

Computer Networks

Unit - 1
(Data Communications)



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Topics

- Introduction to Computer Networks
- Packet Switching and Circuit Switching
- Network Topologies
- Reference Models: ISO/OSI Model and TCP/IP Model.

motivation

- The first thing that comes to our mind when someone talks about computer networks is the internet.
- But what internet actually is? and how it works?
- In this course, we will talk about the internal workings of internet.
- The actual definition of the internet can vary depending upon whom you are asking.

https://www.youtube.com/watch?v=Dxcc6ycZ73M&ab_channel=Code.org

what is internet?

- https://www.youtube.com/watch?v=Dxcc6ycZ73M&ab_channel=Code.org

Introduction

Chapter goal:

- Get “feel,” “big picture,” introduction to terminology
 - more depth, detail *later* in course

Overview/roadmap:

- What *is* the Internet? What *is* a protocol?
- Network edge: hosts, access network, physical media
- Network core: packet/circuit switching, internet structure
- Performance: loss, delay, throughput
- Protocol layers, service models
- Security
- History

Introduction: 1-5



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The Internet: a “nuts and bolts” view



Billions of connected computing *devices*:

- *hosts* = *end systems*
- running *network apps* at Internet's “edge”



Packet switches: forward packets (chunks of data)

- *routers, switches*



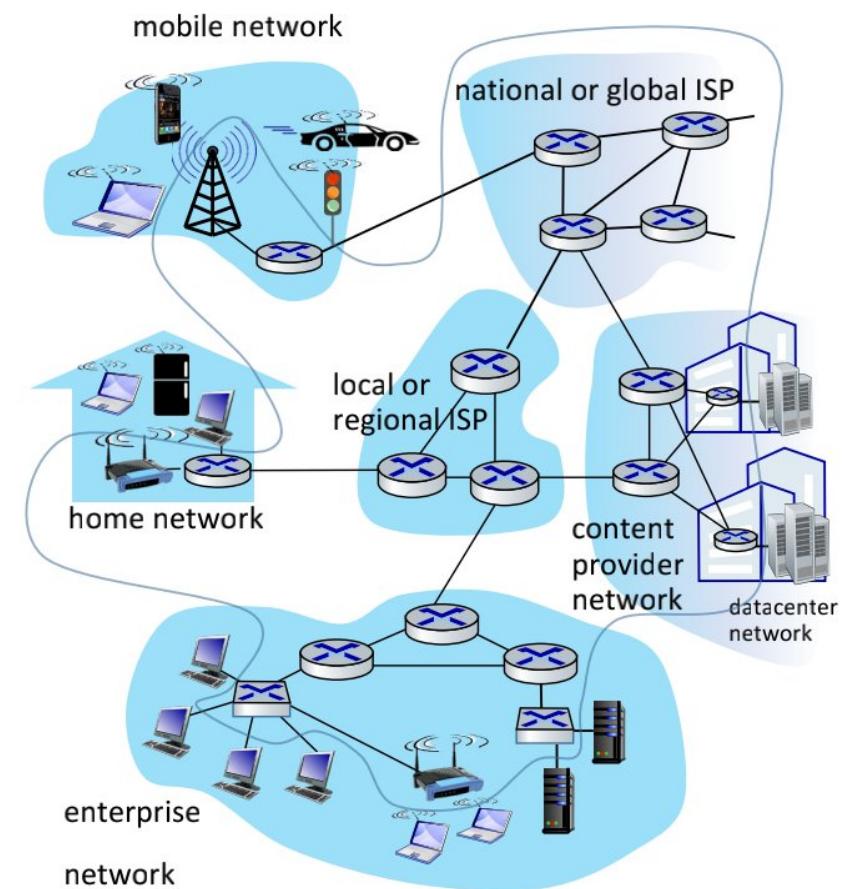
Communication links

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



Networks

- collection of devices, routers, links: managed by an organization



Introduction: 1-6

“Fun” Internet-connected devices



Amazon Echo



Internet refrigerator



Security Camera



Internet phones



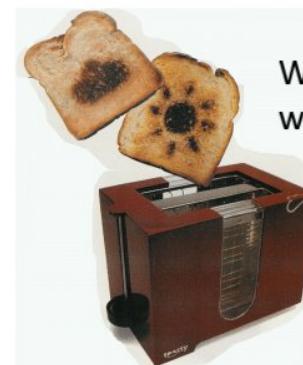
IP picture frame



Slingbox: remote control cable TV



Pacemaker & Monitor



Web-enabled toaster + weather forecaster



sensorized, bed mattress



Fitbit



diapers



Tweet-a-watt: monitor energy use

bikes



cars



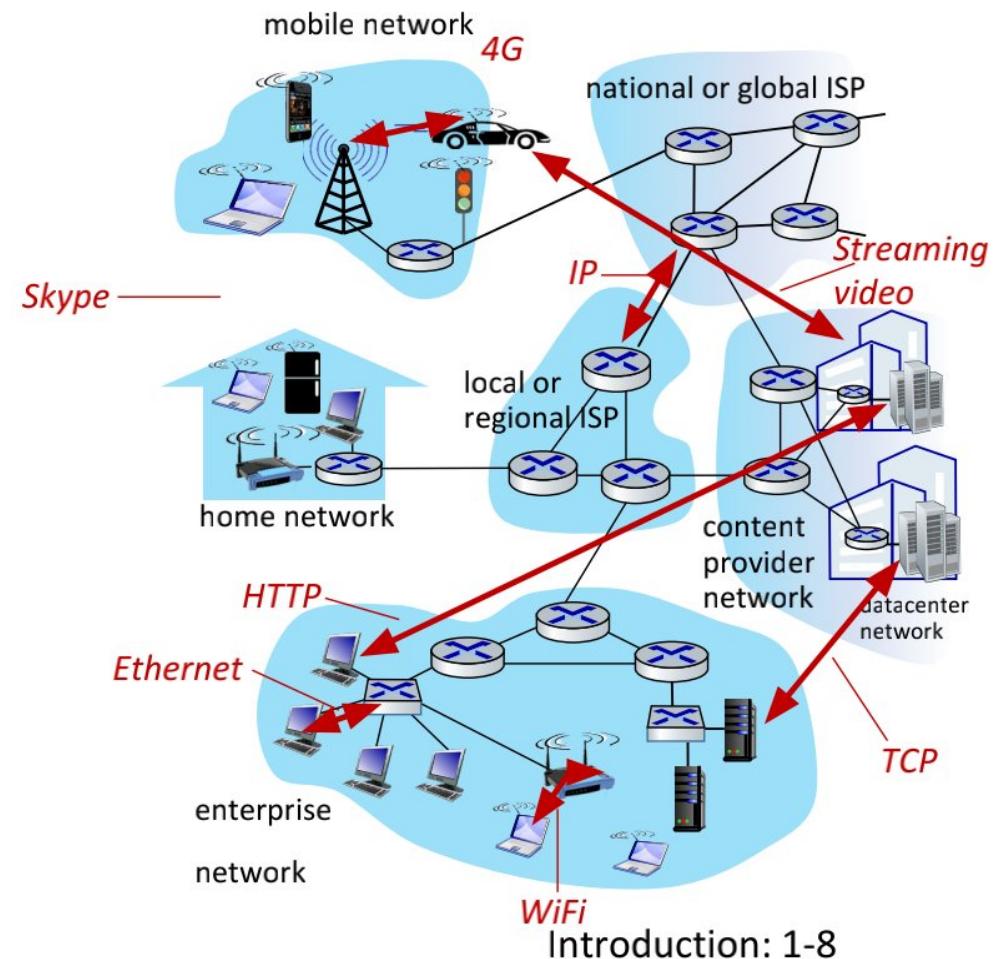
scooters

Others?

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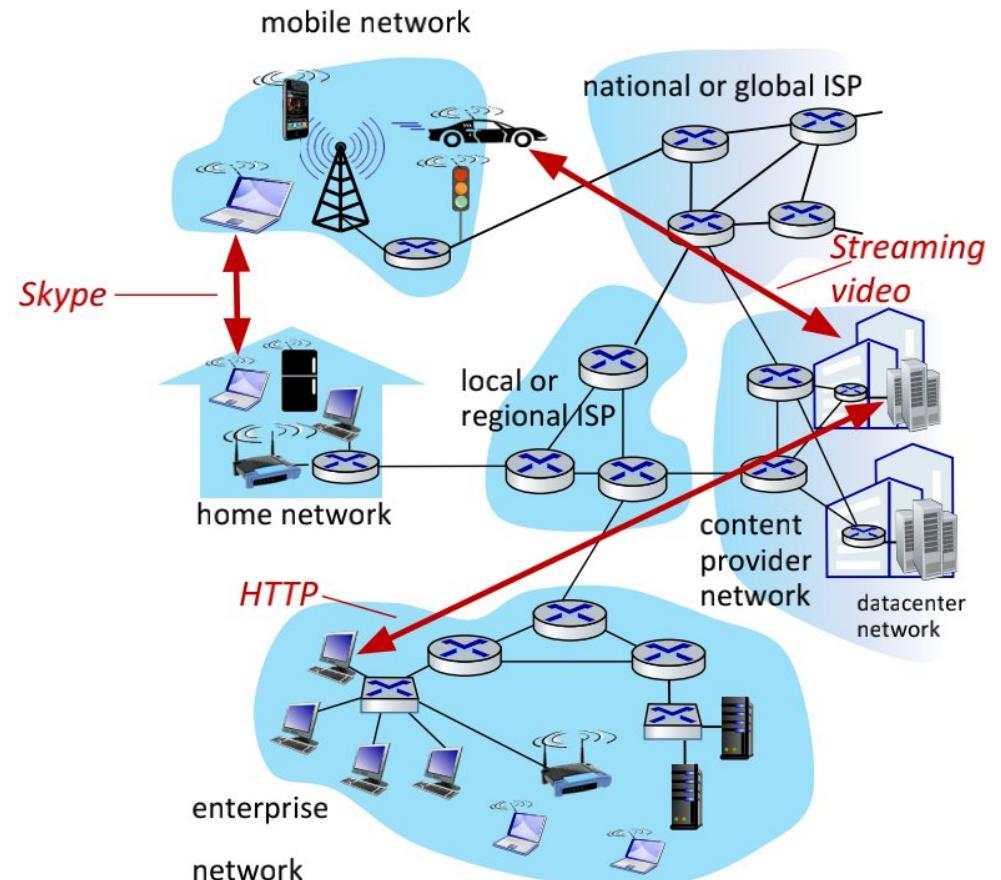
The Internet: a “nuts and bolts” view

- *Internet: “network of networks”*
 - Interconnected ISPs
- *protocols are everywhere*
 - control sending, receiving of messages
 - e.g., HTTP (Web), streaming video, Skype, TCP, IP, WiFi, 4/5G, Ethernet
- *Internet standards*
 - RFC: Request for Comments
 - IETF: Internet Engineering Task Force



The Internet: a “services” view

- *Infrastructure* that provides services to applications:
 - Web, streaming video, multimedia teleconferencing, email, games, e-commerce, social media, inter-connected appliances, ...
- provides *programming interface* to distributed applications:
 - “hooks” allowing sending/receiving apps to “connect” to, use Internet transport service
 - provides service options, analogous to postal service

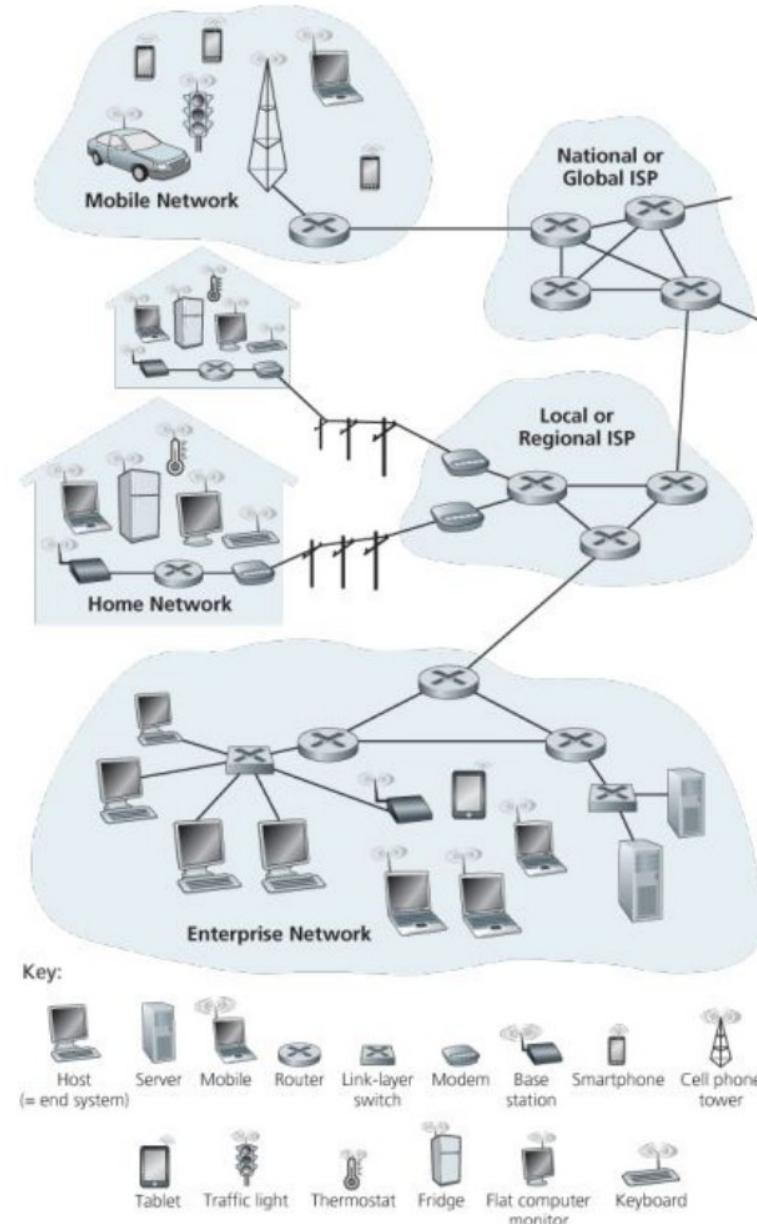


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what is a computer network?

- A computer network is the interconnection of a set of devices capable of communication.
- These devices can be either a **host** (also called **end system** sometimes) such as a large computer, desktop, laptop, workstation, cellular phone, TV, etc.
- Or devices can be **connecting device** such as a router which connects the network to other network, a switch which connects devices together, a modem (modulator-demodulator) that changes the form of data, and so on.
- These devices in a network are connected using wired or wireless transmission media such as ethernet, WiFi, etc.

a computer network



types of computer networks

- Depending upon size and connection range, networks can be devided into several categories -
 - Personal Area Network (PAN)
 - Local Area Network (LAN)
 - Campus Area Network (CAN)
 - Metropolitan Area Network (MAN)
 - Wide Area Network (WAN)
 - Point-to-Point WAN
 - Switched WAN

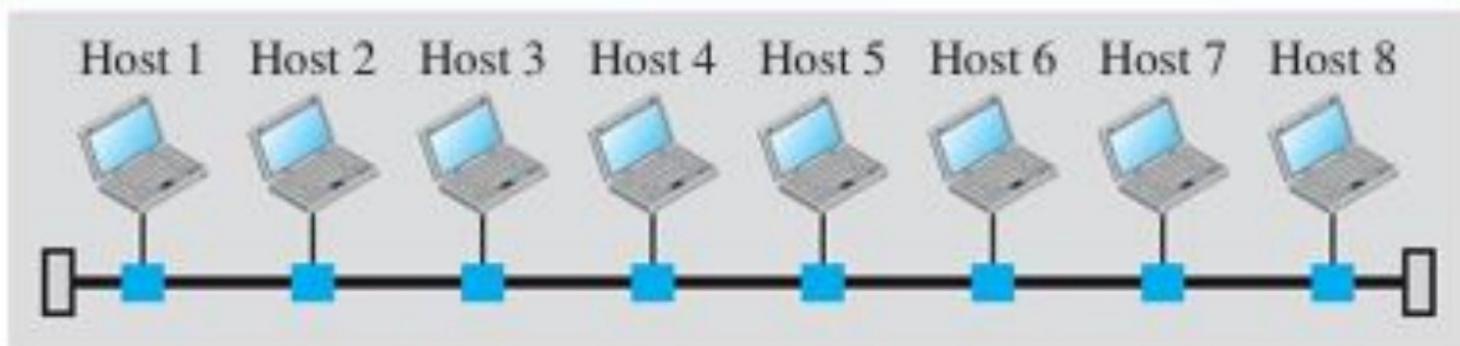
Types of networks

- **Personal Area Network (PAN)**

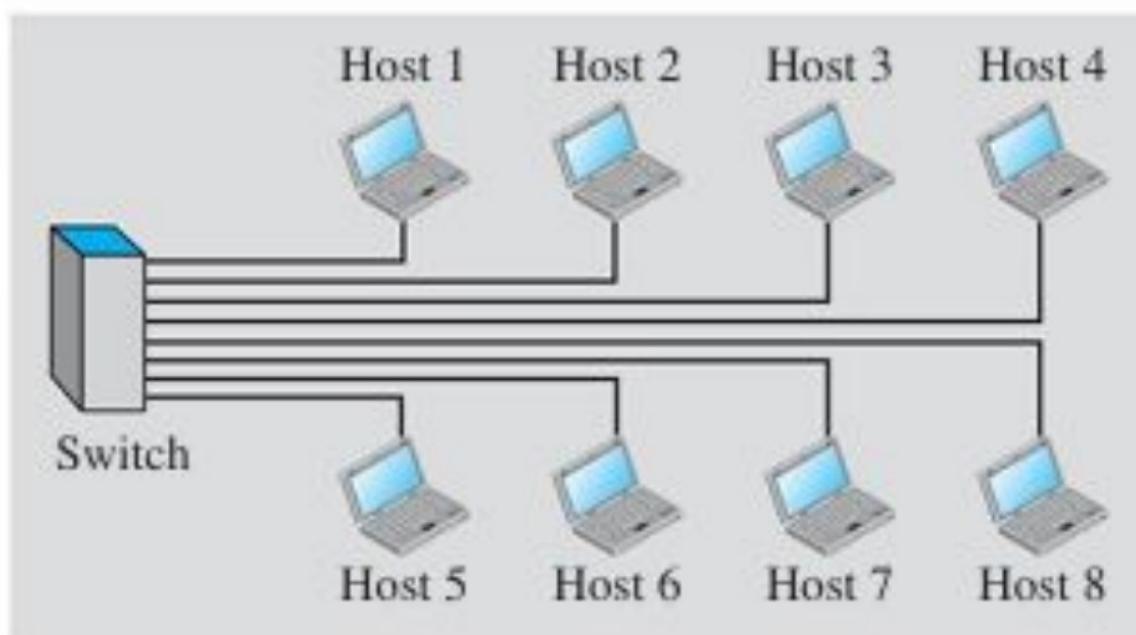
- A PAN is the smallest type of network, covering a very limited area, typically within the range of an individual person.
- Range - Up to 10 meters
- Devices - Smartphones, laptops, tablets, headphones, etc.
- It uses Bluetooth and USB for connections.

