Operating Systems Design
15. Client-Server Networking

Paul Krzyzanowski
pxk@cs.rutgers.edu

Some networking terminology

Local Area Network (LAN)

Communications network

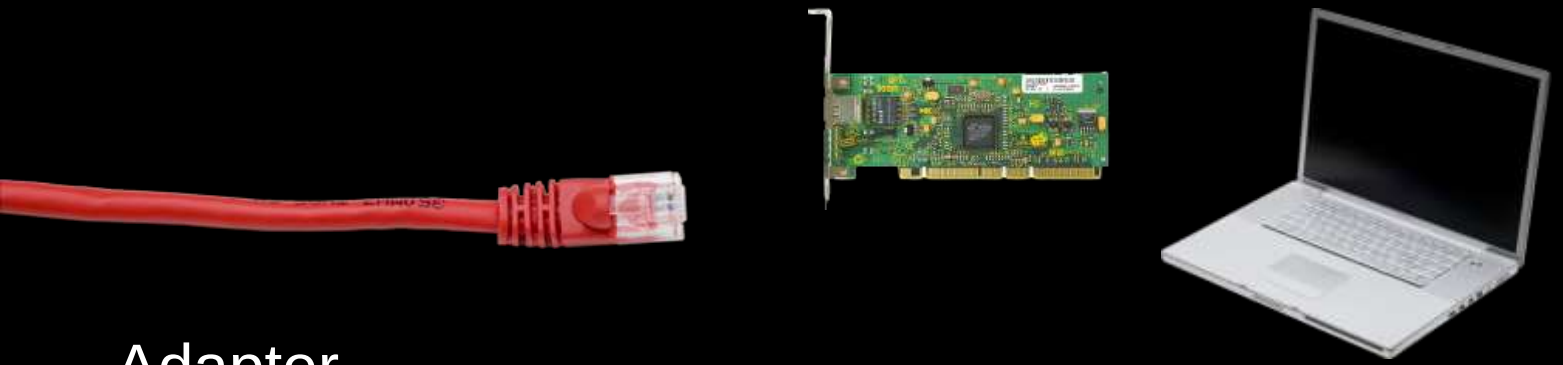
- small area (building, set of buildings)
- same, sometimes shared, transmission medium
- high data rate (often): 1 Mbps – 1 Gbps
- Low latency
- devices are peers
  - any device can initiate a data transfer with any other device

Most elements on a LAN are workstations

- endpoints on a LAN are called **nodes**

Connecting nodes to LANs

Connecting nodes to LANs



Adapter

- expansion slot (PCI, PC Card, USB dongle)
- usually integrated onto main board

Network adapters are referred to as
Network Interface Cards (NICs) or adapters

or Network Interface Component
(since they're often not cards anymore)

Hubs, routers, bridges

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.

Concentrator or **repeater**

- Regenerates data passing through it

Bridge

- Connects two LANs or two segments of a LAN: extends a LAN
- Connection at data link layer (layer 2)

Router

- Determines the next network point to which a packet should be forwarded
- Connects different types of local and wide area networks at network layer (layer 3)

How do nodes share a network?

- Dedicated connection – no sharing: physical circuit
- Talk on different frequencies: broadband
  - Range of frequencies: FDM (Frequency Division Multiplexing)
- Take turns: baseband
  - Short fixed time slots: circuit switching
    - TDM (Time Division Multiplexing)
    - Circuit switching: performance equivalent to an isolated connection
  - Variable size time slots: packet switching
    - *Statistical multiplexing* for network access
    - Easily support many-to-many communication

- *Packet switching is the dominant means of data communication*

Modes of connection

Circuit-switching (virtual circuit network)

- 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

Packet-switching (datagram network)

- 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

Client-Server Networking

What's in the data?

