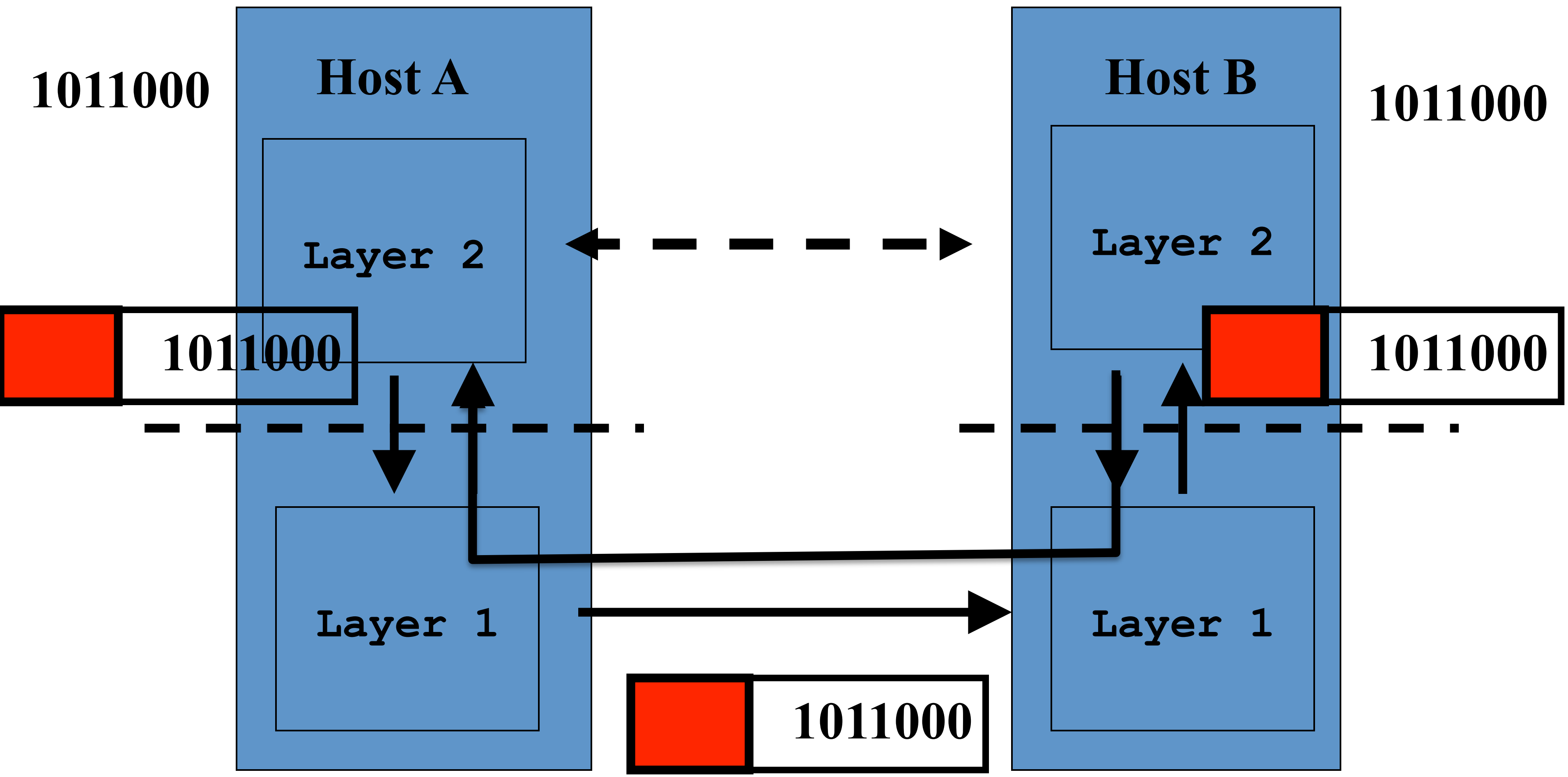


Defining a Protocol

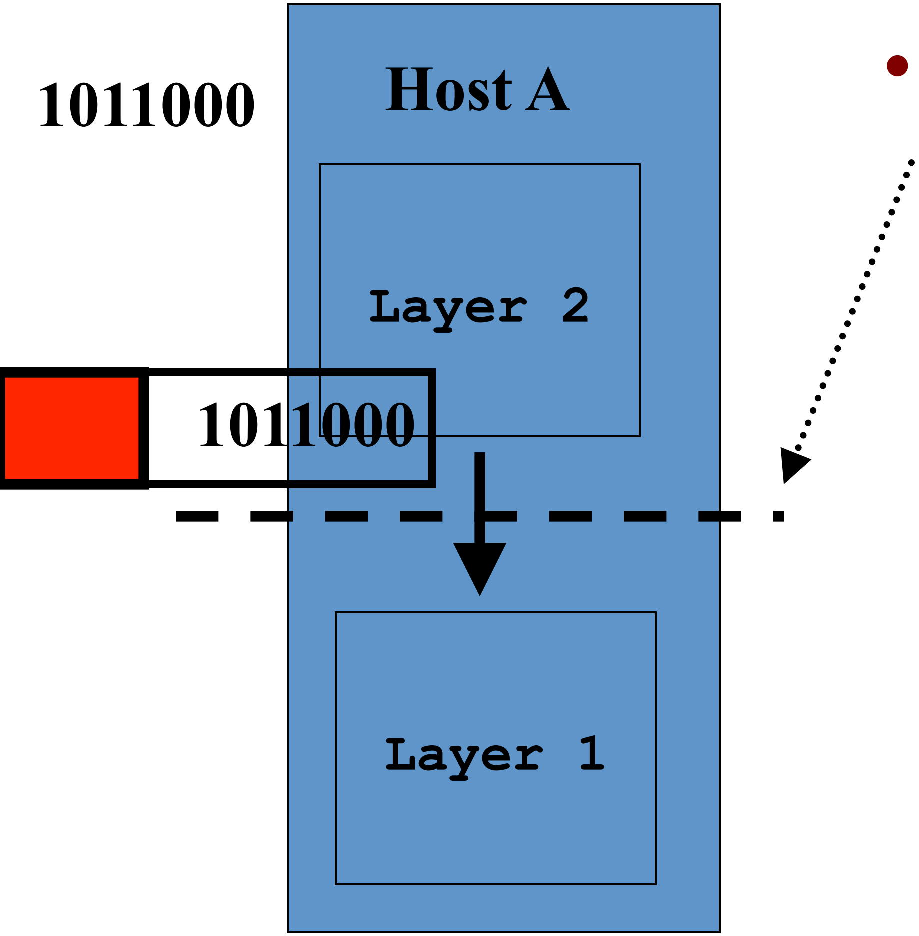
- A protocol is an agreement between two parties or endpoints as to how information is to be transmitted
- A protocol implements this agreement via:
  - **A Header**
  - How each endpoint responds to control info in the header (external input)



How Physical and Data-Link Layers Interact…



Defining a *Service*



- A Service Interface separates two layers
  - Act as standard API
  - Lower layer promises to support API primitives
  - Isolates Physical Layer's implementation from DL Layer Protocol
  - e.g., mail envelope, socket API

Performance of a Data Link Layer Protocol

- Round-trip Time RTT =

  forward propagation delay of 1st bit

  + forward transfer time (width of data packet)

  + processing at the receiver

  + reverse propagation delay of 1st bit

  + reverse transfer time of reply packet

- Transfer time = P/B
  - D = Propagation delay
  - P = Packet Size
  - B = Bit rate or bandwidth of the link

