Operating Systems and Networks

Networks Part 1: Introduction

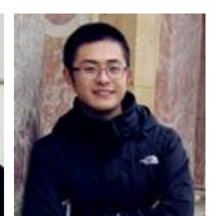
Adrian Perrig
Network Security Group
ETH Zürich

Welcome!

- Brief introduction of lecturer and TAs
  - Adrian Perrig, Professor in Department of Computer Science, Director of Network Security Group
  - Qi Li, PhD
  - Jun Han, Tae-Ho Lee, Chris Pappas, Yao Zhang
  - Network security group research area: design and implementation of secure future Internet architecture (SCION project)





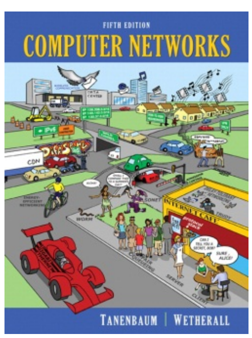
Lecture Style

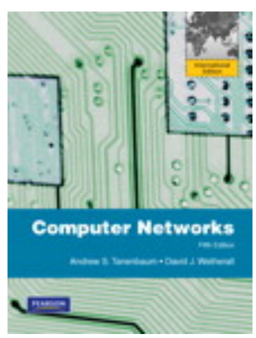
- Student interaction is encouraged!
  - Please ask questions if something is unclear
  - Please point out any errors that you spot
  - Please focus on lecture instead of facebook, twitter, etc.
    - Please turn off cell phone during class

3

Textbook and Slide Credit

- Textbook: TANENBAUM, ANDREW S.; WETHERALL, DAVID J., COMPUTER NETWORKS, 5th Edition, 2011.
- Slides adapted from slide deck by David Wetherall



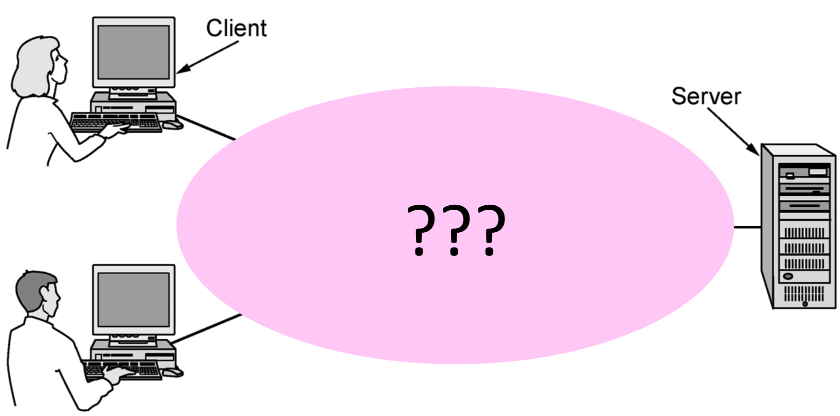


Study Recommendations

- Make list of acronyms, concepts
- Read corresponding sections in text book
  - Available in INFK library
- Participate in exercise sessions, solve homework, and DO THE LABS!

5

Focus of the course



6

Focus of the course (2)

- Three “networking” topics:

Distributed systems
Networking
Communications

- We mainly study the Networking aspects

The Main Point

1. To learn how the Internet works »
   - What really happens when you “browse the web”?
   - What are TCP/IP, DNS, HTTP, NAT, VPNs, 802.11 etc. anyway?

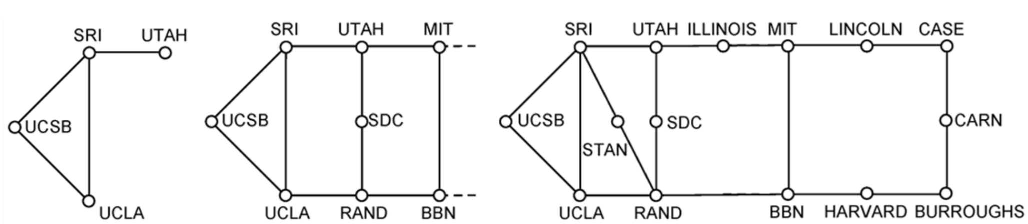
2. To learn the fundamentals of computer networks

Why learn about the Internet?

1. Curiosity »
2. Impact on our world »
3. Job prospects!

From this experimental network …

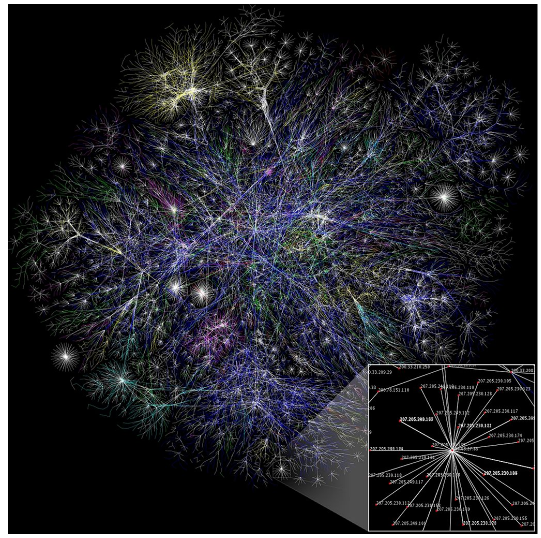
ARPANET ~1970



(a) Dec. 1969. (b) July 1970. (c) March 1971.

To this! Internet ~2005

- An everyday institution used at work, home, and on-the-go
- Visualization contains millions of links



Attribution: By The Opte Project [CC-BY-2.5], via Wikimedia Commons

Computer Networks 11

Internet – Societal Impact

- An enabler of societal change
  - Easy access to knowledge
  - Electronic commerce
  - Personal relationships
  - Discussion without censorship

WIKIPEDIA
PayPal
match.com
Tor

Computer Networks 12

Internet – Economic impact

- An engine of economic growth
  - Advertising-sponsored search
  - "Long tail" online stores
  - Online marketplaces
  - Crowdsourcing

Computer Networks 13

The Main Point (2)

1. To learn how the Internet works
2. To learn the fundamentals of computer networks
   - What hard problems must they solve?
   - What design strategies have proven valuable?

Computer Networks 14

Why learn the Fundamentals?

1. Apply to all computer networks
2. Intellectual interest »
3. Change / reinvention »

Fundamentals – Intellectual Interest

- Example key problem: Reliability!
  - Any part of the Internet might fail
  - Messages might be corrupted
  - So how do we provide reliability?
- Reliability solutions
  - Codes to detect/correct errors
  - Routing around failures ...

