CS 331: Computer Networks

Sameer G Kulkarni

Assistant Professor,

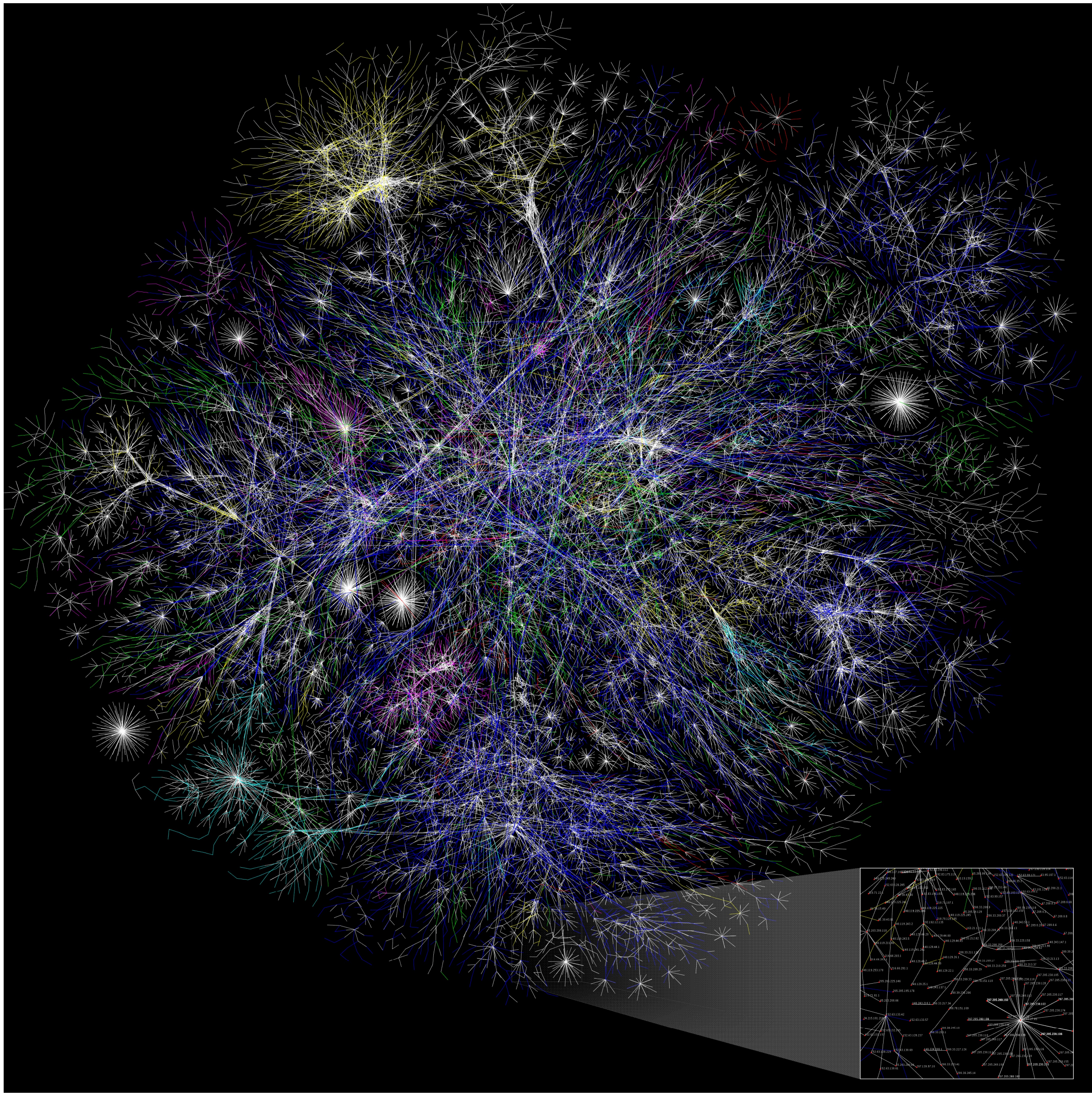
Department of Computer Science and Engineering,

Indian Institute of Technology, Gandhinagar

Today’s Lecture

- Course Logistics
  - Can be revised to suit the needs of the Class
- Introduction to CN
  - Course Overview.
  - Topics and Tools.
- Modus operandi:
  - 3 P’s: Protocols, Principles, and Practices.
  - 3 P’s: Programming, Problems, and Practice.

Source: [Wikipedia]



Class Structure

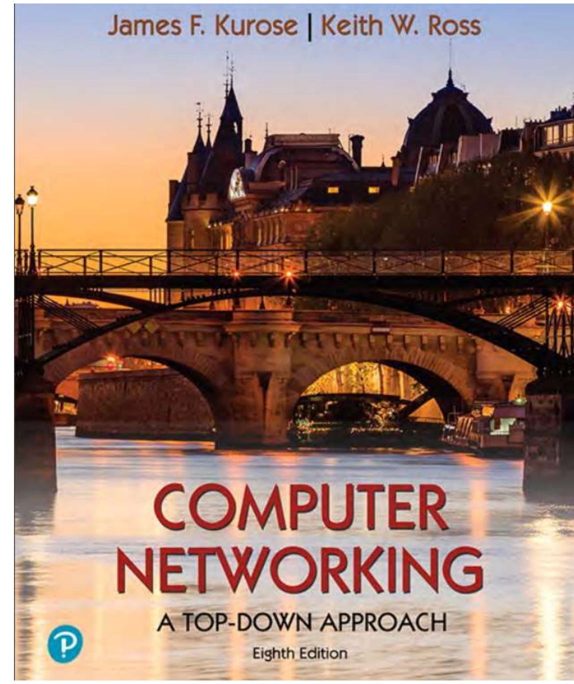
- Lecture Sessions: ~25-28 (AB10/201)
  - Tuesday/Wednesday/Friday 11:30-13:00

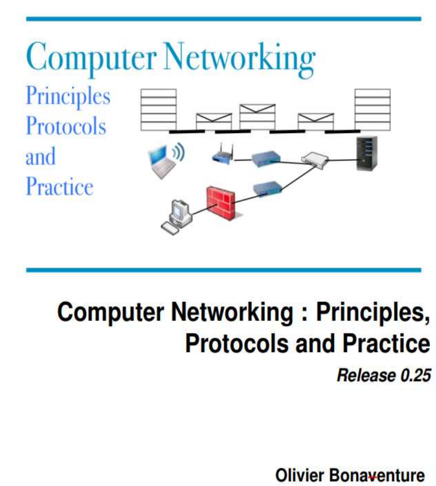
- Tutorial sessions: ~10-12 (AB1/101)
  - Tuesday/Friday 11:30 -13:00
  - Problem Solving, Networking tools and Discussions

- Contacts:
  - Instructor: Sameer Kulkarni (sameergk@iitgn.ac.in)
  - TAs: Ayushman Singh, Mallika Chauhan, Yasir Mohiuddin, Naveen Tiwari
  - ADH: NA
  - Office Hours: Flexible, AB13/405E.
    After Class hours, setup via email.

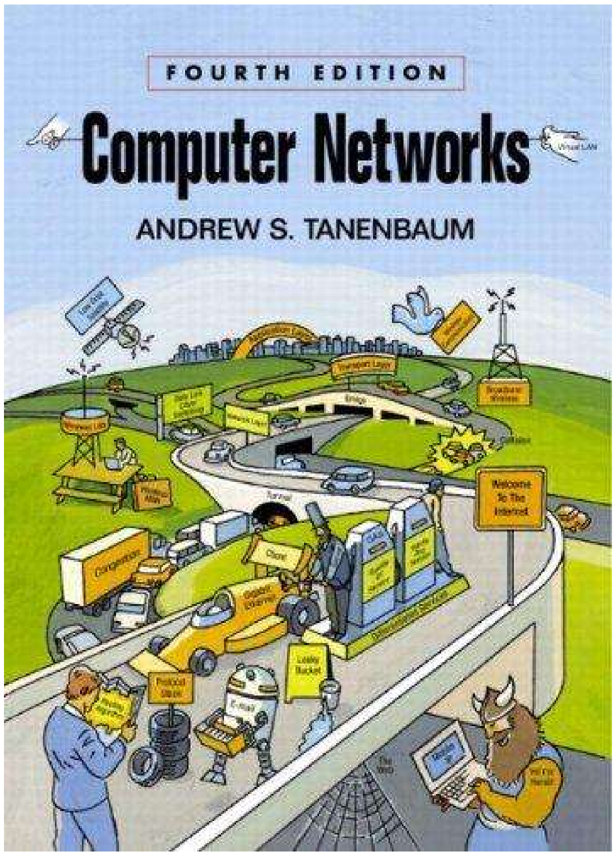
Course Readings

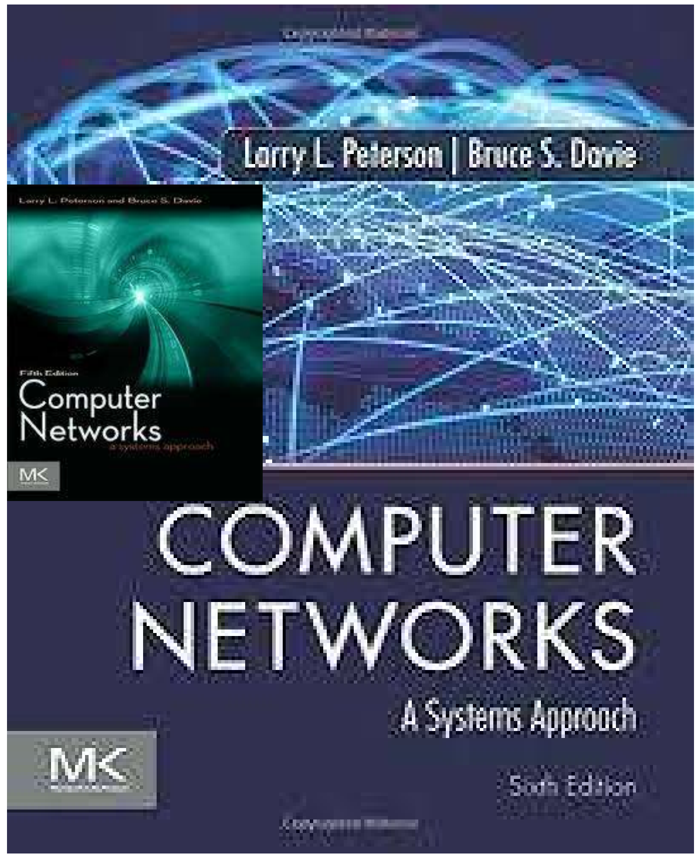
- Textbooks (Recommended)
  - Book1: Computer Networking – A Top Down Approach by Kurose and Ross (6/7/8th edition)
  - Book2: Olivier Bonaventure, *Computer Networking: Principles, Protocols and Practice* 3rd Edition, Online book, 2019.
- Standards and Standards and More Standards!!
  - IETF RFCs and Internet Drafts
- State-of-the-Art Networking/Research works!!
  - Conference and Journal publications by Academia and Industry.

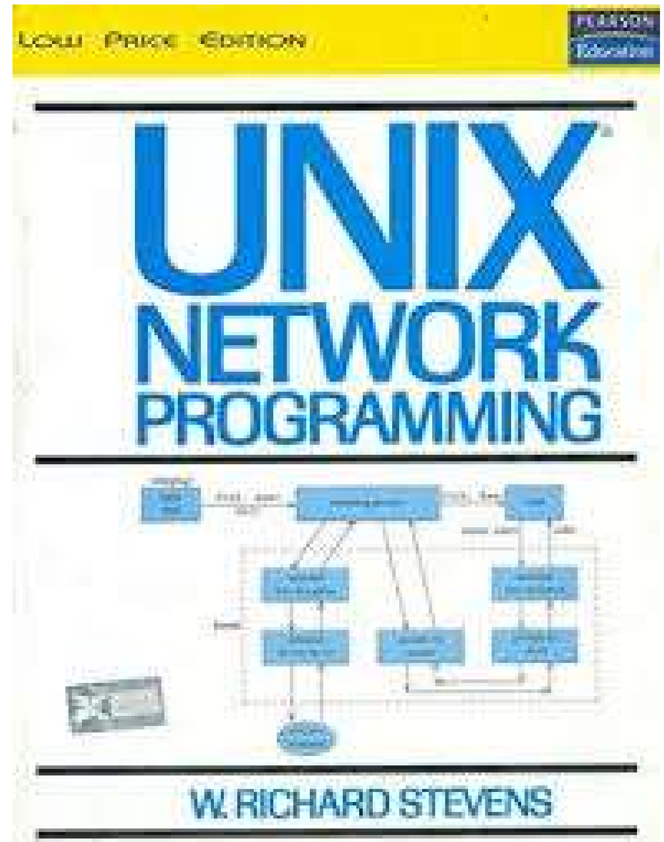




Additional Reference Text books







Other Online Materials

TCP/IP Technical Overview, Tutorial and Guide,

Charles M. Kozierok, Available Online - http://www.tcpipguide.com/

TCP/IP Tutorial and Technical Overview, (IBM Redbook) - Download From http://www.redbooks.ibm.com/abstracts/gg243376.html

Request for Comments (RFC) - IETF - http://www.ietf.org/rfc.html

Research Publications – relevant works will be discussed and distributed time to time

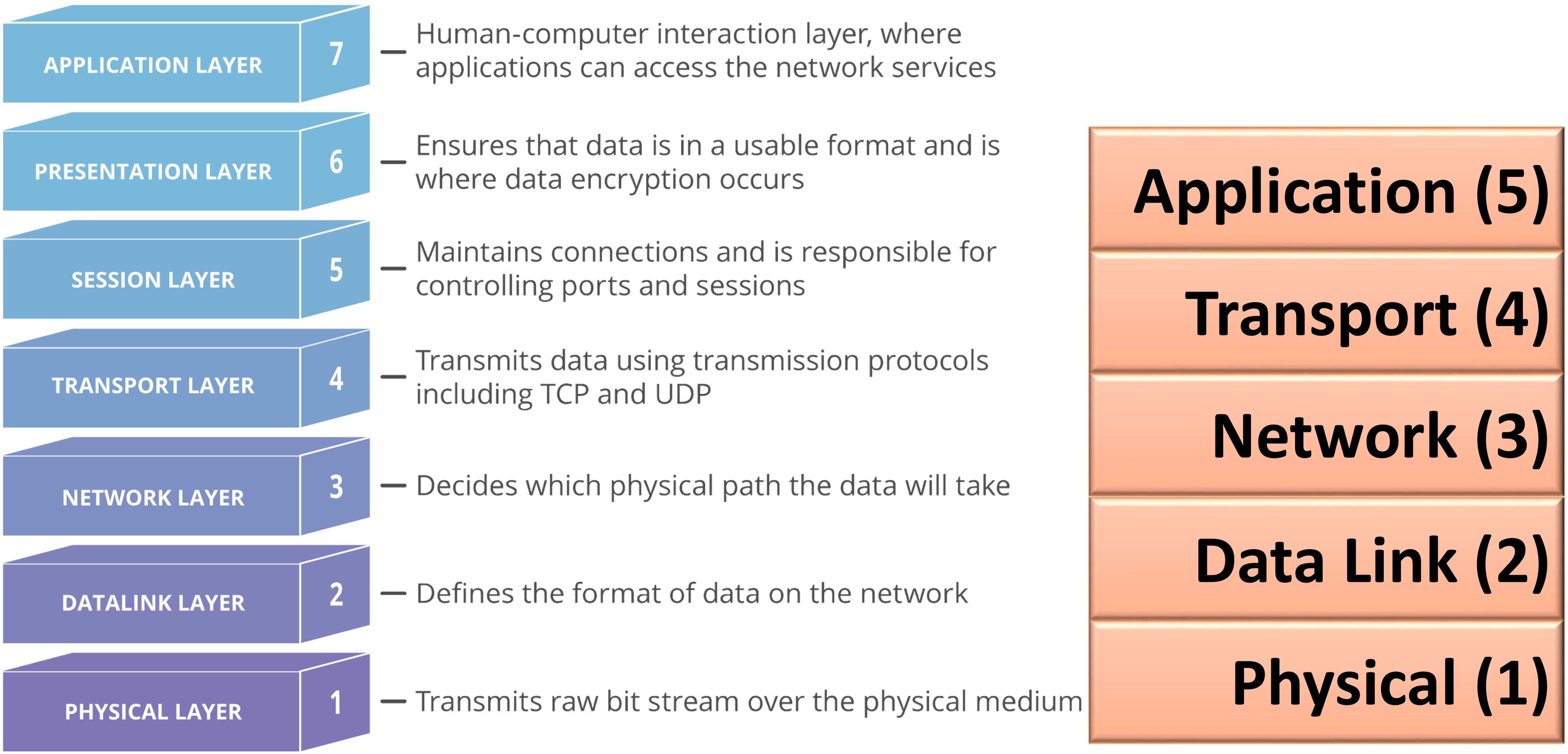
Course Evaluations

- Assignments –10%
  - 2-3 assignments containing both theory and implementation. (within 1 week)
- Quiz (MCQ/MSQ) –15%
  - At-least 3-4 (may be lot more) Quiz Sessions (random/pre-defined date)
- Exam 1 - 25%
  - Midsem will cover up to last content covered till the Lecture (Application and TCP/~~IP~~ layer)
- Exam 2 - 25%
  - Midsem will cover up to last content covered till the Lecture (IP Layer + Application + TCP layer)
- Course-Project - 25% (Group of 3-4 students)
  - Will be done in 3 phases. (Phase-1 pre-midsem, Phase-2,3 post midsem).

