Redes de Computadores

LEIC-A

1 – Introduction

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1

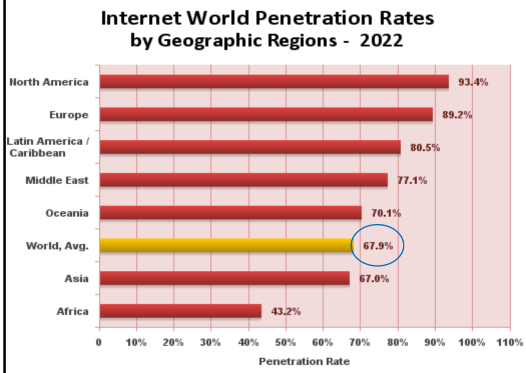
Objectives

- Terminology
- What is a protocol?
- Network edge (hosts, access net, physical media)
- Network core (packet/circuit switching, Internet structure)
- Performance metrics: loss, delay, throughput
- Protocol layers, service models

2

The Internet

- The Internet is a *computer network* that interconnects millions of computing devices throughout the world.



Source: Internet World Stats - www.internetworldstats.com/stats.htm
Penetration Rates are based on a world population of 7,932,791,734
and 5,385,798,406 estimated Internet users in June 30, 2022.
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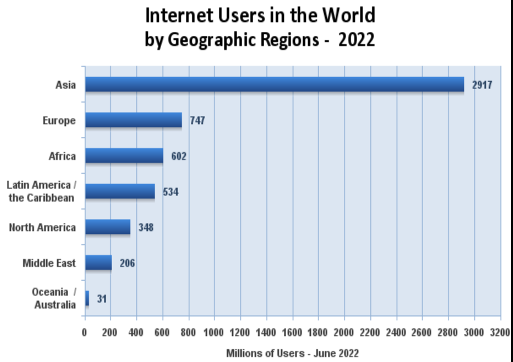

Source: Internet World Stats - www.internetworldstats.com/stats.htm
Basis:5,385,798,406 Internet users estimated in June 30, 2022
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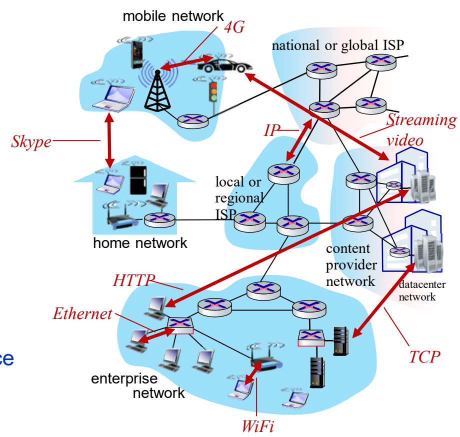
The Internet Needs some Rules…

- *Internet:* "network of networks"
  - loosely hierarchical
  - Interconnected ISPs
- *Protocols* control sending and receiving of messages
  - e.g., TCP, IP, HTTP, Ethernet
- Internet *standards*
  - RFC: Request for Comments
  - IETF: Internet Engineering Task Force



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What is a Protocol?

*A protocol defines the **format** and the **order** of messages sent and received among network entities, as well as the **actions** taken on message transmission/receipt.*

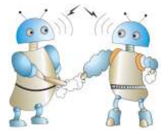
Protocols followed by humans:

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

  - Specific messages are sent
  - Specific actions are taken when messages are received, or other events occur

Network protocols:

- Machines rather than humans
- Internet communication is governed by protocols



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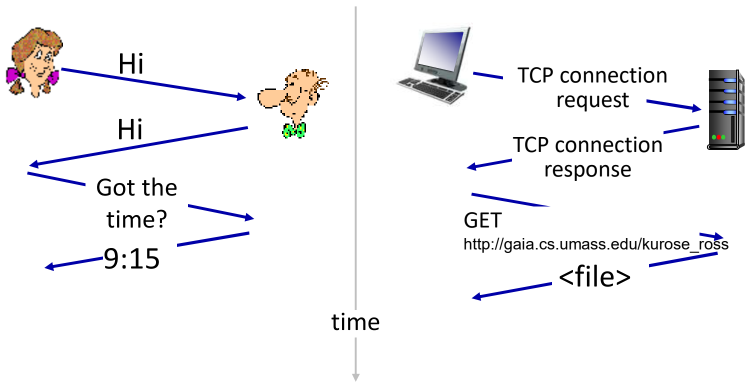
What is a Protocol?

Human protocol

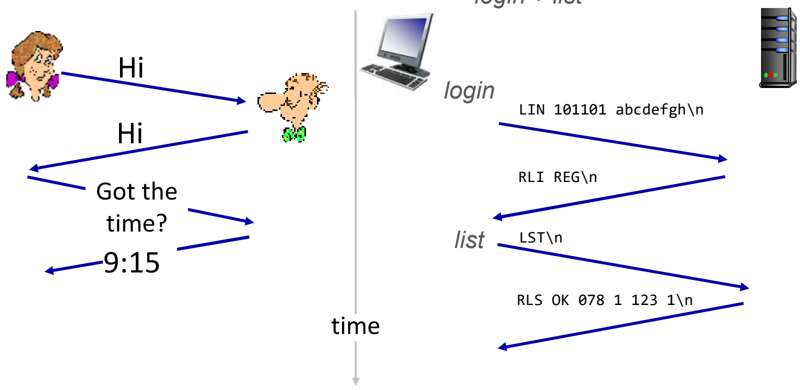
Computer network protocol



What is a Protocol?

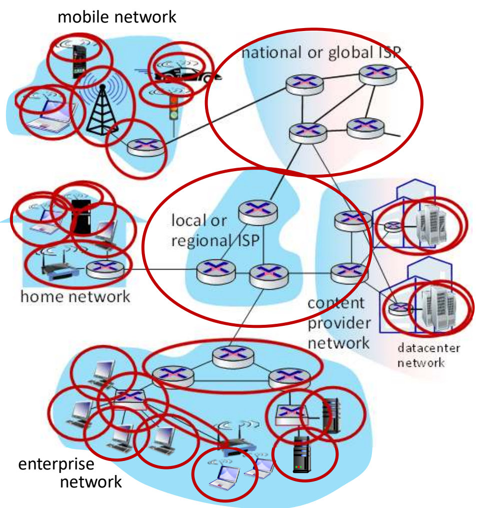
Human protocol

RC Auction
login + list



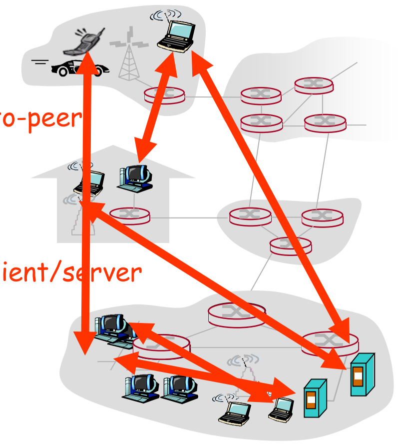
Network Structure

- Network edge:
  applications and hosts
- Access networks, physical media: wired, wireless communication links
- Network core:
  - interconnected routers
  - network of networks



The Network Edge

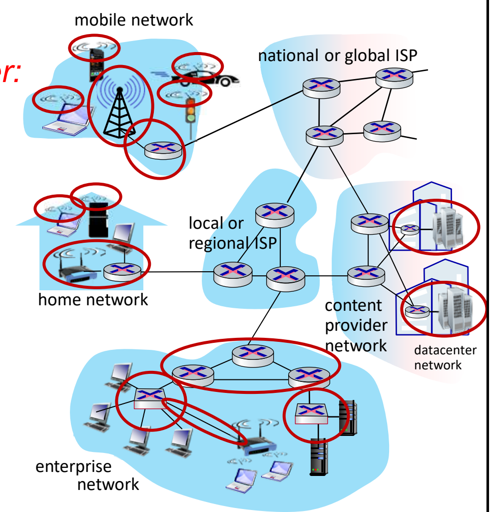
- End systems (hosts):
  - Run application programs, e.g. Web, e-mail, at the “edge of network”
- Client/server model:
  - Client host requests and receives service from always-on server (e.g. Web browser/server; e-mail client/server)
- Peer-to-peer model:
  - Minimal (or no) use of dedicated servers, e.g. Skype, BitTorrent



Access Networks

Connect end systems to edge router:
- **Residential** access networks
- **Institutional** access networks (school, company)
- **Mobile** access networks (WiFi, 4G/5G)

Access network differences:
- Bitrate (bit/s)
- Shared or dedicated
- Wired or wireless
- ...



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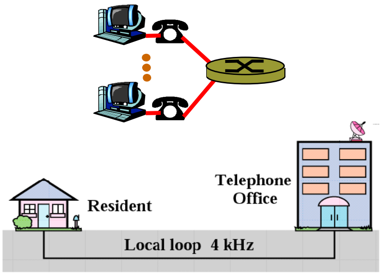
Residential Access: Point to Point

- Dialup via modem
  - Up to 56 kbit/s direct access to router (often less)
  - Can't surf and phone at same time
  - Not "always on"



- DSL: digital subscriber line
  - Deployment: telephone company (typically)
  - > 1 Mbit/s upstream (typically)
  - > 12 Mbit/s downstream (typically)

Both solutions use dedicated physical line to the switching central.

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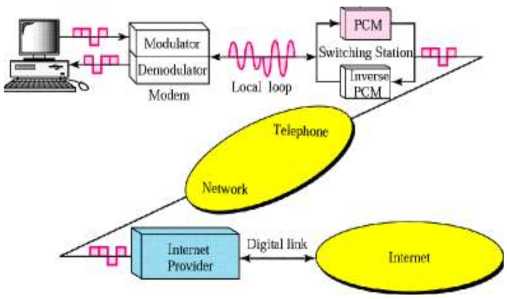
Residential Access: Modem

Dial-up via modem:

- Uses analog telephone network;
- Speeds up to 56 kbit/s;
- Connection to an Internet Service Provider (ISP).



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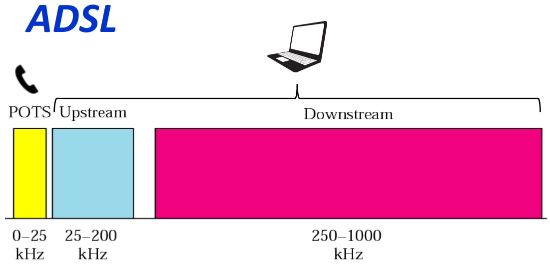
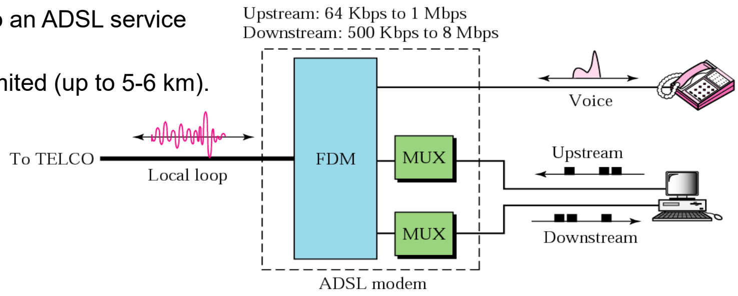
Residential Access: ADSL

ADSL access:

- Uses the analog telephone infrastructure;
- Asymmetric connection: ~1 Mbit/s (upstream), ~12 Mbit/s (downstream);
- Connection to an ADSL service provider;
- Link length limited (up to 5-6 km).





