Distributed Systems

02. Networking

Paul Krzyzanowski

Rutgers University

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Inter-computer communication

- Without shared memory, computers need to communicate

Direct links aren't practical – they don't scale

Connecting computers

Communication network

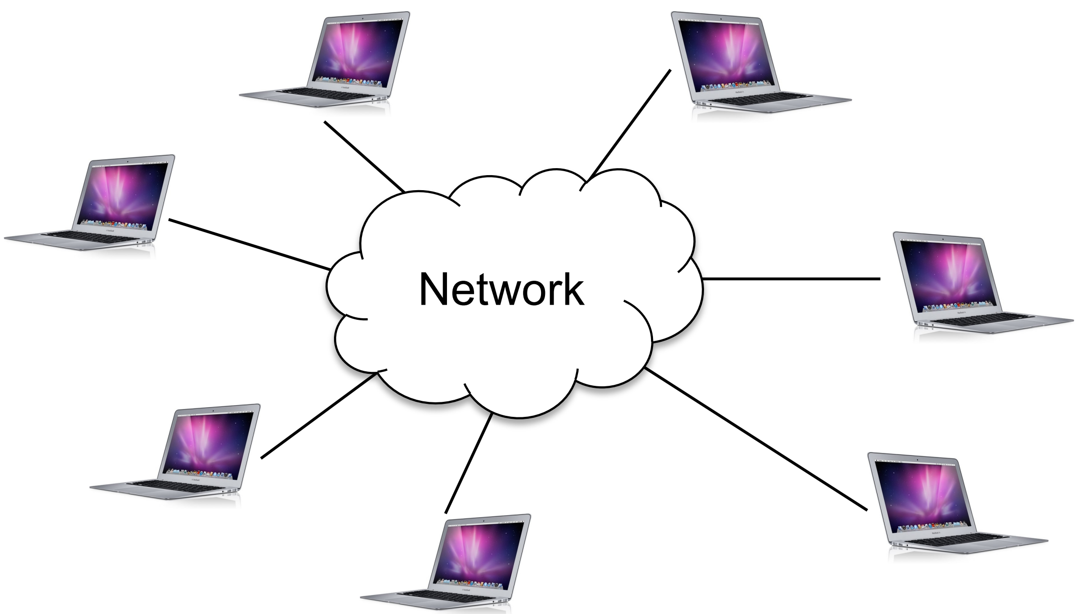
– Share the infrastructure

– Collision: when two nodes transmit at the same time, same channel

- Both signals get damaged

– Multiple access problem

- *How do you coordinate multiple senders?*



Modes of connection

Circuit-switching (virtual circuit)

- Dedicated path (route) – established at setup
- Guaranteed (fixed) bandwidth – routers commit to resources
- Typically fixed-length packets (cells) – each cell only needs a virtual circuit ID
- Constant latency

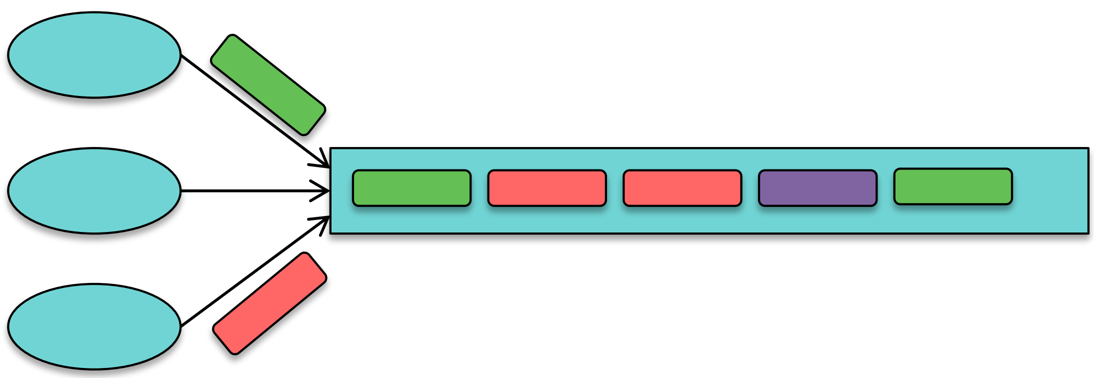
This is what IP uses

Packet-switching (datagram)

- Shared connection; competition for use with others
- Data is broken into chunks called packets
- Each packet contains a destination address
- available bandwidth $\leq$ channel capacity
- Variable latency

Packet switching

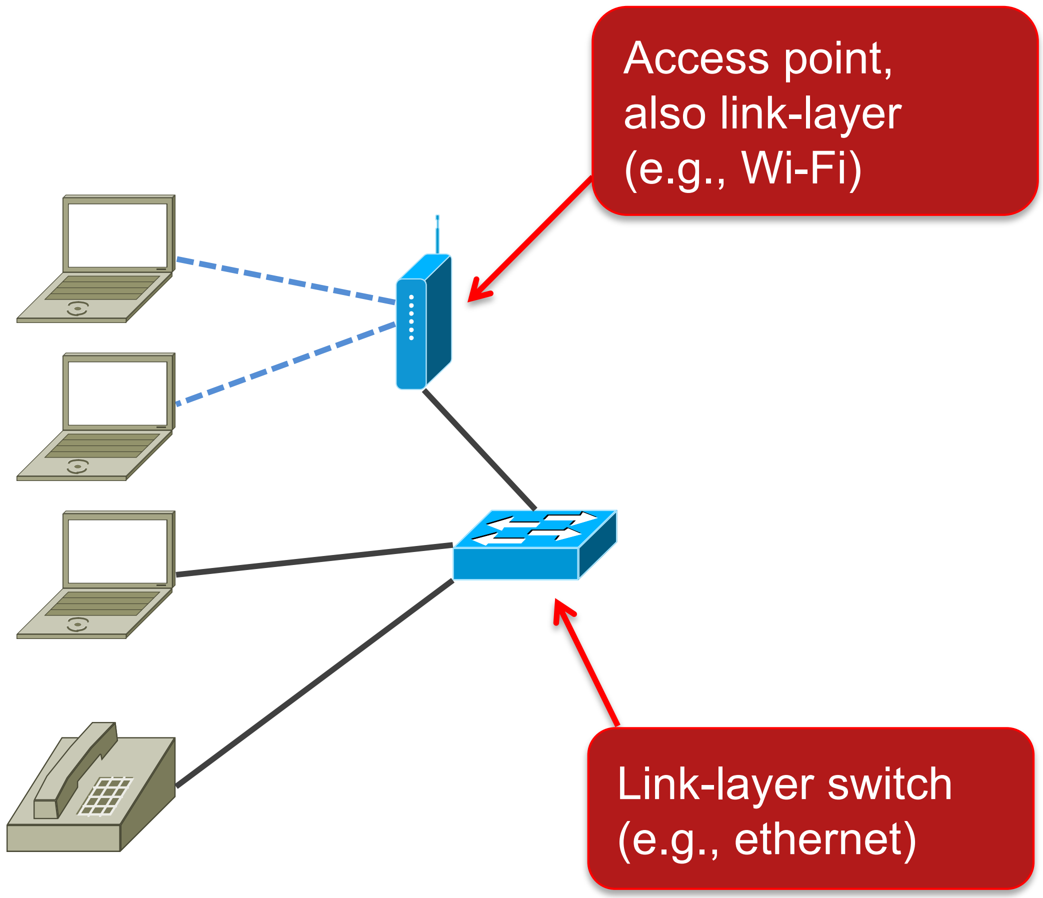
- Random access
  - Statistical multiplexing
  - No timeslots
  - Anyone can transmit when ready
  - But be prepared for collisions or dropped packets