Fundamentals – Intellectual Interest (2)

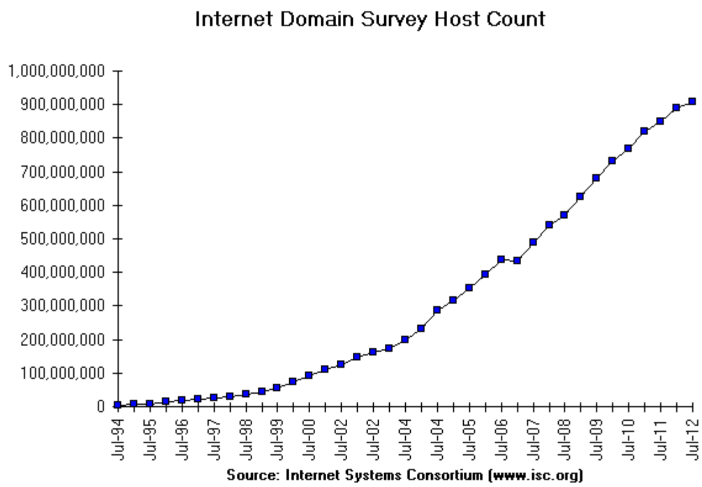
Key problem	Example solutions
Reliability despite failures	Codes for error detection/correction (§3.2, 3.3) Routing around failures (§5.2)
Network growth and evolution	Addressing (§5.6) and naming (§7.1) Protocol layering (§1.3)
Allocation of resources like bandwidth	Multiple access (§4.2) Congestion control (§5.3, 6.3)
Security against various threats	Confidentiality of messages (§8.2, 8.6) Authentication of communicating parties (§8.7)

Fundamentals – Reinvention

- The Internet is constantly being re-invented!
  – Growth over time and technology trends drive upheavals in Internet design and usage »
- Today's Internet is different from yesterday's
  – And tomorrow's will be different again
  – But the fundamentals remain the same

Fundamentals – Reinvention (2)

- At least a billion Internet hosts and growing …



Fundamentals – Reinvention (3)

- Examples of upheavals in the past 1-2 decades

Growth / Tech Driver	Upheaval
Emergence of the web	Content Distribution Networks
Digital songs/videos	Peer-to-peer file sharing
Falling cost/bit	Voice-over-IP calling
Many Internet hosts	IPv6
Wireless advances	Mobile devices

Not a Course Goal

- To learn IT job skills
  - How to configure equipment
    - e.g., Cisco certifications
  - But course material is relevant, and we use hands-on tools

Example Uses of Networks

- Work:
  - Email, file sharing, printing, …
- Home:
  - Movies / songs, news, calls / video / messaging, e-comm
- Mobile:
  - Calls / texts, games, videos, maps, information access …

What do these uses tell us about why we build networks?

For User Communication

- From the telephone onwards:
  - VoIP (voice-over-IP)
  - Video conferencing
  - Instant messaging
  - Social networking

→Enables remote communication
  - Need low latency for interactivity

For Resource Sharing

- Many users may access the same underlying resource
  - E.g., 3D printer, search index, machines in the cloud

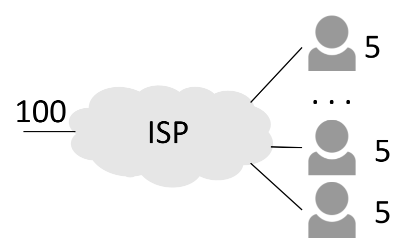
→More cost effective than dedicated resources per user
  - Even network links are shared via statistical multiplexing »

Statistical Multiplexing

- Sharing of network bandwidth between users according to the statistics of their demand
  - (Multiplexing just means sharing)
  - Useful because users are mostly idle and their traffic is bursty
- Key question:
  - How much does it help?

Statistical Multiplexing (2)

- Example: Users in an ISP network
  - Network has 100 Mbps (units of bandwidth)
  - Each user subscribes to 5 Mbps, for videos
  - But a user is active only 50% of the time …

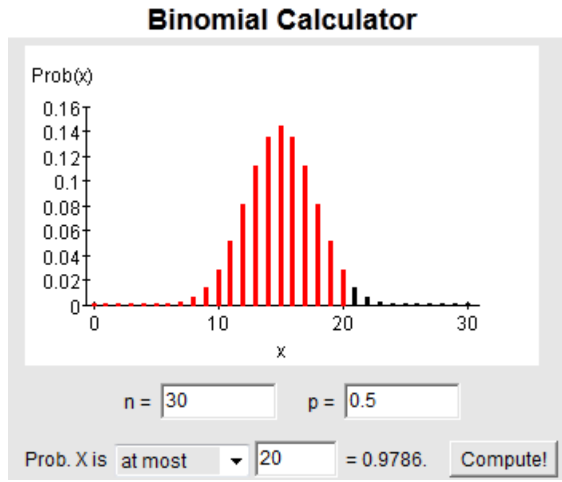


- How many users can the ISP support?
  - With dedicated bandwidth for each user:
  - Probability all bandwidth is used: (assuming independent users)

Statistical Multiplexing (3)

- With 30 independent users, still unlikely (2% chance) to need more than 100 Mbps!
  - Binomial probabilities

→ Can serve more users with the same size network
  - Statistical multiplexing gain is 30/20 or 1.5X
  - But may get unlucky; users will have degraded service



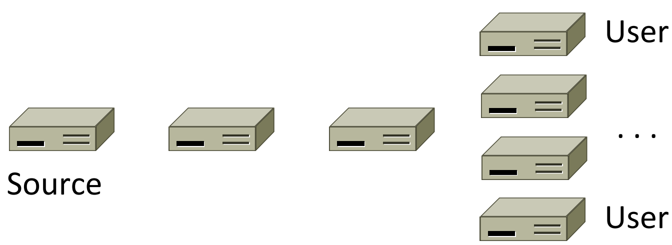
For Content Delivery

- Same content is delivered to many users
  - Videos (large), songs, apps and upgrades, web pages, …

→ More efficient than sending a copy all the way to each user
  - Uses replicas in the network »

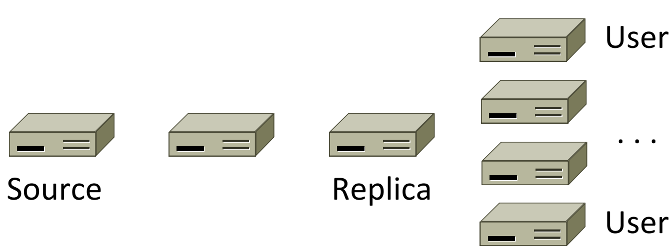
Content Delivery (2)

- Sending content from the source to 4 users takes 4 x 3 = 12 “network hops” in the example



Content Delivery (3)

- But sending content via replicas takes only 4 + 2 = 6 “network hops”



For Computer Communication

- To let computers interact with other computers
  - E.g., e-commerce, reservations

→ Enables automated information processing across different parties

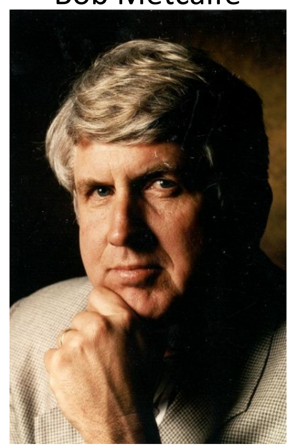
To Connect Computers to the Physical World

- For gathering sensor data, and for manipulating the world
  - E.g., webcams, location on mobile phones, door locks, …
- This is a rich, emerging usage

The Value of Connectivity

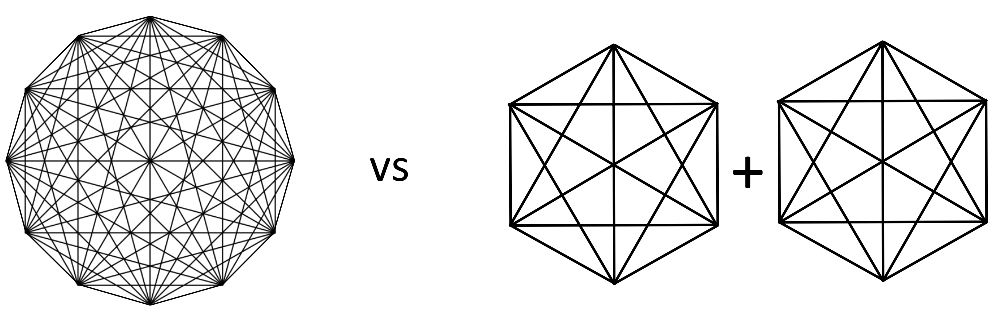
- "Metcalfe's Law" ~1980:
  - The value of a network of N nodes is proportional to N^2
  - Large networks are relatively more valuable than small ones

