Operating Systems and Networks

Networks Part 1: Introduction

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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

Textbook and Slide Credit

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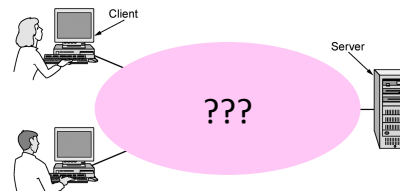- Slides adapted from slide deck by David Wetherall

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!

Focus of the course

Client
Server
???

Focus of the course (2)

- Three "networking" topics:

Distributed systems
Networking
Communications

- We mainly study the Networking aspects

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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
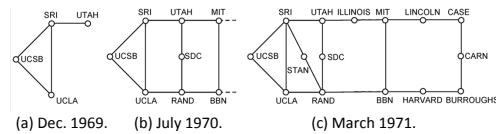
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Why learn about the Internet?

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

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From this experimental network …

ARPANET ~1970

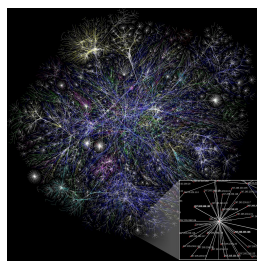(a) Dec. 1969.   (b) July 1970.   (c) March 1971.

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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

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Internet – Societal Impact

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

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Internet – Economic impact

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

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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?

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Why learn the Fundamentals?

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

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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 ...

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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)

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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

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Fundamentals – Reinvention (2)

- At least a billion Internet hosts and growing …

Internet Domain Survey Host Count

Source: Internet Systems Consortium (www.isc.org)

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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

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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

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Example Uses of Networks

- Work:
  - Email, file sharing, printing, …
- Home:
  - Movies / songs, news, calls / video / messaging, e-comm

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

- Mobile:
  - Calls / texts, games, videos, maps, information access …

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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

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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 »

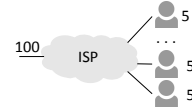Computer Networks 24

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?

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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)

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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

Binomial Calculator

Prob(x)

n = 30   p = 0.5

Prob. X is at most ▼ 20   = 0.9786.   Compute!
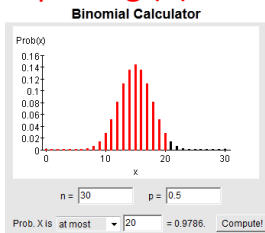
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For Content Delivery

- 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 »

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Content Delivery (2)

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

Source   User … User

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Content Delivery (3)

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

Source   Replica   User … User

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For Computer Communication

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

→ Enables automated information processing across different parties

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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

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The Value of Connectivity

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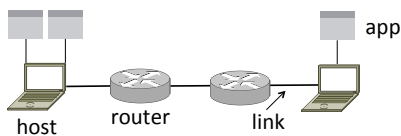 - Large networks are relatively more valuable than small ones

Bob Metcalfe

: © 2009 IEEE

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The Value of Connectivity (2)

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

vs +

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Parts of a Network

app

host   router   link

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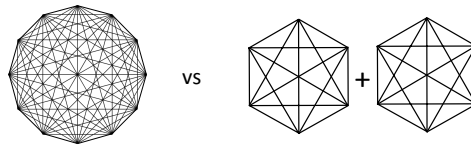
Component Names

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

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Types of Links
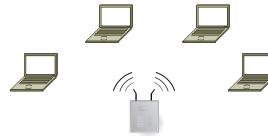
- Full-duplex
  - Bidirectional

- Half-duplex
  - Bidirectional

- Simplex
  - unidirectional

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Wireless Links

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

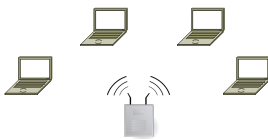Computer Networks   38

Wireless Links (2)

- Often show logical links
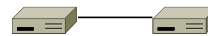 - Not all possible connectivity
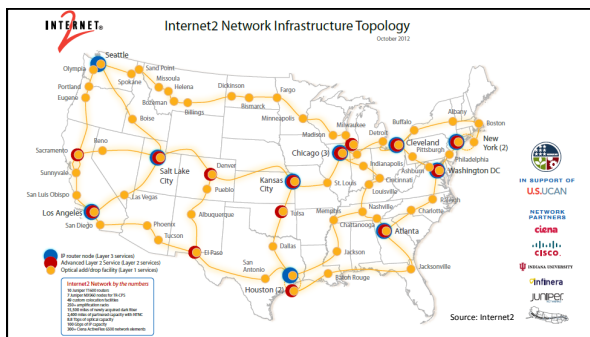

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A Small Network

- Connect a couple of computers

- Next, a large network …

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Internet2 Network Infrastructure Topology
October 2012

Source: Internet2

Example Networks

- Commonly known by type of technology or their purpose

- [see how many you can give]

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Example Networks (2)

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

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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!

