CSE 461: Computer Networks

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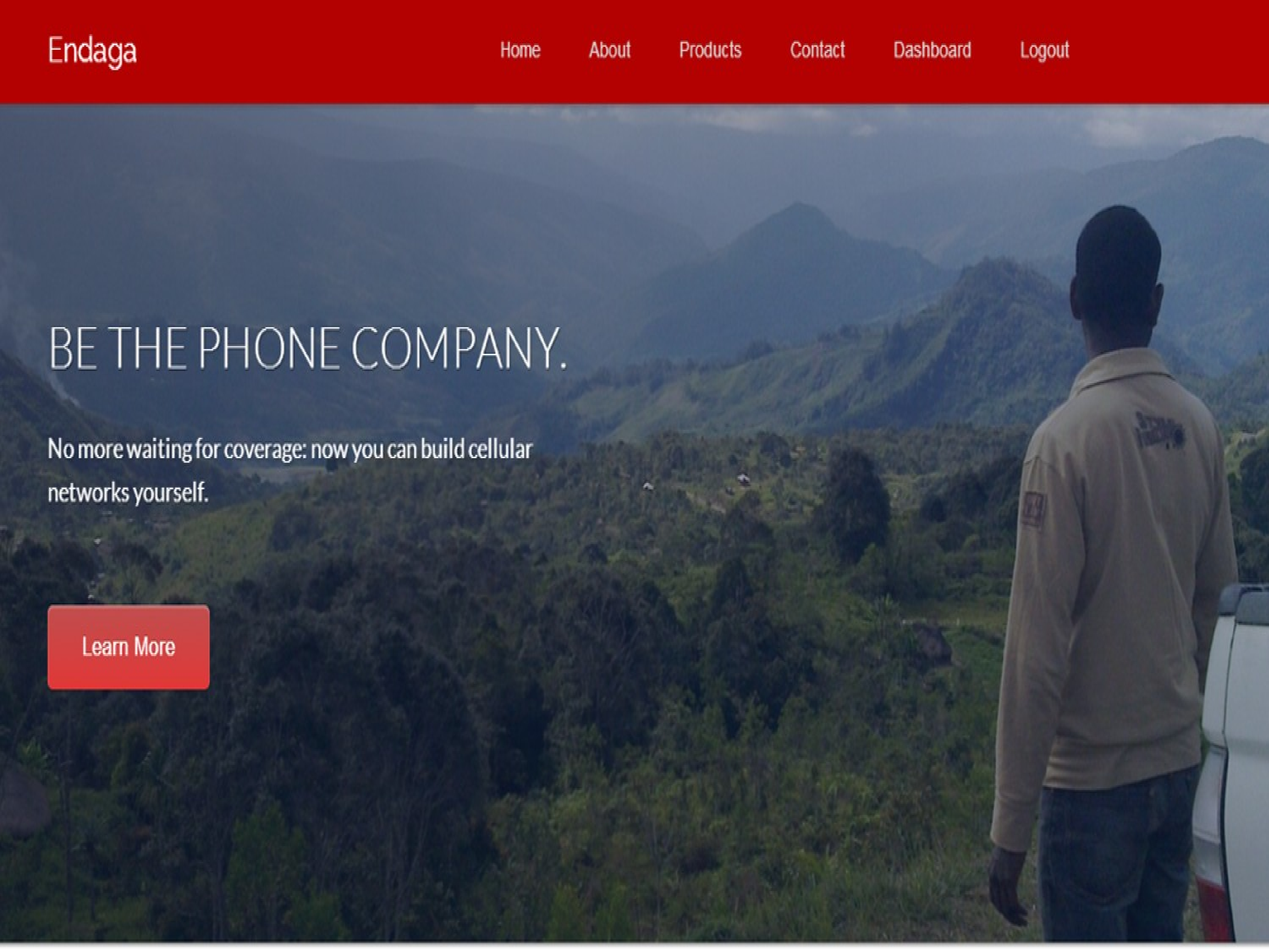
Who we are

ICTD

ICTD

- Information and Communication Technology for Development
  - Development -> Poverty Alleviation (not software development)
  - Broad field covering health, justice, and **access**
- Why?
  - Lots of natural intuition from Alaska, I know rural.
  - Able to use networking skill -> Many opportunities (NSRC)
- My subfield: Cellular access
- My Answer: Community Cellular


Endaga
Home
About
Products
Contact
Dashboard
Logout
BE THE PHONE COMPANY.
No more waiting for coverage: now you can build cellular networks yourself.
Learn More


f
26
3
10
Photo
Status
Facebook

TAs Now!

5th Year Master's student (1st Qtr)

Interested in security & NLP

Favorite Video Game:

LoZ Twilight Princess

Yibo Cao

- Is stuck in a snowstorm :(

Class Structure

Assignments

3 Projects: (25 + 25 + 25)%

- Turn in on canvas
- 3 Projects based on *Mininet* – A Software Defined Networking (SDN) simulator
    - Intro to mininet
    - Routing and switching
    - Bufferbloat

Assignments

3 Projects: (25 + 25 + 25)%

Weekly Reading Responses: 15%

- Set of (2) readings for each topic covered during class lecture
- Will try to do *classic* + *cutting edge*
- Everyone must generate a **response** by 11:59PM the Monday before class on canvas. Response includes:
  1) A summary of the paper and its contribution.
  2) A question you would like resolved in group discussion.
  3) A critique of the work, be it methodological, theoretical, or other.

Assignments

3 Projects: (25 + 25 + 25)%

Weekly Reading Responses: 15%

Paper Leads: 10%

- Everyone must **lead a paper discussion** once in the quarter. This involves:
  - Reading the paper particularly closely
  - Reading peer responses and generating the best topics of discussion
  - Guiding the group through the discussion of that paper. It's your job to keep it lively.
- Sign up for the papers online.

Assignments

3 Projects: (25 + 25 + 25)%
Weekly Reading Responses: 15%
Paper Leads: 10%

Late Policy: Each person gets three late days. Late days will be decided at end of quarter and selected as to have the most positive impact.

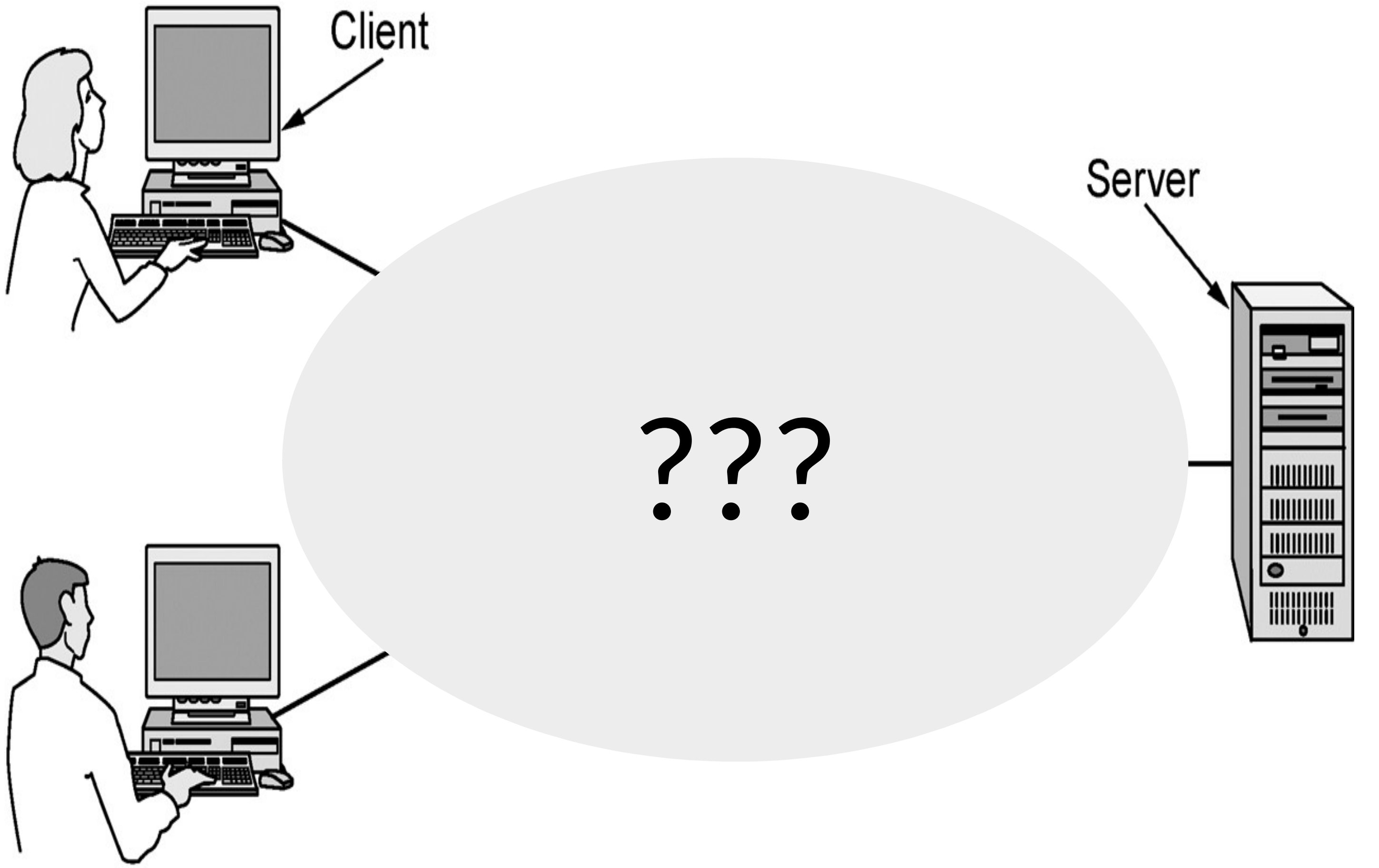
Administrivia

- Office hours
  - Opportunity to have more personal interactions with both me and the TAs.
- Tools
  - Canvas Announcements: Primary mechanism for communication about class changes.
  - Canvas Assignments: Responses and projects
  - Canvas Discussion: Back and forth discussions on class content
  - Canvas Gradebook: Grades will be posted here
- Slides
  - Adapted from David Wetherall, his talks are online
  - I will be posting my own slides right before lecture as well

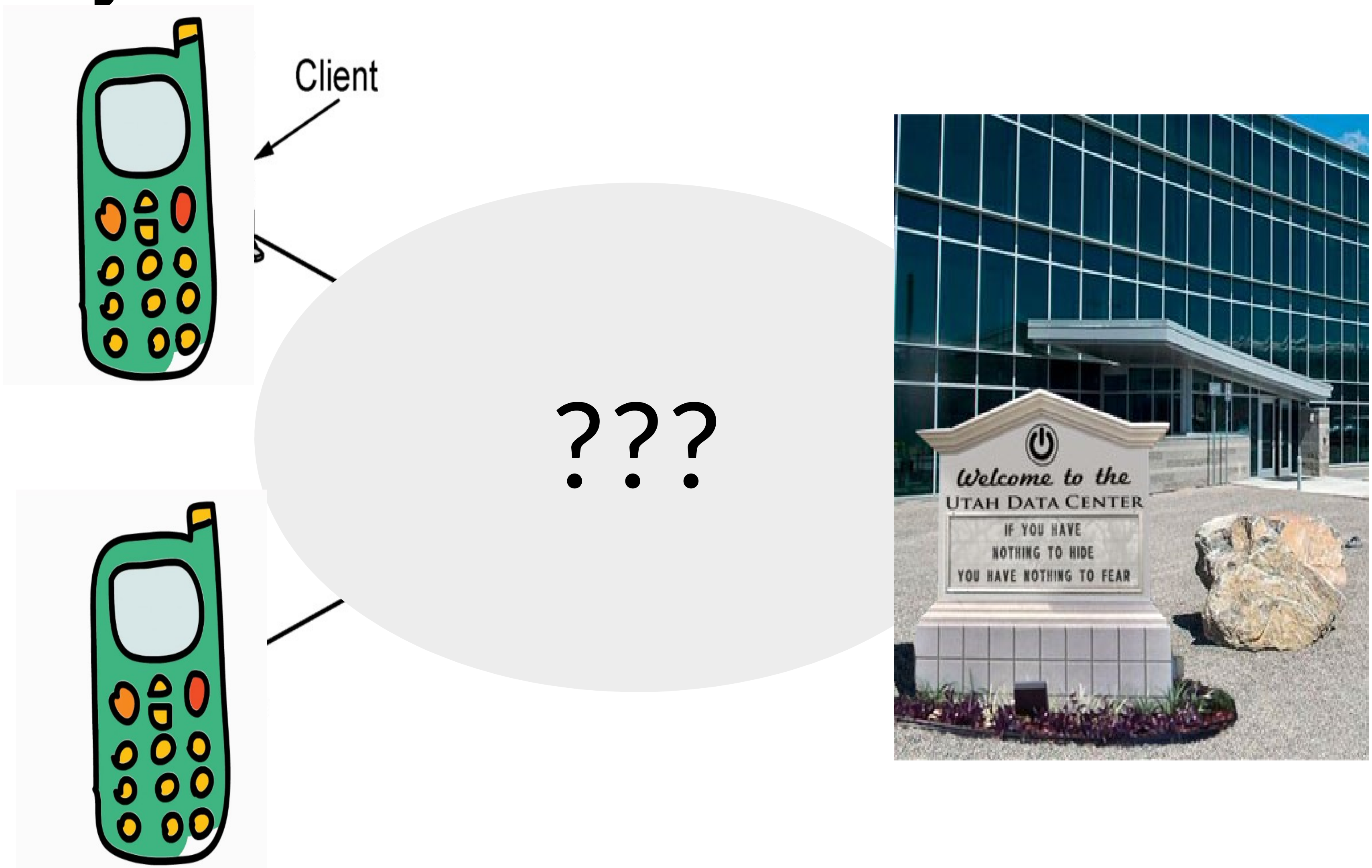
Questions?

CSE 461: Computer Networks

Focus of the course

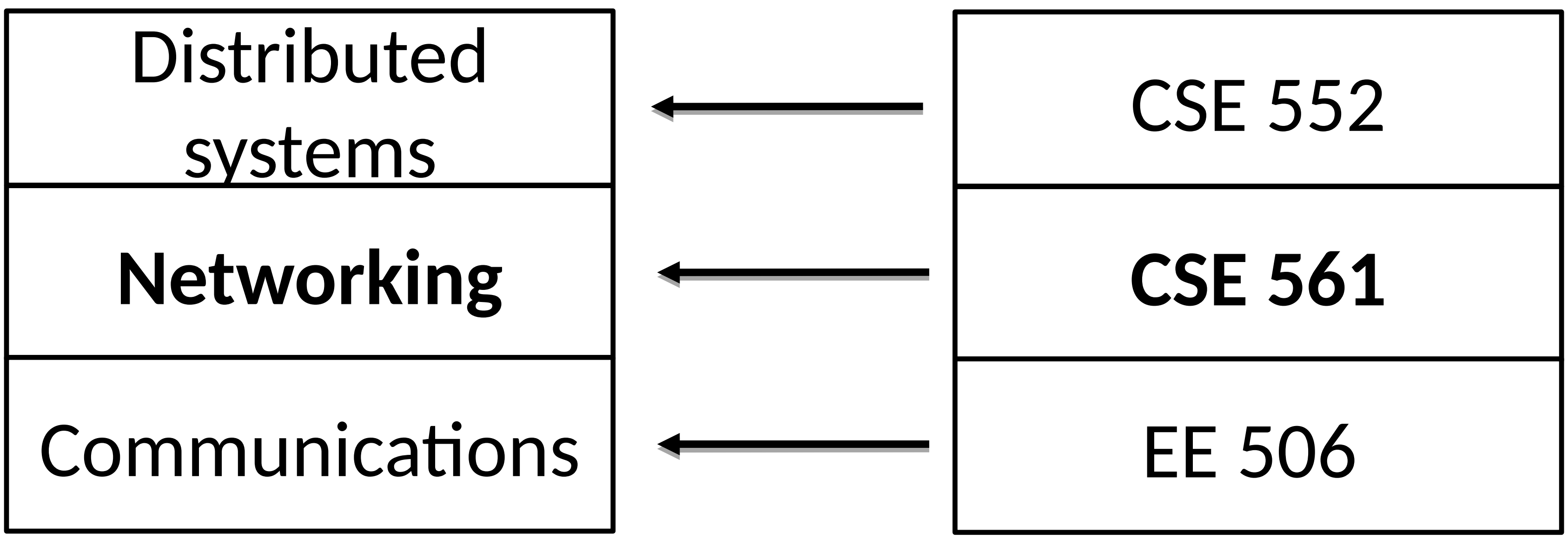


Focus of the course (in today's terms)



Focus of the course (2)

- Three “networking” topics:



The Main Points

1) **To learn the fundamentals of computer networks**
   - Learn how the Internet works
     1) What really happens when you “browse the web”?

