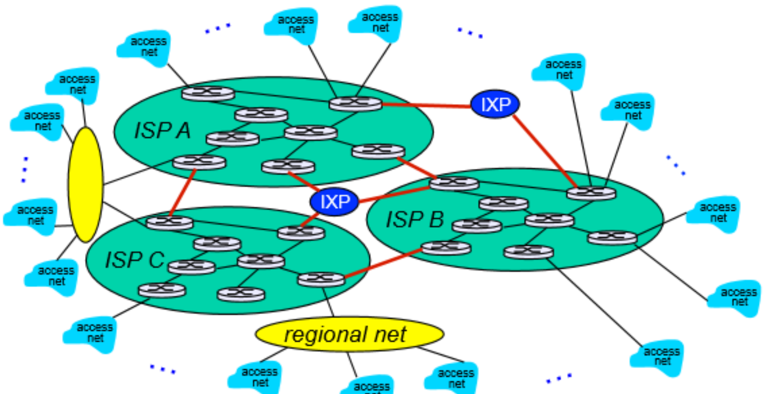
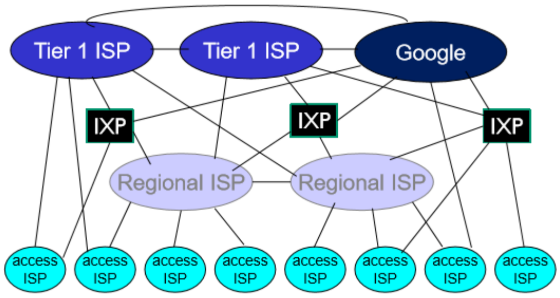
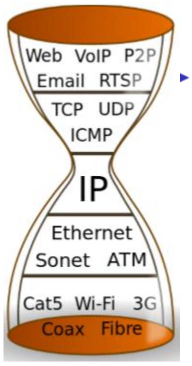


Red: peering link
IXP: internet exchange point
Isp: internet server provider

Content provider network: own network; to bring services,content close to end user (on top of everything)





- at center: small # of well-connected large networks
  - "tier-1" commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
  - content provider network (e.g, Google): private network that connects it data centers to Internet, often bypassing tier-1, regional ISPs

Introduction 1-40

Two methods for organizing communication in a network:

- circuit-switching: for each connection between two endpoints a *part* of the linkspeed is *reserved*.
  Very suitable if the users need a constant number of bits per second; e.g. telephony.
- packet-switching: information flows through the network as packets, which *one after the other* are sent at the *full* link speed.
  Very suitable if the users' needs are very variable; e.g., internet traffic

A packet is a block of bits, which are transmitted over a communication link to transport data from one place to another.

Length typically is variable, but upper-bounded.

A packet typically contains *data* and a *header*.

The header contains control information, e.g. about where the data should go.

Networked systems often use a *layered* design.

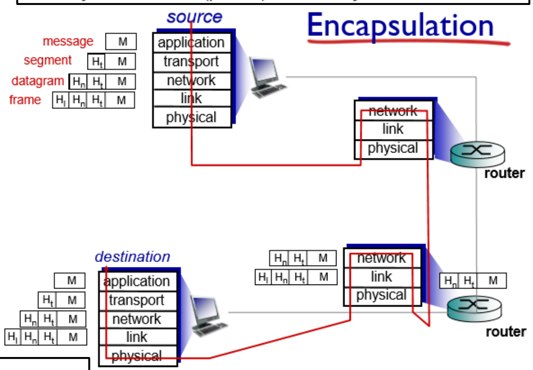
Each layer *uses* the service from the layer *below* it, to *provide* a better / more useful / more complete service to the layer *above* it.

Each layer may introduce its own header.

"One layer's header is (part of) another layer's data."

Layer	Service provided	Internet example
Application	User applications such as web, e-mail, etc.	HTTP, SMTP, etc.
Transport	Reliable delivery of byte stream (Unreliable delivery of packets)	TCP (UDP)
Network	Unreliable delivery of packets troughout a network	IP
Link	Unreliable delivery of packets to neighbour node	Ethernet, WiFi, etc.
Physical	Unreliable delivery of bits to neighbour node	fiber/copper cable, radio channel, etc.

Ipv4 = 32 bit
Ipv6 = 128 bit
Dns: coverts name to IP address and vice versa



Multiple flows of data can exist simultaneously between two hosts.
⇒ also at the transport layer a form of addressing is needed.

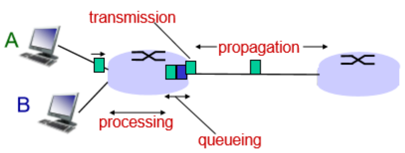
Transport layer header contains port number, of 16 bits.

A TCP connection is uniquely identified by the IP addresses on both sides and the port numbers on both sides.

Some port numbers are associated with specific applications. Other port numbers are used temporarily.

Packets can be lost on their way.
Therefore:

- Data packets contain a sequence number.
- Separate packets in the reverse direction confirm correct reception.
- Data packets which are lost, are retransmitted.



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

d_{proc}: 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

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)
- $d_{prop} = d/s$

All D_{xx} are in seconds.

(a) Layering means dividing the system into layers, where each layer use the services offered by a lower layer, to provide a better service to the higher layer. This makes it much simpler to add a new application: the new application can simply use the reliable transport service offered by the existing transport layer, instead of having to implement all that complexity itself.

Consider sending a message (or file) of F bits over a path of Q links[1]. Each link transmits at R bps. The network is lightly loaded so that there are no queuing delays. Also neglect propagation delays and the length of headers.