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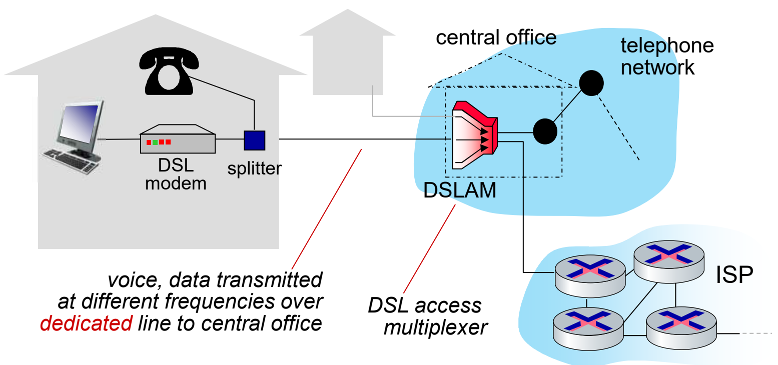
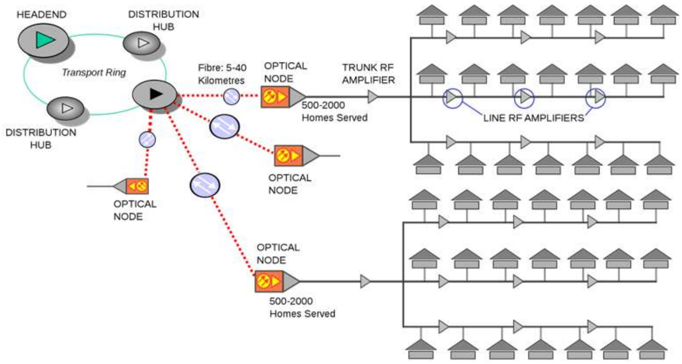
Residential Access: ADSL



Residential Access: Cable Modems

- HFC: hybrid fiber coaxial
- Network of cable and fiber attaches homes to ISP router
  - homes share access to router



Residential Access: Cable Modems

- HFC: hybrid fiber coaxial
- Internet access:
  - Data Over Cable Service Interface Specification (DOCSIS)

DOCSIS version[13]	Production date	Maximum downstream capacity	Maximum upstream capacity	Features
1.0	1997		10 Mbit/s	Initial release
1.1	2001	40 Mbit/s		Added VOIP capabilities and QoS mechanisms
2.0	2002		30 Mbit/s	Enhanced upstream data rates
3.0	2006	1 Gbit/s	200 Mbit/s	Significantly increased downstream/upstream data rates, introduced support for IPv6, introduced channel bonding
3.1	2013	10 Gbit/s	1–2 Gbit/s	Significantly increased downstream/upstream data rates, restructured channel specifications
4.0	2017		6 Gbit/s	Significantly increased upstream rates from DOCSIS 3.1

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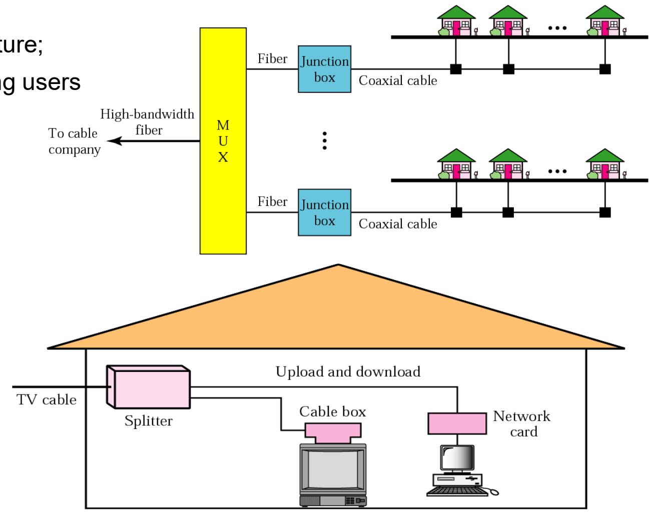
Residential Access: Cable Modems

Cable modem access:

- Uses cable TV infrastructure;
- Connection shared among users in the same cable section;
- Asymmetric connection.



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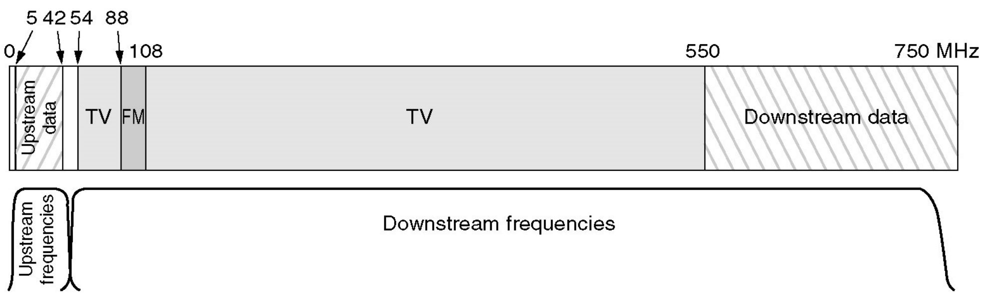
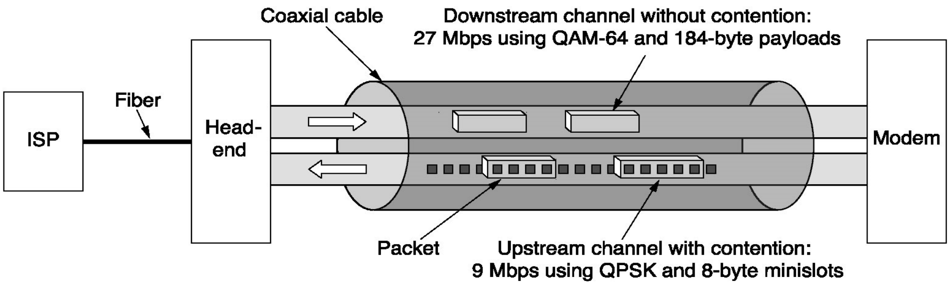
Residential Access: Cable Modems

Example of available spectrum usage in a cable TV system:



Residential Access: Cable Modems

Example of upstream and downstream data channel implementation:



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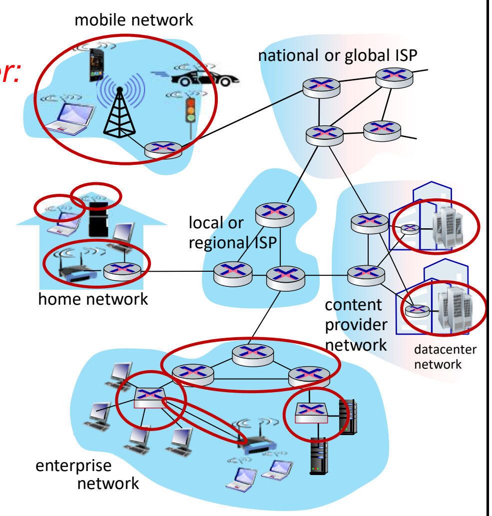
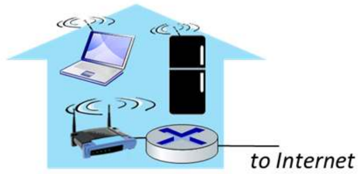
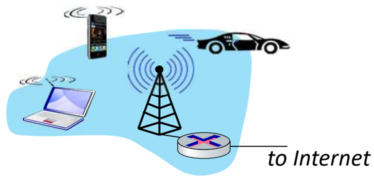


Wireless Access Networks

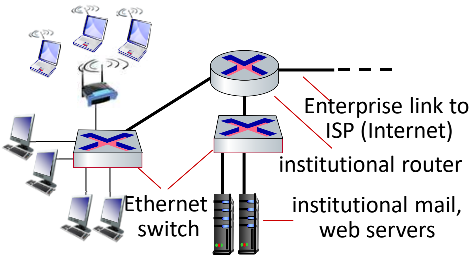
- Shared *wireless* access network connects end system to router
  - Via a base station: “access point” (AP);
- Wireless LANs:
  - 802.11b/g/n/ac/… (**WiFi**): 11, 54-600 Mbps, …;
- Wider-area wireless access:
  - Provided by telecom operator (10’s km);
  - ~1Mbps over cellular mobile (UMTS);
  - Always evolving: 4G (>10s Mbps), 5G (60 Mbps–1 Gbps)...





Business Access: Local Area Networks (LAN)

- Companies, universities, etc.
  - Mix of wired, wireless link technologies, connecting a mix of switches and routers
- Typically use local area networks (LANs) for connection of end systems to edge router;
  - **Ethernet**:
    - 10 Mbs, 100Mbps, 1Gbps, 10Gbps, …
  - **WiFi**:
    - Wireless access point: 11 Mbs, 54 Mbps, 450 Mbps, …



LANs, Wireless LANs: chapters 6 and 7 (8th edition of the book).

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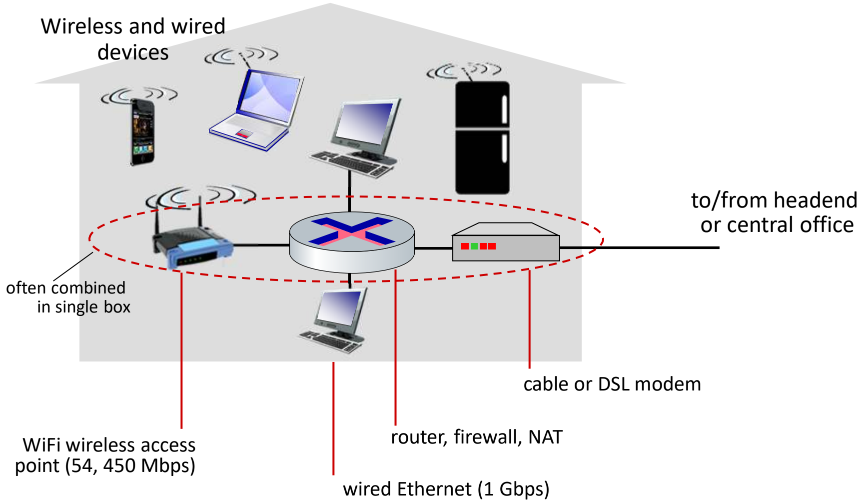
Home Networks



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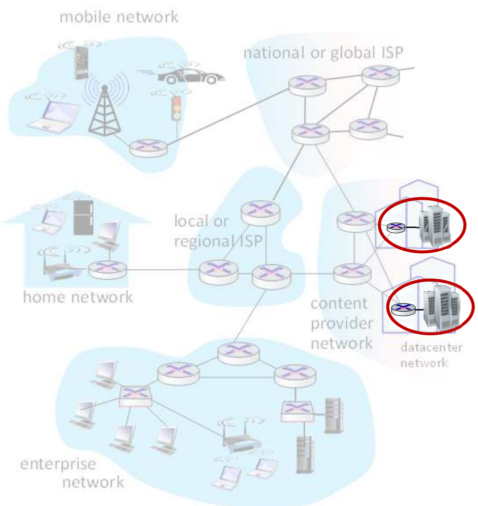
Data Centre Networks

- High-bandwidth links (10s to 100s Gbps) connect hundreds to thousands of servers together, and to Internet

Courtesy: Massachusetts Green High Performance Computing Center (mghpcc.org)



Physical Media

- Data (packets composed of bits) propagates between transmitter and receiver pairs;
- Physical link: what lies between a transmitter and a receiver.

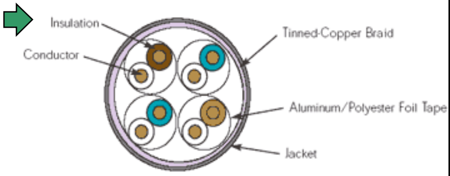
Two types of physical media:

- Guided/**Wired**:
  - Signals propagate in solid media: copper, fiber, coaxial cable;
- Unguided/**Wireless**:
  - Signals propagate freely, e.g., radio.

Guided Physical Media

Twisted Pair (TP)

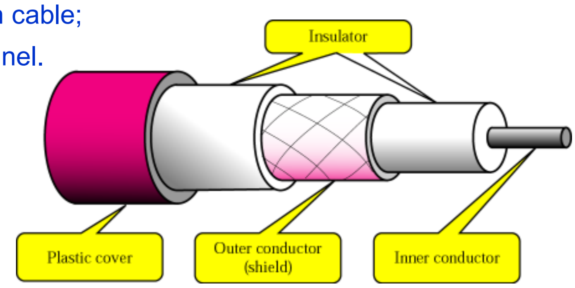
- Two insulated copper wires:
  - Category 3: traditional phone wires, 10 Mbps Ethernet
  - Category 5: 100Mbps Ethernet, 100 m
  - Category 6: up to 1 Gbps
  - Category 7: up to 10 Gbps
  - … 100 Gbps (15m)



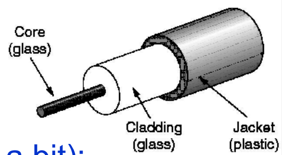
Guided Physical Media

Coaxial cable:

- Two concentric copper conductors;
- Bidirectional;
- Broadband:
  - Multiple channels on cable;
  - 100’s Mbps per channel.