Bandwidth*delay product (BDP) of a Link

- Bandwidth*delay product indicates how many bits can be fit into a given link
  - D: Propagation delay
  - B: Bit rate or bandwidth of the link
  - BDP = B * D
- Assuming a roundtrip time of 2D
  - BDP = B * 2D
- Assuming only one way delay
  - BDP = B * D

Sample Bandwidth Delay Products

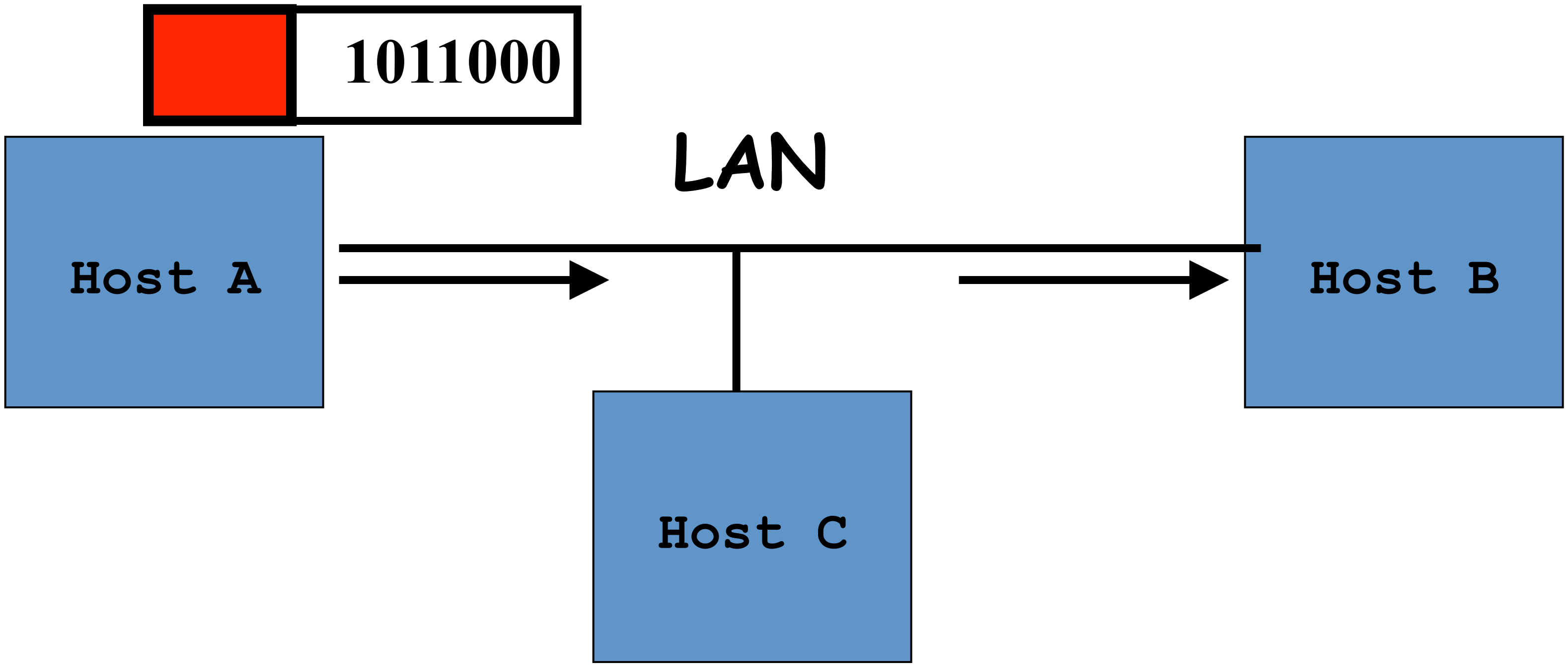
Link Type	Bandwidth (Typical)	Distance (Typical)	RTT	Delay x BW
Dial-up	56 Kbps	10 km	87 μs	5 bits
Wireless LAN	54 Mbps	50 m	33 μs	**1.8 kbits**
Satellite	45 Mbps	35000 km	230 ms	10 Mb
Cross-country fiber	10 Gbps	4000 km	40 ms	400 Mb

BDP Q/A

- What is the maximum number of packets in flight on the link with following characteristics:
  - Bandwidth: 8Mbps
  - RTT between two end hosts: 250ms
  - 1 packet size: 1024 bytes

```
(8*1024*1024*0.25)/(1024*8) = 256 pkts
```

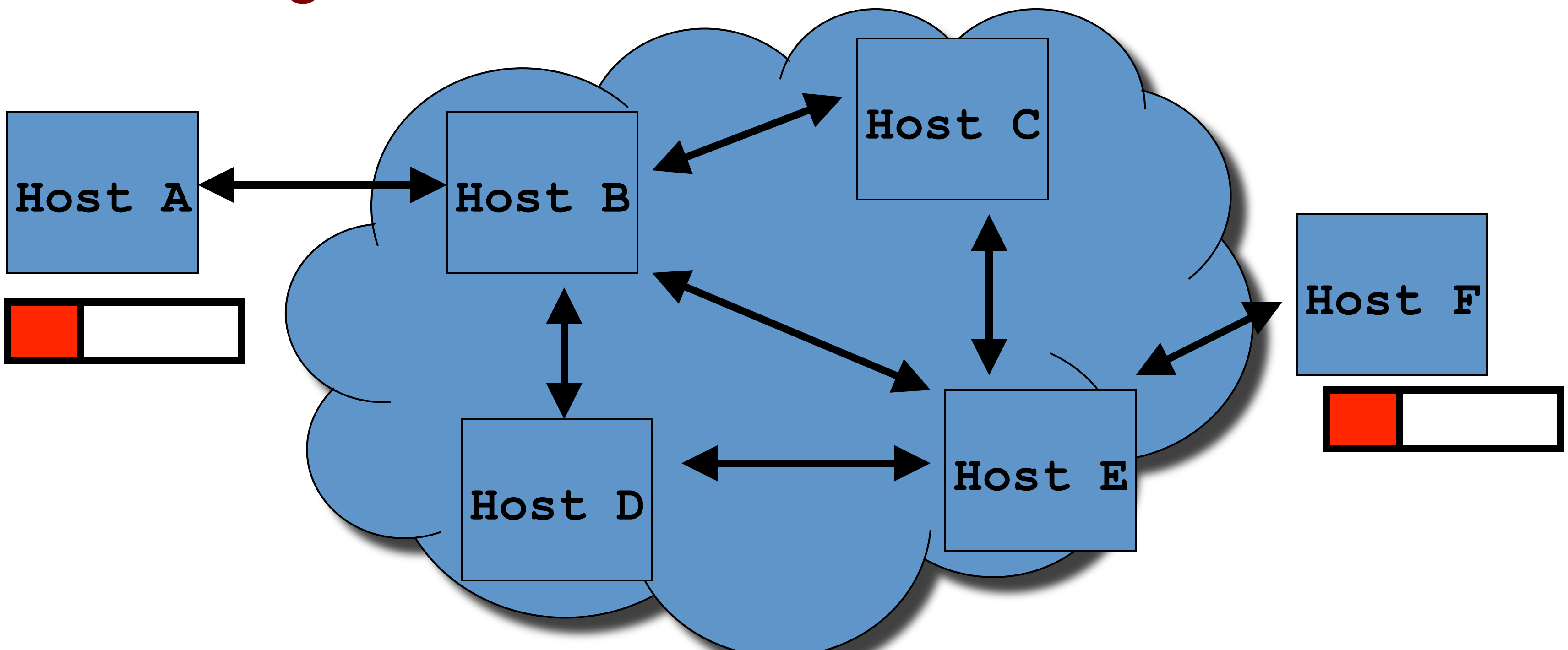
Layer 2: Communication Across a Shared Link (Broadcast Network)