Ethernet

- Packet-based protocol
- Originally designed for shared (bus-based) links
- Each endpoint has a unique ethernet address
  – MAC address: 48-bit number

Local Area Network: **Data Link Layer**



Hub:
- Device that acts as a central point for LAN cables
- Take incoming data from one port & send to all other ports

Switch
- Moves data from input to output port
- Analyzes packet to determine destination port and makes a virtual connection between the ports
- Scales better than a hub

Link-layer switches: create a physical network (e.g., Ethernet, Wi-Fi)

Ethernet service guarantees

- Each packet (frame) contains a CRC checksum
  – Recipient will drop the frame if it is bad

- No acknowledgement of packet delivery

- Unreliable, in-order delivery
  – Packet loss possible

Going beyond the LAN

- We want to communicate beyond the LAN
  - WAN = Wide Area Network
- **Network Layer**
  - Responsible for routing between LANs
- The Internet
  - Evolved from ARPANET (1969)
  - Internet = global network of networks based on the Internet Protocol (IP) family of protocols

Internet Protocol

- A set of protocols designed to handle the interconnection of a large number of local and wide-area networks that comprise the Internet

- IPv4 & IPv6: network layer
  - Other IP-based protocols include TCP, UDP, RSVP, ICMP, etc.
  - Relies on routing from one physical network to another
  - IP is connectionless
    - No state needs to be saved at each router
  - Survivable design: support multiple paths for data
    - … but packet delivery is not guaranteed!

The Internet: Key Design Principles

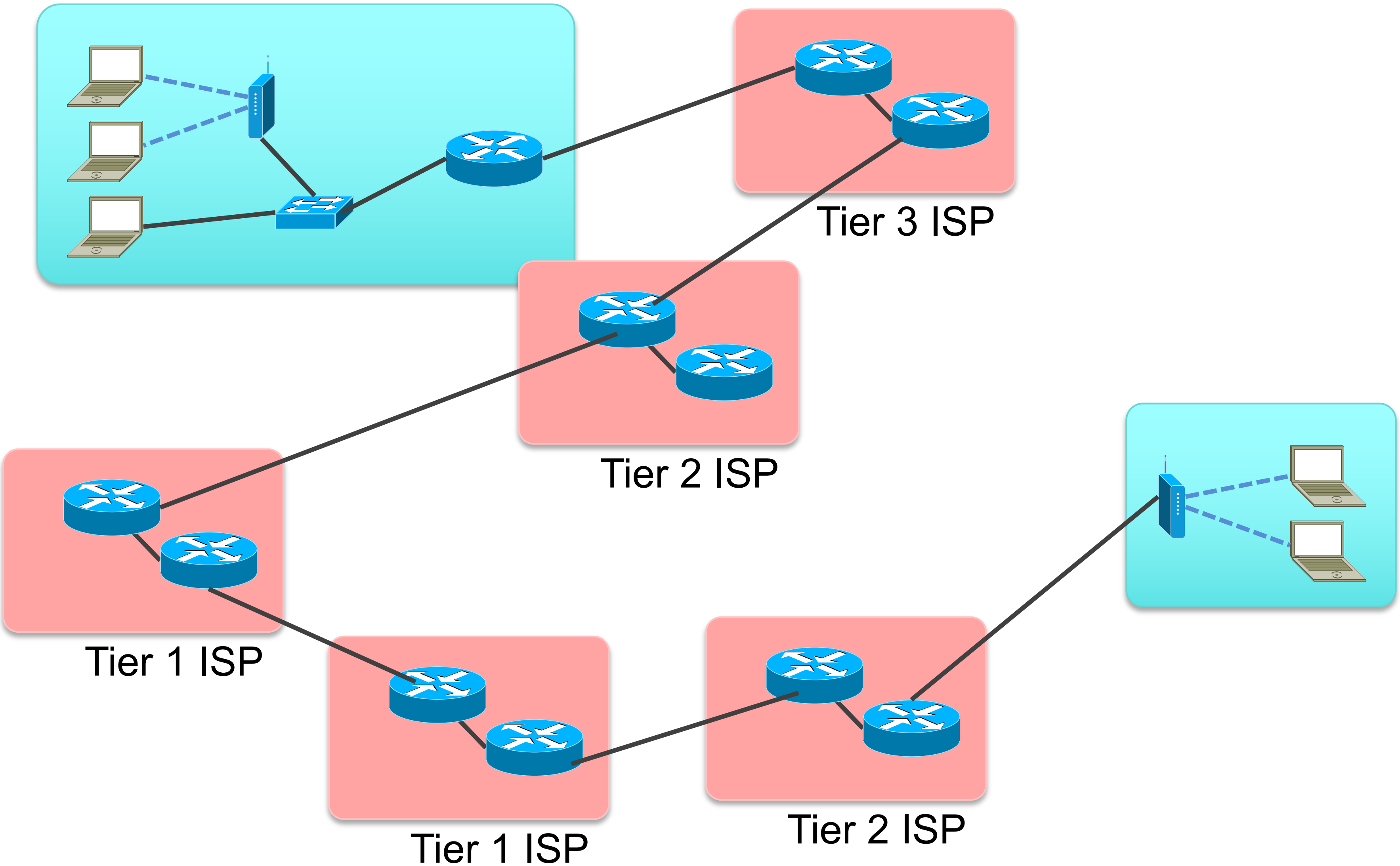
1. Support interconnection of networks
   – No changes needed to the underlying physical network
   – IP is a *logical network*

2. Assume unreliable communication
   – If a packet does not get to the destination, software on the receiver will have to detect it and the sender will have to retransmit it

3. Routers connect networks
   – Store & forward delivery

4. No global (centralized) control of the network

Routers tie LANs together into one Internet



A packet may pass through many networks – within and between ISPs

IP addressing

- Each network endpoint has a unique IP address
  - No relation to an ethernet address
  - IPv4: 32-bit address
  - IPv6: 128-bit address
- Data is broken into packets
  - Each packet contains source & destination IP addresses
- IP gives us machine-to-machine communication

