CSCI-1680
Layering and Encapsulation

Nick DeMarinis

Based partly on lecture notes by Rodrigo Fonseca, David Mazières, Phil Levis, John Jannotti

Administrivia

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- Container setup: due by Thursday
  - If you have issues, please fill out the form

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MY OFFICE HOURS
T/Th 2-4 PM

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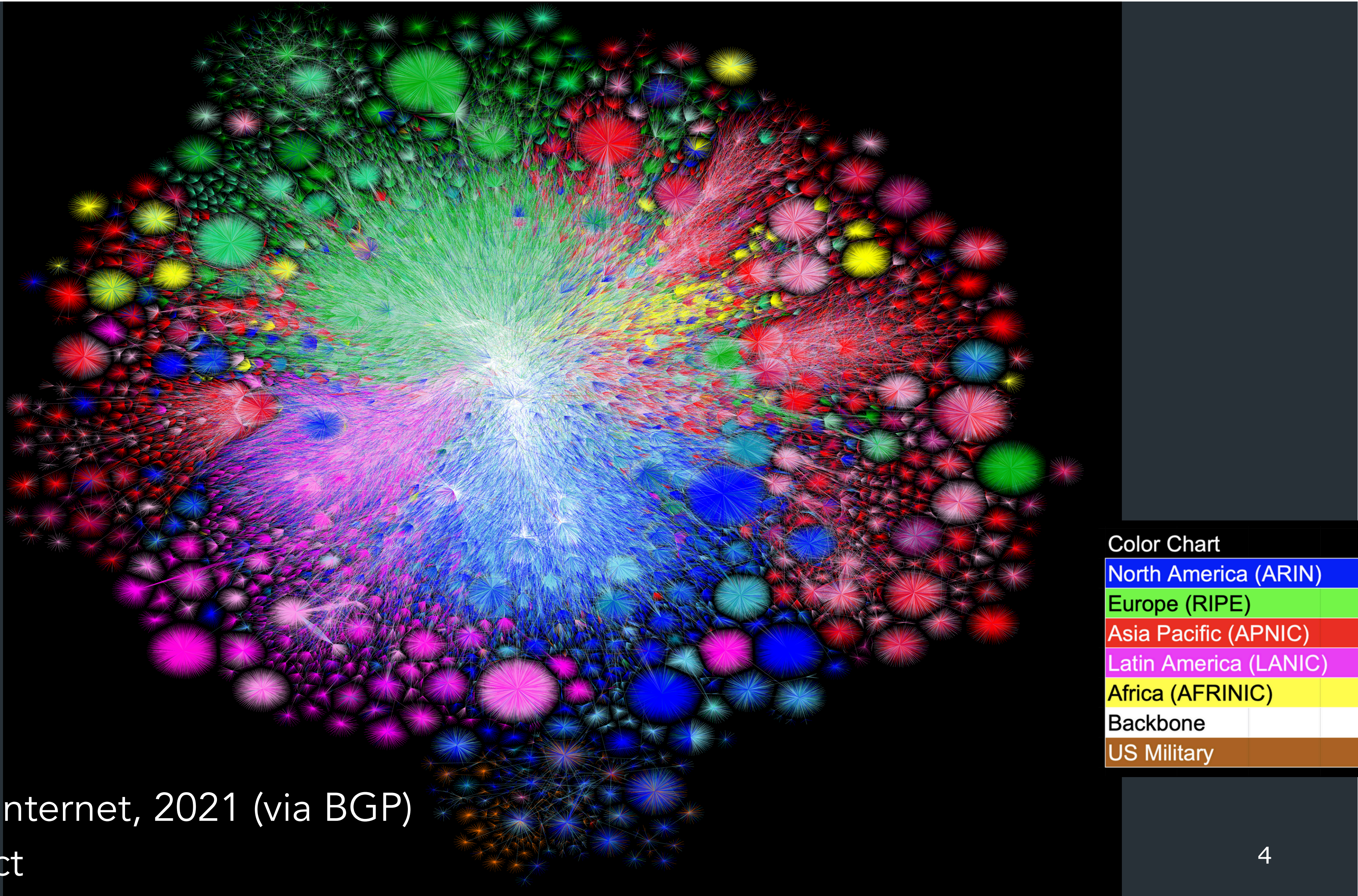
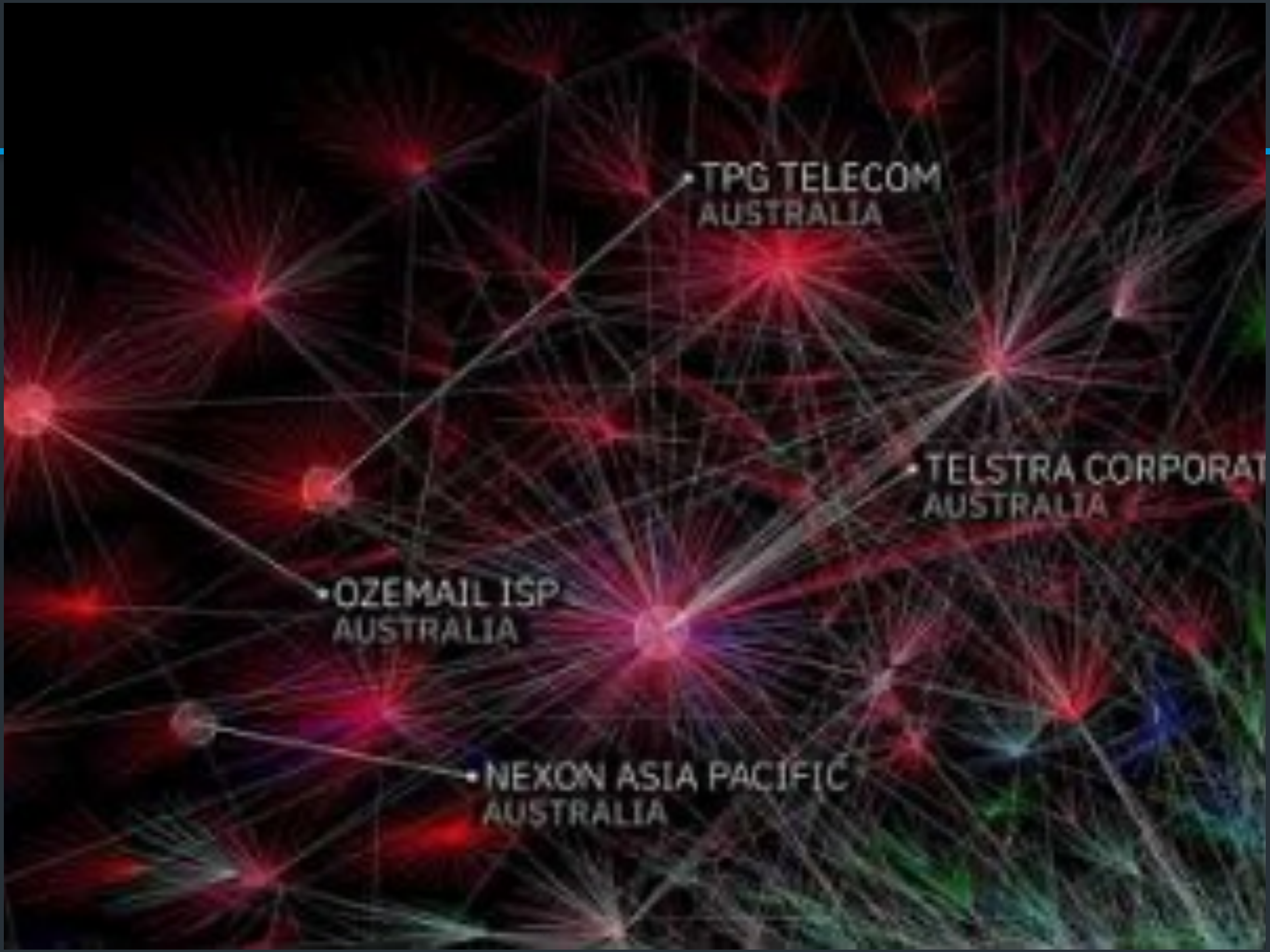
- Milestone due by Tuesday, 9/19 by 11:59pm EDT
  - Warmup and first steps + design doc for the rest

