Introduction to Networking

Computer Systems Programming, Spring 2024

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Logistics

- HW2 Posted Due Friday 3/30 @ 11:59
  - Auto-grader to be released today
- Exam grades to be posted in the next few days
- Mid-semester survey is due this Friday @ 11:59pm
- Check-in01 is due before lecture on Wednesday
- Travis' Office Hours are Cancelled this week due to a conference

Poll Everywhere

pollev.com/tqm

- Any questions before we begin?

Lecture Outline

- **Introduction to Networks**
  - **Layers upon layers upon layers…**

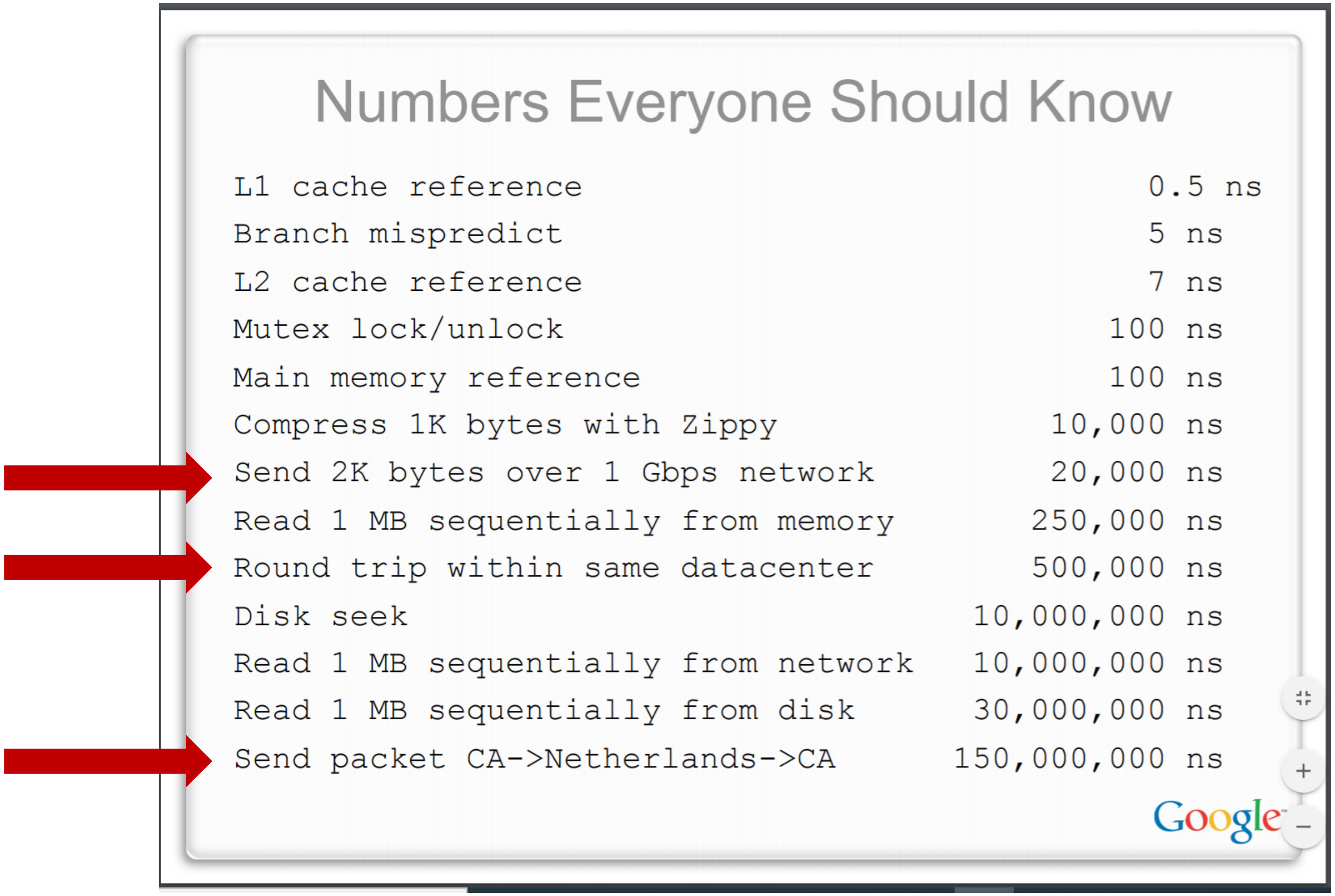
more awesome pictures at THEMETAPICTURE.COM

Today’s Goals

- Networking is a very common programming feature
  - You will likely have to create a program that will read/write over the network at some point in your career
- We want to give you a basic, high-level understanding of how networks work before you use them
  - Lecture will be more “story-like;” we will purposefully skip over most of the details, but hopefully you will learn something new about the Internet today!
  - Take CIS 5530 if you want to know more about the implementations of networks
- Let’s also examine “the network” as a *system*
  - Inputs? Outputs? Reliability? Efficiency?

"Network" Latency is Highly Variable

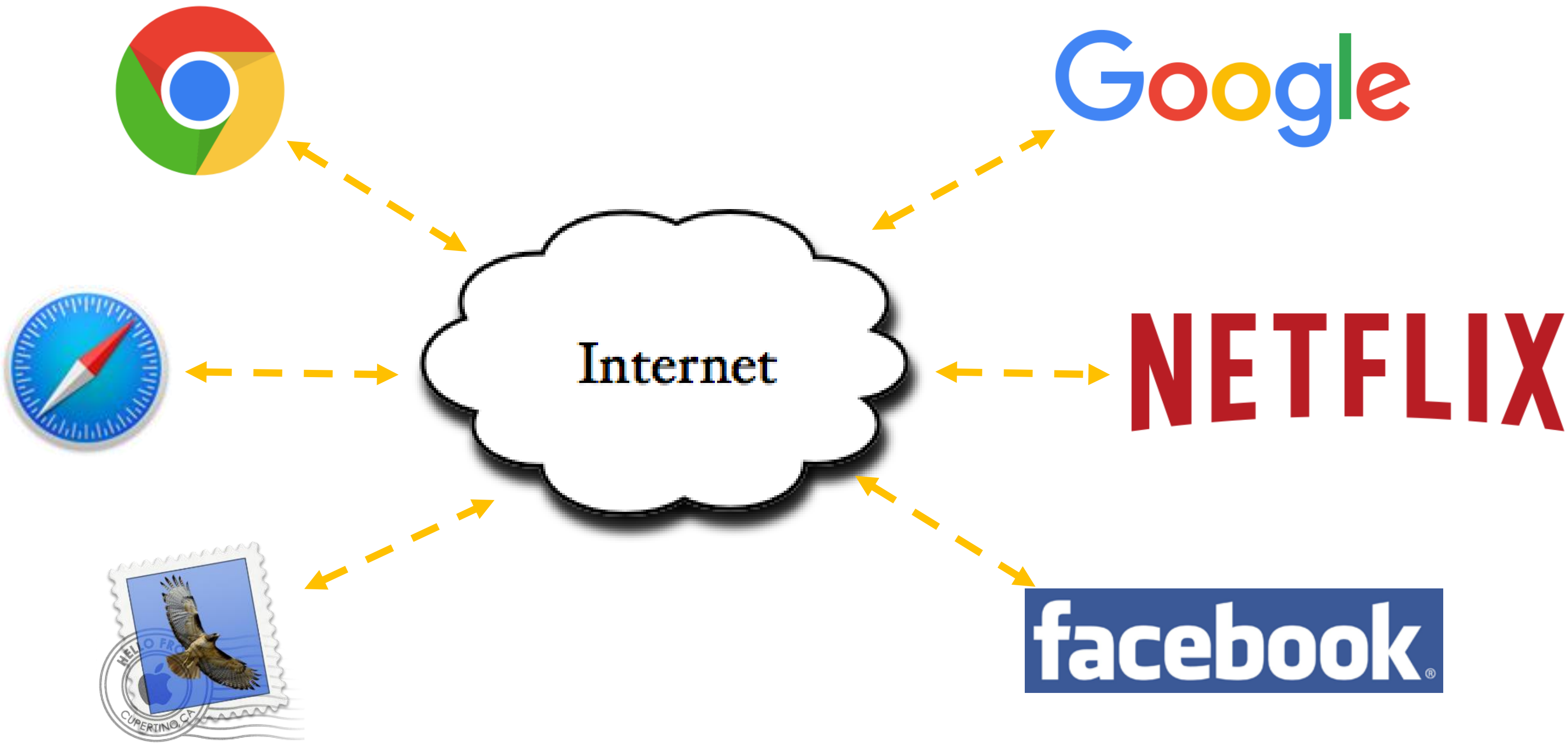
- Jeff Dean's "Numbers Everyone Should Know" (LADIS '09)