- **Local Area Network (LAN)**

- A LAN covers a small geographic area such as a single building, office, or home. It is used to connect computers and devices within close proximity.
- Range - Up to a few kilometers.
- Devices - Computers, servers, printers, etc.

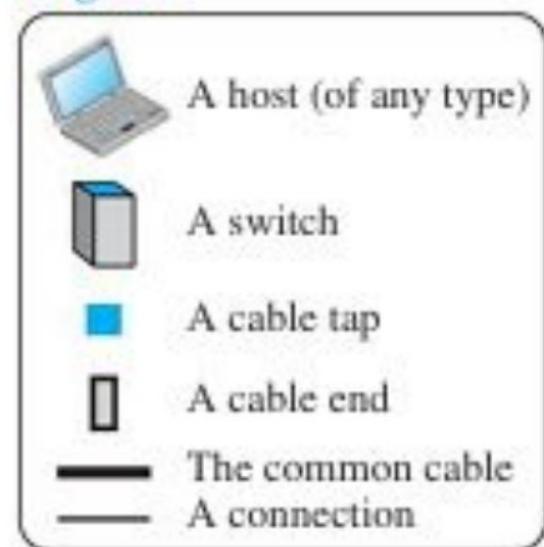


a. LAN with a common cable (past)



b. LAN with a switch (today)

Legend



types of networks

- **Metropolitan Area Network (MAN)**

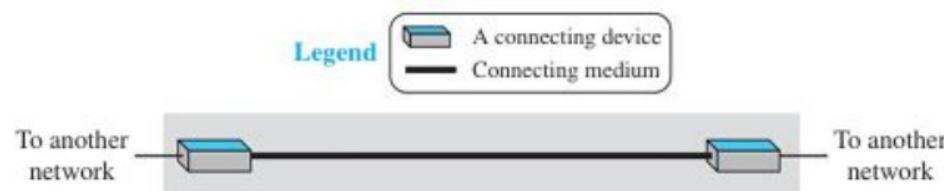
- A MAN covers a large geographic area than a LAN, typically spanning a city or a large campus. It connects multiple LANs within a specific region.
- Range - Up to 50 kilometers.
- Devices - Network infrastructure such as routers, switches, etc.

- **Wide Area Network (WAN)**

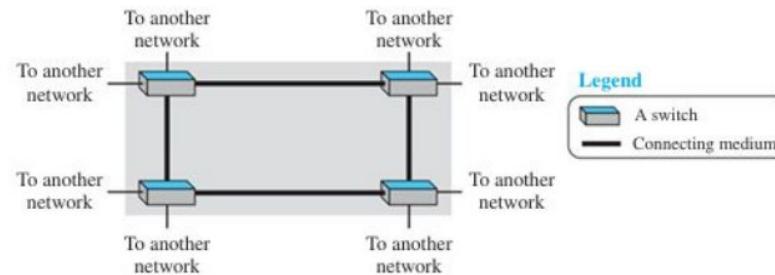
- A WAN covers a broad area, often a country or continent. It connects multiple LANs and MANs.
- Range - Thousands of kilometers.

wide area network

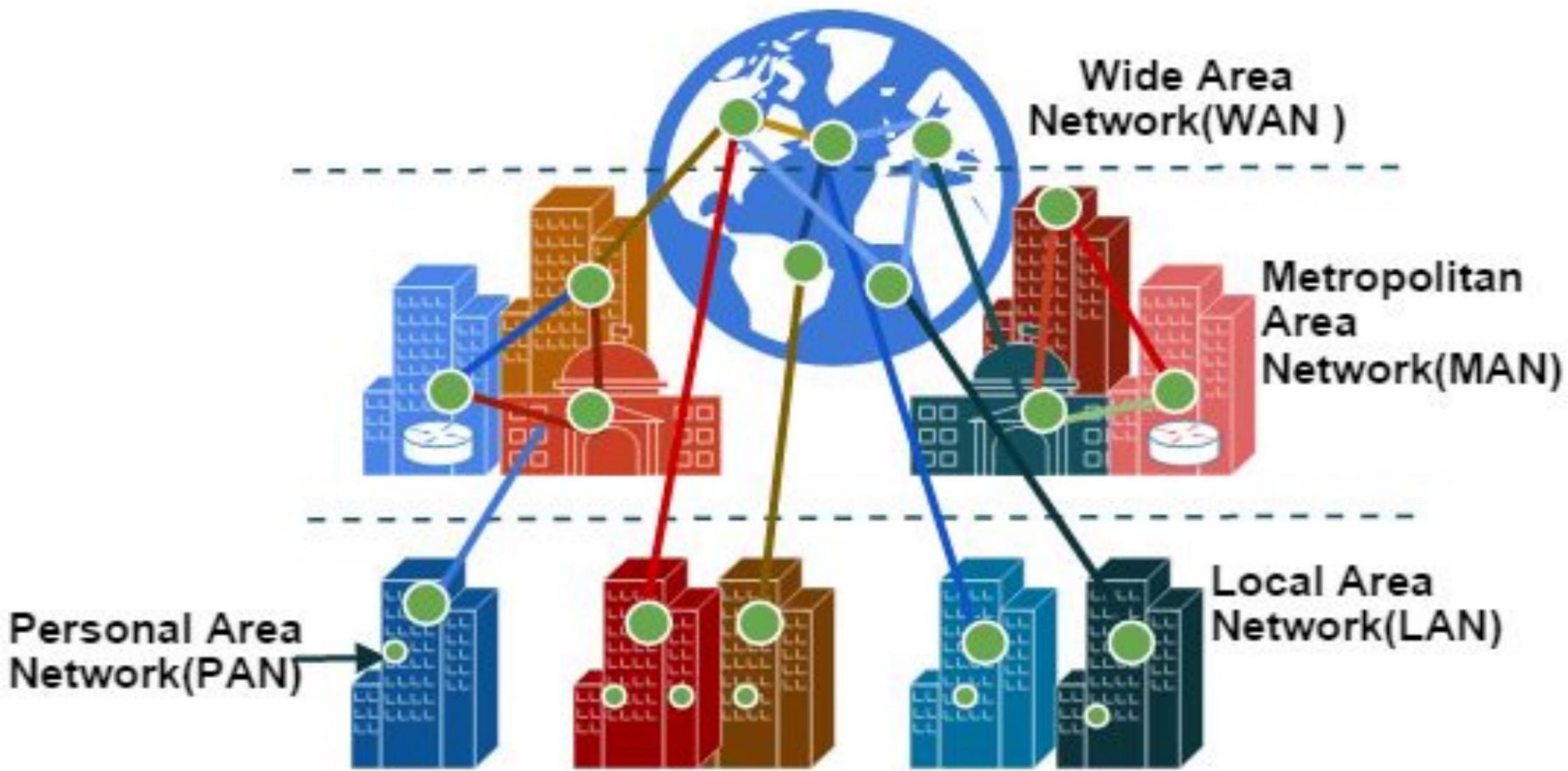
- **Point-to-Point WAN:** A point-to-point WAN is a network that connects two communicating devices through a transmission media (cable or air).



- **Switched WAN:** a type of WAN that connects multiple end nodes (devices) by using a mesh of point-to-point connections

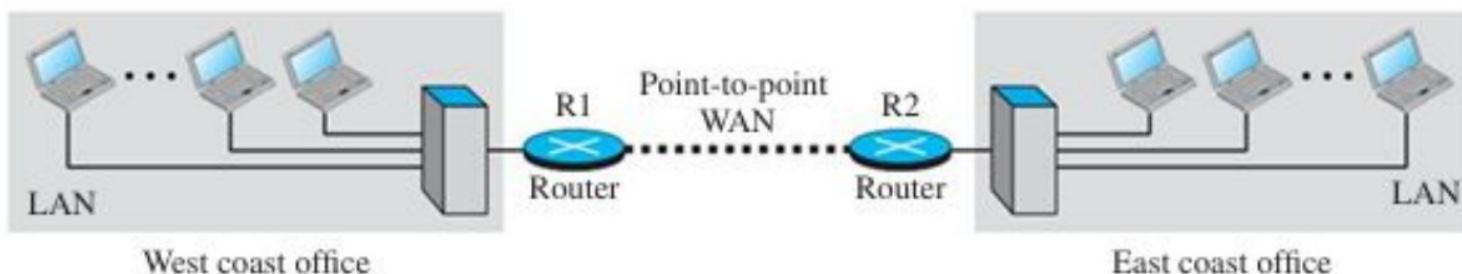


Types of Computer Networks

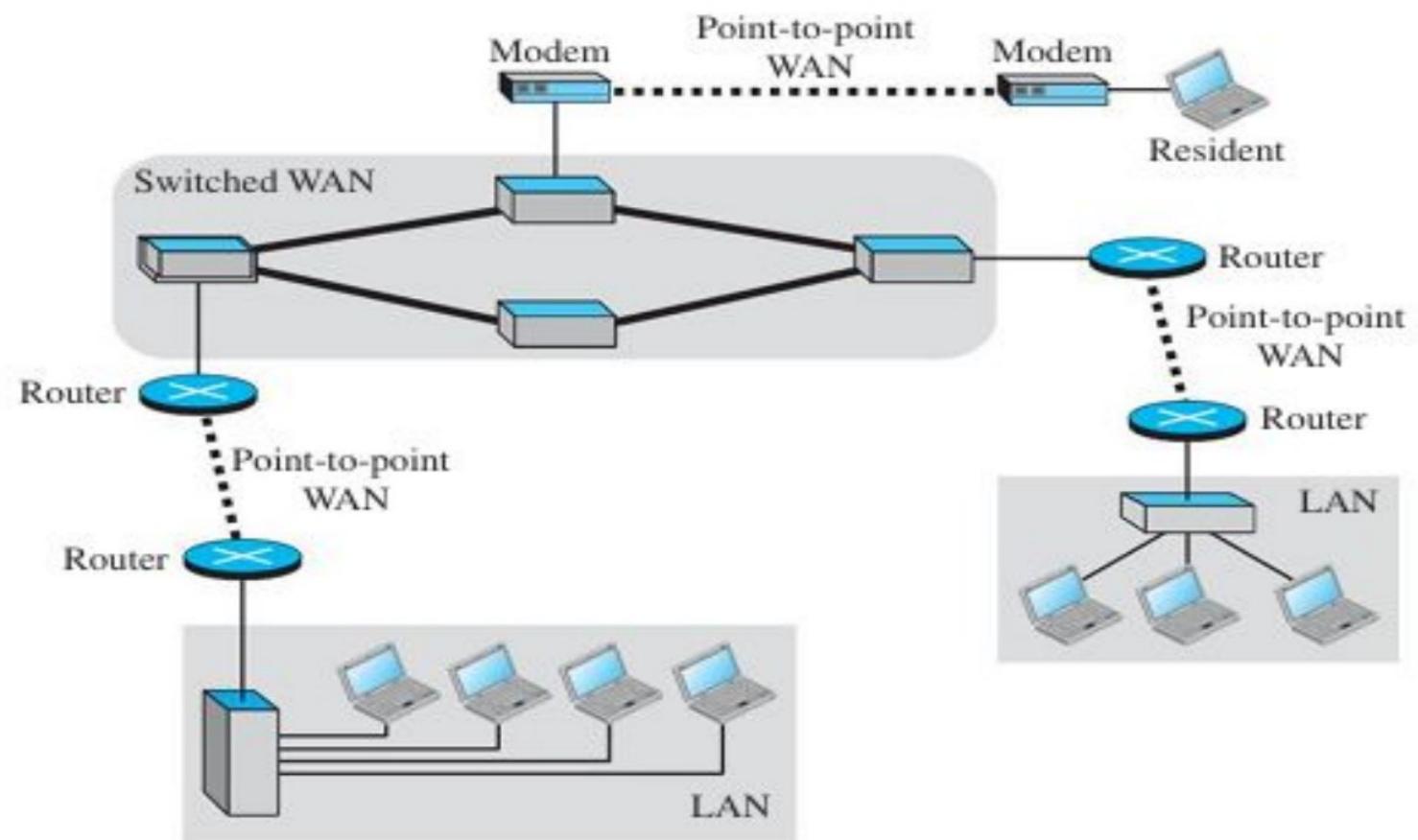


inter-network

- Today, it is very rare to see a LAN or a WAN in isolation; they are connected to one another. When two or more networks are connected, they make an *internetwork*, or **internet**.
- As an example, assume that an organization has two offices, one on the east coast and the other on the west coast. Each office has a LAN that allows all employees in the office to communicate with each other. To make the communication between employees at different offices possible, the management leases a point-to-point dedicated WAN from a service provider, such as a telephone company, and connects the two LANs. Now the company has an internetwork, or a private internet (with lowercase i).



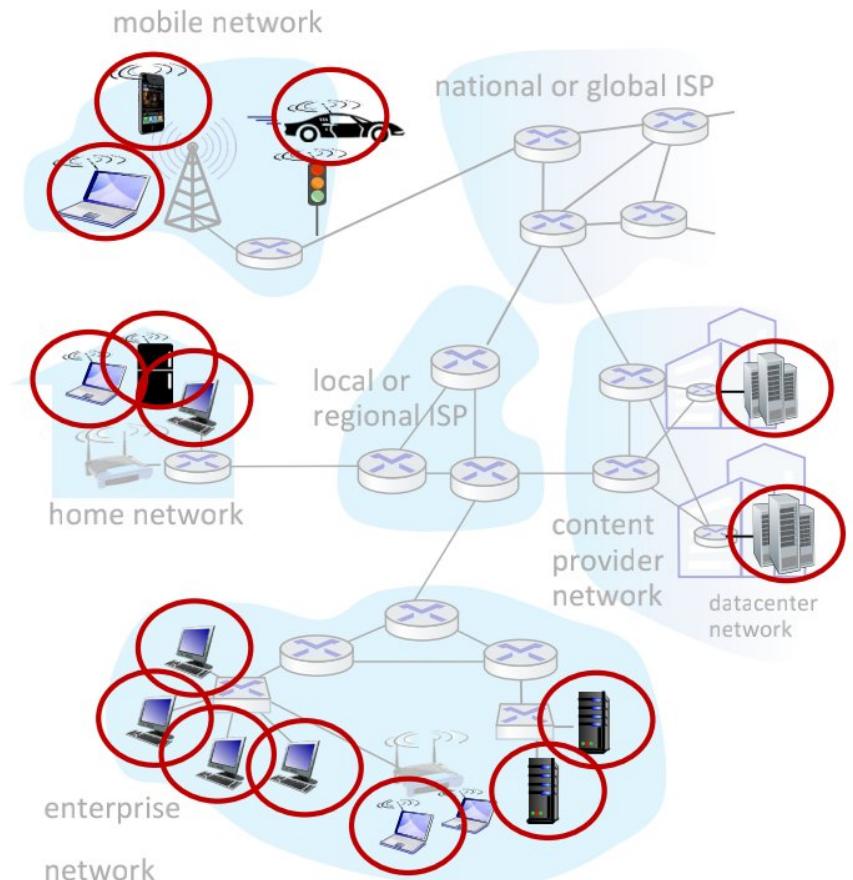
inter-network



A closer look at Internet structure

Network edge:

- hosts: clients and servers
- servers often in data centers



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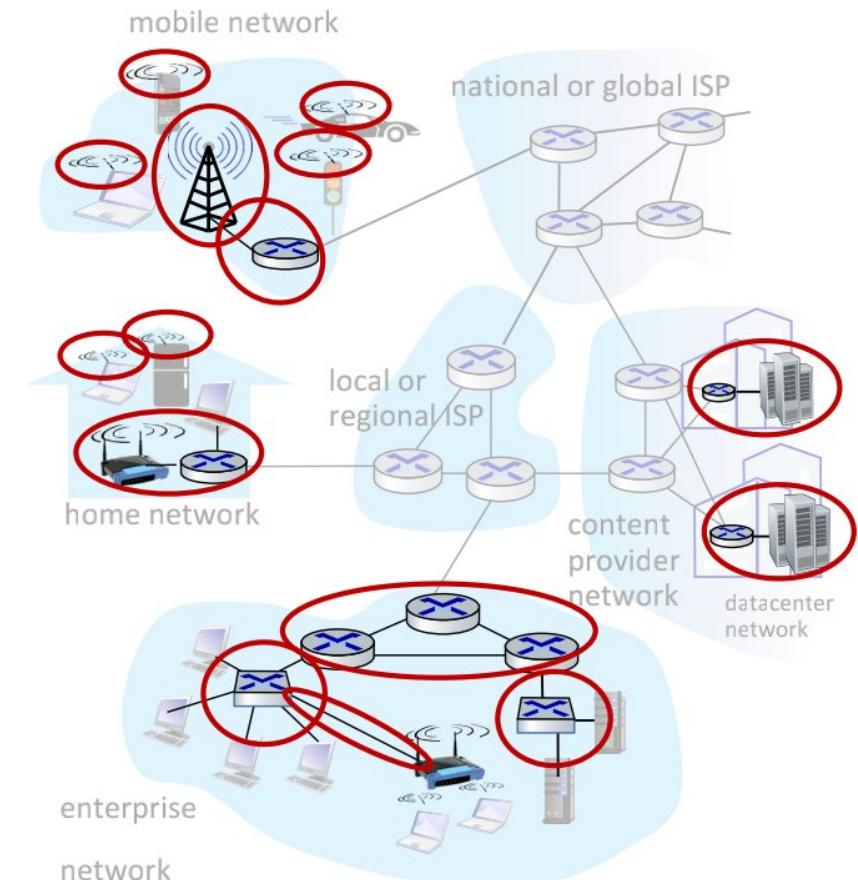
A closer look at Internet structure