Bob Metcalfe

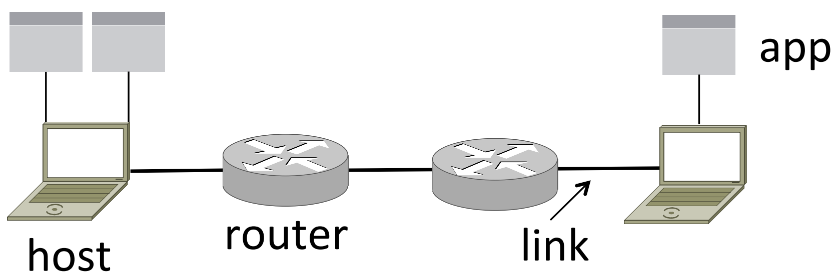


The Value of Connectivity (2)

- Example: both sides have 12 nodes, but the left network has more connectivity



Parts of a Network



Component Names

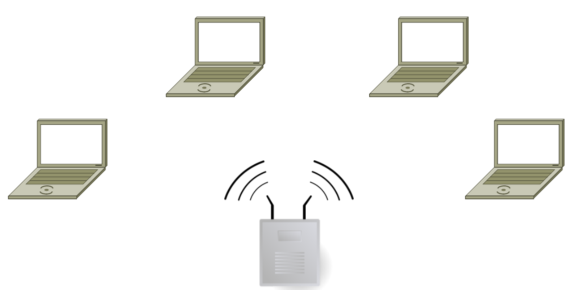
Component	Function	Example
Application, or app, user	Uses the network	Skype, iTunes, Amazon
Host, or end-system, edge device, node, source, sink	Supports apps	Laptop, mobile, desktop
Router, or switch, node, hub, intermediate system	Relays messages between links	Access point, cable/DSL modem
Link, or channel	Connects nodes	Wires, wireless

Types of Links

- <u>Full-duplex</u>
  - Bidirectional
- <u>Half-duplex</u>
  - Bidirectional
- <u>Simplex</u>
  - unidirectional

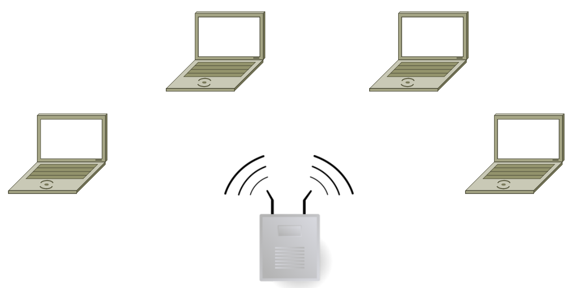
Wireless Links

- Message is <u>broadcast</u>
  - Received by all nodes in range
  - Not a good fit with our model



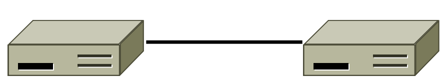
Wireless Links (2)

- Often show logical links
  - Not all possible connectivity

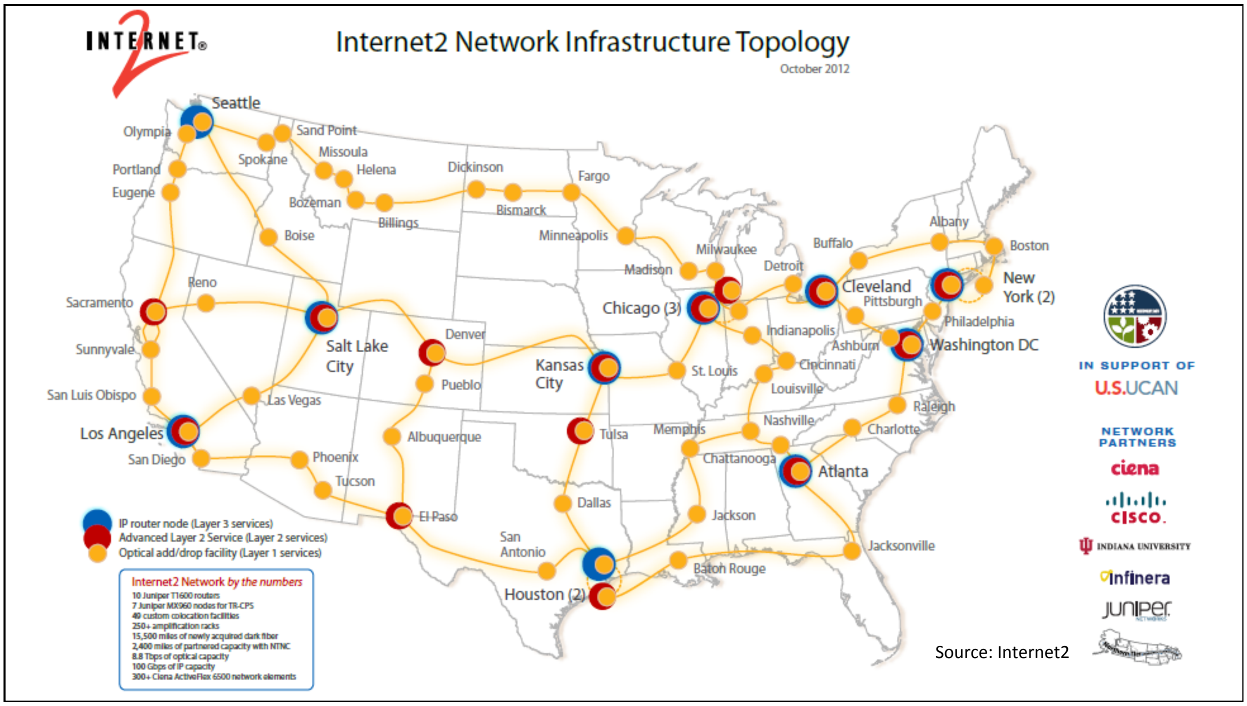


A Small Network

- Connect a couple of computers



- Next, a large network …



Example Networks

- Commonly known by type of technology or their purpose
- [see how many you can give]

Example Networks (2)

- WiFi (802.11)
- Enterprise / Ethernet
- ISP (Internet Service Provider)
- Cable / DSL
- Mobile phone / cellular (2G, 3G, 4G)
- Bluetooth
- Telephone
- Satellite ...

Network names by scale

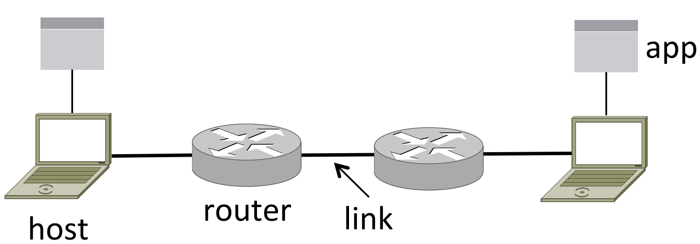
Scale	**Type**	**Example**
Vicinity	PAN (Personal Area Network)	Bluetooth (e.g., headset)
Building	LAN (Local Area Network)	WiFi, Ethernet
City	MAN (Metropolitan Area Network)	Cable, DSL
Country	WAN (Wide Area Network)	Large ISP
Planet	The Internet (network of all networks)	The Internet!