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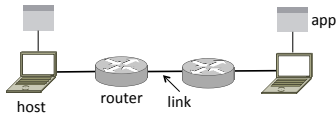
Internetworks

- 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

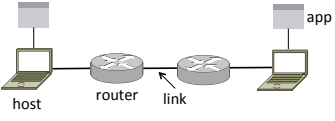Computer Networks   45

Network Boundaries

- What part is the "network"?

host   router   link

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Network Boundaries (2)

- What part represents an "ISP"?

host   router   link

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Network Boundaries (3)

- Cloud as a generic network

host

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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

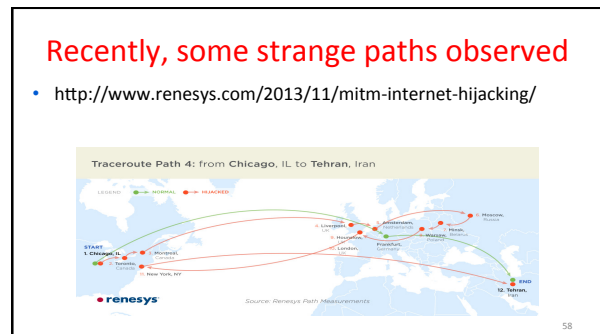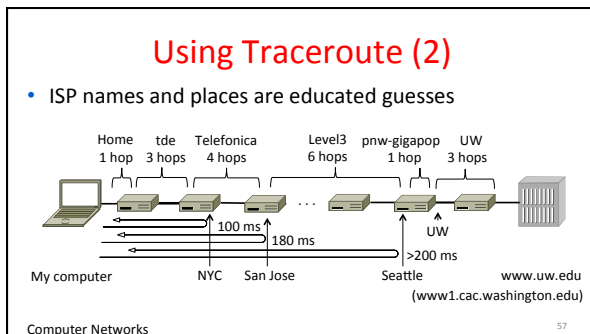: Credit: Wikipedia (public domain)

Traceroute (2)

- Probes successive hops to find network path

Local Host

Remote Host

Traceroute (3)

1 hop 2 hops 3 hops N-1 hops N hops

Local Host

Remote Host

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Using Traceroute

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Using Traceroute (2)

- ISP names and places are educated guesses

Home 1 hop tde 3 hops Telefonica 4 hops Level3 6 hops pnw-gigapop 1 hop UW 3 hops

100 ms
180 ms
>200 ms
UW

My computer NYC San Jose Seattle www.uw.edu
(www1.cac.washington.edu)

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Recently, some strange paths observed

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

Traceroute Path 4: from Chicago, IL to Tehran, Iran

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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
  - …

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Networks Need Modularity

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  - Shares bandwidth among users
  - Secures information in transit
  - Lets many new hosts be added
  - …

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

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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
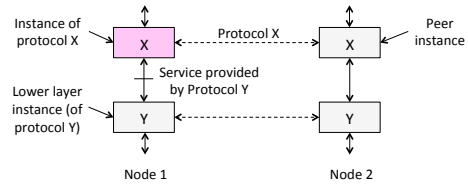 - Each instance of a protocol uses only the services of the lower layer

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Protocols and Layers (2)

- Protocols are horizontal, layers are vertical

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Protocols and Layers (3)

- Set of protocols in use is called a protocol stack
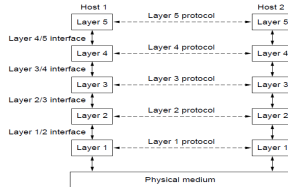
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Protocols and Layers (4)

- 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

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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
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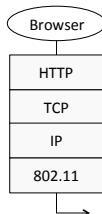
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Encapsulation

- 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

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Encapsulation (2)

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

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Encapsulation (3)

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Encapsulation (4)

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

802.11	IP	TCP	HTTP

First bits on the wire   Last bits

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

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Demultiplexing

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

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Demultiplexing (2)

- Done with demultiplexing keys in the headers

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Advantage of Layering

- Information hiding and reuse

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Advantage of Layering (2)

- Information hiding and reuse

Browser	Server		Browser	Server
HTTP	HTTP		HTTP	HTTP
TCP	TCP	or	TCP	TCP
IP	IP		IP	IP
802.11	802.11		Ethernet	Ethernet

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Advantage of Layering (3)

- Using information hiding to connect different systems

Browser		Server
HTTP		HTTP
TCP		TCP
IP		IP
802.11		Ethernet

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Advantage of Layering (4)