        TCP/IP, DNS, HTTP, NAT, VPNs, 802.11 etc
   - Understand why the internet is designed how it is designed
     - SDN, Load Balancers, Architectures

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)

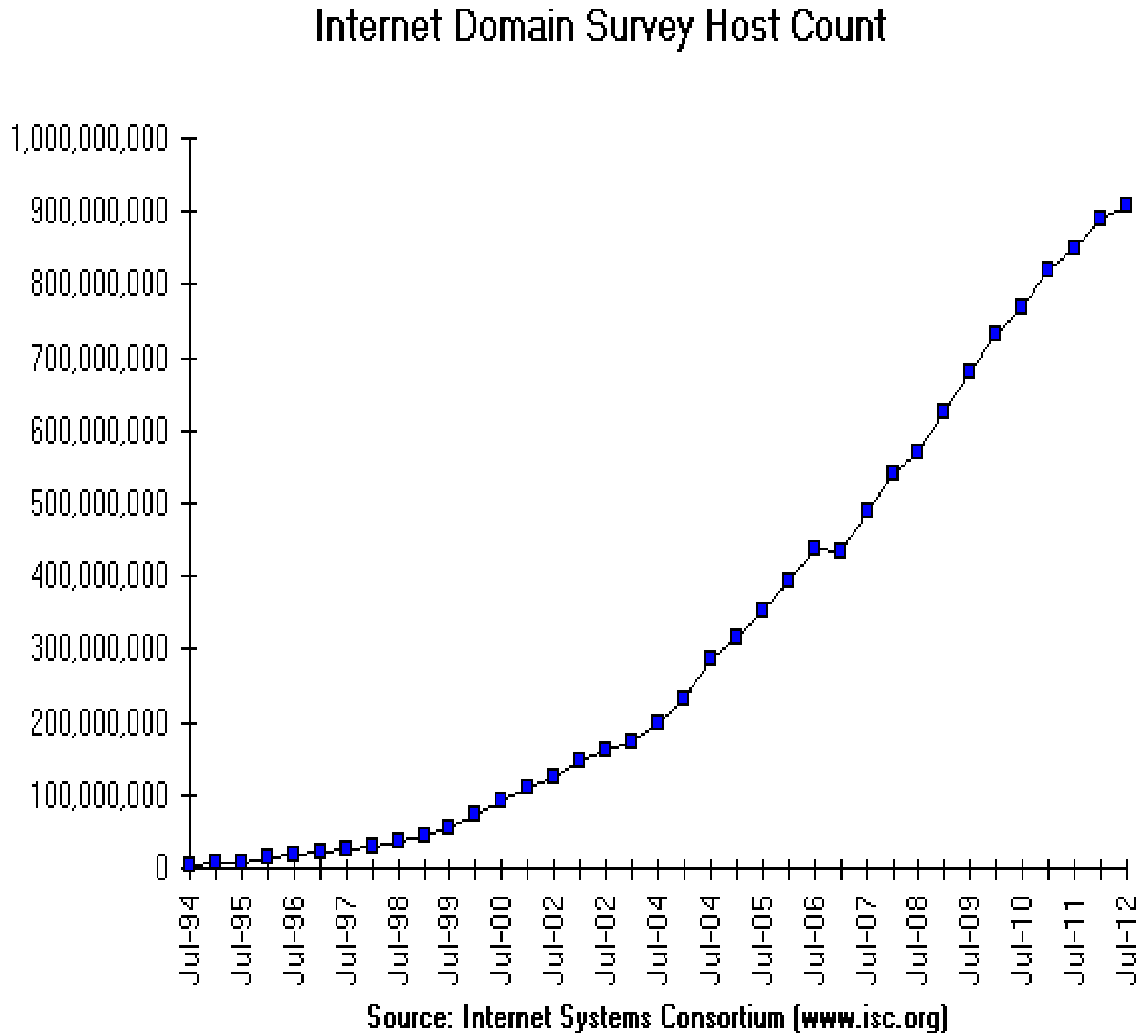
Key problem	**Example solutions**
Reliability despite failures	Codes for error detection/correction (§3.2, 3.3) Routing around failures (§5.2)
Network growth and evolution	Addressing (§5.6) and naming (§7.1) Protocol layering (§1.3)
Allocation of resources (e.g., bandwidth)	Multiple access (§4.2) Congestion 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

- Many billions of Internet hosts and growing …
  - 5B+ on Cell Networks
  - 3B+ on Internet



Fundamentals – Reinvention

- Examples of upheavals in the past 1-2 decades

Change	**Enabling Technology**
Emergence of the web	Content Distribution Networks
Piracy	Peer-to-peer file sharing
Voice over IP (VoIP)	Quality of Service (QoS)*
Internet of Things	IPv6
Mobile Devices	Wireless Networking

*mostly actually enormous spare capacity

Fundamentals – Reinvention (4)

- Upcoming/Ongoing upheavals?

Change	**Enabling Technology**
Fake News	Social Media
No-power devices?	Backscatter
Generic Networks?	SDN
Ubiquitous Networks?	Satellite/Long-Distance Networks
BBR/QUIC	High-Bandwidth Mobile (4G/5G)

The Main Points

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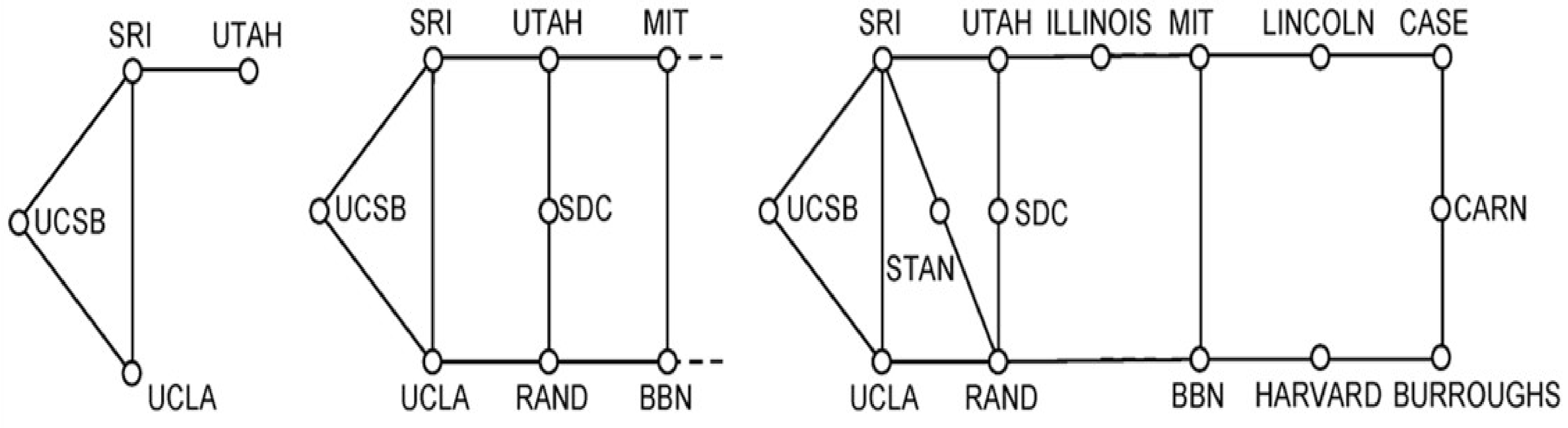
Who cares about the internet?

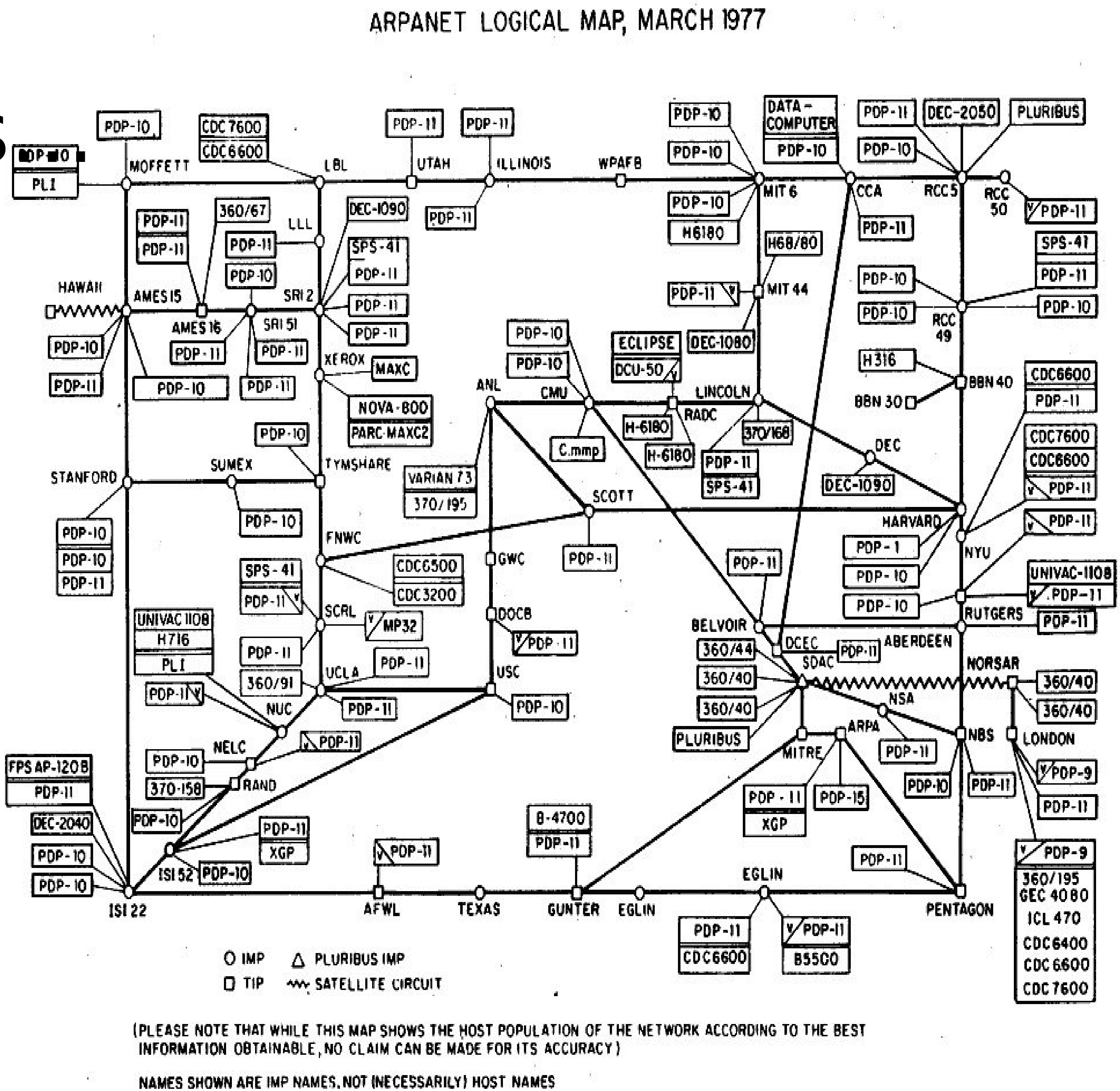
1. Curiosity
2. Impact on our world
3. Job prospects!

From this experimental network (~1970)…

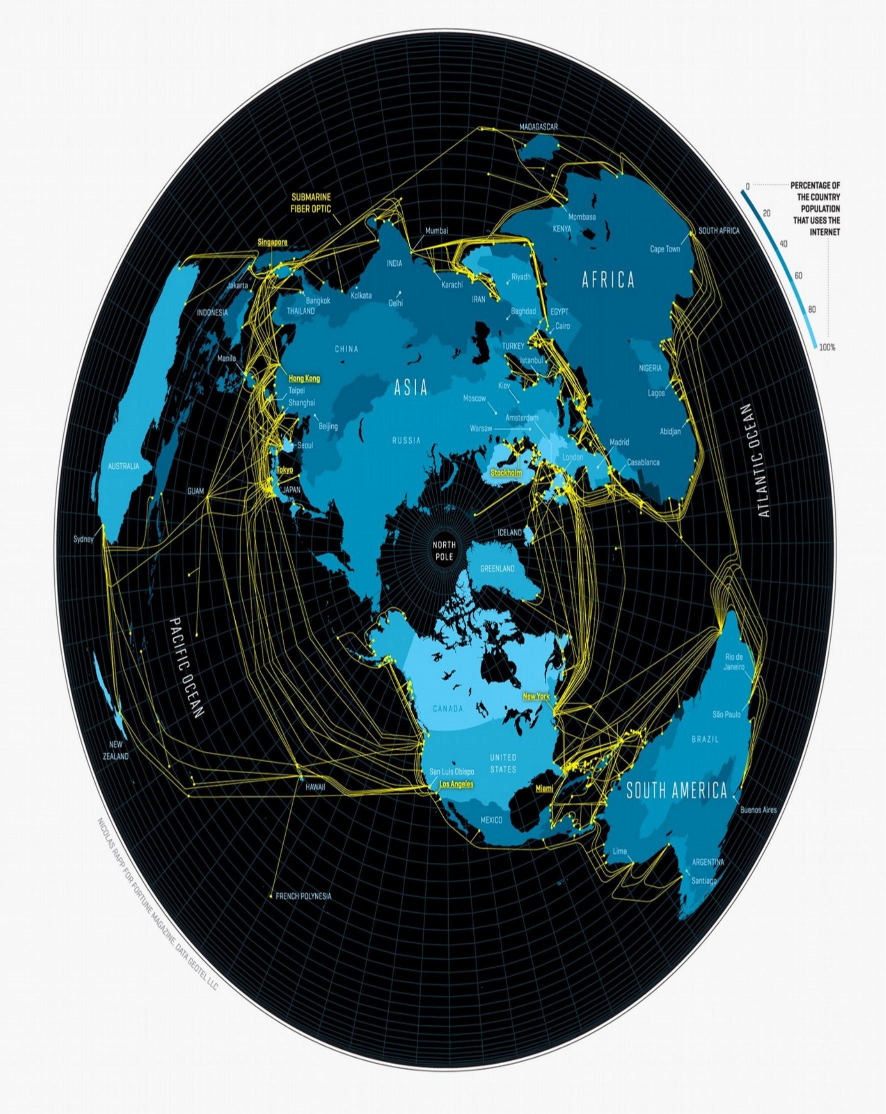


(a) Dec. 1969. (b) July 1970. (c) March 1971.

To this...

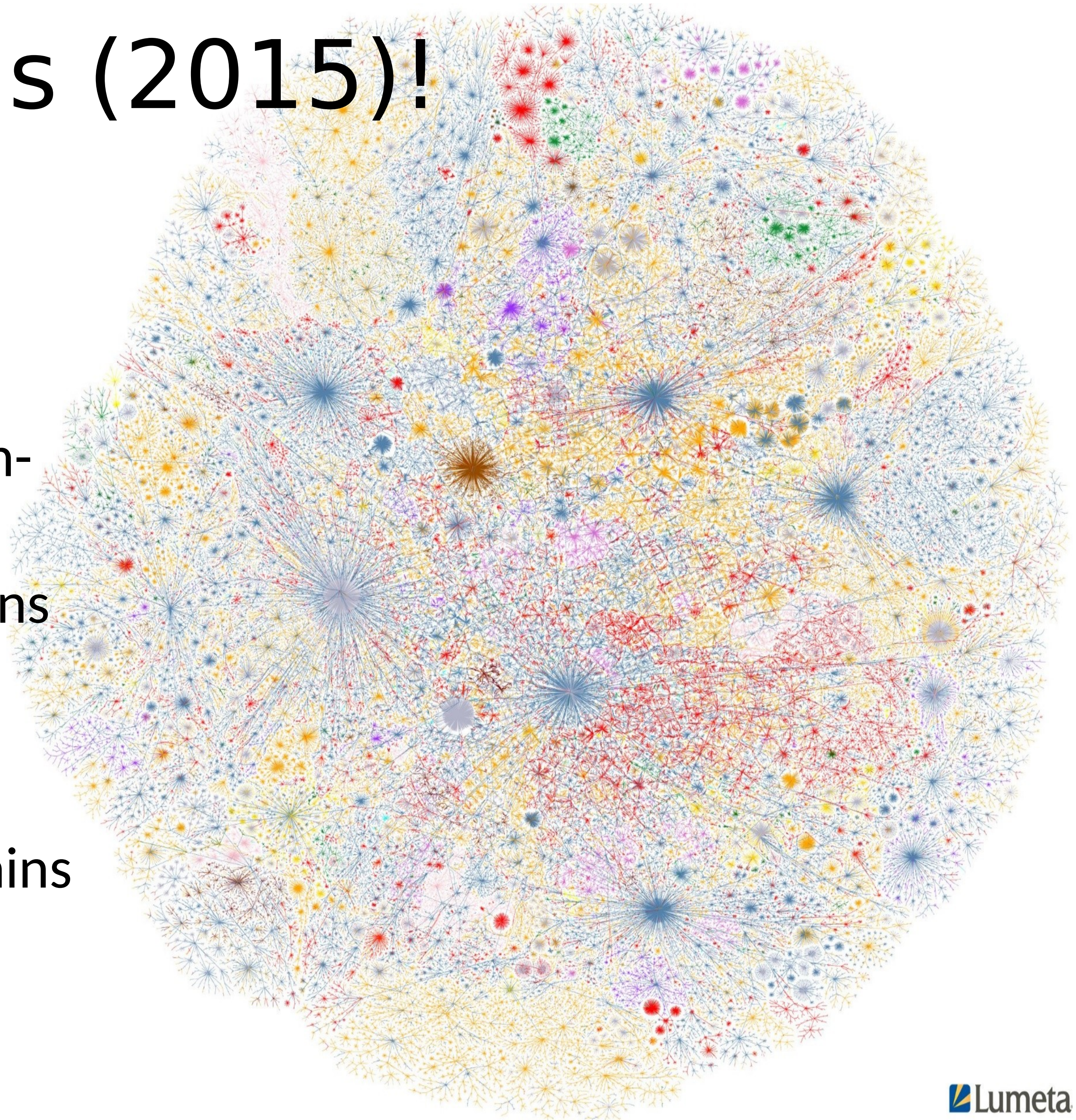

ARPANET LOGICAL MAP, MARCH 1977
PDP-10
PLI
MOFFETT
CDC 7600
CDC 6600
LBL
PDP-11
UTAH
PDP-11
ILLINOIS
WPAFB
PDP-10
PDP-10
DATA-COMPUTER
PDP-10
PDP-11
DEC-2050
PLURIBUS
PDP-10
MIT 6
CCA
RCC 5
RCC 50
PDP-11
PDP-10
H6180
PDP-11
H68/80
SPS-41
PDP-11
PDP-10
360/67
LLL
DEC-1090
PDP-11
PDP-11
PDP-11
SPS-41
PDP-11
PDP-10
PDP-11
MIT 44
PDP-10
RCC 49
PDP-10
HAWAII
AMES 15
AMES 16
SRI 2
SRI 51
PDP-11
PDP-11
DEC-1080
ECLIPSE
DCU-50
PDP-10
PDP-10
PDP-11
PDP-11
PDP-10
PDP-11
XEROX
MAXC
ANL
CMU
RADC
LINCOLN
H316
BBN 40
BBN 30
CDC6600
PDP-11
NOVA-800
PARC-MAXC2
H-6180
H-6180
370/168
PDP-10
C.mmp
PDP-11
SPS-41
DEC
DEC-1090
CDC7600
CDC6600
PDP-11
STANFORD
SUMEX
TYMSHARE
VARIAN 73
370/195
SCOTT
HARVARD
PDP-11
PDP-10
PDP-10
PDP-11
PDP-10
FNWC
PDP-11
PDP-1
NYU
CDC6500
CDC3200
GWC
PDP-11
PDP-10
UNIVAC-1108
PDP-11
SPS-41
PDP-11
SCRL
UNIVAC 1108
H716
PLI
MP32
DOCB
PDP-11
BELVOIR
PDP-10
RUTGERS
PDP-11
DCEC
PDP-11
ABERDEEN
360/44
SDAC
PDP-11
360/40
NORSAR
360/40
UCLA
360/91
PDP-11
USC
360/40
NSA
360/40
PDP-11
NUC
PDP-11
PDP-10
PLURIBUS
ARPA
MITRE
PDP-11
NBS
LONDON
PDP-10
NELC
PDP-11
PDP-9
FPS AP-120B
PDP-11
370-158
RAND
PDP-11
PDP-15
PDP-10
PDP-11
PDP-11
DEC-2040
PDP-10
PDP-11
XGP
XGP
B-4700
PDP-11
PDP-11
PDP-10
ISI 52
PDP-10
PDP-11
EGLIN
PDP-9
360/195
GEC 4080
ICL 470
CDC6400
CDC 6600
CDC 7600
PDP-10
ISI 22
AFWL
TEXAS
GUNTER
EGLIN
PENTAGON
PDP-11
CDC6600
PDP-11
B5500
IMP
PLURIBUS IMP
TIP
SATELLITE CIRCUIT
(PLEASE NOTE THAT WHILE THIS MAP SHOWS THE HOST POPULATION OF THE NETWORK ACCORDING TO THE BEST INFORMATION OBTAINABLE, NO CLAIM CAN BE MADE FOR ITS ACCURACY)
NAMES SHOWN ARE IMP NAMES, NOT (NECESSARILY) HOST NAMES

To this! (2011)


MADAGASCAR
SUBMARINE FIBER OPTIC
PERCENTAGE OF THE COUNTRY POPULATION THAT USES THE INTERNET
0
20
40
60
80
100%
Singapore
Mumbai
Mombasa
KENYA
SOUTH AFRICA
Cape Town
INDIA
Jakarta
Karachi
Riyadh
AFRICA
Kolkata
Delhi
IRAN
Bangkok
INDONESIA
THAILAND
Baghdad
EGYPT
Cairo
CHINA
TURKEY
Istanbul
Manila
NIGERIA
Hong Kong
Taipei
Shanghai
ASIA
Kiev
Moscow
Lagos
Amsterdam
Beijing
Warsaw
Abidjan
Seoul
RUSSIA
Madrid
London
ATLANTIC OCEAN
Casablanca
AUSTRALIA
Tokyo
Stockholm
JAPAN
GUAM
ICELAND
NORTH POLE
Sydney
GREENLAND
PACIFIC OCEAN
Rio de Janeiro
New York
CANADA
São Paulo
BRAZIL
NEW ZEALAND
UNITED STATES
San Luis Obispo
Los Angeles
Miami
SOUTH AMERICA
HAWAII
Buenos Aires
MEXICO
Lima
ARGENTINA
Santiago
FRENCH POLYNESIA
NICOLAS RAPP FOR FORTUNE MAGAZINE, DATA GEOTEL LLC

And this (2015)!