- A shared medium connects A, B, and C
  - Ethernet – copper wire
  - WiFi, 802.11 – wireless
- Problems to solve – collisions ! In MAC layer

Layer 3: The Network Layer

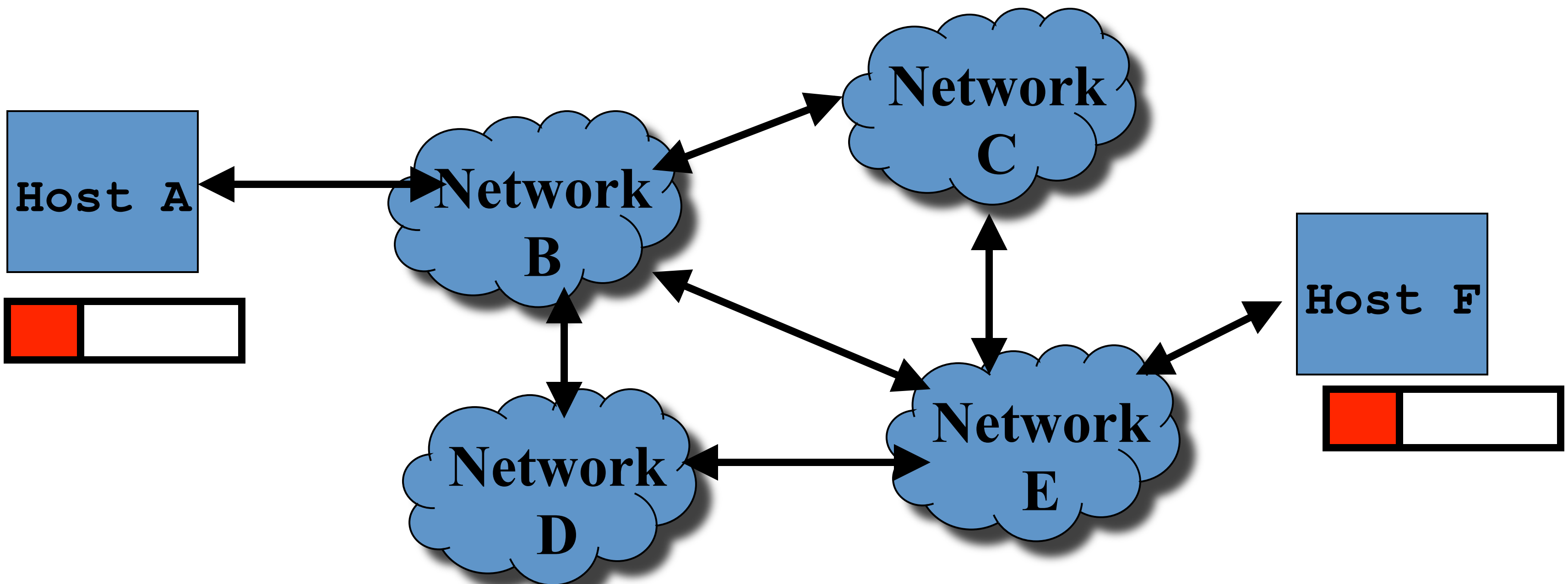
- The *Network* layer is responsible for *routing* a message across an interconnected mesh of hosts



- Network often represented as a “cloud”
- Routers have specialized hardware & OS’s, but initially were just computer hosts

Internet: Communication Across a Network of Networks

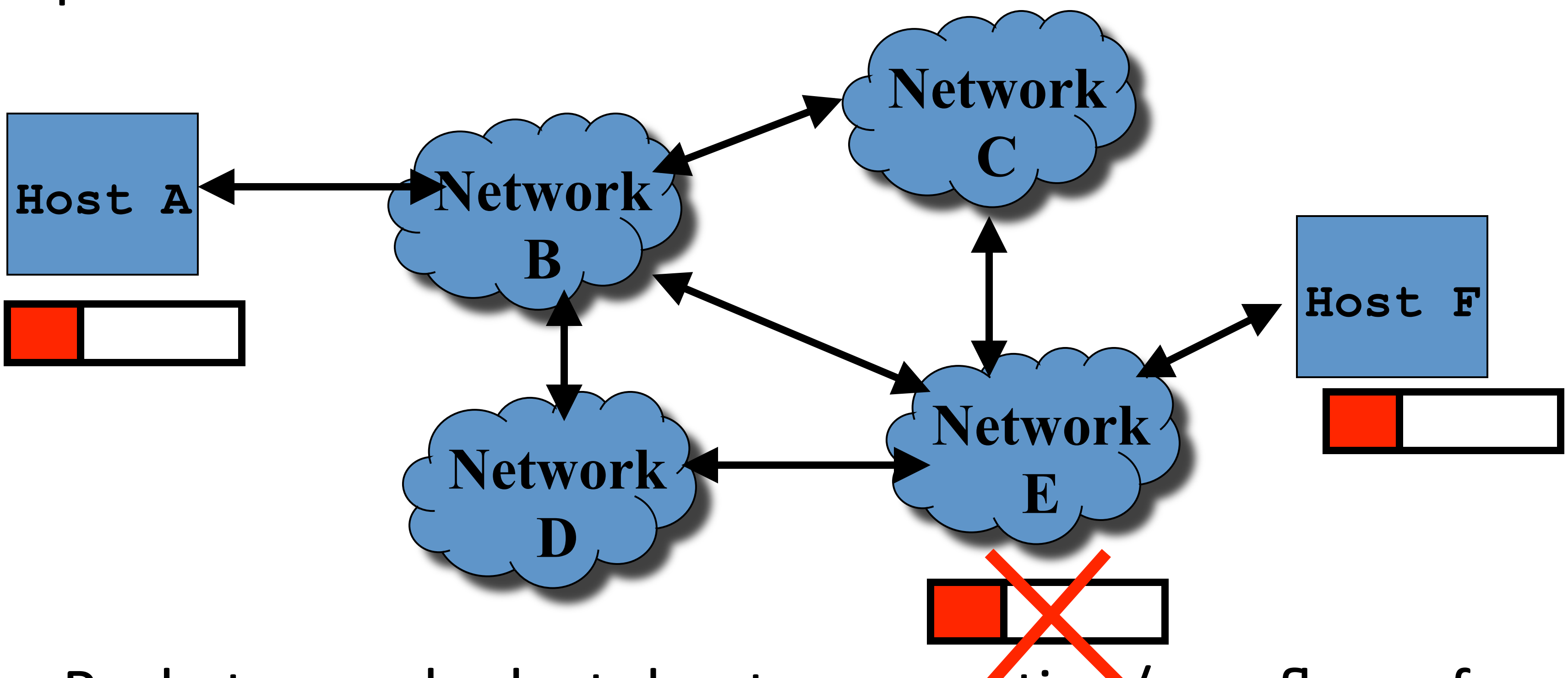
- The Internet is a *network of heterogeneous networks*



- The *Internet Protocol*, or *IP*, is an example of a Network Layer protocol
- IP routers at entry/exit to cloud (& possibly within cloud)

Layer 4: The Transport Layer

- The Transport Layer offers *end-to-end* delivery of packets across a network



- Packets may be lost due to congestion/overflow of shared buffers, router failure, misconfigured routing, bad link, etc.