Transport Layer: UDP & TCP

Transport Layer

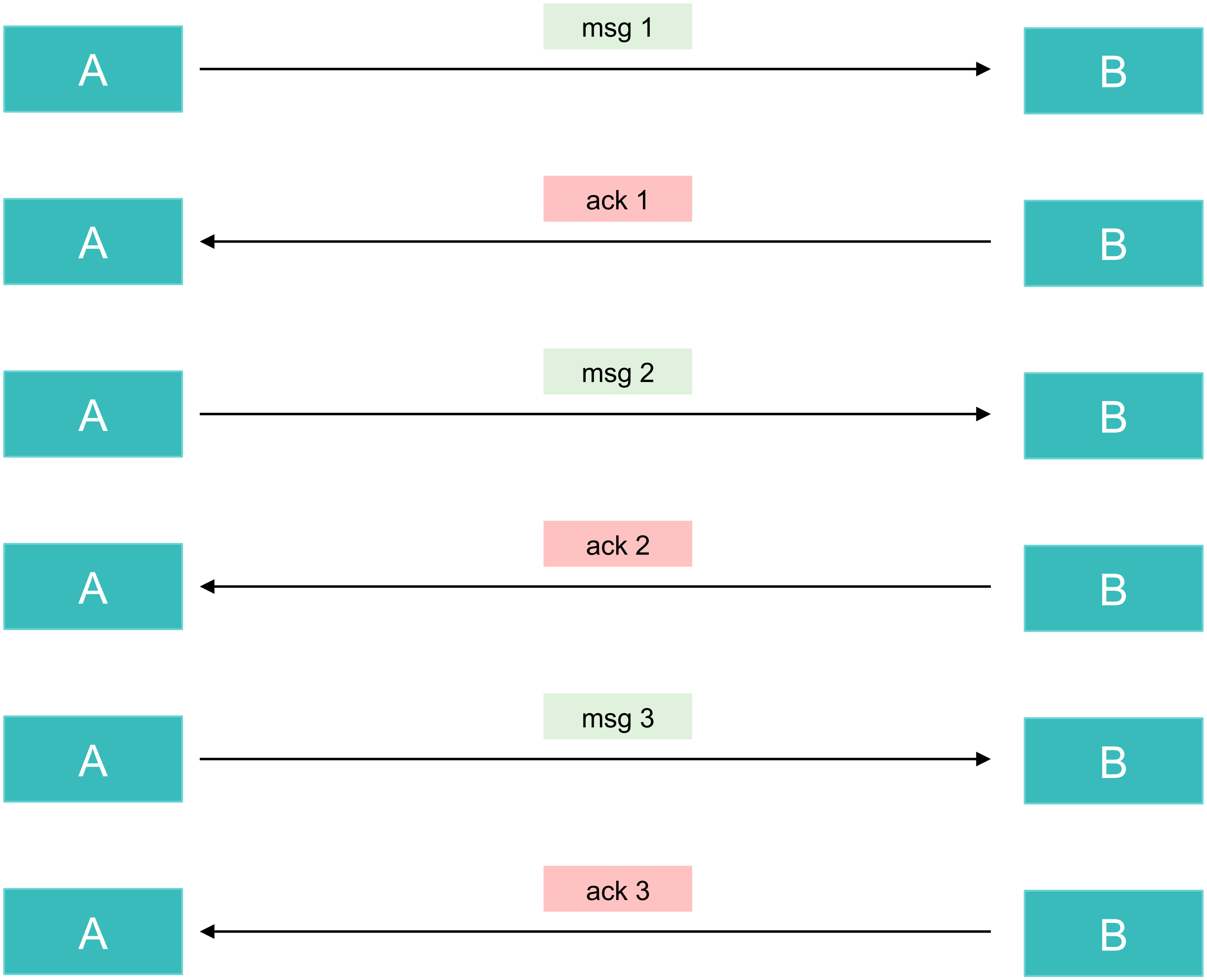
- We want to communicate between applications
- The transport layer gives us logical "channels" for communication
  - Processes can write to and receive from these channels
- Two transport layer protocols in IP are TCP & UDP
  - A port number identifies a unique channel on each computer

IP transport layer protocols

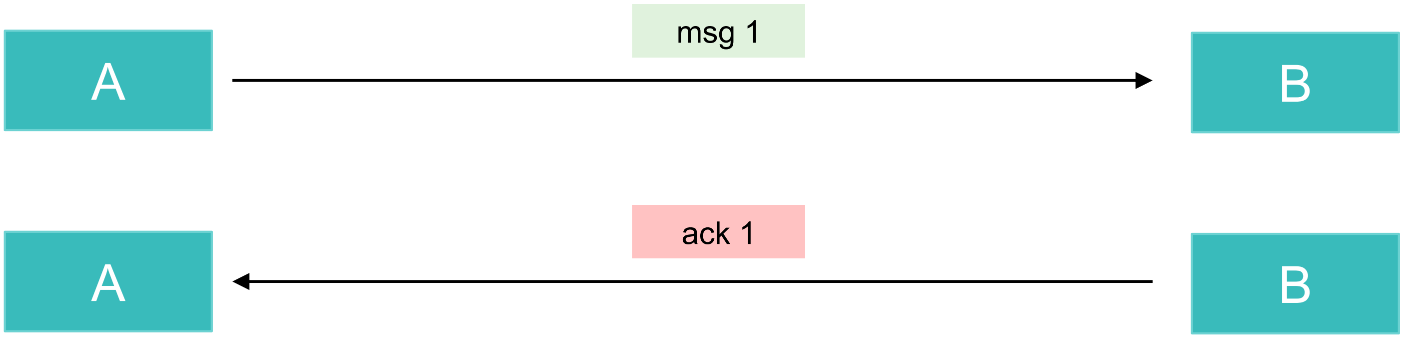
IP gives us two transport-layer protocols for communication

- **TCP: Transmission Control Protocol**
  - Connection-oriented service – operating system keeps state
  - Full-duplex connection: both sides can send messages over the same link
  - Reliable data transfer: the protocol handles retransmission
  - In-order data transfer: the protocol keeps track of sequence numbers
  - Flow control: receiver stops sender from sending too much data
  - Congestion control: “plays nice” on the network – reduce transmission rate
  - 20-byte header
- **UDP: User Datagram Protocol**
  - Connectionless service: lightweight transport layer over IP
  - Data may be lost
  - Data may arrive out of sequence
  - Checksum for corrupt data: operating system drops bad packets
  - 8-byte header