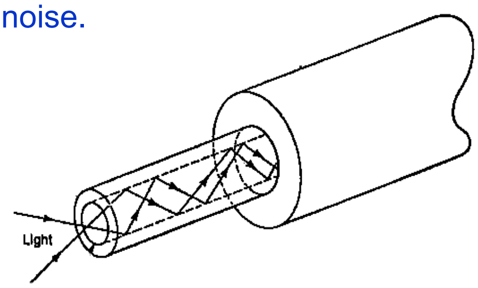


Guided Physical Media



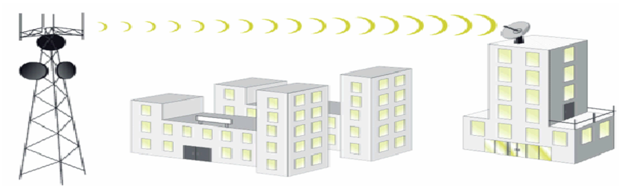
Fiber optic cable:

- Glass fiber carrying light pulses (each pulse a bit);
- High-speed point-to-point transmission (10’s-100’s Gbps);
- Low error rate: repeaters spaced far apart;
- Immune to electromagnetic noise.



Unguided/Wireless Physical Media

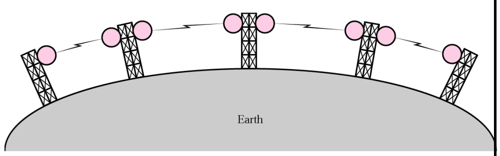
- No physical “wire”;
- Signal transmitted between sending and receiving antennas;
- Bidirectional;
- Propagation environment effects:
  - Reflection;
  - Obstruction by objects;
  - Interference.



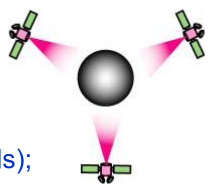
Unguided Physical Media

Radio link types:

- Terrestrial microwave
  - e.g. up to 45 Mbps channels;

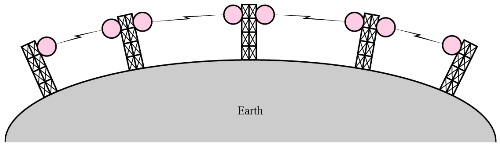


- Wireless LAN (WiFi)
  - 10-100’s Mbps; 10’s of meters;
- Wide-area (e.g., cellular)
  - 3G: ~ 1 Mbps; 4G: ~10 Mbps; 5G;
  - over ~10 km



- Satellite
  - kbps to 45 Mbps channel (or multiple smaller channels);
  - Geosynchronous (GEO) versus low altitude (LEO);
  - ~270 ms end-end delay (GEO).

Unguided Physical Media

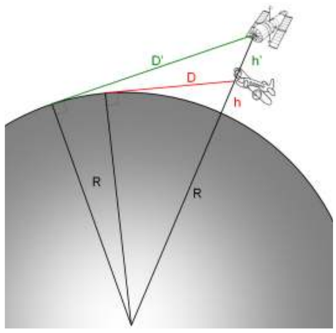


Terrestrial microwave

- Distance to the horizon:

$$D^2 + R^2 = (R + h)^2$$
$$D = \sqrt{2hR + h^2}$$

R = 6371 km = 6371000 m
with h=1,8 m → D = 4,8 km
with h=40 m → D = 22,6 km



Objectives

- Terminology
- What is a protocol?
- Network edge (hosts, access net, physical media)
- **Network core**
  - **Circuit switching, Packet switching, Internet structure**
- Performance metrics: loss, delay, throughput
- Protocol layers, service models

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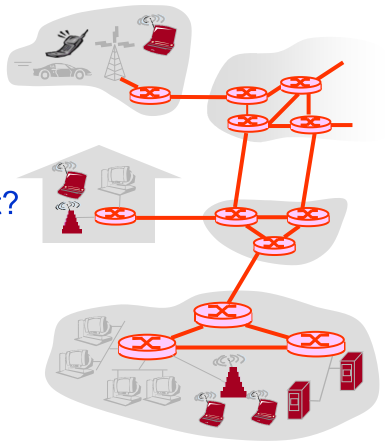
The Network Core

- Mesh of interconnected routers.
- *The* fundamental question:
  How is data transferred through the net?
  - Circuit switching:
    Dedicated circuit per call;
    e.g.: telephone network.
  - Packet-switching:
    Data sent through net in discrete "chunks".



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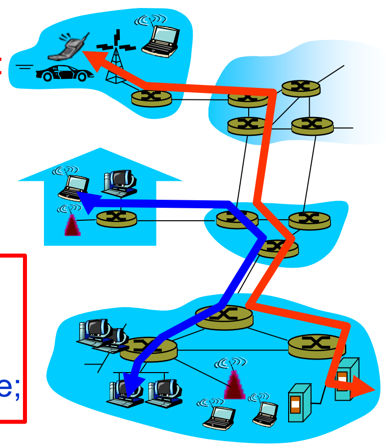
Circuit Switching

End-end **resources** **reserved** for "call":

- Link bandwidth;
- Switch capacity;

- Call setup required;
- Dedicated resources: **no sharing**;
- Circuit-like (guaranteed) performance;

Not used for computer networks!



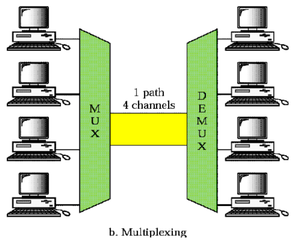
Circuit Switching

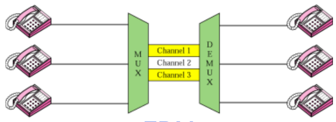
Network resources (e.g., bandwidth) divided into "pieces":

- Pieces allocated to calls;
- Resource piece *idle* if not used by owning call *(<u>no sharing</u>)*.

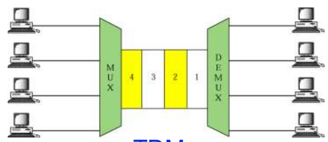
Dividing link bandwidth into "pieces" (**multiplexing**), e.g.:

- Frequency division (FDM);
- Time division (TDM).





FDM

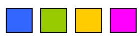


TDM

Circuit Switching: FDM and TDM

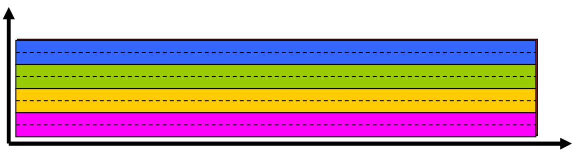
Example:

4 users



FDM

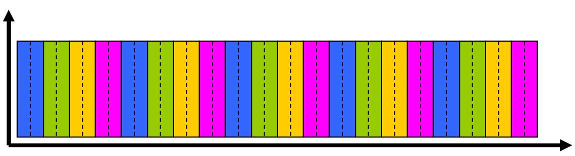
frequency



time

TDM

frequency



time

Circuit Switching: Numerical Example

- How long does it take to send a file of 640,000 bits from host A to host B over a circuit-switched network?
  - The bit rate of available links is 2.048 Mbps;
  - Each link is shared using TDM, with 32 slots/line;
  - It takes 500 msec to establish end-to-end circuit.

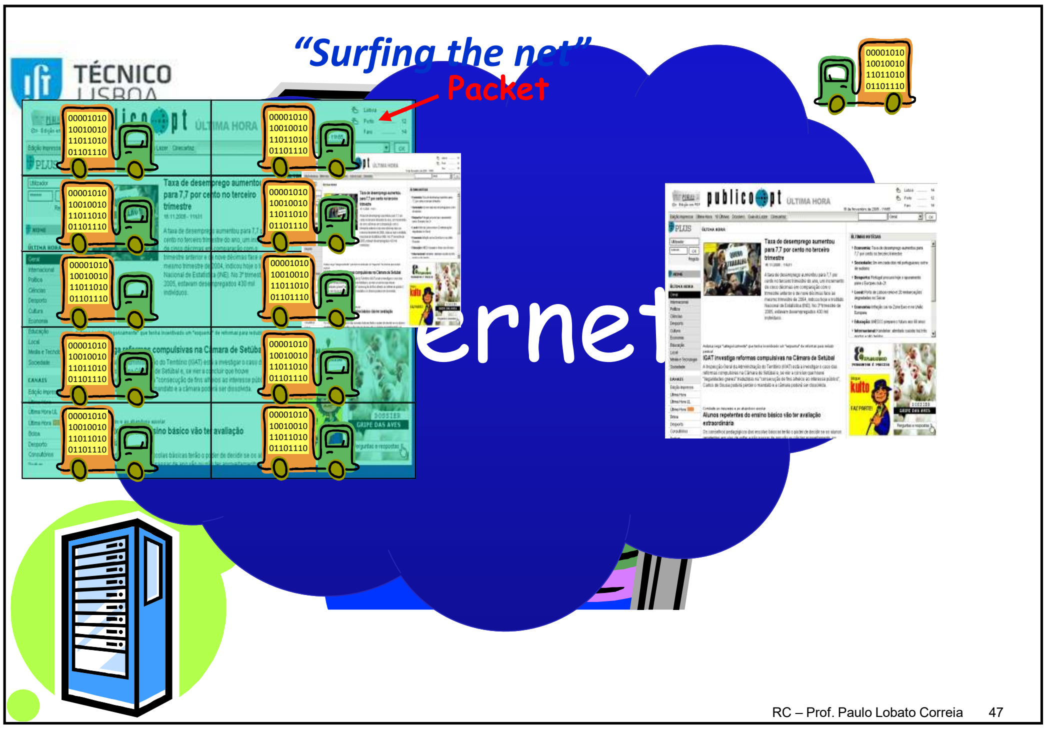
Let's work it out!

Packet Switching

Each end-end data stream is divided into ***packets***:
- Packets from different users ***share*** network resources;
- Each packet uses **full link bandwidth**;
- Resources ***used as needed***

~~Bandwidth division into "pieces"~~
~~Dedicated allocation~~
~~Resource reservation~~

Resource contention:
- Aggregate demand can exceed resources available;
- **Congestion**: packets queue, waiting for link (eventual loss);
- **Store and forward**: packets move one hop at a time:
  - Node receives complete packet before forwarding.



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"Surfing the net"
Packet
ernet
RC – Prof. Paulo Lobato Correia 47

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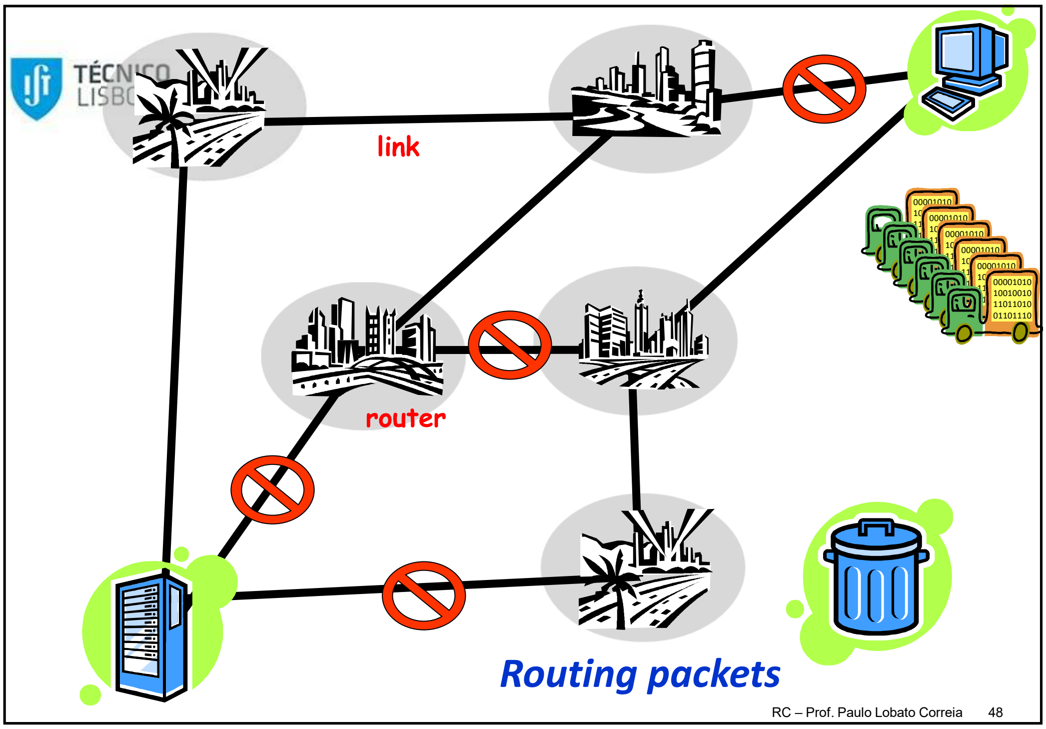