Internet Transport Layers: TCP and UDP

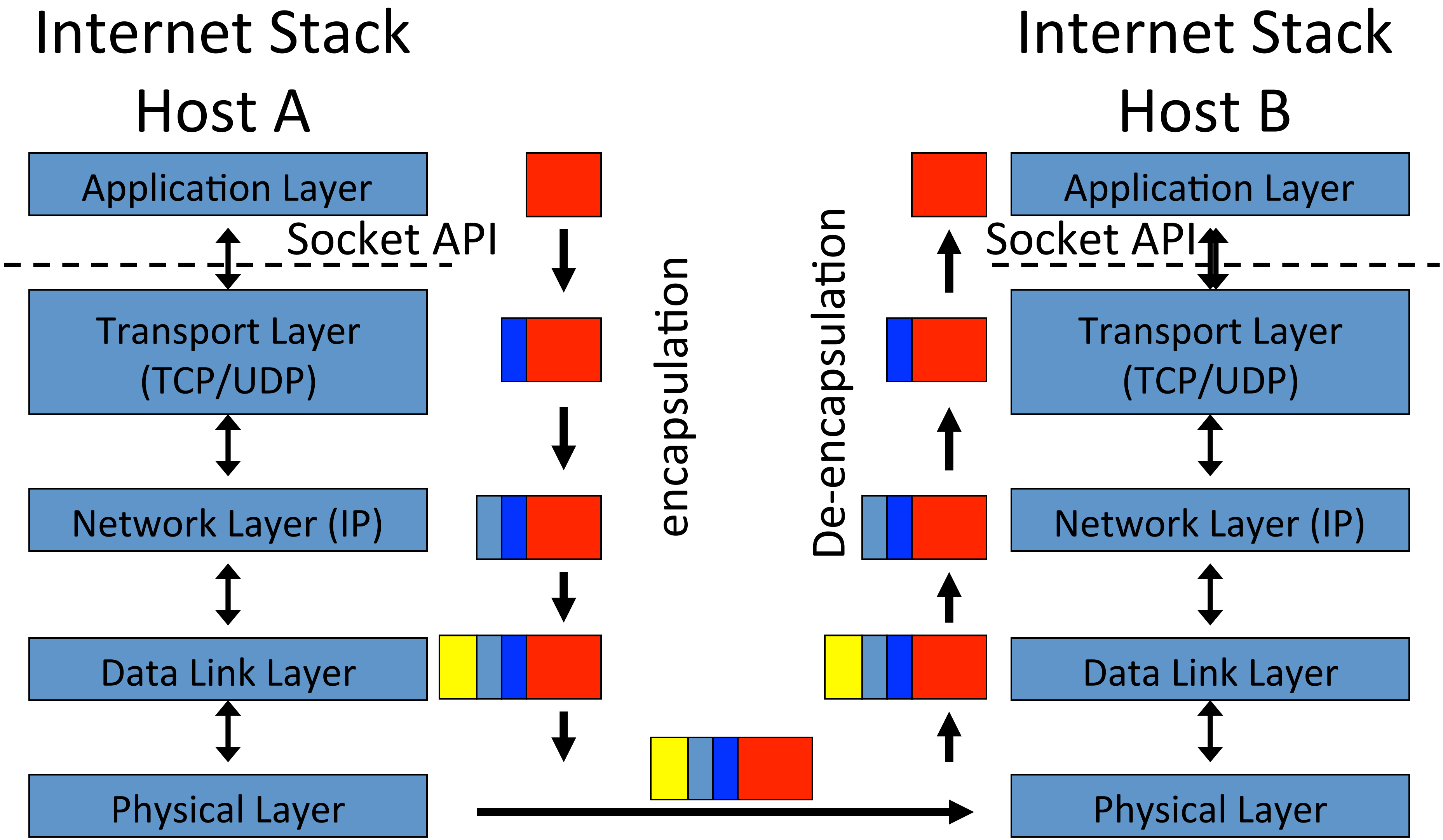
- The Transmission Control Protocol, or TCP is a reliable Transport Layer protocol above IP
  - Reliable delivery
  - In-order or stream delivery
- The User Datagram Protocol, or UDP is an unreliable protocol above IP
  - Unreliable packet delivery
  - Out-of-order packet delivery
- Why would you ever want unreliable out-of-order delivery?
  - When speed is more important than 100% reliability, e.g., real-time audio/video

Layer 5: The Internet Application Layer

- Given reliable in-order delivery by TCP, the Internet application-level protocols above TCP include:
  - HTTP : Hypertext Transport Protocol
  - SMTP : Simple Mail Transfer Protocol
  - FTP: File Transfer Protocol
  - NNTP: Network News Transfer Protocol
  - …

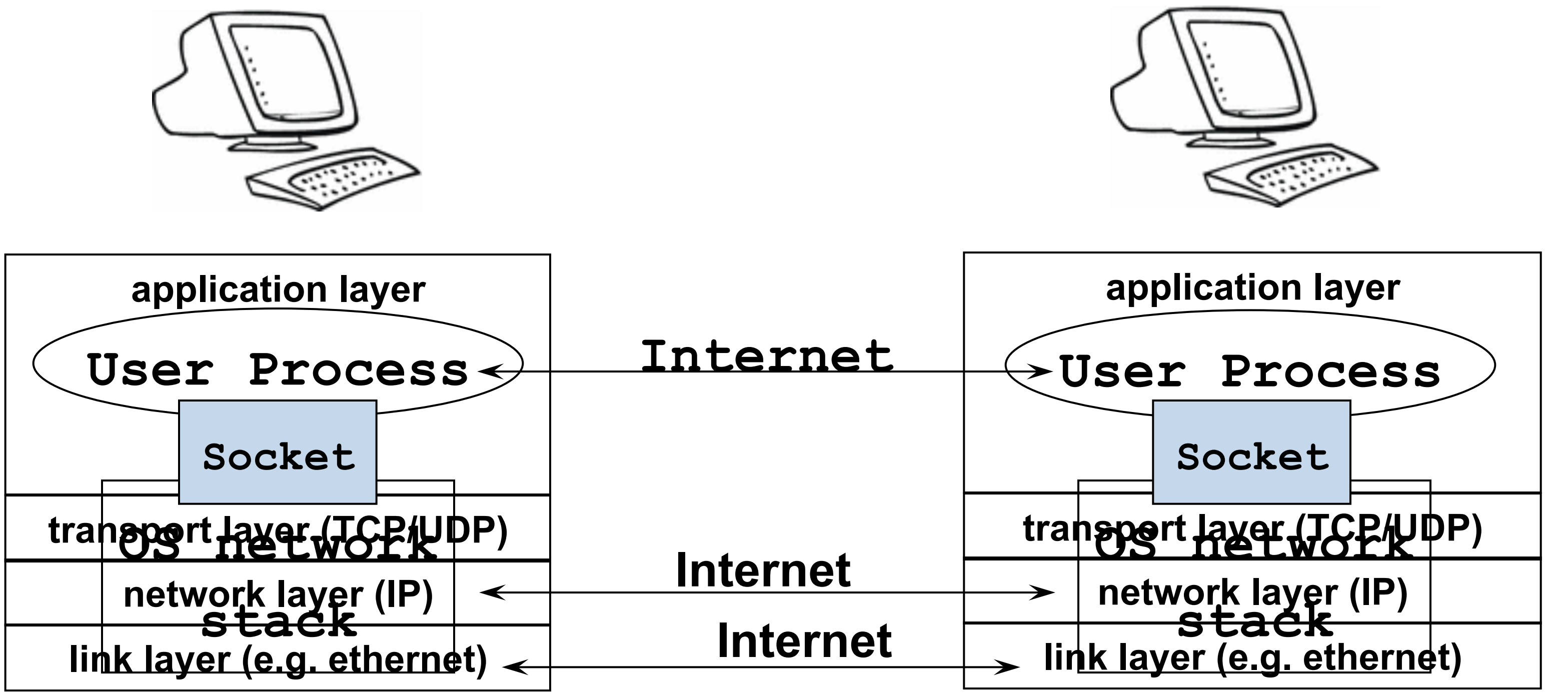
- The Open Systems Interconnection (OSI) model expands its Application Layer into 3 sub-layers: Application, Presentation, and Session