Reliable delivery

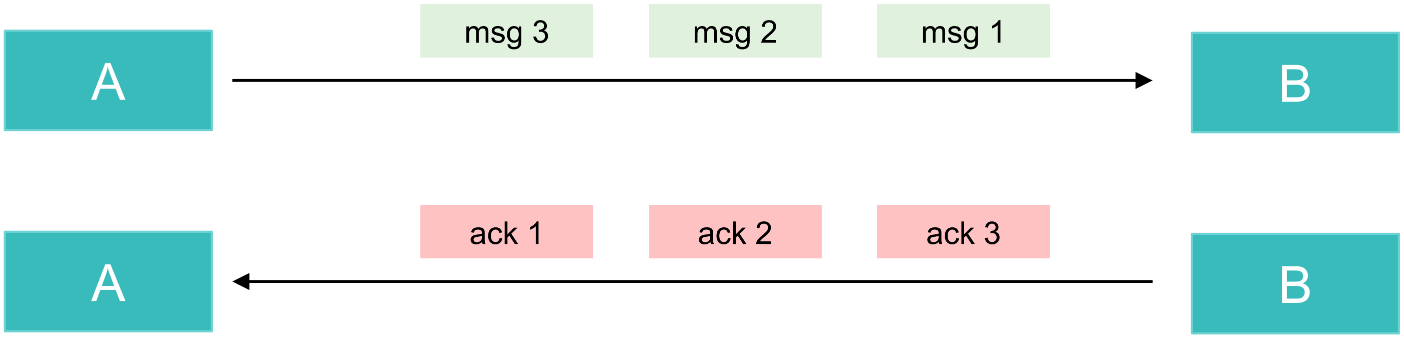


Reliable delivery



- This slows us down A LOT!
  - Cannot send a message until the previous one reaches the destination AND the acknowledgement comes back

Transmit up to *N* messages



- Pipelining
  - Send a bunch of packets without waiting for an ack from each one
- Piggybacked acknowledgements
  - Don't waste a separate acknowledgement message
  - If we have data to send back, send the ack in that packet
- Cumulative acknowledgements
  - If we have no data, don't send lots of individual acks
  - Cumulative ack = "the next byte I need" – byte count of all bytes received so far
- TCP uses all of these

Layering

Most popular model of guiding (not specifying) protocol layers is

OSI reference model

Adopted and created by ISO

7 layers of protocols

OSI = Open Systems Interconnection
From the ISO = International Organization for Standardization

OSI Reference Model: Layer 1

Transmits and receives raw data to communication medium

Does not care about contents

Media, voltage levels, speed, connectors

Deals with representing bits

1 **Physical**

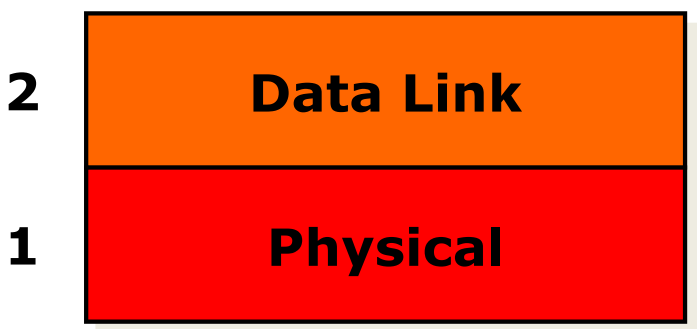
Examples: USB, Bluetooth, 1000BaseT, Wi-Fi

OSI Reference Model: Layer 2

Detects and corrects errors

Organizes data into frames before passing it down. Sequences packets (if necessary)

Accepts acknowledgements from immediate receiver



Examples: Ethernet MAC, PPP

OSI Reference Model: Layer 2

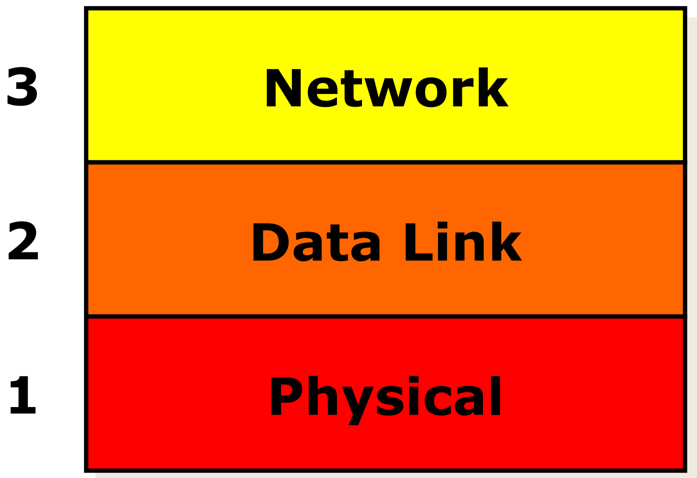
An ethernet switch is an example of a device that works on layer 2

It forwards ethernet frames from one host to another as long as the hosts are connected to the switch (switches may be cascaded)

This set of hosts and switches defines the local area network (LAN)

2	**Data Link**
1	**Physical**

OSI Reference Model: Layer 3

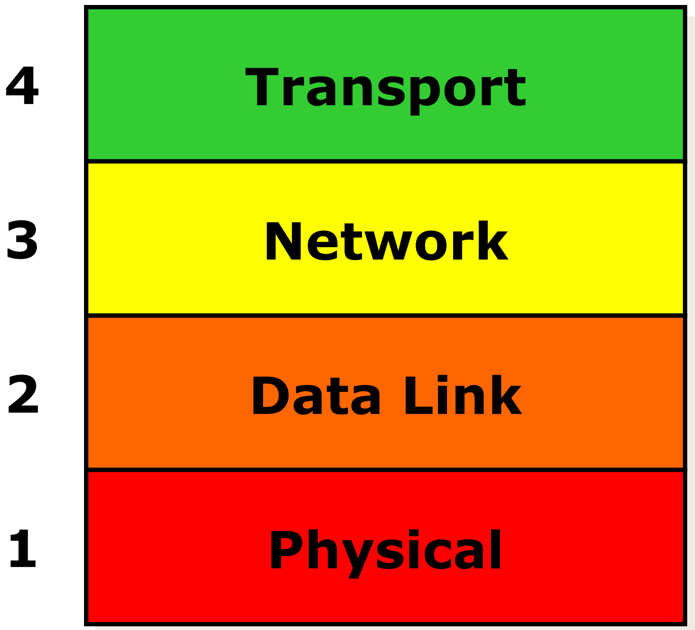


Relay and route information to destination

Manage journey of datagrams and figure out intermediate hops (if needed)