Course Related Information

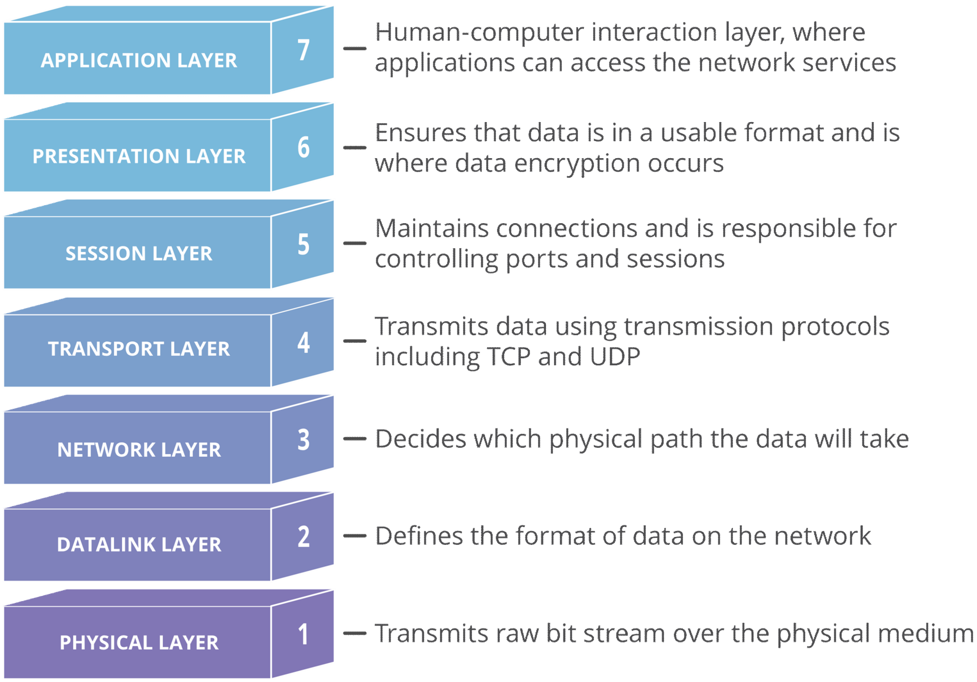
- Course Website:
  - MS Teams:
    - LINK
    - code: **n82jvw2**

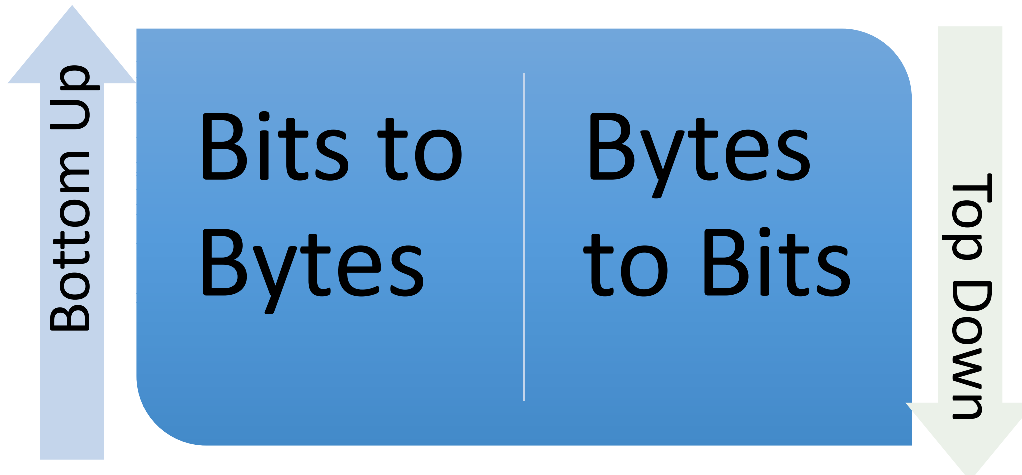
NETWORKING MOUNTAIN: ISO/OSI (7-LAYER) AND TCP/IP (5-LAYER) MODELS



Source: https://www.cloudflare.com/learning/ddos/glossary/open-systems-interconnection-model-osi/

APPROACH: TOP DOWN OR BOTTOM UP?





What you will Learn in this Course

Application Layer: Study of Protocols and Applications: DNS, FTP, HTTP, and SMTP. *Socket Interface and Socket programming.*

Transport Layer: Connection oriented and Connectionless protocols: TCP and UDP; Details of TCP: Buffer Management, Flow Control and Congestion control; Study of TCP variants such as Reno, Tahoe, Vegas and CUBIC. Reliable transmission and Automatic Repeat Request (ARQ) protocols: Stop-and-Wait, Go-back-N, Selective Repeat.

Network Layer: Design Principles: Protocols, Addressing and Routing. Study of Internet Protocol (IP) suite; Hierarchical network architectures; IPv4 and IPv6 addressing and headers; Routing protocols: distance-vector and link-state approaches; Interior and Exterior Gateway Protocol concepts; Routing Algorithms including Dijkstra's algorithm and distributed Bellman-Ford algorithm; Example protocols: OSPF, RIP, BGP.

What you will Learn in this Course

Advanced topics and recent trends in Computer Networks and Future Internet: Information Centric networking, Software Defined Networking (SDN), Network Function Virtualization (NFV), Internet of Things (IoT), Docker and Container Networking (CNIs), Programmable switches, OVS, and SmartNICs.

Miscellaneous: Introduction to Datacenter Networks, Different RFCs.
Case Studies: Linux/Unix TCP IP Stack.

Physical and Link Layers: Basics of communications; Delay, Loss and Throughput. Physical media types and their important bandwidth and bit-error-rate characteristics; Wired and Wireless media including copper cables, optical fiber and wireless. Framing; Error control: Bit-parity, CRC.

Medium Access Control (MAC): Shared media systems; Bus, Star and Ring topologies; TDMA, FDMA, CSMA, CSMA/CD, Ethernet and IEEE 802.3; IEEE 802.11 including CSMA/CA protocols; Shared and Switched Ethernet; Introduce protocols such as ARP, RARP and ICMP.

Hands-on Tutorials

Networking Utilities: IP/IFconfig Tcpdump, Wireshark, netcat, Scapy, dig.

Network Programming: Socket Programming, HTTP Server, DNS Server, OpenFlow, etc. AND ***Term Projects*** – *Applications, Novel Protocols, Analysis..*

Previous Projects*: N/w Monitoring, Security, eBPF, Mini-Facebook, Mini-Tweet, Mini-Class, Web Portals, and other Real-world problems.*

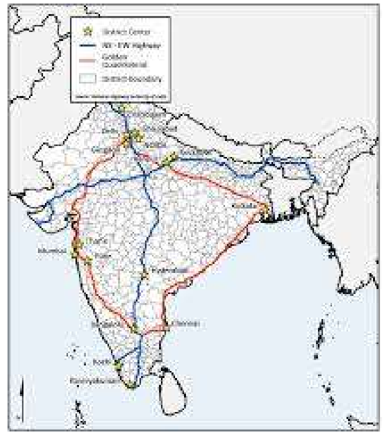
Network Simulators: NS-2/3, OMNet++, GNS3, Mininet.
Third party Tools: Cisco Packet Tracer* -- Network in your pocket!!

Similar Courses offered at other Top Universities

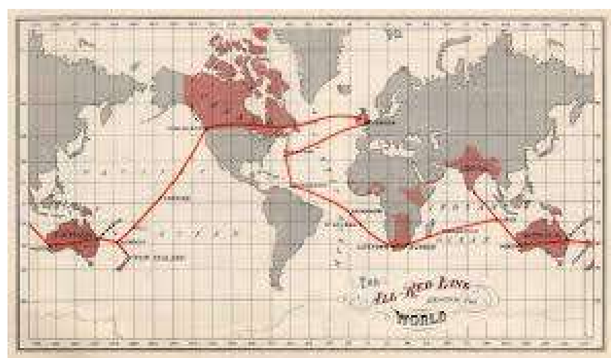
- MITx
- Edx (Online course)
- MIT 1
- UC Berkeley
- Stanford
- UGOE
- UCR
- IITB
- IITK
- IITKGP

DIFFERENT KINDS OF NETWORKS WE KNOW…

- Transportation Networks
  - Road Network
  - Rail Networks
  - Airline Networks



- Communication Networks
  - Postal Networks
  - Telegraph Networks
  - Telephone Networks.



- Utility Networks: Power Grid/Water/Gas Supply
- Infection Network: COVID-19

COMMONALITIES IN THESE DIFFERENT KINDS OF NETWORKS..

- ***What are the common aspects among these?***
  - ***Different Entities,***
  - ***Interaction through certain medium, and***
  - ***Flow/Exchange of some kind of data***

TAKEAWAY QUESTION

Q: What is the difference between Communication and Networks?

Very Basic Network Terminologies

- Client, Server, Peer, End-hosts
- Hub, Switch, Router, Gateway,
- Middlebox, NAT, Firewall, IDS/IPS, relay,
- Protocol, *Segment*, Packet, Frame, PDU, SDU
- Delay, Latency.
- Bandwidth, Throughput
- Loss, Burst, Jitter

IP picture frame
http://www.ceiva.com/

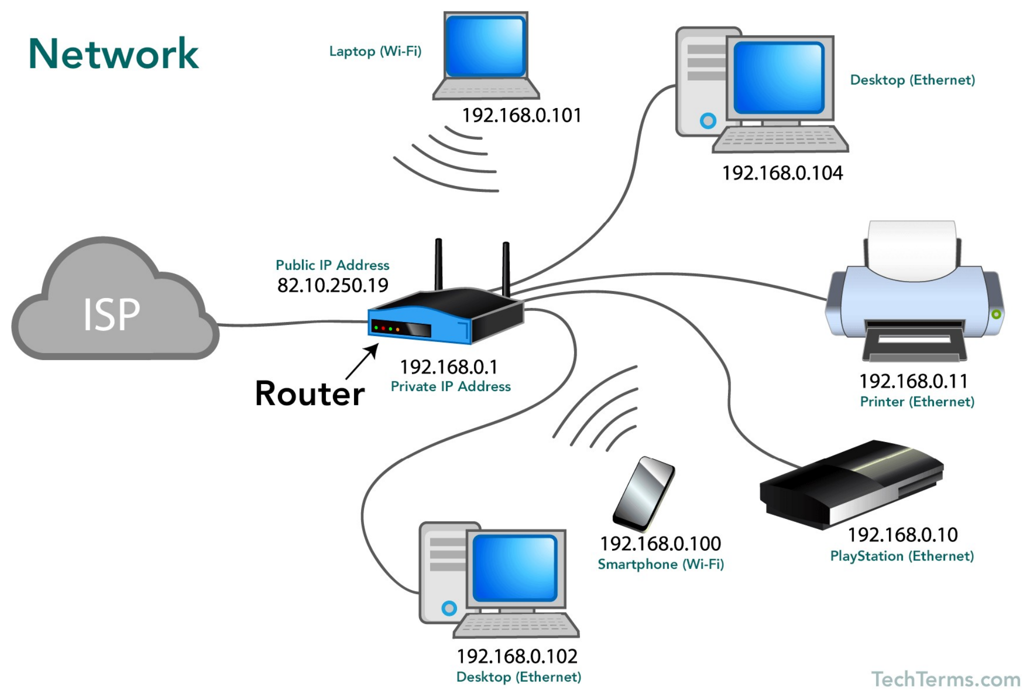
Tweet-a-watt:
monitor energy use

Internet
refrigerator

Internet phones

WHAT DO WE MEAN BY COMPUTER NETWORKS?

- What is a Network?
  - A system of interconnected things (a representation of group).
  - Facilitators of communication (exchange of information) across distributed entities.



- **Computer Networks**: Infrastructure/system that facilitates the communication (information sharing) across computers/digital devices.
  - Infrastructure includes communications devices, transmission media, and protocols.

Network and Communication Bytes

Byte System		
Name (symbol)	Power of 10 Value (in bytes)	Power of 2 Value (in bytes)
kilobyte (kB)	10^3	2^{10}
megabyte (MB)	10^6	2^{20}
gigabyte (GB)	10^9	2^{30}
terabyte (TB)	10^{12}	2^{40}
petabyte (PB)	10^{15}	2^{50}
exabyte (EB)	10^{18}	2^{60}
zettabyte (ZB)	10^{21}	2^{70}
yottabyte (YB)	10^{24}	2^{80}

Examples and comparisons with SI prefixes	
one **kibibit**	1 Kibit = 2^{10} bit = **1024 bit**
one **kilobit**	1 kbit = 10^3 bit = **1000 bit**
one **byte**	1 B = 2^3 bit = **8 bit**
one **mebibyte**	1 MiB = 2^{20} B = **1 048 576 B**
one **megabyte**	1 MB = 10^6 B = **1 000 000 B**
one **gibibyte**	1 GiB = 2^{30} B = **1 073 741 824 B**
one **gigabyte**	1 GB = 10^9 B = **1 000 000 000 B**

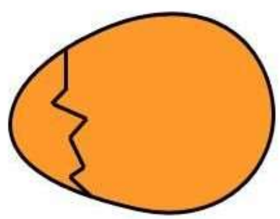
Factor	Name	Symbol	Origin	Derivation
2^{10}	kibi	Ki	kilobinary: $(2^{10})^1$	kilo: $(10^3)^1$
2^{20}	mebi	Mi	megabinary: $(2^{10})^2$	mega: $(10^3)^2$
2^{30}	gibi	Gi	gigabinary: $(2^{10})^3$	giga: $(10^3)^3$
2^{40}	tebi	Ti	terabinary: $(2^{10})^4$	tera: $(10^3)^4$
2^{50}	pebi	Pi	petabinary: $(2^{10})^5$	peta: $(10^3)^5$
2^{60}	exbi	Ei	exabinary: $(2^{10})^6$	exa: $(10^3)^6$

Source: https://physics.nist.gov/cuu/Units/binary.html

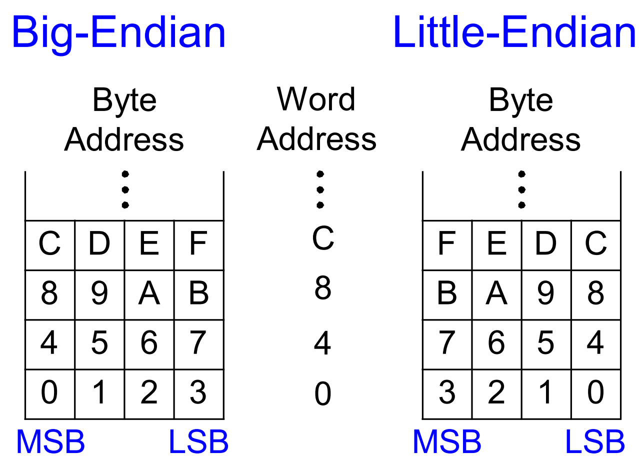
https://groups.ischool.berkeley.edu/archive/how-much-info/datapowers.html
http://www.ccsf.caltech.edu/~roy/dataquan/

- From Jonathan Swift's Gulliver's Travels where the Little- Endians broke their eggs on the little end of the egg and the Big-Endians broke their eggs on the big end.
  - **As indicated by the farcical name, it doesn't really matter which addressing type is used – except when the two systems need to share data!**

BIG ENDIAN - The way people always broke their eggs in the Lilliput land



LITTLE ENDIAN - The way the king then ordered the people to break their eggs



HAVE YOU HEARD THIS BROWSERS CONVERSATION?