Following a Packet Through The Layered Network Stack



UNIX Sockets

Socket and Process Communication



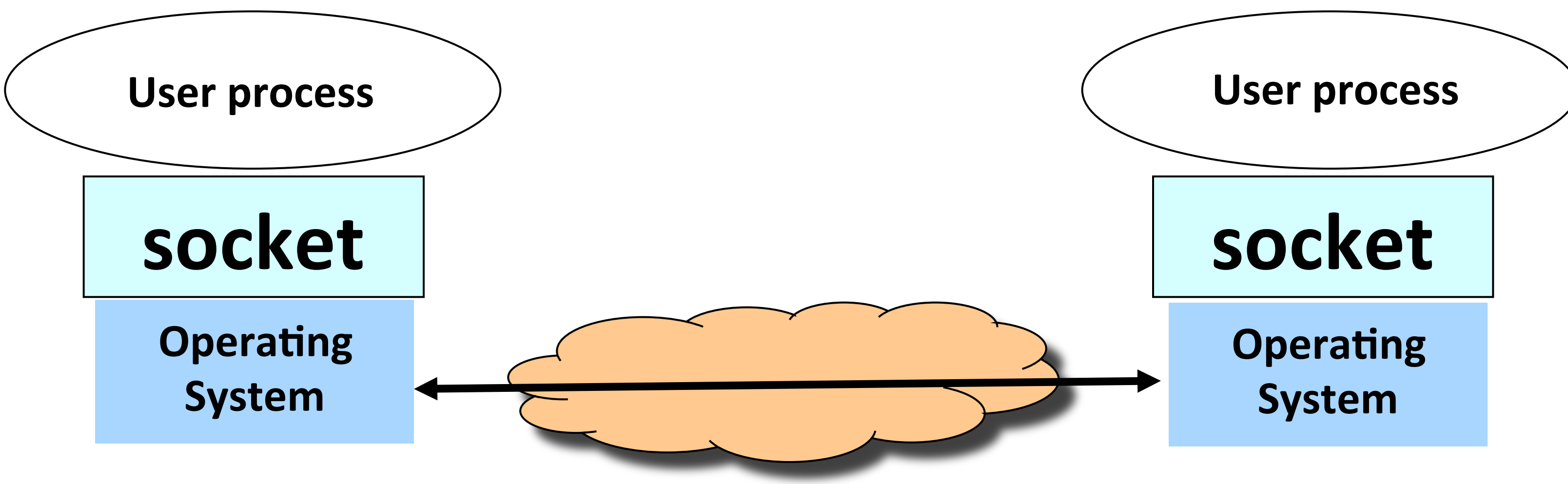
The interface that the OS provides to its networking subsystem

Delivering the Data: Division of Labor

- Network
  - Deliver data packet to the destination host
  - Based on the destination IP address
- Operating system
  - Deliver data to the destination socket
  - Based on the destination port number (e.g., 80)
- Application
  - Read data from and write data to the socket
  - Interpret the data (e.g., render a Web page)

Socket: End Point of Communication

- Sending message from one process to another
  - Message must traverse the underlying network
- Process sends and receives through a "socket"
  - In essence, the doorway leading in/out of the house
- Socket as an Application Programming Interface
  - Supports the creation of network applications



Two Types of Application Processes Communication

- Datagram Socket (UDP)
  - Collection of messages
  - Best effort
  - Connectionless
- Stream Socket (TCP)
  - Stream of bytes
  - Reliable
  - Connection-oriented

User Datagram Protocol (UDP): Datagram Socket

UDP	Postal Mail
• Single socket to receive messages	• Single mailbox to receive letters
• No guarantee of delivery	• Unreliable
• Not necessarily in-order delivery	• Not necessarily in-order delivery
• Datagram – independent packets	• Letters sent independently
• Must address each packet	• Must address each mail

Example UDP applications
Multimedia, voice over IP (Skype)

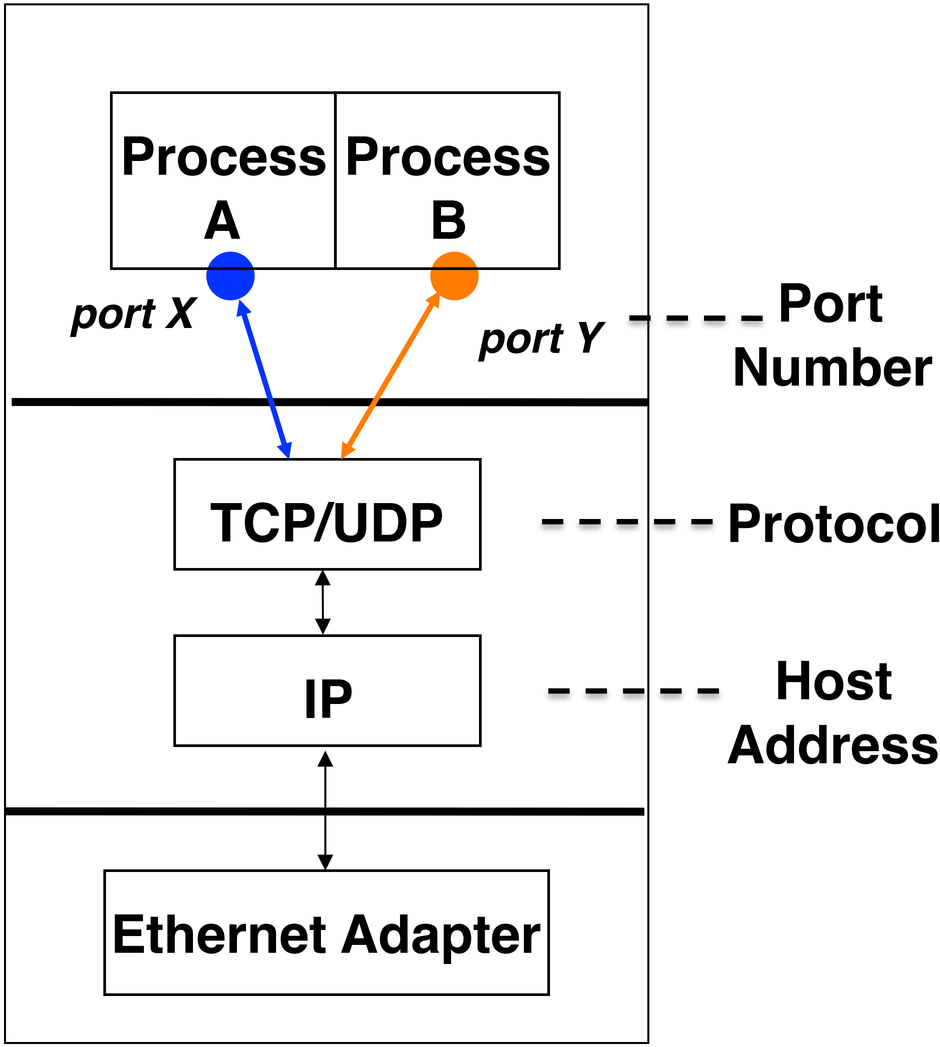
Transmission Control Protocol (TCP): Stream Socket