- An everyday institution used at work, home, and on-the-go
- Visualization contains millions of servers
  - Red = .com, Yellow= .org
- Network now contains literally 3 billion **people**!



Internet – Societal Impact

- An enabler of societal change
  - Easy access to knowledge
  - Electronic commerce
  - Personal relationships
  - Private communications

Internet – Economic impact

- An engine of economic growth
  - Information sources
    - And lots of ethical questions!
  - Online marketplaces
  - Social media/Crowdsourcing

The Main Points

1) To learn the fundamentals of computer networks
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     1) What really happens when you "browse the web"?

        TCP/IP, DNS, HTTP, NAT, VPNs, 802.11 etc
   - **Understand why the internet is designed how it is designed**
   - SDN, Load Balancers, Architectures

Architectures

- Lots of ways to build networks with different **tradeoffs**
- Goals:
  - Open Access (Internet)
    - Safety--, Security--, Flexibility++, Privacy++
  - Identity First (Cellular)
    - Safety++, Security++, Privacy --, Flexibility--
  - Centralized (Comcast)
    - Complexity++, Freedom--
  - Decentralized (Mesh)
    - Complexity--, Freedom++

The Main Points

1) To learn the fundamentals of computer networks
2) **To learn about where networks are going**
   - Know modern advances and technologies

     BBR/QUIC, SDN, TOR, etc…
   - See future agendas and changes

     The end of the Internet?

Not a Course Goal

To learn IT job skills

- How to configure specific equipment or technologies
  - e.g., Cisco certifications,
  - Technical whack-a-mole
- But course material is relevant, and we use hands-on tools
  - Hopefully you’ll be able to use these tools to build stuff at the end of class

The Agenda

1) **To learn the fundamentals of computer networks (lecture available online)**
   - 1.5 hr of lecture content a week
2) **To learn about where networks are going (not available online)**
   - 1 hour of paper discussion a week (following last week's lecture content)

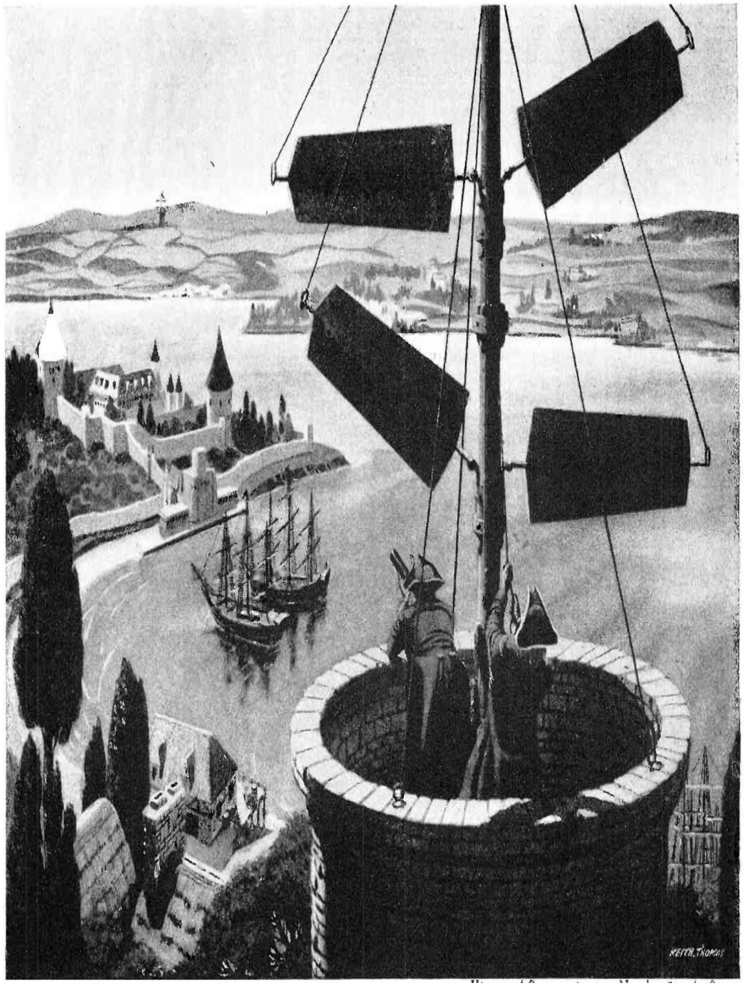
Questions?

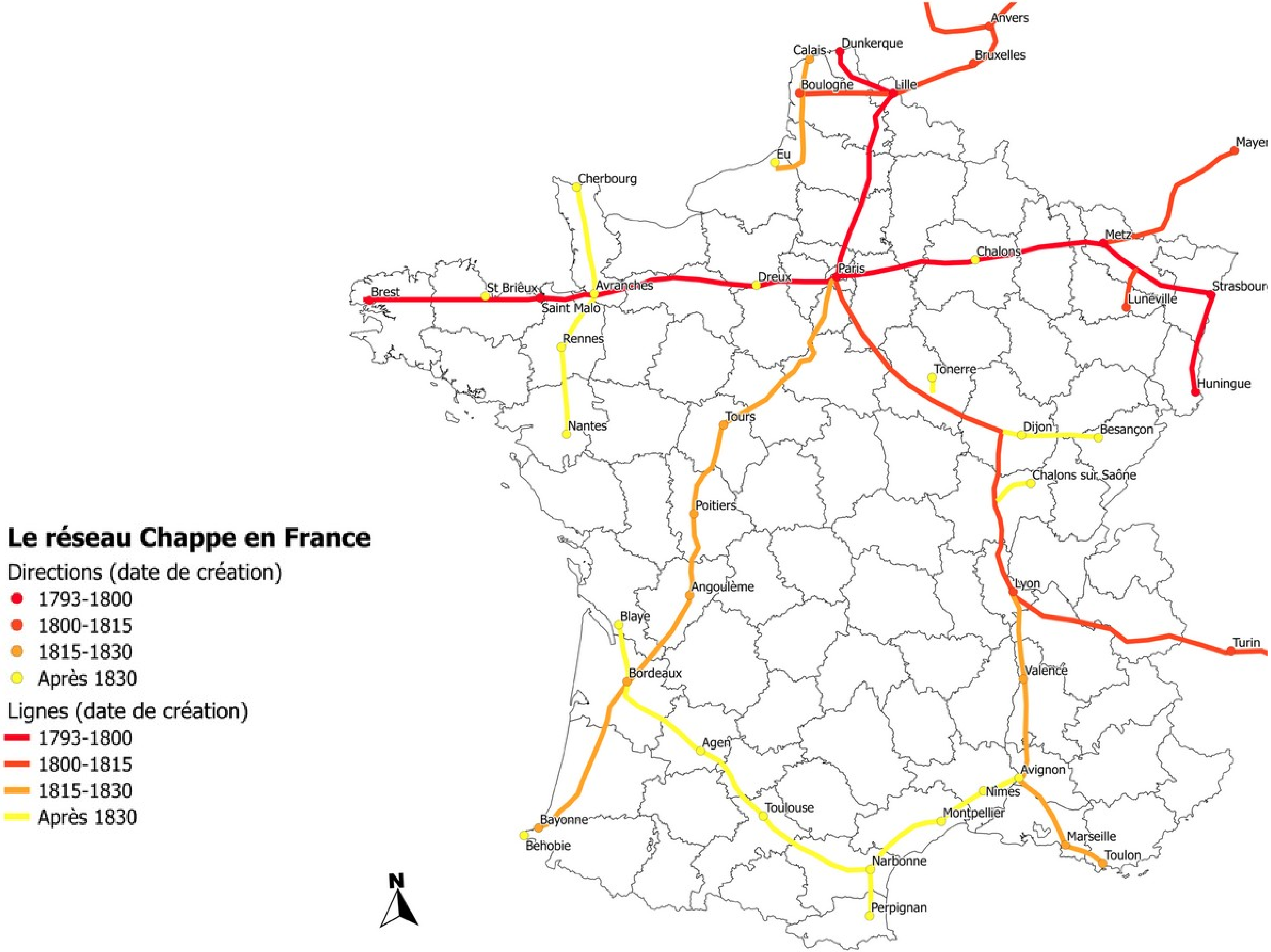
History of the Internet

What are some pre-Internet communication technologies?

Optical Semaphores

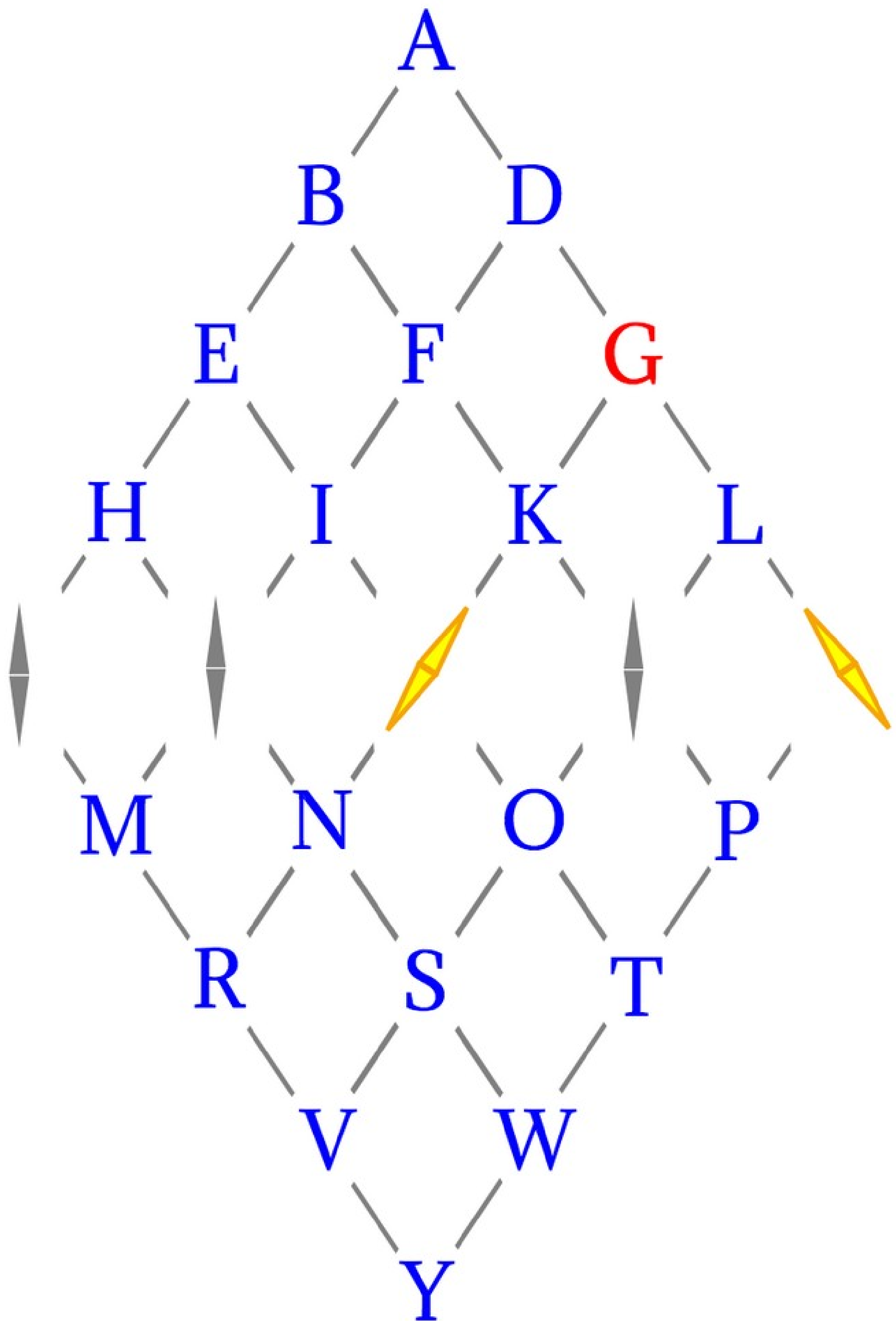
- Basic idea: Use visual indications of letters to signal next tower.
- Claude Chappe (France, 1792): Built 556 of these stations across France for communicating about war effort.
- First Message:“Si vous réussissez, vous serez bientôt couverts de gloire” (If you succeed, you will soon bask in glory) – 16km
- “Mechanical Internet”




Le réseau Chappe en France
Directions (date de création)
1793-1800
1800-1815
1815-1830
Après 1830
Lignes (date de création)
1793-1800
1800-1815
1815-1830
Après 1830
N
Anvers
Calais
Dunkerque
Bruxelles
Boulogne
Lille
Eu
Mayen
Cherbourg
Metz
Chalons
Paris
Dreux
Avranches
St Brieux
Brest
Saint Malo
Strasbourg
Luneville
Rennes
Tonerre
Huningue
Tours
Nantes
Dijon
Besançon
Chalons sur Saône
Poitiers
Lyon
Angoulème
Blaye
Turin
Bordeaux
Valence
Agen
Avignon
Nimes
Toulouse
Montpellier
Bayonne
Behobie
Marseille
Toulon
Narbonne
Perpignan

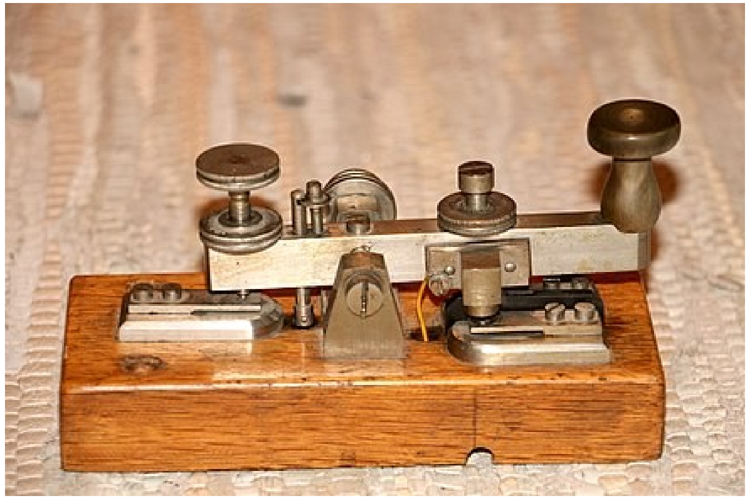
Telegraph

- Robust work in trying to use electricity to transmit information instead.
- Many problems: Didn't have consistent generators so coding was hard; some solutions used a wire for each letter.
- Eventually Gauss developed working system: Positive signal would move needle one way, negative another then alphabet
- Cooke and Wheatstone build this ->


A
B D
E F G
H I K L
M N O P
R S T
V W
Y

Telegraph

- Samuel Morse changes this to have the signal move a pen, creating a mark.
- Morse first message: was in 1838
  - 3 miles in New Jersey
- More famously sent "WHAT HATH GOD WROUGHT?“ 44 miles between DC and Baltimore
- Core innovation: Relays at frequent intervals that send a message through ten miles (16 km) of wire.



Telephone

- Basic problem: How to modulate voice onto electrical signals
- Reis (1861 Germany): "Das Pferd frisst keinen Gurkensalat" (The horse does not eat cucumber salad). Speech issues.
- Elisha Gray (1876) patents first method for encoding.
- Bell (1876) makes first call: "Mr. Watson, come here, I want to see you.“ Wins patent war.

Circuit-Switching

- In January 1878, the first telephone switch went into operation in New Haven Connecticut
- Establish a complete circuit every time there's a communication
- Still the case in cellular!
  - Circuit is established to "packet gateway"

Issues w/ Circuit Switching

- ?

Issues w/ Circuit Switching

- Large setup cost
  - Switching costs all along circuit
- Contention
  - Only X links, what if X+1 want to use?
- Inefficient
  - Circuit established even if not in use
- Fragile
  - Intermediary links go down circuit is broken

USAF wanted their networks to survive nuclear strikes… circuits would not.

Pre-internet: Packetization

The solution focused on three big ideas:

1. Use decentralized network with multiple paths between any two points
2. Divide user messages into message blocks, later called **packets**
3. Deliver these messages by store and forward switching.

Pre-Internet: Why Packetization?