Numbers Everyone Should Know

L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	100 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	10,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns
Disk seek	10,000,000 ns
Read 1 MB sequentially from network	10,000,000 ns
Read 1 MB sequentially from disk	30,000,000 ns
Send packet CA->Netherlands->CA	150,000,000 ns

Networks From 10,000 ft

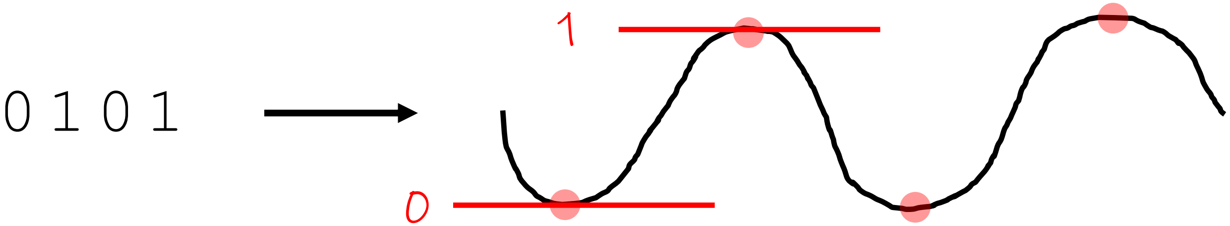


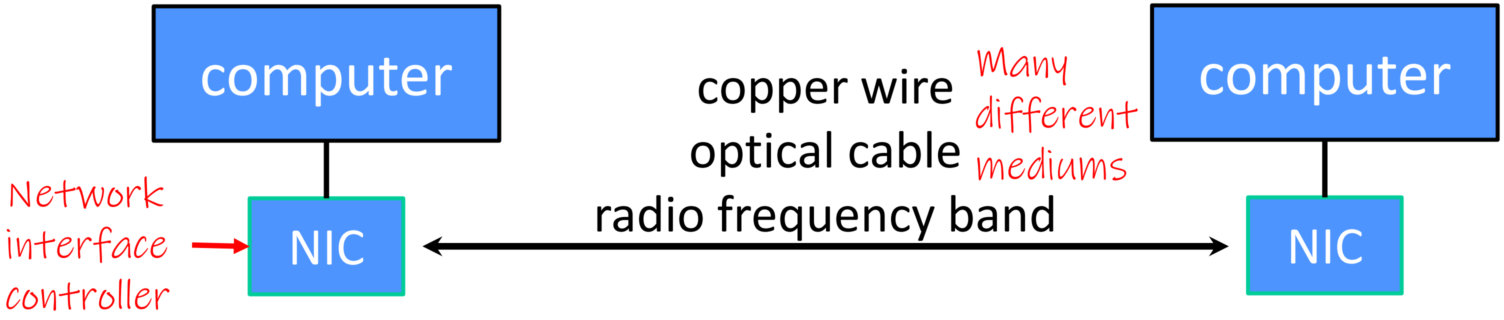
clients

servers

The Physical Layer

- Individual bits are modulated onto a wire or transmitted over radio
  - Physical layer specifies how bits are encoded at a signal level
  - Many choices, e.g., encode "1" as +1v, "0" as -0v; or "0"=+1v, "1"=-1v, …





copper wire
optical cable
radio frequency band

Many different mediums

physical
physical

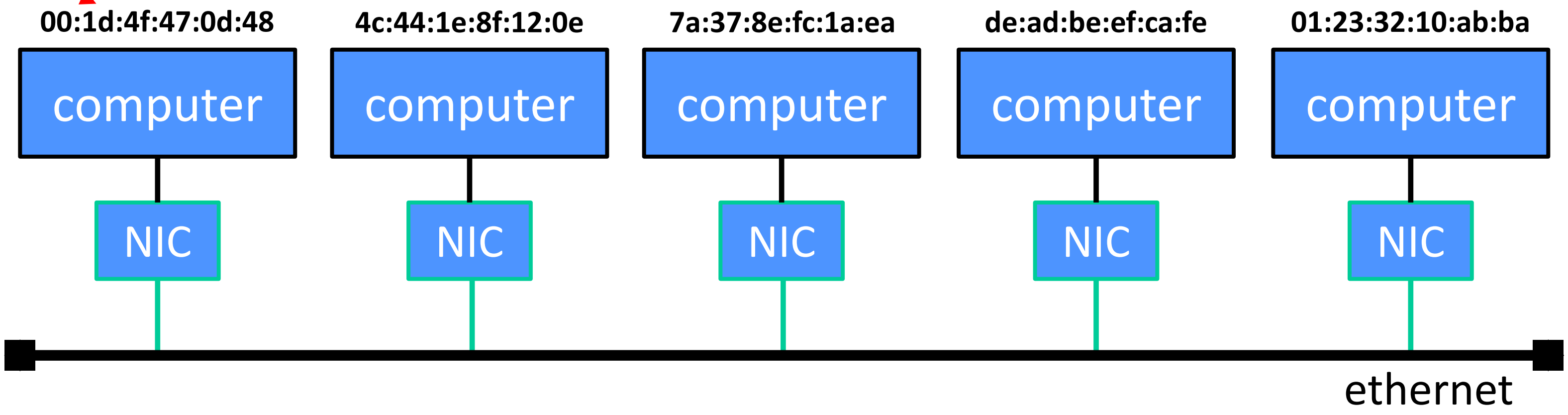
Materials Matter – Latency

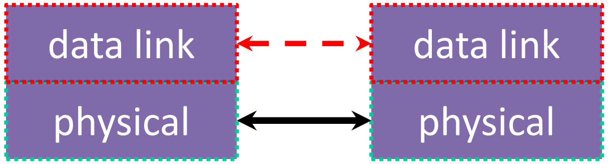
- Fiber optic cables are lower-latency and higher-bandwidth than traditional copper wiring
  - Much of the internet's "long haul" data is transmitted on these
  - (signal attenuation is much better too)