Network edge:

- hosts: clients and servers
- servers often in data centers

Access networks, physical media:

- wired, wireless communication links



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A closer look at Internet structure

Network edge:

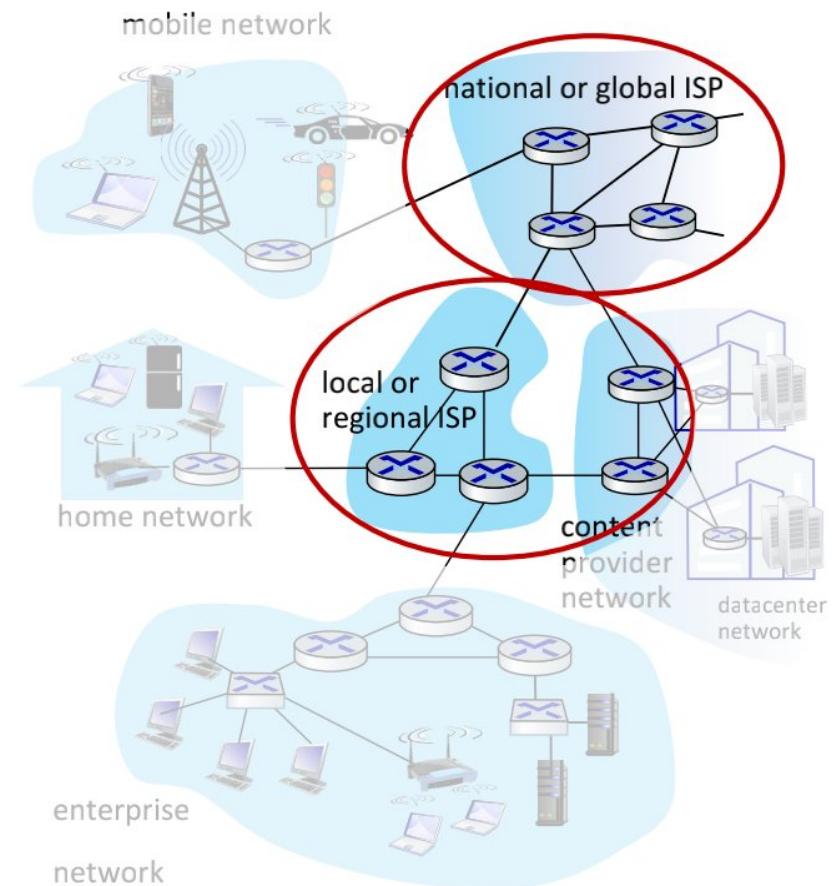
- hosts: clients and servers
- servers often in data centers

Access networks, physical media:

- wired, wireless communication links

Network core:

- interconnected routers
- network of networks

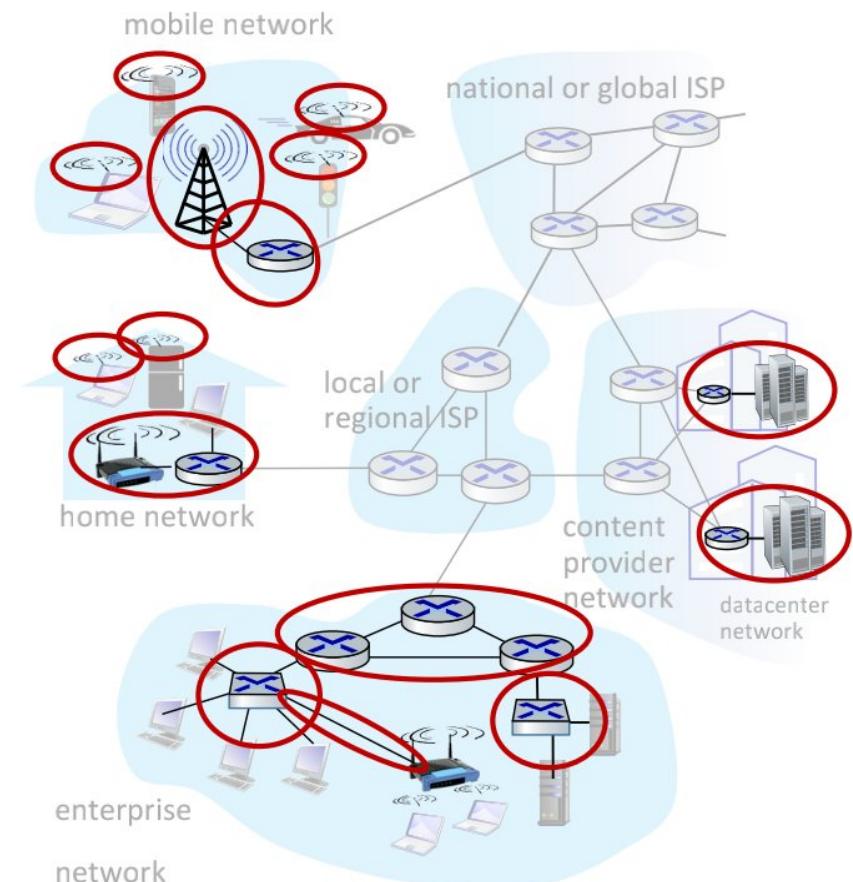


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Access networks and physical media

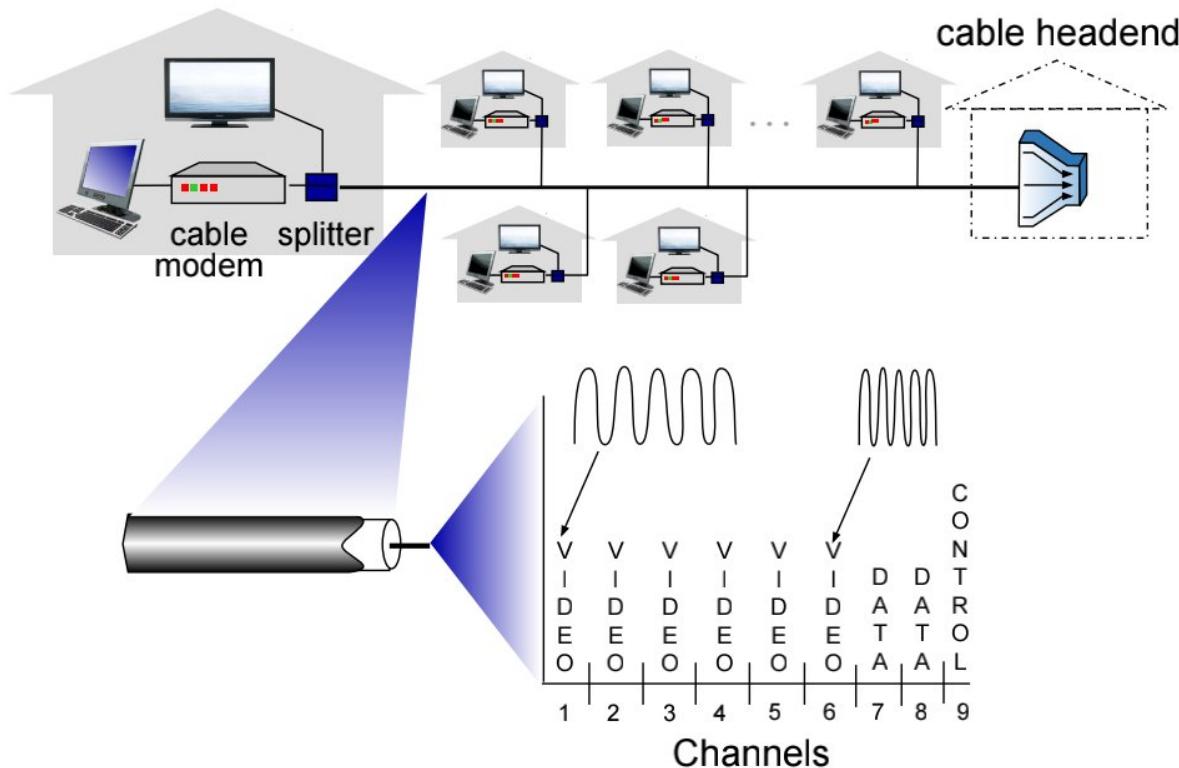
Q: How to connect end systems to edge router?

- residential access nets
- institutional access networks (school, company)
- mobile access networks (WiFi, 4G/5G)



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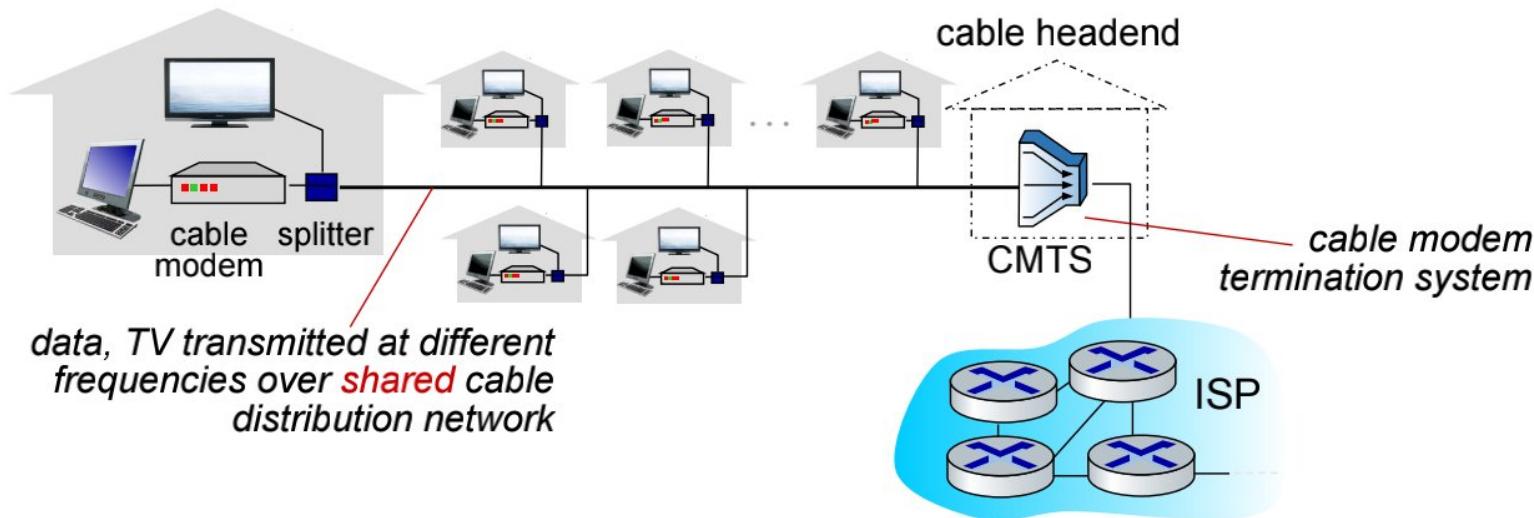
Access networks: cable-based access



frequency division multiplexing (FDM): different channels transmitted in different frequency bands

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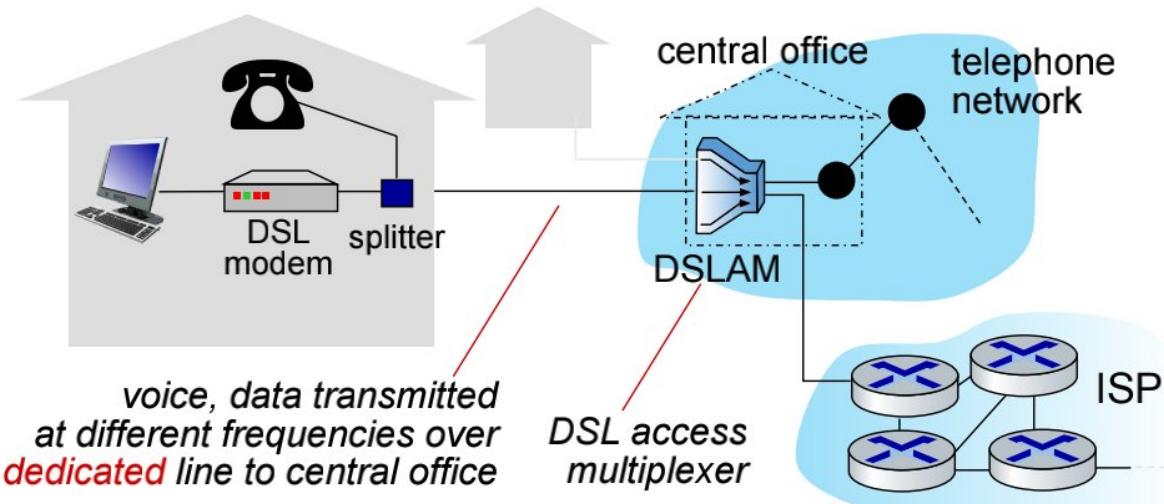
Access networks: cable-based access



- **HFC: hybrid fiber coax**
 - asymmetric: up to 40 Mbps – 1.2 Gbps downstream transmission rate, 30-100 Mbps upstream transmission rate
- **network** of cable, fiber attaches homes to ISP router
 - homes **share access network** to cable headend

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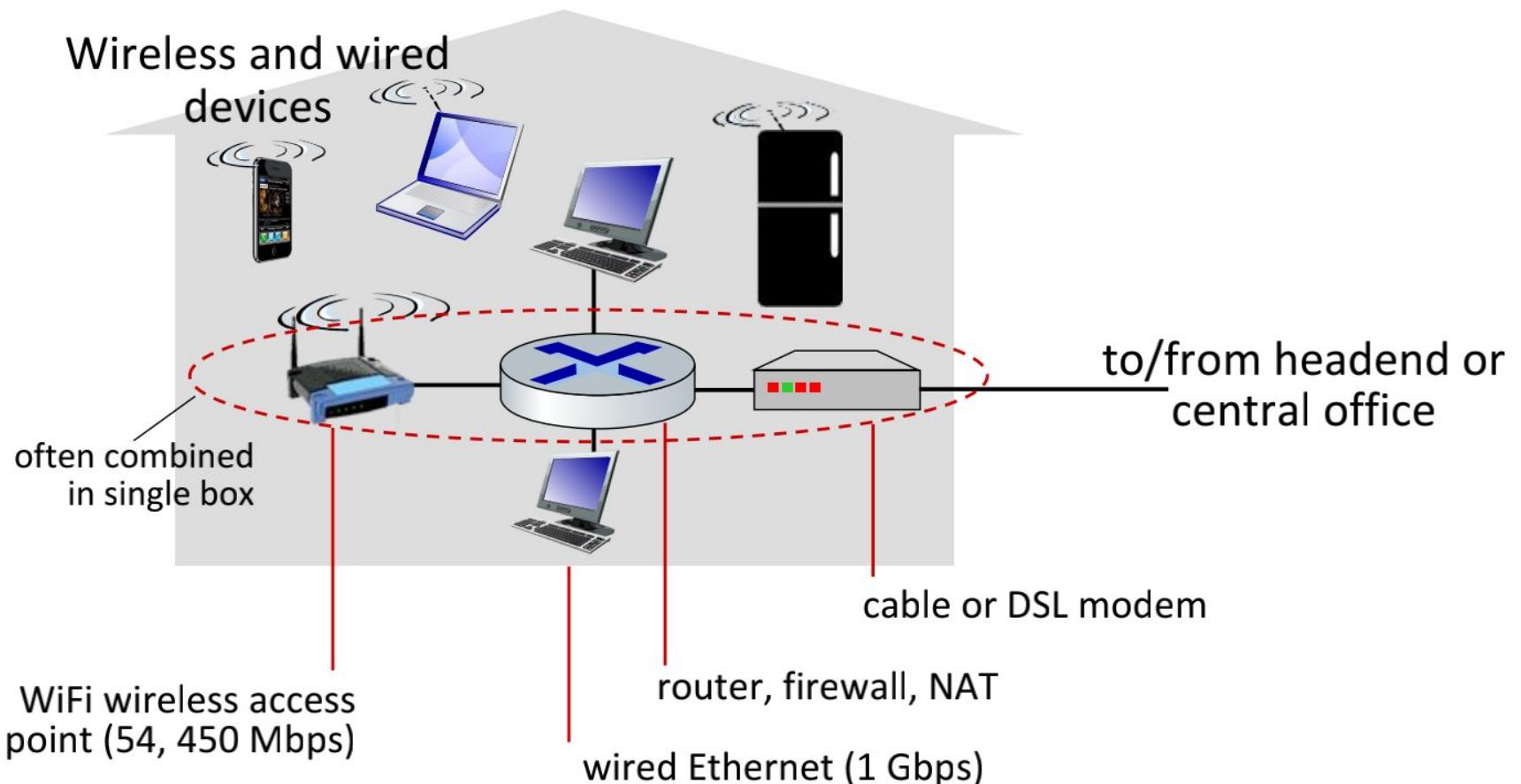
Access networks: digital subscriber line (DSL)