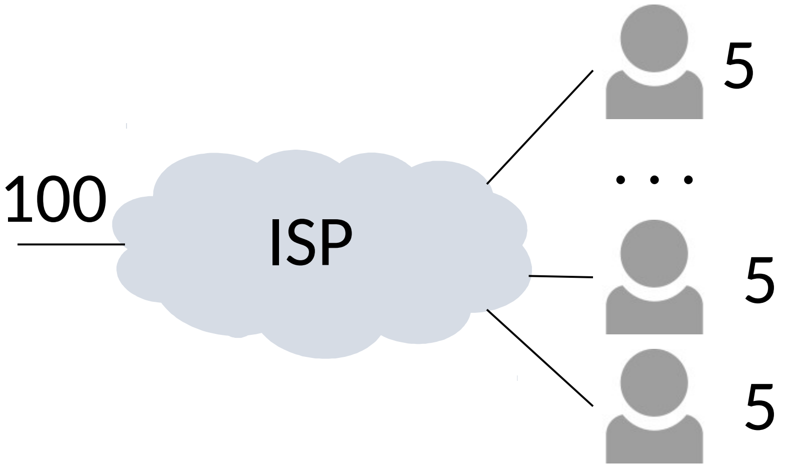
- Efficiency
  - Lines only used when trafficked
- Handles contention
  - Queue packets
- Robust
  - Routes can change
- Kleinrock (UCLA, 1969)
  - UCLA -> SRI
  - “Lo” – Was supposed to be “LOGIN” but crashed

Efficiency: Statistical Multiplexing

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

Efficiency: 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 …



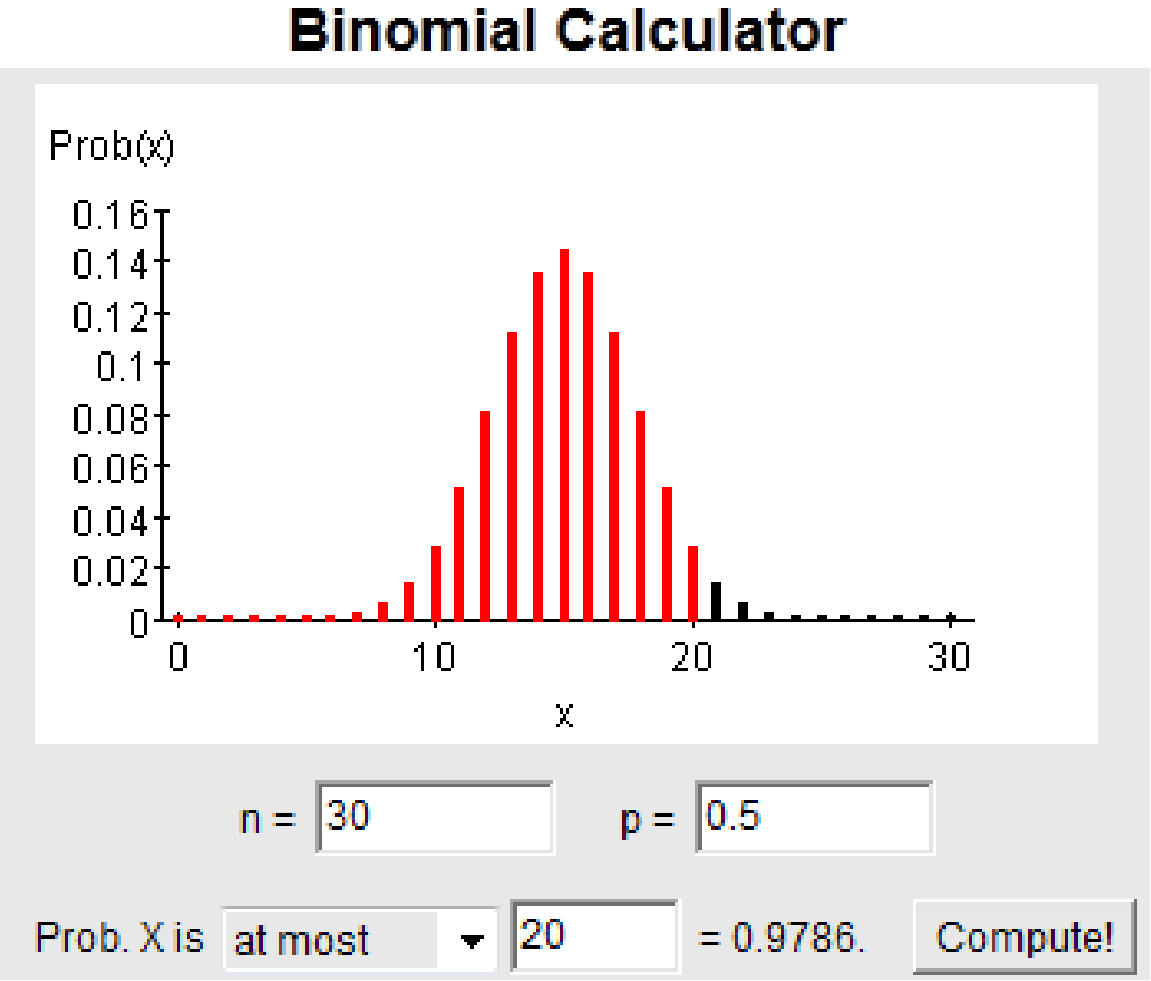
- How many users can the ISP support?
  - With dedicated bandwidth for each user:
  - Probability all bandwidth is used: (assuming independent users)

Efficiency: 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



Pre-Internet: Networks

Started building individual packet networks at different institutions:

- Octopus Network
  - 4 Machines at the Lawrence Livermore National Lab
- ALOHAnet
  - Wireless packets at University of Hawaii
- CYCLADES
  - French network exploring network responsibilities
- ARPANET
  - First packet network, a few universities online

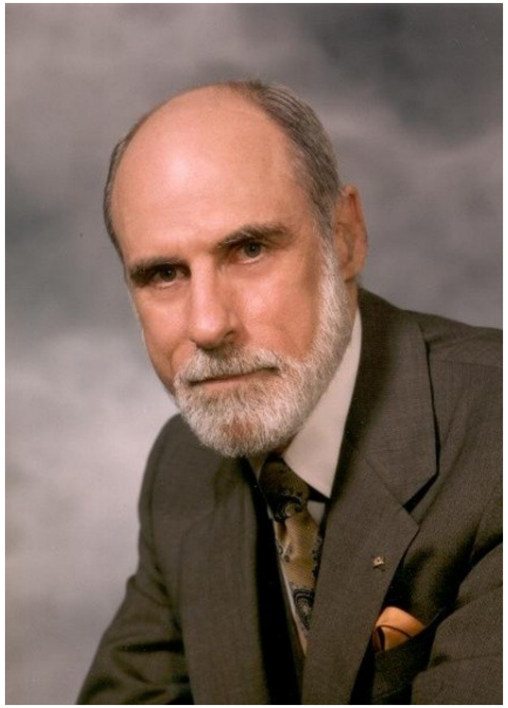
The Beginning – ARPANET

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

ARPANET

- In the early ARPANET
  - <u>Internetworking</u> 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



© 2009 IEEE

Bob Kahn

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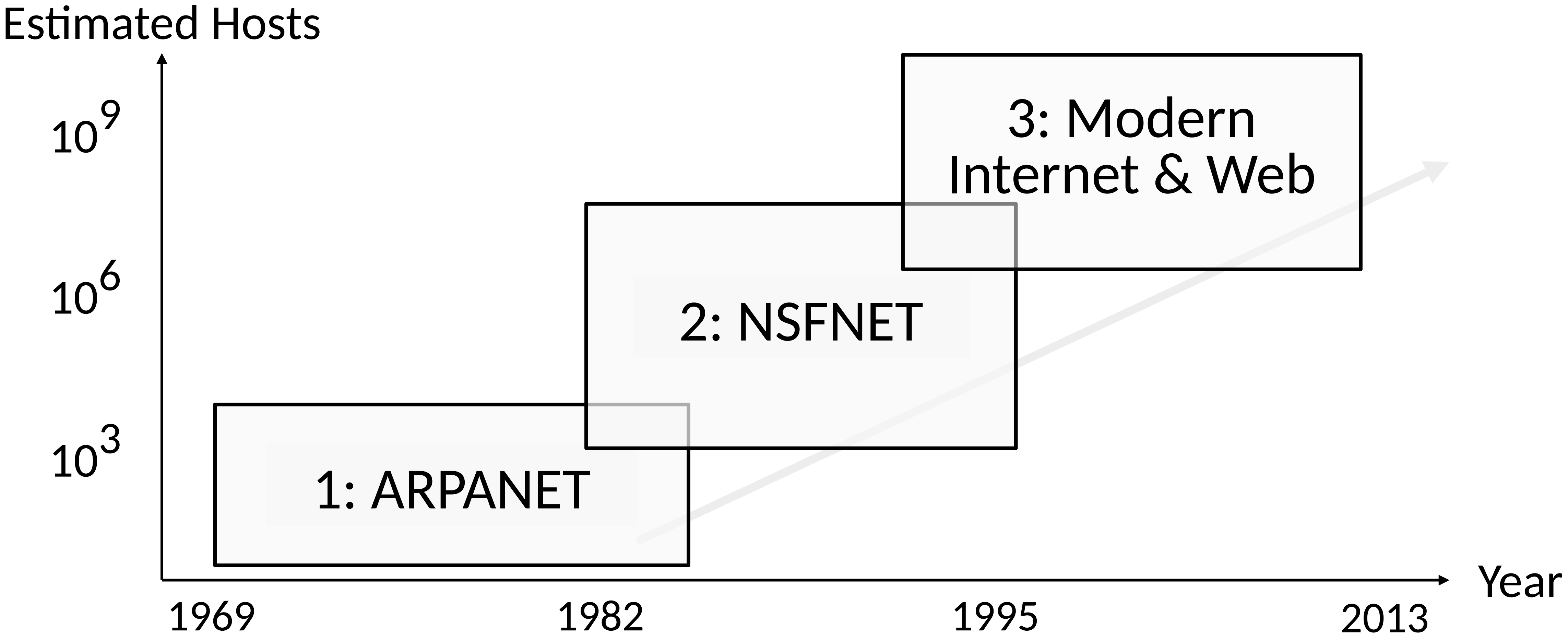
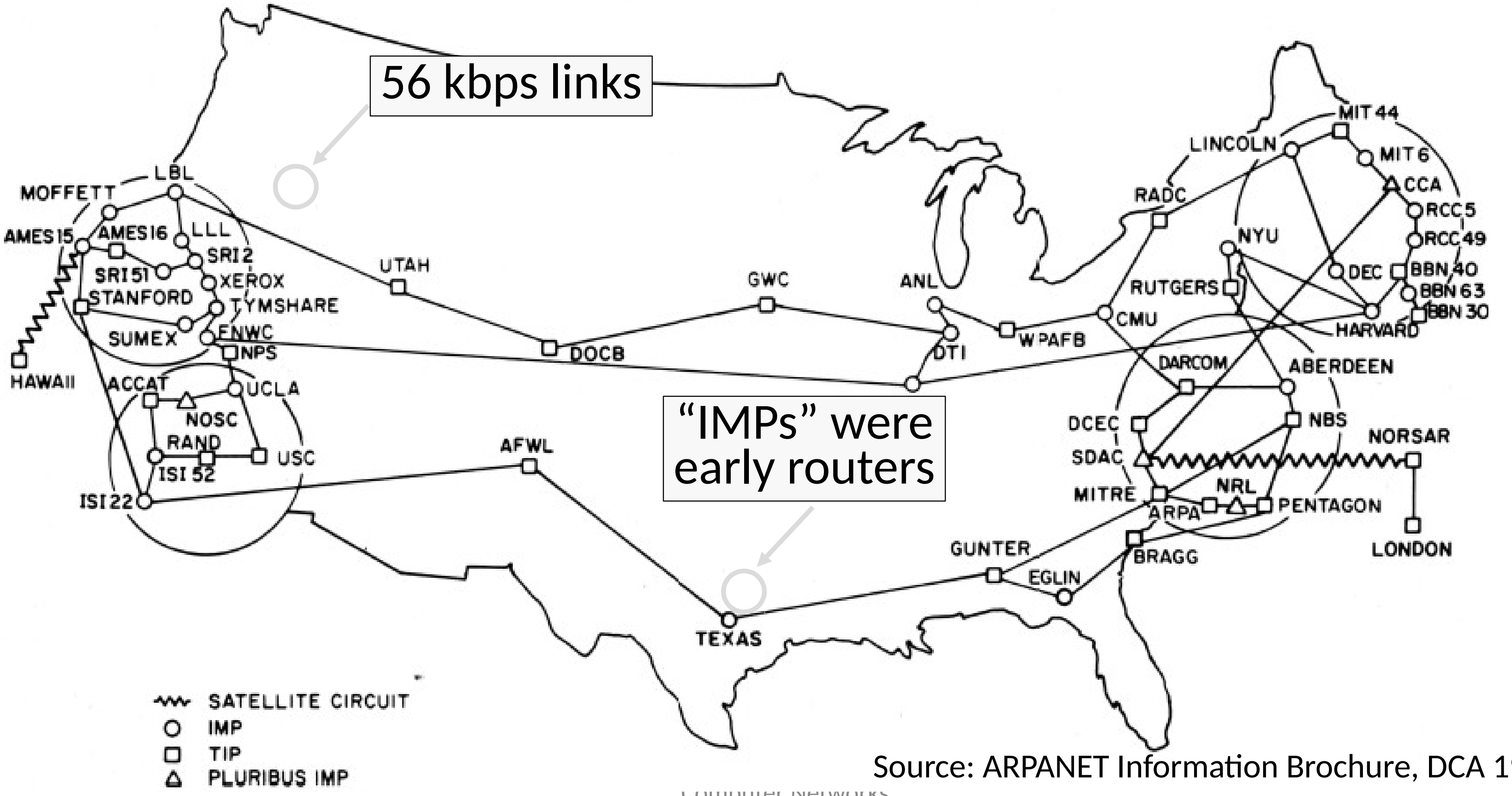
Rough Internet Timeline



ARPANET Geographical Map (Dec. 1978)

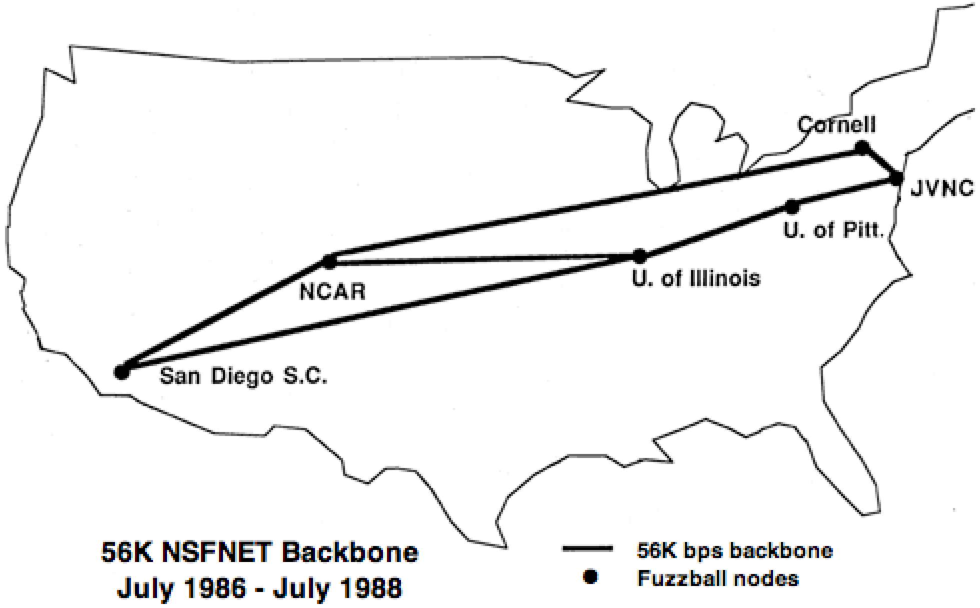


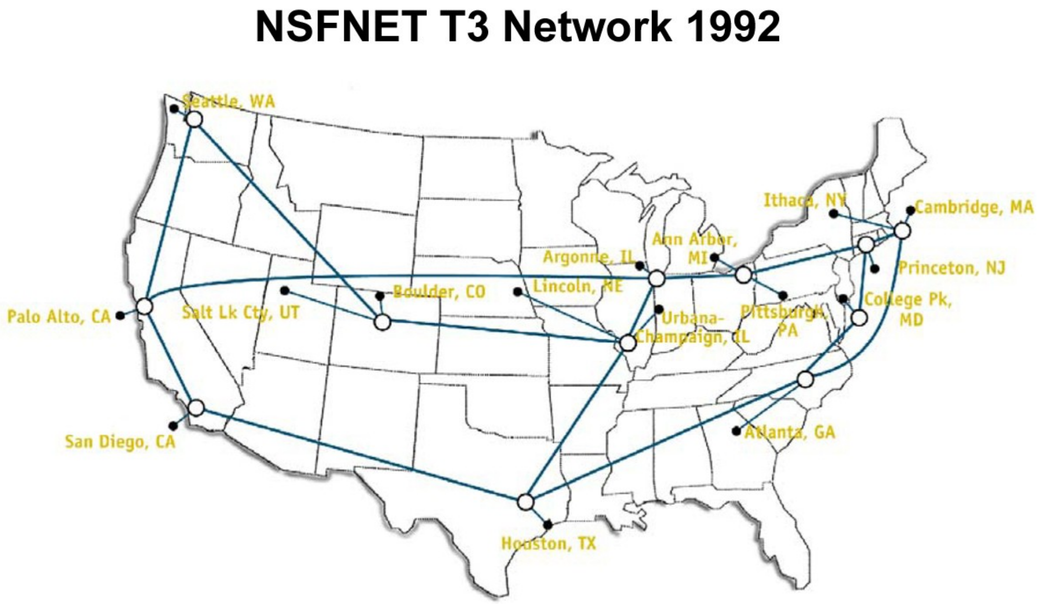
Source: ARPANET Information Brochure, DCA 1979