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link
router
Routing packets
RC – Prof. Paulo Lobato Correia 48

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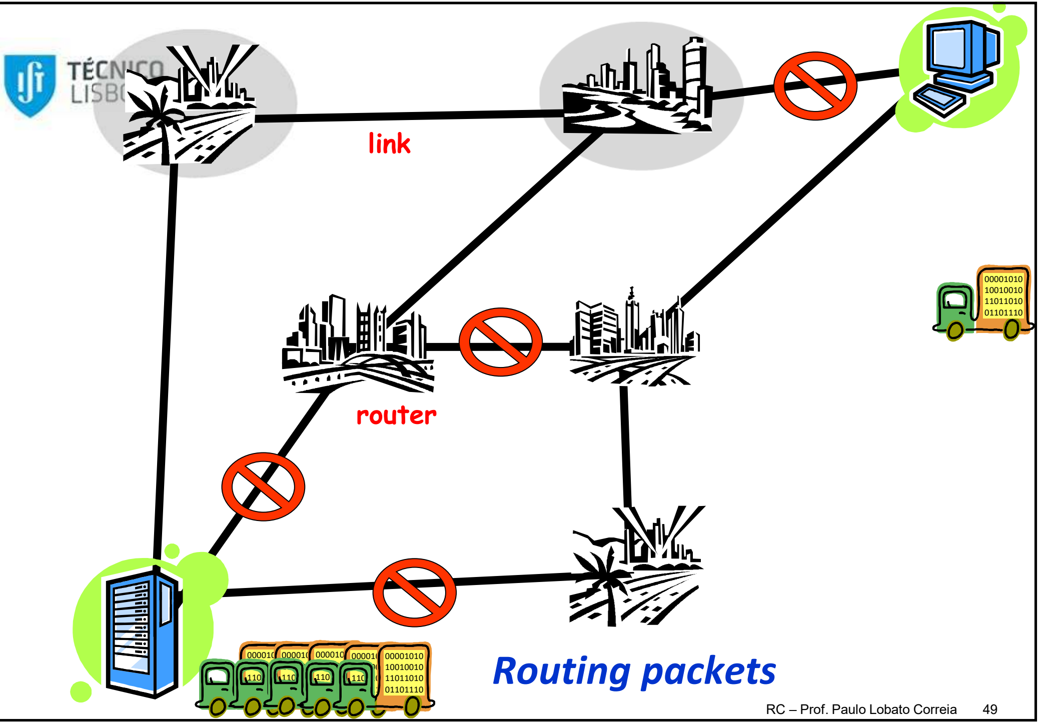
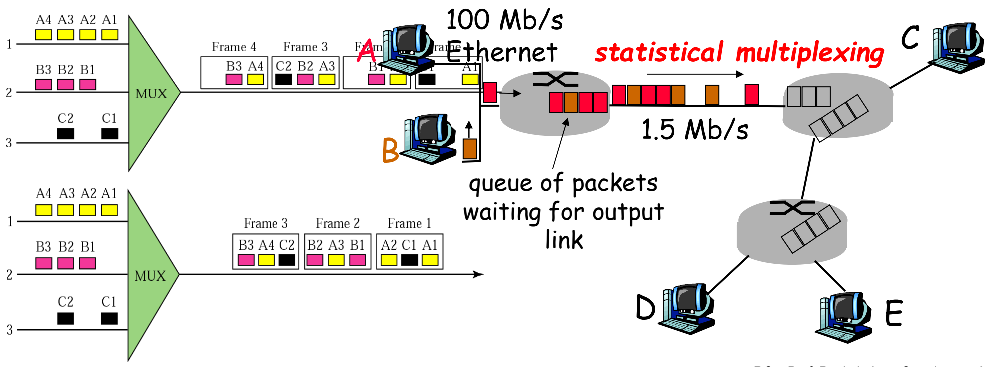


Routing packets

Packet Switching: Statistical Multiplexing

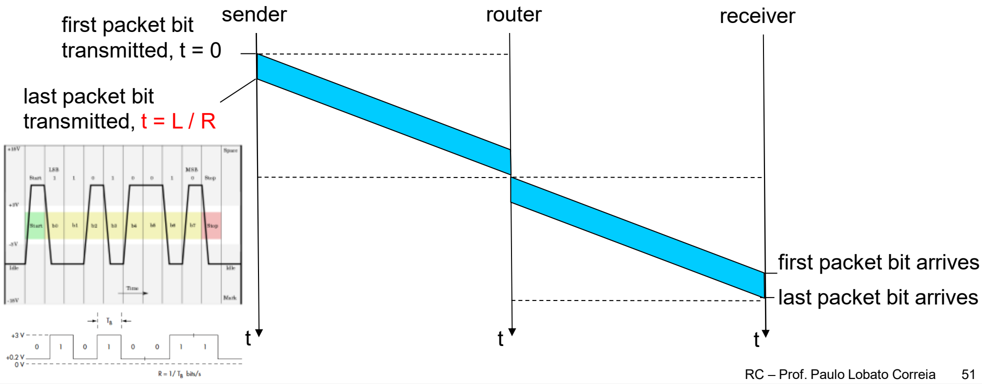
TDM: each host always gets the same slot in a revolving TDM frame.

Packet switching: sequence of packets has no fixed pattern; bandwidth is shared on demand → ***statistical multiplexing***.

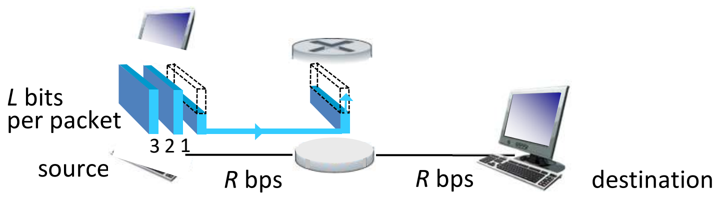


Packet Switching: Store-and-Forward

- It takes L/R seconds to transmit a packet of L bits on link at R bps;
- ***Store and forward***:
  entire packet must arrive at router before transmission on next link;



Packet Switching: Store-and-Forward



Packet **transmission delay**:

- takes **L/R** seconds to transmit (push out) L-bit packet into link at R bit/s

Store and forward:

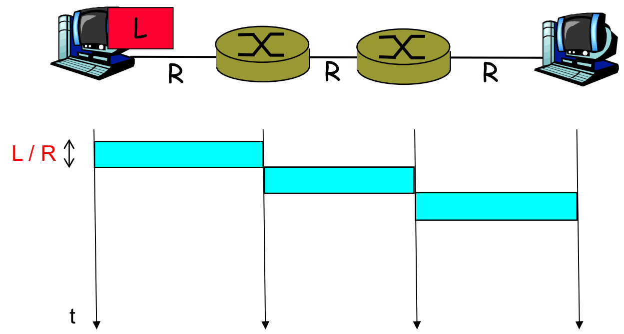
- entire packet must arrive at router
  before it can be transmitted on next link

Packet Switching: Store-and-Forward

Problem 1

Example:

- L = 7.5 Mbits
- R = 1.5 Mbps



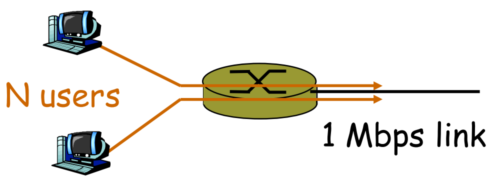
delay = 3L/R (assuming zero propagation delay).

transmission delay = 15 sec

Packet Switching versus Circuit Switching

Packet switching allows more users to use network!

- 1 Mb/s link
- Each user:
  - 100 kbit/s when “active”
  - Active 10% of time



- *Circuit-switching:*
  - 10 users
- *Packet switching:*
  - with 35 users, probability > 10 active at same time is less than .0004 !

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Packet Switching versus Circuit Switching

- Packet switching is great for bursty data:
  - Resource sharing;
  - Simpler, no call setup;
- With excessive congestion:
  - Packet delay and loss;
  - Protocols needed for reliable data transfer, congestion control;

Q: How to provide circuit-like behavior?

- Bandwidth guarantees needed for audio/video applications!
- Still an unsolved problem (chapter 7)…

Q: human analogies of reserved resources (circuit switching) versus on-demand allocation (packet-switching)?

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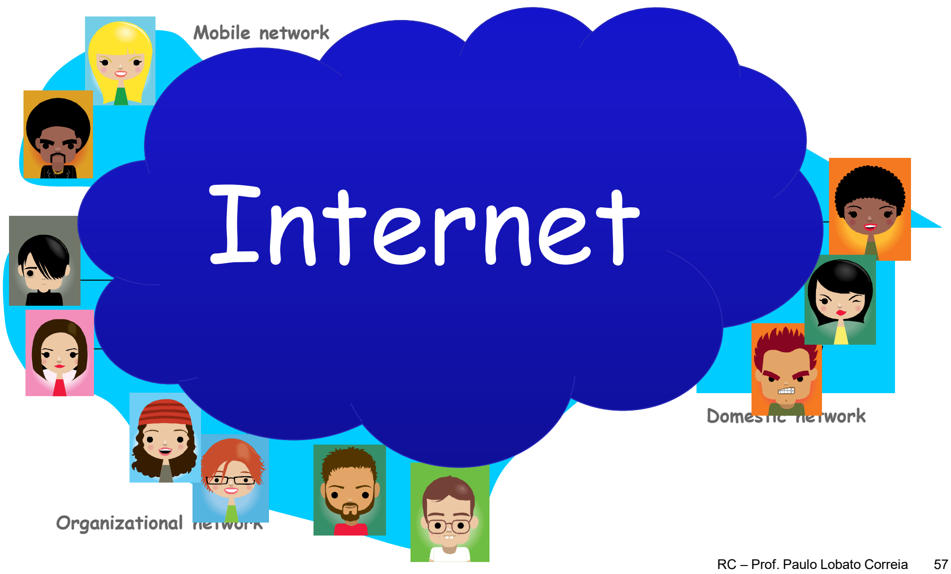
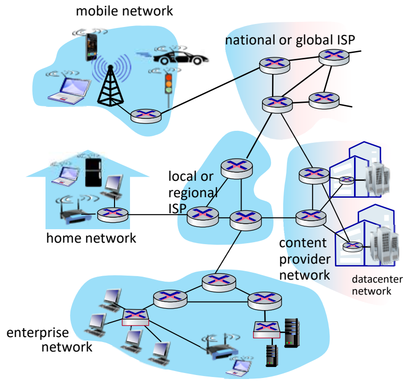
Internet Structure: Network of Networks



Internet structure: a "network of networks"

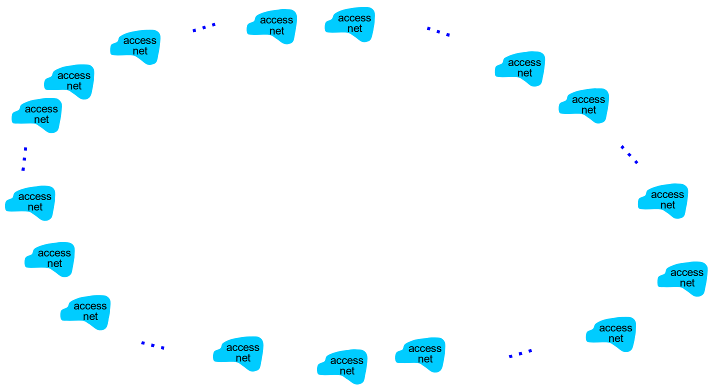
- hosts connect to Internet via access Internet Service Providers (ISPs)
- access ISPs in turn must be interconnected
  - so that *any* two hosts *(anywhere!)* can send packets to each other
- resulting network of networks is very complex
  - evolution driven by economics, national policies



Let's take a stepwise approach to describe current Internet structure

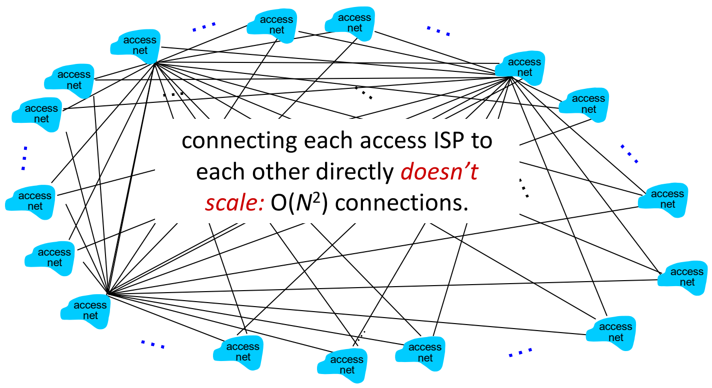
Internet structure: a "network of networks"

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



Internet structure: a "network of networks"

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



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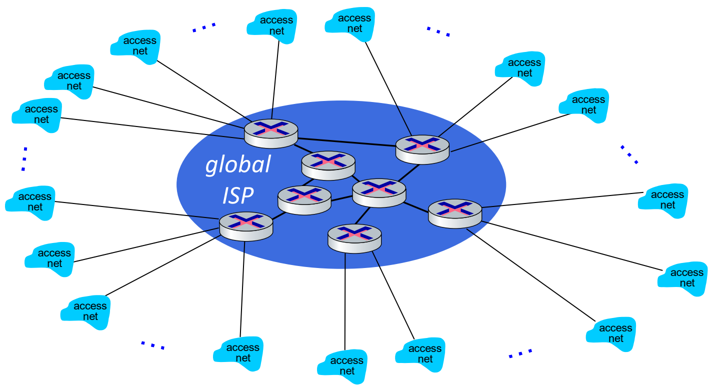
Internet structure: a "network of networks"

Option: *connect each access ISP to one global transit ISP?*
Customer and provider ISPs have economic agreement.