- use *existing* telephone line to central office DSLAM
 - data over DSL phone line goes to Internet
 - voice over DSL phone line goes to telephone net
- 24-52 Mbps dedicated downstream transmission rate
- 3.5-16 Mbps dedicated upstream transmission rate

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Access networks: home networks



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Wireless access networks

Shared *wireless* access network connects end system to router

- via base station aka “access point”

Wireless local area networks (WLANs)

- typically within or around building (~100 ft)
- 802.11b/g/n (WiFi): 11, 54, 450 Mbps transmission rate



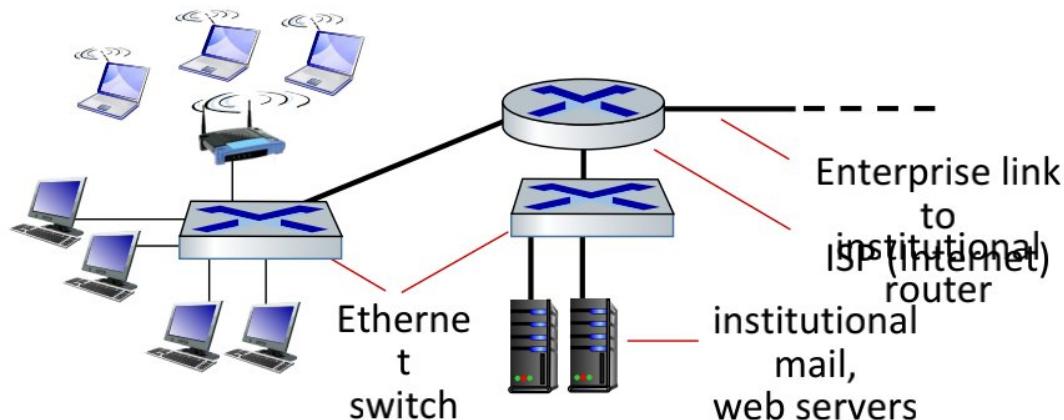
Wide-area cellular access networks

- provided by mobile, cellular network operator (10's km)
- 10's Mbps
- 4G/5G cellular networks



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Access networks: enterprise networks



- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
 - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
 - WiFi: wireless access points at 11, 54, 450 Mbps

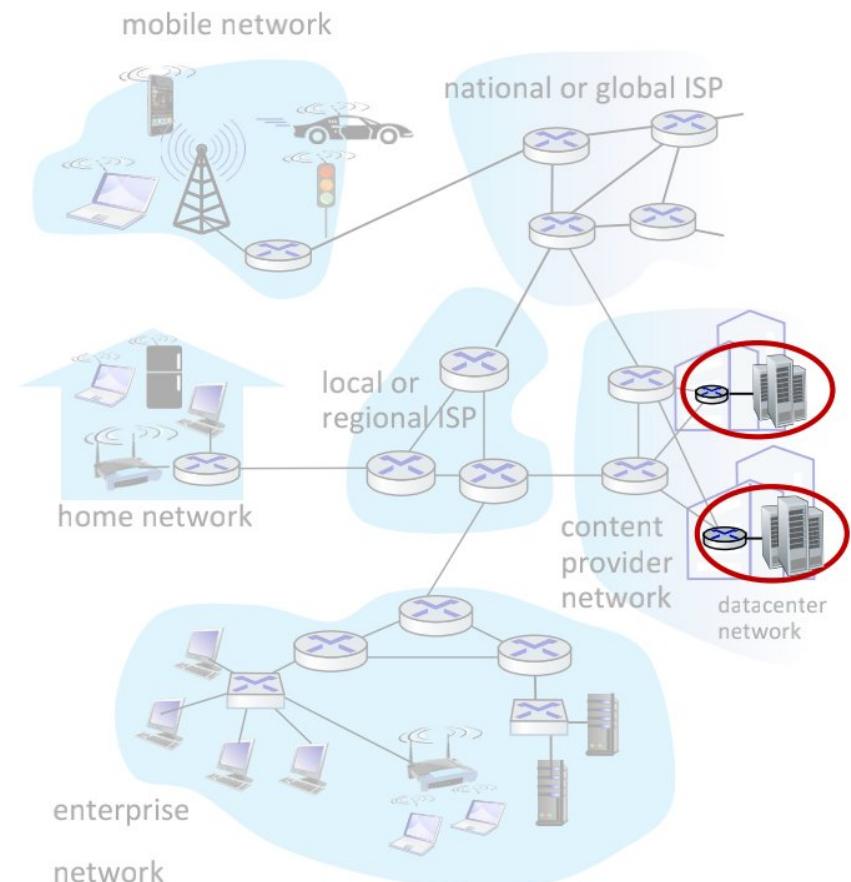
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Access networks: data center networks

- 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)

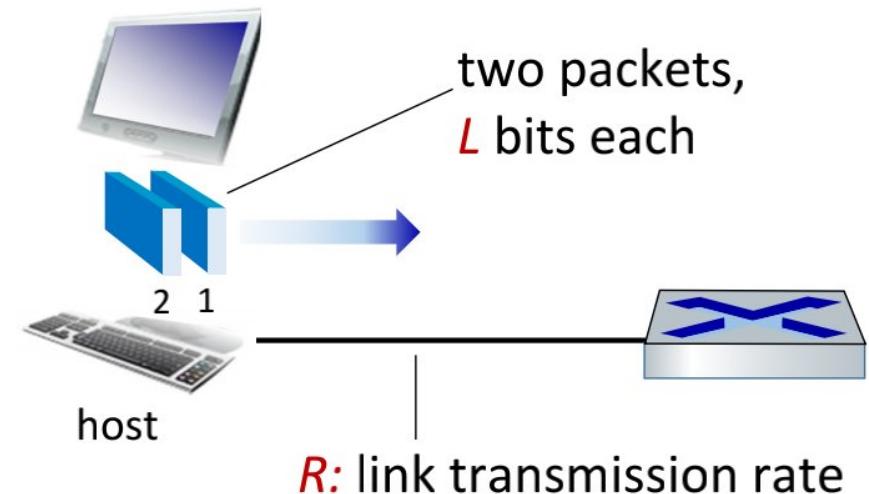


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Host: sends *packets* of data

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*



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

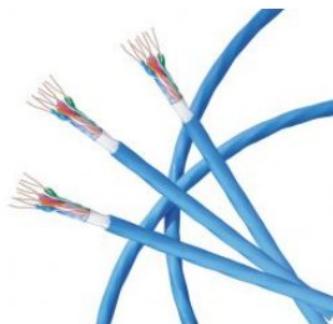
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Links: physical media

- **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

Twisted pair (TP)

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



Introduction: 1-32

Links: physical media

Coaxial cable:

- two concentric copper conductors
- bidirectional
- broadband:
 - multiple frequency channels on cable
 - 100's Mbps per channel



Fiber optic cable:

- glass fiber carrying light pulses, each pulse a bit
- high-speed operation:
 - high-speed point-to-point transmission (10's-100's Gbps)
- low error rate:
 - repeaters spaced far apart
 - immune to electromagnetic noise



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Links: physical media

Wireless radio

- signal carried in various “bands” in electromagnetic spectrum
- no physical “wire”
- broadcast, “half-duplex” (sender to receiver)
- propagation environment effects:
 - reflection
 - obstruction by objects
 - Interference/noise

Radio link types:

- **Wireless LAN (WiFi)**
 - 10-100's Mbps; 10's of meters
- **wide-area** (e.g., 4G/5G cellular)
 - 10's Mbps (4G) over ~10 Km
- **Bluetooth**: cable replacement
 - short distances, limited rates
- **terrestrial microwave**
 - point-to-point; 45 Mbps channels
- **satellite**
 - up to < 100 Mbps (Starlink) downlink
 - 270 msec end-end delay (geostationary)

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protocols & layered architecture of internet

Introduction: 1-35



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protocols

- As we have discussed that internet is a complex network containing many hosts, routers, transmission links, etc. So how is this complex structure is managed or operates?
- The answer is Protocols. A protocol defines the rules that both sender and receiver and all intermediate devices need to follow to be able to communicate effectively.
- To reduce the complexity, the internet architecture is divided into protocol layers, where each layer serve a different purpose in the communication between two end-systems in the internet.

Example: organization of air travel



end-to-end transfer of person plus baggage

ticket (purchase)

baggage (check)

gates (load)

runway takeoff

airplane routing

ticket (complain)

baggage (claim)

gates (unload)

runway landing

airplane routing

airplane routing

How would you *define/discuss* the system of airline travel?

- a series of steps, involving many services

Introduction: 1-37

Example: organization of air travel



layers: each layer implements a service

- via its own internal-layer actions
- relying on services provided by layer below

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Why layering?

Approach to designing/discussing complex systems:

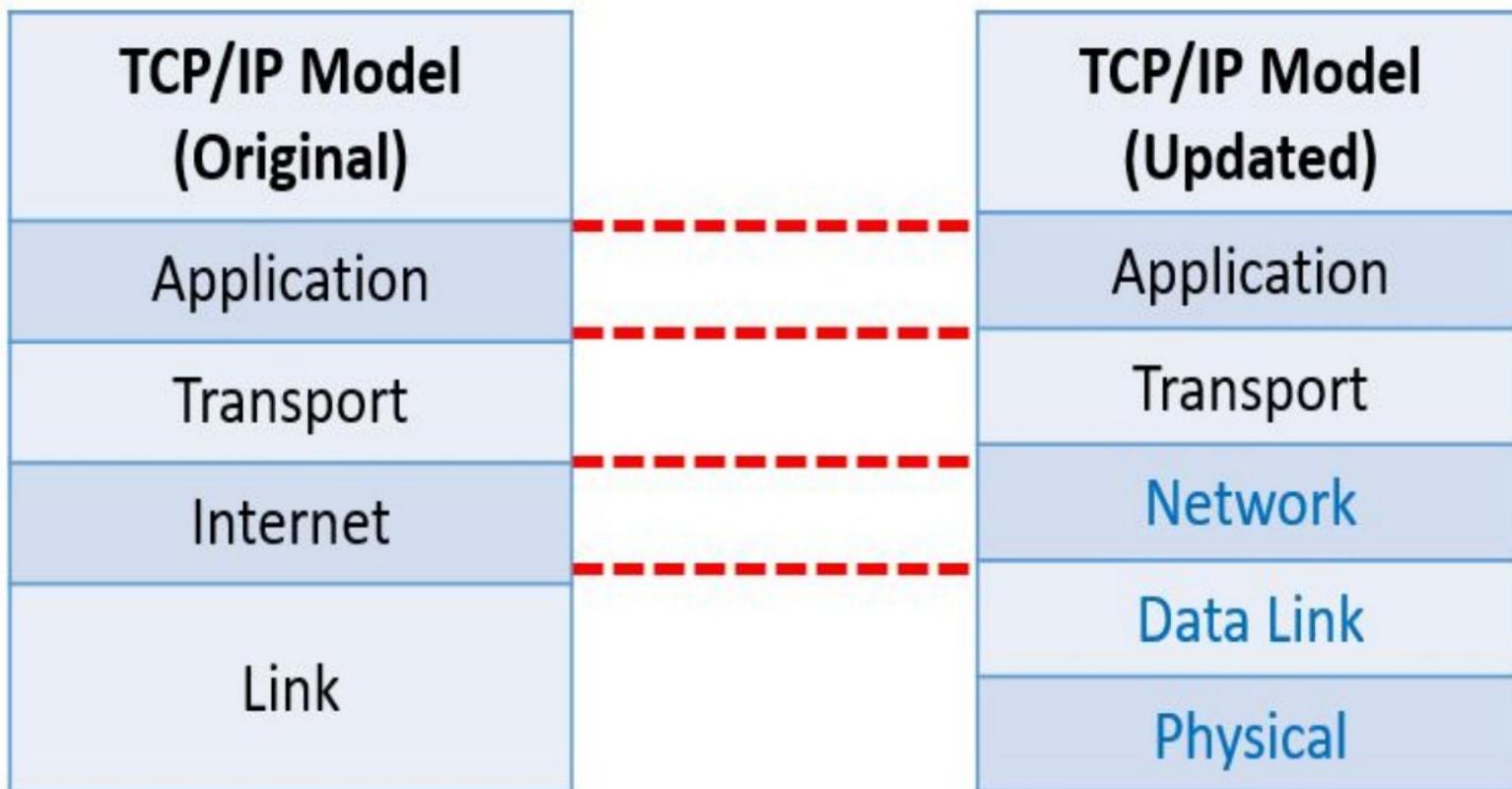
- explicit structure allows identification, relationship of system's pieces
 - layered *reference model* for discussion
- modularization eases maintenance, updating of system
 - change in layer's service *implementation*: transparent to rest of system
 - e.g., change in gate procedure doesn't affect rest of system

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tcp/ip protocol suite

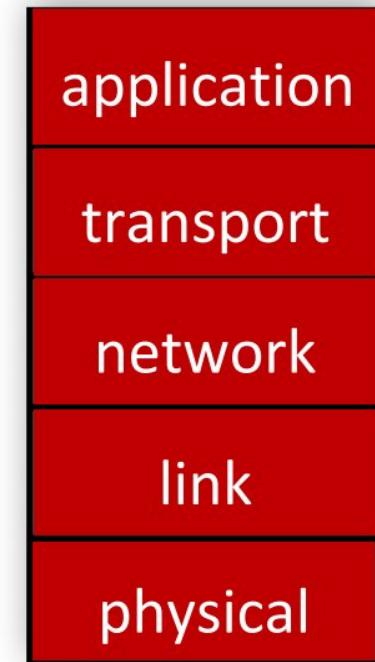
- TCP/IP (Transmission Control Protocol / Internet Protocol) is the protocol suite (a set of protocols organized in different layers) which is used in the internet today.
- TCP/IP is a hierarchical protocol made up of interactive modules, each of which provides a specific functionality.
- The term hierarchical means that each upper level protocol is supported by the services provided by one or more lower level protocols.
- The original TCP/IP protocol suite was defined as four software layers built upon the hardware. Today, however, TCP/IP is thought of as a five-layer model.

layers in tcp/ip protocol suite



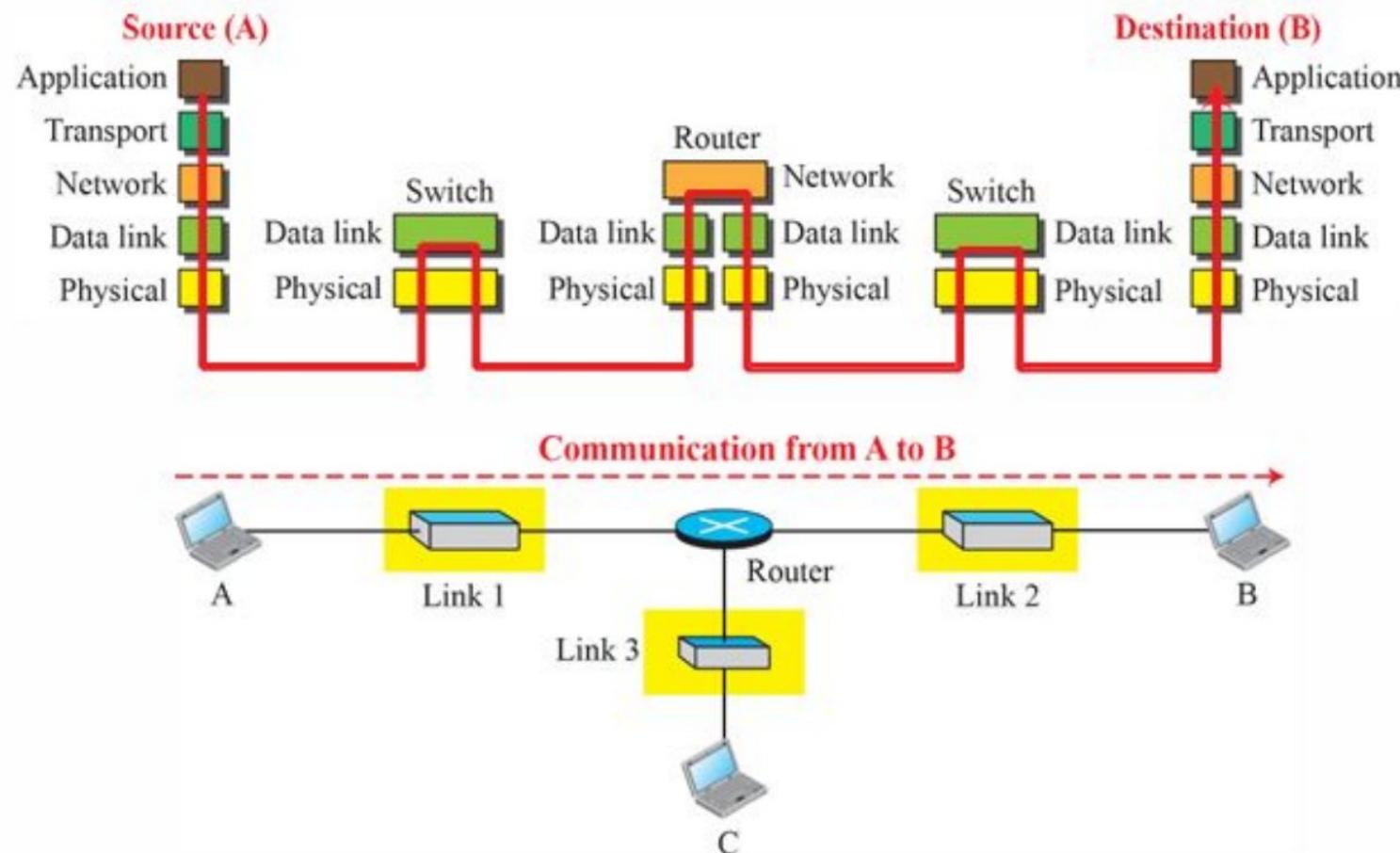
Layers in TCP/IP Stack

- **application:** supporting network applications
 - HTTP, IMAP, SMTP, DNS
- **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”