Examples: IP, X.25

OSI Reference Model: Layer 4

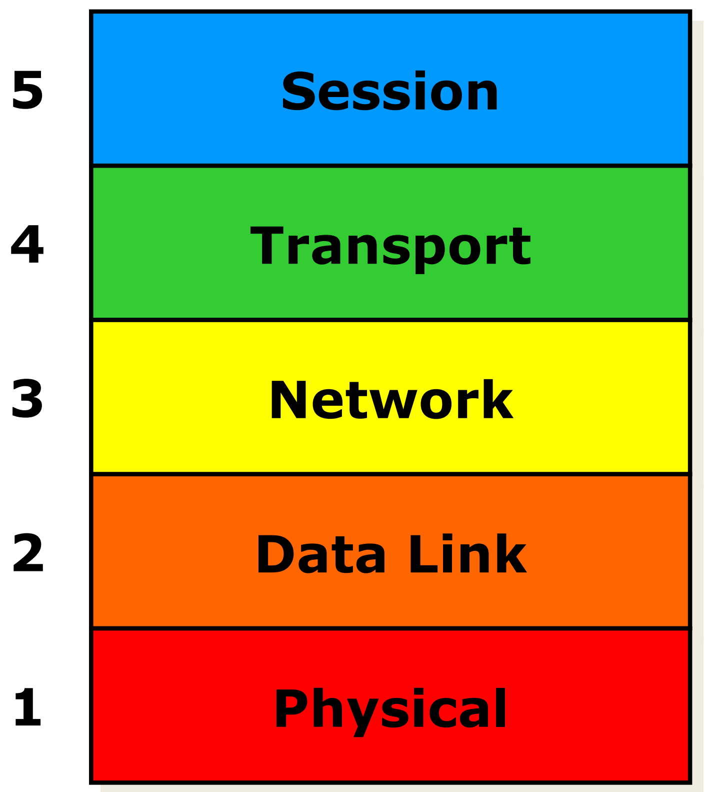


Provides an interface for end-to-end (application-to-application) communication: sends & receives segments of data. Manages flow control. May include end-to-end reliability