Growing Up – NSFNET

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

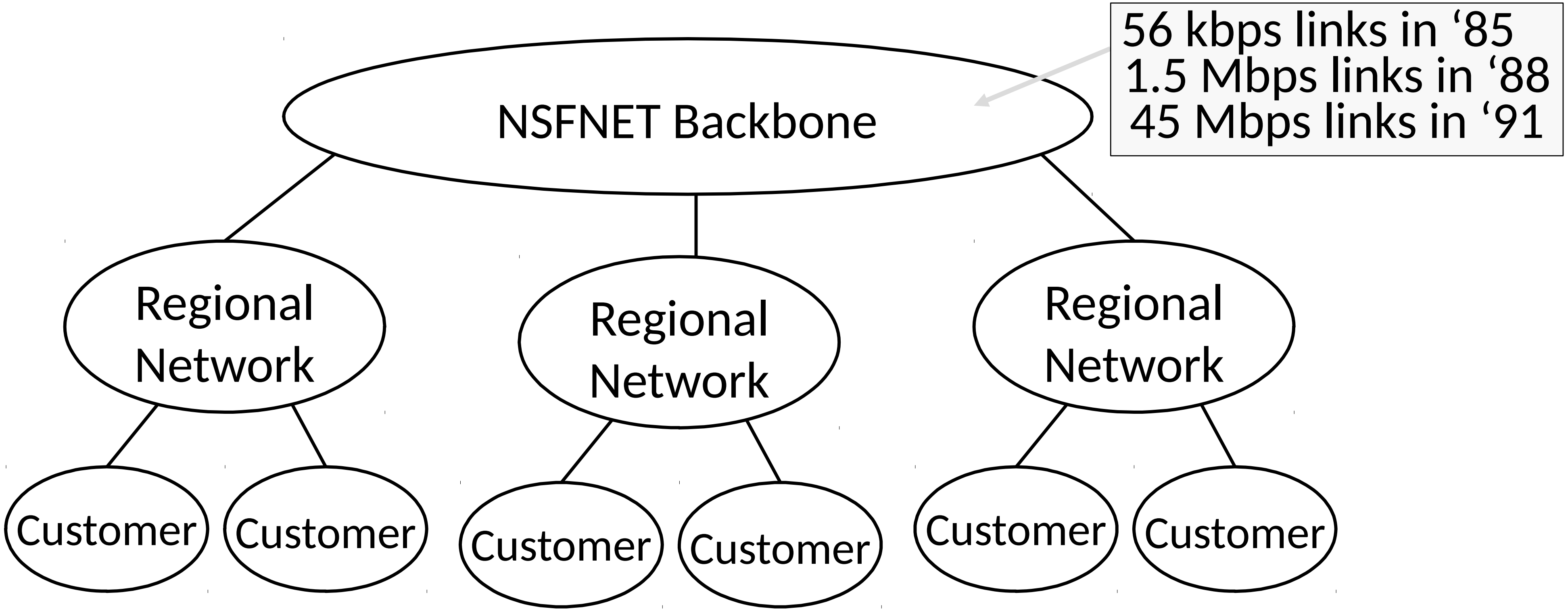
Growing Up- NSFNET





Early Internet Architecture

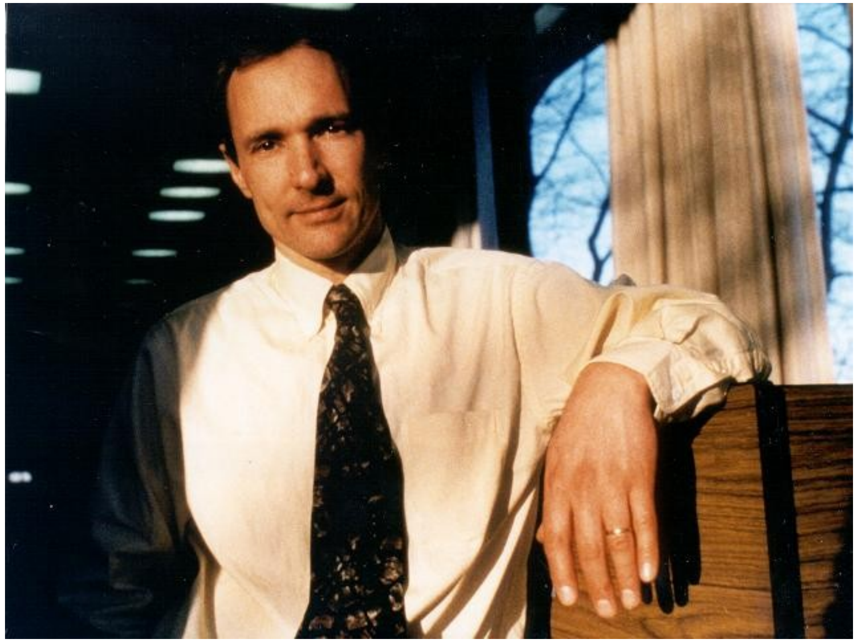
- Hierarchical, with NSFNET as the backbone



Modern Internet – Birth of the Web

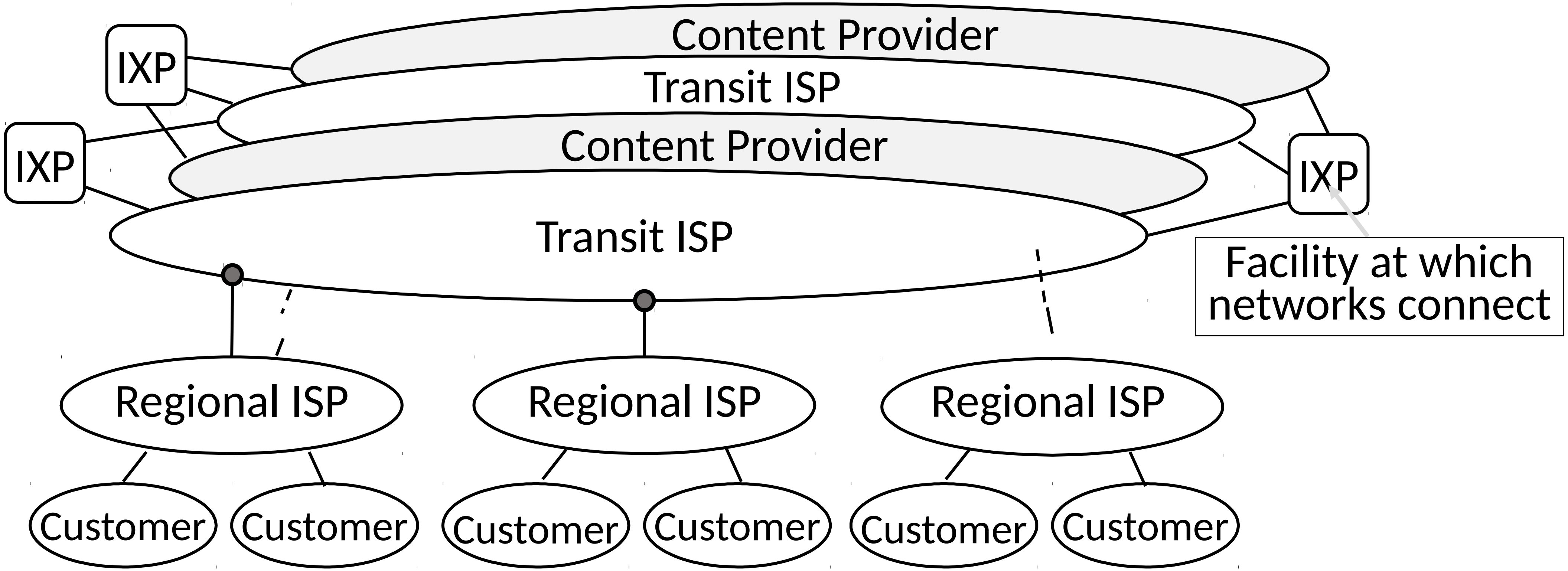
- After ’95, connectivity is provided by large ISPs who are competitors
  - They connect at Internet eXchange Point (IXP) facilities
  - Later, large content providers connect
- Web bursts on the scene in ’93
  - Key idea: Hyperlink
  - Growth leads to CDNs, ICANN in ‘98
  - Most bits are video (soon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

Tim Berners-Lee



Modern Internet Architecture

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



Modern Internet Architecture (2)

Major Transit ISPs:

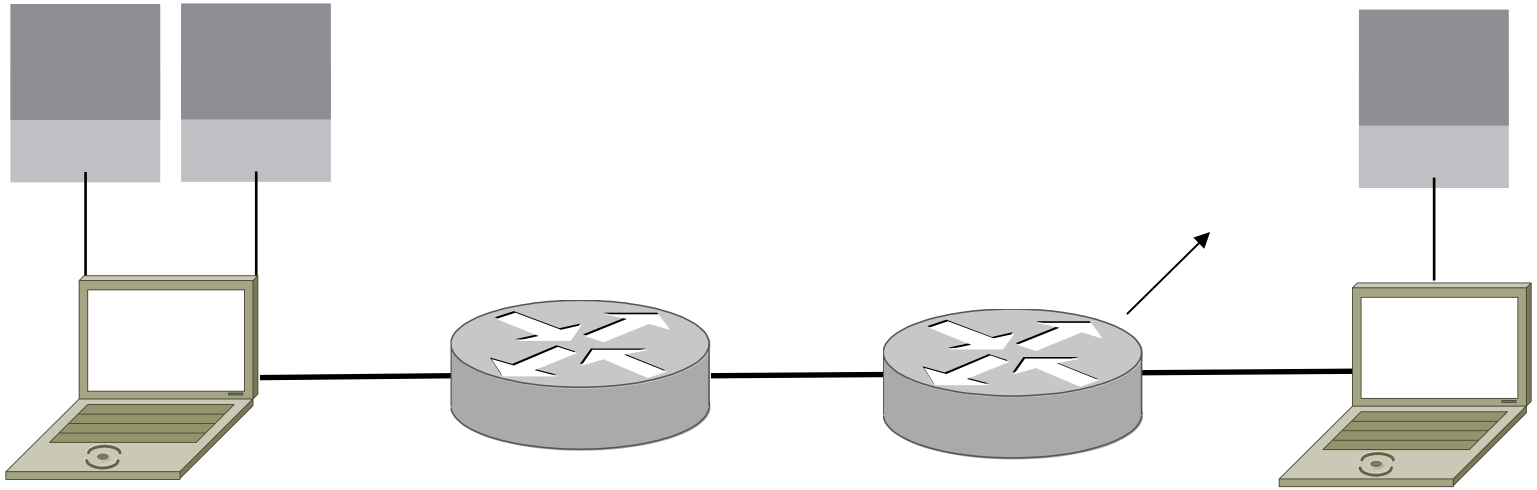
- Level 3 (200,000mi of fiber)
- Century Link (550,000mi)
- ATT (410,000mi)
- Verizon (500,000mi)

Major Regional ISPs

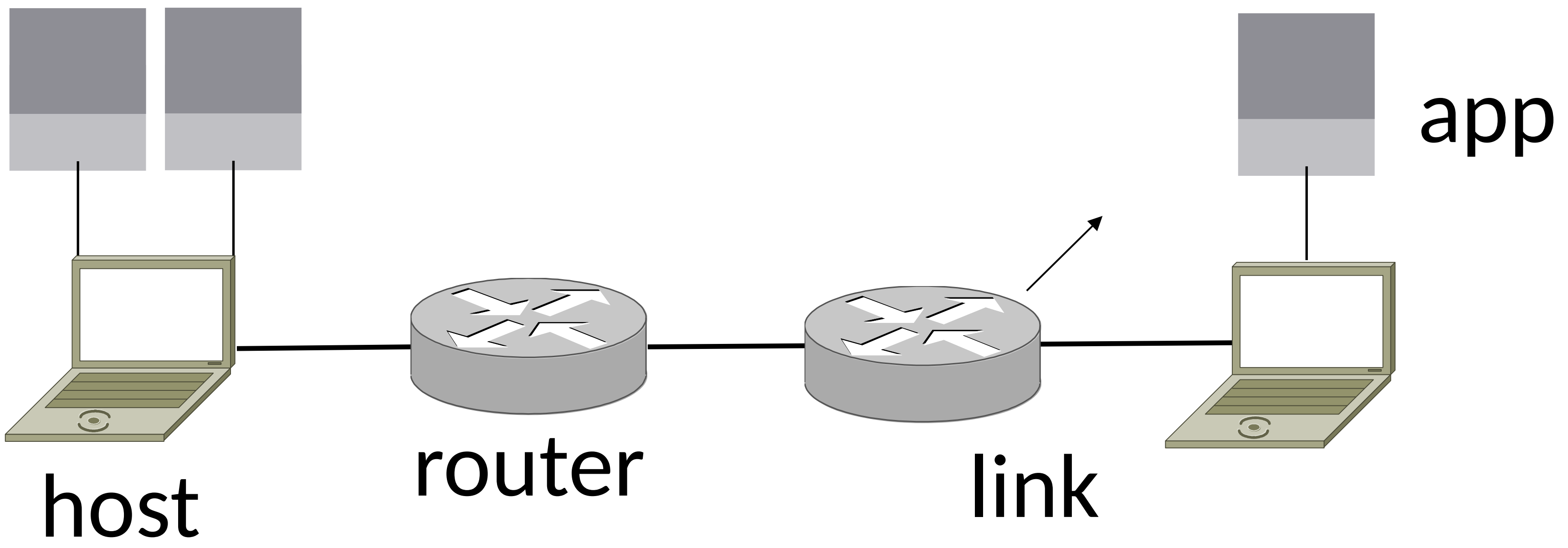
- Dakotanet
- Dixienet
- Local telecoms (e.g., MTA)
- US West

Network Components

Parts of a Network



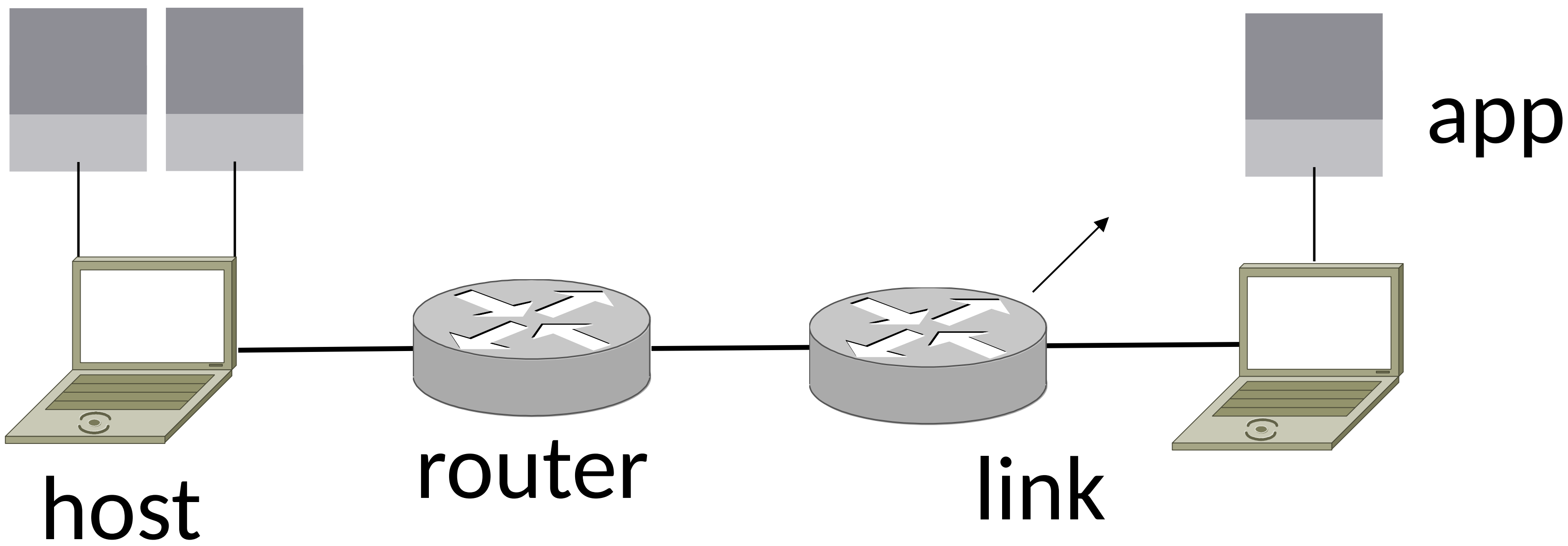
Parts of a Network



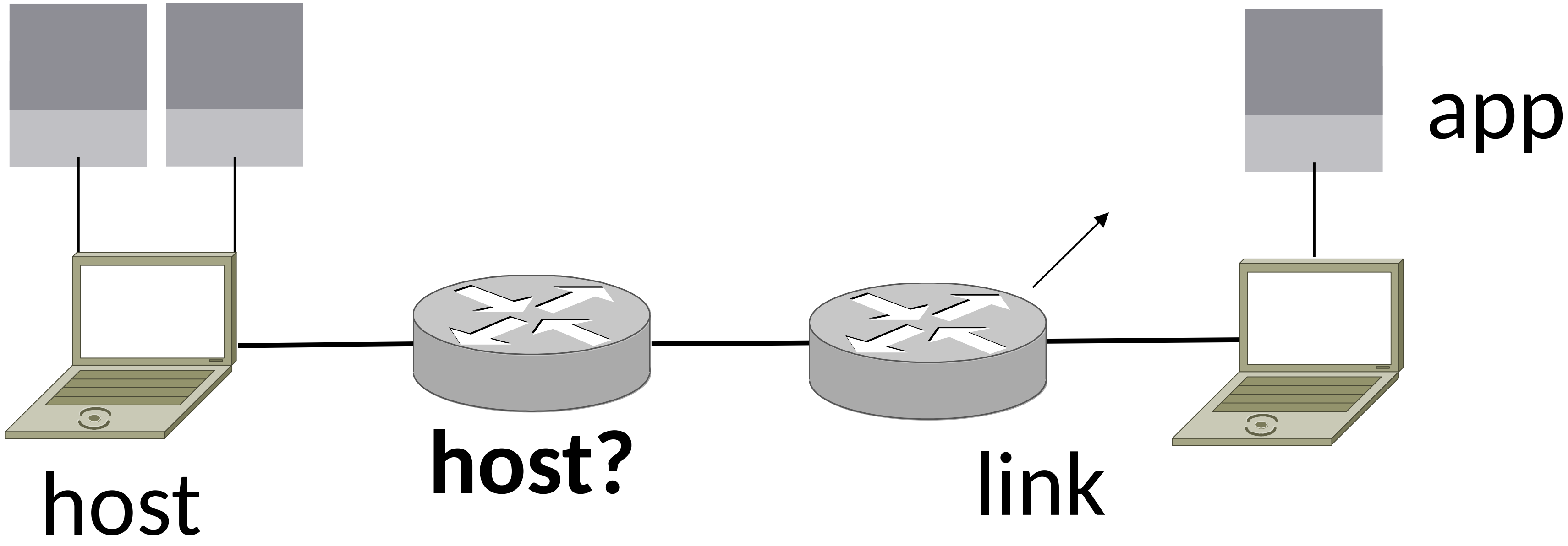
Component Names

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

Parts of a Network



Parts of a Network

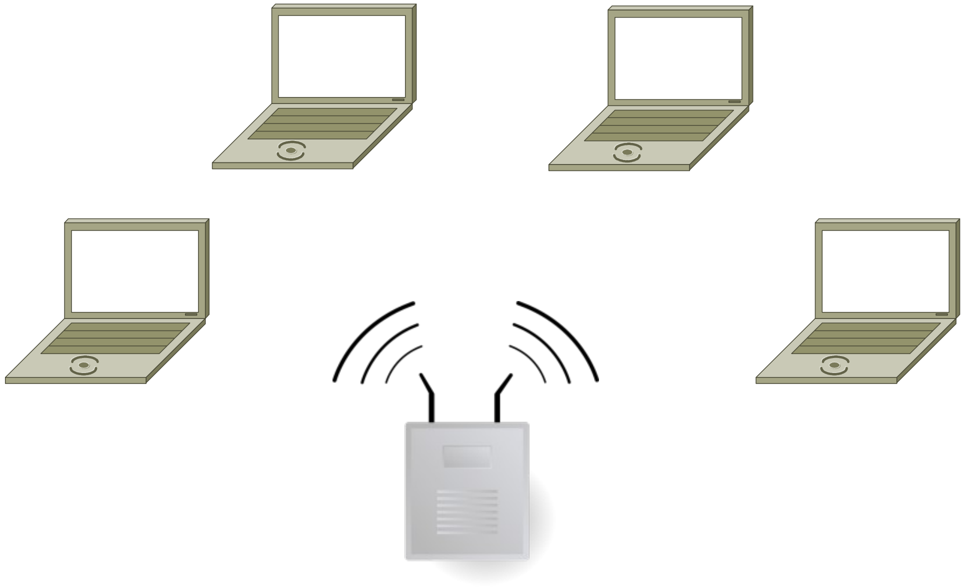


Types of Links

- Full-duplex
  - Bidirectional
- Half-duplex
  - Bidirectional
- Simplex
  - unidirectional