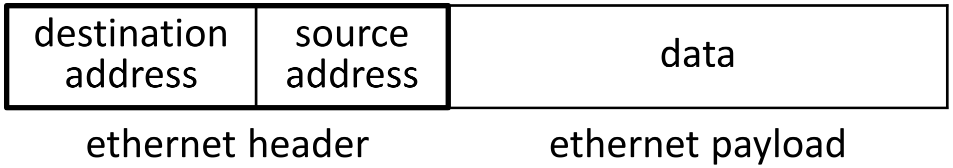
The Data Link Layer

- Multiple computers on a LAN contend for the network medium
  - Media access control (MAC) specifies how computers cooperate
  - Link layer also specifies how bits are "packetized" and network interface controllers (NICs) are addressed

MAC address

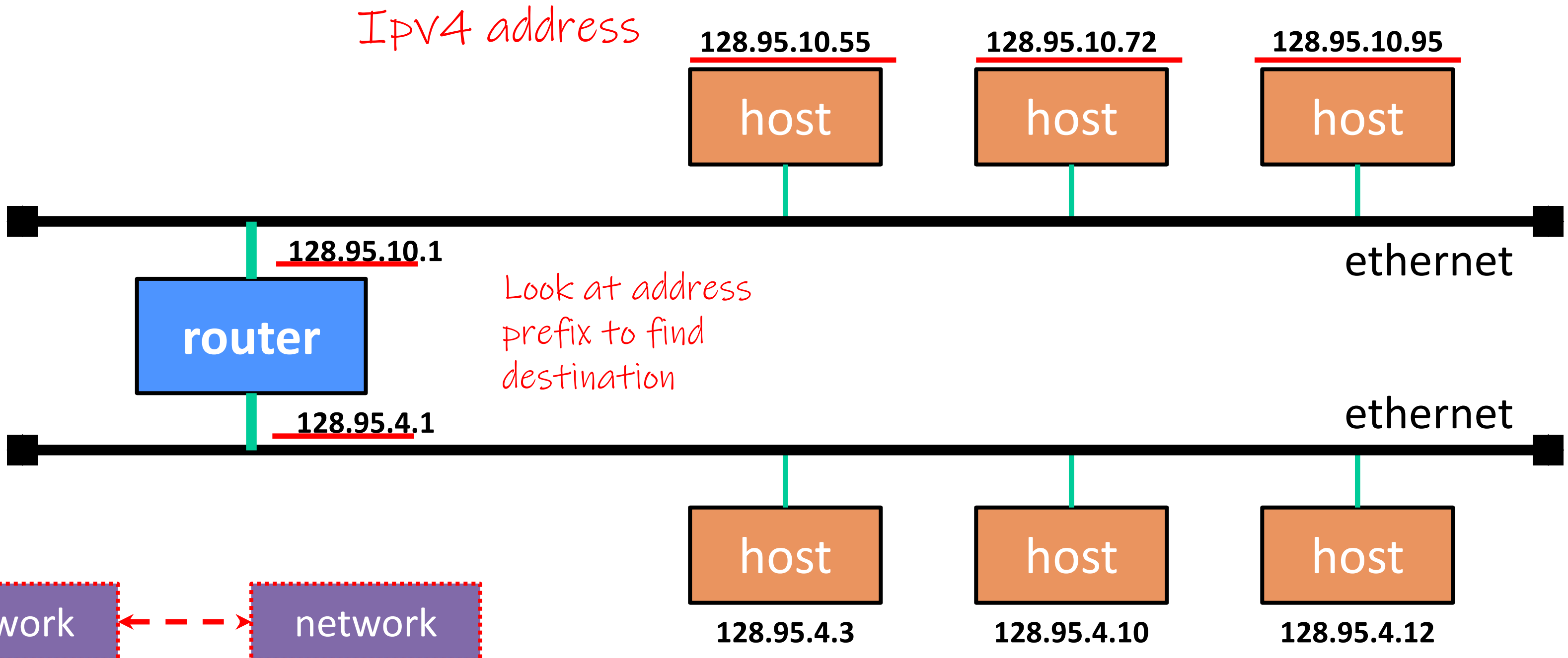


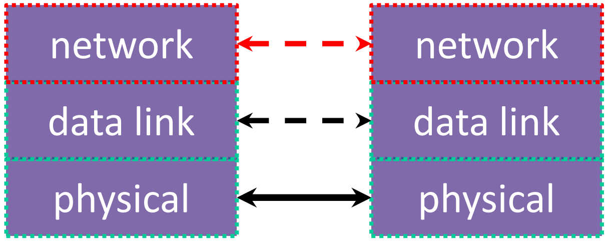




The Network Layer (IP)

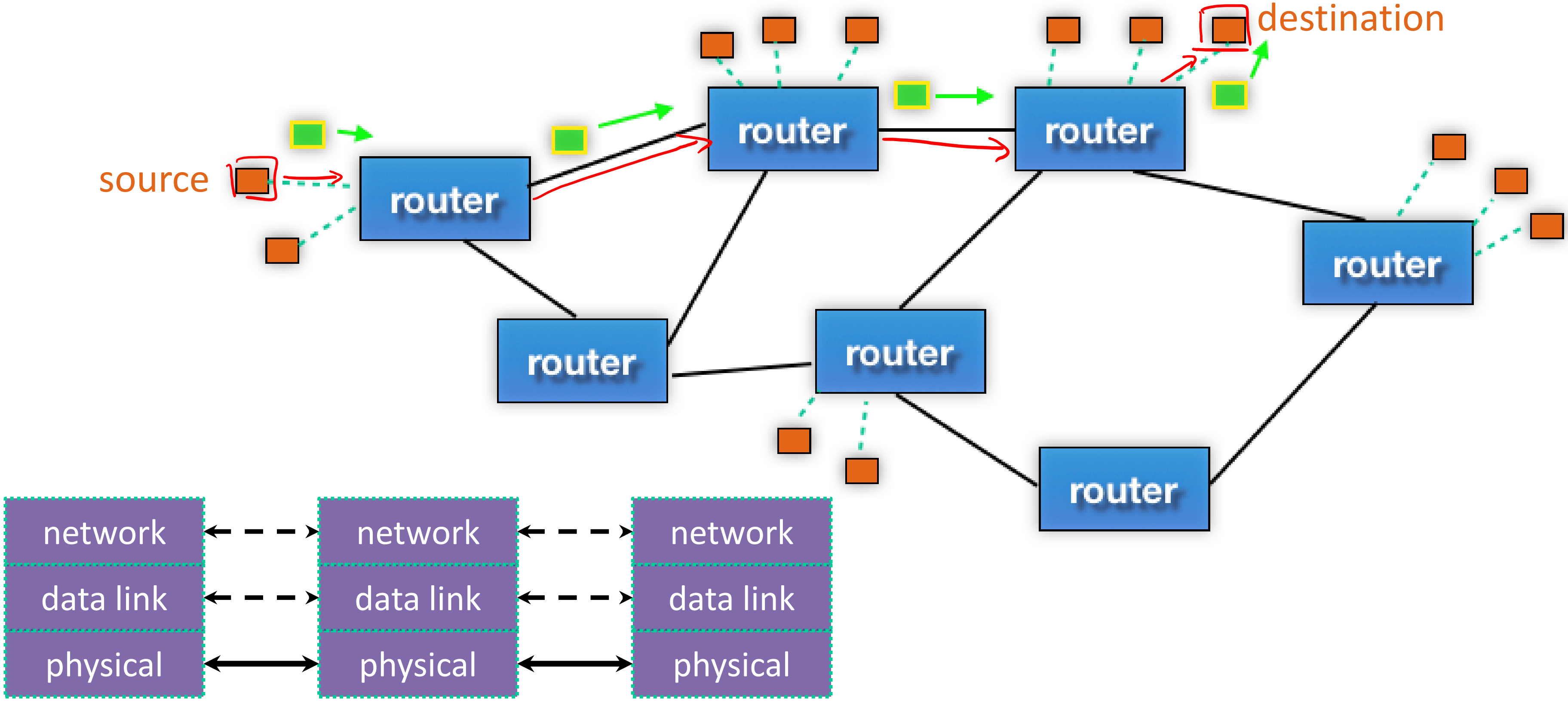
- Internet Protocol (IP) routes packets across multiple networks
  - Every computer has a unique IP address
  - Individual networks are connected by routers that span networks