Network interface is similar to a mailbox

Examples: TCP, UDP

OSI Reference Model: Layer 5



Services to coordinate dialogue and manage data exchange

Software implemented switch

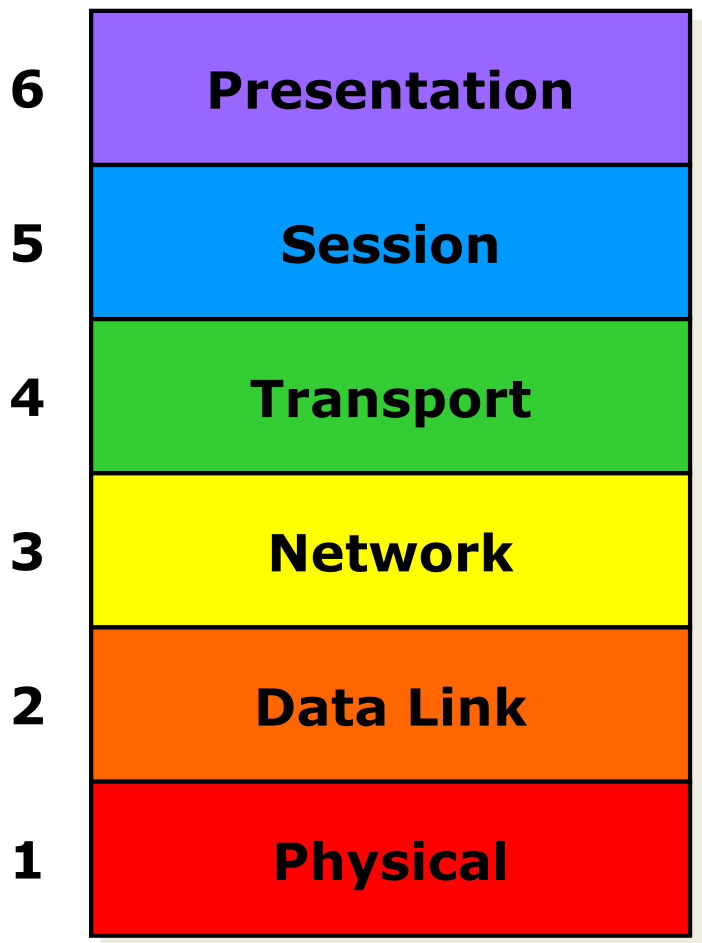
Manage multiple logical connections

Keep track of who is talking: establish & end communications

Deals with data streams

Examples: HTTP 1.1, SSL

OSI Reference Model: Layer 6



Data representation

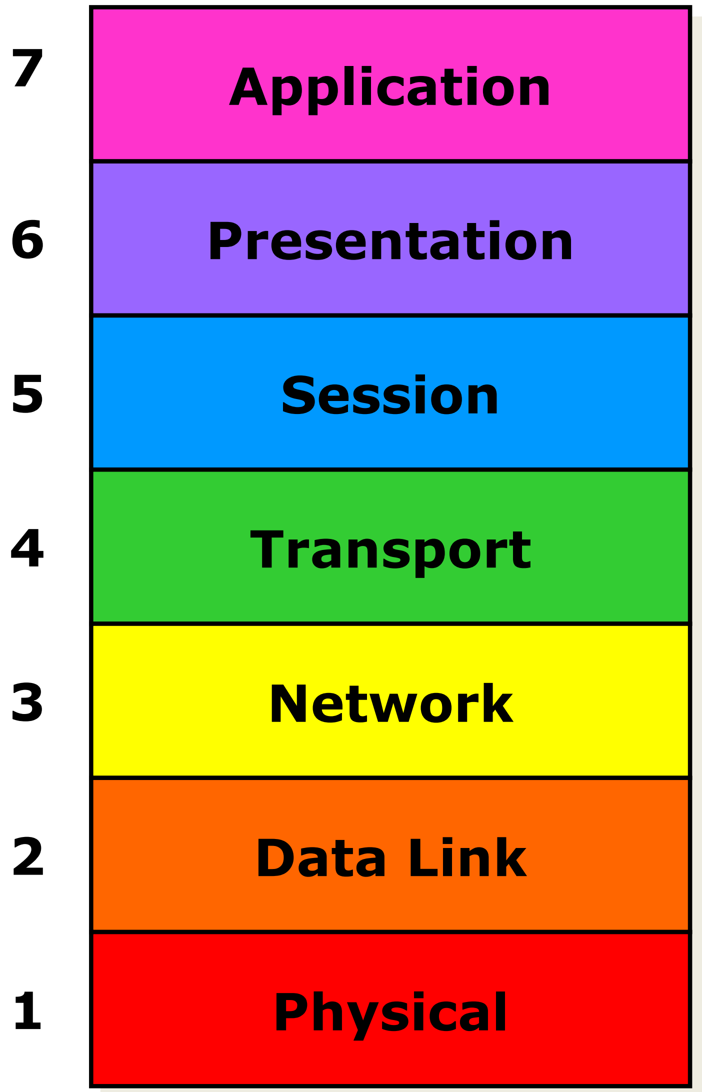
Concerned with the meaning of data bits

Convert between machine representations

Deals with objects

Examples: XDR, ASN.1, MIME, JSON, XML

OSI Reference Model: Layer 7



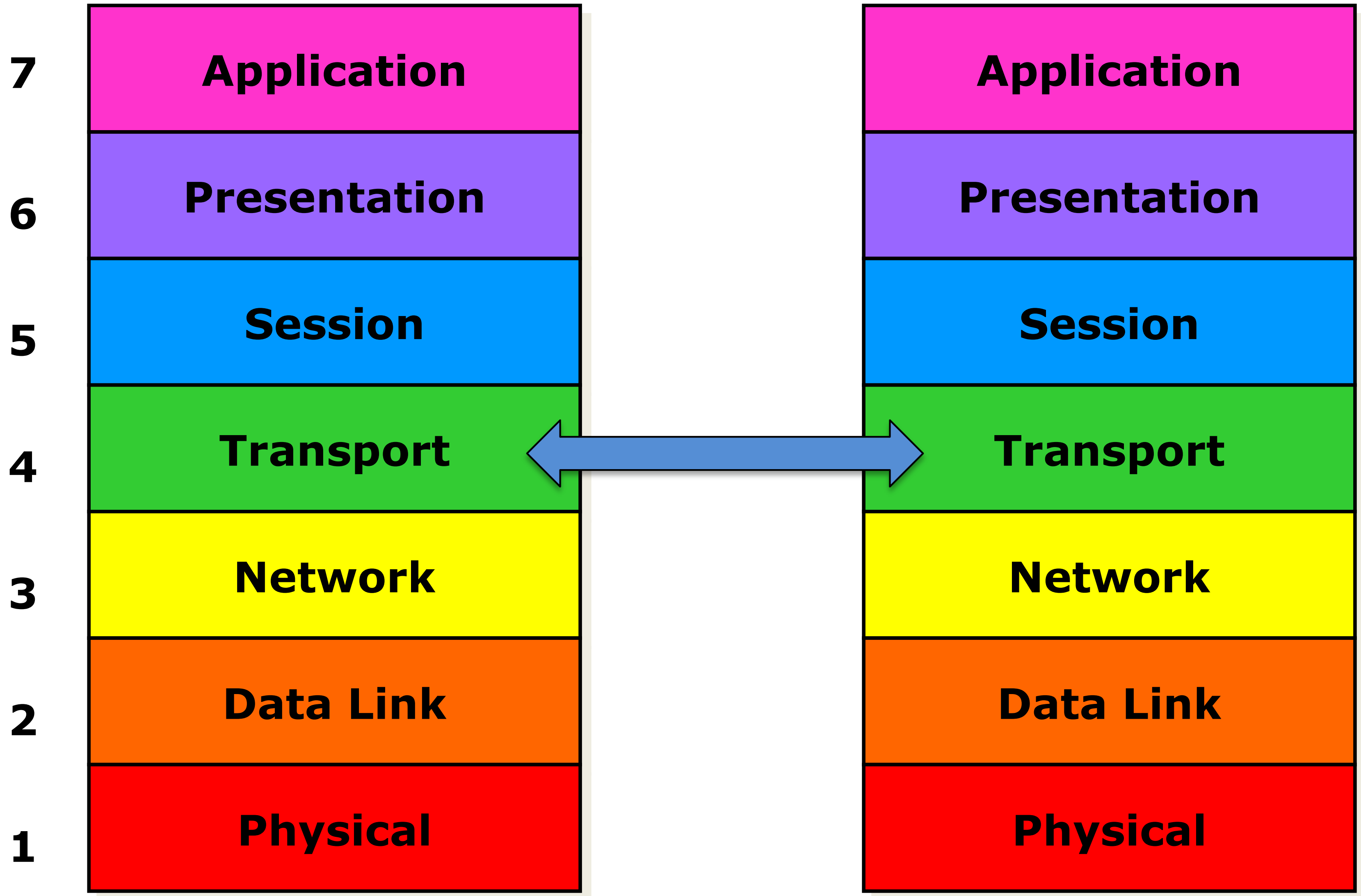
Collection of application-specific protocols

Deals with app-specific protocols

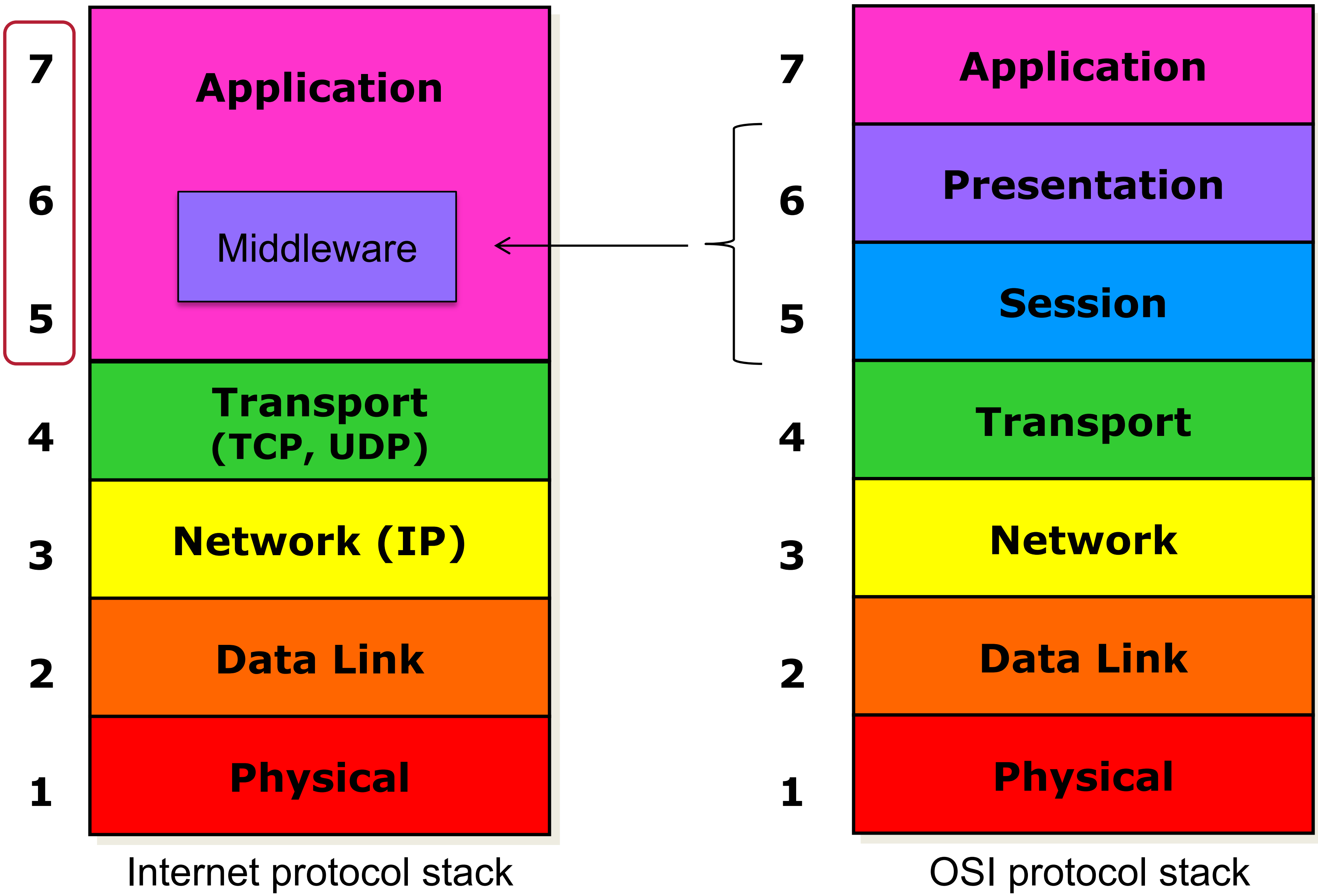
Examples:
- web (HTTP)
- email (SMTP, POP, IMAP)
- file transfer (FTP)
- directory services (LDAP)