Topics for Today

- Layering and Encapsulation
- Intro to IP, TCP, UDP
- Demo on sockets



Map of the Internet, 2021 (via BGP)
OPTE project



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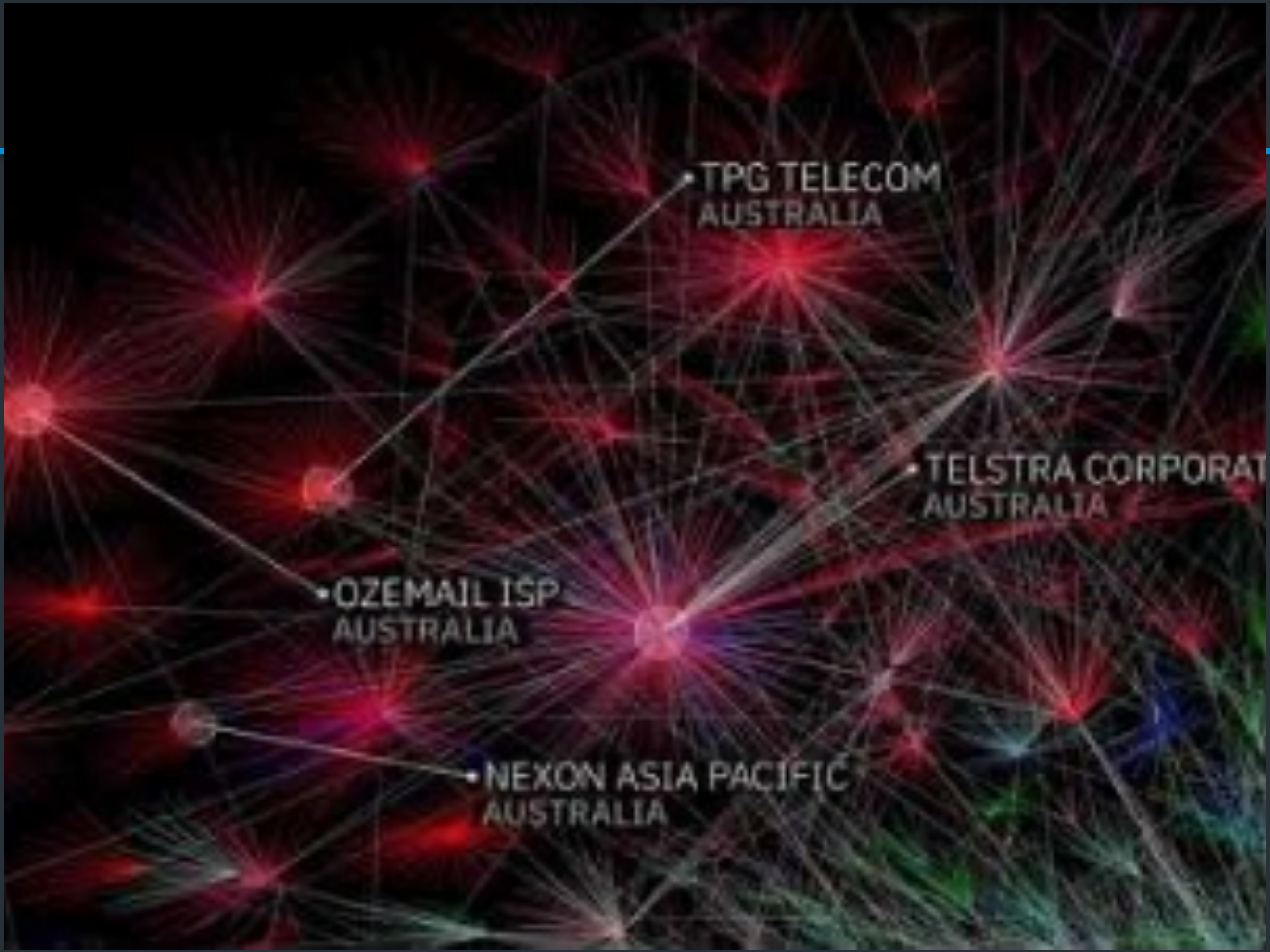

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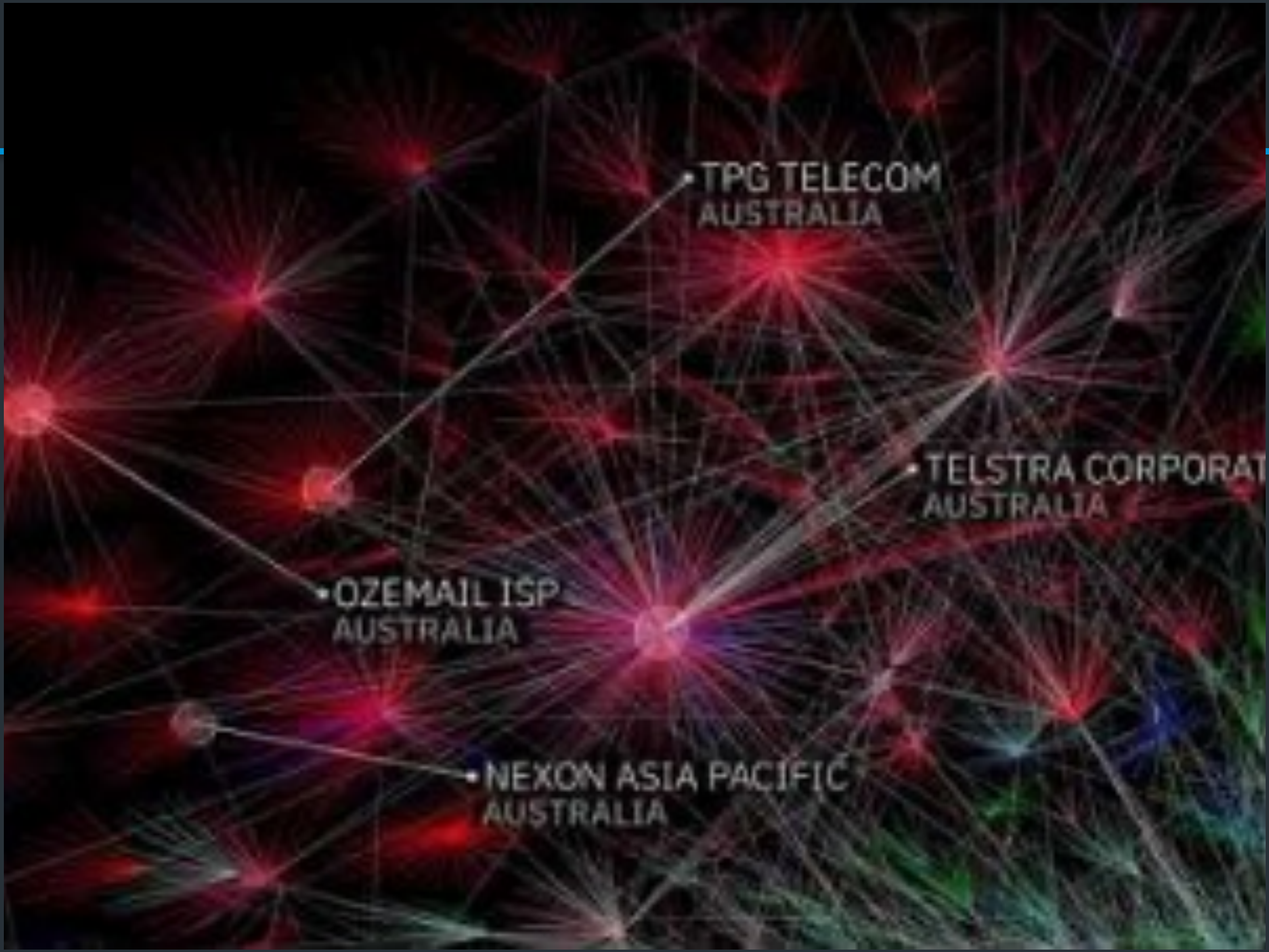

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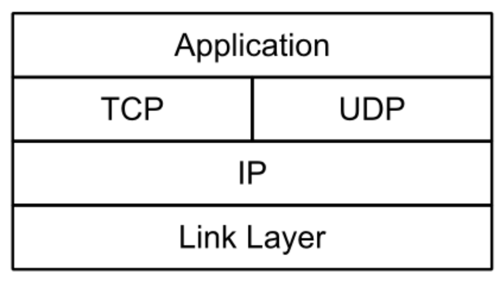
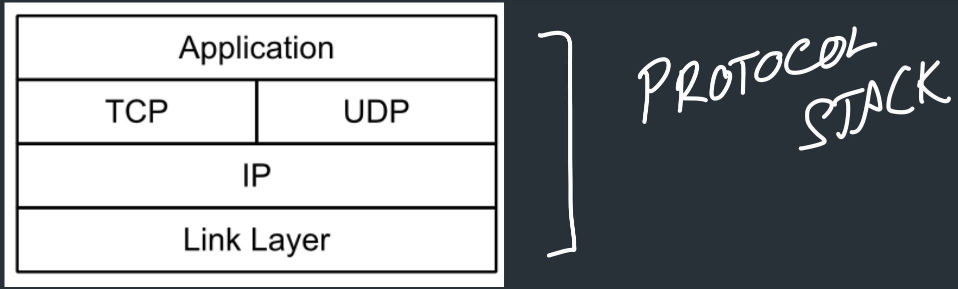
How do we make sense of all this?

- Very large number of computers
- Incredible variety of technologies
  - Each with very different constraints
- Lots of multiplexing
- No single administrative entity
- Evolving demands, protocols, applications
  - Each with very different requirements!