TAKEAWAY QUESTION..

Q: How do we exchange information?

And How do computers exchange information?

- Layers, Network Stack, **ISO/OSI vs TCP/IP**
- What do we mean by Protocols?
- Layering Principle: SDU and PDU

How do we communicate?

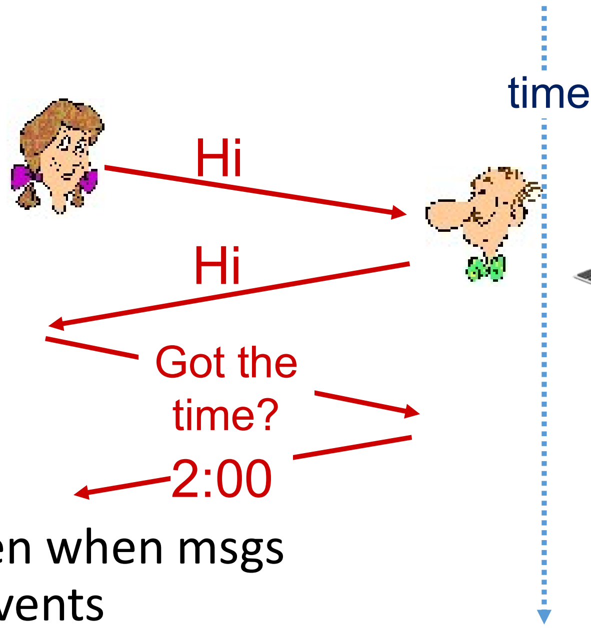
a human protocol and a computer network protocol:

human protocols:

- Introductions…
- "I have a question"
- "what's the time?"

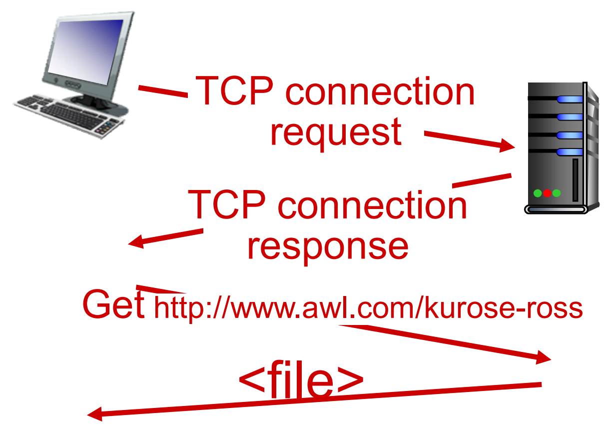
… specific msgs sent

… specific actions taken when msgs received, or other events



network protocols:

- machines rather than humans.



protocols: <**Conventions of Communication**>

define format, order of msgs sent and received among network entities, and actions taken on msg transmission, receipt

THREE KEY ASPECTS OF A NETWORKING PROTOCOLS

1 Syntax

- Format of each message
- Representation of data items
- Encoding of bits in electromagnetic signals

2 Semantics

- Meaning of each message
- Procedures used to exchange messages
- Actions to take when an error occurs

3 Sequence/Timing

- Specifies "When" the message/information exchange occurs
- And is some cases frequency/speed

But Designing Protocols is not easy!!

Steps In Protocol Design

Look at the facilities the underlying hardware provides

Imagine an abstract communication mechanism as a user would like it to work

Design an efficient implementation of the abstraction

The key to success: ***A good abstraction***

Internet Architecture and Key Design Principles

Robustness Principle – Design principle that maximizes interoperability (John Postel)

Be conservative in what you send and be liberal in what you accept.

Communication in good faith, survive and cooperate to avoid disruptions!

Layering Principle - Layered protocols enforce an invariant:

Layer N at the destination receives an exact copy of the message sent by layer N at the source. All headers and other modifications added by lower layers at the source must be removed by lower layers at the destination.

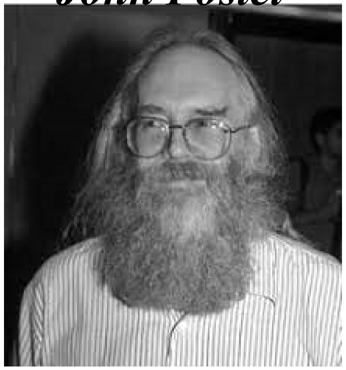
Allows protocol designer to focus on one layer at a time!

End2End Principle: "Minimal, Dumb" Network and "Intelligent" end points.

The function in question can completely and correctly be implemented only with the knowledge and help of the application standing at the end points of the communication system.

Network is stateless and only the end-hosts manage state.

John Postel



David Clark

The principle of constant change is perhaps the only principle of the Internet that should survive indefinitely.
Architectural Principles of the Internet [RFC 1958, RFC 3439] – B. Carpenter

PRINCIPLES OF NETWORKING AND NETWORK DESIGN PHILOSOPHY

- Protocol for Packet Network Intercommunication --
  Vinton G. Cerf & Robert E. Kahn, 1974 [Link], [*>1700 Citations*]

- End-to-End Arguments in System Design –
  Saltzer, Reed and Clark, 1984 [Link], [*>3500 Citations*]

- The Design Philosophy of the DARPA Internet Protocols –
  David D. Clark, 1988[Link], [*>1700 Citations*]

WHY LAYERING?

5

1) **Modularity**– one problem is decomposed into a number of smaller more manageable subproblems

⇒ reduced complexity: focus on simpler problem statement.

⇒ more flexibility: in designing, modifying and evolving computer networks.

⇒ standardized interfaces: ease of development.

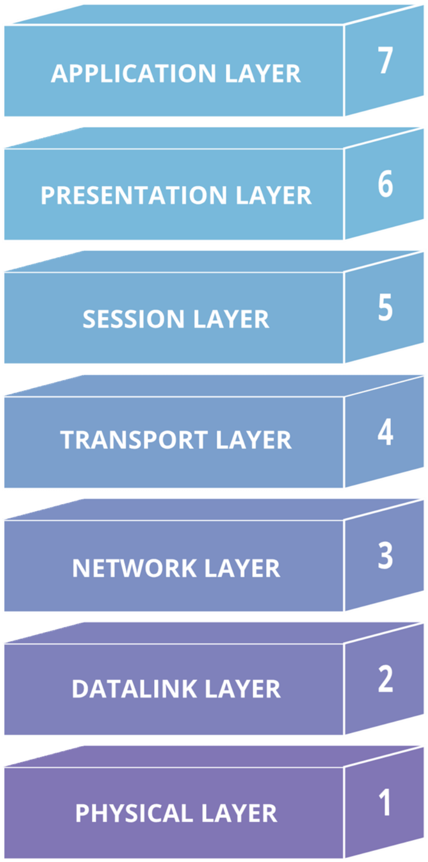
2) **Functionality reuse** –a common functionality of a lower layer can be shared by many upper layers.

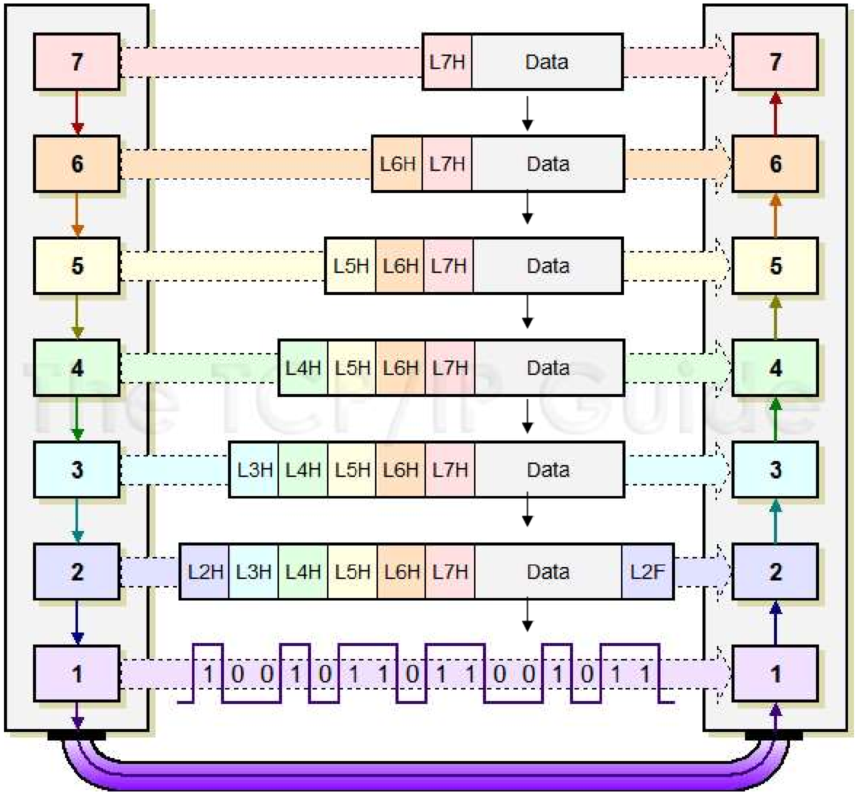
3) **Adaptability** – mix and match functionalities across different layers.

Layered approach accommodates incremental changes much more rapidly.

A monolithic design that uses a single large body of hardware and software to meet all network requirements can quickly become obsolete and is extremely difficult and expensive to modify.

LAYERED ARCHITECTURE OF COMPUTER NETWORKS – IN PRINCIPLE

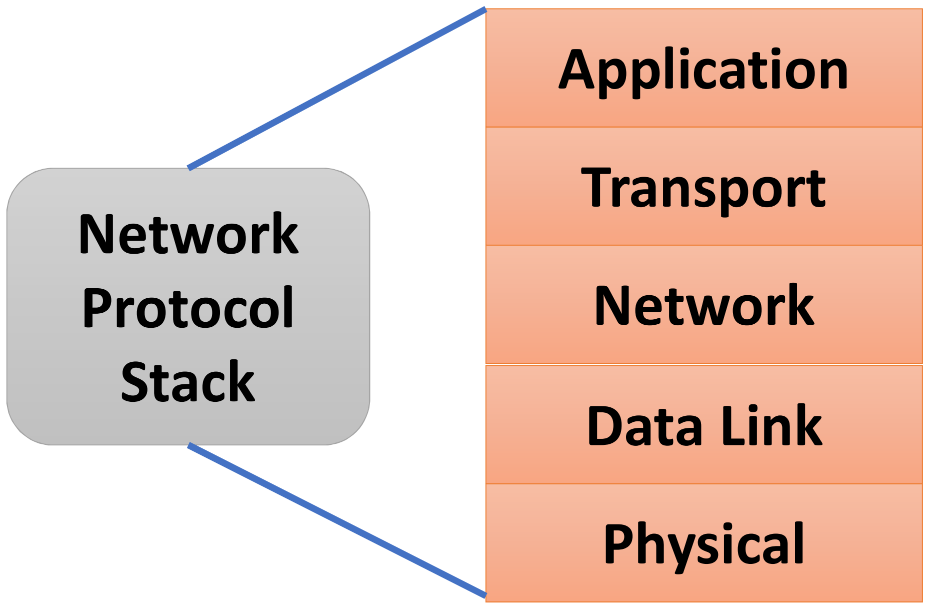




http://www.tcpipguide.com/free/t_DataEncapsulationProtocolDataUnitsPDUsandServiceDa.htm

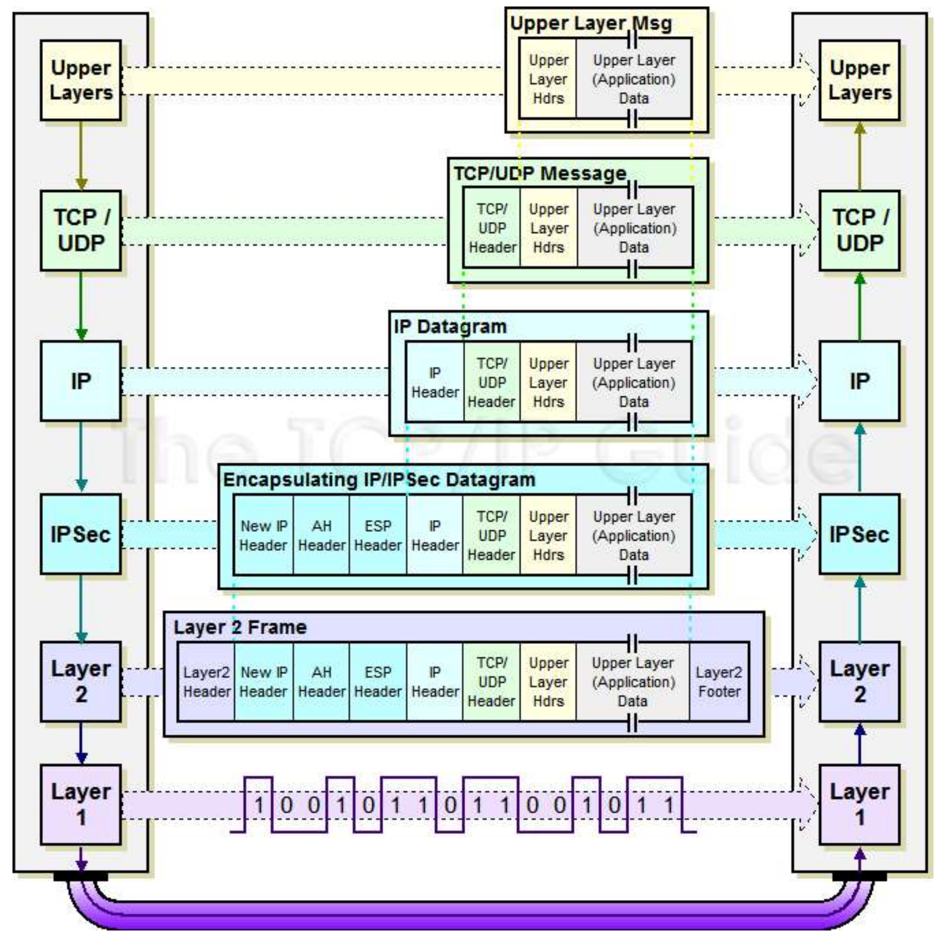
NETWORK PROTOCOL STACK OR THE TCP/IP STACK – IN PRACTICE

- *application:* supporting network applications
  - FTP, SMTP, HTTP
- *transport:* process-process data transfer
  - TCP, UDP
- *network:* routing of datagrams from source to destination
  - IP, routing protocols
- *link:* data transfer between neighboring network elements
  - Ethernet, 802.11 (WiFi), PPP
- *physical:* bits "on the wire"