For effective communication

- same language, same conventions

For computers:

- electrical encoding of data
- where is the start of the packet?
- which bits contain the length?
- is there a checksum? where is it? how is it computed?
- what is the format of an address?
- byte ordering

Protocols

These instructions and conventions are known as **protocols**

Protocols

Exist at different levels

understand format of address
and how to compute a checksum

humans vs. whales
different wavelengths

versus

request web page

French vs. Hungarian

Layering

To ease software development and maximize flexibility:

- Network protocols are generally organized in layers
- Replace one layer without replacing surrounding layers
- Higher-level software does not have to know how to format an Ethernet packet

… or even know that Ethernet is being used

Layering

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

OSI reference model

Adopted and created by ISO

7 layers of protocols

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

Physical

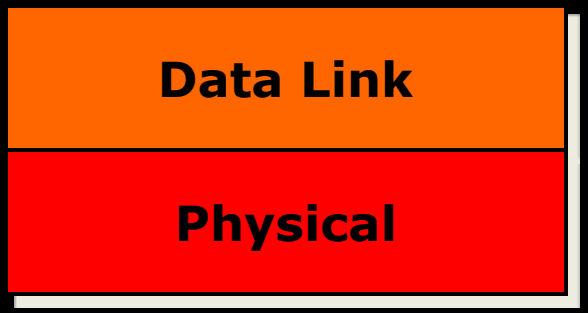
Examples: USB, Bluetooth, 1000BaseT, Wi-Fi

OSI Reference Model: Layer 2

Detects and corrects errors

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

Accepts acknowledgements from receiver



Deals with frames

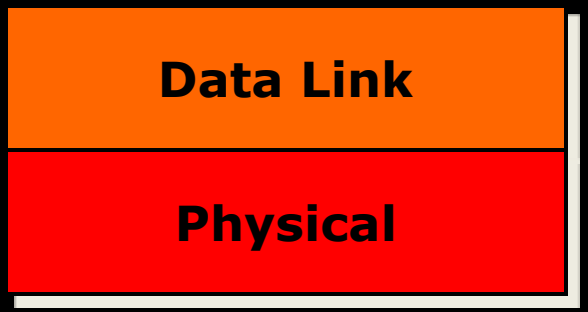
Examples: Ethernet MAC, PPP

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)

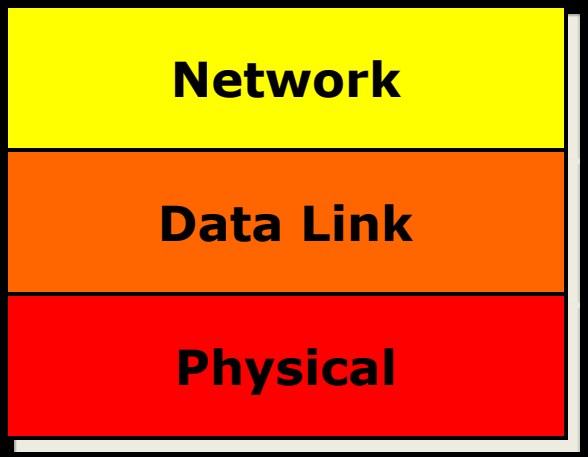
This set of hosts and switches defines the local area network (LAN)



OSI Reference Model: Layer 3

Relay and route information to destination

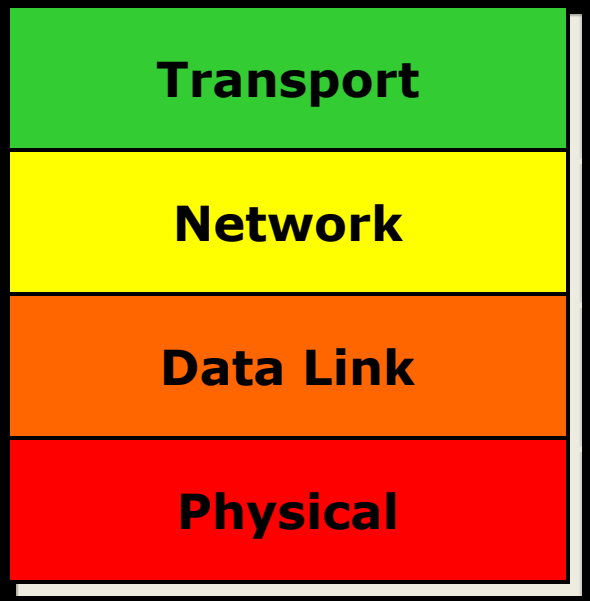
Manage journey of datagrams and figure out intermediate hops (if needed)