TCP	Telephone Call
Reliable – guarantee delivery	Guaranteed delivery
Byte stream – in-order delivery	In-order delivery
Connection-oriented – single socket per connection	Connection-oriented
Setup connection followed by data transfer	Setup connection followed by conversation

Example TCP applications
Web, Email, Telnet

Socket Identification

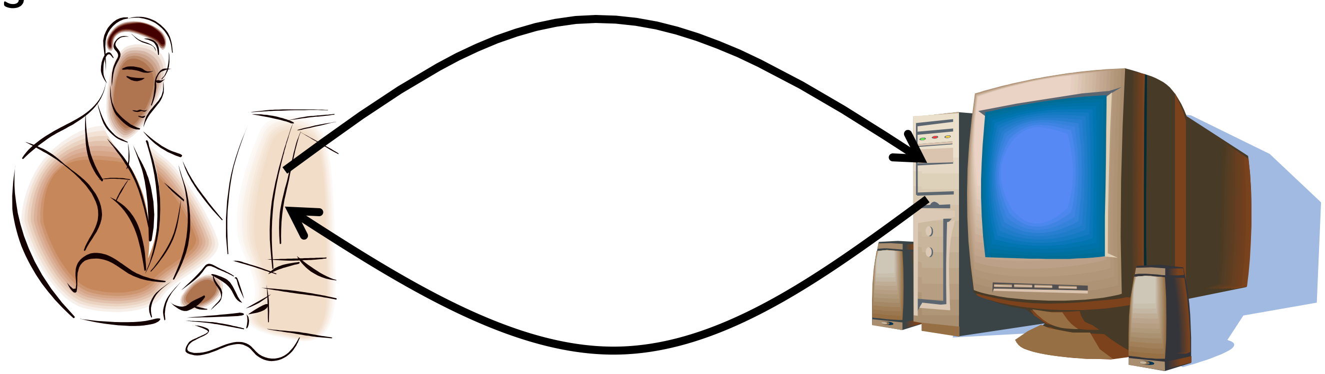
- Receiving host
  - Destination **address** that uniquely identifies host
  - **IP address**: 32-bit quantity
- Receiving socket
  - Host may be running many different processes
  - Destination **port** that uniquely identifies socket
  - **Port number:** 16-bits



Client-Server Communication

- Client "sometimes on"
  - Initiates a request to the server when interested
  - E.g., Web browser on your laptop or cell phone
  - Doesn't communicate directly with other clients
  - Needs to know server's address

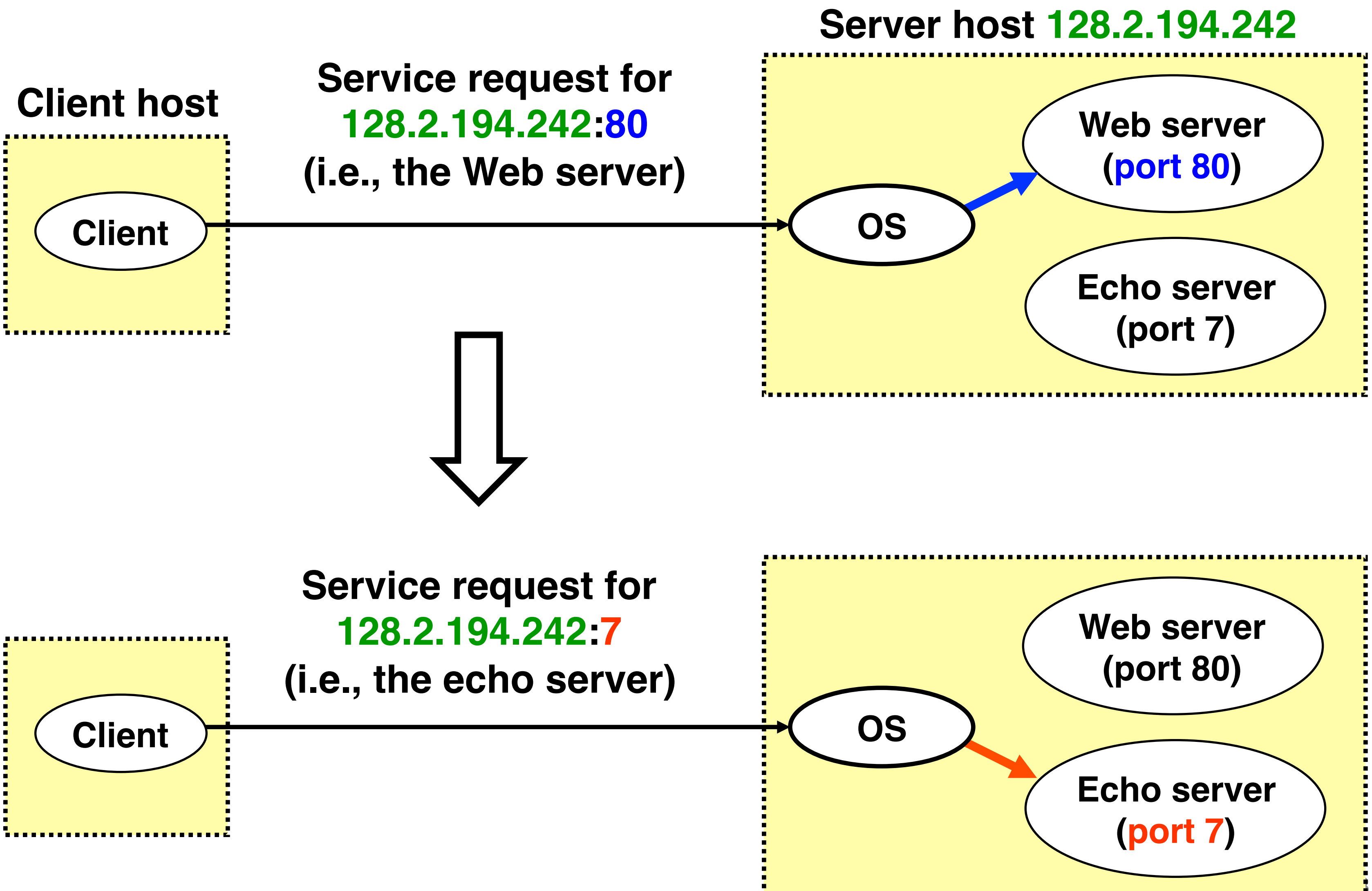
- Server is "always on"
  - Handles services requests from many client hosts
  - E.g., Web server for the www.cnn.com Web site
  - Doesn't initiate contact with the clients
  - Needs fixed, known address



Knowing What Port Number To Use

- Popular applications have well-known ports
  - E.g., port 80 for Web and port 25 for e-mail
  - See http://www.iana.org/assignments/port-numbers
- Well-known vs. ephemeral ports
  - Server has a well-known port (e.g., port 80)
    - Between 0 and 1023 (requires root to use)
  - Client picks an unused ephemeral (i.e., temporary) port
    - Between 1024 and 65535
- "5 tuple" uniquely identifies traffic between hosts
  - Two IP addresses and two port numbers
  - + underlying transport protocol (e.g., TCP or UDP)