LAYERED ARCHITECTURE OF COMPUTER NETWORKS – IN PRACTICE

Application
Transport
Network
Data Link
Physical

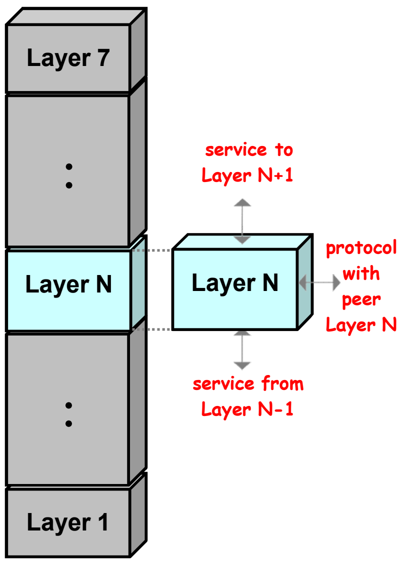


http://www.tcpipguide.com/free/t_IPSecModesTransportandTunnel-3.htm

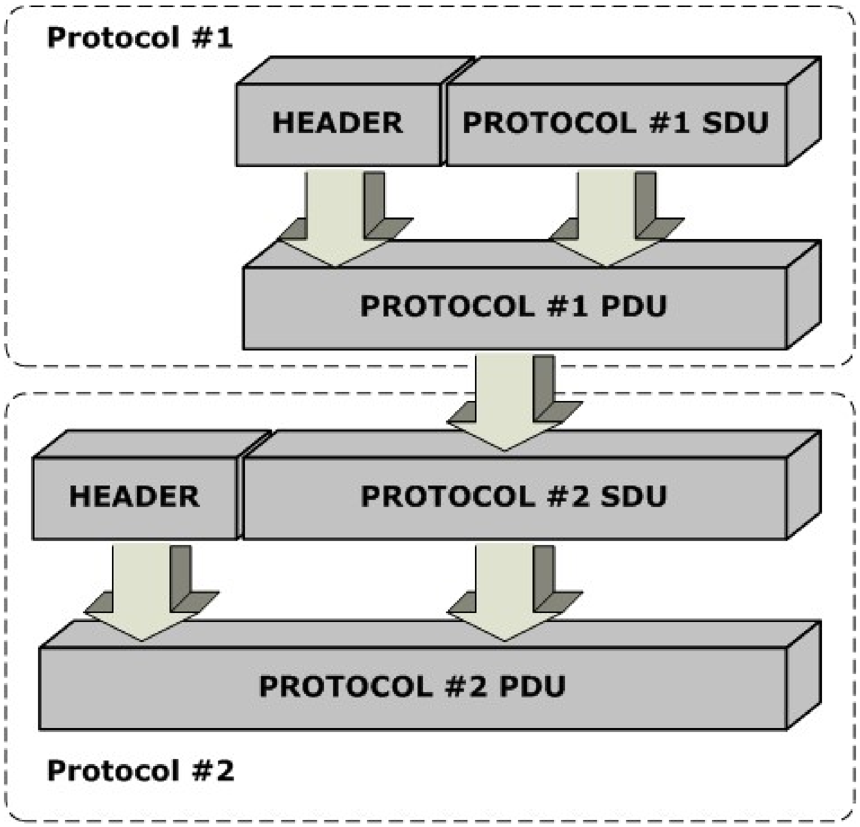
Layered Architecture: SDU and PDU

Protocol Layering

– **grouping of related communication functions into hierarchical set of layers**



- **each layer:**
  - (1) performs a subset of functions required for communication with another system
  - (2) relies on next lower layer to perform more primitive functions
  - (3) provides service to next higher layer
  - (4) implements protocol for communication with peer layer in other systems
- **vertical communication** – commun. between adjacent layers – requires mutual understanding of what services and/or information lower layer must provide to layer above
- **horizontal communication** – commun. between software or hardware elements running at the same layer on different machines



Communication between peer processes is virtual, i.e. indirect.

$$PDU_{(N)} = HDR_{(N)} + SDU_{(N)}$$

$$SDU_{(N)} = PDU_{(N+1)}$$

LAYERED ARCHITECTURE - PROTOCOLS AND SERVICES

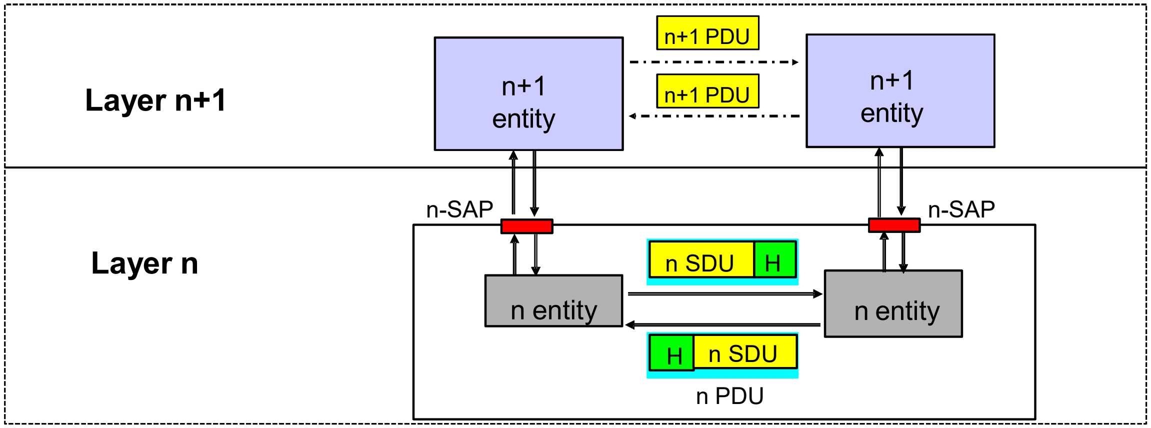
7

Protocol – set of rules that govern data comm. between peer entities

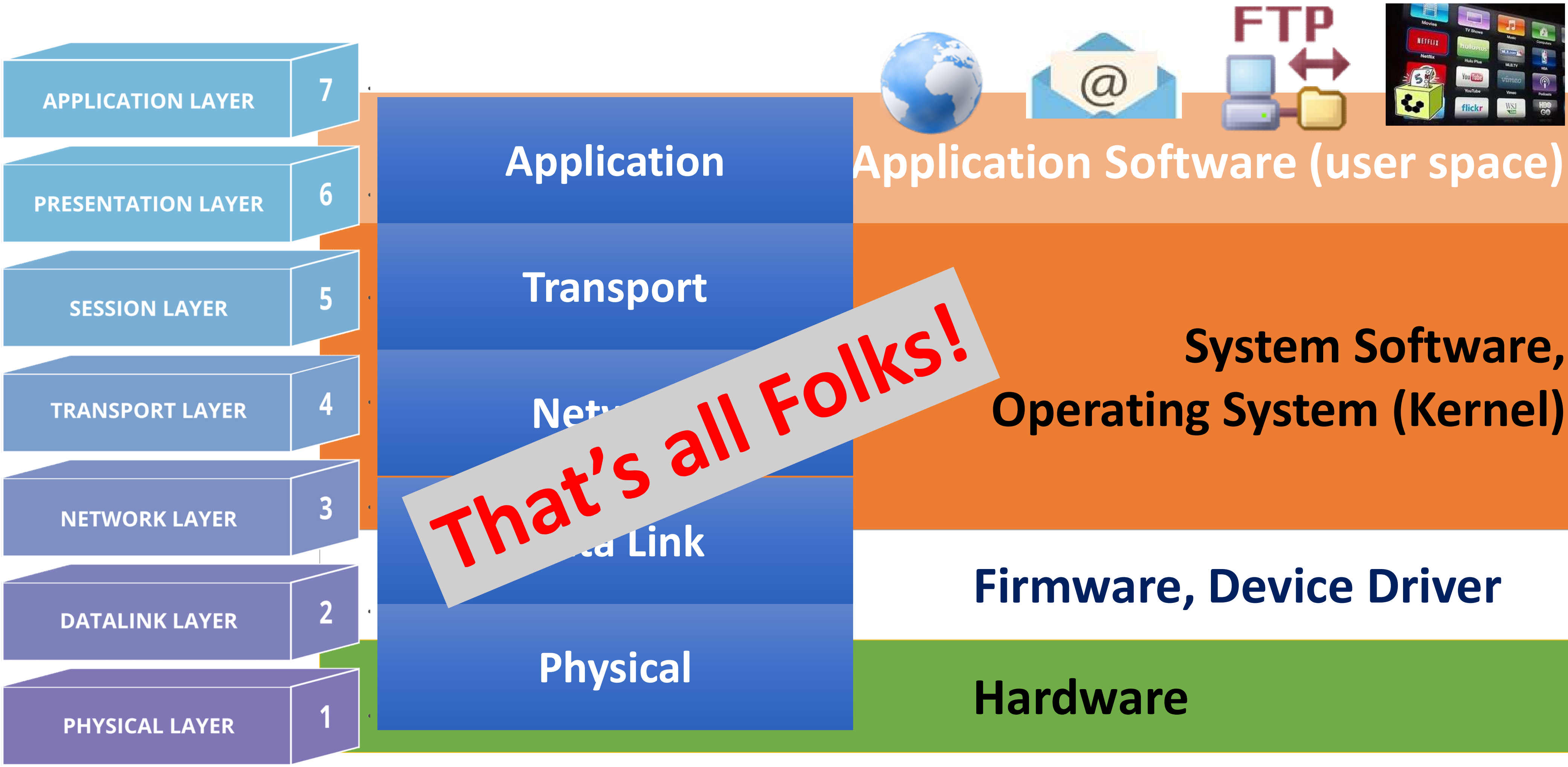
- layer-n peer processes communicate by exchanging **Protocol Data Units** (PDUs)

Service – can be accessed through **Service Access Points** (SAP's)

- layer n+1 PDU = layer n SDU (SDU = **Service Data Unit**)
- layer n process adds control information (**header**) to its SDU to produce layer n PDU – **encapsulation**!
- layer n does not interpret or make use of information contained in its SDU



Network Protocol Stack



TAKEAWAY QUESTION..

Q: What is Internet?

What is World Wide Web (WWW)?

Today's Discussion aspects:

- Internet Structure and Services
- Communication Modes and Medium
- Key Performance Metrics
- Computer Networks - Standard Bodies

Digression: Fascinating video on how Internet is Physically set:

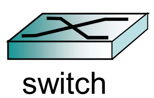
https://www.youtube.com/watch?v=kx3qwqtZvs4

Deep Sea Internet cables

- **Multi-Tr~~B~~illion dollars business***

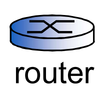
A CLOSER LOOK AT NETWORK STRUCTURE:

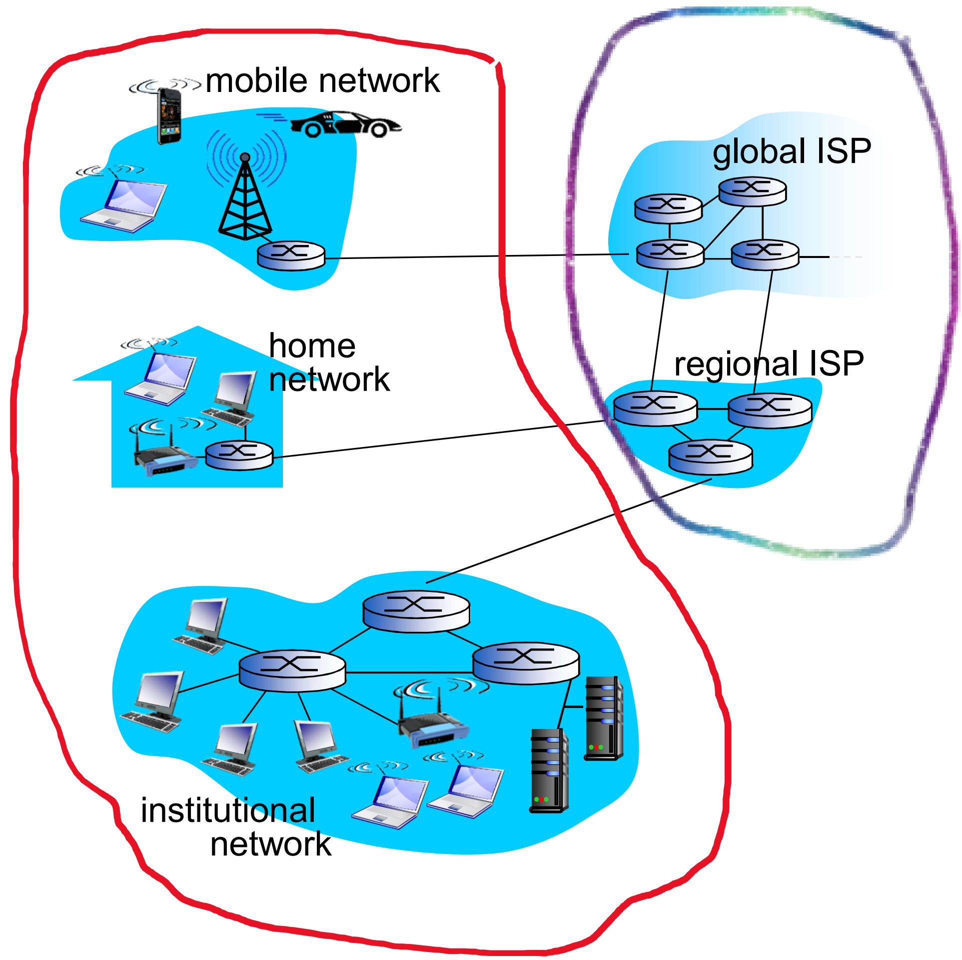
❖ *network edge:*
- hosts: clients and servers
- servers often in data centers



❖ *access networks, physical media:* wired, wireless communication links

❖ *network core:*
- interconnected routers
- network of networks





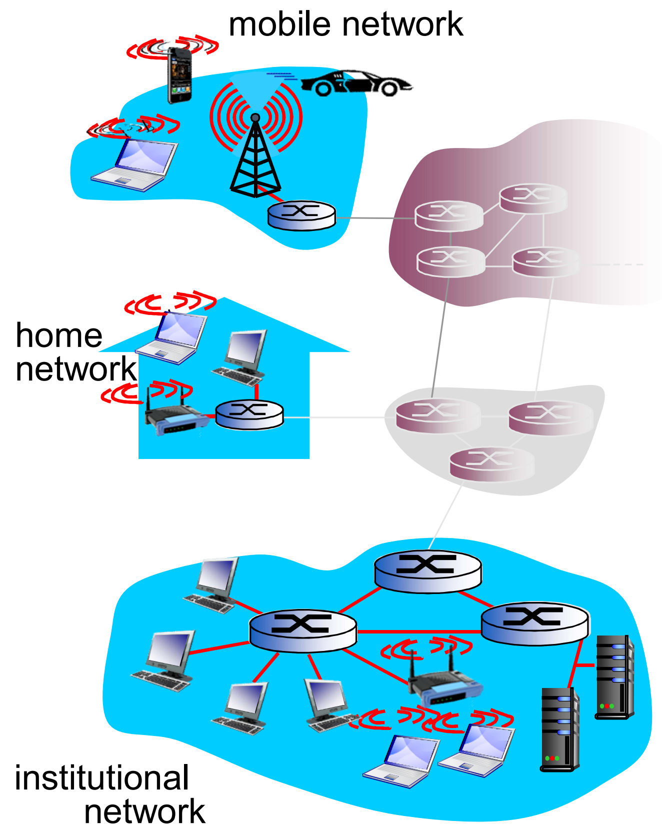
ACCESS NETWORKS AND PHYSICAL MEDIA

Q: How to connect end systems to edge router?