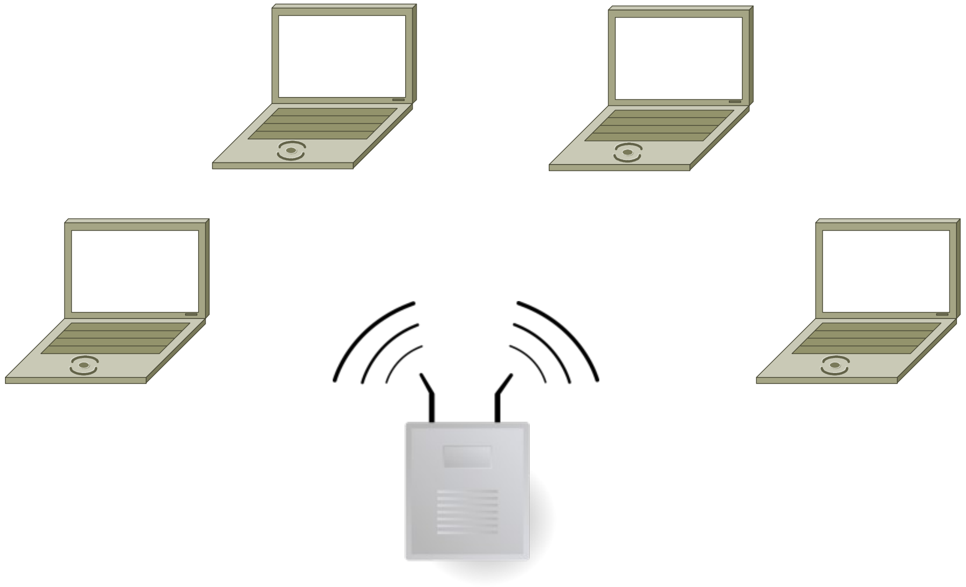
Wireless Links

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



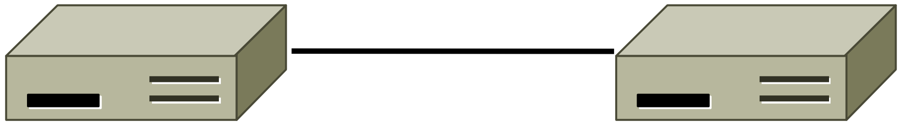
Wireless Links (2)

- Often show logical links
  - Not all possible connectivity



A Small Network

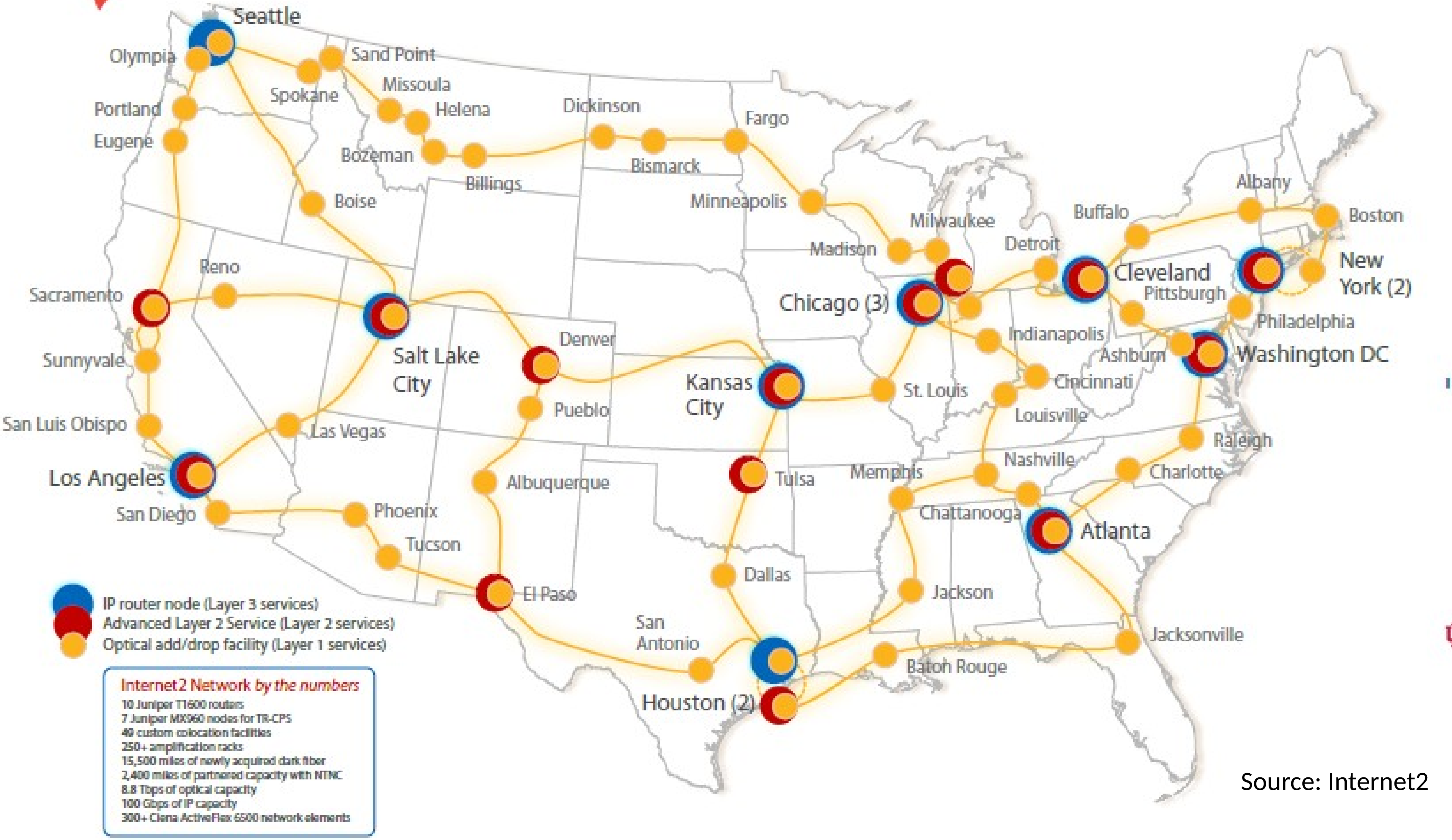
- Connect a couple of computers



- Next, a large network …

Internet2 Network Infrastructure Topology

October 2012



IN SUPPORT OF U.S.UCAN

NETWORK PARTNERS

Source: Internet2

Computer network names by scale

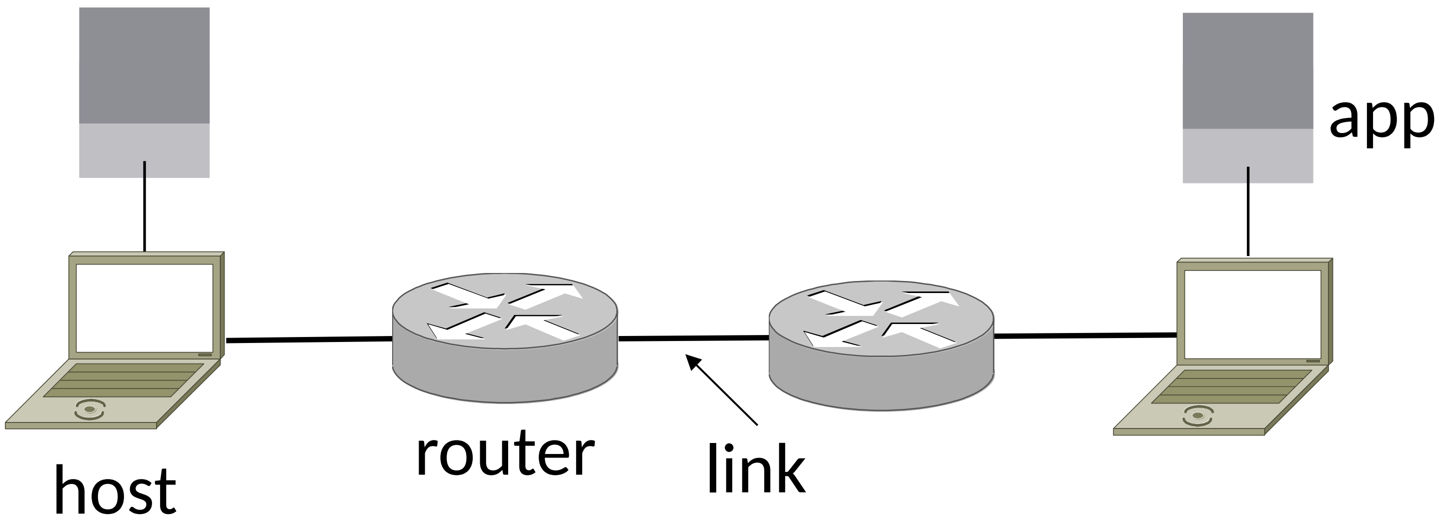
Scale	**Type**	**Example**
Vicinity	PAN (Personal Area Network)	Bluetooth (e.g., headset)
Building	LAN (Local Area Network)	WiFi, Ethernet
City	MAN (Metropolitan Area Network)	Cable, DSL
Country	WAN (Wide Area Network)	Large ISP
Planet	The Internet (network of all networks)	The Internet!

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

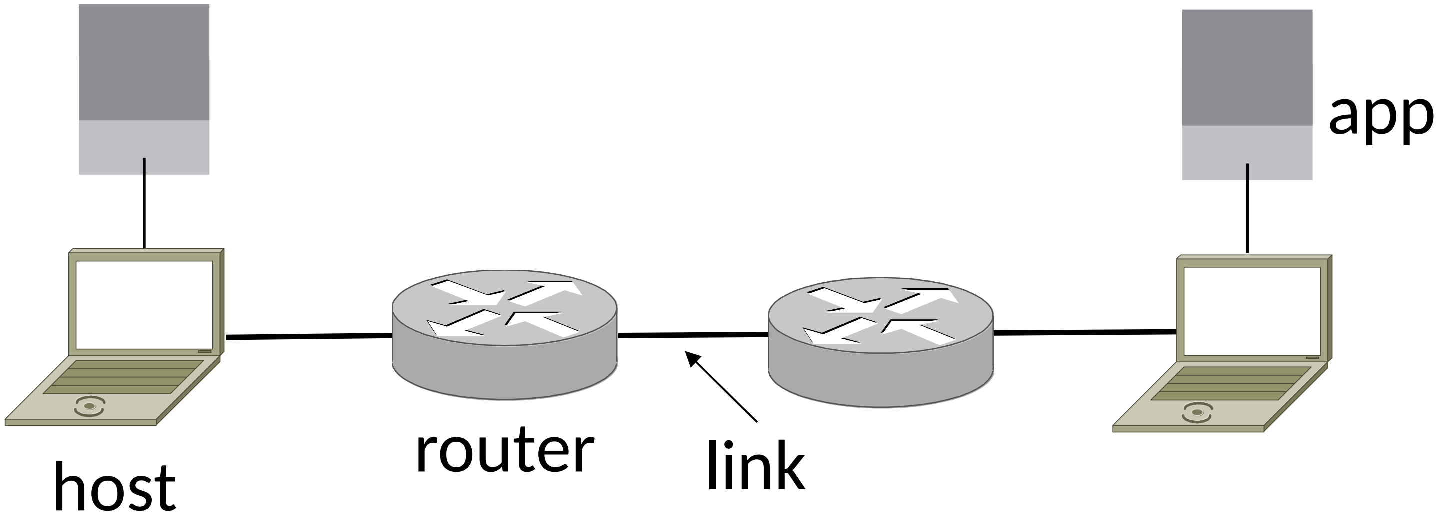
Network Boundaries

- What part is the "network"?



Network Boundaries (2)

- What part represents an “ISP”?

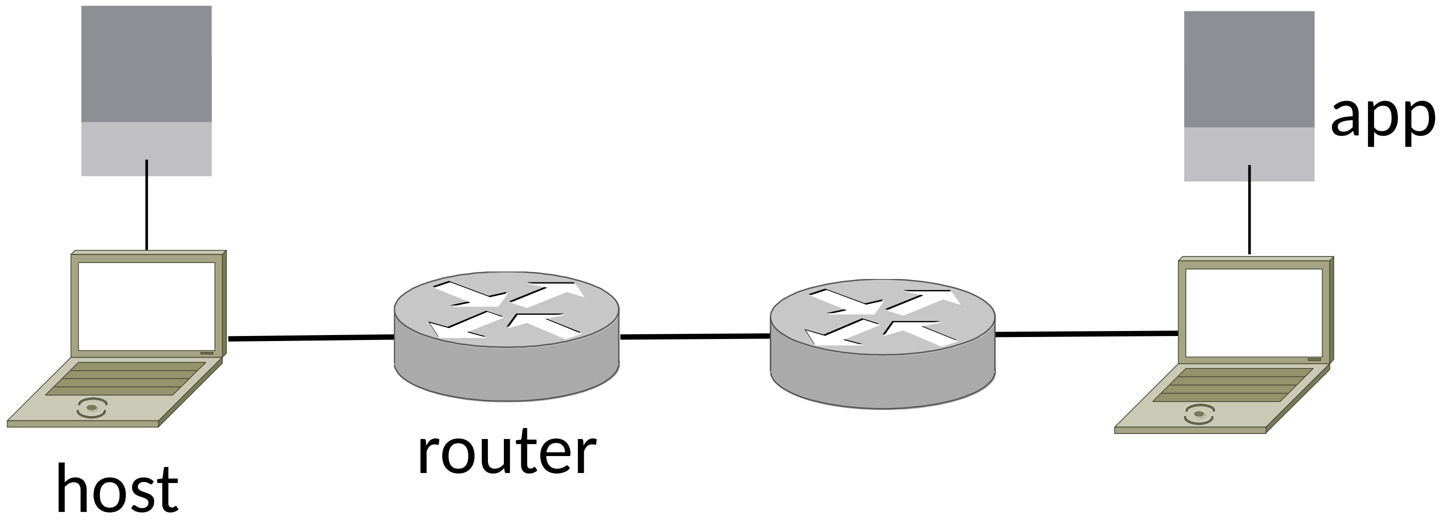


Network Boundaries (3)

- Cloud as a generic network

Key Interfaces

- Between (1) apps and network, and (2) network components



What API should networks provide?