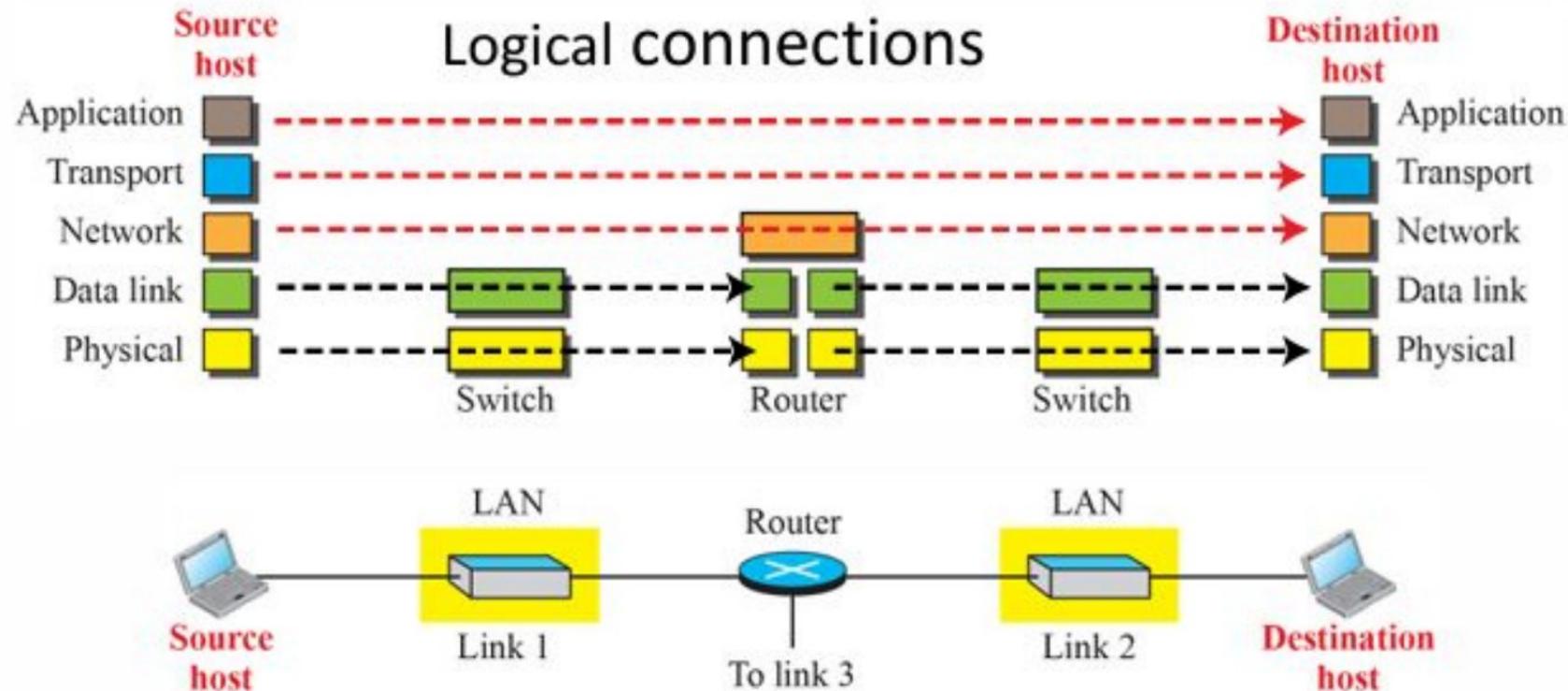


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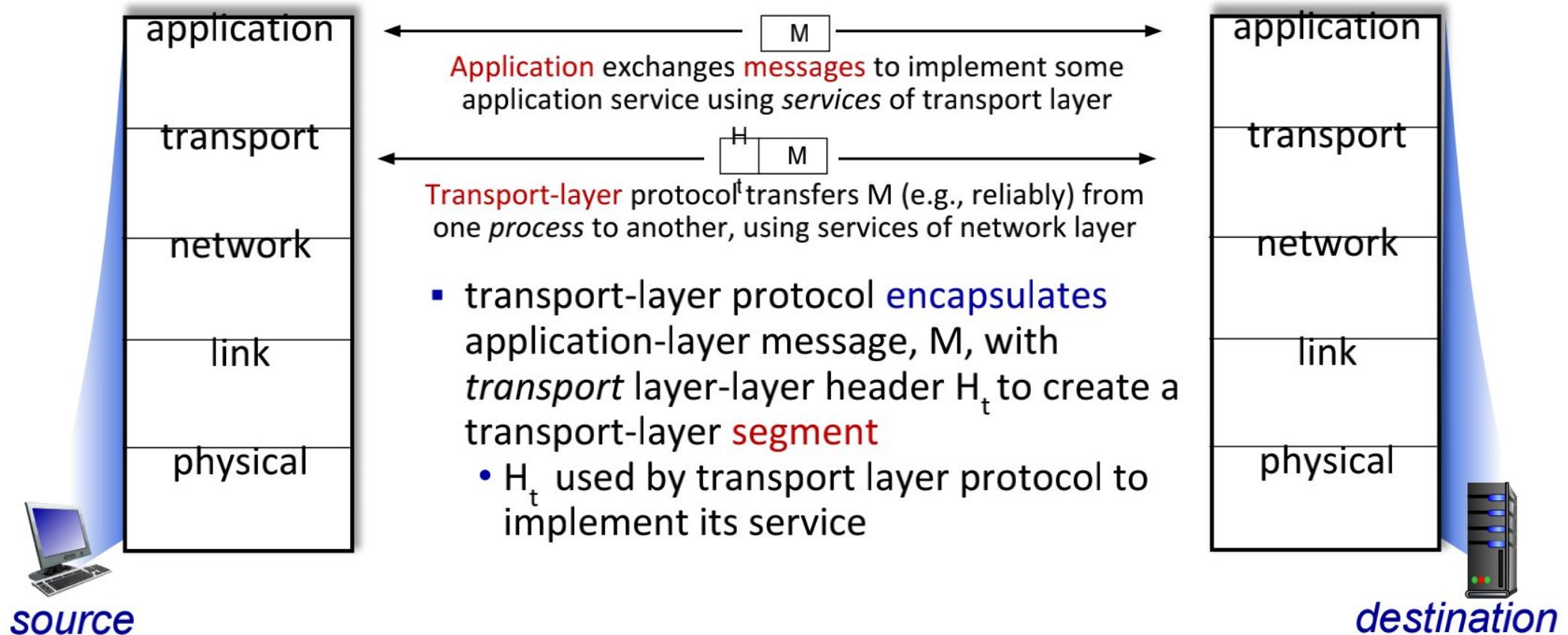
Packet Transmission in TCP/IP Stack



Logical Connections between layers in TCP/IP

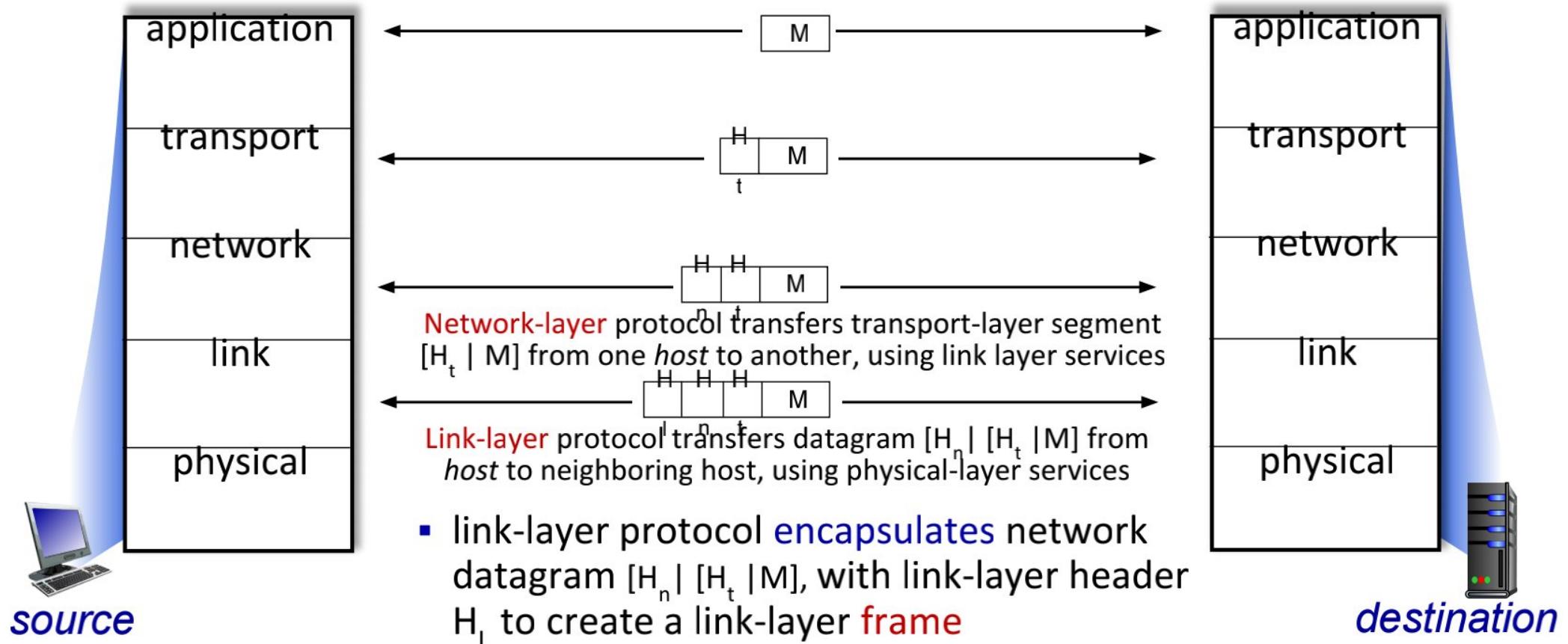


Services, Layering and Encapsulation



Introduction: 1-45

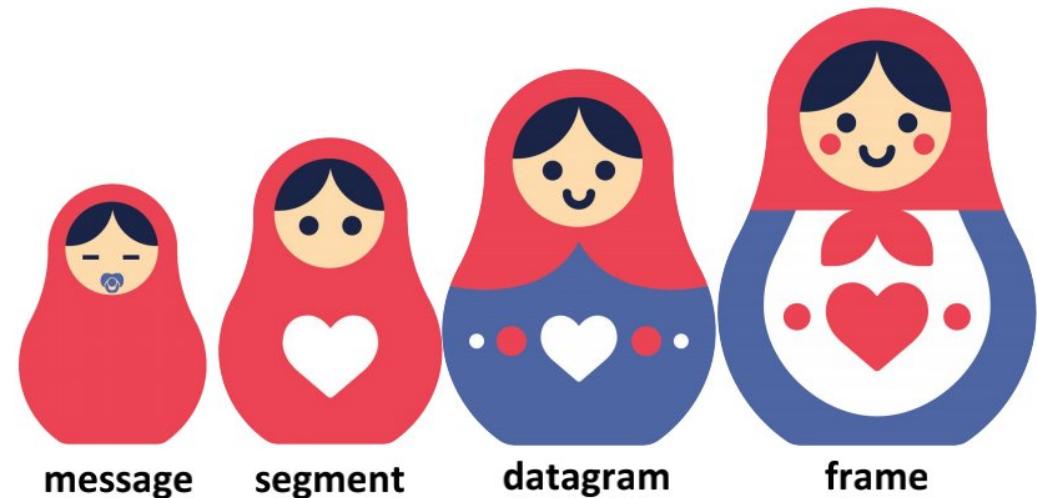
Services, Layering and Encapsulation



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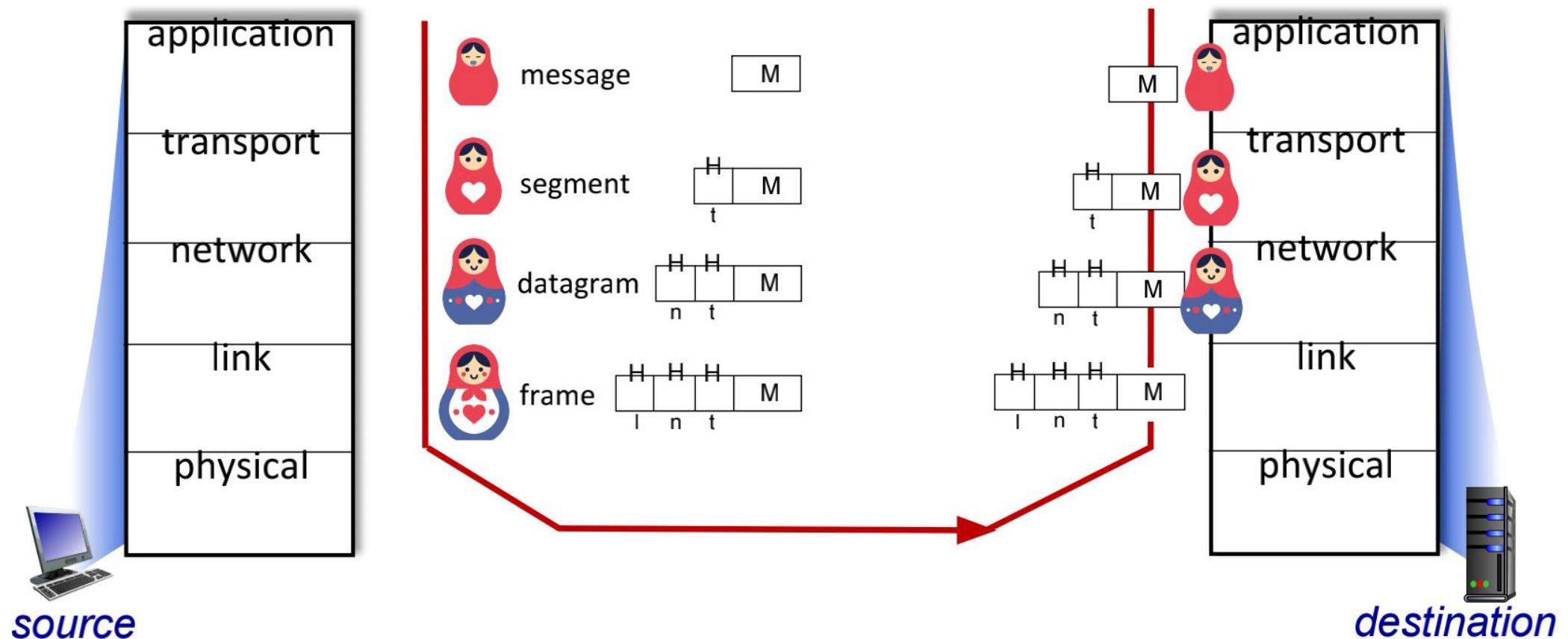
Encapsulation

Matryoshka dolls (stacking dolls)



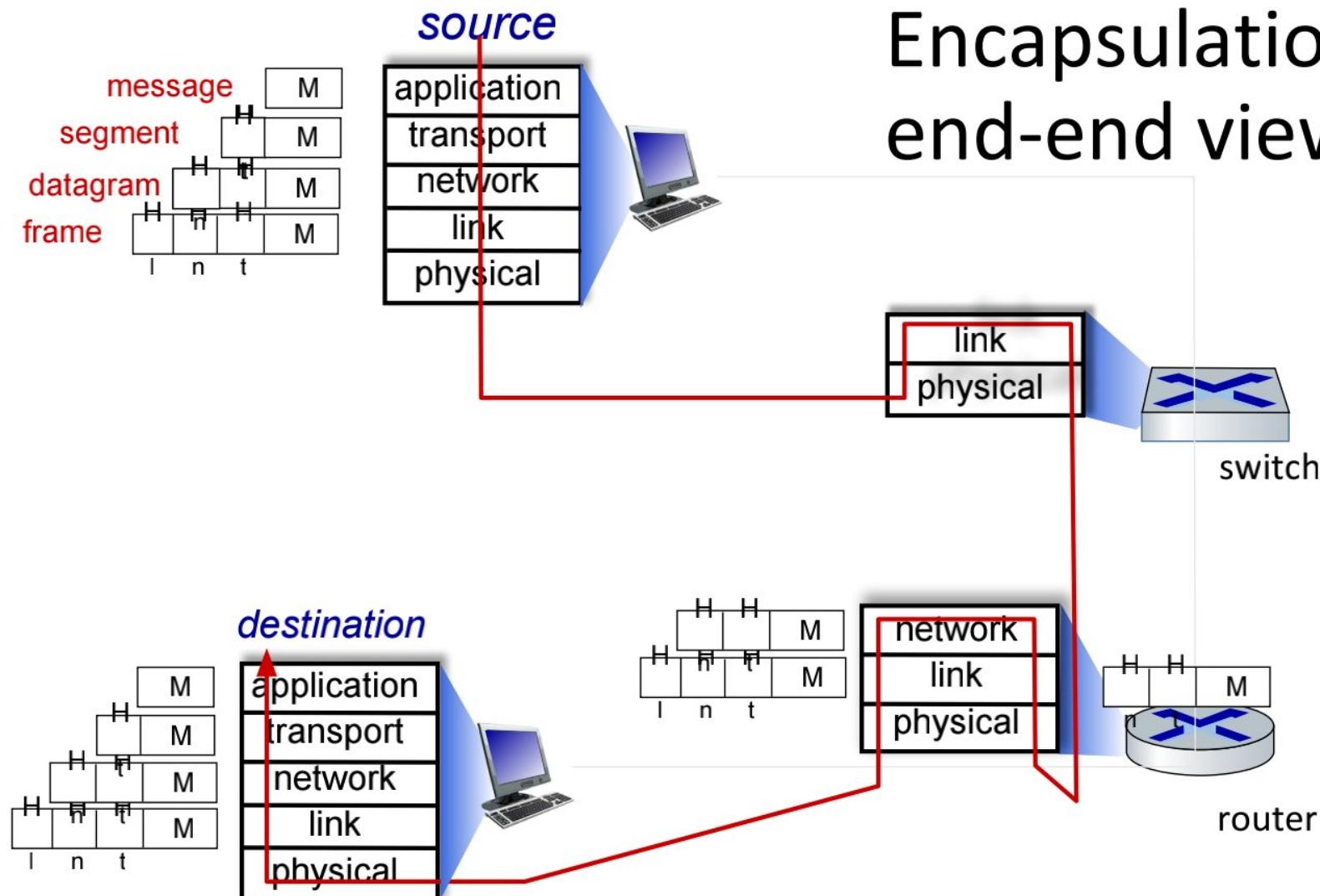
Credit: <https://dribbble.com/shots/7182188-Babushka-Boi>