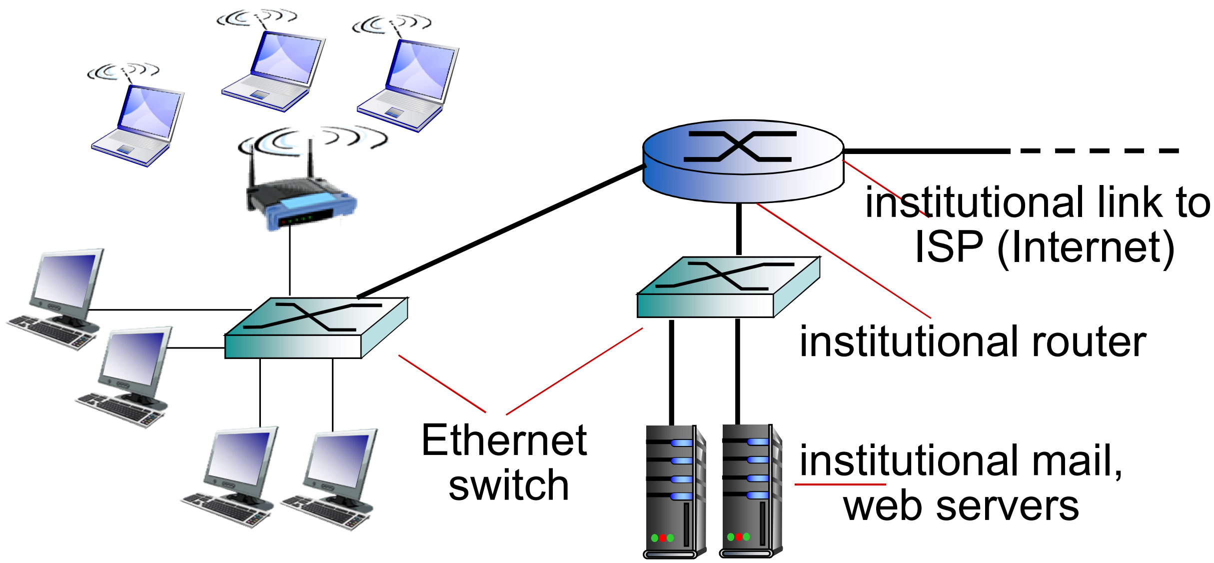
- residential access networks
  - Digital Subscriber Line (DSL/ADSL+)
  - Cable Networks (DOCSIS)
  - Ethernet, WiFi Networks
- Institutional access networks (school, company)
  - Ethernet, WiFi Networks
- mobile access networks
  - Cellular, Satellite Networks

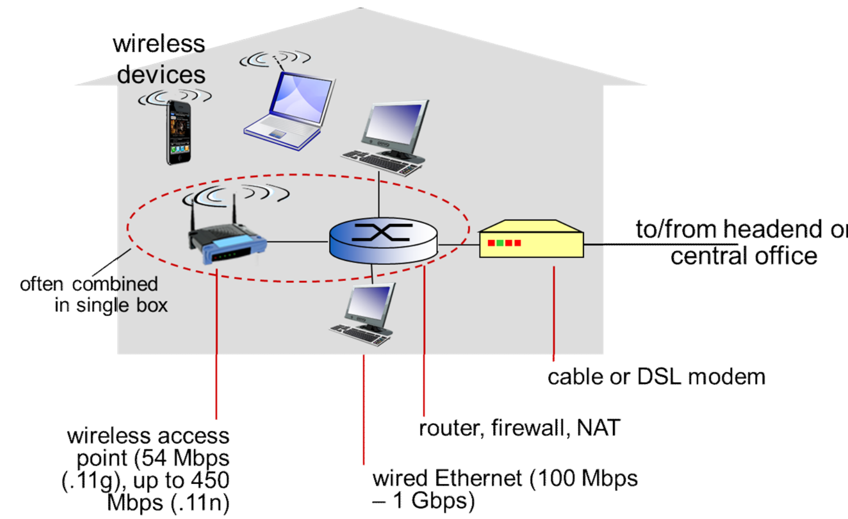
keep in mind:

- shared or dedicated connection?
- bandwidth (bits per second) of access network?



ENTERPRISE/HOME ACCESS NETWORKS (ETHERNET)





- typically used in companies, universities, etc
- 10 Mbps, 100 Mbps, 1Gbps, 10Gbps, 100 Gbps transmission rates
- today, end systems typically connect into Ethernet switch

PHYSICAL MEDIA (WIRED AND WIRELESS)

- bit: propagates between transmitter/receiver pairs
- physical link: what lies between transmitter & receiver
- guided media:
  - signals propagate in solid media: copper, fiber, coax
- unguided media:
  - signals propagate freely, e.g., radio; wireless

twisted pair (TP)

- two insulated copper wires
  - CAT 5: 100 Mbps, 1 Gpbs Ethernet
  - CAT 6: 10Gbps

fiber optic cable:

glass fiber carrying light pulses, each pulse a bit

high-speed point-to-point transmission:

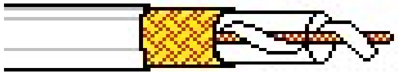
- 10's-100's Gbps transmission rate

low error rate:

- immune to electromagnetic noise
- repeaters spaced far apart

coaxial cable:

- two concentric copper conductors
- Bidirectional; broadband:
  - multiple channels on cable
  - HFC



WIRELESS ACCESS NETWORKS

- shared *wireless* access network connects end system to router
  - via base station aka "access point"

wireless LANs:

- within building (100 ft)
- 802.11a/b/g/n/ac/ax/be/az (WiFi 4,5,6,)
- Transmission rates: 11, 54,450 Mbps
- WiFi6E (802.11 ax) ~3.4Gbps.
- WiFi7 (802.11 be) ~9.6Gbps.

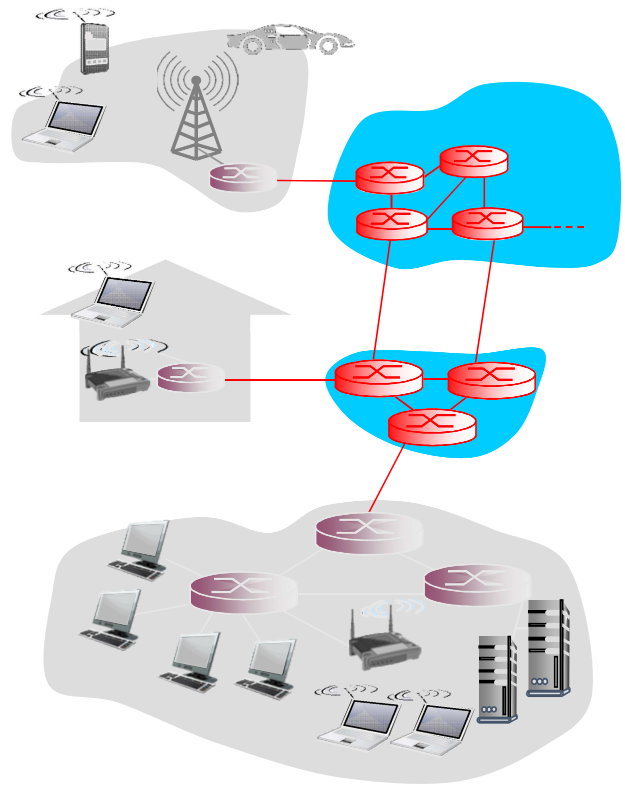
to Internet

wide-area wireless access:

- provided by telco (cellular) operator, 10's km
- 3G, 4G, LTE, 5G
- Satellite Networks
  - Geosynchronous versus low altitude
  - Satellite Internet: [Starlink] https://www.starlink.com/

to Internet

- mesh of interconnected routers
- packet-switching: hosts break application-layer messages into *packets*
  - forward packets from one router to the next, across links on path from source to destination
  - each packet transmitted at full link capacity

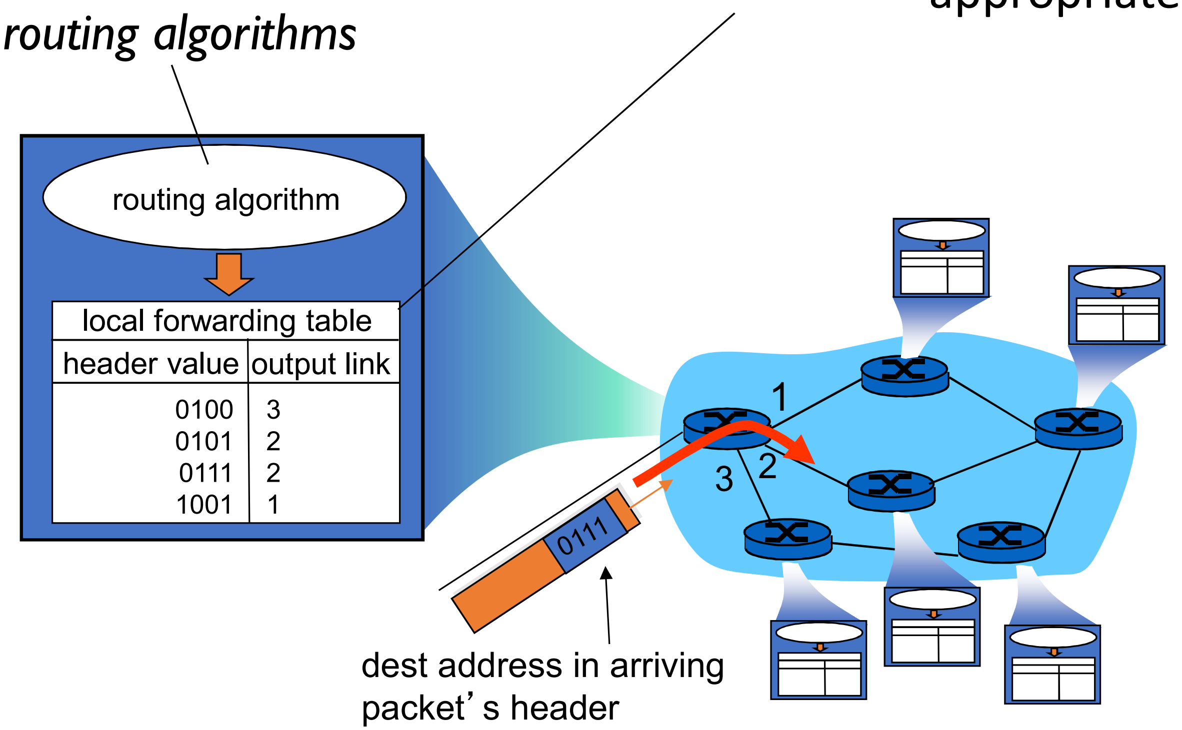


TWO KEY NETWORK-CORE FUNCTIONS

routing: determines source-destination route taken by packets

- *routing algorithms*

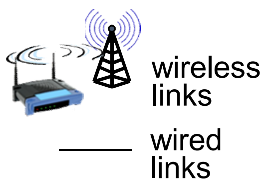
forwarding: move packets from router's input to appropriate router output



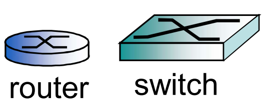
WHAT'S THE INTERNET: "NUTS AND BOLTS" VIEW

https://internet-map.net/#9-89.99819116692478-103.34518032026763

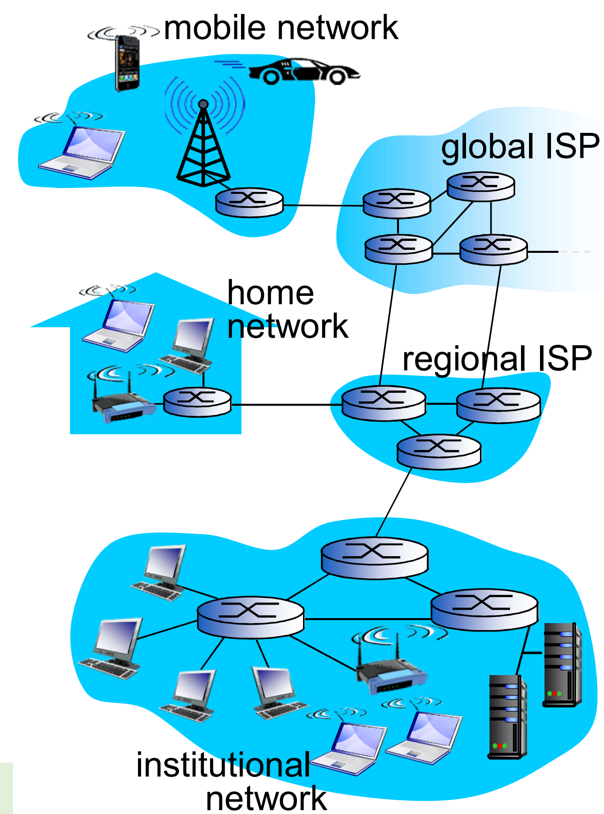
- billions of connected computing devices:
  - *hosts* = *end systems*
  - running *network apps*



- *communication links*
  - fiber, copper, radio, satellite
  - transmission rate: *bandwidth*



- *Packet switches:* forward packets (chunks of data)
  - *routers* and *switches*



Internet: network of networks;
Interconnected ISPs

INTERNET STRUCTURE: NETWORK OF NETWORKS

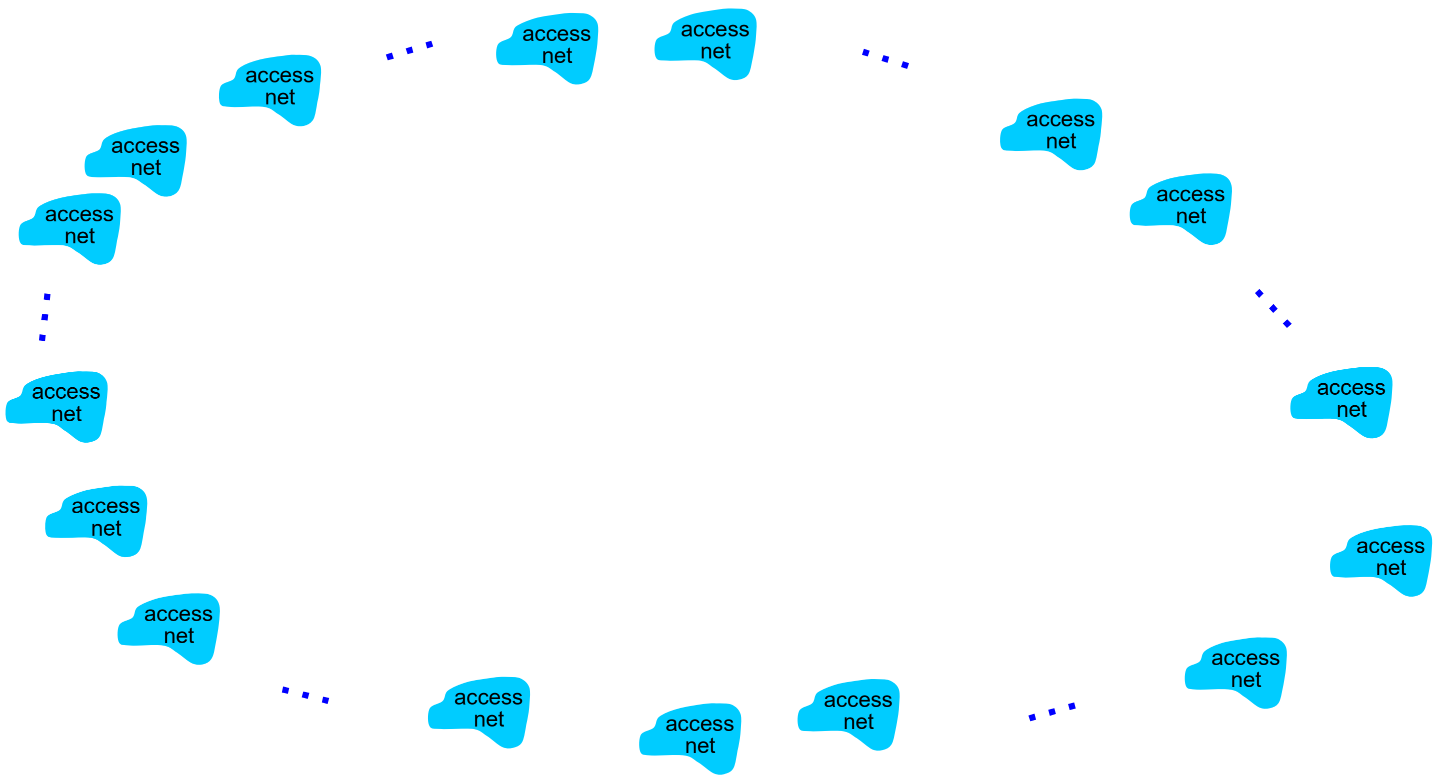
- End systems connect to Internet via access ISPs (Internet Service Providers)
  - Residential, company and university ISPs

- Access ISPs in turn must be interconnected.
  - So that any two hosts can send packets to each other