Networks Need Modularity

- 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:
  - Secures information in transit
  - Lets many new hosts be added
  - …

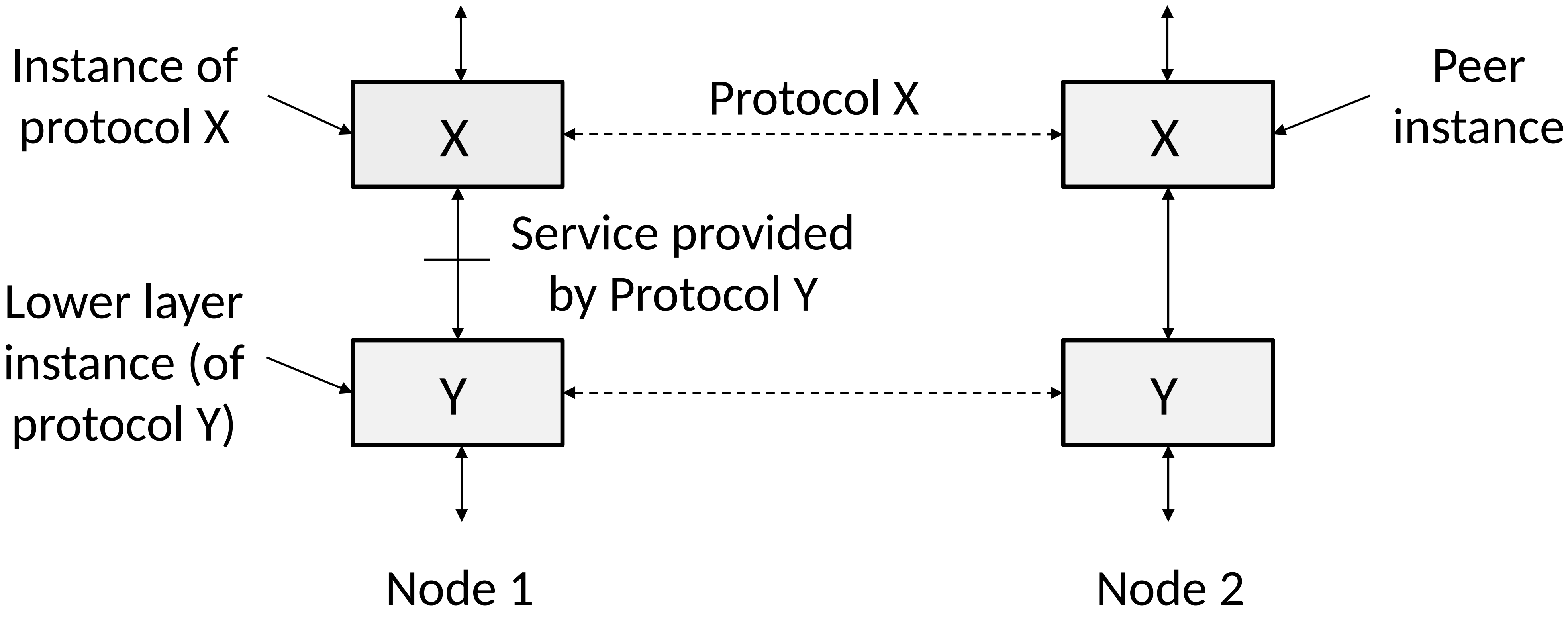
We need a form of modularity, to help manage complexity and support reuse

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

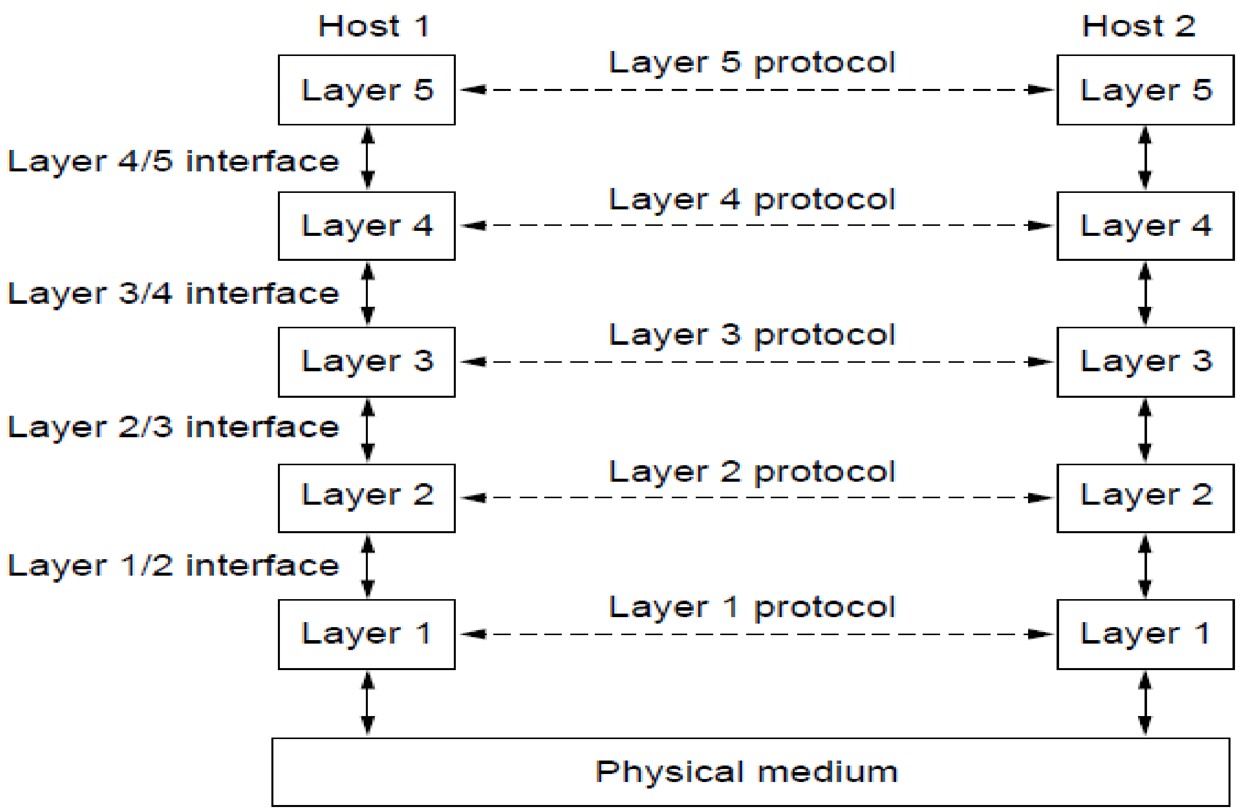
Protocols and Layers (2)

- Protocols are horizontal, layers are vertical



Protocols and Layers (3)

- Set of protocols in use is called a protocol stack

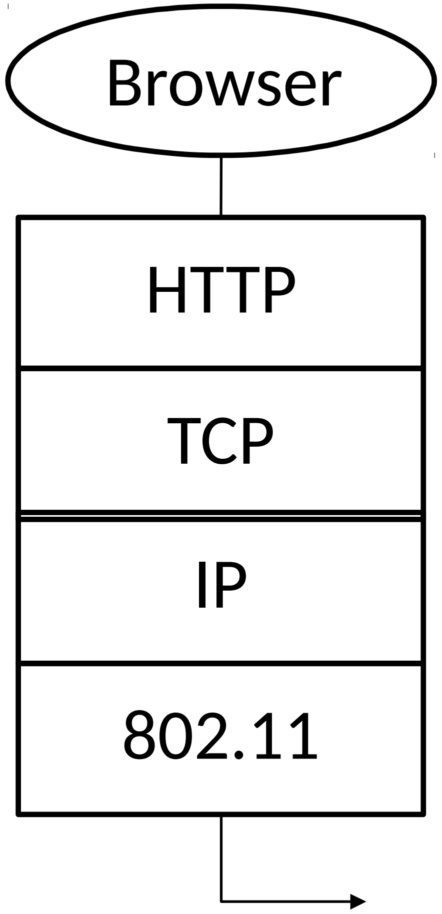


Protocols and Layers (4)

- Protocols you’ve probably heard of:
  - TCP, IP, 802.11, Ethernet, HTTP, SSL, DNS, … and many more

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

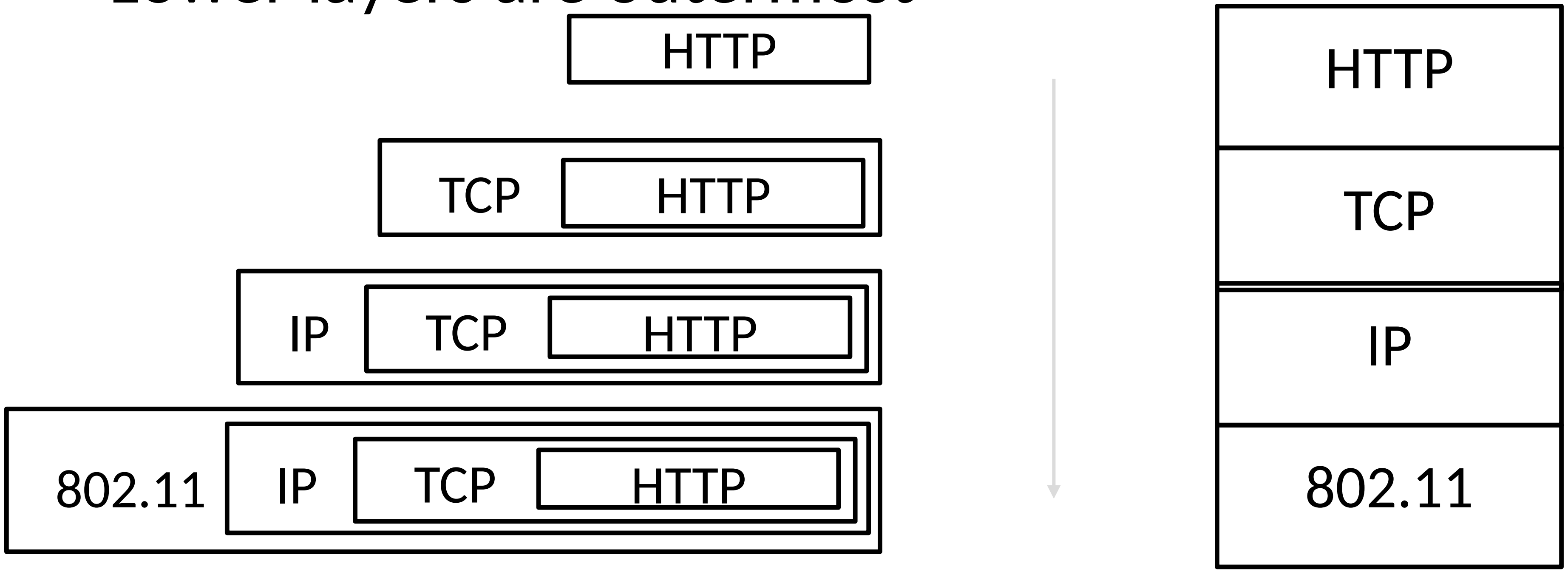


Encapsulation

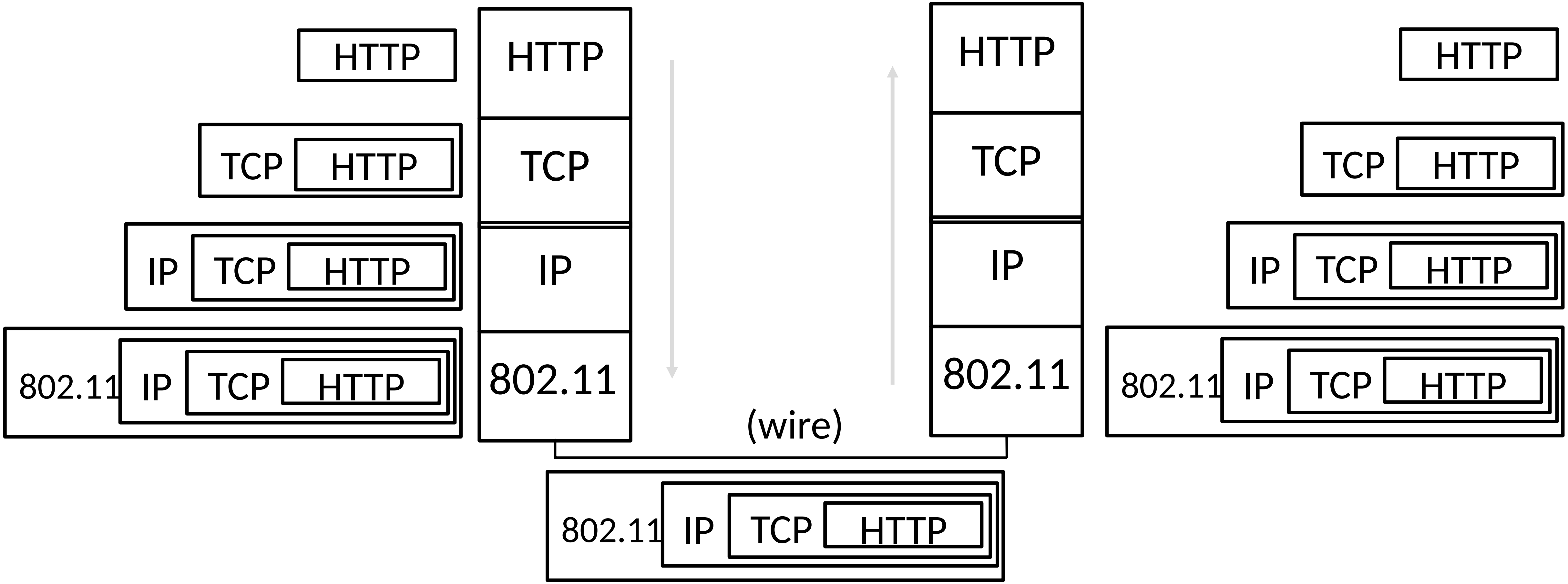
- Encapsulation is the mechanism used to effect protocol layering
  - Lower layer wraps higher layer content, adding its own information to make a new message for delivery
  - Like sending a letter in an envelope; postal service doesn't look inside

Encapsulation (2)

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

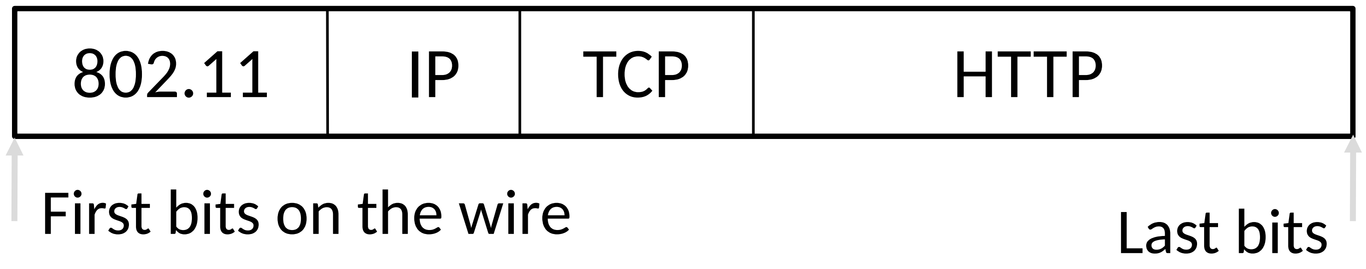


Encapsulation (3)



Encapsulation (4)

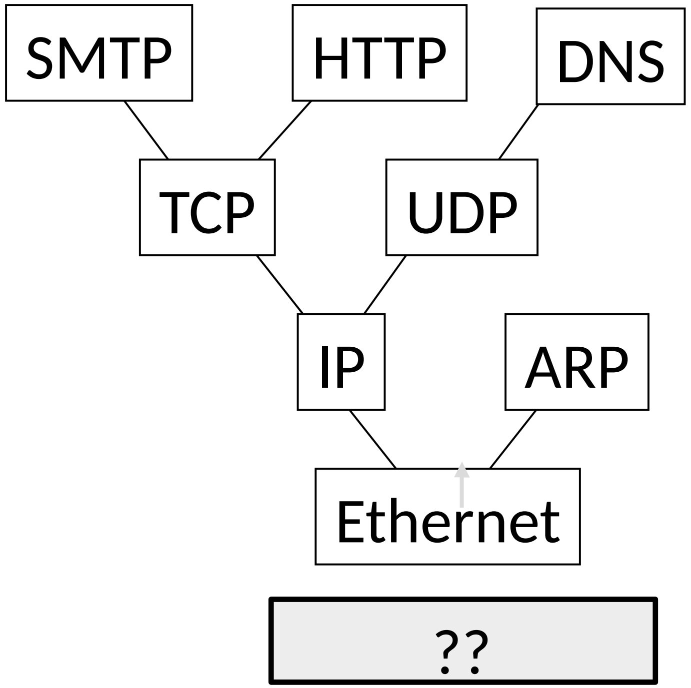
- Normally draw message like this:
  - Each layer adds its own header



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

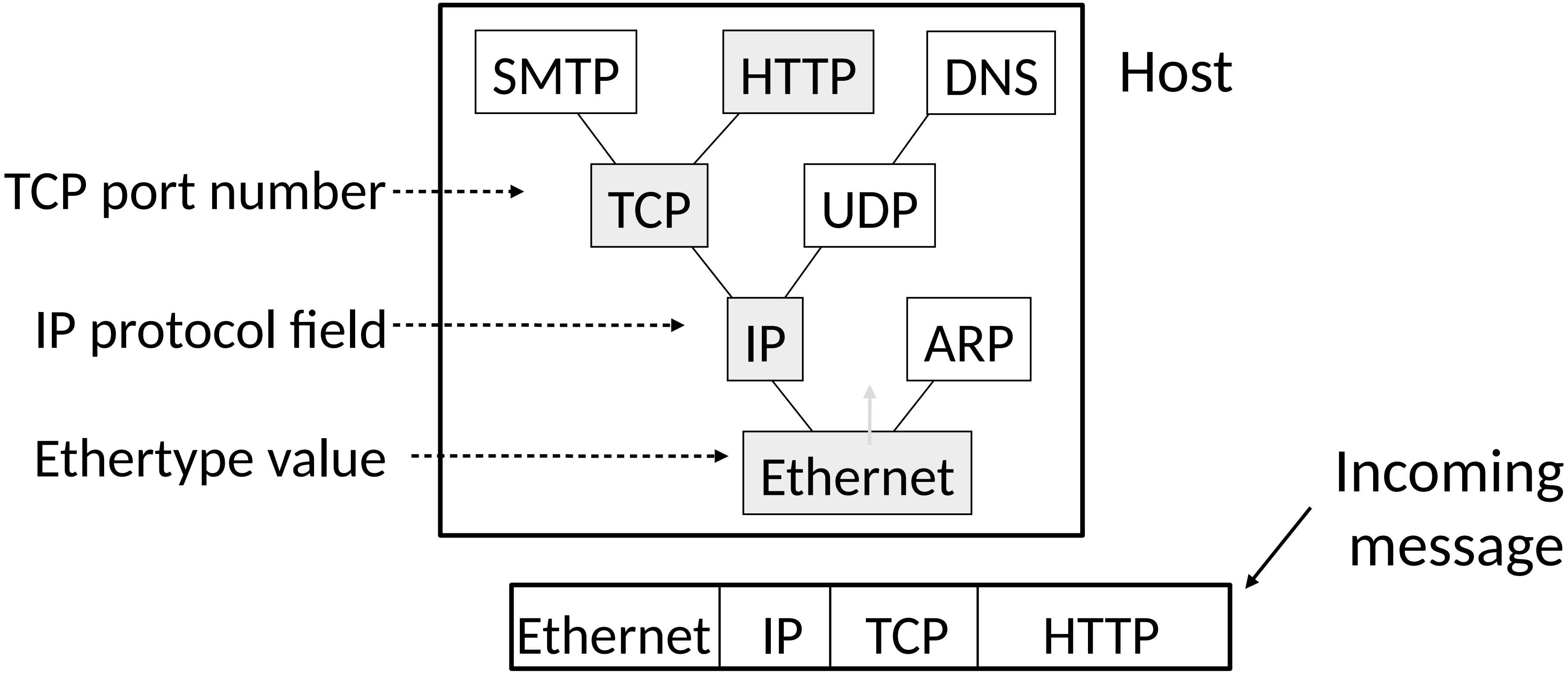
Demultiplexing

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



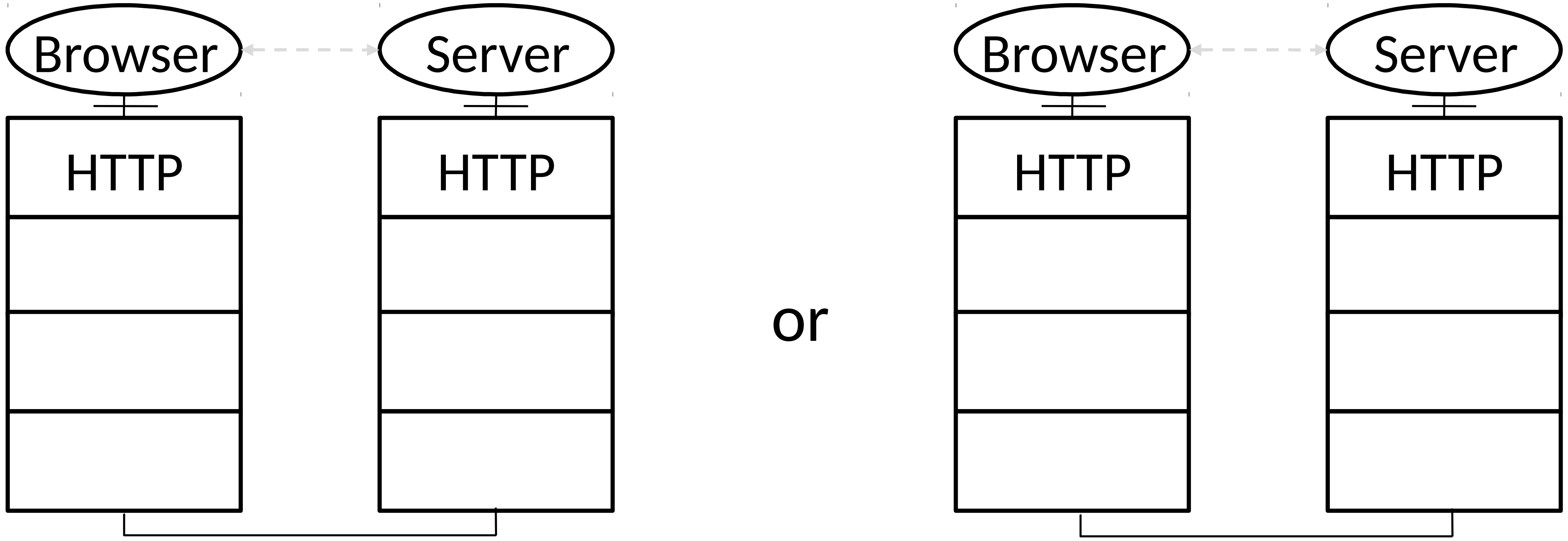
Demultiplexing (2)