A layer communicates with its counterpart

Logical View



IP vs. OSI stack



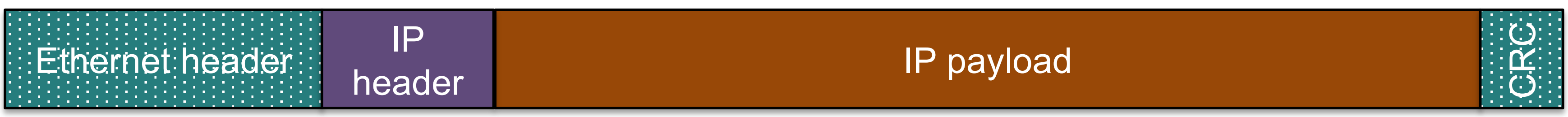
Protocol Encapsulation

At any layer

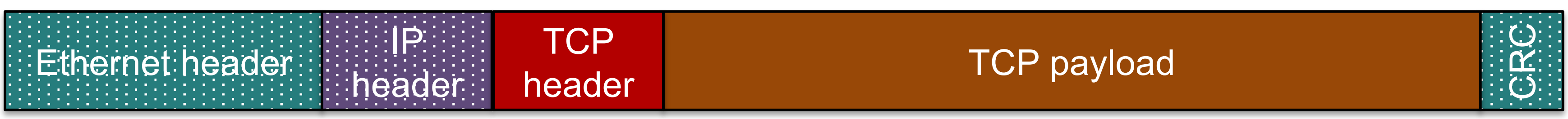
- The higher level protocol headers are just treated like data
- Lower level protocol headers can be ignored

An ethernet switch or ethernet driver sees this:

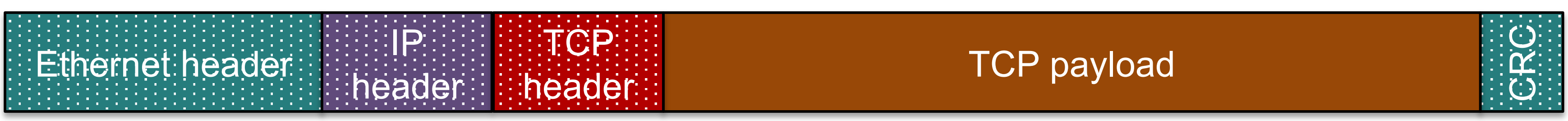
A router or IP driver sees this:



A TCP driver sees this:



An application sees this:



Programming for networking

Network API

- App developers need access to the network
- A *Network Application Programming Interface (API)* provides this
  - Core services provided by the operating system
    - Operating System controls access to resources
  - Libraries may handle the rest

Programming: connection-oriented protocols

	analogous to phone call
1. establish connection	*dial phone number*
2. [negotiate protocol]	*[decide on a language]*
3. exchange data	*speak*
4. terminate connection	*hang up*

Reliable byte stream service (TCP)

– provides illusion of having a dedicated circuit
– messages guaranteed to arrive in-order
– application does not have to address each message

Programming: connectionless protocols

- no call setup
- send/receive data
  (each packet addressed)
- no termination

analogous to mailbox

drop letter in mailbox
(each letter addressed)

Datagram service (UDP)

– client is not positive whether message arrived at destination
– no state has to be maintained at client or server

Sockets

- Dominant API for transport layer connectivity
- Created at UC Berkeley for 4.2BSD Unix (1983)
- Design goals
  - Communication between processes should not depend on whether they are on the same machine
  - Communication should be efficient
  - Interface should be compatible with files
  - Support different protocols and naming conventions
    - *Sockets is not just for the Internet Protocol family*

What is a socket?

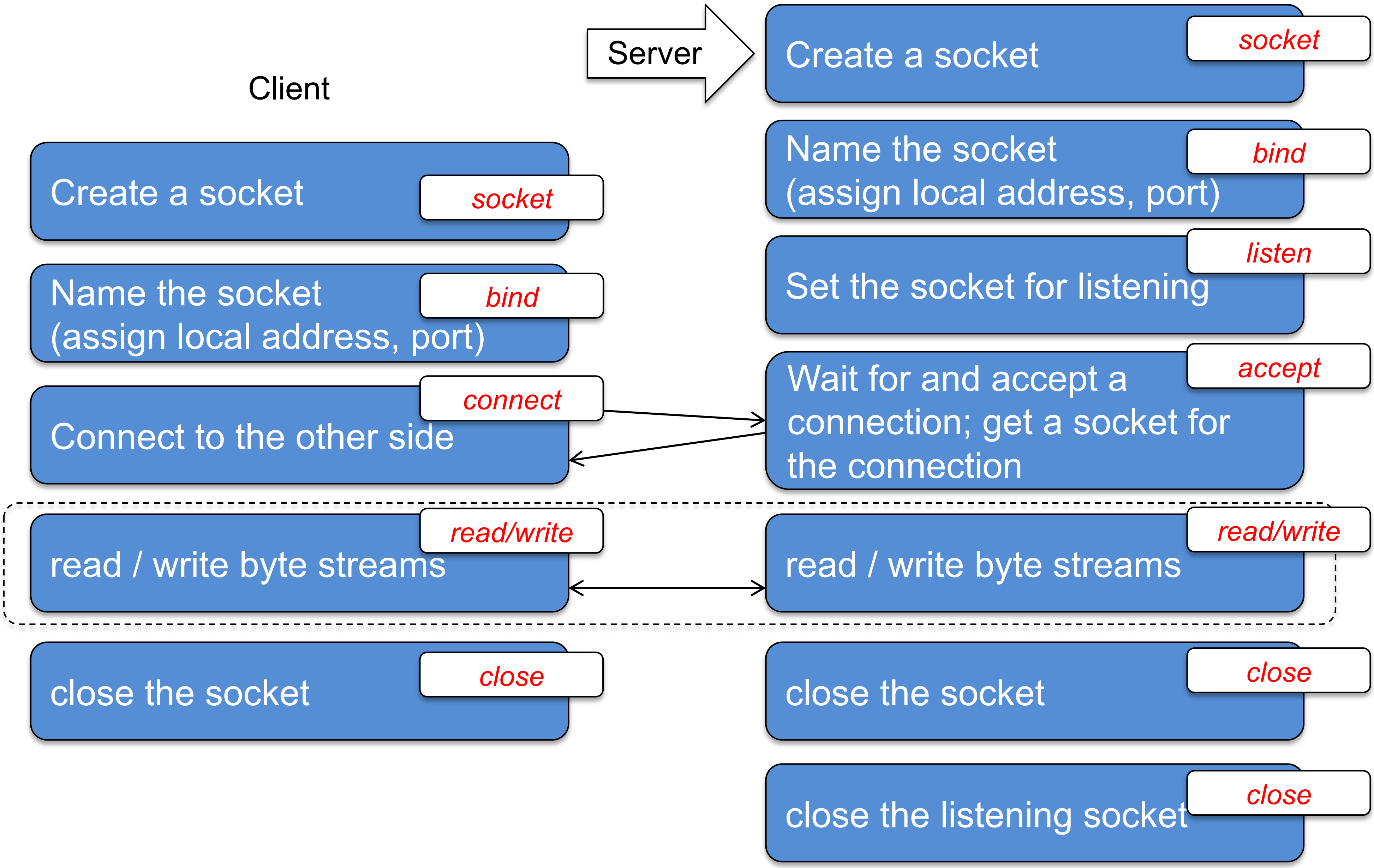
Abstract object from which messages are sent and received