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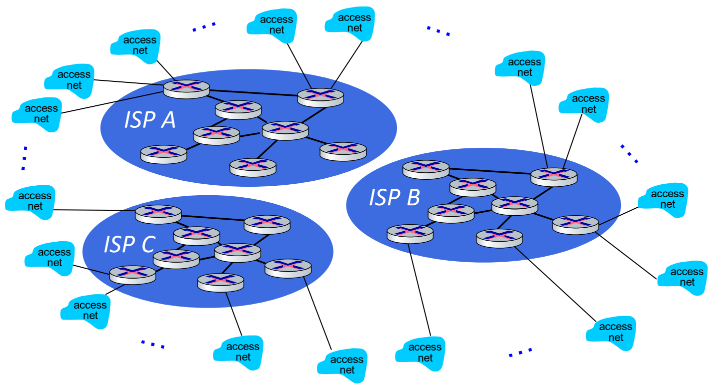
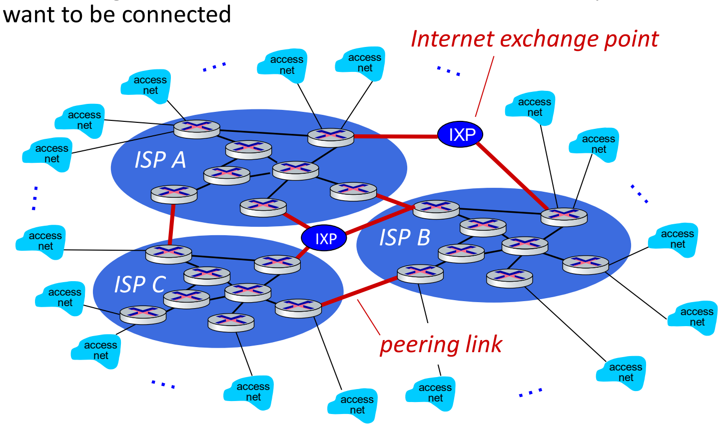
Internet structure: a "network of networks"

But if one global ISP is viable business, there will be competitors ….



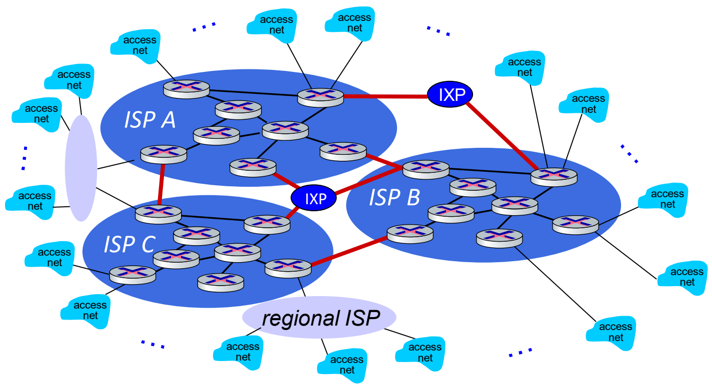
Internet structure: a "network of networks"

But if one global ISP is viable business, there will be competitors …. who will want to be connected



Internet structure: a "network of networks"

... and regional networks may arise to connect access nets to ISPs



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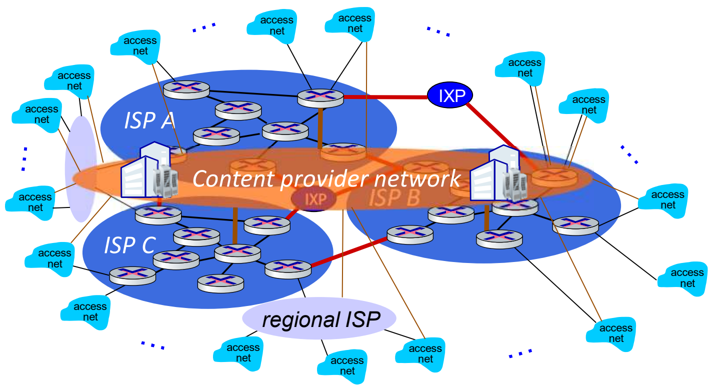
Internet structure: a "network of networks"

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



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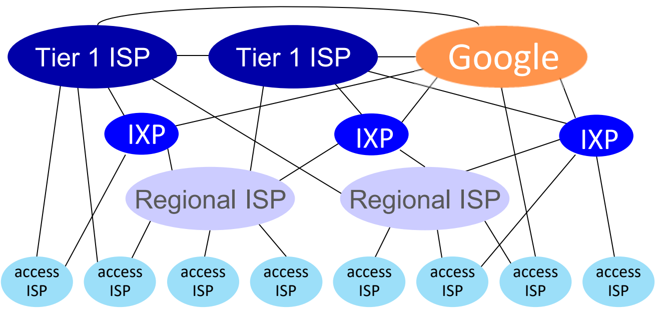
Internet structure: a "network of networks"



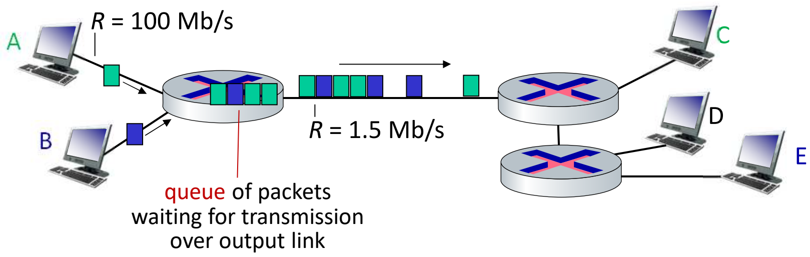
At "center": small # of well-connected large networks

- "tier-1" commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
- content provider networks (e.g., Google, Facebook): private network that connects its data centers to Internet, often bypassing tier-1, regional ISPs

Objectives

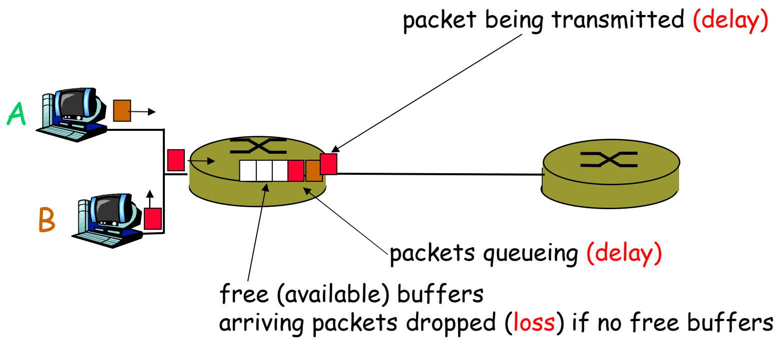
- Terminology
- What is a protocol?
- Network edge (hosts, access net, physical media)
- Network core (circuit/packet switching, Internet structure)
- **Performance metrics:**
  - **Loss**
  - **Delay**
  - **Throughput**
- Protocol layers, service models

Packet Switching: Delay and Loss



Queueing occurs when work arrives faster than it can be serviced

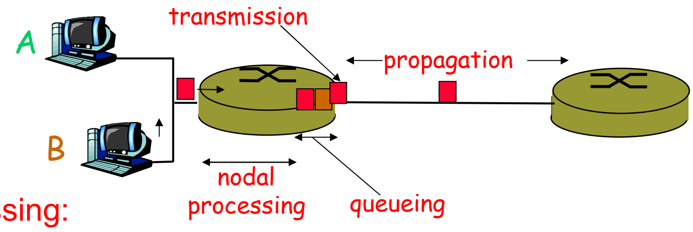
Packet Switching: Delay and Loss



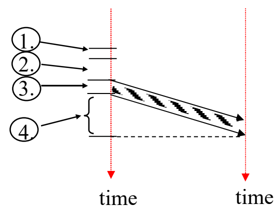
Arrival rate > transmission rate:

- packets will queue, waiting to be transmitted on output link
- packets can be dropped (**lost**) if memory (buffer) in router fills up

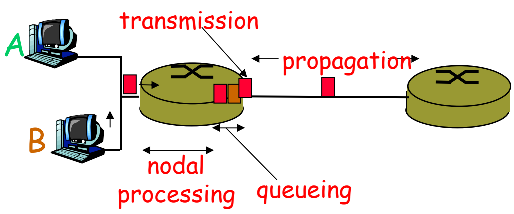
Delay in Packet Switched Networks



- 1. Nodal processing:
  - Check bit errors;
  - Determine output link;
  - ...
- 2. Queueing
  - Time waiting for output link for transmission;
  - Depends on congestion level of router.



Delay in Packet Switched Networks



3. Transmission delay:

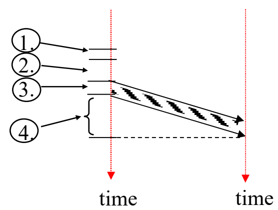
- **R** = link bandwidth (bps);
- **L** = packet length (bits).

Time to send bits into link = L/R

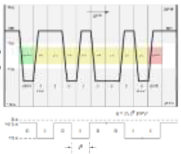
4. Propagation delay:

- **d** = length of physical link
- **s** = propagation speed in medium (~2×10^8 m/sec)

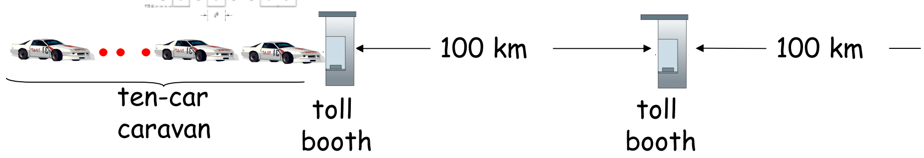
Propagation delay = d/s



Note: *s* and *R* are *very* different quantities!



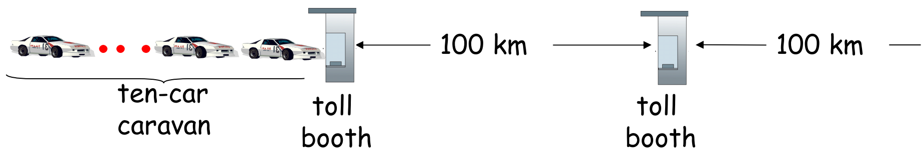
Caravan Analogy



- car ~ bit;
- caravan ~ packet (always travel together);
- toll booth takes 12 sec to service one car (transmission time);
- cars "propagate" at 100 km/h;
- Q: How long until caravan is lined up before 2nd toll booth?

- Time to "push" entire caravan through toll booth onto highway = 12*10 = 120 sec (transmission time: L/R)
- Time for last car to propagate (d/s) from 1st to 2nd toll both: 100km/(100km/h) = 1 h
- A: 62 minutes

Caravan Analogy



- Cars now "propagate" at 1000 km/h;
- Toll booth now takes 1 min / car;
- Q: Will cars arrive to 2nd booth before all cars serviced at 1st booth?