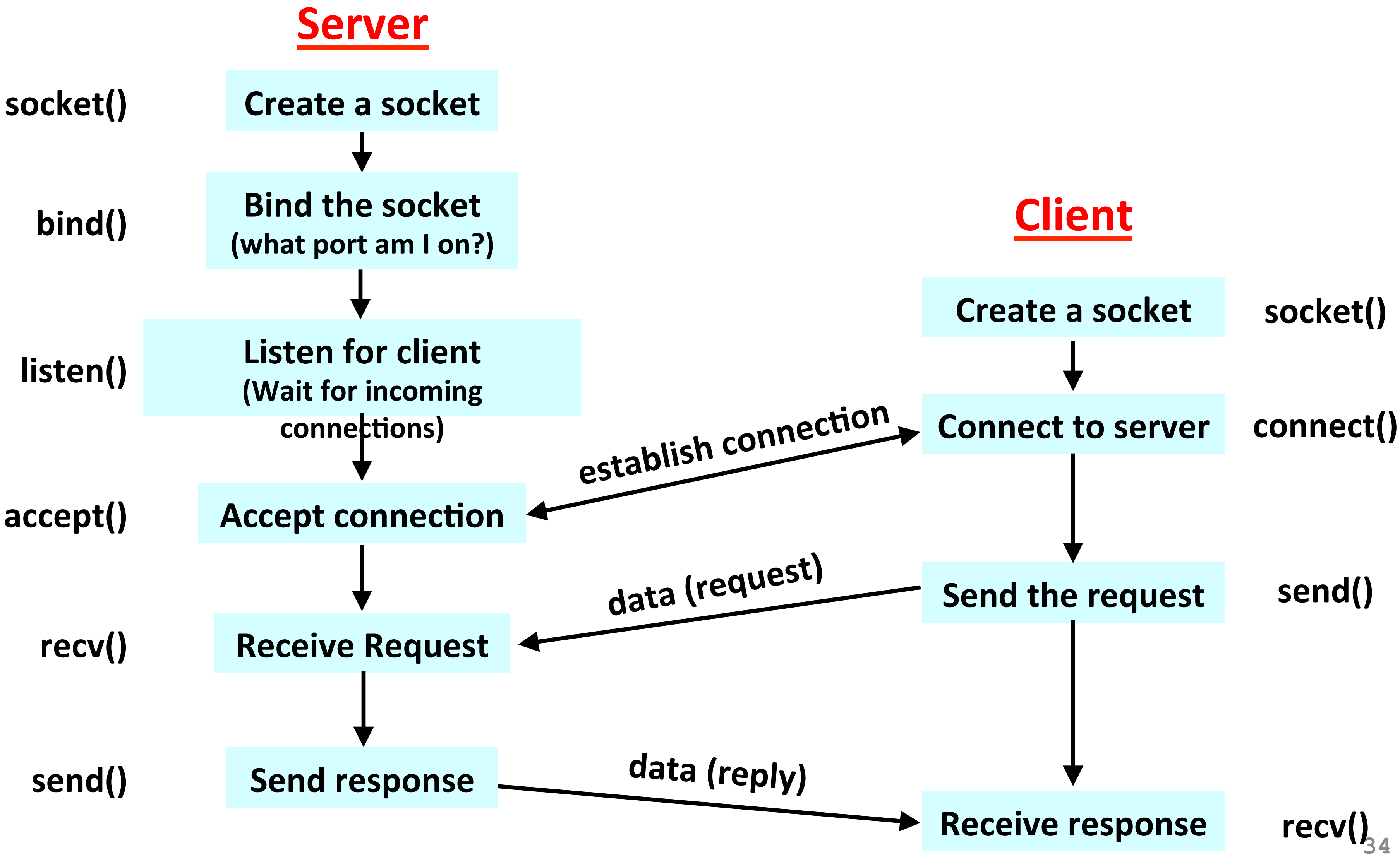
Using Ports to Identify Services



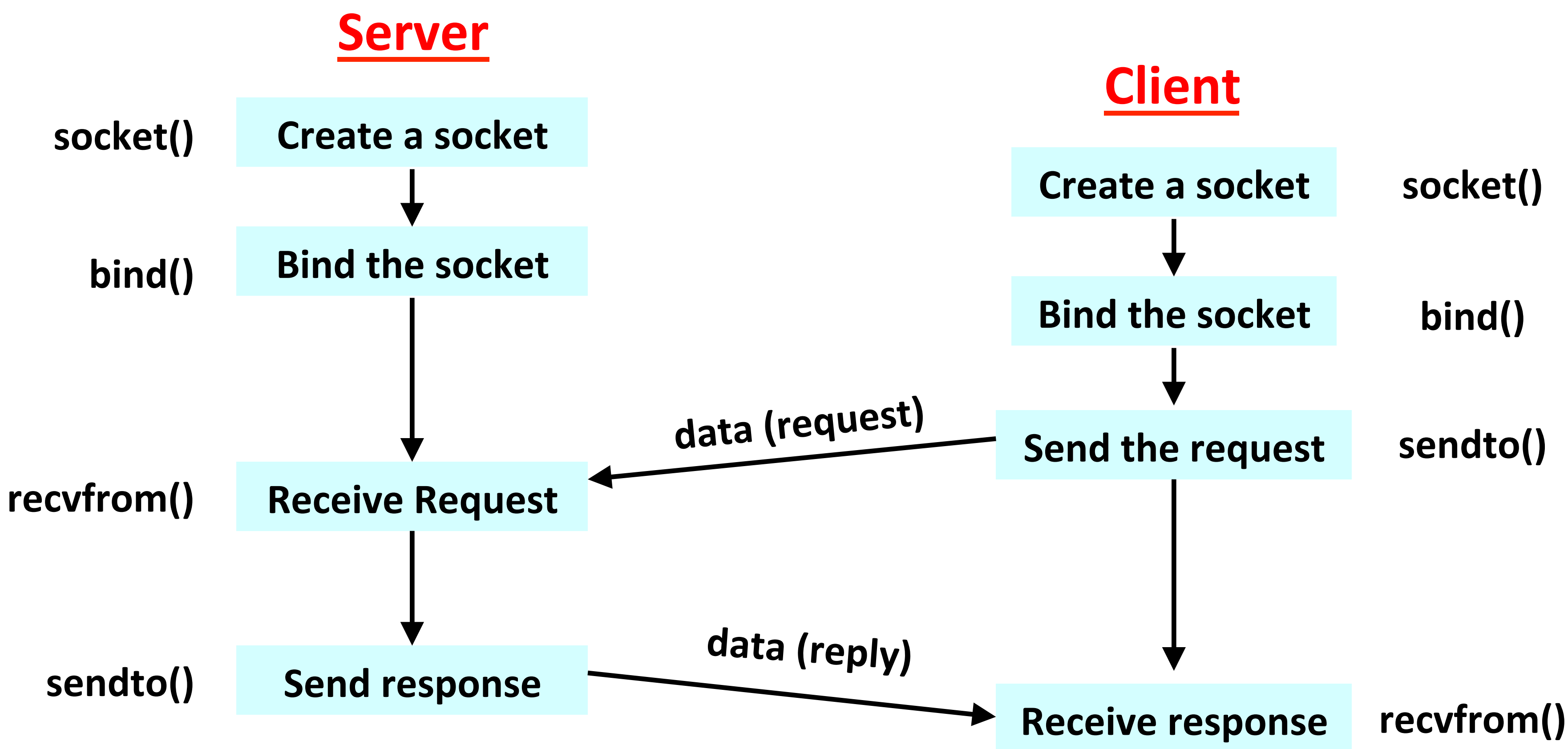
UNIX Socket API

- In UNIX, everything is like a file
  - All input is like reading a file
  - All output is like writing a file
  - File is represented by an integer file descriptor
- API implemented as system calls
  - E.g., connect, send, recv, close, …