Services, Layering and Encapsulation



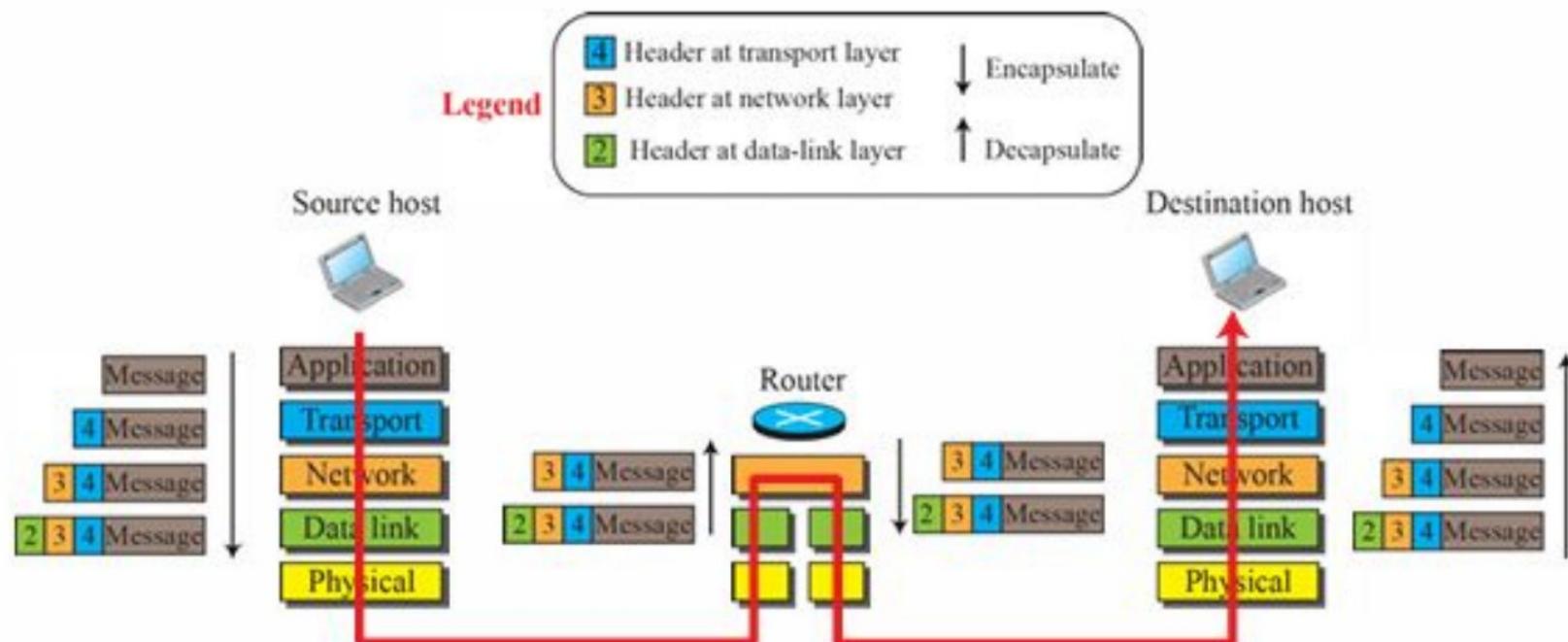
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Encapsulation: an end-end view

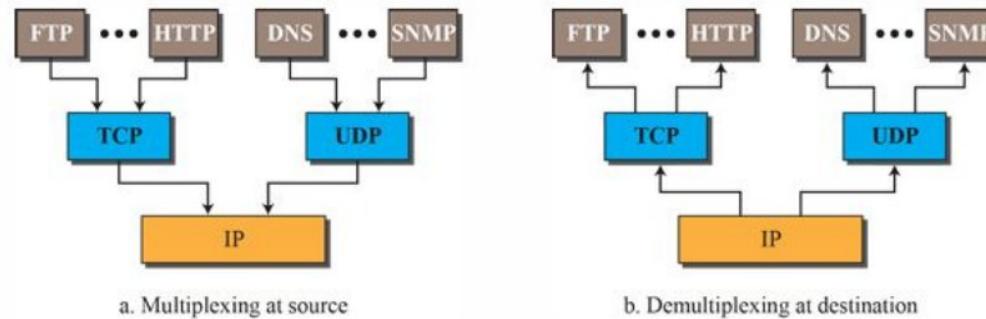


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Encapsulation and Decapsulation



Multiplexing and Demultiplexing

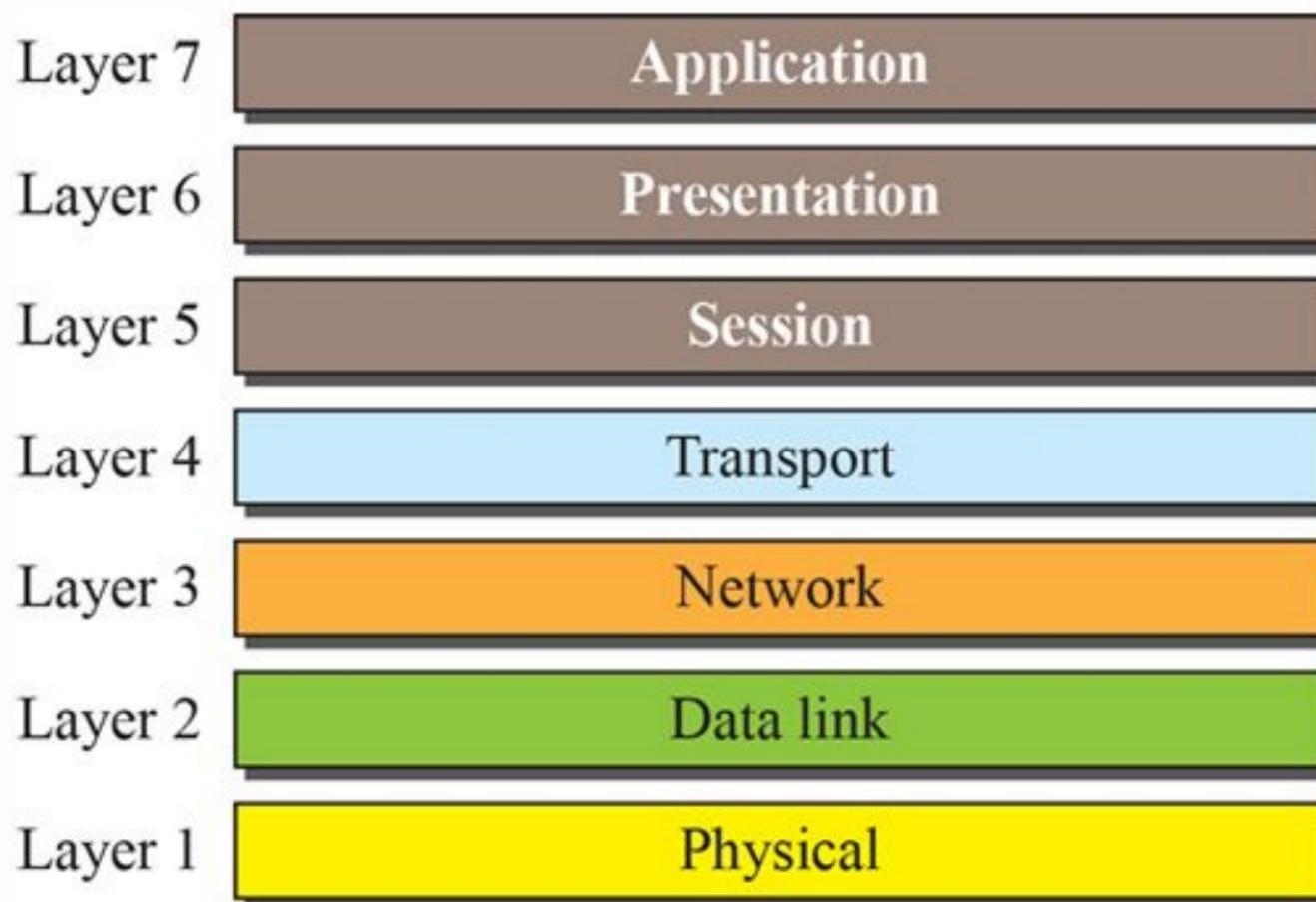


- **Multiplexing** - At the source, a protocol at a layer can take data packets from several next-higher layer protocols one at a time and encapsulate them together. This means that data from different applications can be combined into a single packet.
- **Demultiplexing** - At the destination, the receiving protocol can identify and extract the encapsulated packets from the received data packet and deliver them to their respective next-higher layer protocols one at a time. This ensures that the data is correctly routed to the appropriate application or service.

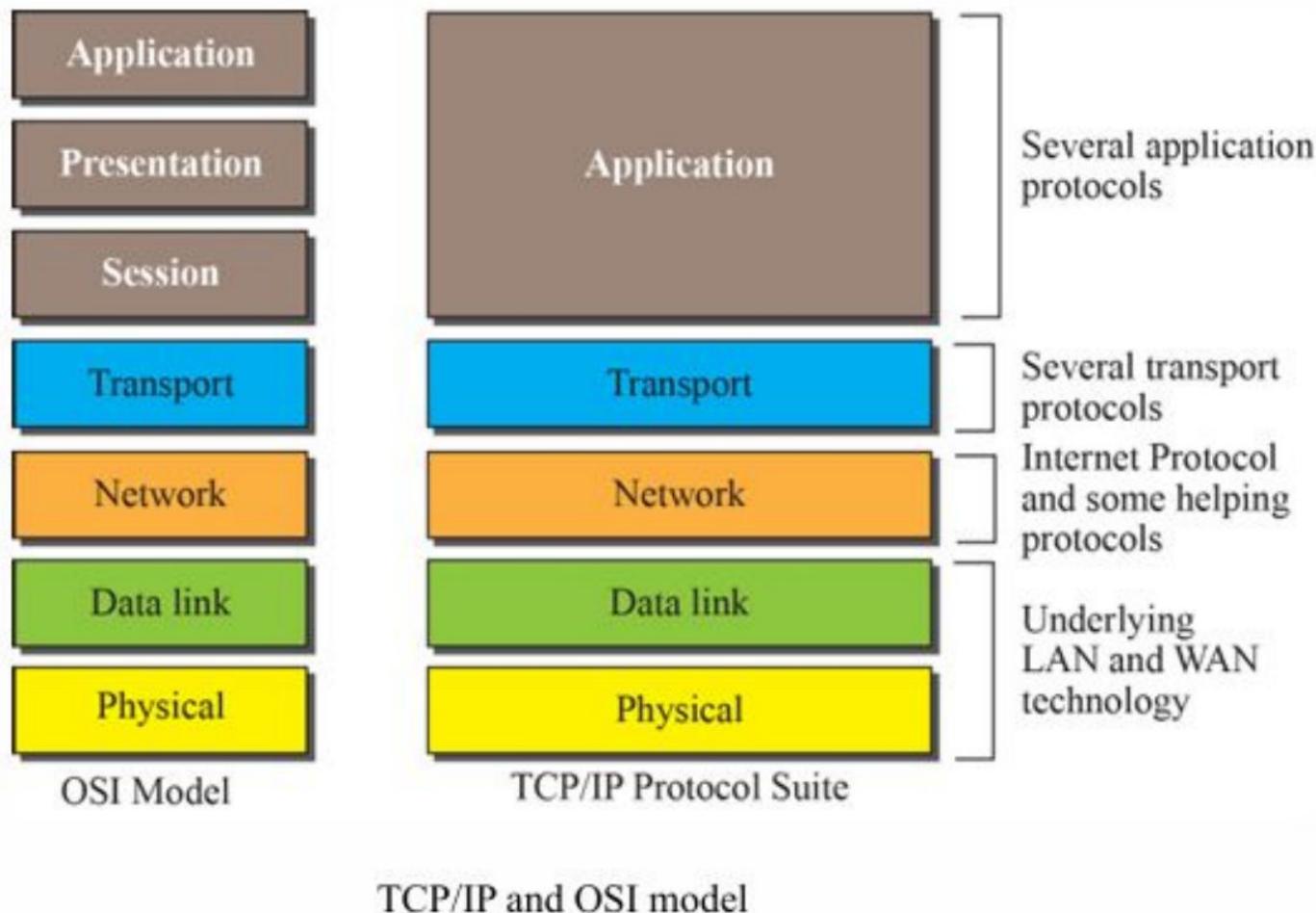
the osi model

- Established in 1947, the **International Organization for Standardization (ISO)** is a multinational body dedicated to worldwide agreement on international standards.
- An ISO standard that covers all aspects of network communications is the **Open Systems Interconnection (OSI) model**. It was first introduced in the late 1970s.
- An **open system is like a universal translator** that enables different systems to talk to each other, regardless of their differences. The OSI model is a blueprint that shows how to make this communication happen without changing the underlying hardware or software.
- The OSI model is a layered framework for the design of network systems that allows communication between all types of computer systems. It consists of **seven separate but related layers, each of which defines a part of the process of moving information across a network**

The OSI Model



OSI Vs TCP/IP



osi vs tcp/ip

- **Multiple Transport-layer Protocols:** TCP/IP has more than one **transport-layer protocol**, and some of them **provide functionalities that were originally associated with the session layer** in the OSI model.
- **Application Layer Variability:** The **application layer in TCP/IP is not limited** to a single piece of software. Instead, multiple applications can be developed at this layer. If a specific application requires functionalities similar to those in the session and presentation layers, those functionalities can be included in the application's development.
- The **absence of session and presentation layers in TCP/IP was a deliberate decision**, influenced by the presence of multiple transport layer protocols and the flexibility of the application layer to accommodate various application specific functionalities.

Lack of osi model's success

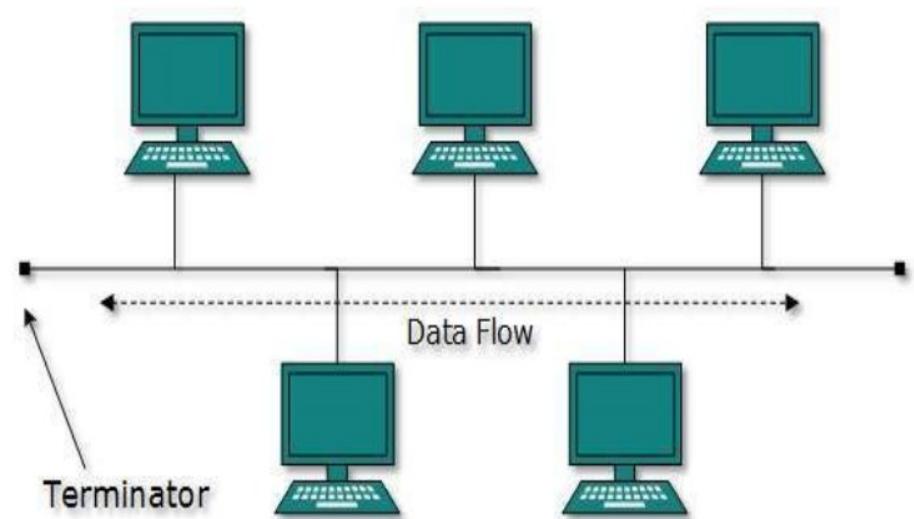
- **Timing and Cost:** By the time the OSI model was completed, TCP/IP was already widely implemented and used. Switching to the **OSI model would have required a significant amount of time, effort, and money to replace the existing TCP/IP infrastructure**, which was not practical.
- **Incomplete Definitions:** Some layers in the OSI model, like the presentation and session layers, were not fully defined with concrete protocols and software. Although **the services provided by these layers were listed, the actual implementation details were lacking**, making it difficult for organizations to adopt them.
- **Performance Issues:** When organizations attempted to implement the OSI model in different applications, it **didn't demonstrate significantly better performance than the established TCP/IP protocol suite**. As a result, there was no compelling reason for the Internet authority to switch from TCP/IP to OSI.

Network topologies

- Network topology refers to **the arrangement of different elements like nodes, links, and devices** in a computer network.
- It defines how these **components are connected and interact with each other**.
- Understanding various types of network topologies **helps in designing efficient and robust networks**.
- Common types **include bus, star, ring, mesh, and tree topologies**, each with its own advantages and disadvantages.