- Using information hiding to connect different systems

Browser			Server
HTTP	IP TCP HTTP		HTTP
TCP			TCP
IP	IP	IP	IP
802.11	802.11	Ethernet	Ethernet

| 802.11 | IP | TCP | HTTP | | Ethernet | IP | TCP | HTTP |

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Disadvantage of Layering

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

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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 »

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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

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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

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Internet Reference Model (2)

- With examples of common protocols in each layer

7 Application
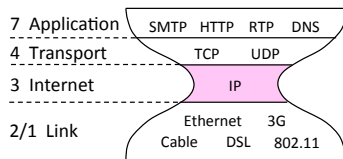4 Transport
3 Internet
2/1 Link
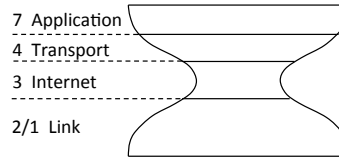
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Internet Reference Model (3)

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

7 Application   SMTP HTTP RTP DNS
4 Transport   TCP   UDP
3 Internet   IP
2/1 Link   Ethernet   3G
                 Cable   DSL   802.11

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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

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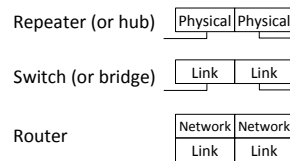
Layer-based Names

- For units of data:

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

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Layer-based Names (2)

- For devices in the network:

Repeater (or hub) | Physical | Physical |

Switch (or bridge) | Link | Link |

Router | Network | Network |
          | Link | Link |

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Layer-based Names (3)

- For devices in the network:

Proxy or
middlebox
or gateway

App	App
Transport	Transport
Network	Network
Link	Link

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

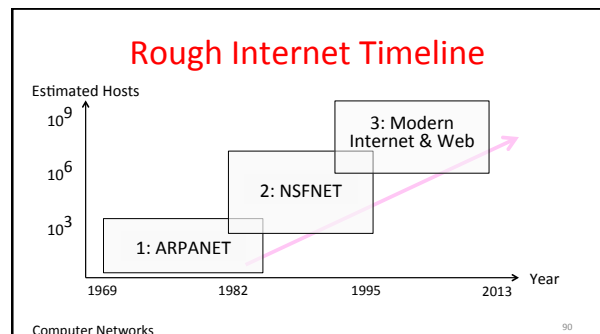| 7	Application	– Programs that use network service
4	Transport	– Provides end-to-end data delivery
3	Network	– Send packets over multiple networks
2	Link	– Send frames over one or more links
1	Physical	– Send bits using signals

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

Estimated Hosts

10^9

10^6

10^3

3: Modern
Internet & Web

2: NSFNET

1: ARPANET

1969   1982   1995   2013   Year

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

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ARPANET – Influences

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

Paul Baran   Donald Davies   Len Kleinrock

Credit: Internet Hall of Fame   Credit: Internet Hall of Fame   Credit: Internet Hall of Fame

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ARPANET – Influences (2)

- In the early ARPANET

Vint Cerf   Bob Kahn

  - 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"

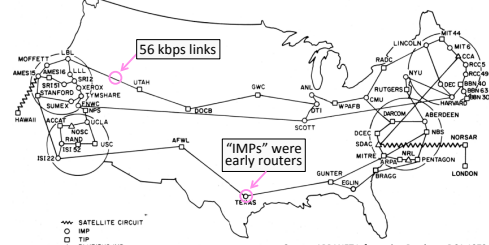© 2009 IEEE   © 2009 IEEE

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ARPANET Geographical Map (Dec. 1978)

56 kbps links

"IMPs" were early routers

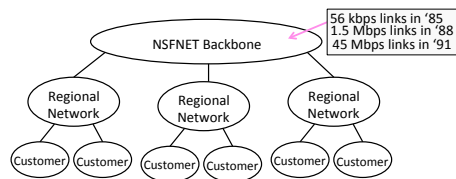Source: ARPANET Information Brochure, DCA 1979

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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 …

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Early Internet Architecture

- Hierarchical, with NSFNET as the backbone

56 kbps links in '85
1.5 Mbps links in '88
45 Mbps links in '91

NSFNET Backbone

Regional Network   Regional Network   Regional Network

Customer Customer   Customer Customer   Customer Customer

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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

© 2009 IEEE

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Modern Internet Architecture

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

Content Provider
Transit ISP
Content Provider
Transit ISP
IXP
IXP
IXP
Regional ISP
Regional ISP
Regional ISP
Customer
Facility at which networks connect

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