Layering

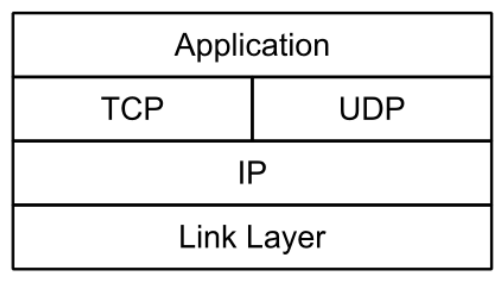


Layering



Abstraction to the rescue!

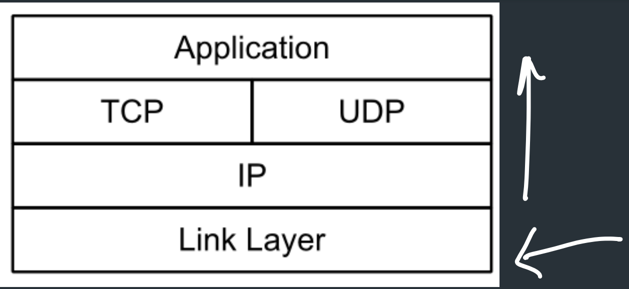
Layering



<u>Abstraction to the rescue!</u>

- Break problem into separate parts, solve part independently

Layering



Abstraction to the rescue!

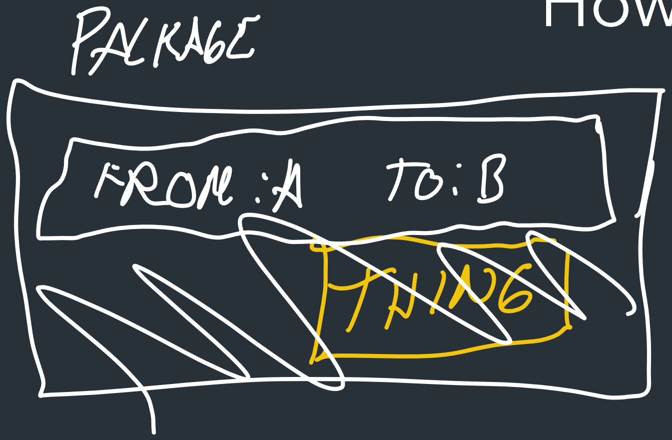
- Break problem into separate parts, solve part independently
- Abstract data from the layer above inside data from the layer be

Encapsulate data from "higher layer" inside "lower layer"

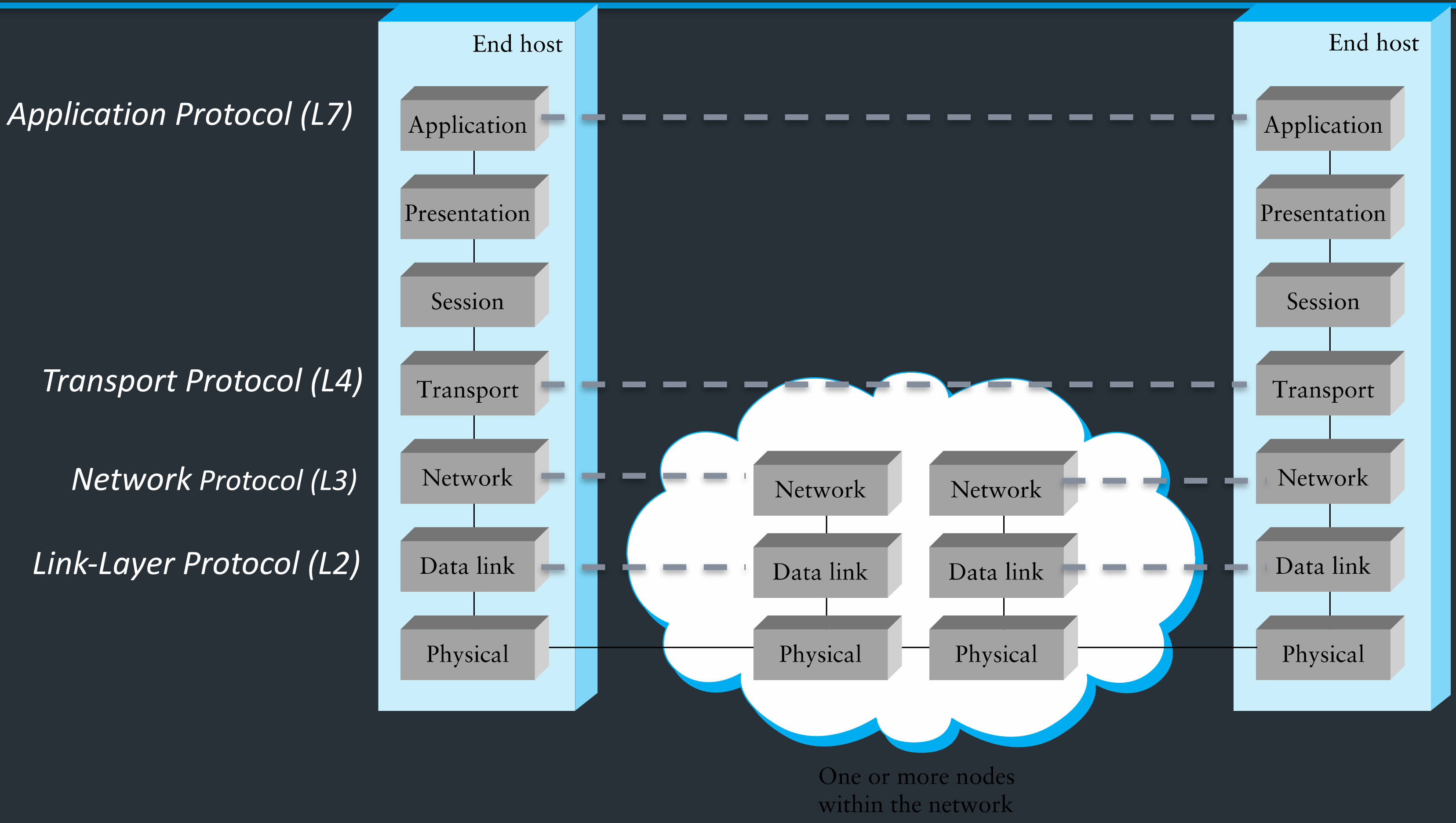
=> Lower layer can handle data without caring what's above it!

An analogy

How to deliver a package?



The big complex picture



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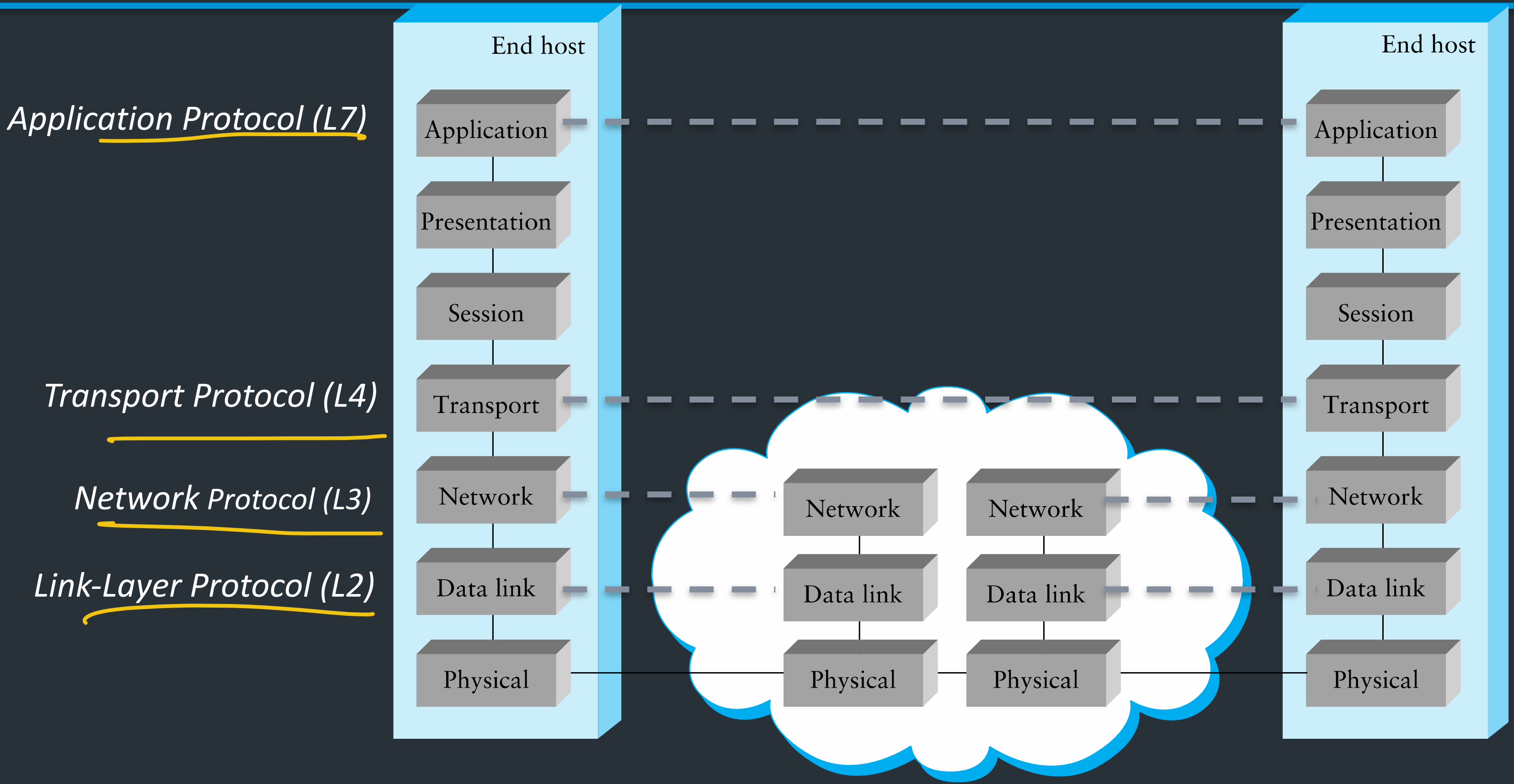
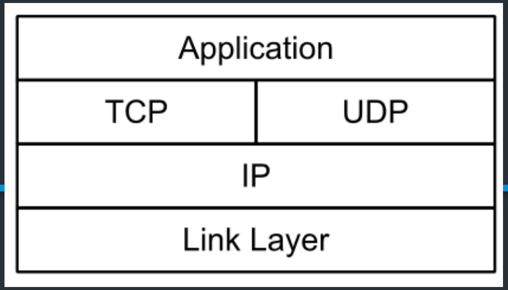