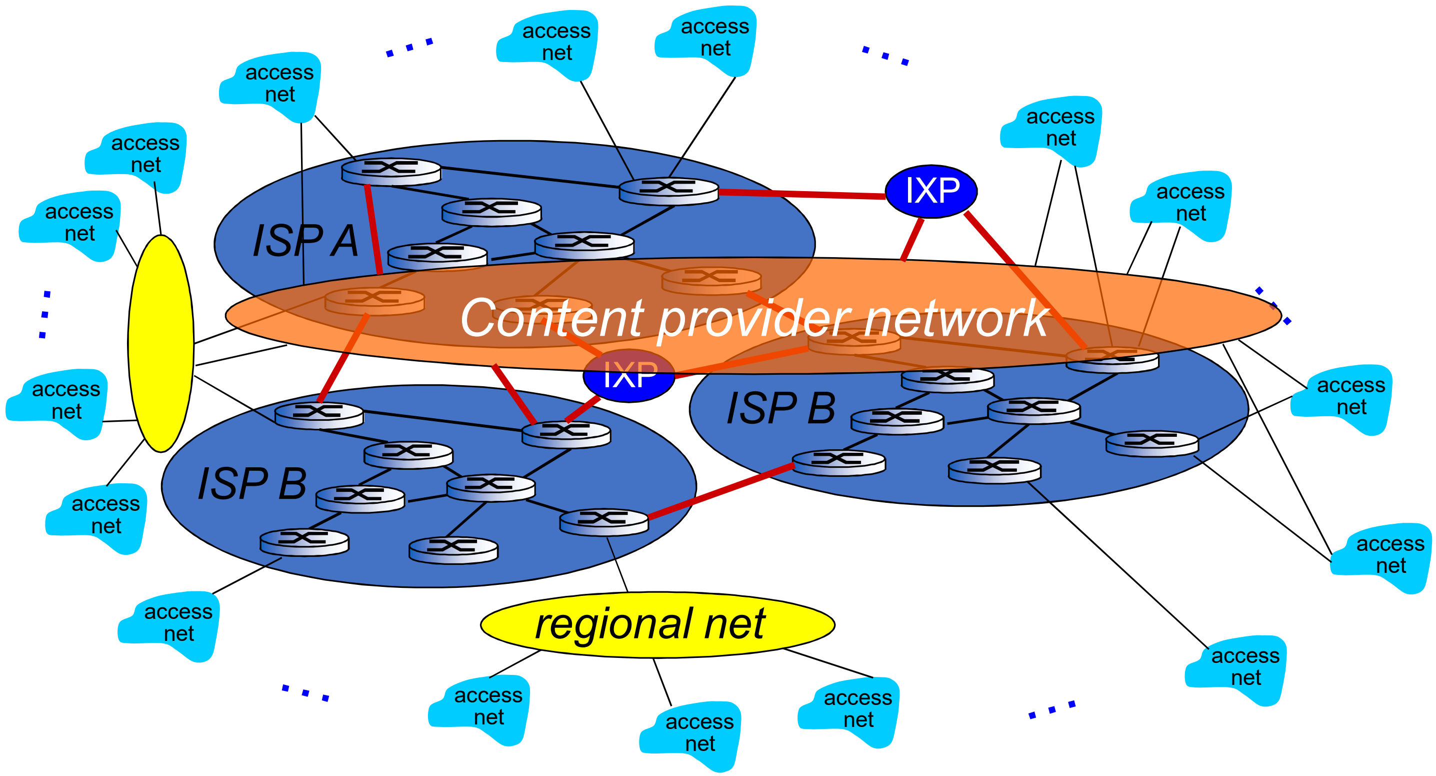
- Resulting network of networks is very complex
  - Evolution was driven by economics and national policies

INTERNET STRUCTURE: NETWORK OF NETWORKS

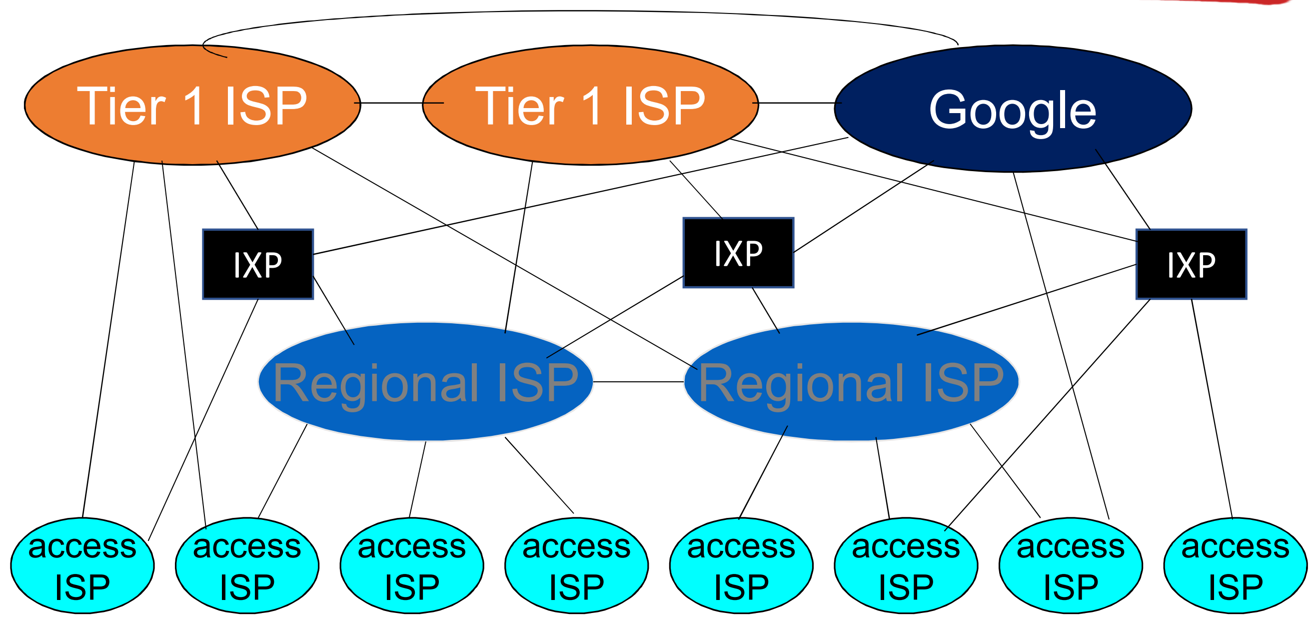
Question: given *millions* of access ISPs, how to connect them together?



… and content provider networks (e.g., Google, Microsoft, Akamai) may run their own network, to bring services, content close to end users



INTERNET STRUCTURE: NETWORK OF NETWORKS



- at center: small # of well-connected large networks
  - "tier-1" commercial ISPs (e.g., VSNL, Bharati, TATA, Reliance.)
  - content provider/delivery network (e.g, Google, Akamai): private network that connects it data centers to Internet, often bypassing tier-1, regional ISPs

INDIA TELECOMMUNICATION AND NETWORKING BODIES

1. Telecommunications Regulatory Authority of India
https://www.trai.gov.in/

2. National Internet Exchange of India
https://www.nixi.in/

3. DNS and Registry
https://irinn.in/
https://www.registry.in/

4. National Research and Educational Network
https://ernet.in/

5. National Knowledge Network
http://nkn.gov.in/en/

No.	Tier 1 ISP	Landing Stations	Cables
1	Tata Communications	Chennai (1), Cochin (1), Mumbai (3).	7
2	Bharti Airtel	Chennai (2), Mumbai (1).	4
3	Reliance Jio	Chennai (1), Mumbai (1).	3
4	Global Cloud Exchange	Mumbai (1), Trivandrum (1).	2
5	Vodafone	Mumbai (1).	1
6	Sify Technologies	Mumbai (1).	1
7	BSNL	Tuticorin (1).	2

This information is subject to change with addition and subtraction of new data.

https://atulhost.com/tier-1-internet-service-providers-in-india

IPV6 Readiness Tracker
https://ipv6.nixi.in/#/home

TAKEAWAY QUESTION..

Q: How do we transmit data in computer networks?

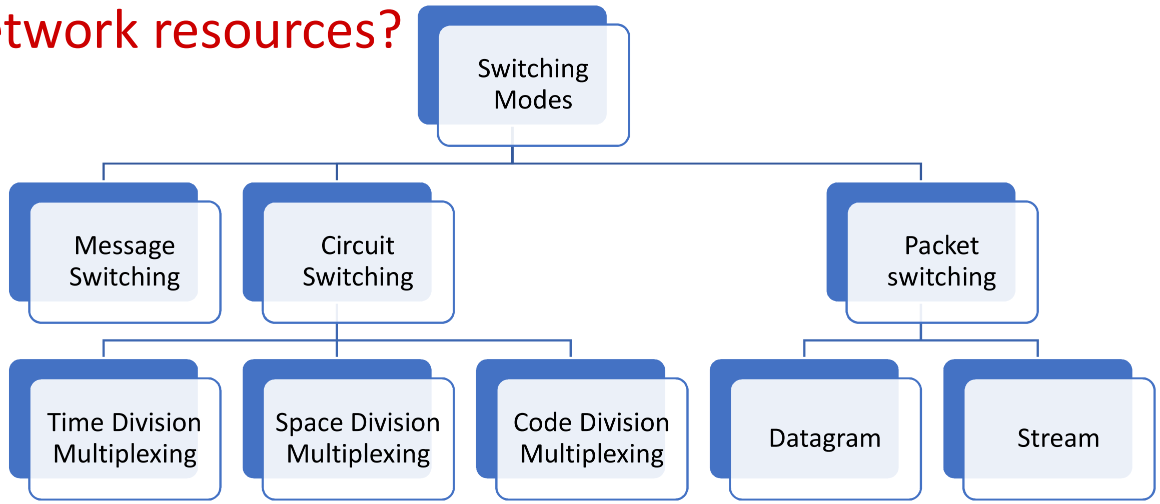
Network Data Transmission!

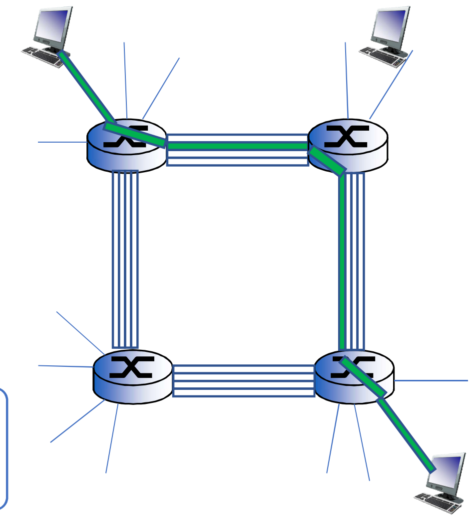
Today's Focus:
- Types of Data Transmission (Switching):
- Modes of Data Transmission (Direction, Timing)
- Types of Messaging, Delivery mode (Addressing)

Switching Techniques: Ways to Deliver your Message in the Network

How do you move data through a network of devices from one end to the other?

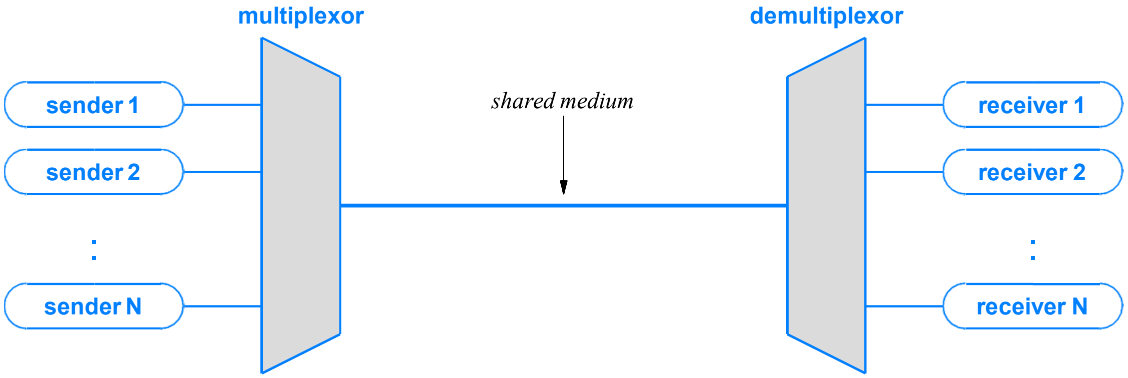
How to share the network resources?



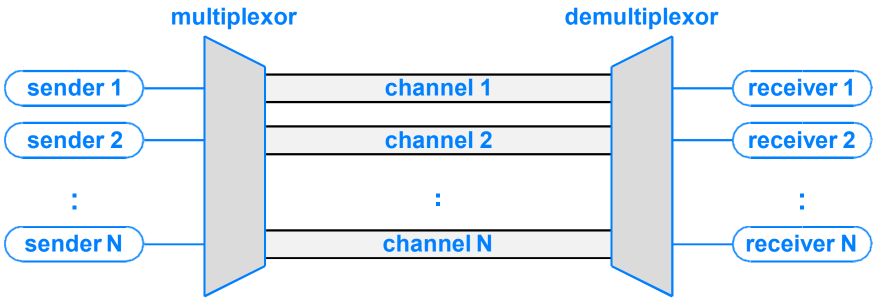


Characteristic	Message Switching	Circuit Switching	Packet Switching
Transmission mode	Hop-by-hop basis	End-to-End	Hop-by-hop
Delivery Mechanism	Store-and-forward	Cut-through (only forward)	Store-and-forward
Resource Reservation	Hop-by-hop (Dedicated)	End-to-End (Dedicated)	No reservation
Data-ordering	Same order as sent	Same order as sent	Ordering can change
Bandwidth usage and Scale	High, Poor	Poor, Poor	High, High
Example	Telegram	Telephone	Internet

Concept Of Multiplexing And Types



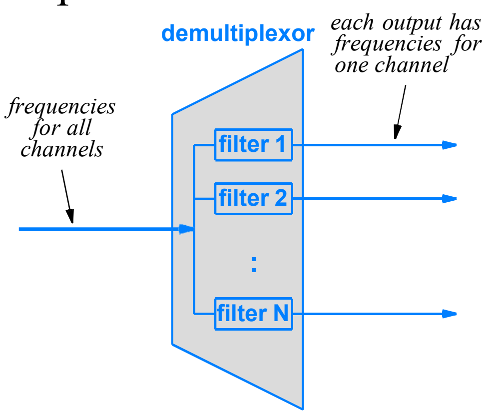
Used in broadcast radio and cable TV



Types:

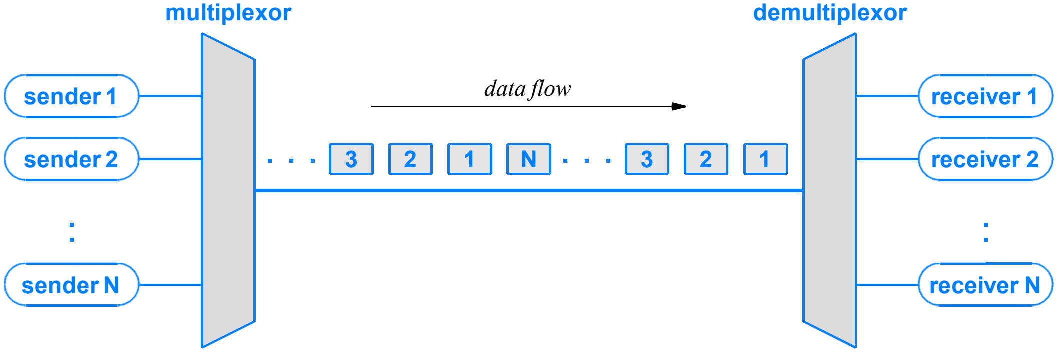
- Time division multiplexing
- Frequency division multiplexing
- Wavelength division multiplexing
- Code division multiplexing

Demultiplexing implemented with sets of filters



TIME DIVISION MULTIPLEXING

❖ Senders take turns transmitting



❖ Synchronous TDM

– Each sender assigned a slot (typically round-robin)

– Used by the telephone company

❖ Statistical TDM

– Sender only transmits when ready (e.g., Ethernet)

Source: Douglas Comer: Computer Networks and Internets

TAKEAWAY QUESTION..