- Yes! After 7 min, 1st car at 2nd booth and 3 cars still at 1st booth.
- 1st bit of packet can arrive at 2nd router before packet is fully transmitted at 1st router!
- See applet at AWL Web site: https://media.pearsoncmg.com/aw/ecs_kurose_compnetwork_7/cw/content/interactiveanimations/transmission-vs-propogation-delay/transmission-propagation-delay-ch1/index.html

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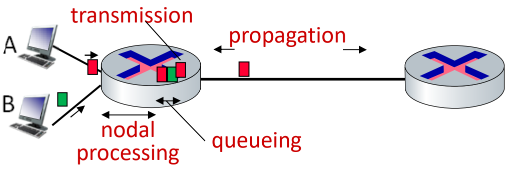
Nodal Delay



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

d_{proc} - processing delay
- typically < microsecs

d_{queue} - queuing delay
- depends on congestion

d_{trans} - transmission delay
- d_{trans} = L/R, significant for low-speed links

d_{prop} - propagation delay
- d_{prop} = d/s, a few microsecs to hundreds of msecs

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

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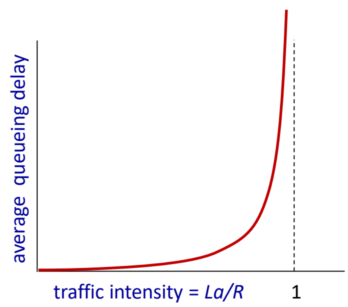
Queueing Delay

- **R** = link bandwidth (bps)
- **L** = packet length (bits)
- **a** = average packet arrival rate



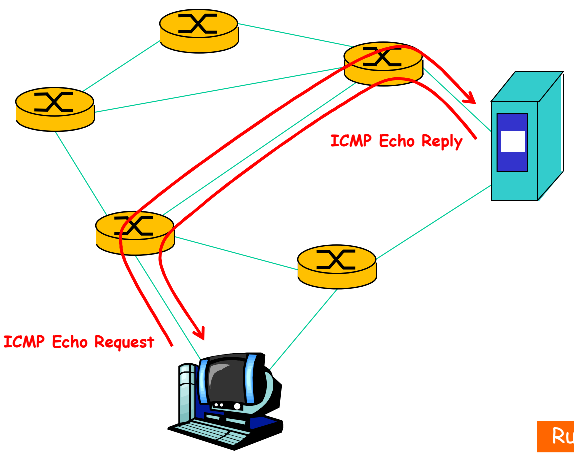
Traffic intensity = L.a/R

- L.a/R ~ 0: average queueing delay small
- L.a/R → 1: delays become (very) big
- L.a/R > 1: more “work” arriving than can be serviced - average delay infinite!

La/R ~ 0

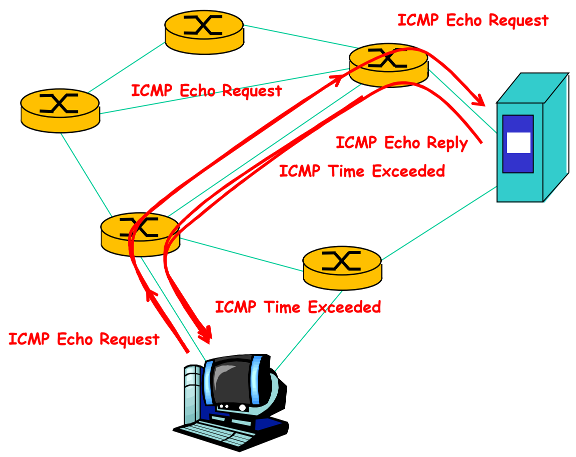
La/R → *1*

Testing Internet Destinations: the `ping` Command



Run ping

Discovering Internet Routes: `traceroute`



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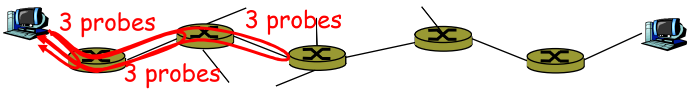
"Real" Internet Delays and Routes

- What do "real" Internet delay & loss look like?
- **Traceroute** program: (windows: *tracert*; linux: *traceroute*)
  - Provides delay measurement from source to router along end-end Internet path towards destination.
    For all ***i***:
    - Sends three packets that will reach router *i* on path towards destination;
    - Router ***i*** will return packets to sender;
    - Sender times interval between transmission and reply.



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"Real" Internet Delays and Routes

traceroute: gaia.cs.umass.edu to www.eurecom.fr

Three delay measurements from gaia.cs.umass.edu to cs-gw.cs.umass.edu

```
1  cs-gw (128.119.240.254)  1 ms  1 ms  2 ms
2  border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145)  1 ms  1 ms  2 ms
3  cht-vbns.gw.umass.edu (128.119.3.130)  6 ms 5 ms 5 ms
4  jn1-at1-0-0-19.wor.vbns.net (204.147.132.129)  16 ms 11 ms 13 ms
5  jn1-so7-0-0-0.wae.vbns.net (204.147.136.136)  21 ms 18 ms 18 ms
6  abilene-vbns.abilene.ucaid.edu (198.32.11.9)  22 ms  18 ms  22 ms
7  nycm-wash.abilene.ucaid.edu (198.32.8.46)  22 ms  22 ms  22 ms
8  62.40.103.253 (62.40.103.253)  104 ms 109 ms 106 ms
9  de2-1.de1.de.geant.net (62.40.96.129)  109 ms 102 ms 104 ms
10  de.fr1.fr.geant.net (62.40.96.50)  113 ms 121 ms 114 ms
11  renater-gw.fr1.fr.geant.net (62.40.103.54)  112 ms  114 ms  112 ms
12  nio-n2.cssi.renater.fr (193.51.206.13)  111 ms  114 ms  116 ms
13  nice.cssi.renater.fr (195.220.98.102)  123 ms  125 ms  124 ms
14  r3t2-nice.cssi.renater.fr (195.220.98.110)  126 ms  126 ms  124 ms
15  eurecom-valbonne.r3t2.ft.net (193.48.50.54)  135 ms  128 ms  133 ms
16  194.214.211.25 (194.214.211.25)  126 ms  128 ms  126 ms
17  * * *
18  * * *
19  fantasia.eurecom.fr (193.55.113.142)  132 ms  128 ms  136 ms
```

trans-oceanic link

* means no response (probe lost, router not replying)

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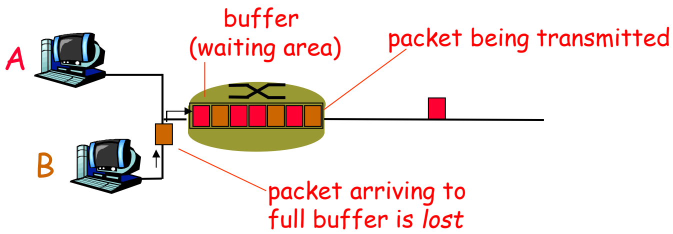
Packet Loss

- Queue (buffer) preceding link has finite capacity;
- Packet arriving to full queue is dropped (lost);
- Lost packet may be retransmitted:
  - By previous node, by source end system, or not at all.



See applet at AWL Web site:
https://media.pearsoncmg.com/aw/ecs_kurose_compnetwork_7/cw/content/interactiveanimations/queuing-loss-applet/index.html

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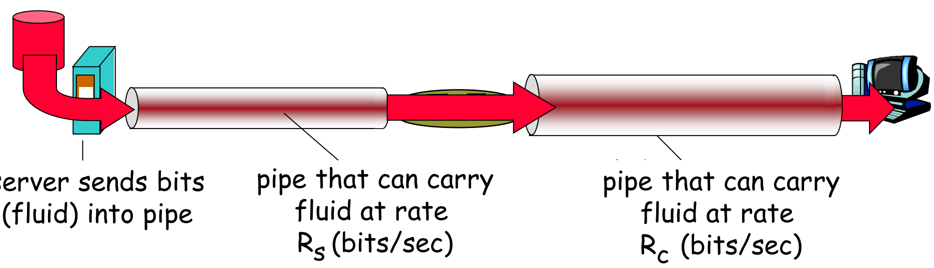
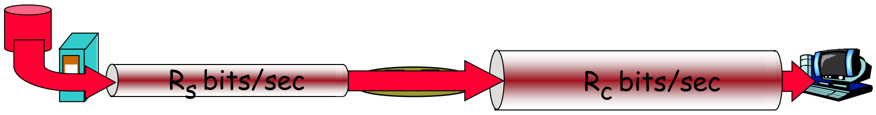
Throughput

- *Throughput:* rate (bits/time unit) at which bits are transferred between sender and receiver:
  - *Instantaneous:* rate at a given instant;
  - *Average:* rate over a longer period of time.



Throughput

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



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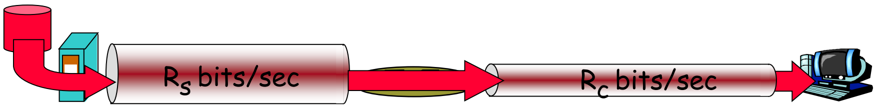
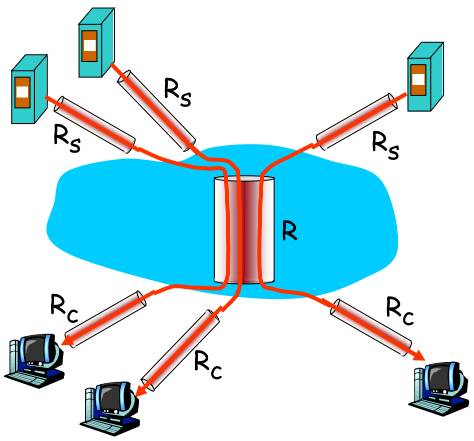


Bottleneck link:

the 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



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

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Objectives

- Terminology
- What is a protocol?
- Network edge (hosts, access net, physical media)
- Network core (circuit/packet switching, Internet structure)
- Performance metrics (Loss, Delay, Throughput)
- **Protocol layers and Service models**

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Protocol "Layers"

Networks are complex!

- Many "pieces":
  - hosts
  - routers
  - links of various media
  - applications
  - protocols
  - hardware, software

Question:

Is there any hope of *organizing* network structure?

Network Architecture: Needed Functionality

Functionality required:

- Mechanical specification of plugs, modulation type, ...
- Segmentation, reconstruction and delimitation of packets;
- Multiplexing/demultiplexing;
- Error and flow control;
- Routing;
- Congestion control;
- Data presentation formatting;
- Authentication;
- ...

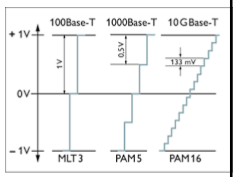

Figure 7. Voltage coding for Ethernet: Lower signal clearances for Gigabit Ethernet with PAM (Pulse Amplitude Modulation) increase the risk of disturbances when compared to Fast Ethernet with MLT (Multi Link Trunk).

Modular approach:

- Easier to design and to understand;
- Flexibility, possibility of module interface standardization.

Why Layering?