"OSI reference model" or "7-layer model"

Applications (Layer 7)



The applicatons/programs/etc you use every day

Examples:

- HTTP/HTTPS: Web traffic (browser, etc)
- SSH: secure shell
- FTP: file transfer
- DNS (more on this later)
- …

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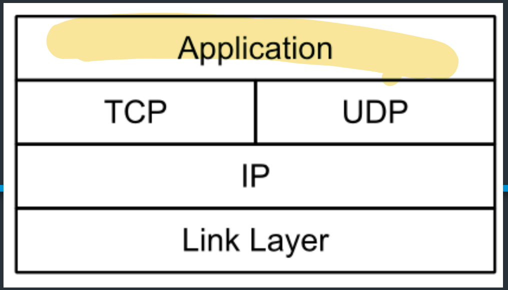

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Examples:

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- SSH: secure shell
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- …

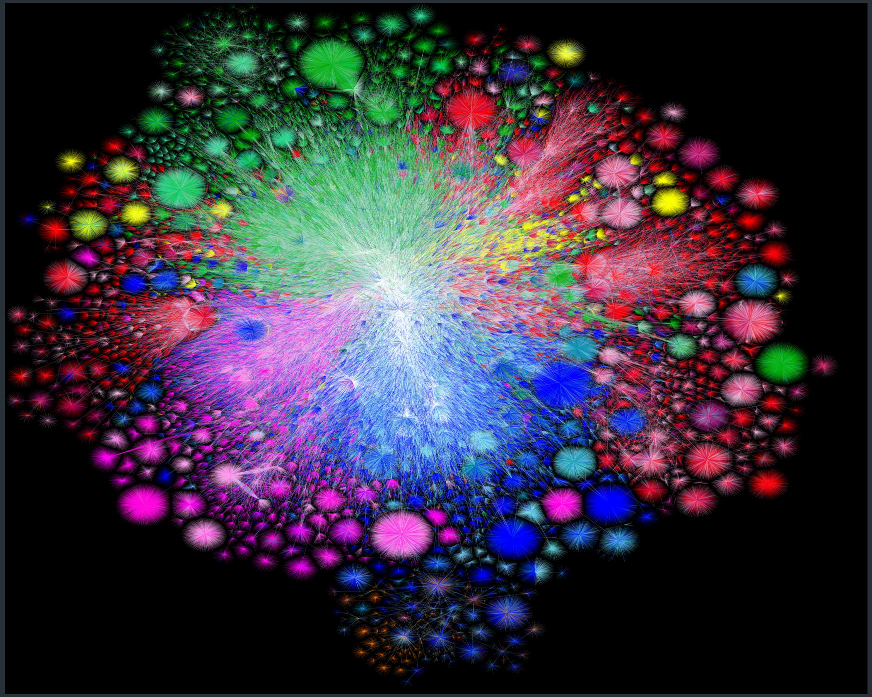
When you're building programs, you usually work here

How to make apps use the network?

```
print("Hello world")
```

↓

```
send("Hello world")
```



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```
print("Hello world")
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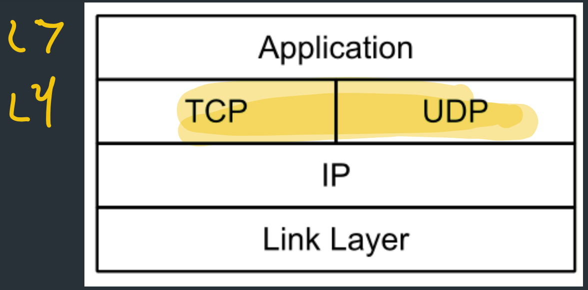
⇒ Want to send useful messages , not packets

⇒ Don't have to care about how path packet takes to get from A->B, we just want it to get there

Apps rely on: transport layer (layer 4)



API

- Generally provided by OS as socket interface
- For app, creates a "pipe" to send/recv data to/from another endpoint (think like a file descriptor)

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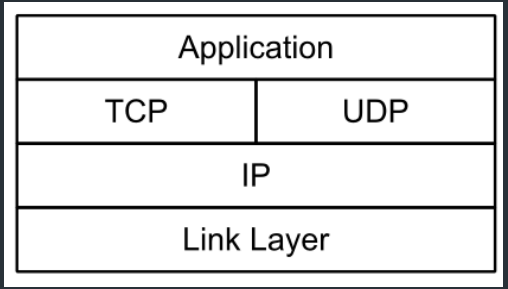
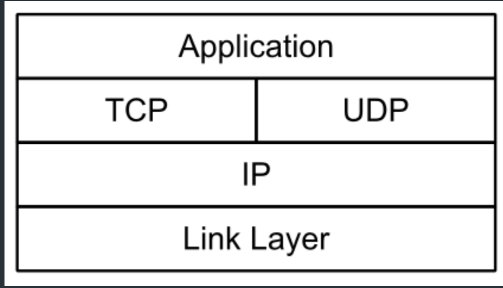


- Generally provided by OS as socket interface
- For app, creates a "pipe" to send/recv data to/from another endpoint (think like a file descriptor)
- OS keeps track of sockets which sockets belong to which app => multiplexing

Key transport layer details for now

- Multiplexing provided by port numbers
  - 16-bit number 0 – 65535
  - Servers use well-known port numbers, clients typically choose one at random



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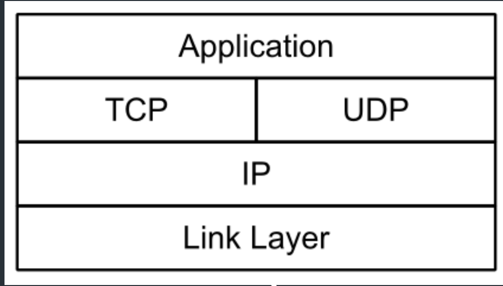

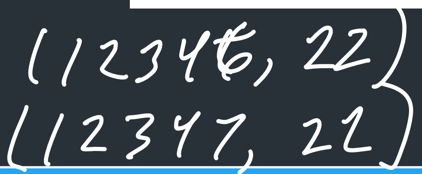

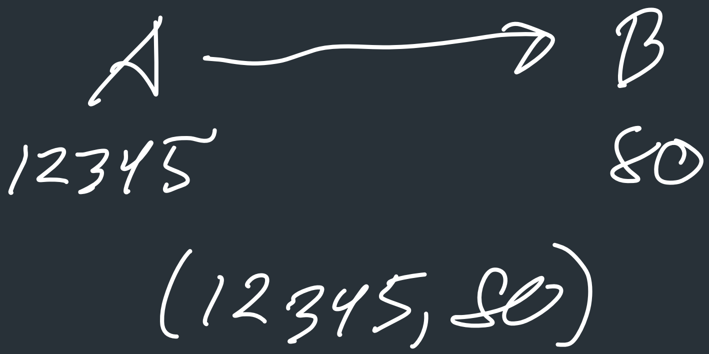

Port	Service
22	Secure Shell (SSH)
25	SMTP (Email)
80	HTTP (Web traffic)
443	HTTPS (Secure Web traffic)
16800	Snowcast

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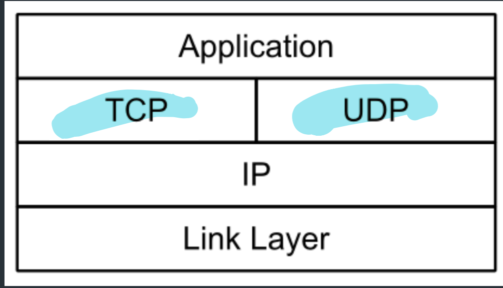