- Done with demultiplexing keys in the headers



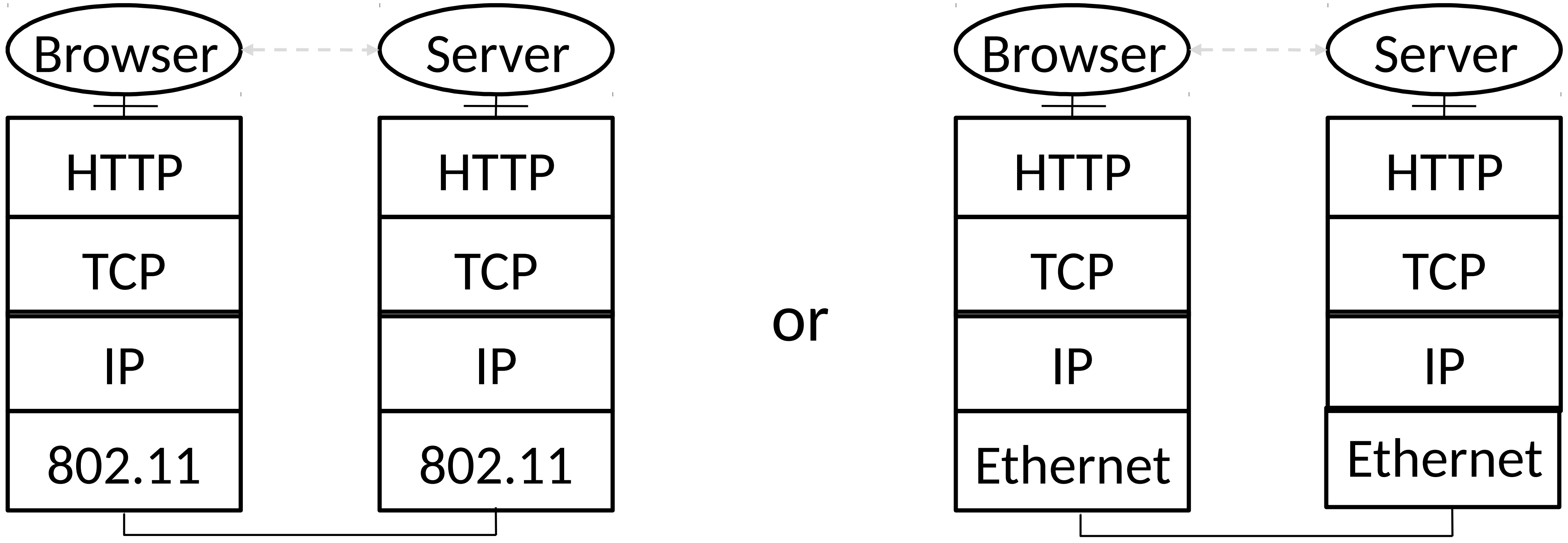
Advantage of Layering

- Information hiding and reuse



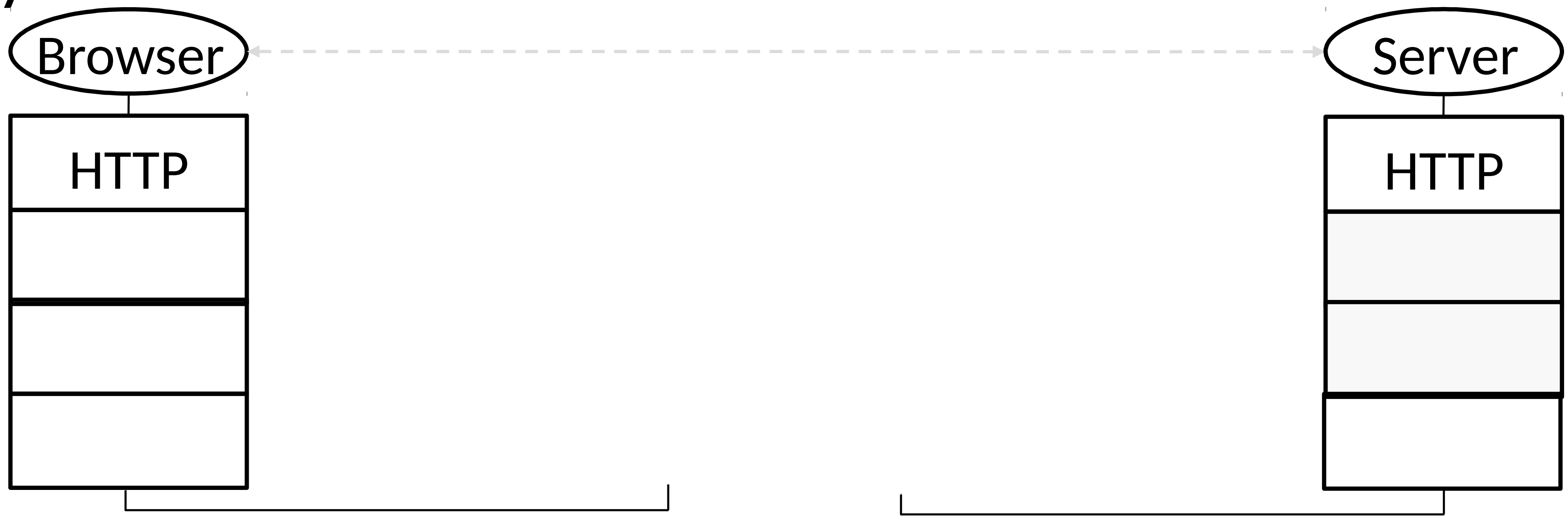
Advantage of Layering (2)

- Information hiding and reuse



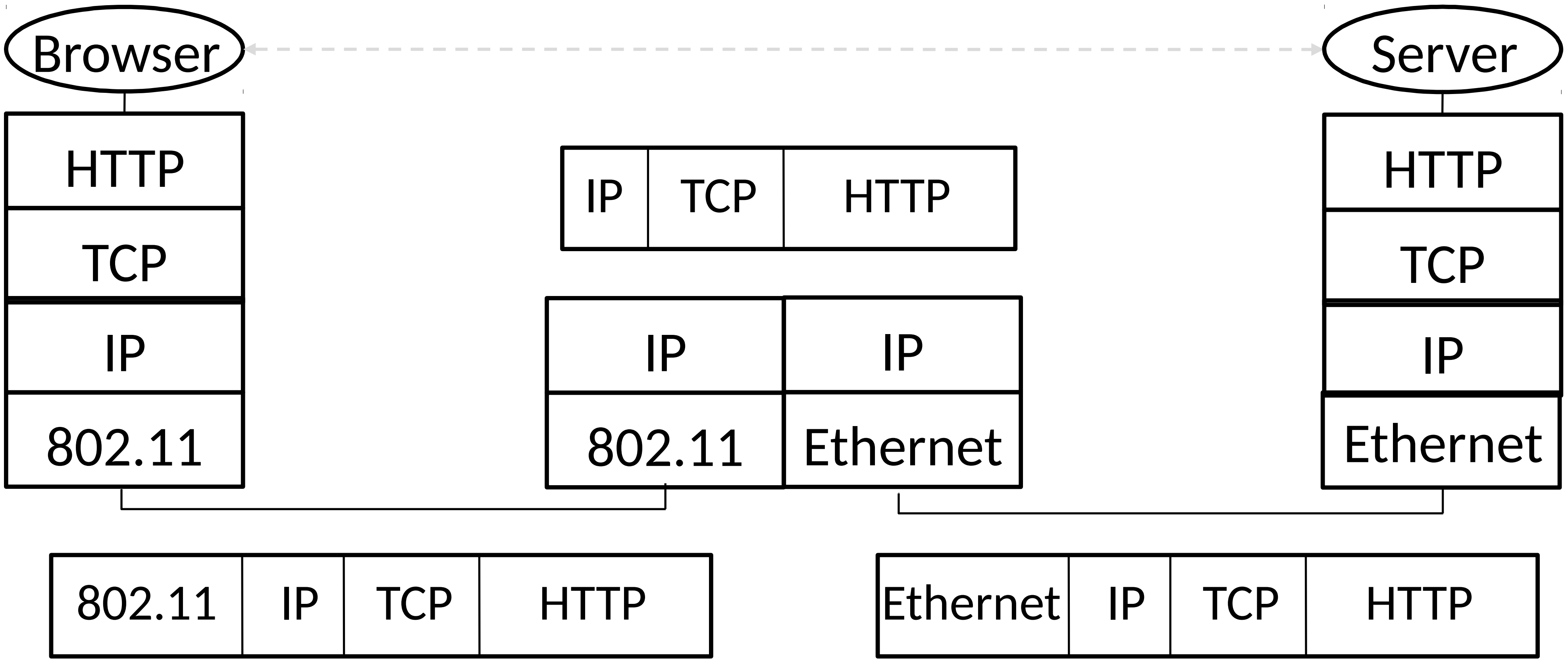
Advantage of Layering (3)

- Using information hiding to connect different systems



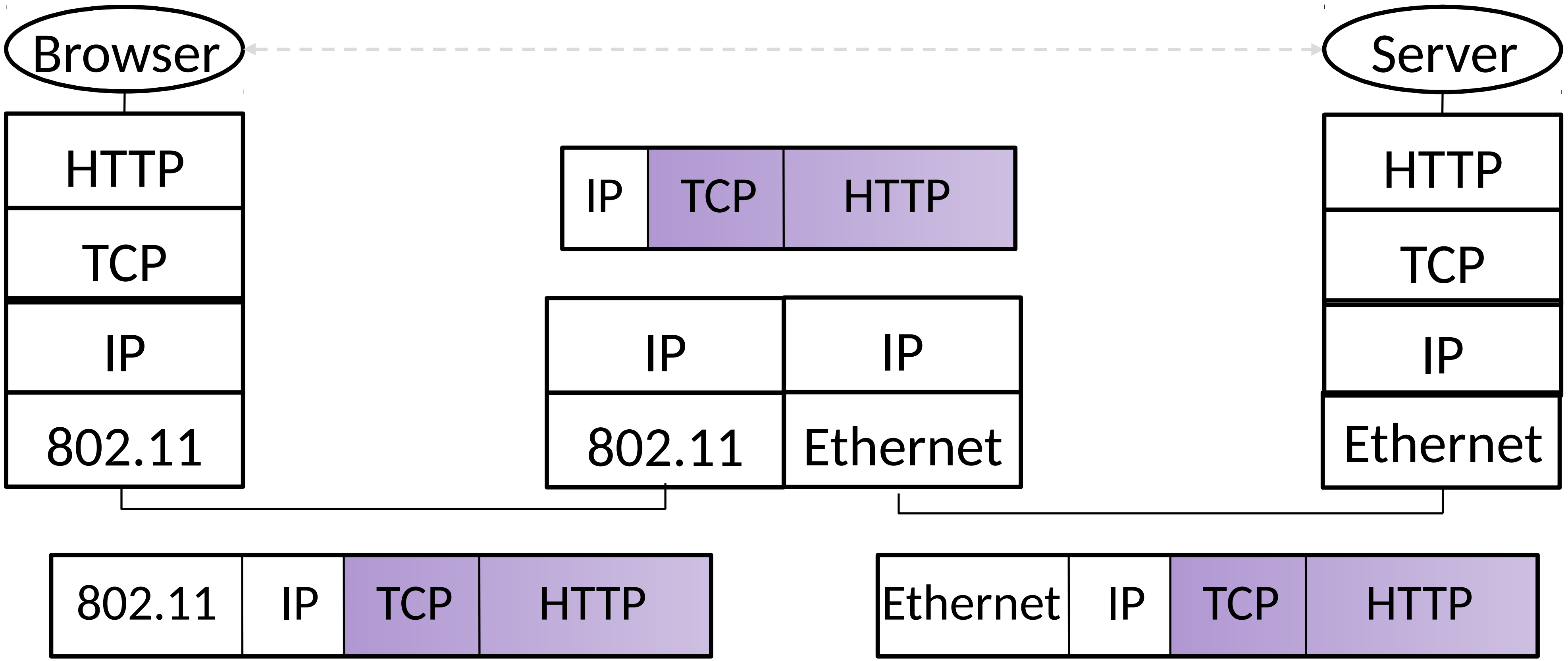
Advantage of Layering (4)

- Information hiding to connect different systems



Advantage of Layering (5)

- Information hiding to connect different systems



Disadvantages of Layering

- ?

Disadvantage of Layering

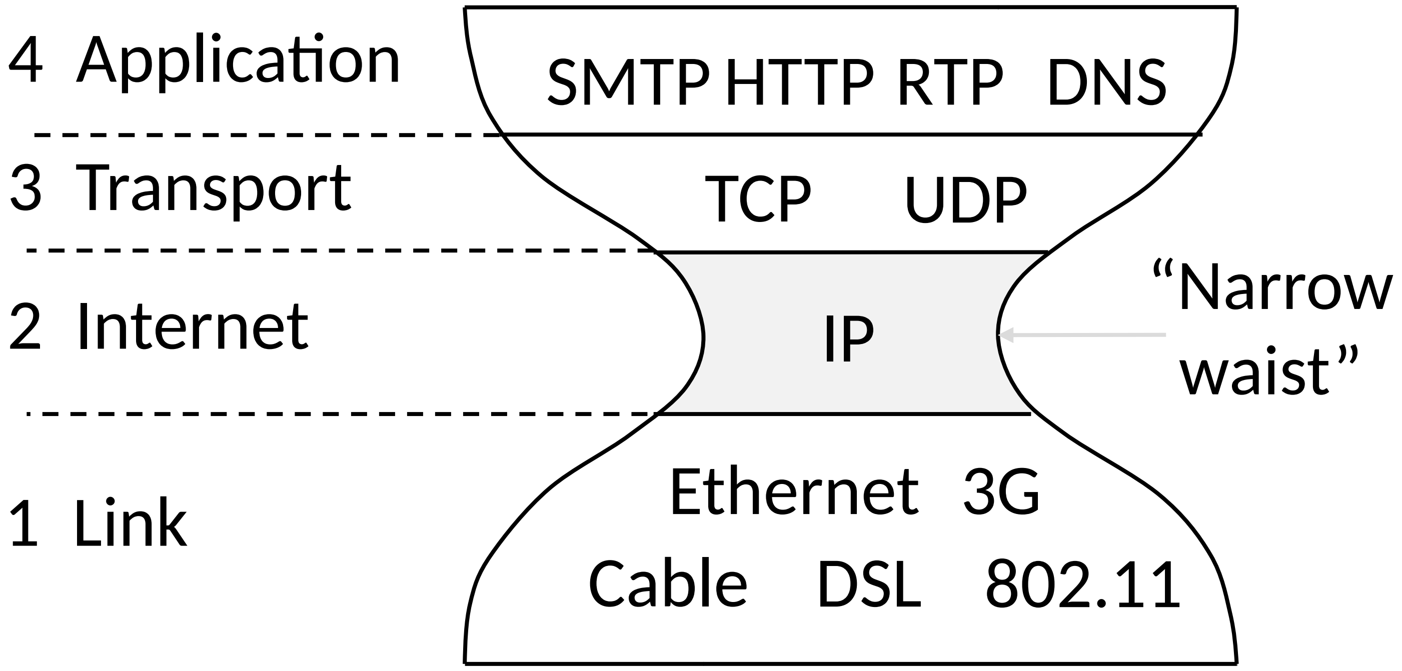
- Adds overhead
  - More problematic with short messages
- Hides information
  - App might care about network properties (e.g., latency, bandwidth, etc)
  - Network may need to know about app priorities (e.g., QoS)

OSI Layers

Layer	Function	Example
Application (7)	Services that are used with end user applications	SMTP,
Presentation (6)	Formats the data so that it can be viewed by the user Encrypt and decrypt	JPG, GIF, HTTPS, SSL, TLS
Session (5)	Establishes/ends connections between two hosts	NetBIOS, PPTP
Transport (4)	Responsible for the transport protocol and error handling	TCP, UDP
Network (3)	Reads the IP address form the packet.	Routers, Layer 3 Switches
Data Link (2)	Reads the MAC address from the data packet	Switches
Physical (1)	Send data on to the physical wire.	Hubs, NICS, Cable

Protocols and Layering

- The real internet protocol stacks:



Course Reference Model

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

5	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:

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

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