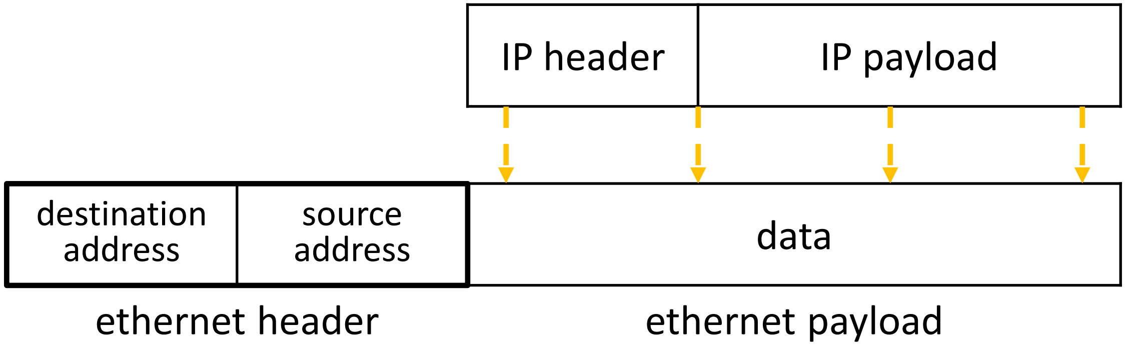
The Network Layer (IP)

- There are protocols to:
  - Let a host map an IP to MAC address on the same network
  - Let a router learn about other routers to get IP packets one step closer to their destination



The Network Layer (IP)

- Packet encapsulation:
  - An IP packet is encapsulated as the payload of an Ethernet frame
  - As IP packets traverse networks, routers pull out the IP packet from an Ethernet frame and plunk it into a new one on the next network



IP header

IP payload

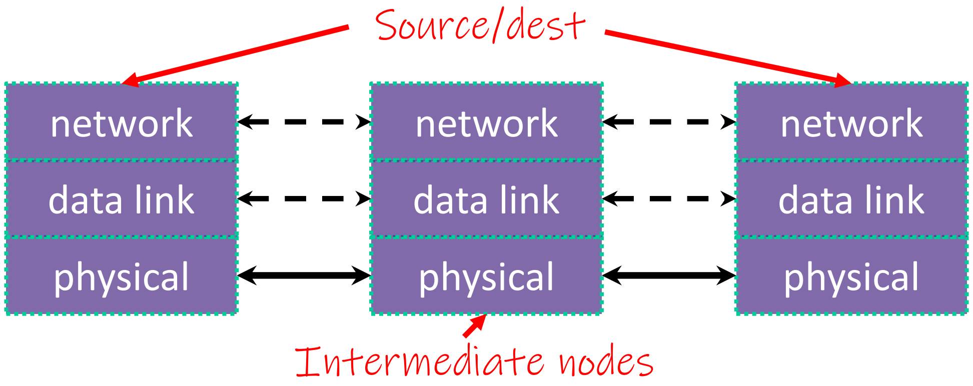
destination address

source address

data

ethernet header

ethernet payload



Source/dest

network

data link

physical

network

data link

physical

network

data link

physical

Intermediate nodes

Distance Matters – Latency

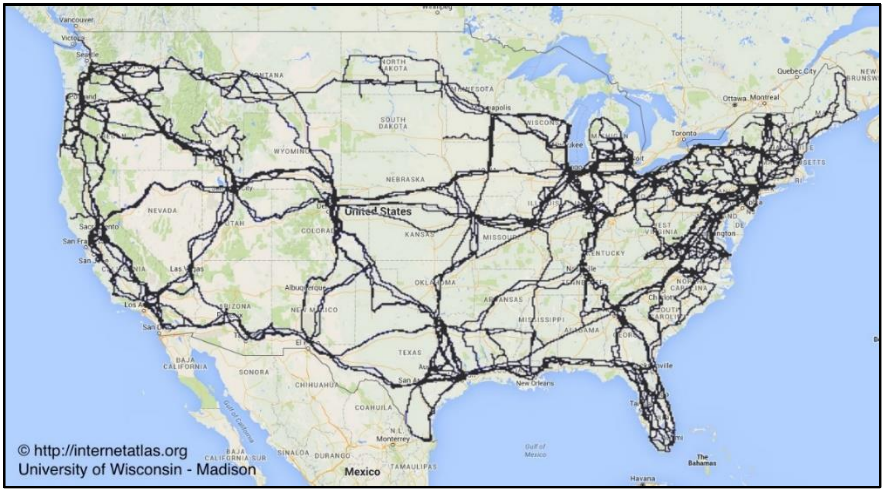
- Distances within a single datacenter are smaller than distances across continents
- Even within a datacenter, distances can sometimes matter

123Net Data Center, Wikimedia

Topology Matters – Latency and Reliability

- Some places are surprisingly well- or poorly-connected to "backbone" infrastructure like fiber optic cables

- Unintuitive topology can create interesting failures
  - *e.g.*, 2006 7.0-magnitude Hengchun Earthquake disrupted communications to Singapore, Philippines, Thailand, China, etc. for a month