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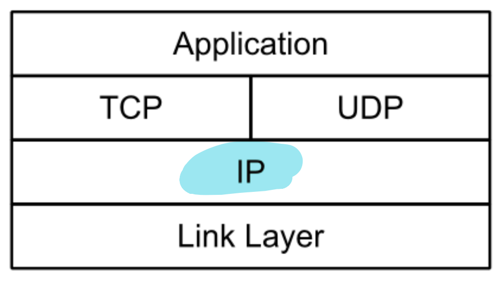
- Two main forms
  - TCP: reliable transport
  - UDP: unreliable transport

(more details later)

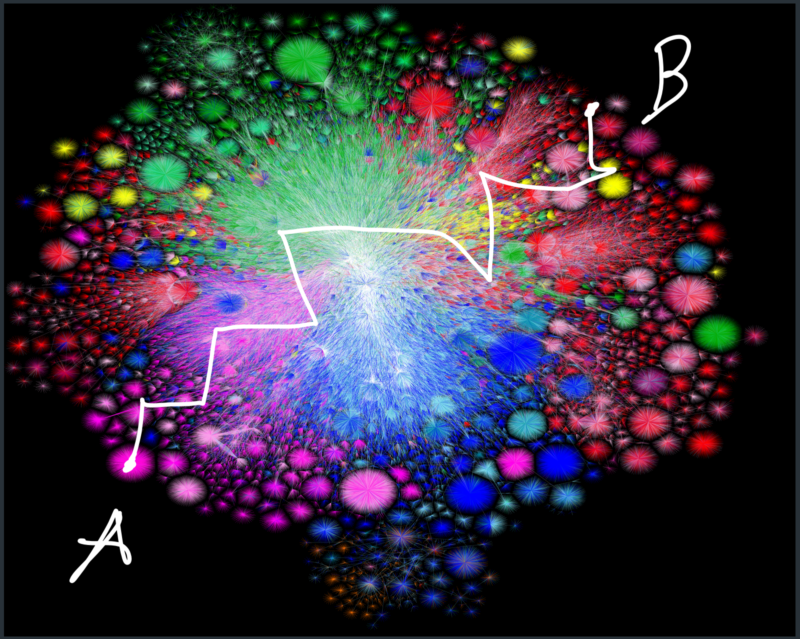
What service does the transport layer need?

Layer 3: Network layer



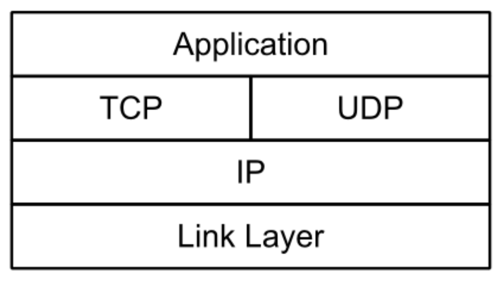
Provided by: Internet Protocol (IP)

- Move packets between any two hosts anywhere on the Internet
- Responsible for routing and forwarding between nodes



IPv4 IPv6

Layer 3: Network layer



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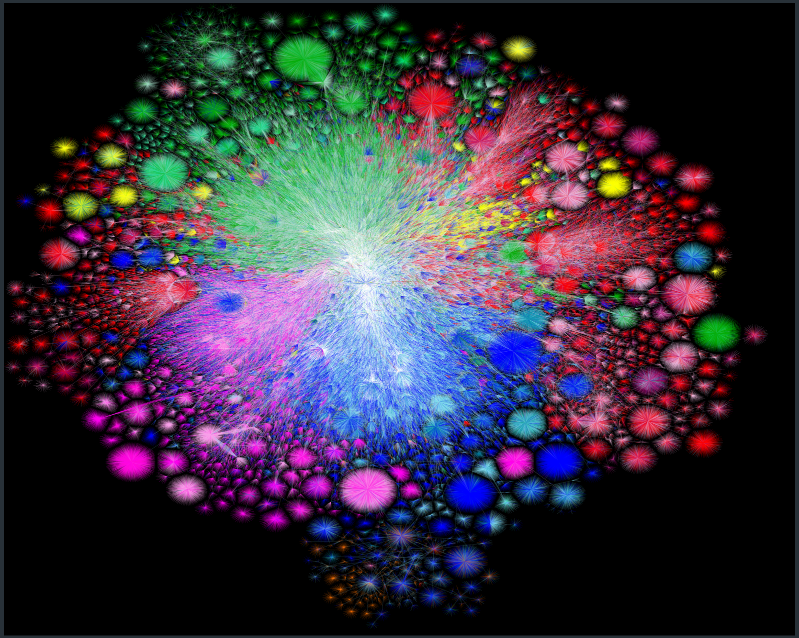

- Every host has a unique address:

www.cs.brown.edu => 128.148.32.110

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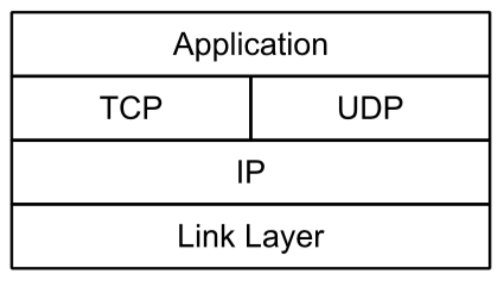

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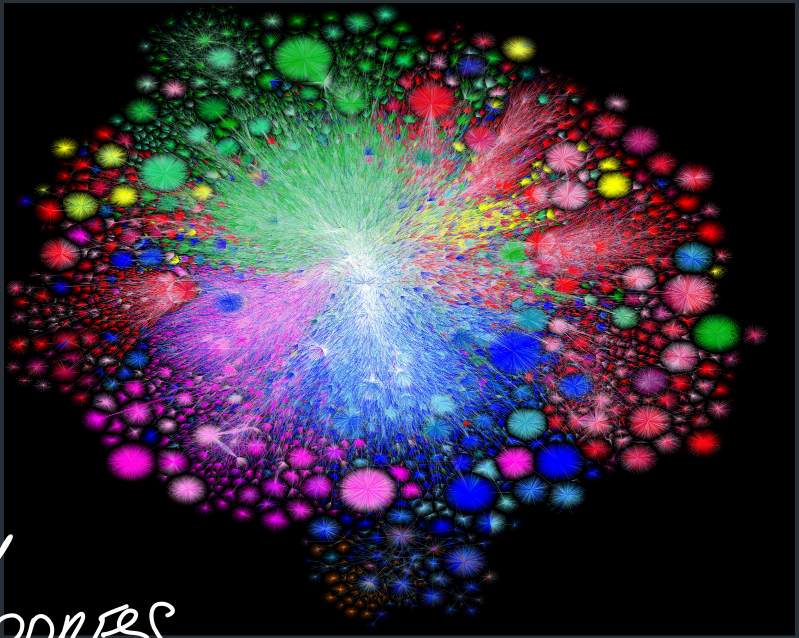

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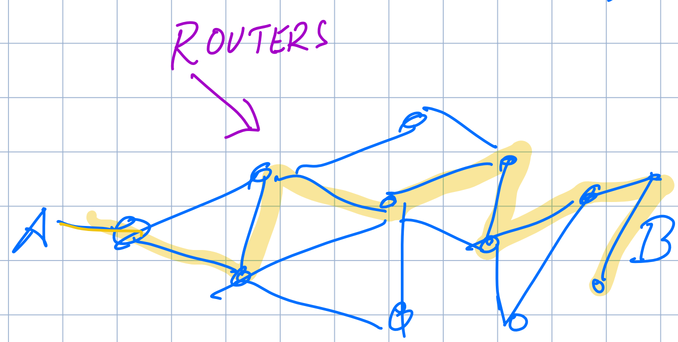
IPv4 ADDRESS