(a) Suppose that the network is a circuit-switched network. Further suppose that the transmission rate of the circuit between source and destination is R bps. How long does it take for the entire file to reach the destination?

(b) Suppose the network is a "message-switched" network: the entire message (file) is sent as a single, very large, packet. How long does it take for the entire file to reach the destination?

(c) Finally, suppose the network is a packet-switched network and the F bits are broken up into M packets of L bits each (with M and L such that $F = M \cdot L$). How long does it take for the entire file to reach the destination?
Hint: don't forget that while the first packet travels over the second link, the second packet can already travel over the first link.

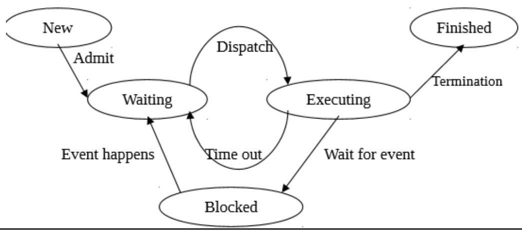
(a) Because there are no store-and-forward delays, the total delay is F/R.
(b) QF/R.
(c) The time to transmit one packet onto a link is L/R. The time to deliver the first of the M packets to the destination is QL/R. After this, every L/R seconds a new packet from the $M-1$ remaining packets arrives at the destination. Thus the total latency is $(Q+M-1)L/R$.

Multiple programs at same time:
If multiple processors (cores), 1 per processor
Otherwise: alternately execute instructions of one and another program
Is done by operating system

Tasks OS: managing computer hardware and connected peripheral equipment

Process management, **memory management**, file management, input+output, protection, communication (via network/internet)

Process management

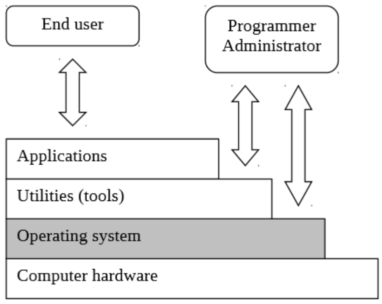


Memory man.: assigning parts of memory to programs. Swapping. Virtual memory (using hard disk to pretend there is more memory than there physically is)

File man.: data on hard disk. Bookkeeping (keep track of which file is stored in which sector of hard disk). Meta-information (name,size,owner,creationdate). Files are organised in directories(folders)

Input/output: controlling peripheral hardware: keyboard,mouse,screen,harddisk,sound,printer

Protection: distinguish between users;authentication of users; user permissions (read/write file; acces I/O equipment)



6.17 Bandwidth-delay product Suppose two hosts, A and B, are separated by 20 000 kilometers and are connected by a direct link of $R = 2$ Mbps. Suppose the propagation speed over the link is $2.5 \cdot 10^8$ m/s.

(a) Calculate the bandwidth-delay product, $R \cdot d_{prop}$.
(b) Consider sending a file of 800 000 bits from Host A to Host B. Suppose the file is sent continuously as one large message. What is the maximum number of bits that will be in the link at any given time?
(c) Provide an interpretation of the bandwidth-delay product.
(d) What is the width (in meters) of a bit in the link? Is it longer than a football field?
(e) How long does it take for the entire file to reach host B, assuming it is sent continuously?
(f) Suppose now the file is broken up into 10 packets with each packet containing 80 000 bits. Suppose that each packet is acknowledged by the receiver and the transmission time of an acknowledgement packet is negligible. Finally, assume that the sender cannot send a packet until the preceding one is acknowledged. How long does it take for the entire file to reach host B?
(g) Compare the previous two answers.

□

Answer to 6.17.

(a) $d_{prop} = 20000 \cdot 10^3 / 2.5 \cdot 10^8 = 0.08$ seconds; then $R \cdot d_{prop} = 160000$ bits.
(b) 160 000 bits.
(c) The bandwidth-delay product of a link is the maximum number of bits that can be in the link.
(d) 1 bit is $2.5 \cdot 10^8 / 2 \cdot 10^6 = 125$ meters long, which is longer than a football field.
(e) $d_{trans} + d_{prop} = 0.4 + 0.08 = 0.48$ seconds.

[1]By this we mean the links are arranged one after the other, so everything sent from source to destination needs to go through all of the links.

(f) $10 \cdot (d_{trans} + 2d_{prop}) = 10 \cdot (0.04 + 0.16) = 2$ seconds.
Or, arguably, 1 d_{prop} less, because by that time the last bit of the file has reached B, only it's ack has not yet returned to A.

Suppose users share a 3 Mbps link. Also suppose each user requires 150 kbps when transmitting, but each user transmits only 10 % of the time.

(a) If circuit switching is used, how many users can be supported?

Henceforth, suppose packet switching is used.

(b) Find the probability that a given user is transmitting.
(c) Suppose there are 120 users. Find the probability that at any given time, exactly n users are transmitting simultaneously. (Hint: Use the binomial distribution.)
(d) Find the probability that there are 21 or more users transmitting simultaneously.

□

Answer to 6.18.

(a) 20 users can be supported because each user requires one twentieth (150 kbps / 3 Mbps) of the bandwidth.
(b) It's given as 10%.
(c) $\binom{120}{n} \cdot 0.1^n \cdot 0.9^{120-n}$
(d) $1 - \sum_{n=0}^{20} \binom{120}{n} p^n (1-p)^{120-n} \approx 0.0079$ (with $p = 0.1$).
With graphical calculator: binomcdf(n, p, x) = given n experiments and a probability p for success, what is the probability of $\leq x$ successes. Therefore, we can calculate the requested probability (21 or more users transmitting simultaneously) as follows: 1 - binomcdf(120, 0.1, 20) = 0.0079