- Looks like a file descriptor

- Application can select particular style of communication
  - Virtual circuit (connection-oriented), datagram (connectionless), message-based, in-order delivery

- Unrelated processes should be able to locate communication endpoints
  - Sockets can have a name
  - Name should be meaningful in the communications domain
    - E.g., Address & port for IP communications

Connection-Oriented (TCP) socket operations



Java provides shortcuts that combine calls

Example

Java

```
Socket s = new Socket("www.rutgers.edu", 2211)
```

C

```
int s = socket(AF_INET, SOCK_STREAM, 0);
```

```
struct sockaddr_in myaddr; /* initialize address structure */
myaddr.sin_family = AF_INET;
myaddr.sin_addr.s_addr = htonl(INADDR_ANY);
myaddr.sin_port = htons(0);

bind(s, (struct sockaddr *)&myaddr, sizeof(myaddr));
```

```
/* look up the server's address */
struct hostent *hp;       /* host information */
struct sockaddr_in servaddr;    /* server address */

memset((char*)&servaddr, 0, sizeof(servaddr));
servaddr.sin_family = AF_INET;
servaddr.sin_port = htons(2211);
hp = gethostbyname("www.rutgers.edu");
```

```
if (connect(fd, (struct sockaddr *)&servaddr, sizeof(servaddr)) < 0) {
        /* connect failed */
}
```

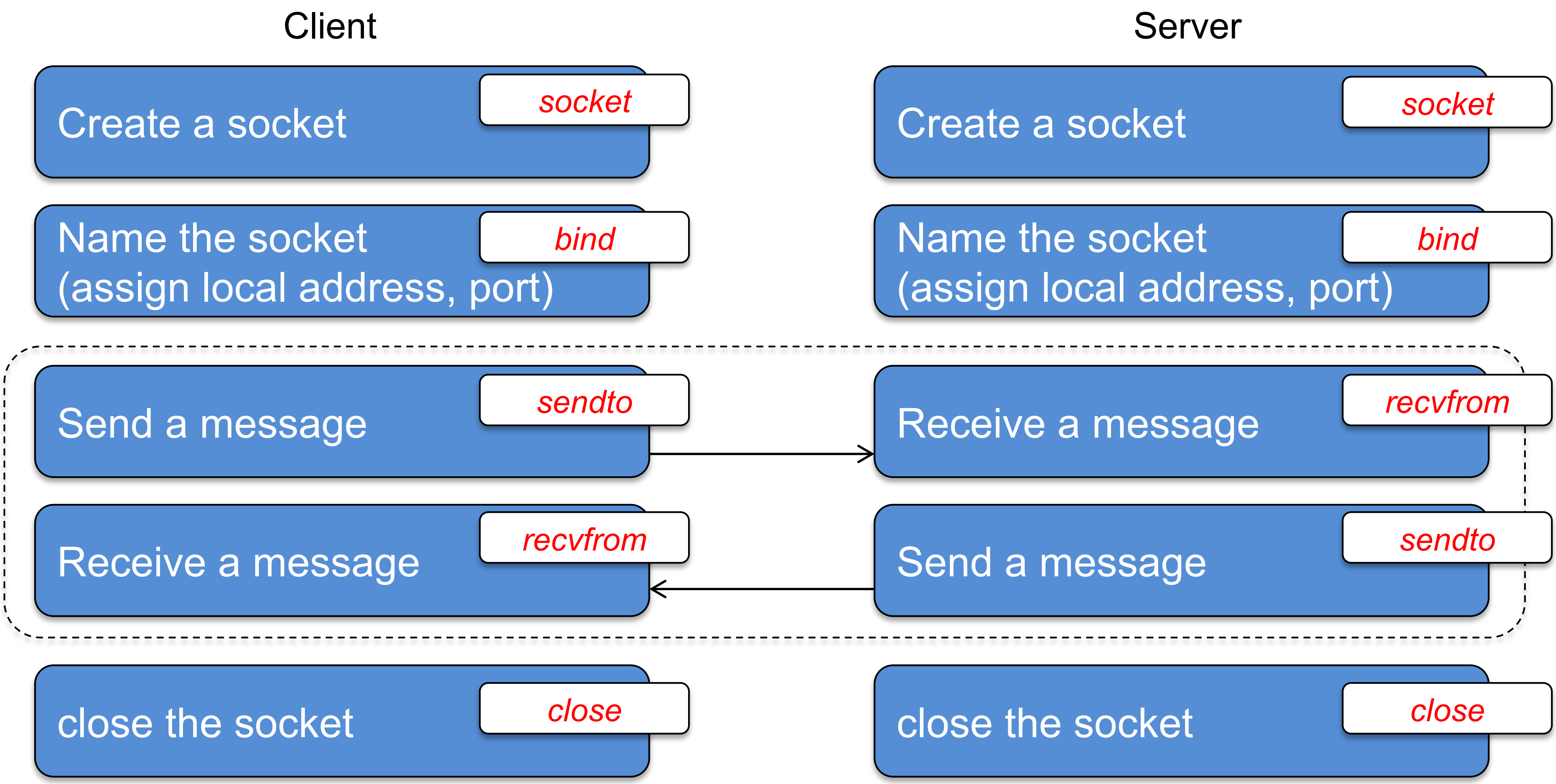
Python Example

Note: try/except blocks are missing

```
import socket

s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
remote_addr = socket.gethostbyname(host)
s.connect(remote_addr, port)
s.sendall(message)
# …
```

```
import socket

s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
s.bind((HOST, PORT))
s.listen(5)

while 1:
	conn, addr = s.accept()
	# do work on socket conn
	msg = conn.recv()
s.close
```

Connectionless (UDP) socket operations



The end