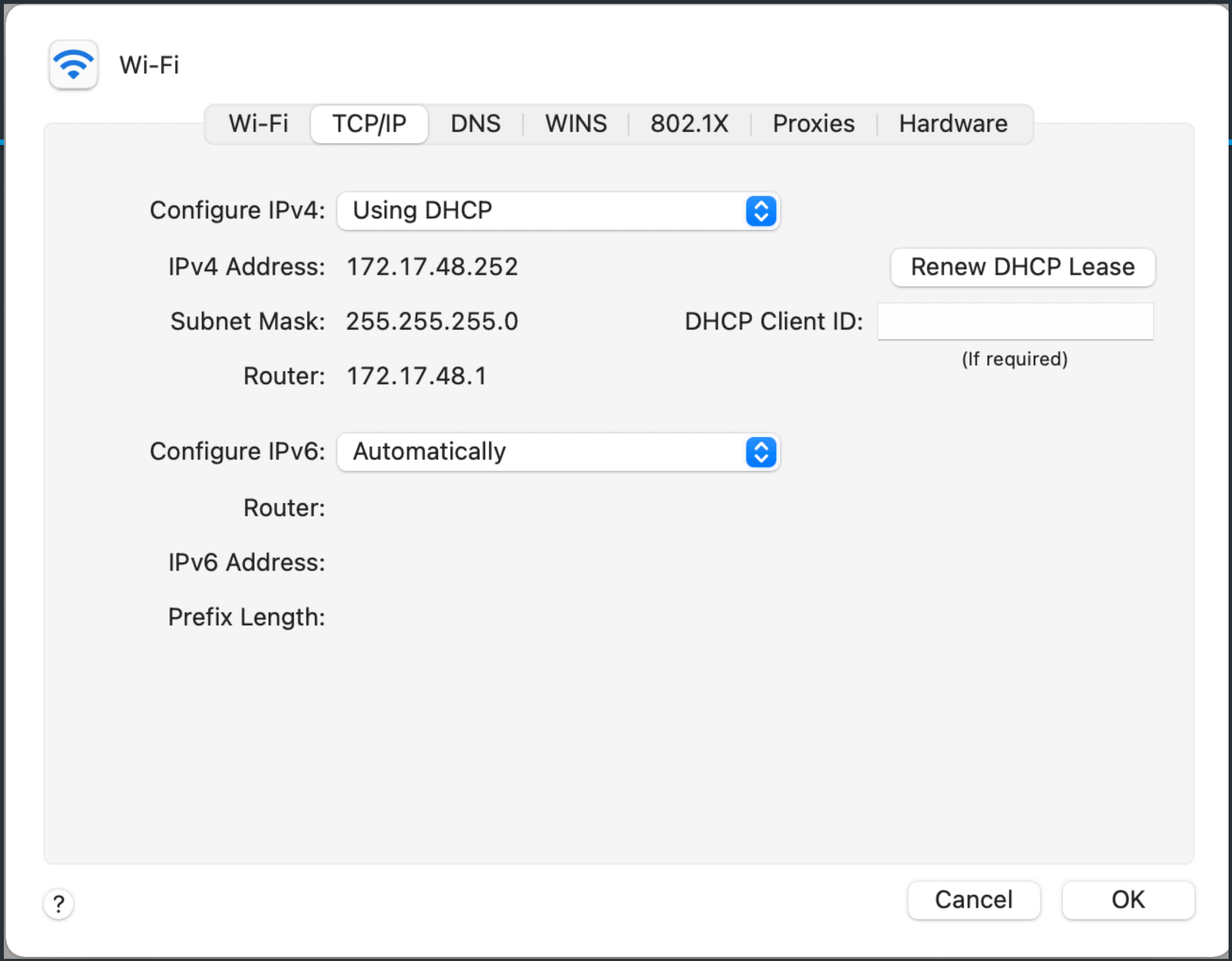
Given address, the network knows how to get the packet there

L4
TRANSPORT

L3
NETWORK

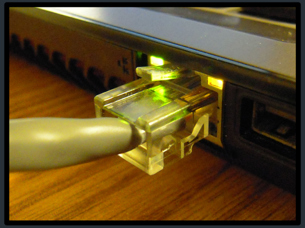


148.128.34.110
128.148.x.x


Wi-Fi
Wi-Fi
TCP/IP
DNS
WINS
802.1X
Proxies
Hardware
Configure IPv4:
Using DHCP
IPv4 Address:
172.17.48.252
Renew DHCP Lease
Subnet Mask:
255.255.255.0
DHCP Client ID:
(If required)
Router:
172.17.48.1
Configure IPv6:
Automatically
Router:
IPv6 Address:
Prefix Length:
?
Cancel
OK

Link layer (L2)

- Internet == Network of networks
- Networks are made up of many different types of links!
- Each type of link has its own challenges, protocols, etc depending on the medium



Examples

- Wifi
- Cellular Data
- Ethernet
- Fiber optic
- …

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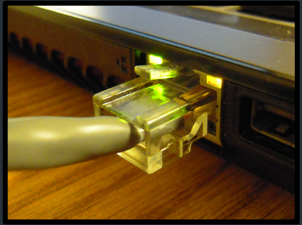

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- WIFI
- CELLULAR
- ETHERNET

Examples
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The OS sees links as interfaces
=> Each one probably has a driver that implements that particular protocol

Physical layer (Layer 1)

- How we move packets across one individual link
- Deals with individual bits
- More about electrical engineering/physics than computer science
- We'll talk about this briefly

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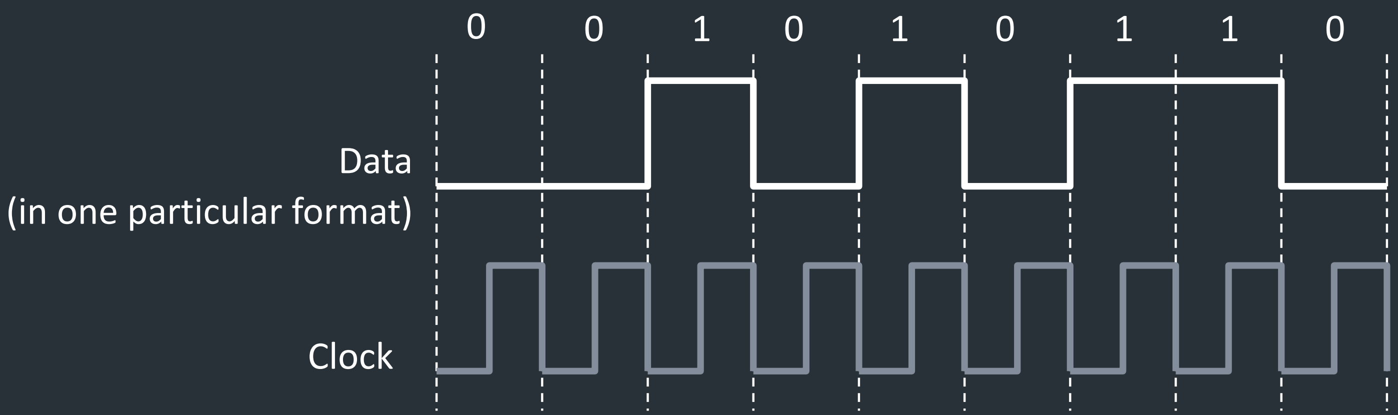

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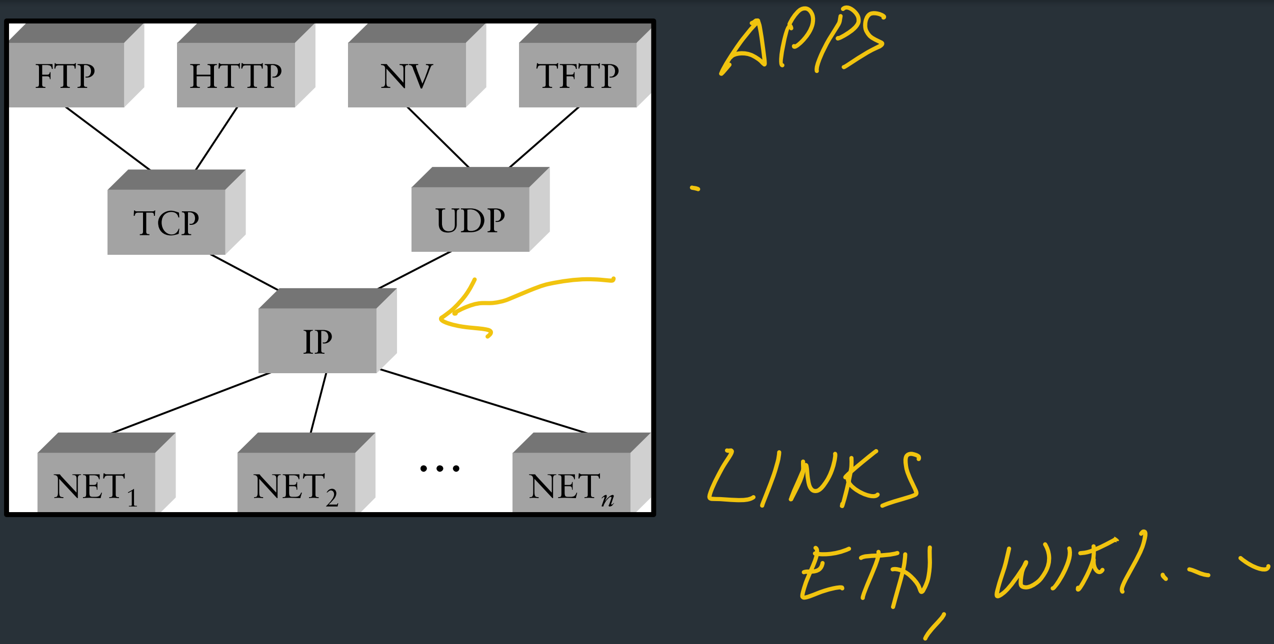
IP: the "Narrow Waist"



- Applications built using IP; IP, Designed to connect many networks
- "Hourglass" structure => one (actually two) core abstractions!