Deals with datagrams

Examples: IP, X.25

OSI Reference Model: Layer 4



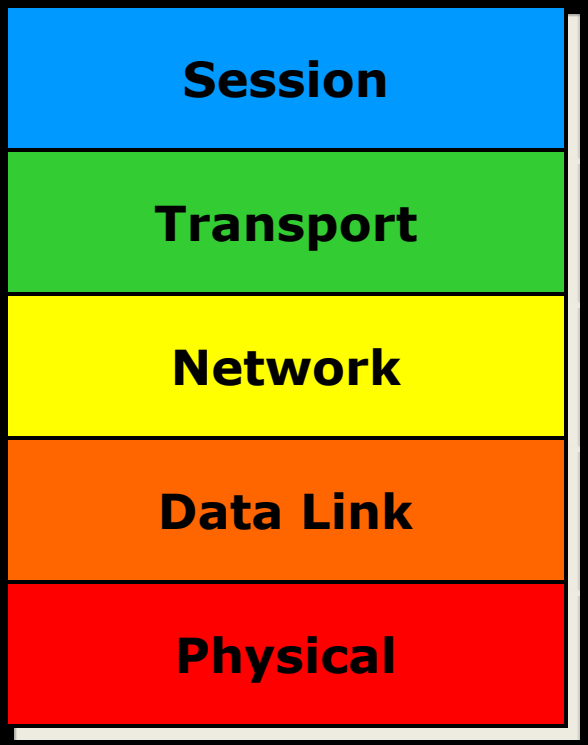
Provides an interface for end-to-end (application-to-application) communication: sends & receives segments of data. Manages flow control. May include end-to-end reliability