Internetworks

- An internetwork, or internet, is what you get when you join networks together
  - Just another network
- The Internet (capital "I") is the internet we all use

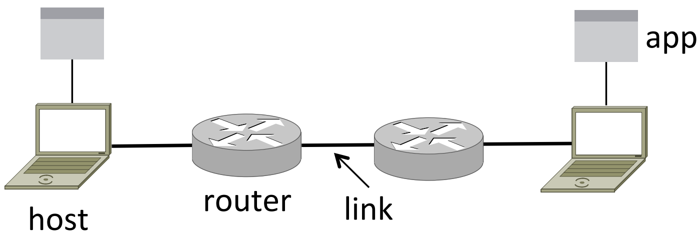
Network Boundaries

- What part is the "network"?



Network Boundaries (2)

- What part represents an "ISP"?

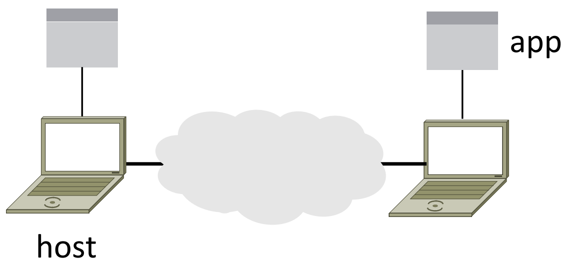


Network Boundaries (3)

- Cloud as a generic network

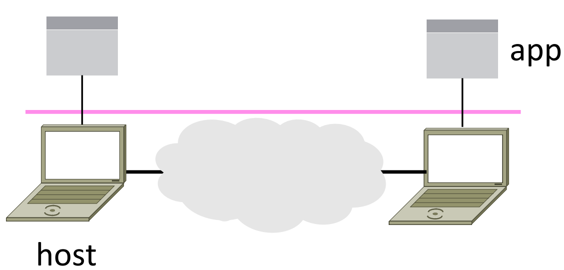
Key Interfaces

- Between (1) apps and network, and (2) network components
  - More formal treatment later on



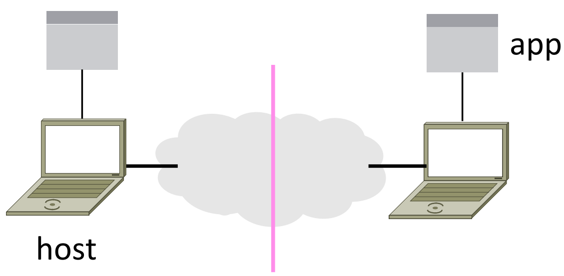
Key Interfaces (2)

1. Network-application interfaces define how apps use the network
   - Sockets are widely used in practice



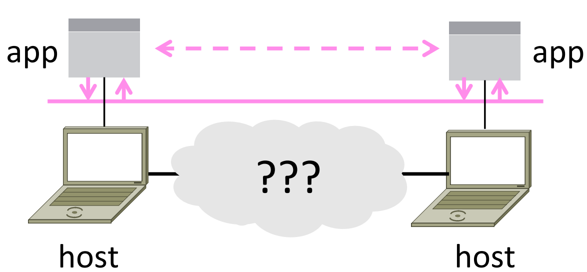
Key Interfaces (3)

2. Network-network interfaces define how nodes work together
   – Traceroute can peek inside the network



Network Service API Hides Details

- Apps talk to other apps with no real idea of what is inside the network
  – This is good! But you may be curious …



Traceroute

- Widely used command-line tool to let hosts peek inside the network
  - On all OSes (tracert on Windows)
  - Developed by Van Jacobson ~1987
  - Uses a network-network interface (IP) in ways we will explain later

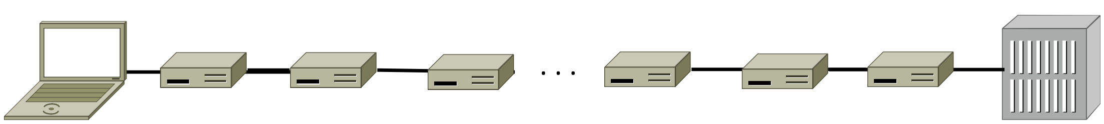
Van Jacobson

: Credit: Wikipedia (public domain)

Computer Networks 53

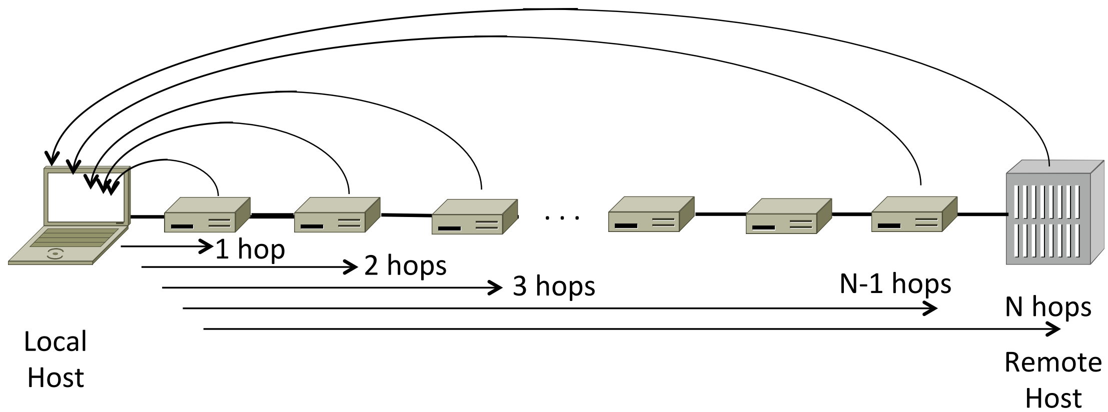
Traceroute (2)

- Probes successive hops to find network path



Computer Networks 54

Traceroute (3)