What you should take away from this

Each layer is defined by some protocol

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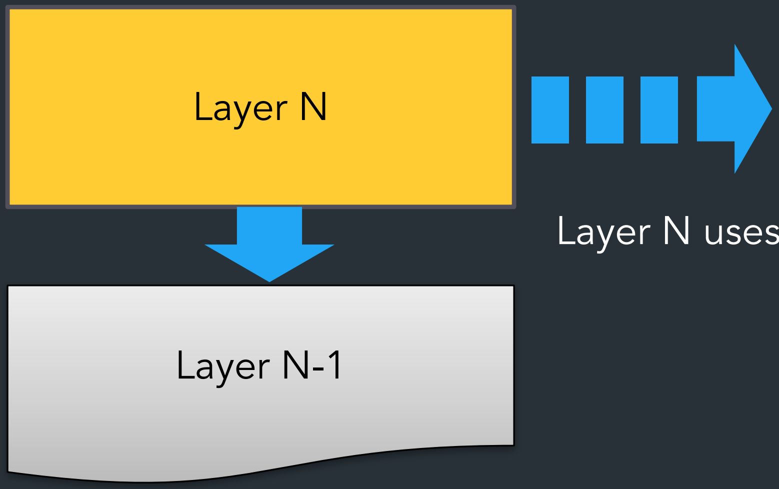

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Layer N uses the services provided by N-1 to operate

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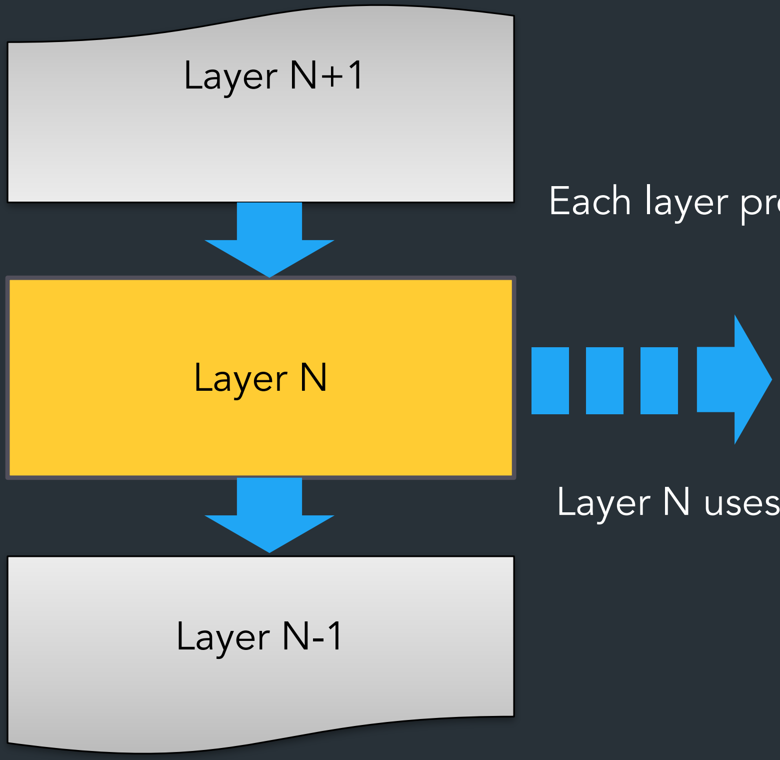

Each layer provides a service for the layers “above” it

Each layer is defined by some protocol

Layer N uses the services provided by N-1 to operate

Why do we do this?

- Helps us manage complexity
- Different implementations at one “layer” use same interface
- Allows independent evolution

To recap

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3. Network

Service: move packets to any other node in the network
IP: Unreliable, best-effort service model

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Where do we handle, eg, security, reliability, fairness?

How/where to handle challenges?

- Can decide on how to distribute certain problems
  - What services at which layer?
  - What to leave out?
  - More on this later (End-to-end principle)

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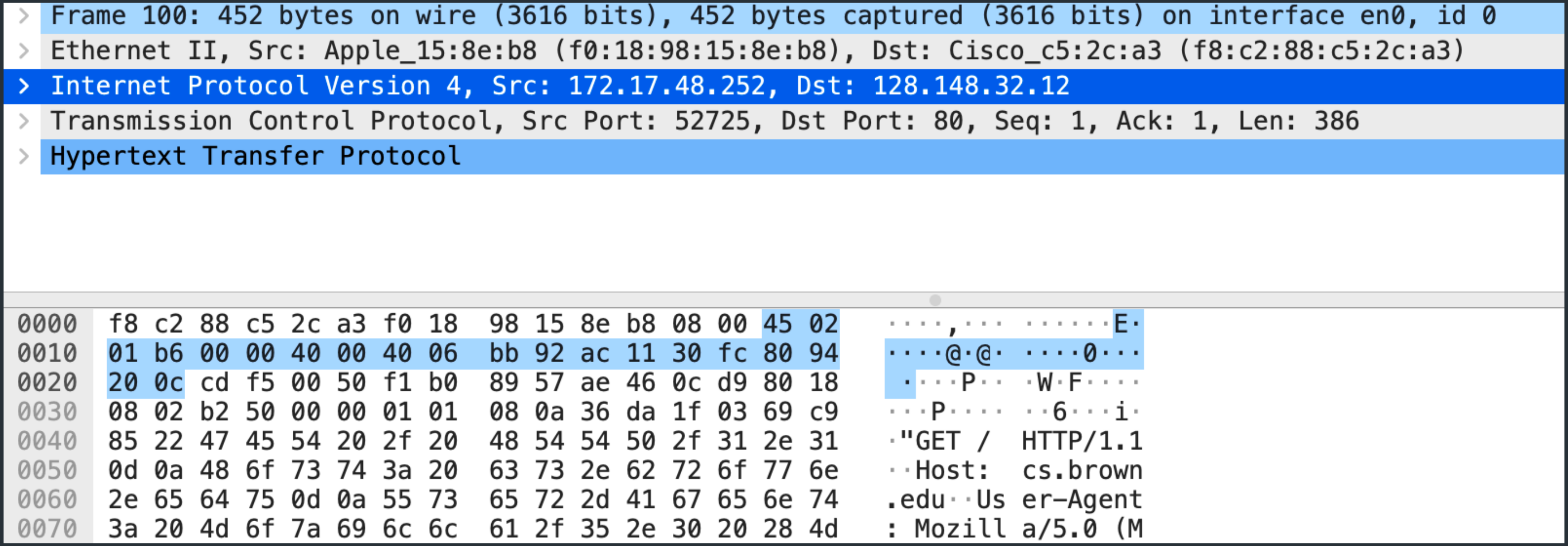
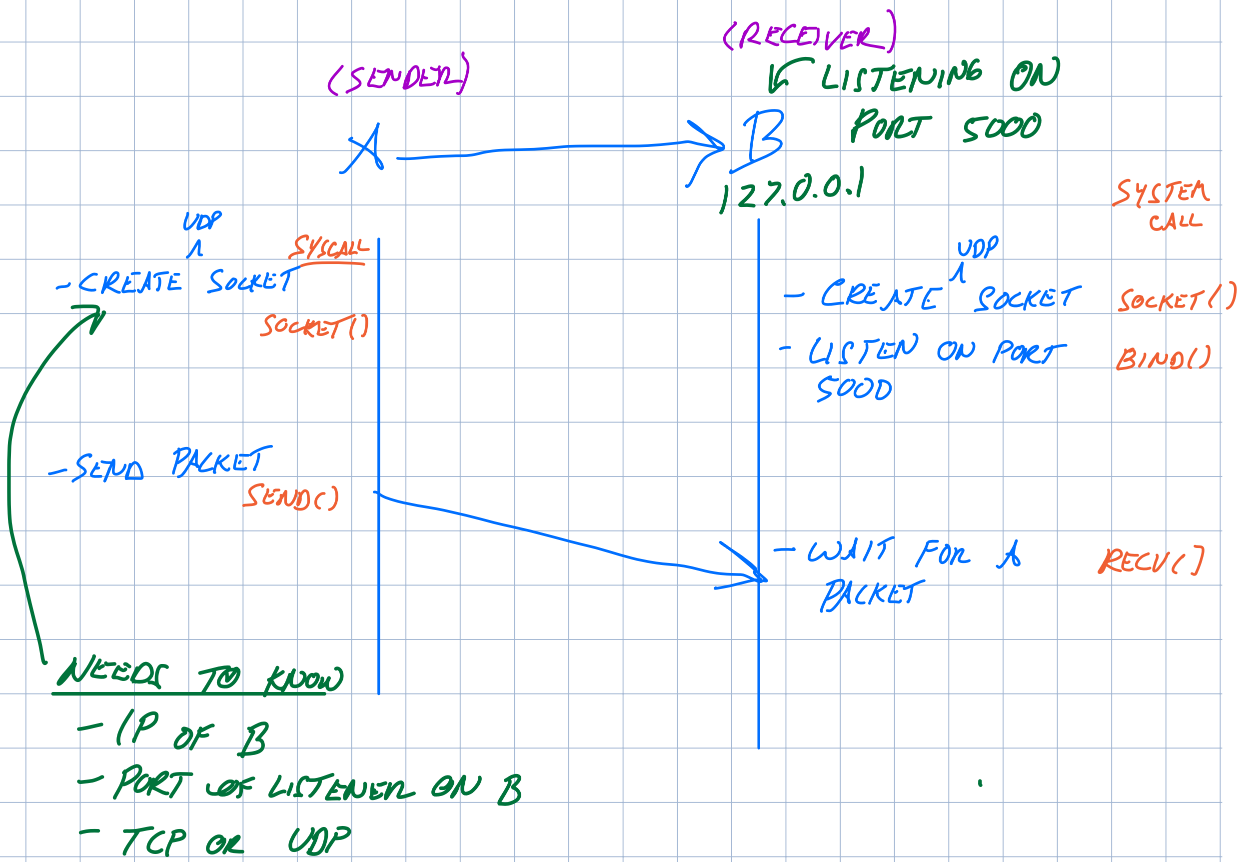
Get to decide where (and if) to pay the "cost" of certain features