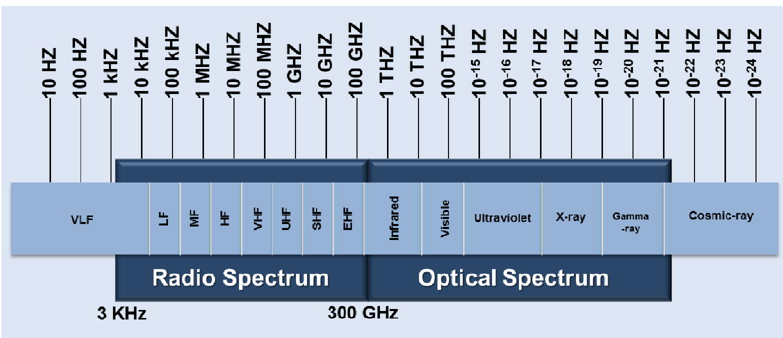
Q: How to Quantify Computer Networks?

Network Performance!

Today's Focus:
- Key Performance Metrics:
- Bandwidth, Throughput, Latency, Jitter
- Computer Networks - Standard Bodies

BANDWIDTH

- **Bandwidth** – an important concept in Communications & Networks.
  - ***Communications*** – the width of frequency bands (range of signals). Unit "Hz"
  - ***Networks*** - max. capacity to transmit data in unit time (data transfer rate). Unit 'bps'



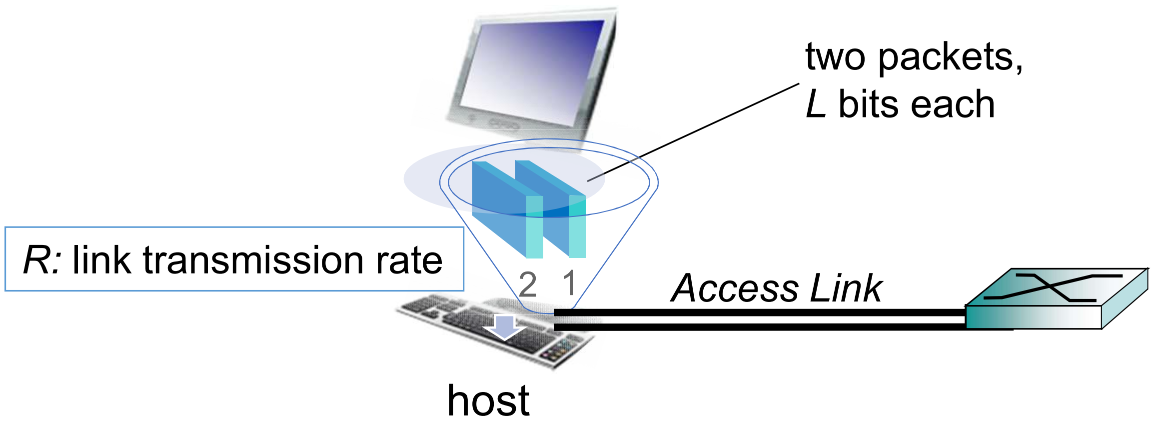
- **Bandwidth –** Amount/Volume of Information/data per unit time that the transmission medium can handle. (i.e. the maximum capacity to transmit data per unit time.) - also known as link transmission rate (*R*).

- **Throughput –** Practical measure/Achieved data transfer rate or the measured performance of a system. (Tp ≤ Bandwidth.)

HOST: SENDS *PACKETS* OF DATA

host sending function:

- takes application message
- breaks into smaller chunks, known as *packets*, of length *L* bits
- transmits packet into access network at *transmission rate R*
  - link transmission rate, aka link *capacity, aka link bandwidth*



$$\text{packet transmission delay} = \text{time needed to transmit } L\text{-bit packet into link} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

TRANSMISSION DELAY

- Say 1500B (**byte**) packet = 12000 bits
- Link Speed = 1 Kbit/sec.

Transmission Delay for Link speed of 1Kbps = L/R = 12000/1000

= 12 seconds!

As Link Speed Goes Up the Transmission Delay goes Down!!

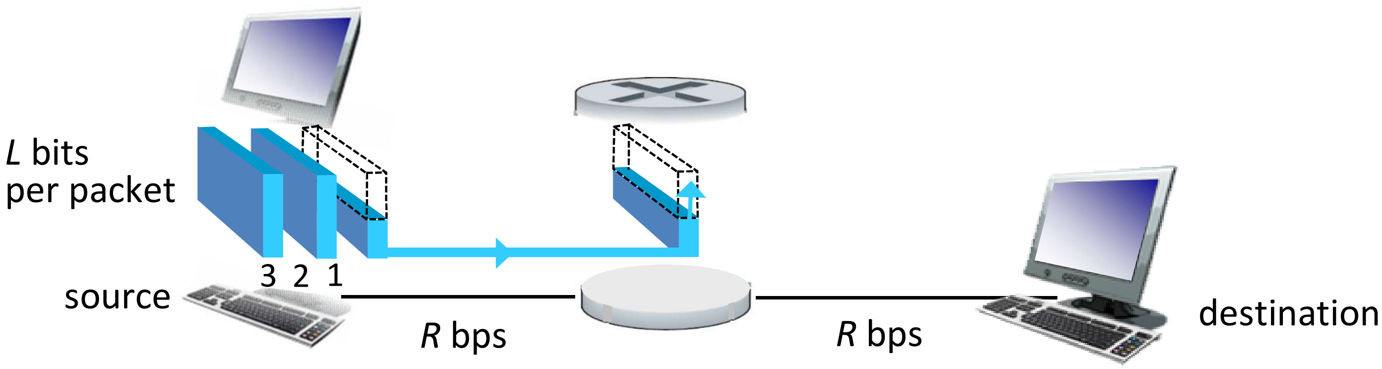
- Transmission Delay for 10 Mbit/sec (Ethernet) = 12000/10,000,000

  = 1.2 milliseconds

- Transmission Delay for 10 Gbit/sec = 12000/10^9

  = 1.2 microseconds

PACKET-SWITCHING: STORE-AND-FORWARD



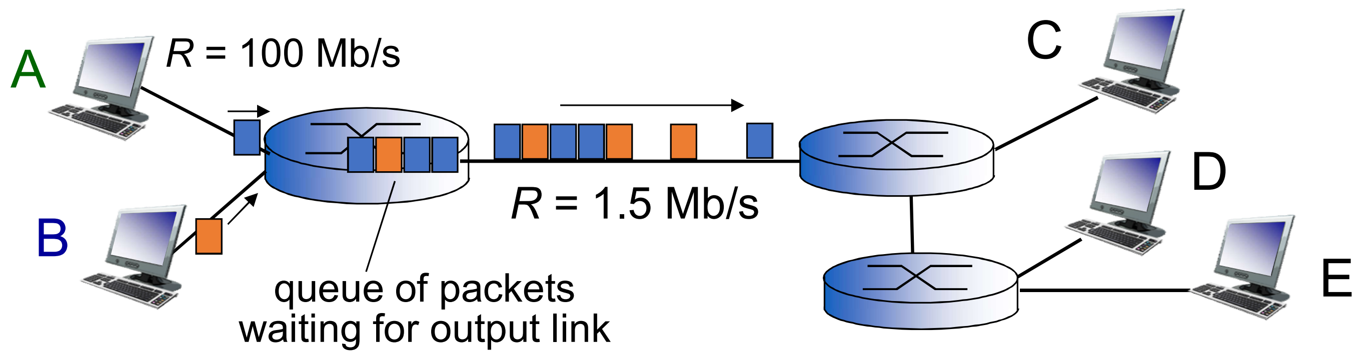
- takes L/R seconds to transmit (push out) L-bit packet into link at R bps
- *store and forward:* entire packet must arrive at router before it can be transmitted on next link
  - end-end delay = $2L/R$ (assuming zero propagation delay)

more on delay shortly …

one-hop numerical example:

- L = 7.5 Mbits
- R = 1.5 Mbps
- one-hop transmission delay = 5 sec

PACKET SWITCHING: QUEUEING DELAY, LOSS



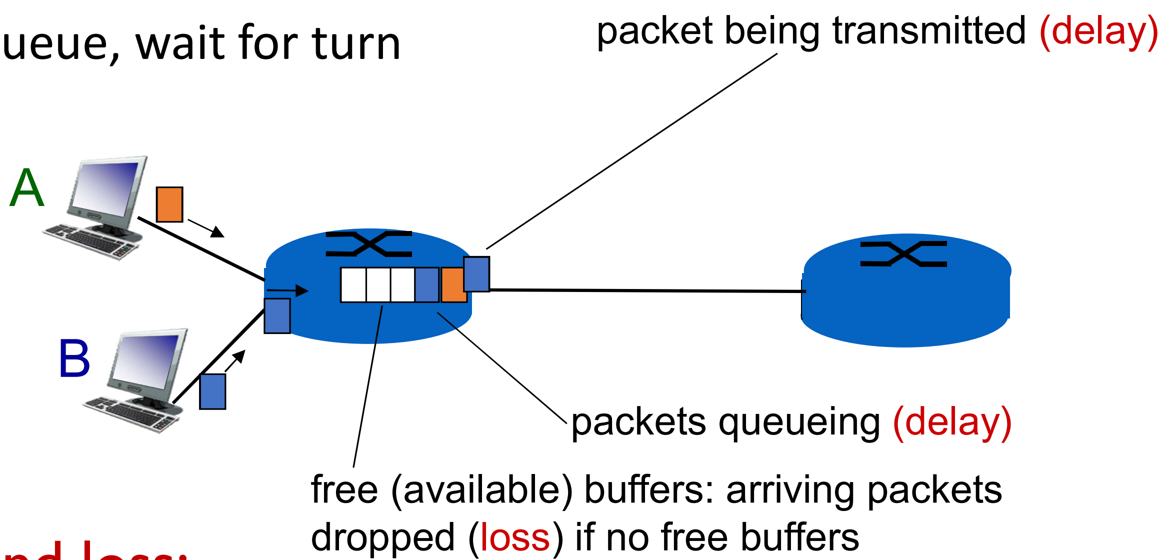
queuing and loss:

- If arrival rate (in bits/s) to link exceeds transmission rate of link for a period of time:
  - packets will queue, wait to be transmitted on link
  - packets can be dropped (lost) if memory (buffer) fills up

HOW DO LOSS AND DELAY OCCUR?

packets *queue* in router buffers

- packet arrival rate to link (temporarily) exceeds output link capacity
- packets queue, wait for turn



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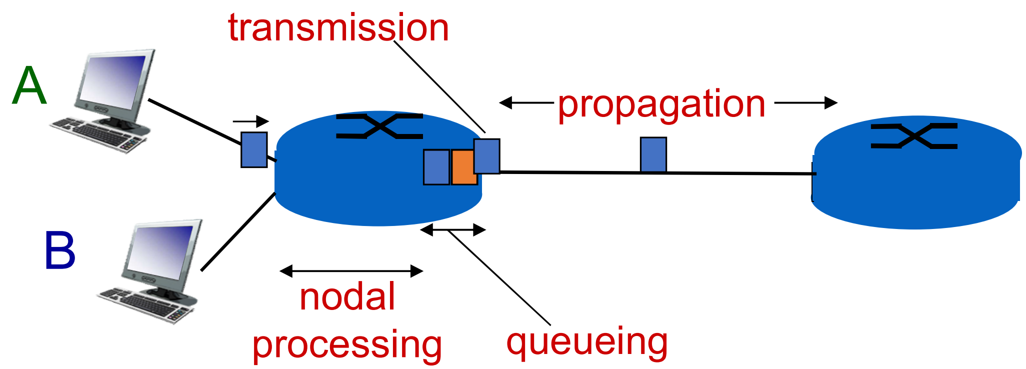
FOUR SOURCES OF PACKET DELAY



$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

d_{proc}: nodal processing

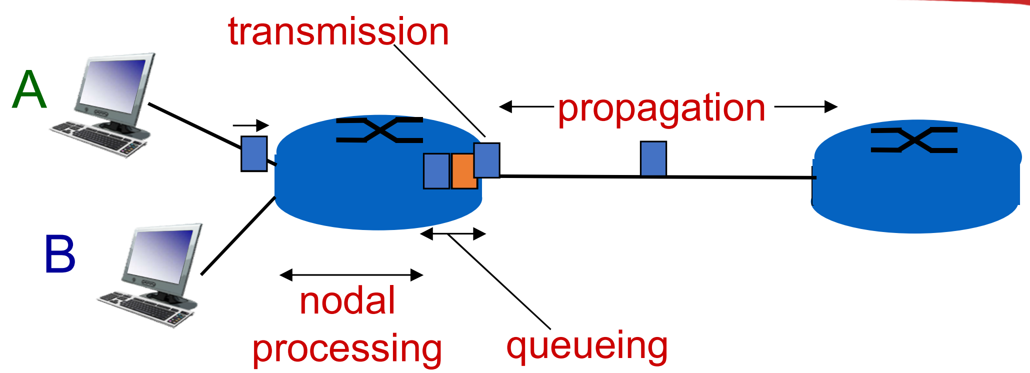
- check bit errors
- determine output link
- typically < msec

d_{queue}: queueing delay

- time waiting at output link for transmission
- depends on congestion level of router

Network Jargon: Ingress and Egress

FOUR SOURCES OF PACKET DELAY



$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

d_{trans}: transmission delay:
- *L*: packet length (bits)
- *R*: link *bandwidth (bps)*
- $d_{trans} = L/R$

d_{trans} and d_{prop} *very* different

d_{prop}: propagation delay:
- *d*: length of physical link
- *s*: propagation speed in medium ($\sim 2 \times 10^8$ m/sec)
- $d_{prop} = d/s$

Concept: Propagation delay of different materials

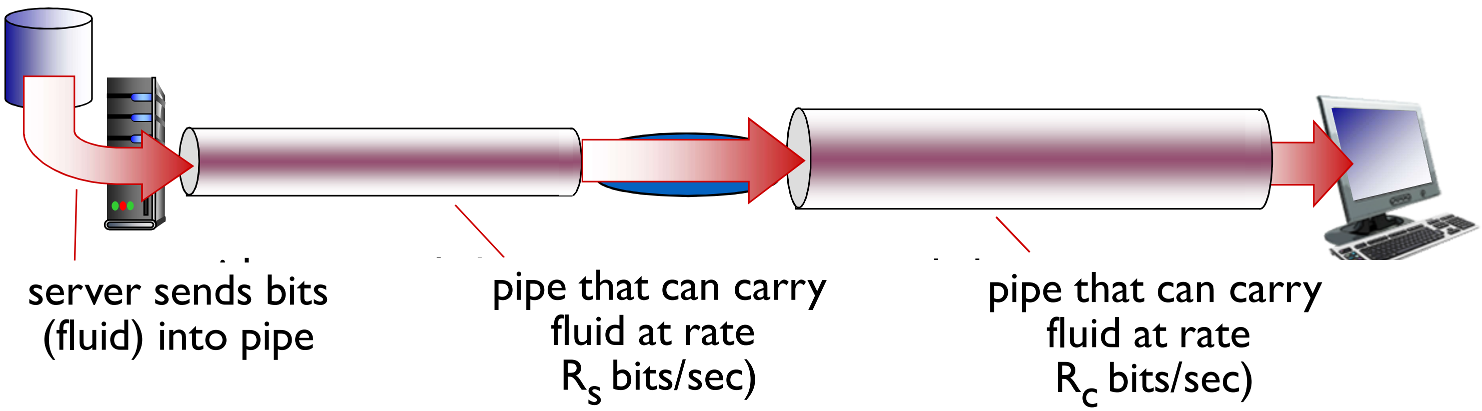
TRANSMISSION VS PROPAGATION DELAY

Web Applet:
https://www2.tkn.tu-berlin.de/teaching/rn/animations/propagation/

Today's Focus:
- Throughput
- ~~Computer Networks – History & Evolution~~
- Computer Networks - Standard Bodies

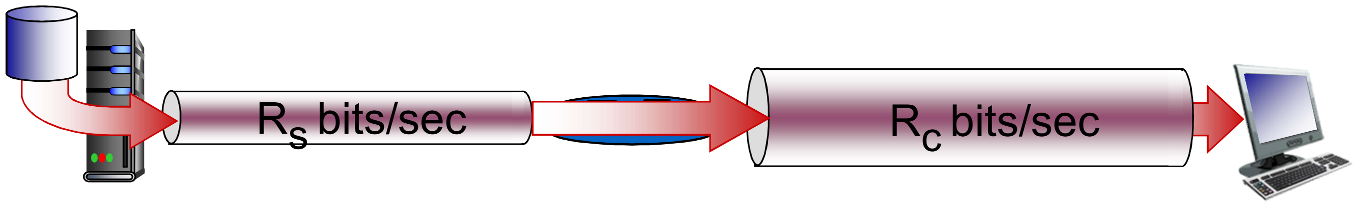
THROUGHPUT

- *throughput:* rate at which bits get transferred between sender & receiver (bits/time unit)
  - *instantaneous:* rate at given point in time
  - *average:* rate over longer period of time



THROUGHPUT (MORE)

- $R_s < R_c$ What is average end-end throughput?