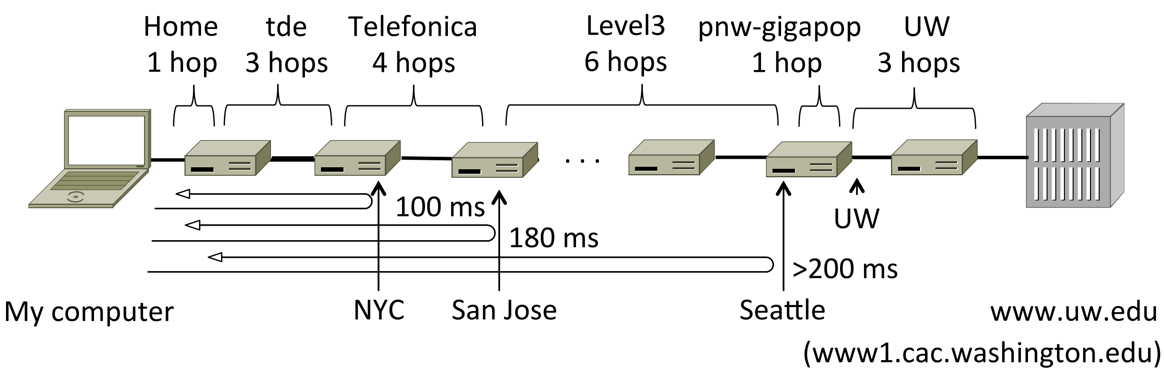
Using Traceroute

Administrator: Command Prompt

```
C:\Users\djw>tracert www.uw.edu

Tracing route to www.washington.edu [128.95.155.134]
over a maximum of 30 hops:

  1     1 ms    <1 ms     2 ms  192.168.1.1
  2     8 ms     8 ms     9 ms  88.Red-80-58-67.staticIP.rima-tde.net [80.58.67.88]
  3    16 ms     5 ms    11 ms  169.Red-80-58-78.staticIP.rima-tde.net [80.58.78.169]
  4    12 ms    12 ms    13 ms  217.Red-80-58-87.staticIP.rima-tde.net [80.58.87.217]
  5     5 ms    11 ms     6 ms  et-1-0-0-1-101-GRTBCNES1.red.telefonica-wholesale.net [94.142.103.20
5]
  6    40 ms    38 ms    38 ms  176.52.250.226
  7   108 ms   106 ms   136 ms  xe-6-0-2-0-grtnycpt2.red.telefonica-wholesale.net [213.140.43.9]
  8   180 ms   179 ms   182 ms  Xe9-2-0-0-grtpaopx2.red.telefonica-wholesale.net [94.142.118.178]
  9   178 ms   175 ms   176 ms  te-4-2.car1.SanJose2.Level3.net [4.59.0.225]
 10   190 ms   186 ms   187 ms  vlan80.csw3.SanJose1.Level3.net [4.69.152.190]
 11   185 ms   185 ms   187 ms  ae-82-82.ebr2.SanJose1.Level3.net [4.69.153.25]
 12   268 ms   205 ms   207 ms  ae-7-7.ebr1.Seattle1.Level3.net [4.69.132.50]
 13   334 ms   202 ms   195 ms  ae-12-51.car2.Seattle1.Level3.net [4.69.147.132]
 14   195 ms   196 ms   195 ms  PACIFIC-NOR.car2.Seattle1.Level3.net [4.53.146.142]
 15   197 ms   195 ms   196 ms  ae0--4000.iccr-sttlwa01-02.infra.pnw-gigapop.net [209.124.188.132]
 16   196 ms   196 ms   195 ms  vl4000.uwbr-ads-01.infra.washington.edu [209.124.188.133]
 17     *        *        *     Request timed out.
 18   201 ms   194 ms   196 ms  ae4--583.uwar-ads-1.infra.washington.edu [128.95.155.131]
 19   197 ms   196 ms   195 ms  www1.cac.washington.edu [128.95.155.134]

Trace complete.
```

Using Traceroute (2)

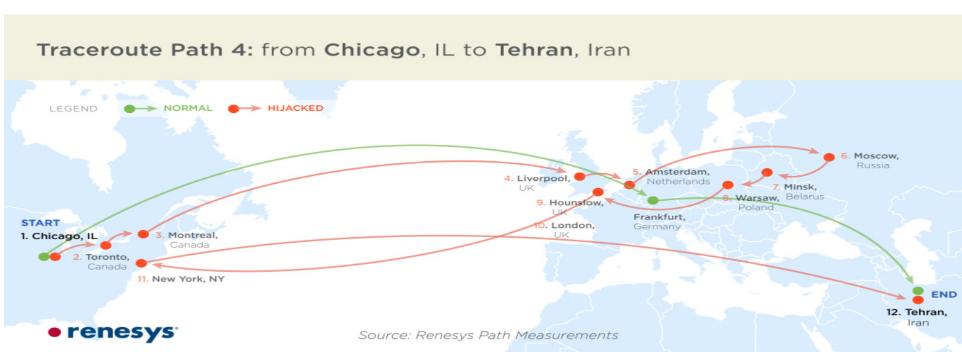
- ISP names and places are educated guesses



Computer Networks 57

Recently, some strange paths observed

- http://www.renesys.com/2013/11/mitm-internet-hijacking/



58

Networks Need Modularity (§1.3)

- The network does much for apps:
  - Make and break connections
  - Find a path through the network
  - Transfers information reliably
  - Transfers arbitrary length information
  - Send as fast as the network allows
  - Shares bandwidth among users
  - Secures information in transit
  - Lets many new hosts be added
  - …

Networks Need Modularity

- The network does much for apps:
  - Make and break connections
  - Lets many new hosts be added
  - …

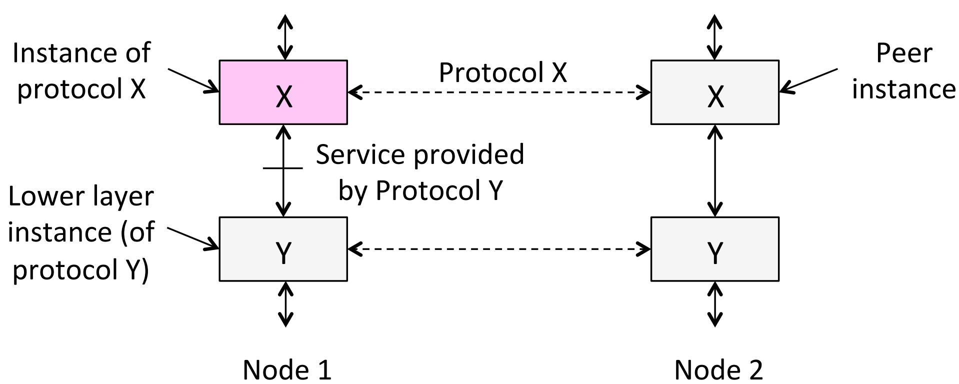
We need a form of modularity, to help manage complexity and support reuse

Protocols and Layers

- Protocols and layering is the main structuring method used to divide up network functionality
  - Each instance of a protocol talks virtually to its peer using the protocol
  - Each instance of a protocol uses only the services of the lower layer

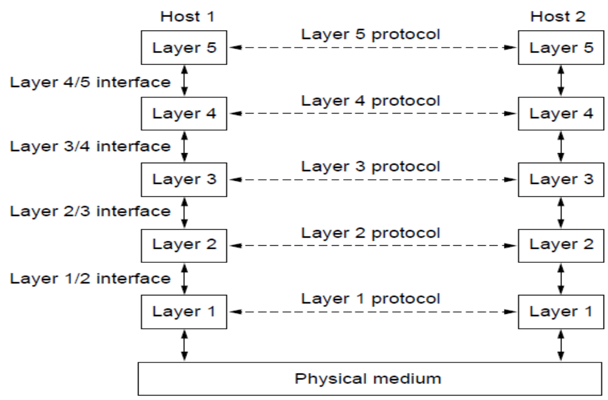
Protocols and Layers (2)

- Protocols are horizontal, layers are vertical



Protocols and Layers (3)

- Set of protocols in use is called a protocol stack

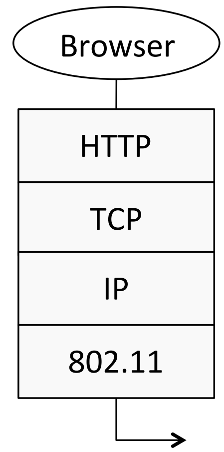


Protocols and Layers (4)

- Protocols you've probably heard of:
  – TCP, IP, 802.11, Ethernet, HTTP, SSL, DNS, … and many more
- An example protocol stack
  – Used by a web browser on a host that is wirelessly connected to the Internet

Protocols and Layers (5)

- Protocols you've probably heard of:
  - TCP, IP, 802.11, Ethernet, HTTP, SSL, DNS, … and many more
- An example protocol stack
  - Used by a web browser on a host that is wirelessly connected to the Internet