Network interface is similar to a mailbox

Deals with segments

Examples: TCP, UDP

OSI Reference Model: Layer 5



Services to coordinate dialogue and manage data exchange

Software implemented switch

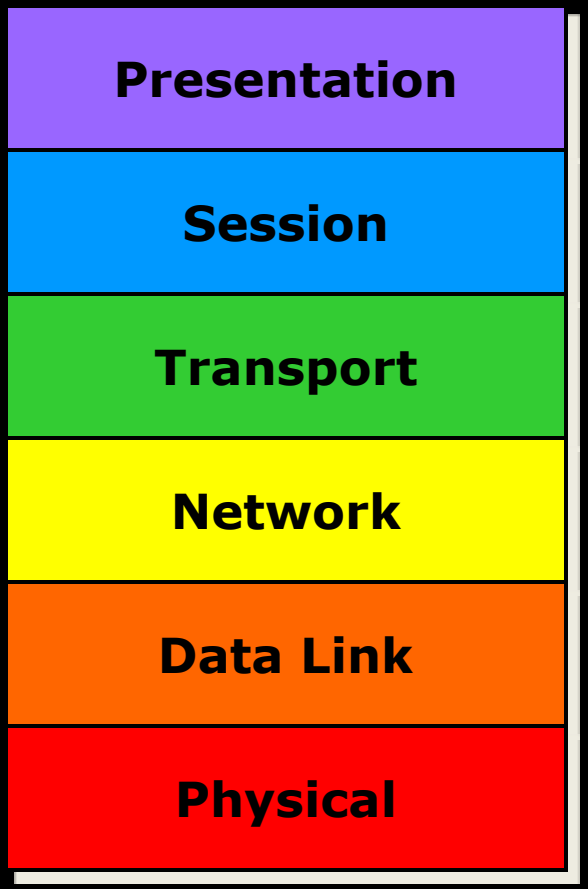
Manage multiple logical connections

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

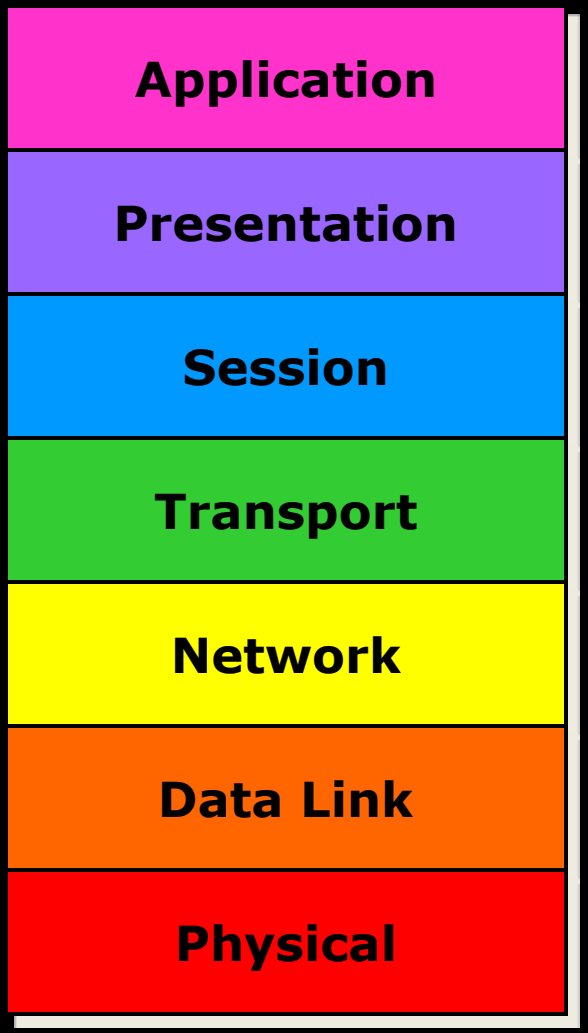
Concerned with the meaning of data bits

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 services: app-specific protocols

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

IP – Internet Protocol

Born in 1969 as a research network of 4 machines

Funded by DoD's ARPA

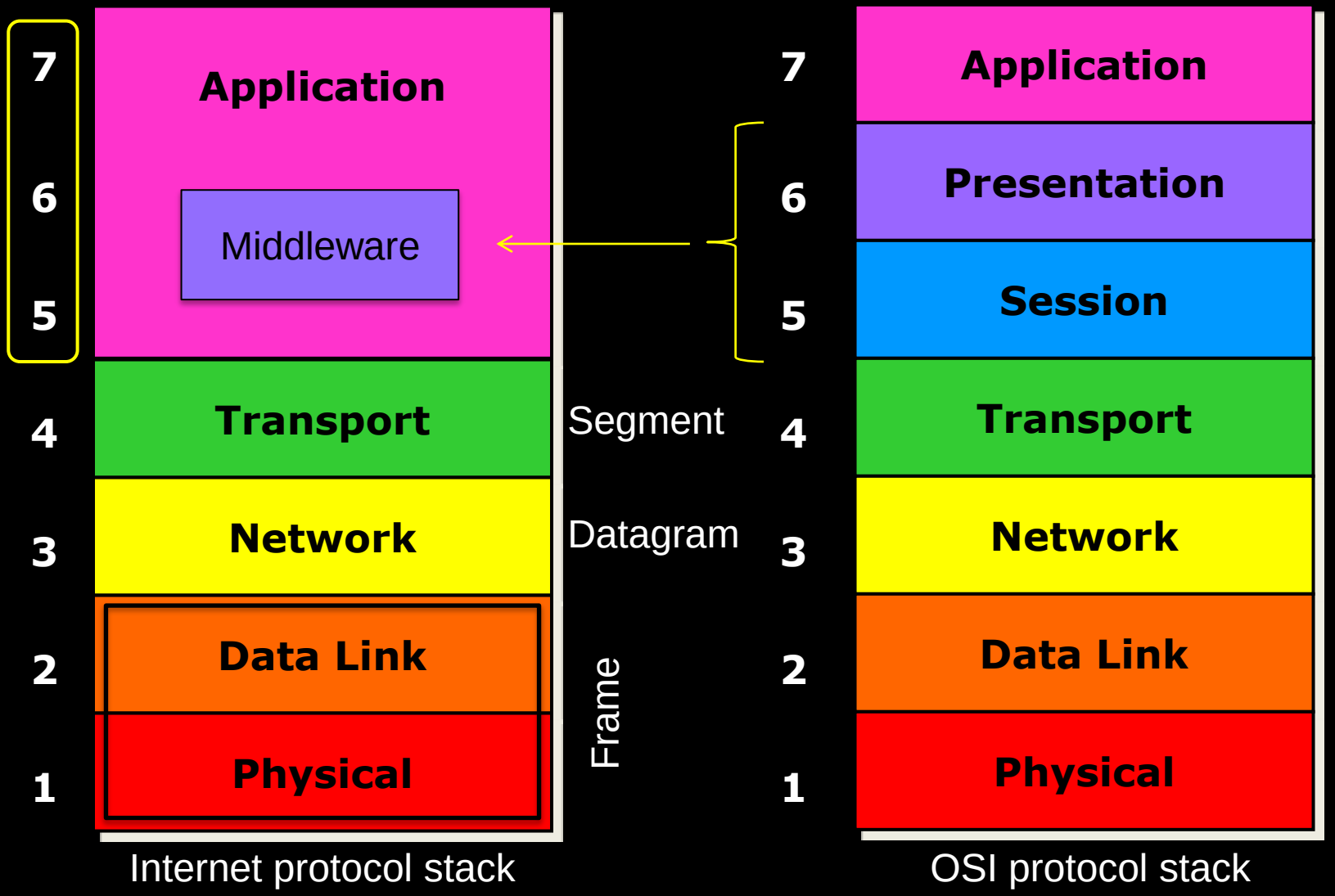
Goal:

Build an efficient fault-tolerant network that could connect heterogeneous machines and link separately connected networks.

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
  - IP: network layer – other protocols include TCP, UDP, ICMP, etc.
- The IP layer relies on routing from one physical network to another
- At the network layer, 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!

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:

Client – Server Communication

Addressing machines (data link layer)

Each interface on a host has a unique MAC address

- E.g., aramis.rutgers.edu: 48-bit ethernet address =
  = 00:03:ba:09:1b:b0

- This isn't too interesting to us as programmers
  - We can send ethernet frames to machines on the same LAN

Addressing machines (network layer)

Each interface on a host is given a unique IP address

- The IP address is *not* the network hardware address
  - IP is a *logical network* that overlays & connects physical networks
- IPv4 (still the most common in the U.S.): 32-bit number
  - Example, cs.rutgers.edu = 128.6.4.2 = `0x80060402`
- IPv6: 128-bit number
  - Example, cs.rutgers.edu = `0:0:0:0:0:FFFF:128.6.4.2` =
    = `::FFFF:8006:0402`

- Routable across networks
  - We can send IP packets to machines on the Internet
  - BUT … we want to talk to applications

Ethernet & IP Reliability

- Ethernet
  - LAN connectivity
  - Higher-level protocols (IP) encapsulated inside
  - Unreliable delivery
    - Frames may be lost to congestion, errors, or collision
- IP
  - Datagram delivery is also unreliable
  - Frames may be lost due to dropped ethernet frames, errors, congestion, or time-to-live expiration

Address translation

- Domain name → IP address translation
  - Domain Name System (DNS)
    - Hierarchical human-friendly names (e.g., www.cs.rutgers.edu)
  - User-level network service to look up IP domain names
  - Cache results to avoid future look-ups
  - The kernel's network drivers do not handle domain names

- IP → Ethernet address translation
  - Address Resolution Protocol (ARP)
  - How does the OS know which ethernet address to use?
  - Broadcast an ARP query and wait for a response
    "*Who has 128.6.4.2?*"
  - Cache results to avoid future look-ups

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

- We will only look at IP-based communication

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*

virtual circuit service (example: TCP)

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

Not to be confused with virtual circuit networks

- Which provide constant latency & guaranteed bandwidth
- TCP simulates a virtual circuit network … sort of (except for bandwidth and latency guarantees)

Programming: connectionless protocols

analogous to mailbox

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

drop letter in mailbox
(each letter addressed)

datagram service (example: UDP)

- client is not positive whether message arrived at destination
- no state has to be maintained at client or server
- cheaper but less reliable than virtual circuit service

IP transport layer

IP give us two transport-layer protocols

- **TCP: Transmission Control Protocol**
  - Connection-oriented service
    - Operating system keeps state: simulates a virtual circuit over a datagram network
  - 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
- **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

Addressing applications (transport layer)

Communication endpoint at the machine

- **Port number**: 16-bit value
- Port number = transport endpoint
  - Allows application-application communication
  - Identifies a specific data stream
- Some services use well-known port numbers (0 – 1023)
  - IANA: Internet Assigned Numbers Authority (www.iana.org)
  - Also see the file /etc/services

  ftp: 21/TCP ssh: 22/tcp smtp: 25/tcp http: 80/tcp ntp: 123/udp
- Ports for proprietary apps: 1024 – 49151
- Dynamic/private ports: 49152 – 65535

- To communicate with applications, we use a transport layer protocol and an IP address and port number

The End