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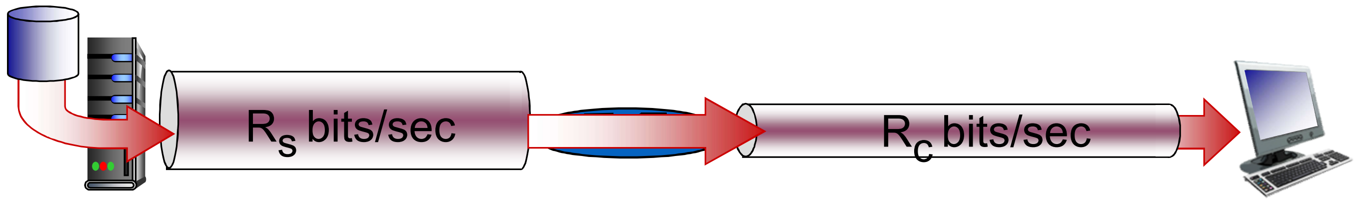
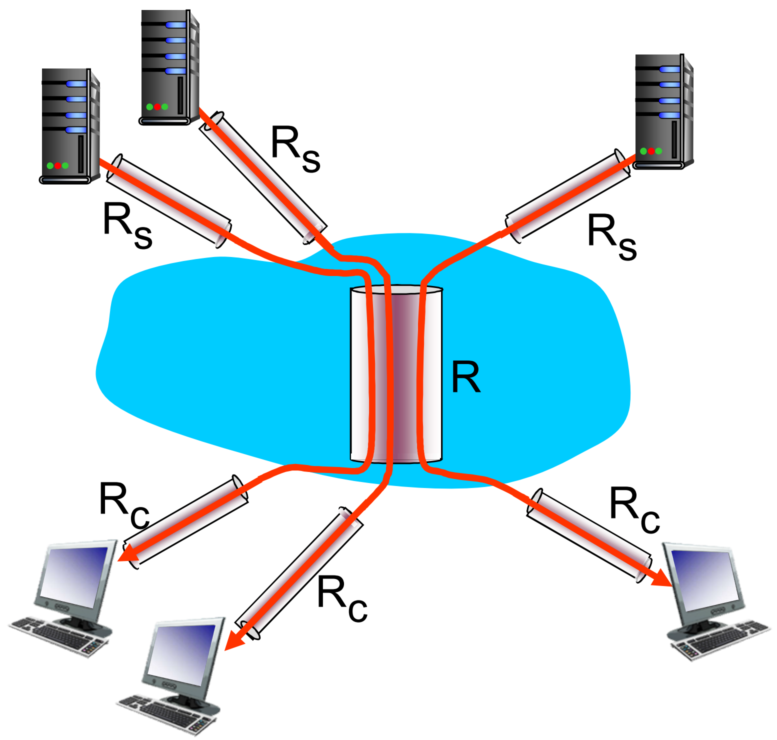


bottleneck link

link on end-end path that constrains end-end throughput

THROUGHPUT: INTERNET SCENARIO

- per-connection end-end throughput: $\min(R_c, R_s, R/10)$
- in practice: R_c or R_s is often bottleneck



Assume: 10 connections (fairly) share backbone bottleneck link R bits/sec

Checkout:

https://www.internet2.edu/products-services/performance-analytics/performance-tools/

HIGH PERFORMANCE BROWSER NETWORKING

★★★★½ (463): GoodReads ⊘ Amazon ⊘ O'Reilly ⊘

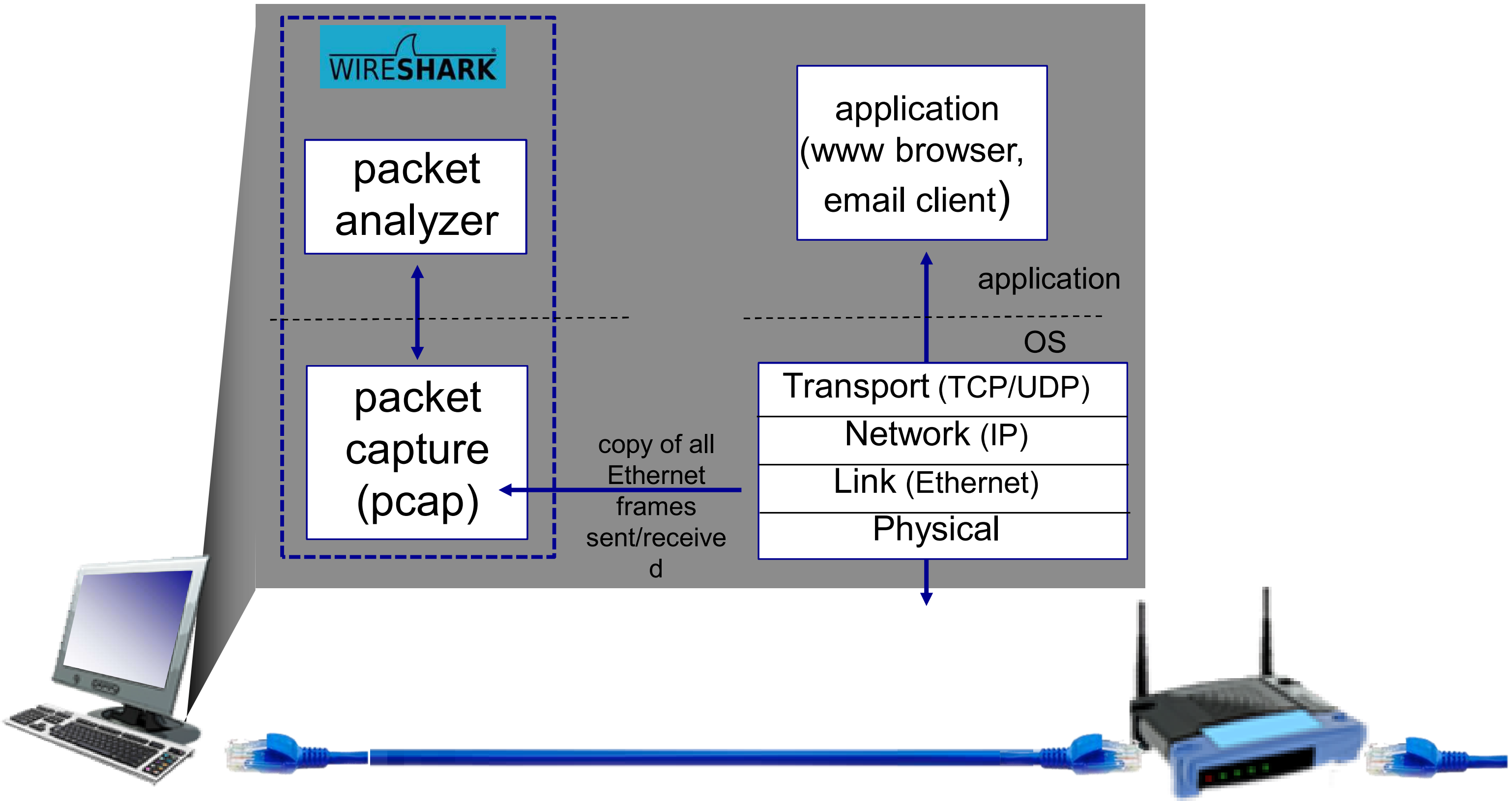
> *This book is required reading for anyone who cares about web performance; it's already established as the go-to reference on the topic.*
>
> *—Mark Nottingham (IETF HTTPBis Chair)*

High Performance Browser Networking --- An Online Book by Ilya Grigorik

– Web Performance Engineer (Google), co-chair W3C Web Performance Working Group

https://hpbn.co/#toc

PACKET CAPTURE AND ANALYSIS



- wireshark software is a (free) packet-sniffer – We will learn more about it in the next tutorial.

Suggested Reading

History and timeline of computer Networks..

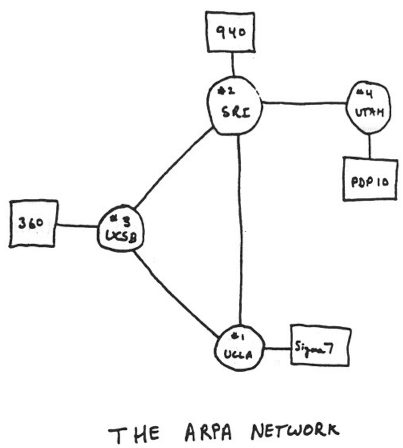
https://www.computerhistory.org/timeline/networking-the-web/

1933 (Telex network) - till date (5G era)

Today's Focus:
- Computer Networks – History & Evolution
- Computer Networks - Standard Bodies

1961-1972: Early packet-switching principles

- 1961: Kleinrock - queueing theory shows effectiveness of packet-switching
- 1964: Baran - packet-switching I n military nets
- 1967: ARPAnet conceived by Advanced Research Projects Agency
- 1969: first ARPAnet node operational



- 1972:
  - ARPAnet public demo
  - ***NCP*** (Network Control Protocol) first host-host protocol
  - first e-mail program
  - ARPAnet has 15 nodes

INTERNET HISTORY

1972-1980: Internetworking, new and proprietary nets

- 1970: ALOHAnet satellite network in Hawaii
- 1973: First version of reliable transmission TCP [Link]
- 1974/75: Cerf and Kahn - architecture for interconnecting networks. Shift from TCP → TCP/IP model
- 1976: Ethernet at Xerox PARC
- late70's: proprietary architectures: DECnet, SNA, XNA
- late 70's: switching fixed length packets (ATM precursor)
- 1979: ARPAnet has 200 nodes

Cerf and Kahn's internetworking principles:

- minimalism, autonomy - no internal changes required to interconnect networks
- best effort service model
- stateless routers
- decentralized control

define today's Internet architecture

INTERNET HISTORY: PHASE-1 (EMERGENCE)

1980-1990: new protocols, a proliferation of networks

- 1982: smtp e-mail protocol defined RFC 788
- 1983: deployment of TCP/IP
- 1984: DNS for name-to-IP-address translation
- 1984: ISO/OSI Architecture Standardized.
- 1985: A new version of ftp protocol defined
- 1988: TCP congestion control

- new national networks: Csnet, BITnet, NSFnet, Minitel
- 100,000 hosts connected to confederation of networks

History of FTP

1971: The original specification for the File Transfer Protocol was written by Abhay Bhushan and published as RFC 114 on 16 April 1971, before TCP and IP even existed.

1980: The old version of File Transfer Protocol is replaced with RFC 765.

1985: A new version of the File Transfer Protocol, RFC 959, is published. This is the same specifications that are being used today.

1997: In June of 1996 a revision was made to RFC 959 to add security extension to the File Transfer Protocol (RFC 2228).

1998: In September of 1998 another revision was made to RFC 959 to add support for IPv6 and defined a new type of passive mode (RFC 2428).

INTERNET HISTORY PHASE-2 (DOMINANCE)

1990, 2000's: commercialization, the Web, new apps

- early 1990's: ARPAnet decommissioned
- 1991: NSF lifts restrictions on commercial use of NSFnet (decommissioned, 1995)
- early 1990s: Web
  - hypertext [Bush 1945, Nelson 1960's]
  - HTML, HTTP: Berners-Lee
  - 1994: Mosaic, later Netscape
  - late 1990's: commercialization of the Web

late 1990's – 2000's:

- more killer apps: instant messaging, P2P file sharing
- network security to forefront
- est. 50 million host, 100 million+ users
- backbone links running at Gbps

INTERNET HISTORY- PHASE-3 (CONVERGENCE)

2005-present

- ~750 million hosts
  - Smartphones and tablets; ***Exceeding 30 Billion devices..***
- Aggressive deployment of broadband access
- Increasing ubiquity of high-speed wireless access
- Emergence of online social networks:
  - Facebook: ~1.6 Billion users (From less than 1 Million in 2004, 1.3 Million in 2014)
- Service providers (Google, Microsoft) create their own networks
  - Bypass Internet, providing "instantaneous" access to search, email, etc.
- E-commerce, universities, enterprises running their services in "cloud" (eg, Amazon EC2)

Growth of Connected Devices and the Challenges they bring along:
https://www.helpnetsecurity.com/2019/05/23/connected-devices-growth/

COMPUTER NETWORKS INTRODUCTION : CHAPTER SUMMARY

- Internet overview
- what's a protocol?
- What is Internet?
  - network edge, core, access network
  - packet-switching versus circuit-switching
  - Internet structure
- performance: loss, delay, throughput
- layering, service models
- Network Security
- Brief History

NETWORK MANAGEMENT AND CONTROL – CROSS LAYER PROTOCOLS

Layer	Protocols	
Application	HTTP, FTP, SMTP	DNS
Transport	TCP, UDP, RTP	SNMP
Network	IPv4, IPv6, MPLS	ARP, DHCP
Data Link	Ethernet, WiFi, Bluetooth, UMTS, LTE	
Physical		

NETWORKS, PROTOCOLS AND STANDARDIZATION

What are Standards? Standardization Bodies and their roles…

Networking supports communication among multiple entities.

Agreement needed to make communication correct, efficient, and meaningful.

Which Organizations Issue Standards?

IEEE (*Institute of Electrical and Electronics Engineers*)

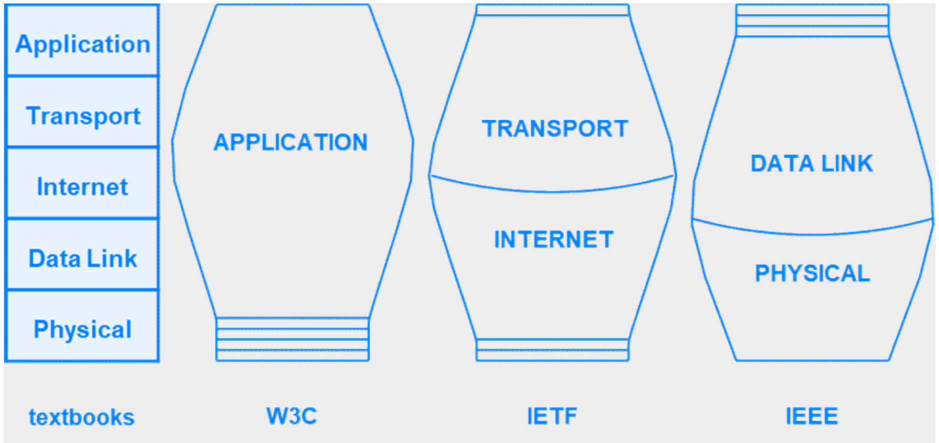
IETF (*Internet Engineering Task Force*)

ITU (*International Telecommunications Union*)

ISO (*International Organization for Standardization*)

W3C (*World Wide Web Consortium*) …and many others

Each emphasize certain layers of n/w stack



Joke: Why is networking so difficult?

Because there is no standard among standards! so many standards to choose from…

DATA TRANSFER BETWEEN TWO REMOTE MACHINES