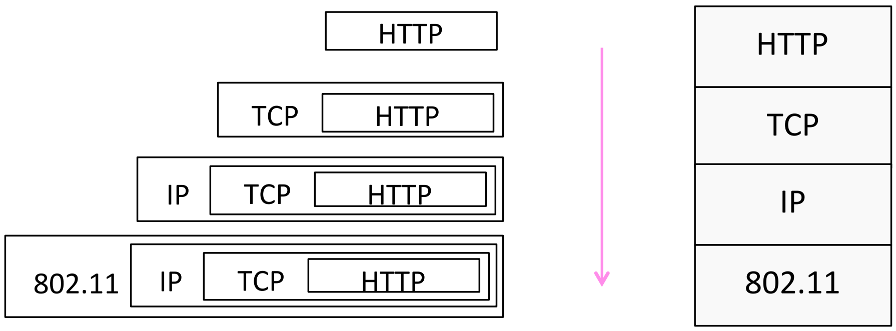


Encapsulation

- Encapsulation is the mechanism used to effect protocol layering
  - Lower layer wraps higher layer content, adding its own information to make a new message for delivery
  - Like sending a letter in an envelope; postal service doesn't look inside

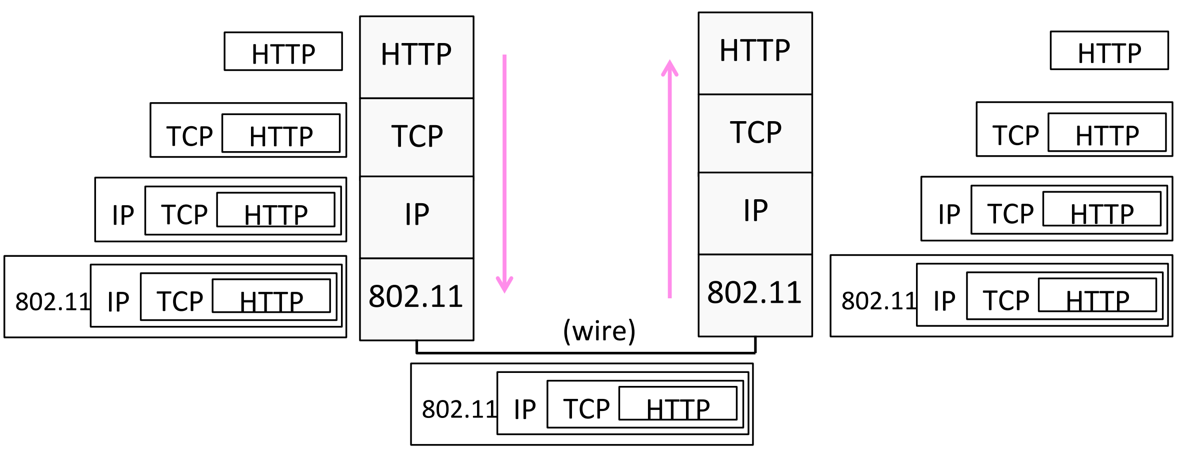
Encapsulation (2)

- Message “on the wire” begins to look like an onion
  - Lower layers are outermost



Computer Networks 67

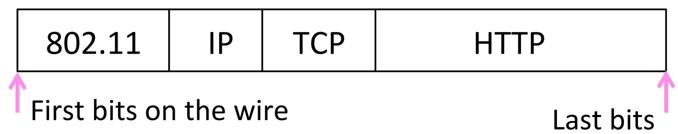
Encapsulation (3)



Computer Networks 68

Encapsulation (4)

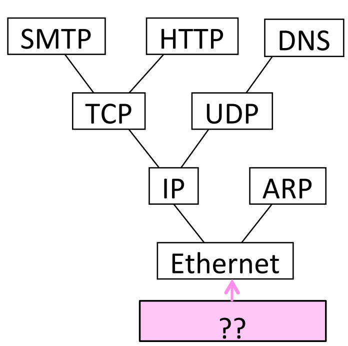
- Normally draw message like this:
  - Each layer adds its own header



- More involved in practice
  - Trailers as well as headers, encrypt/compress contents
  - Segmentation (divide long message) and reassembly

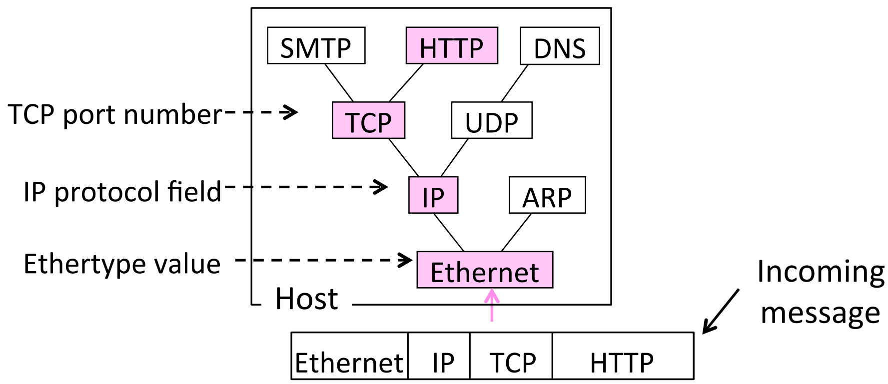
Demultiplexing

- Incoming message must be passed to the protocols that it uses



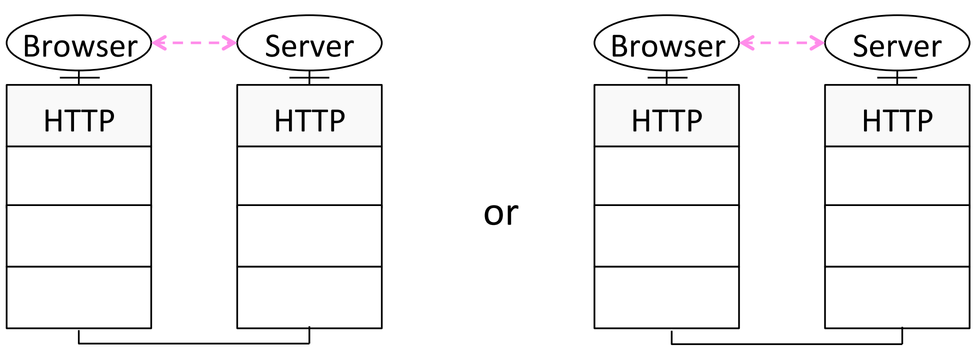
Demultiplexing (2)

- Done with demultiplexing keys in the headers



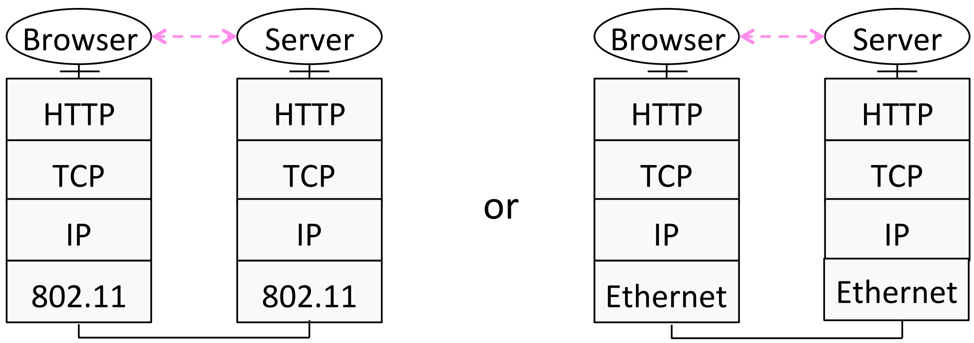
Advantage of Layering

- Information hiding and reuse



Advantage of Layering (2)