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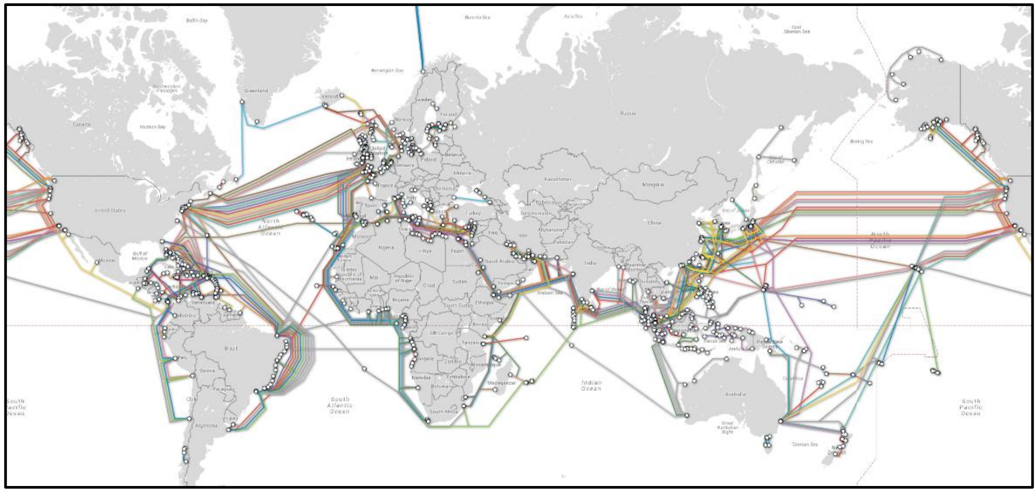
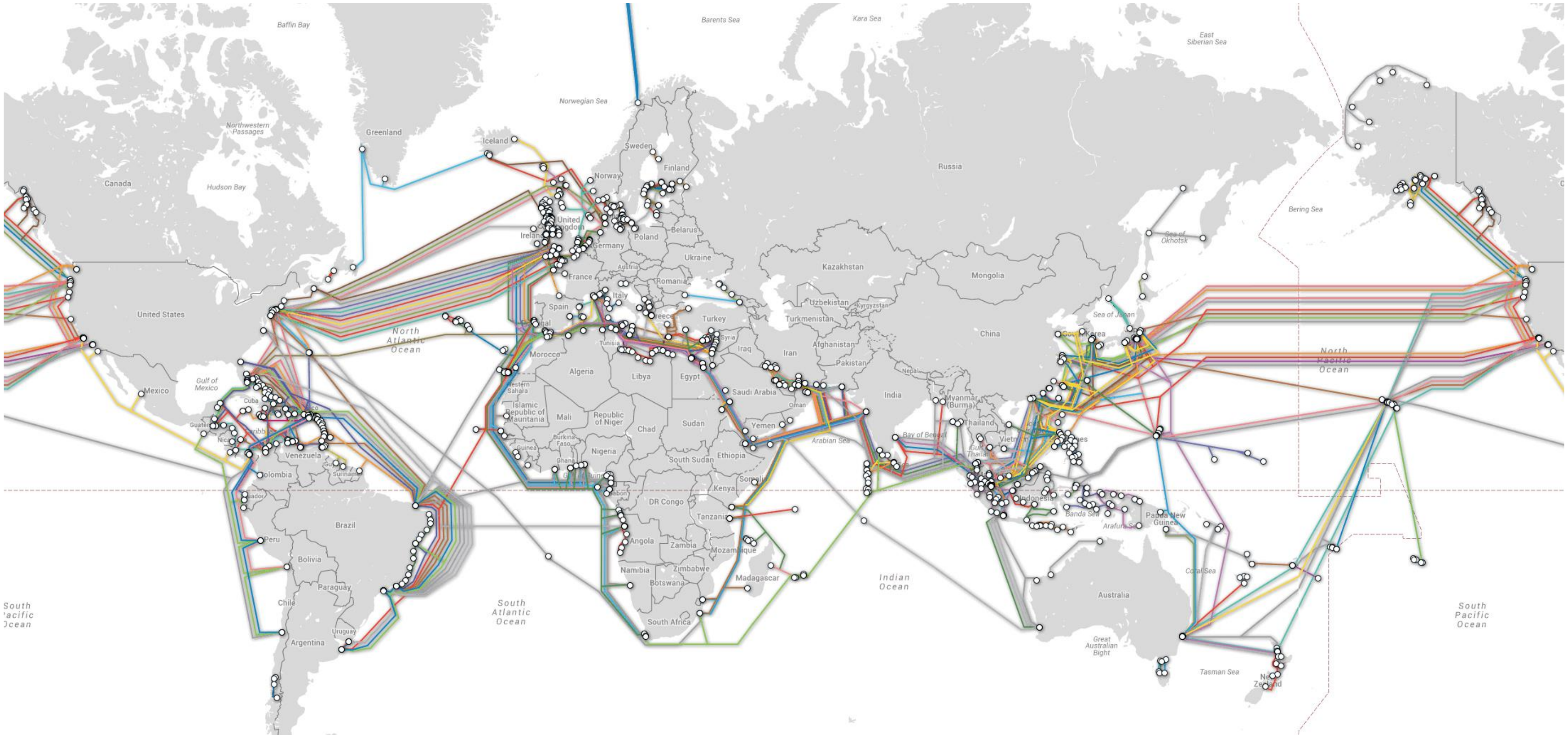


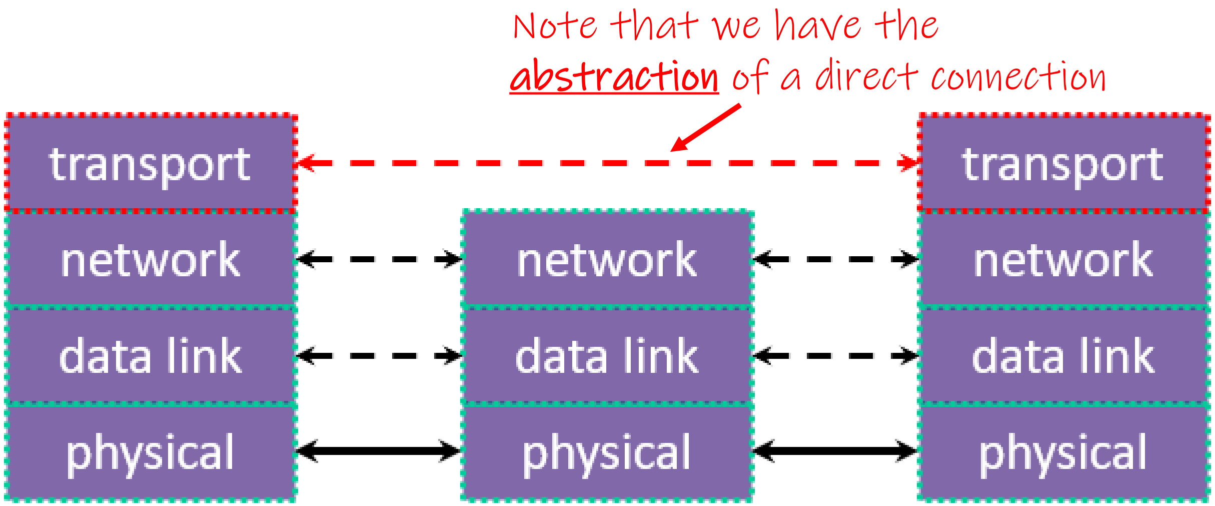
Reliability

- Packet loss?
- Physical interference?
- Link going down?