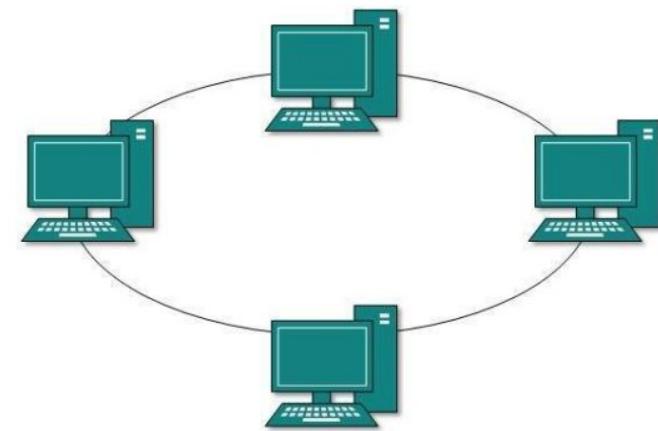
types of network topology

- **Bus Topology**
 - In case of Bus topology, all devices share single communication line or cable.
 - It is one of the simple forms of networking where a failure of a device does not affect the other devices. But failure of the shared communication line can make all other devices stop functioning.
 - Both ends of the shared channel have line terminator. The data is sent in only one direction and as soon as it reaches the extreme end, the terminator removes the data from the line.



types of network topology

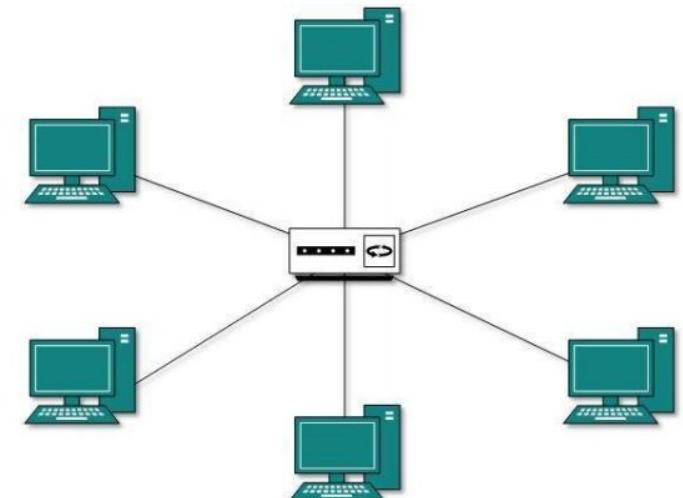
- Ring Topology -
 - In ring topology, each host machine connects to exactly two other machines, creating a circular network structure.
 - When one host tries to communicate or send message to a host which is not adjacent to it, the data travels through all intermediate hosts.
 - To connect one more host in the existing structure, the administrator may need only one more extra cable.
 - Failure of any host results in failure of the whole ring. Thus, every connection in the ring is a point of failure.



types of network topology

- **Star Topology -**

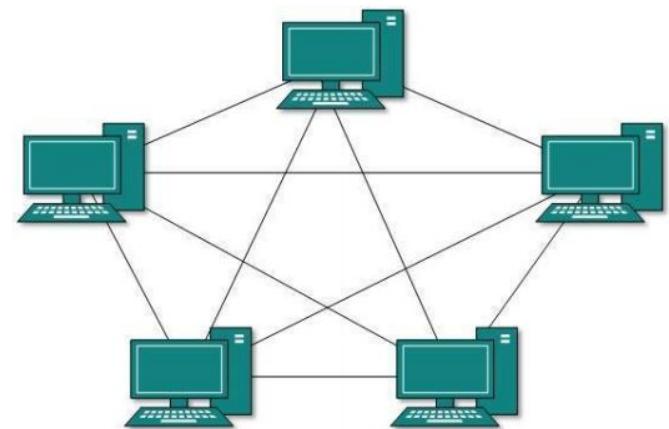
- In Star Topology, all the devices are connected to a single hub through a cable.
- This hub is the central node and all other nodes are connected to the central node.
- If hub fails, connectivity of all hosts to all other hosts fails. Every communication between hosts, takes place through only the hub.
- Star topology is not expensive as to connect one more host, only one cable is required and configuration is simple.



types of network topology

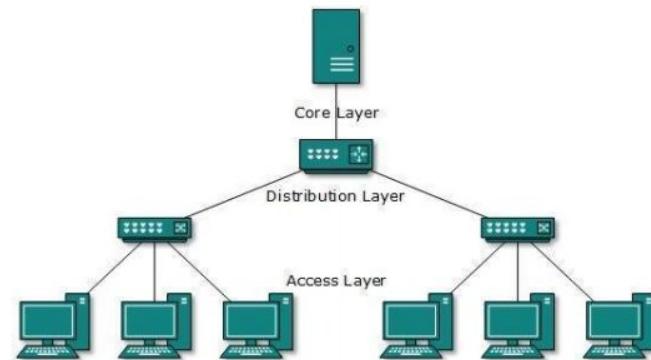
- **Mesh Topology -**

- In this type of topology, a host is connected to one or multiple hosts.
- This topology has hosts in point-to-point connection with every other host or may also have hosts which are in point-to-point connection to few hosts only.
- Hosts in Mesh topology also work as relay for other hosts which do not have direct point-to-point links.
- Full Mesh - All hosts have a point-to-point connection to every other host in the network. Thus for every new host $n(n-1)/2$ connections are required. It provides the most reliable network structure among all network topologies.
- Partially Mesh - Not all hosts have point-to-point connection to every other host. Hosts connect to each other in some arbitrarily fashion. This topology exists where we need to provide reliability to some hosts out of all.



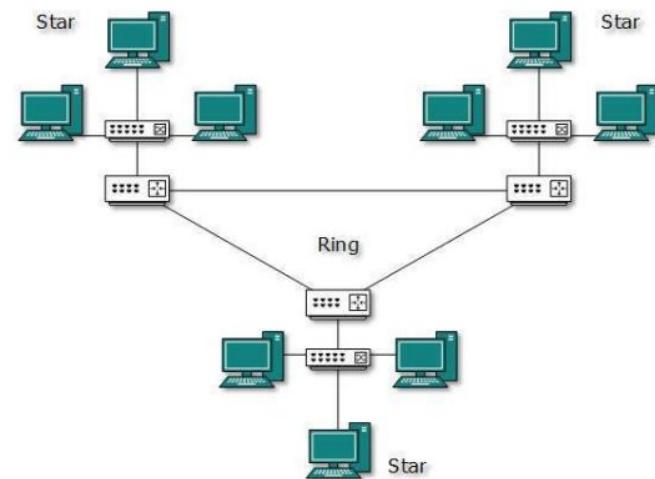
types of network topology

- Tree Topology or Hierarchical Topology
 - This topology divides the network in to multiple levels/layers of network.
 - Mainly in LANs, a network is bifurcated into three types of network devices. The lowermost is access-layer where computers are attached.
 - The middle layer is known as distribution layer, which works as mediator between upper layer and lower layer.
 - The highest layer is known as core layer, and is central point of the network, i.e. root of the tree from which all nodes fork.
 - Similar to the Bus topology, if the root goes down, then the entire network suffers even though it is not the single point of failure.
 - Every connection serves as point of failure, failing of which divides the network into unreachable segment.



types of network topology

- Hybrid Topology
 - A network structure whose design contains more than one topology is said to be hybrid topology. Hybrid topology inherits merits and demerits of all the incorporating topologies.
 - Most WANs are connected by means of Dual-Ring topology and networks connected to them are mostly Star topology networks.
 - Internet is the best example of largest Hybrid topology.



comparison of network topologies

Topology	Advantages	Disadvantages
Bus	Simple, cost-effective, easy to extend	Difficult to troubleshoot, limited length and nodes, single point of failure (backbone)
Star	Easy to install/manage, failure isolation	Central point of failure (hub/switch), more cabling
Ring	High speed, no collisions	Failure of one device affects all, difficult to troubleshoot
Mesh	Highly reliable, redundant paths	Expensive, complex configuration
Tree	Scalable, easy management	More cabling, backbone failure affects entire network
Hybrid	Flexible, robust, scalable	Complex design/maintenance, costly

Switching

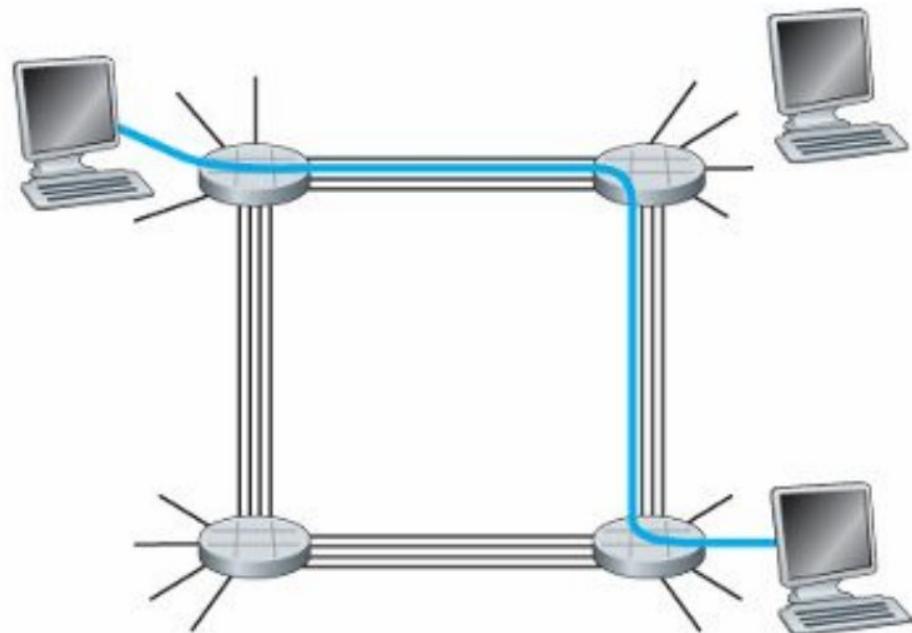
- We have discussed that internet is a network of networks in which two or more networks are connected to each other via switches and routers i.e. we can say that **internet is a *switched network***.
- Switching is the process of **transferring data packets from one device to another in a network**, or from one network to another via switches.
- There are two types of switching popular in computer networks -
 - Circuit Switching
 - Packet Switching

Circuit switching

- In a circuit-switched network, a dedicated connection, called a **circuit**, is always available between two end systems; **the switch can only make it active or inactive**.
- In circuit-switched networks, the **resources needed along a path (buffers, link transmission rate) to provide for communication between the end systems are reserved** for the duration of the communication session between the end systems.
- **Traditional telephone networks are examples** of circuit-switched networks.

circuit switching

- In the example, a dedicated connection (in blue) is created between two end systems. This connection or circuit will be reserved for the entire duration of communication.
- **Because each link has four circuits, for each link used by the end-to-end connection, the connection gets one fourth of the link's total transmission capacity for the duration of the connection.** Thus, for example, if each link between adjacent switches has a transmission rate of 1 Mbps, then each end-to-end circuit-switch connection gets 250 kbps of dedicated transmission rate.



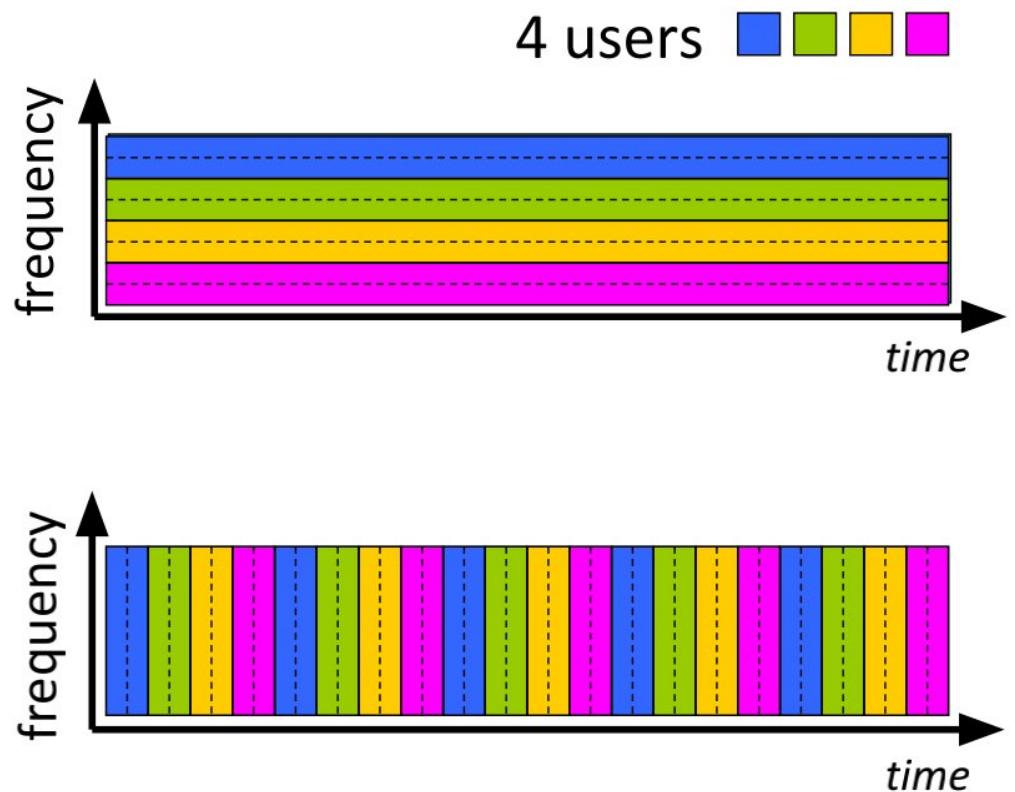
Circuit switching: FDM and TDM

Frequency Division Multiplexing (FDM)

- optical, electromagnetic frequencies divided into (narrow) frequency bands
- each call allocated its own band, can transmit at max rate of that narrow band

Time Division Multiplexing (TDM)

- time divided into slots
- each call allocated periodic slot(s), can transmit at maximum rate of (wider) frequency band (only) during its time slot(s)



Introduction: 1-68

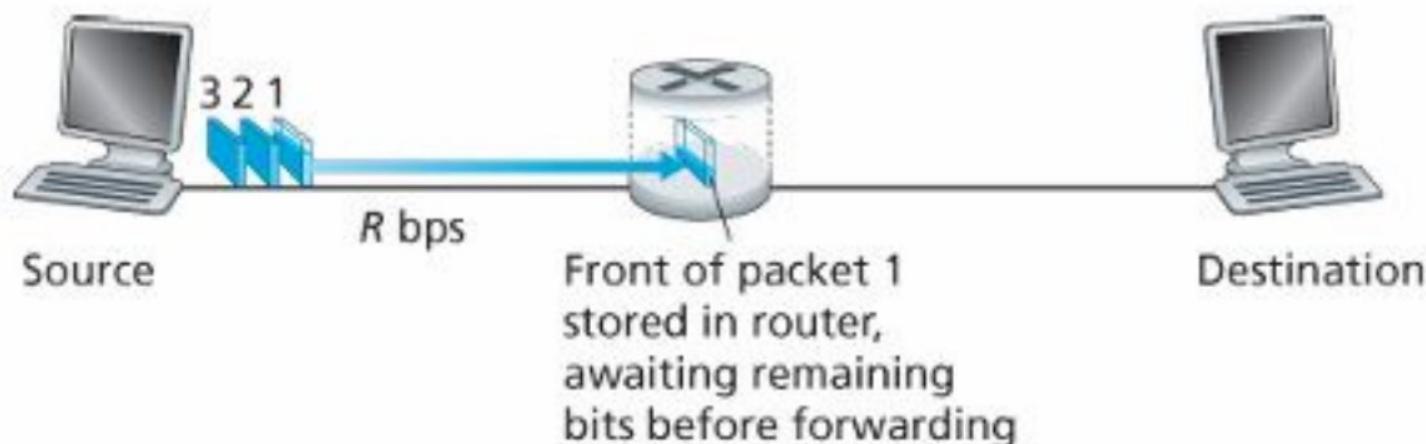


packet switching

- In a network application, end-systems exchanges messages with each other. These messages can be anything like a connection request or maybe some data transfer message like an email, file transfer, etc.
- To send a message from a source end-system to a destination end-system, the **source breaks long messages into smaller chunks of data** known as **packets**.
- Between source and destination, each **packet travels through communication links and *packet switches*** (routers, link-layer switches, etc.).
- Packets are transmitted over each communication link at full transmission rate of the link. So if a source end system or a packet switch is sending a packet of **L bits** over a link with transmission rate **R bits / second** then the time to transmit the packet is **L / R seconds**.

packet switching: store-and-forward transmission

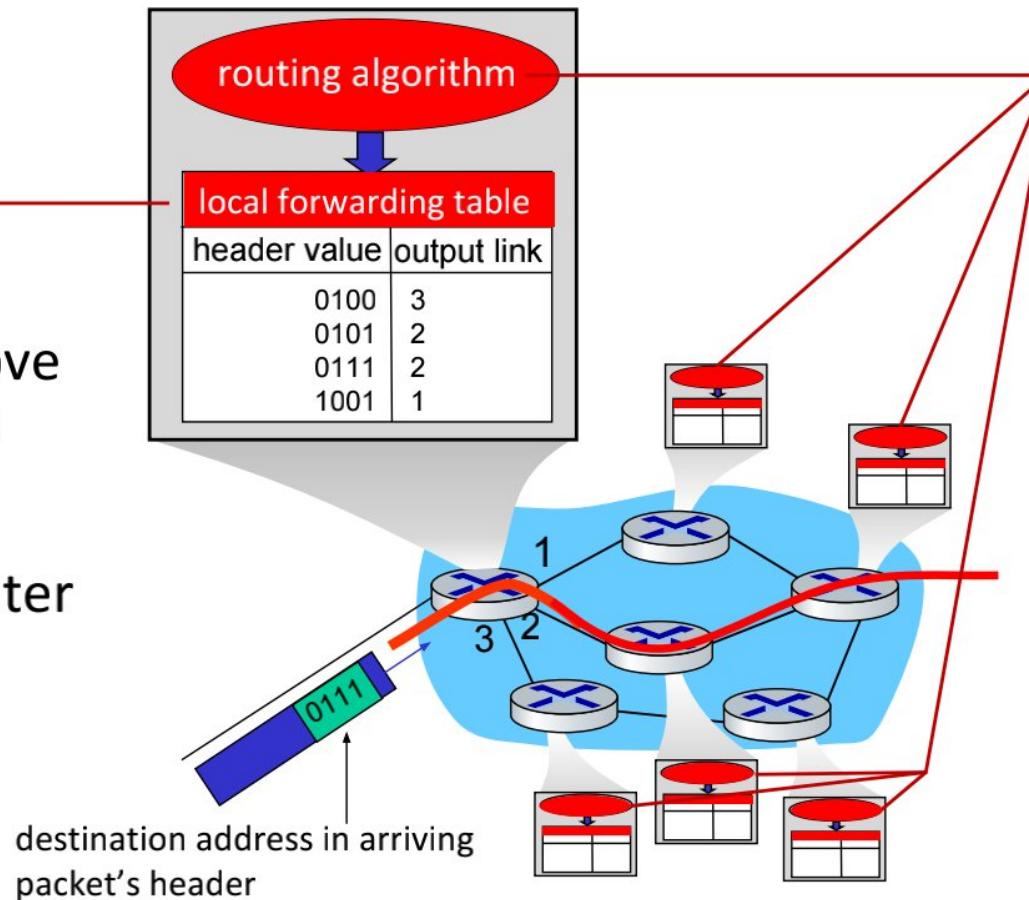
- Most packet switches use store-and-forward transmission at the inputs to the links. Store-and-forward transmission means that the packet switch must receive the entire packet before it can begin to transmit the first bit of the packet onto the outbound link.