Anatomy of a packet



UDP EXAMPLE


(SENDER)
A
(RECEIVER)
LISTENING ON PORT 5000
B
127.0.0.1
UDP
SYSCALL
- CREATE SOCKET
SOCKET()
- SEND PACKET
SEND()
SYSTEM CALL
UDP
- CREATE SOCKET
SOCKET()
- LISTEN ON PORT 5000
BIND()
- WAIT FOR A PACKET
RECV()
NEEDS TO KNOW
- IP OF B
- PORT OF LISTENER ON B
- TCP OR UDP

MORE CONTENT WE WILL COVER LATER ⟶

(FEEL FREE TO READ AHEAD, THOUGH)

Transport: UDP and TCP

UDP and TCP: most popular protocols atop IP

- Both use 16-bit port number & 32-bit IP address
- Applications bind a port & receive traffic on that port

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- UDP – User (unreliable) Datagram Protocol
  - Send packets to a port (… and not much else)
  - Sent packets may be dropped, reordered, even duplicated
- TCP – Transmission Control Protocol
  - Provides illusion of reliable ‘pipe’ or ‘stream’ between two processes anywhere on the network
  - Handles congestion and flow control

Uses of TCP

- Most applications use TCP
  - Easier to program (reliability is convenient)
  - Automatically avoids congestion (don't need to worry about taking down the network
- Servers typically listen on well-known ports:
  - SSH: 22
  - SMTP (email): 25
  - HTTP (web): 80, 443

Uses of UDP

In general, when you have concerns other than a reliable “stream” of packets:

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Examples

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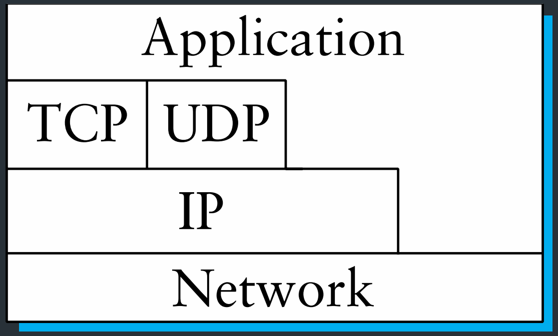
- Streaming multimedia/gaming (sometimes)

A note on layering



Strict layering not required

- TCP/UDP "cheat" to detect certain errors in IP-level information like address
- Overall, allows evolution, experimentation

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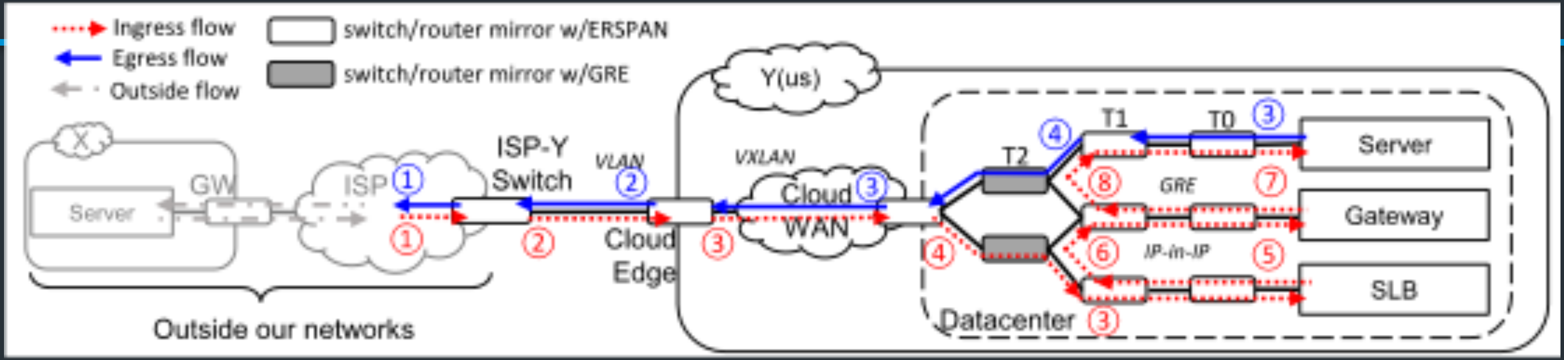
- Layering defines interfaces well
  - What if I get an Ethernet frame, and send it as the payload of an IP packet across the world?
- Layering can be recursive
  - Each layer agnostic to payload!
- Many examples
  - Tunnels: e.g.,
    VXLAN is ETH over UDP (over IP over ETH again…)
  - Our IP assignment: IP on top of UDP "links"

Example



Number	Header Format										
	Headers Added after Mirroring			Mirrored Headers							
①	ETHERNET	IPV4	ERSPAN	ETHERNET						IPV4	TCP
②	ETHERNET	IPV4	ERSPAN	ETHERNET					802.1Q	IPV4	TCP
③	ETHERNET	IPV4	ERSPAN	ETHERNET		IPV4	UDP	VXLAN	ETHERNET	IPV4	TCP
④	ETHERNET	IPV4	GRE			IPV4	UDP	VXLAN	ETHERNET	IPV4	TCP
⑤	ETHERNET	IPV4	ERSPAN	ETHERNET	IPV4	IPV4	UDP	VXLAN	ETHERNET	IPV4	TCP
⑥	ETHERNET	IPV4	GRE		IPV4	IPV4	UDP	VXLAN	ETHERNET	IPV4	TCP
⑦	ETHERNET	IPV4	ERSPAN	ETHERNET		IPV4	GRE		ETHERNET	IPV4	TCP
⑧	ETHERNET	IPV4	GRE			IPV4	GRE		ETHERNET	IPV4	TCP

* This is just an example, do not worry about the details, or the specific protocols!

From: Yu et al., A General, Easy to Program and Scalable Framework for Analyzing In-network Packet Traces, NSDI 2019

How do we use these protocols?

Using TCP/IP

How can applications use the network?

- Sockets API.
  - Originally from BSD, widely implemented (*BSD, Linux, Mac OS, Windows, …)
  - Important to know and do once
  - Higher-level APIs build on them

- After basic setup, it’s a lot like working with files

Sockets: Communication Between Machines

- Network sockets are file descriptors too
- Datagram sockets (eg. UDP): unreliable message delivery
  - Send atomic messages, which may be reordered or lost
- Stream sockets (TCP): bi-directional pipes
  - Stream of bytes written on one end, read on another
  - Reads may not return full amount requested, must re-read

System calls for using TCP

Client

Server

System calls for using TCP

Client

Server

`socket` – make socket

System calls for using TCP

<u>Client</u>

<u>Server</u>

`socket` – make socket

`bind` – assign address, port

System calls for using TCP

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`socket` – make socket

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`listen` – listen for clients

System calls for using TCP

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`socket` – make socket

Server

`socket` – make socket

`bind` – assign address, port

`listen` – listen for clients

System calls for using TCP

<u>Client</u>

`socket` – make socket

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System calls for using TCP

Server

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`listen` – listen for clients

Client

`socket` – make socket

`bind*` – assign address

`connect` – connect to listening socket

System calls for using TCP

<u>Client</u>

<u>Server</u>

`socket` – make socket

`bind` – assign address, port

`listen` – listen for clients

`socket` – make socket

`bind*` – assign address

`connect` – connect to listening socket

`accept` – accept connection

- This call to bind is optional, connect can choose address & port.

Socket Naming

- TCP & UDP name communication endpoints
  - IP address specifies host (128.148.32.110)
  - 16-bit port number demultiplexes within host
  - Well-known services listen on standard ports (e.g. ssh – 22, http – 80, mail – 25)
  - Clients connect from arbitrary ports to well known ports
- A connection is named by 5 components
  - Protocol, local IP, local port, remote IP, remote port

Dealing with Data

- Many messages are binary data sent with precise formats

- Data usually sent in Network byte order (Big Endian)
  - Remember to always convert!
  - In C, this is htons(), htonl(), ntohs(), ntohl()