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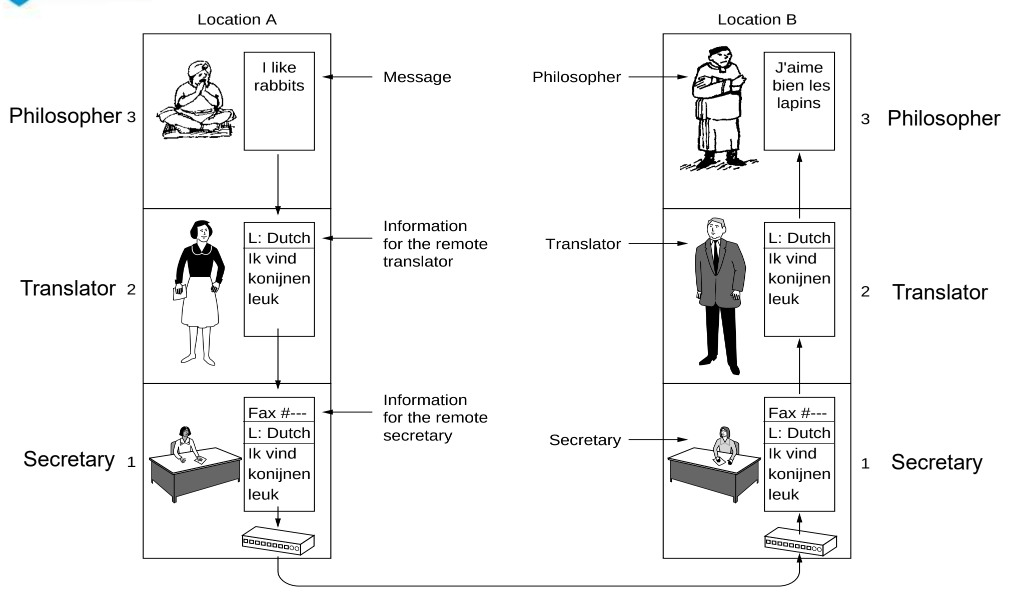
Dealing with complex systems:

- Explicit structure allows identification and perceiving the relationship of complex system's pieces:
  - Layered reference model for discussion;
- Modularization eases maintenance, updating of system:
  - Change of implementation of layer's service transparent to rest of system;
  - e.g., change in access network doesn't affect rest of system.
- Layering opposition:
  - Duplication of functions;
  - Violations of layer separation principle.

Layered Communication System



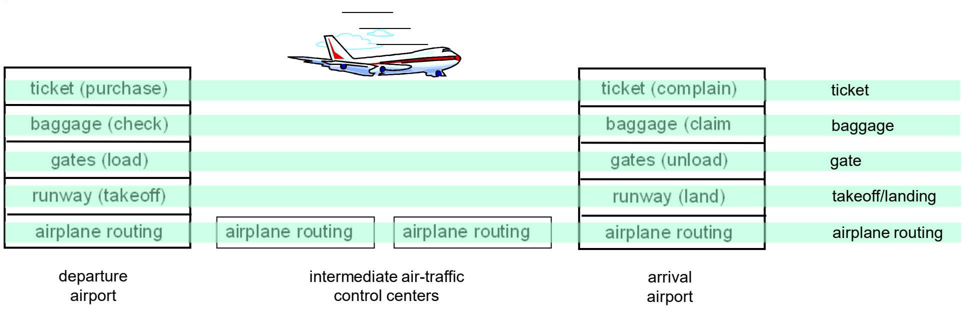
Organization of Air Travel

ticket (purchase)	ticket (complain)
baggage (check)	baggage (claim)
gates (load)	gates (unload)
runway takeoff	runway landing
airplane routing	airplane routing

airplane routing

- A series of steps

Layering of Airline Functionality



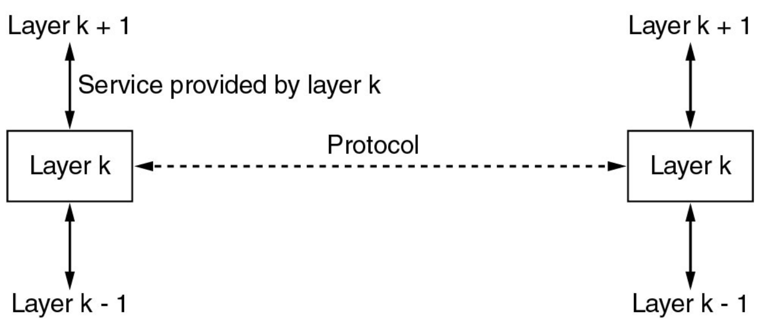
Layers – each layer implements a service:

- Via its own **internal-layer actions;**
- Relying on **services provided by layer below.**

Network Architecture

Protocol: set of rules to be followed between two peer entities, to ensure a successful data exchange;

Service: each layer offers a service to the layer above and uses the services made available by the layer below.



Network Architecture: Protocols

Peer entities of the same layer execute a distributed algorithm;

Protocols define the communication rules between peer entities:

- Format of the exchanged messages;
- Sequence to follow when sending and receiving messages;
- Actions to take when a message is sent or received;

Messages used by layer *n* protocol: ***n*-PDU** (*Protocol Data Unit*):

- Header;
- Payload;
- Trailer.

Network Architecture: Service Interface

A **service interface** specifies which services are offered by layer *n* to layer *n*+1;

Connection-oriented service:

- Session establishment;
- Message exchange;
- Session termination;

Connectionless service:

- No session establishment or termination.

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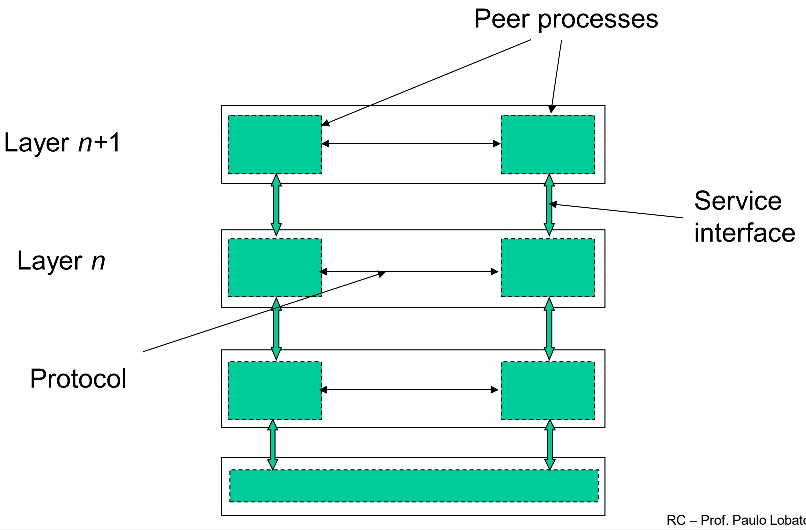
Network Architecture: Layered Architecture



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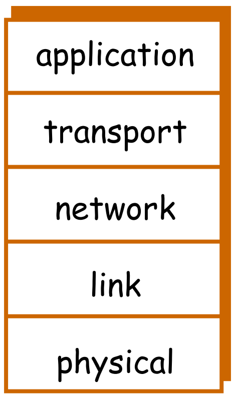
Internet Protocol Stack

- 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
  - PPP, Ethernet
- Physical: bits "on the wire"
  - RS-232c, V.92



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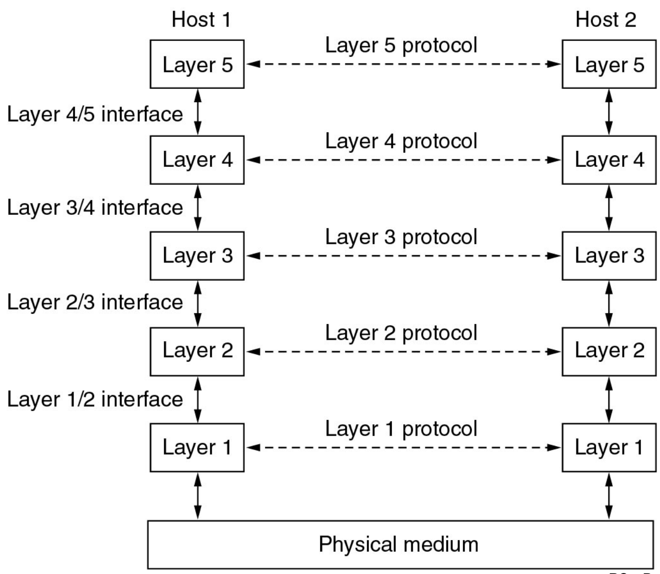
Network Architecture



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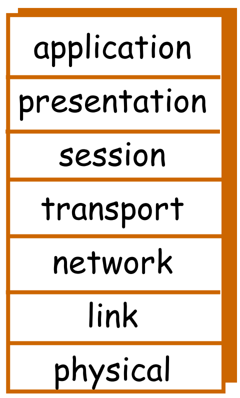
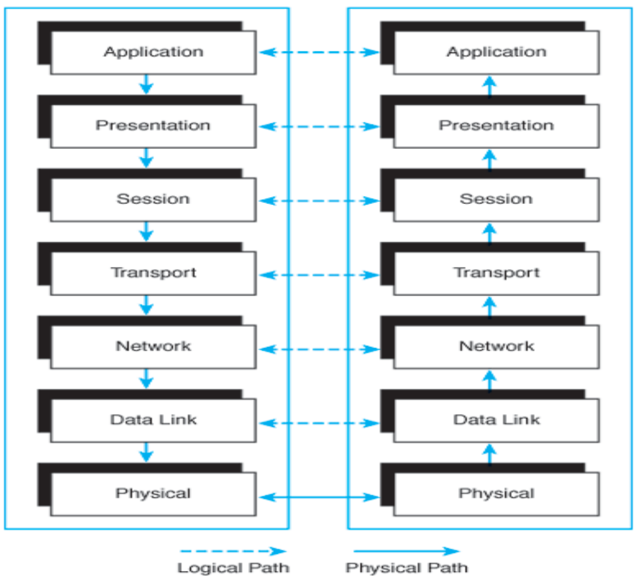
ISO/OSI Reference Model

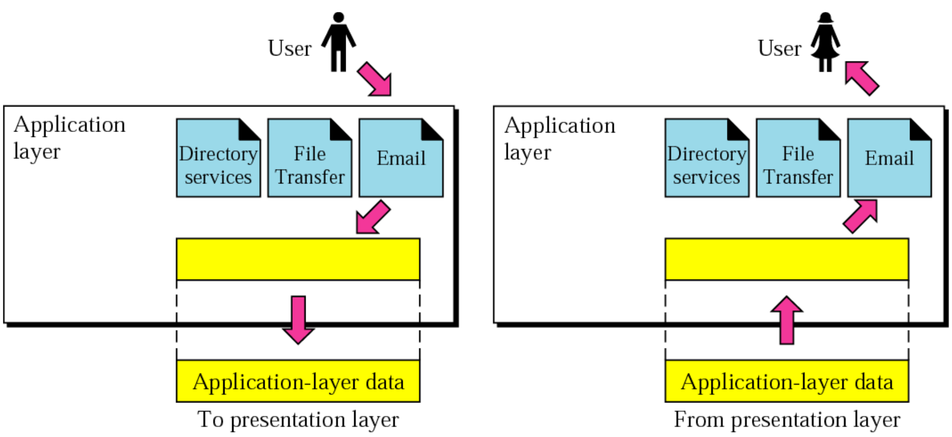
- Presentation: allow applications to interpret meaning of data, e.g., encryption, compression, machine-specific conventions;
- Session*:* synchronization, checkpoints, recovery of data exchange;
- Internet stack "missing" these layers!
  - These services, *if needed,* must be implemented in application;