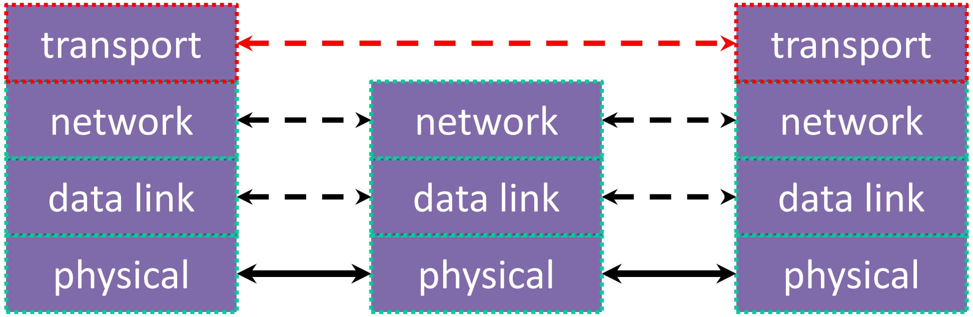
The Transport Layer

- Provides an interface to treat the network as a *data stream*
- Provides different protocols to interface between source and destination:
  - *e.g.*, Transmission Control Protocol (TCP), User Datagram Protocol (UDP)
  - These protocols still work with packets, but manages their order, reliability, multiple applications using the network…


Note that we have the **abstraction** of a direct connection

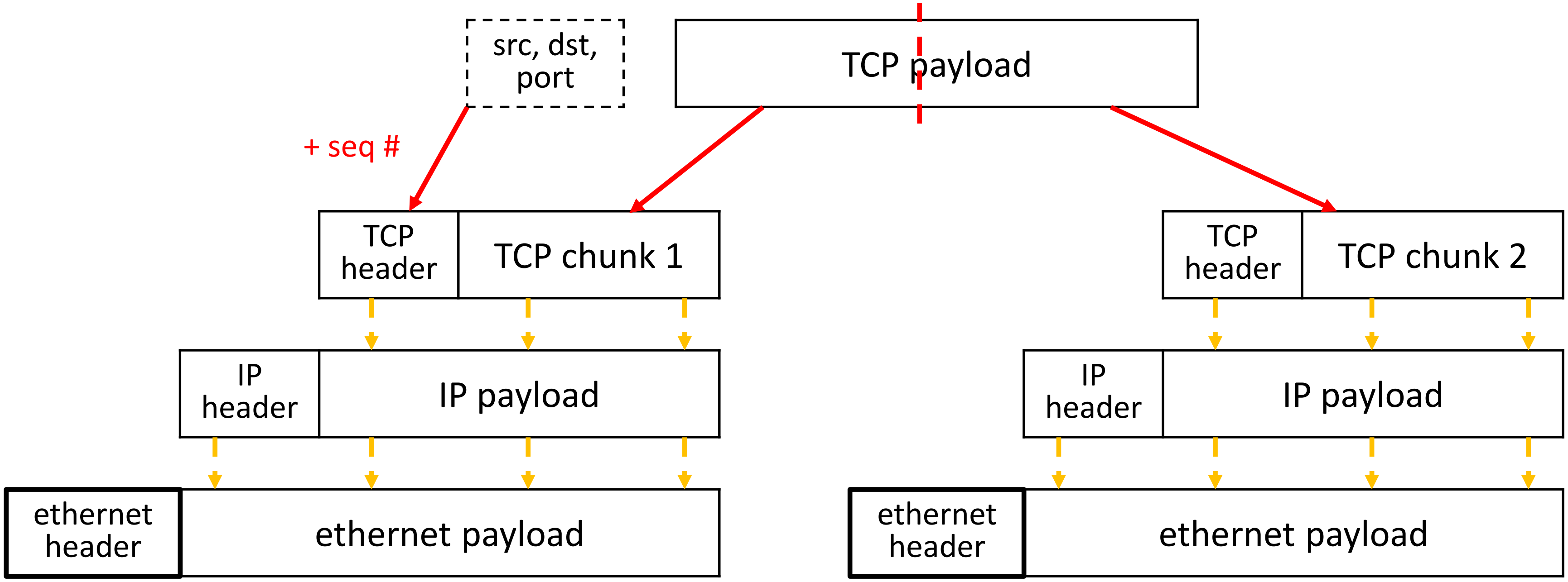
The Transport Layer (TCP)

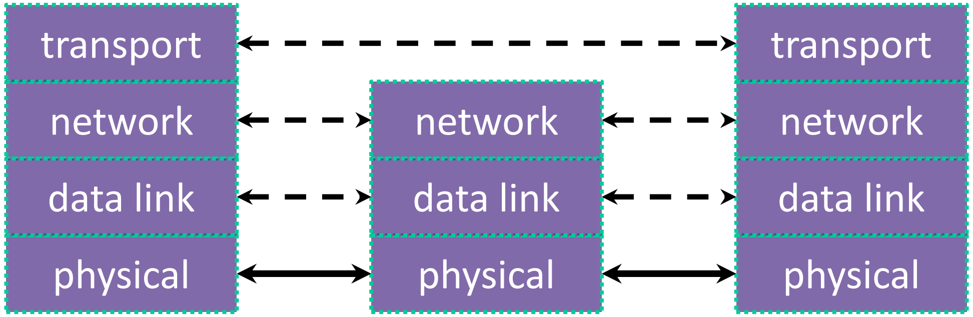
- Transmission Control Protocol (TCP):
  - Provides applications with reliable, ordered, congestion-controlled byte streams
    - Sends stream data as multiple IP packets (differentiated by sequence numbers) and retransmits them as necessary
    - When receiving, puts packets back in order and detects missing packets
  - A single host (IP address) can have up to 2^{16} = 65,535 "ports"
    - Kind of like an apartment number at a postal address (your applications are the residents who get mail sent to an apt. #)



The Transport Layer (TCP)

- Packet encapsulation – one more nested layer!

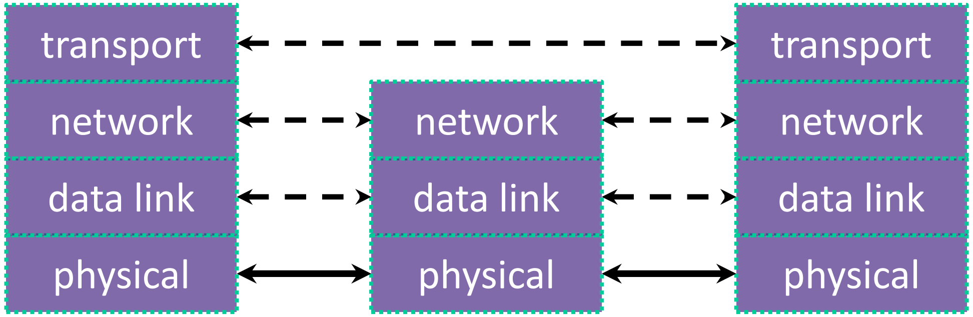




The Transport Layer (TCP)

- Applications use OS services to establish TCP streams:
  - The "Berkeley sockets" API
    - A set of OS system calls (Part of POSIX on linux)
  - Clients `connect()` to a server IP address + application port number
  - Servers `listen()` for and `accept()` client connections
  - Clients and servers `read()` and `write()` data to each other