- Information hiding and reuse

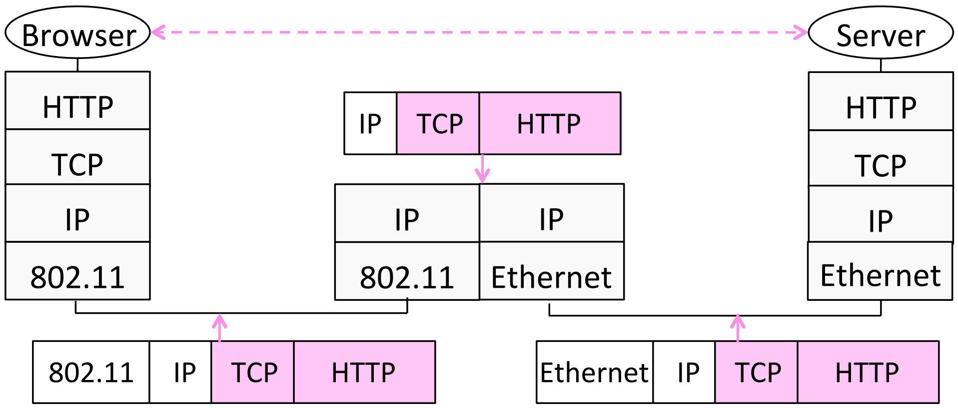


Advantage of Layering (3)

- Using information hiding to connect different systems

Advantage of Layering (4)

- Using information hiding to connect different systems



Computer Networks 75

Disadvantage of Layering

- Adds overhead
  - But minor for long messages
- Hides information
  - App might care whether it is running over wired or wireless!

Computer Networks 76

A Little Guidance Please … (§1.4, §1.6)

- What functionality should we implement at which layer?
  - This is a key design question
  - Reference models provide frameworks that guide us »

Computer Networks 77

OSI "7 layer" Reference Model

- A principled, international standard, to connect systems
  - Influential, but not used in practice. (Woops)

7	Application	– Provides functions needed by users
6	Presentation	– Converts different representations
5	Session	– Manages task dialogs
4	Transport	– Provides end-to-end delivery
3	Network	– Sends packets over multiple links
2	Data link	– Sends frames of information
1	Physical	– Sends bits as signals

Computer Networks 78

Internet Reference Model

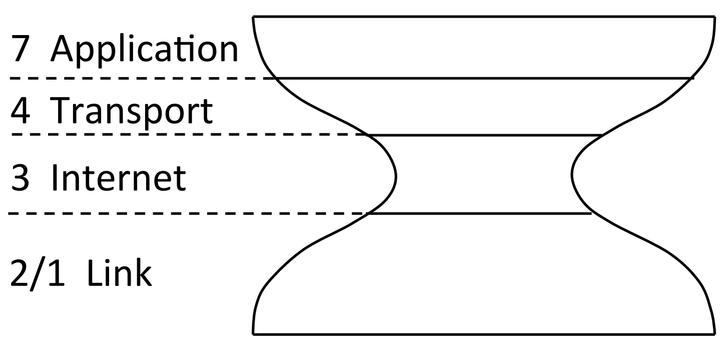
- A four layer model based on experience; omits some OSI layers and uses IP as the network layer.

Application	– Programs that use network service
Transport	– Provides end-to-end data delivery
Internet	– Send packets over multiple networks
Link	– Send frames over a link

Computer Networks 79

Internet Reference Model (2)

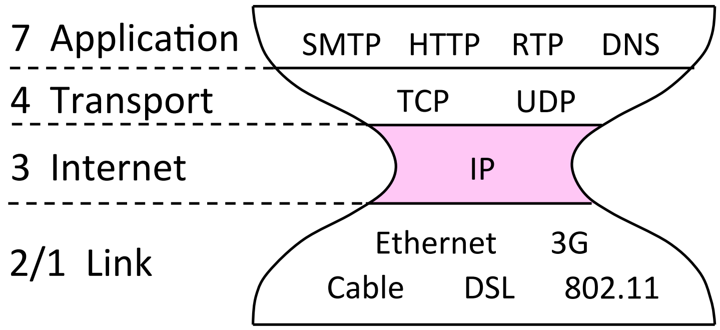
- With examples of common protocols in each layer



Computer Networks 80

Internet Reference Model (3)

- IP is the "narrow waist" of the Internet
  - Supports many different links below and apps above



Standards Bodies

- Where all the protocols come from!
  - Focus is on interoperability

Body	Area	Examples
ITU	Telecom	G.992, ADSL H.264, MPEG4
IEEE	Communications	802.3, Ethernet 802.11, WiFi
IETF	Internet	RFC 2616, HTTP/1.1 RFC 1034/1035, DNS
W3C	Web	HTML5 standard CSS standard

Layer-based Names

- For units of data:

Layer	**Unit of Data**
Application	Message
Transport	Segment
Network	Packet
Link	Frame
Physical	Bit

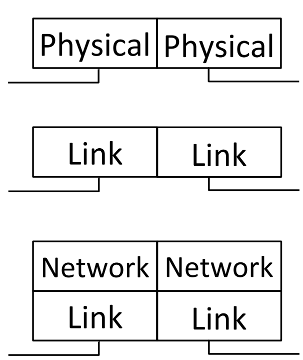
Layer-based Names (2)

- For devices in the network:

Repeater (or hub)

Switch (or bridge)

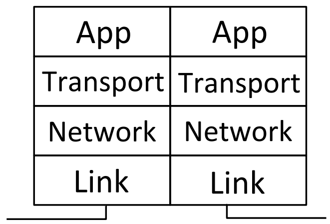
Router



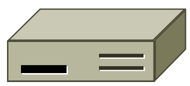
Layer-based Names (3)

- For devices in the network:

Proxy or middlebox or gateway



But they all look like this!



A Note About Layers

- They are guidelines, not strict
  - May have multiple protocols working together in one layer
  - May be difficult to assign a specific protocol to a layer

Course Reference Model

- We mostly follow the Internet
  - A little more about the Physical layer, and alternatives

7	Application	– Programs that use network service
4	Transport	– Provides end-to-end data delivery
3	Network	– Send packets over multiple networks
2	Link	– Send frames over one or more links
1	Physical	– Send bits using signals

Lecture Progression

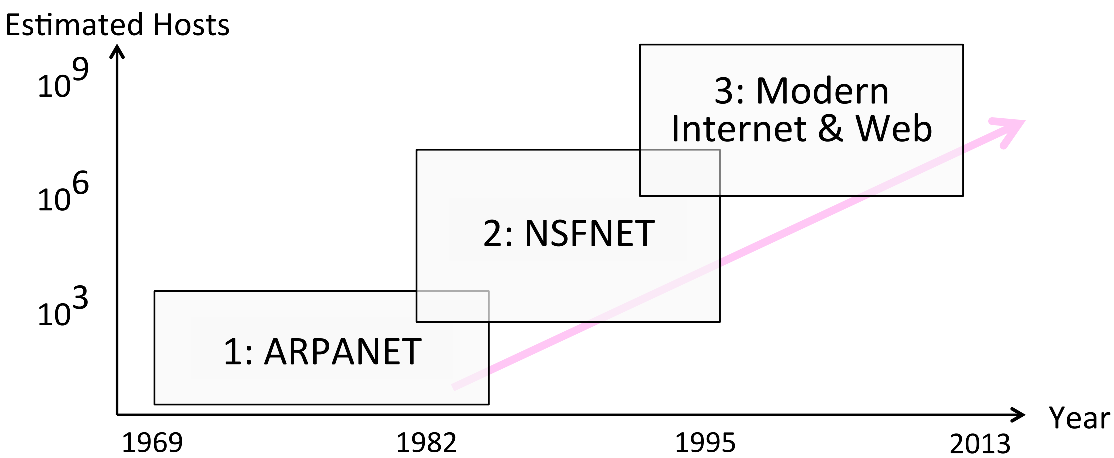
- Bottom-up through the layers:

Application	- HTTP, DNS, CDNs
Transport	- TCP, UDP
Network	- IP, NAT, BGP
Link	- Ethernet, 802.11
Physical	- wires, fiber, wireless

- Followed by more detail on:
  - Quality of service, Security (VPN, SSL)

Bonus Material: History of the Internet
History of the Internet (§1.5.1)

Rough Internet Timeline



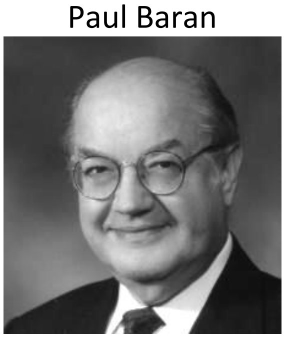
The Beginning – ARPANET

- ARPANET by U.S. DoD was the precursor to the Internet
  - Motivated for resource sharing
  - Launched with 4 nodes in 1969, grew to hundreds of hosts
  - First "killer app" was email

ARPANET – Influences

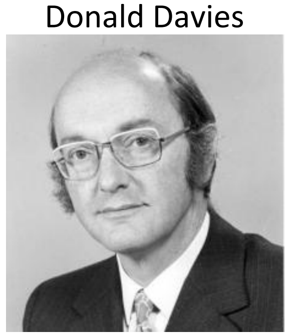
- Leading up to the ARPANET (1960s):
  - Packet switching (Kleinrock, Davies), decentralized control (Baran)

Paul Baran



Credit: Internet Hall of Fame

Donald Davies



Credit: Internet Hall of Fame

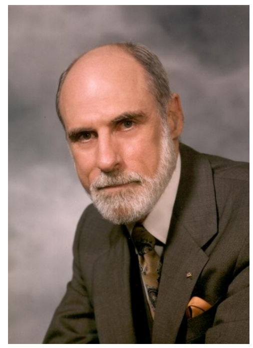
Len Kleinrock

Credit: Internet Hall of Fame

ARPANET – Influences (2)

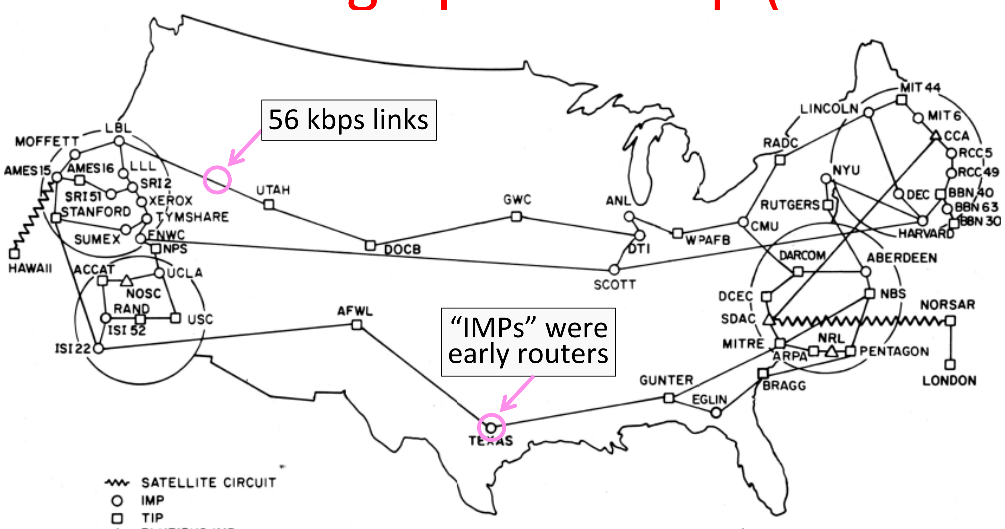
- In the early ARPANET
  - Internetworking became the basis for the Internet
  - Pioneered by Cerf & Kahn in 1974, later became TCP/IP
  - They are popularly known as the "fathers of the Internet"

Vint Cerf



Bob Kahn

ARPANET Geographical Map (Dec. 1978)



Source: ARPANET Information Brochure, DCA 1979

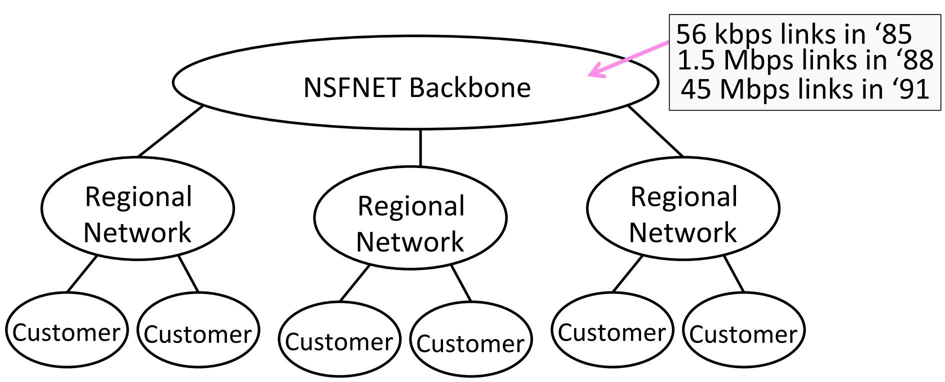
Growing Up – NSFNET

- NSFNET '85 supports educational networks
  - Initially connected supercomputer sites, but soon became the backbone for all networks
- Classic Internet protocols we use emerged
  - TCP/IP (transport), DNS (naming), Berkeley sockets (API) in '83, BGP (routing) in '93
- Much growth from PCs and Ethernet LANs
  - Campuses, businesses, then homes
  - 1 million hosts by 1993 …

Computer Networks 95

Early Internet Architecture

- Hierarchical, with NSFNET as the backbone

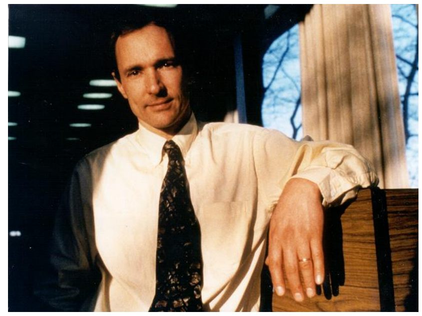


Computer Networks 96

Modern Internet – Birth of the Web

- After '95, connectivity is provided by large ISPs who are competitors
  - They connect at Internet eXchange Point (IXP) facilities
  - Later, large content providers connect
- Web bursts on the scene in '93
  - Growth leads to CDNs, ICANN in '98
  - Most bits are video (soon wireless)
  - Content is driving the Internet

Tim Berners-Lee



Modern Internet Architecture

- Complex business arrangements affect connectivity
  - Still decentralized, other than registering identifiers