Client-Server Communication
Stream Sockets (TCP): Connection-oriented



Client-Server Communication Datagram Sockets (UDP): Connectionless



Client: Learning Server Address/Port

- Server typically known by name and service
  - E.g., "www.cnn.com" and "http"
- Need to translate into IP address and port #
  - E.g., "64.236.16.20" and "80"

- Get address info with given host name and service
  - ```
    int getaddrinfo( char *node,
                     char *service,
                     struct addrinfo *hints,
                     struct addrinfo **result)
    ```

  - *node: host name (e.g., "www.cnn.com") or IP address
  - *service: port number or service listed in */etc/services* (e.g. ftp)
  - hints: points to a *struct addrinfo* with known information
    ```

Client: Learning Server Address/Port (cont.)

- Data structure to host address information

```
struct addrinfo {
    int                 ai_flags;
    int                 ai_family;    //e.g. AF_INET for IPv4
    int                 ai_socketype; //e.g. SOCK_STREAM for TCP
    int                 ai_protocol;  //e.g. IPPROTO_TCP
    size_t              ai_addrlen;
    char                *ai_canonname;
    struct sockaddr     *ai_addr; // point to sockaddr struct
    struct addrinfo     *ai_next;
}
```

- Example

```
hints.ai_family = AF_UNSPEC;     // don't care IPv4 or IPv6
hints.ai_socktype = SOCK_STREAM; // TCP stream sockets
int status = getaddrinfo("www.cnn.com", "80", &hints, &result);
// result now points to a linked list of 1 or more addrinfos
// etc.
```

Client: Creating a Socket

- Creating a socket
  - `int socket(int domain, int type, int protocol)`
  - Returns a file descriptor (or handle) for the socket
- Domain: protocol family
  - PF_INET for IPv4
  - PF_INET6 for IPv6
- Type: semantics of the communication
  - SOCK_STREAM: reliable byte stream (TCP)
  - SOCK_DGRAM: message-oriented service (UDP)
- Protocol: specific protocol
  - UNSPEC: unspecified
  - (PF_INET and SOCK_STREAM already implies TCP)
- Example

```
sockfd = socket(  result->ai_family,
                  result->ai_socktype,
                  result->ai_protocol);
```

Client: Connecting Socket to the Server

- Client contacts the server to establish connection
  - Associate the socket with the server address/port
  - Acquire a local port number (assigned by the OS)
  - Request connection to server, who hopefully accepts
  - connect is **blocking**
- Establishing the connection
  - **`int connect( int sockfd, struct sockaddr *server_address, socketlen_t addrlen )`**

```
int connect( int sockfd,
             struct sockaddr *server_address,
             socketlen_t addrlen  )
```

  - Args: socket descriptor, server address, and address size
  - Returns 0 on success, and -1 if an error occurs
  - E.g. `connect( sockfd, result->ai_addr, result->ai_addrlen);`

```
connect(  sockfd,
          result->ai_addr,
          result->ai_addrlen);
```

Client: Sending Data

- Sending data
  - `int send( int sockfd, void *msg,`
    `size_t len, int flags)`
  - Arguments: socket descriptor, pointer to buffer of data to send, and length of the buffer
  - Returns the number of bytes written, and -1 on error
  - send is **blocking**: return only after data is sent
  - Write short messages into a buffer and send once

Client: Receiving Data

- Receiving data
  - `int recv( int sockfd, void *buf, size_t len, int flags)`
  - Arguments: socket descriptor, pointer to buffer to place the data, size of the buffer
  - Returns the number of characters read (where 0 implies "end of file"), and -1 on error
  - Why do you need len? What happens if buf's size < len?
  - recv is **blocking**: return only after data is received

Byte Order

- Network byte order
  - Big Endian
- Host byte order
  - Big Endian (IBM mainframes, Sun SPARC) *or* Little Endian (x86)
- Functions to deal with this
  - htons() & htonl() (host to network short and long)
  - ntohs() & ntohl() (network to host short and long)
- When to worry?
  - putting data onto the wire
  - pulling data off the wire

Server: Server Preparing its Socket

- Server creates a socket and binds address/port
  - Server creates a socket, just like the client does
  - Server associates the socket with the port number

- Create a socket
  - ```
    int socket( int domain,
                int type, int protocol  )
    ```

- Bind socket to the local address and port number
  - ```
    int bind( int sockfd,
              struct sockaddr *my_addr,
              socklen_t addrlen )
    ```

Server: Allowing Clients to Wait

- Many client requests may arrive
  - Server cannot handle them all at the same time
  - Server could reject the requests, or let them wait
- Define how many connections can be pending
  - `int listen(int sockfd, int backlog)`
  - Arguments: socket descriptor and acceptable backlog
  - Returns a 0 on success, and -1 on error
  - Listen is **non-blocking**: returns immediately
- What if too many clients arrive?
  - Some requests don't get through
  - The Internet makes no promises…
  - And the client can always try again

Server: Accepting Client Connection

- Now all the server can do is wait…
  - Waits for connection request to arrive
  - **<u>Blocking</u>** until the request arrives
  - And then accepting the new request

- Accept a new connection from a client
  - ```
    int accept( int sockfd,
                struct sockaddr *addr,
                socketlen_t *addrlen)
    ```
  - Arguments: sockfd, structure that will provide client address and port, and length of the structure
  - Returns descriptor of socket for this new connection
    ```

Client and Server: Cleaning House

- Once the connection is open
  - Both sides and read and write
  - Two unidirectional streams of data
  - In practice, client writes first, and server reads
  - … then server writes, and client reads, and so on
- Closing down the connection
  - Either side can close the connection
  - … using the `int close(int sockfd)`
- What about the data still "in flight"
  - Data in flight still reaches the other end
  - So, server can `close()` before client finishes reading

Server: One Request at a Time?

- Serializing requests is inefficient
  - Server can process just one request at a time
  - All other clients must wait until previous one is done
  - What makes this inefficient?
- May need to time share the server machine
  - Alternate between servicing different requests
    - Do a little work on one request, then switch when you are waiting for some other resource (e.g., reading file from disk)
    - "Nonblocking I/O"
  - Or, use a different process/thread for each request
    - Allow OS to share the CPU(s) across processes
  - Or, some hybrid of these two approaches

Handle Multiple Clients using fork()

- Steps to handle multiple clients
  - Go to a loop and accept connections using accept()
  - After a connection is established, call fork() to create a new child process to handle it
  - Go back to listen for another socket in the parent process
  - close() when you are done.

- Want to know more?
  - Checkout out *Beej's guide to network programming*

```
while (1) {
  fd = accept (srv_fd, (struct sockaddr *) &caddr, &clen);
  ...
  pid = fork(); children++;
  /* child process to handle request */
  if (pid == 0) {
     /* exit(0) on success, exit(1) on error */
  }
  /* parent process */
  else if (pid > 0) {
     while ((waitpid(-1, &status, WNOHANG)) > 0)
        children--;
     if (children > MAX_PROCESSES)
        ...
  }
  else {
    perror("ERROR on fork");
    exit(1);
}}
```