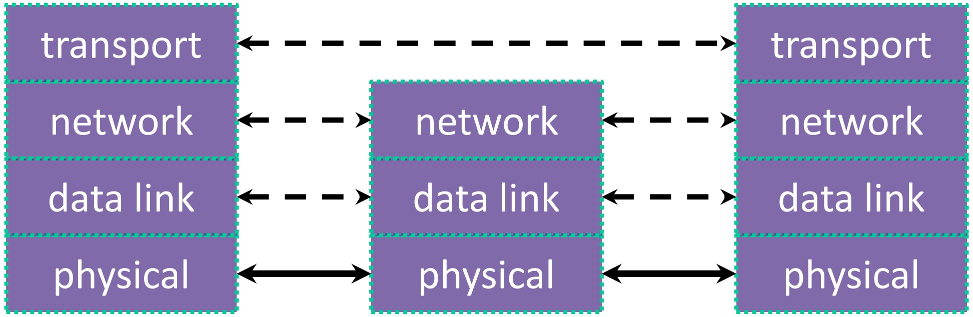
Used same as in File I/O



The Transport Layer (UDP)

- User Datagram Protocol (UDP):
  - Provides applications with *unreliable* packet delivery
  - UDP is a really thin, simple layer on top of IP
    - Datagrams still are fragmented into multiple IP packets

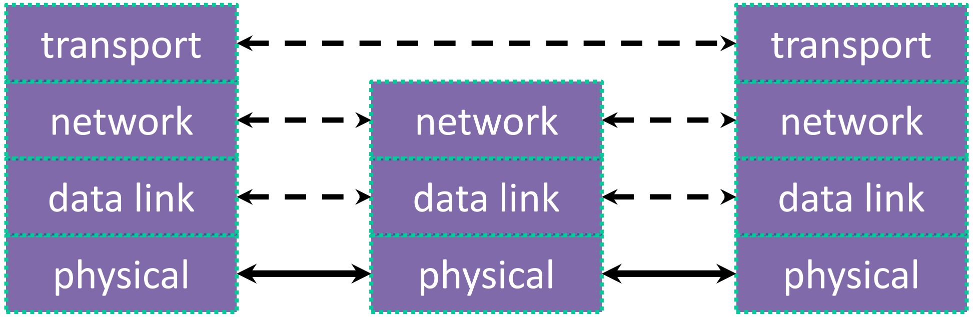
Ok when we want speed. (VOIP or ZOOM)



The Transport Layer

TCP:

UDP:



transport transport

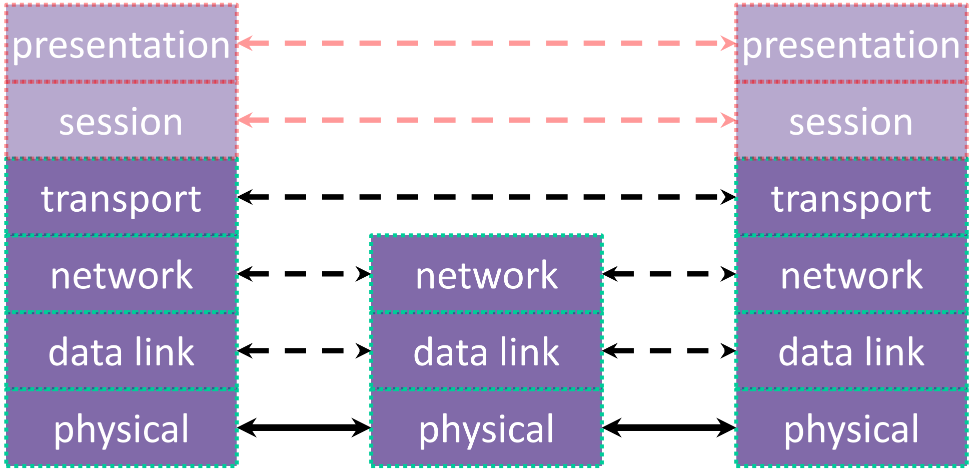
network network network

data link data link data link

physical physical physical

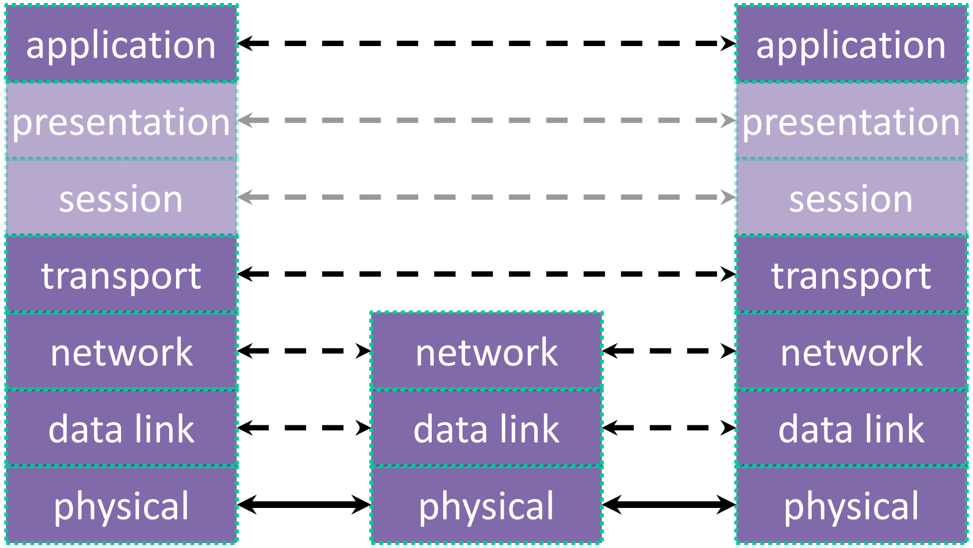
The (Mostly Missing) Layers 5 & 6

- Layer 5: Session Layer
  - Supposedly handles establishing and terminating application sessions
  - Remote Procedure Call (RPC) kind of fits in here
- Layer 6: Presentation Layer
  - Supposedly maps application-specific data units into a more network-neutral representation
  - Encryption (SSL) kind of fits in here