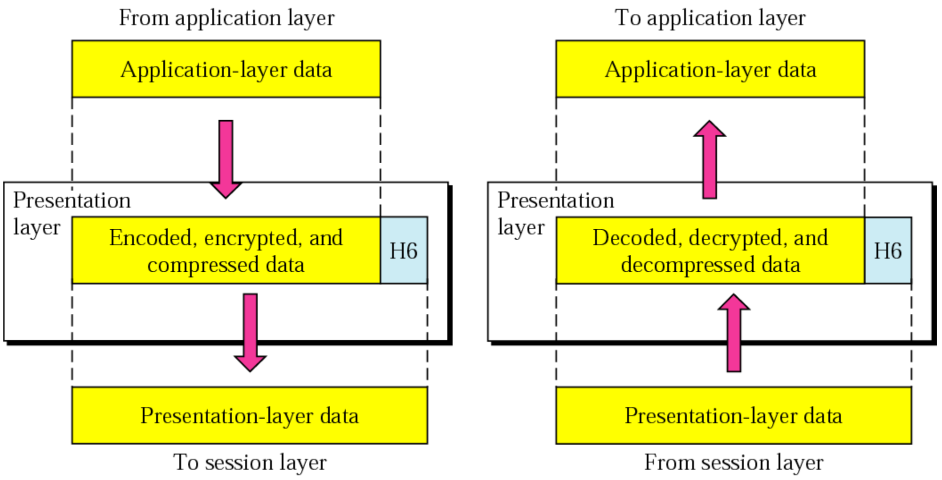
ISO/OSI Reference Model



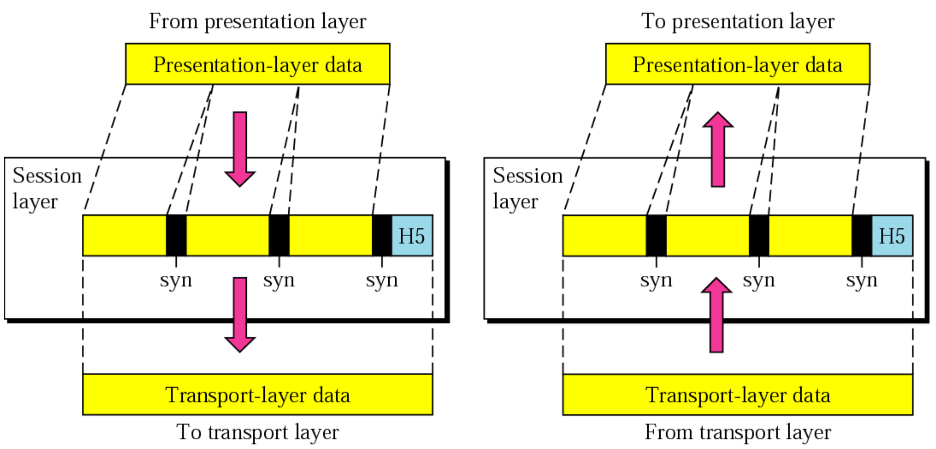
OSI Model: Application Layer



OSI Model: Presentation Layer



OSI Model: Session Layer



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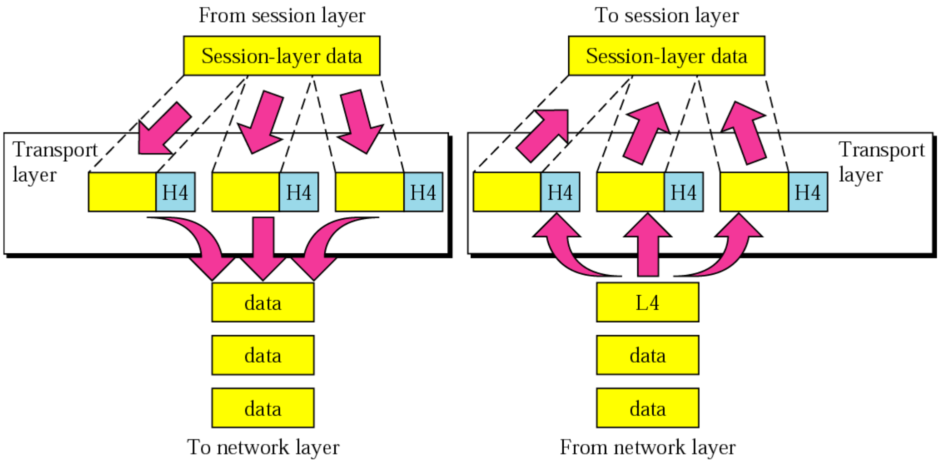
OSI Model: Transport Layer



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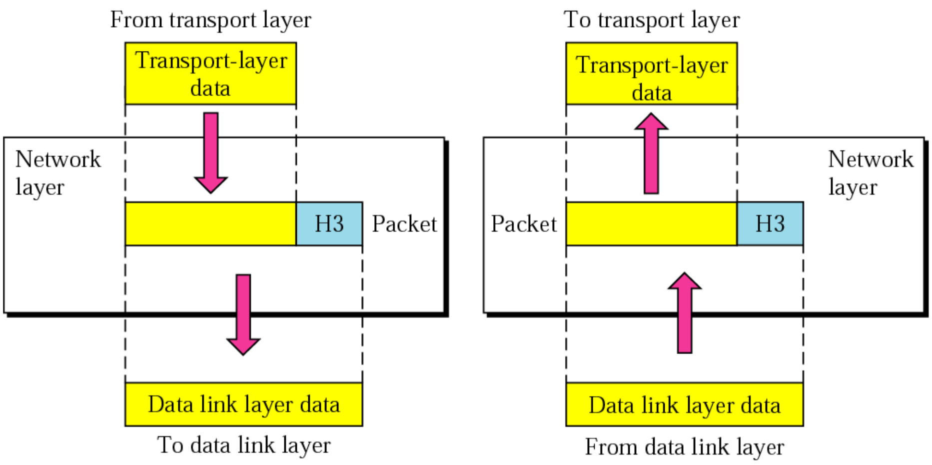
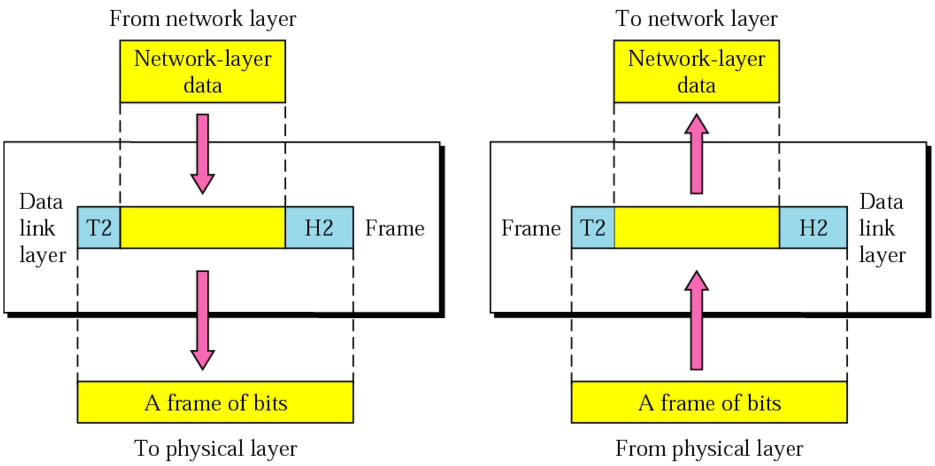
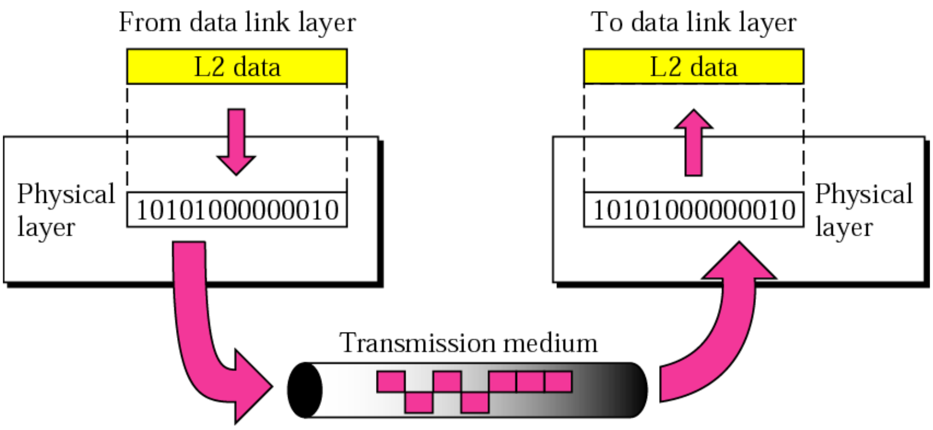
OSI Model: Network Layer



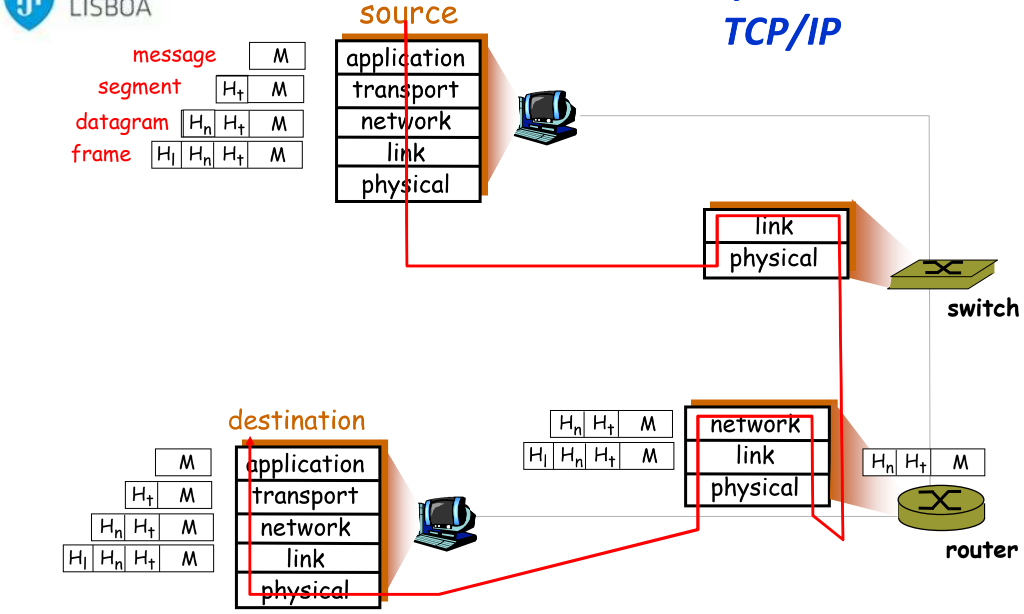
OSI Model: Data Link Layer



OSI Model: Physical Layer



Encapsulation: TCP/IP



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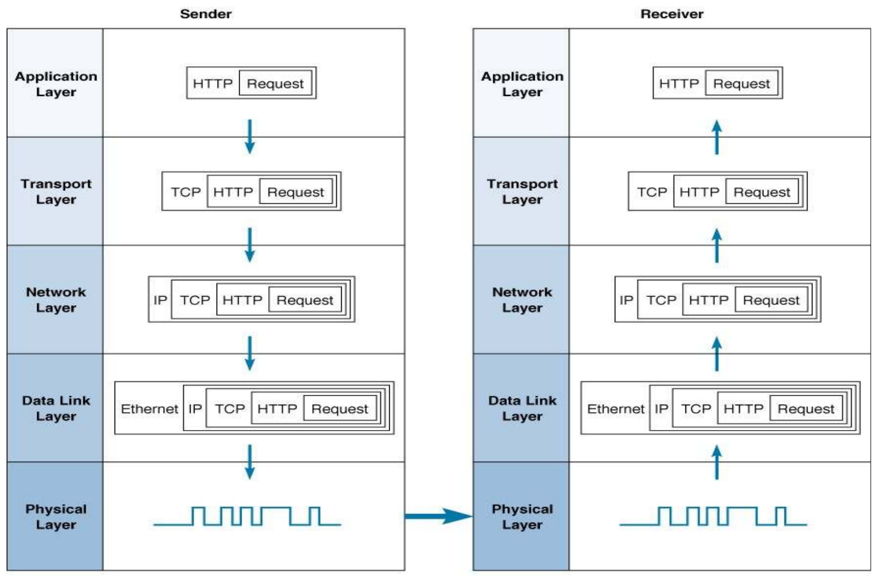
Encapsulation Example: HTTP



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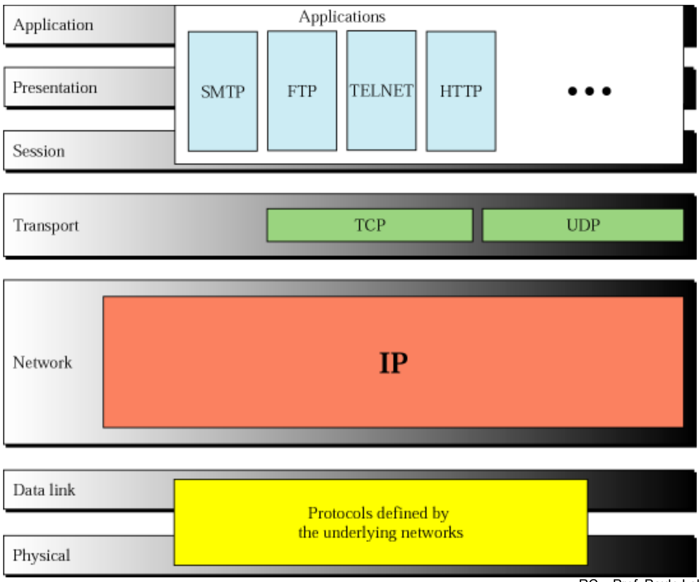
TCP/IP vs. OSI



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Introduction: Summary

Covered a lot of material!

- Internet overview;
- What's a protocol?
- Network edge, core, access network:
  - Packet-switching versus circuit-switching;
  - Internet structure;
- Performance: loss, delay, throughput;
- Layering, service models.

You now have:

- Context, overview, "feel" of networking;
- More detail *to follow!*