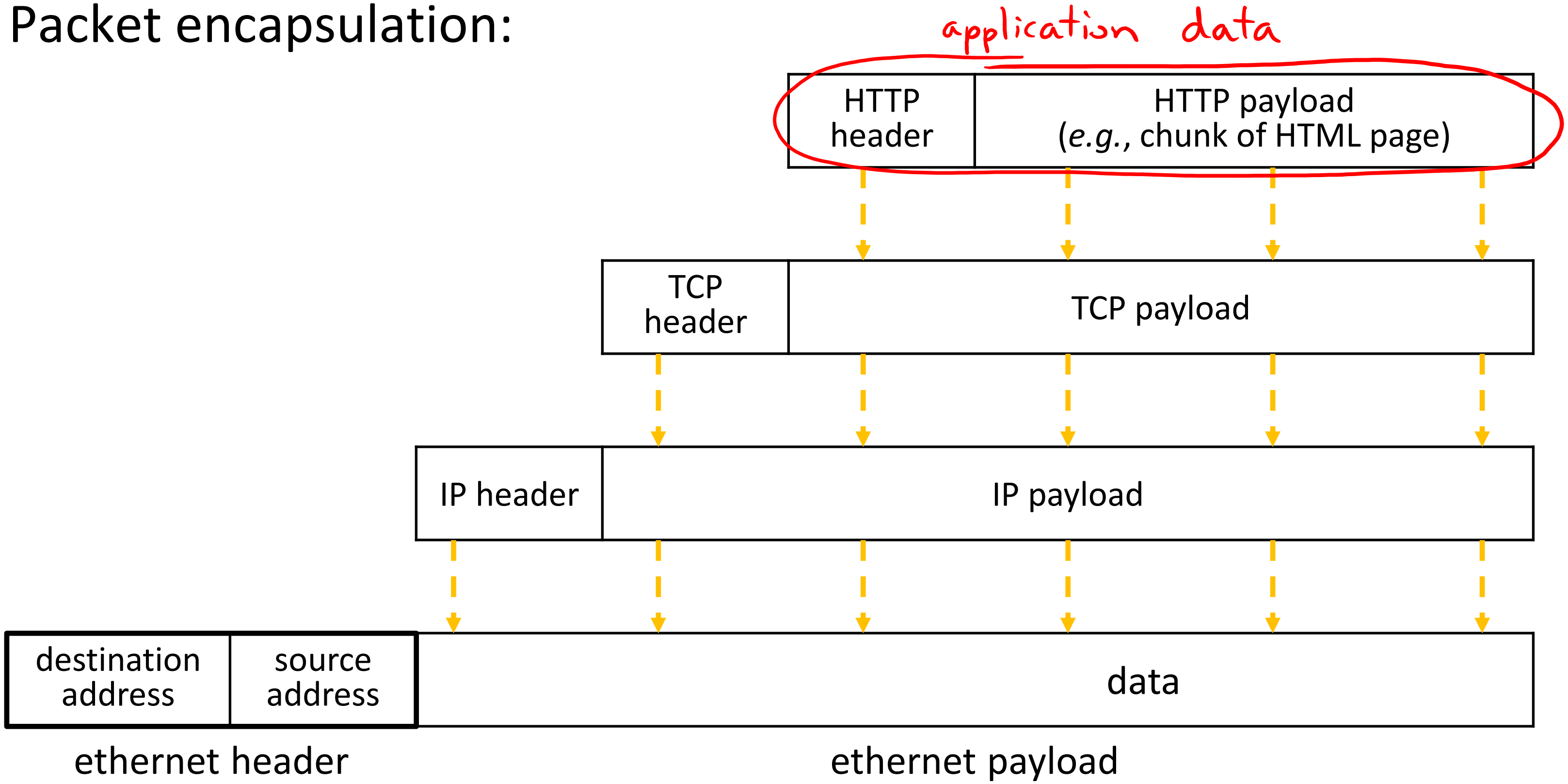
The Application Layer

- Application protocols
  - The format and meaning of messages between application entities
  - *e.g.*, HTTP is an application-level protocol that dictates how web browsers and web servers communicate
    - HTTP is implemented *on top of* TCP streams



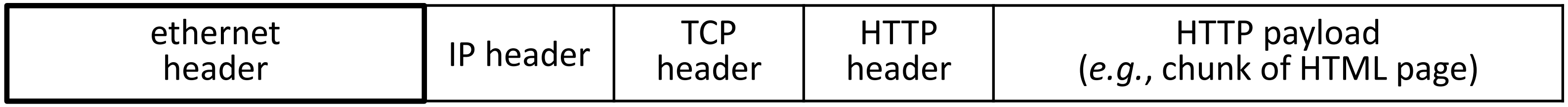
The Application Layer

- Packet encapsulation:



The Application Layer

- Packet encapsulation:



ethernet header

IP header

TCP header

HTTP header

HTTP payload (*e.g.*, chunk of HTML page)

The Application Layer

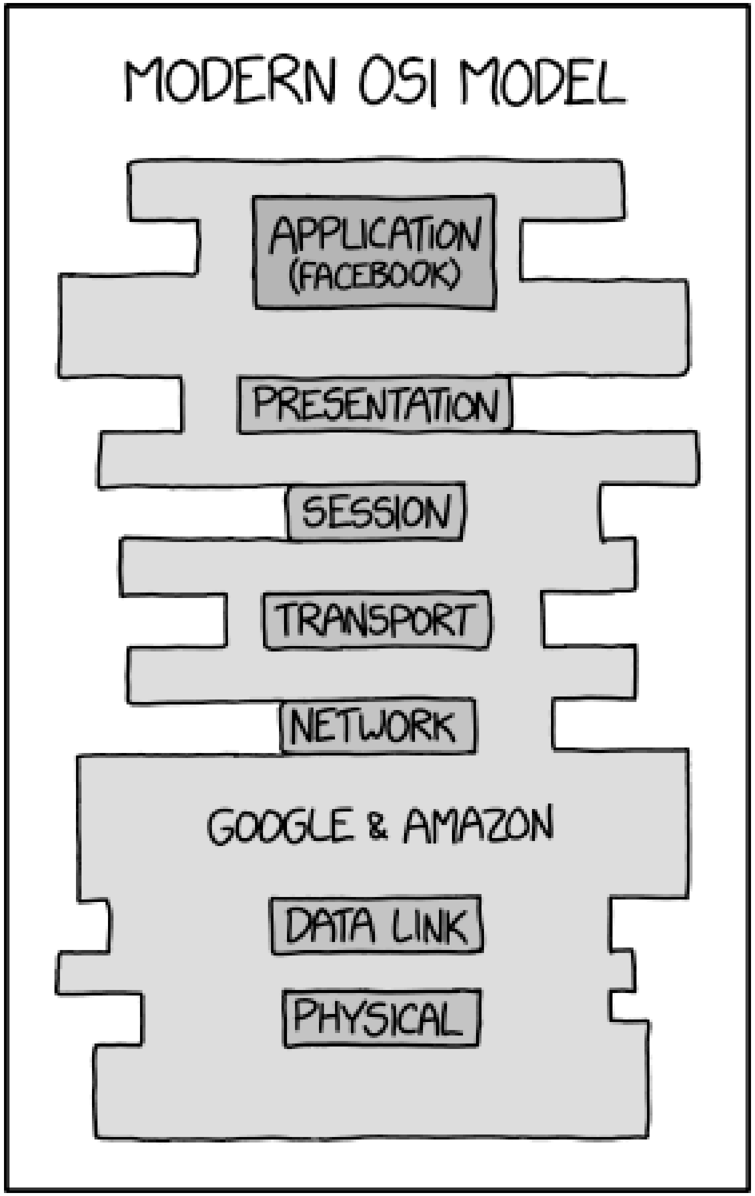
- Popular application-level protocols:
  - **DNS:** translates a domain name (*e.g.*, www.google.com) into one or more IP addresses (*e.g.*, 74.125.197.106)
    - Domain Name System
    - An hierarchy of DNS servers cooperate to do this
  - **HTTP:** web protocols
    - Hypertext Transfer Protocol
  - **SMTP, IMAP, POP:** mail delivery and access protocols
    - Secure Mail Transfer Protocol, Internet Message Access Protocol, Post Office Protocol
  - **SSH:** secure remote login protocol
    - Secure Shell
  - **bittorrent:** peer-to-peer, swarming file sharing protocol

netcat demo (if time)

- netcat (`nc`) is “a computer networking utility for reading from and writing to network connections using TCP or UDP”
  - https://en.wikipedia.org/wiki/Netcat

  - Listen on port: `nc -l <port>`
  - Connect: `nc <IPaddr> <port>`
    - Local host: `127.0.0.1`

In Other Words…



https://xkcd.com/2105/