Two key network-core functions

Forwarding:

- aka “switching”
- *local* action: move arriving packets from router’s input link to appropriate router output link



Routing:

- *global* action: determine source-destination paths taken by packets
- routing algorithms

Introduction: 1-72

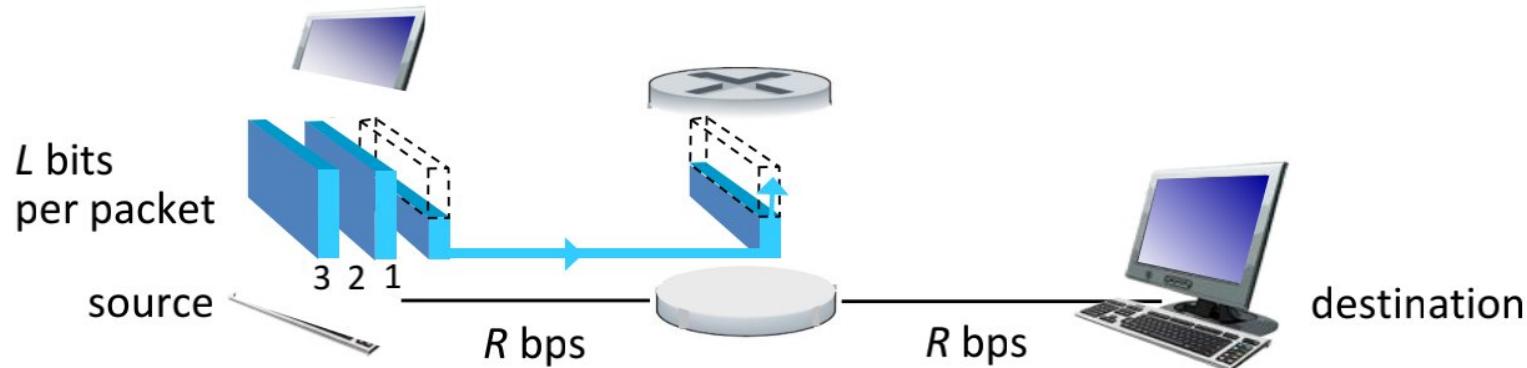


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Packet-switching: store-and-forward

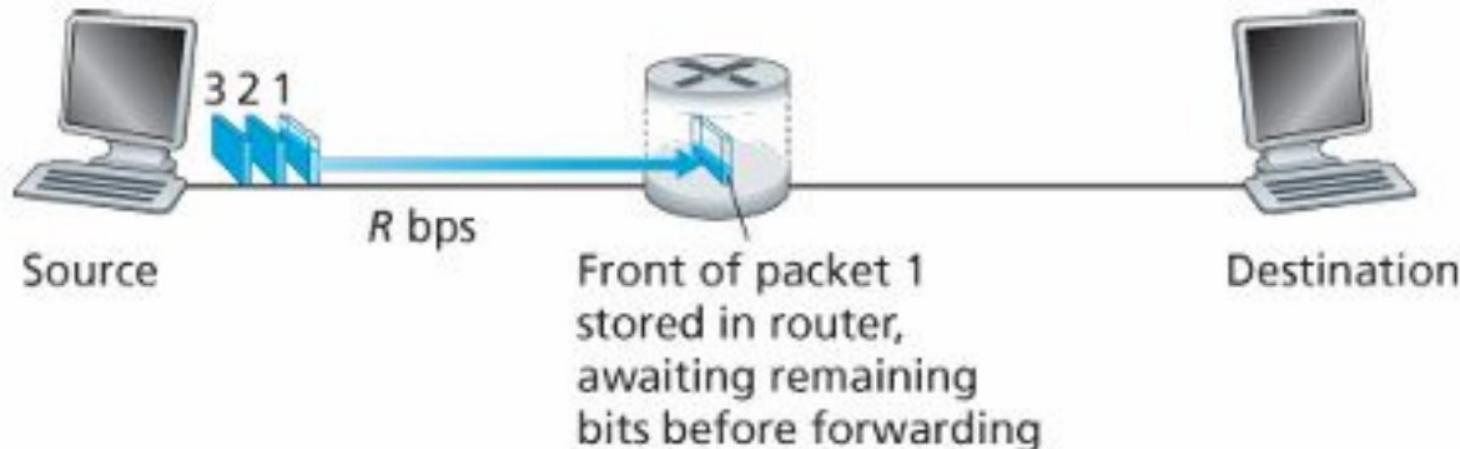


- **packet transmission delay:** takes L/R seconds to transmit (push out) L -bit packet into link at R bps
- **store and forward:** entire packet must arrive at router before it can be transmitted on next link

One-hop numerical example:

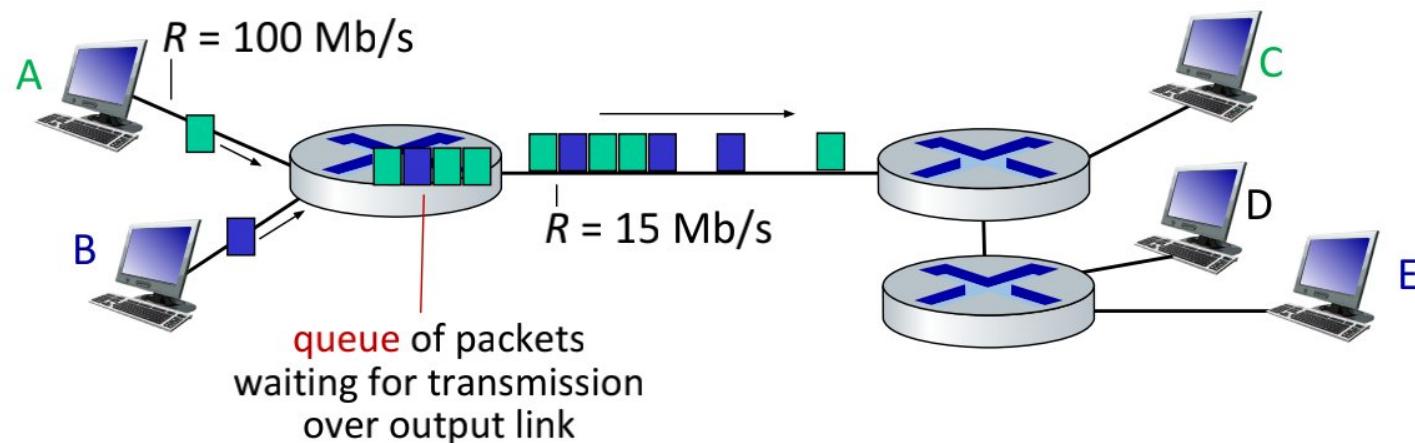
- $L = 10$ Kbits
- $R = 100$ Mbps
- one-hop transmission delay = 0.1 msec

exercise



- In given example, how much time will it take for 1st packet to reach the destination?
- Total time taken in transmitting all three packets from source to destination?

Packet-switching: queueing delays and packet loss

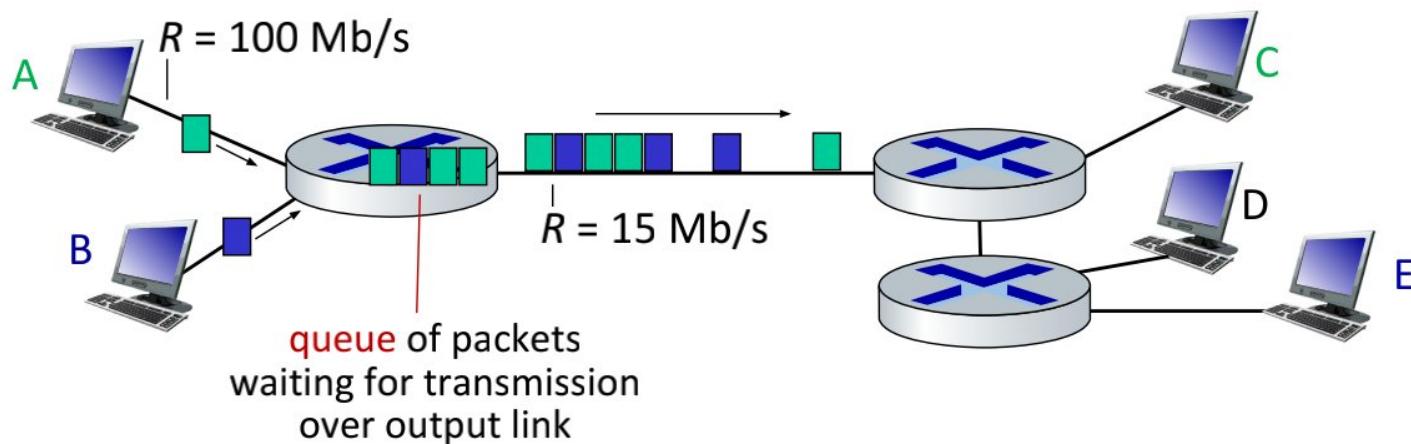


Queueing occurs when work arrives faster than it can be serviced:



Introduction: 1-77

Packet-switching: queueing delays and packet loss



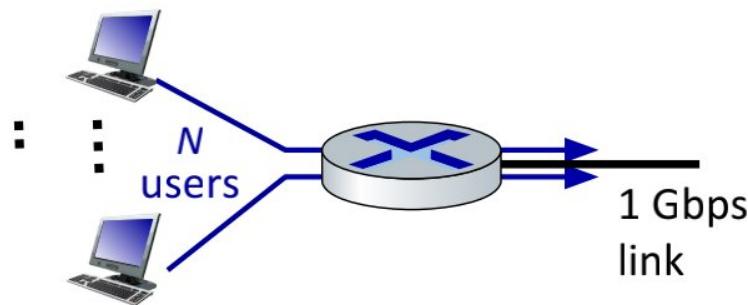
Packet queuing and loss: if arrival rate (in bps) to link exceeds transmission rate (bps) of link for some period of time:

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

Packet switching versus circuit switching

example:

- 1 Gb/s link
- each user:
 - 100 Mb/s when “active”
 - active 10% of time



Q: how many users can use this network under circuit-switching and packet switching?

▪ *circuit-switching:* 10 users

▪ *packet switching:* with 35 users,
probability > 10 active at same time
is less than .0004 *

Q: how did we get value 0.0004?

A: HW problem (for those with
course in probability only)

Introduction: 1-79

Packet switching versus circuit switching

Is packet switching a “slam dunk winner”?

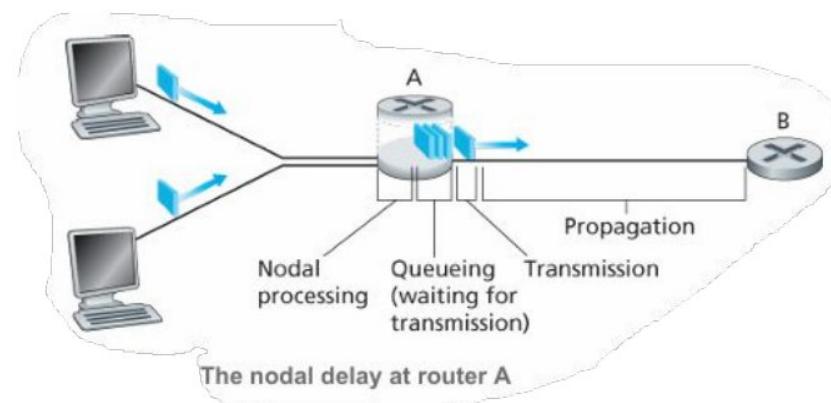
- great for “bursty” data – sometimes has data to send, but at other times not
 - resource sharing
 - simpler, no call setup
- **excessive congestion possible:** packet delay and loss due to buffer overflow
 - protocols needed for reliable data transfer, congestion control
- **Q: How to provide circuit-like behavior with packet-switching?**
 - “It’s complicated.” We’ll study various techniques that try to make packet switching as “circuit-like” as possible.

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

Introduction: 1-80

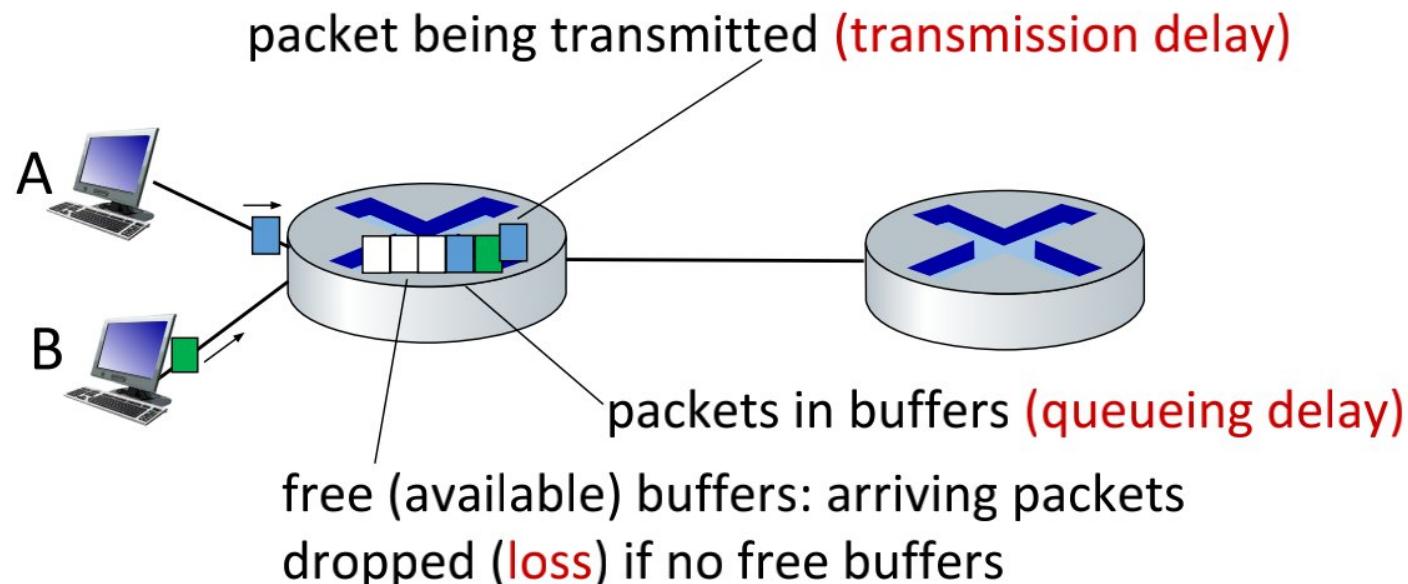
delay in packet-switched networks

- As a packet travels from one node (host or router) to the subsequent node (host or router) while going from source to destination, the packet suffers from several types of delays at each node along the path.
- The most important of these delays are the ***nodal processing delay***, ***queueing delay***, ***transmission delay***, and ***propagation delay***; together, these delays accumulate to give a ***total nodal delay***.



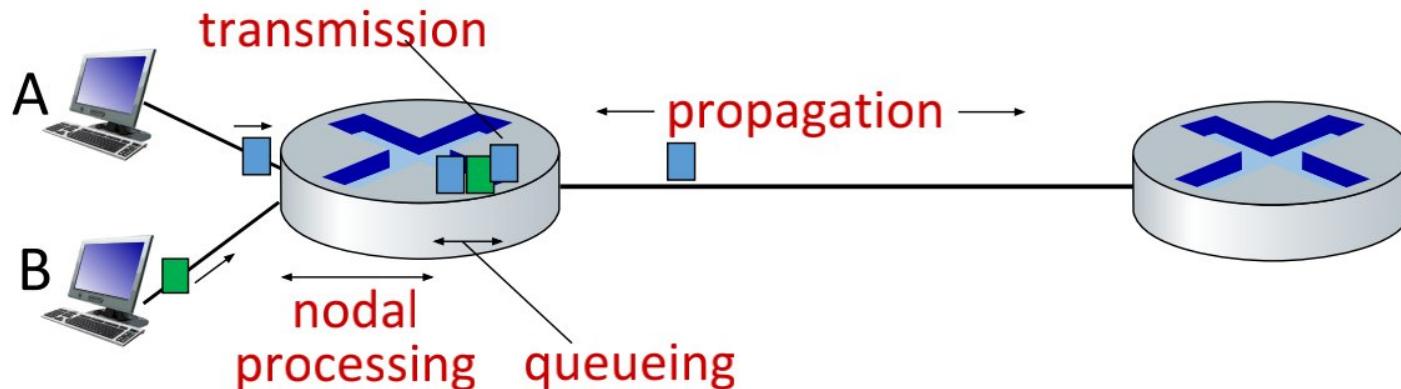
Delay in Packet-Switched Networks

- packets *queue* in router buffers, waiting for turn for transmission
 - queue length grows when arrival rate to link (temporarily) exceeds output link capacity
 - packet *loss* occurs when memory to hold queued packets fills up



Introduction: 1-82

Packet delay: four sources



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

d_{proc} : nodal processing

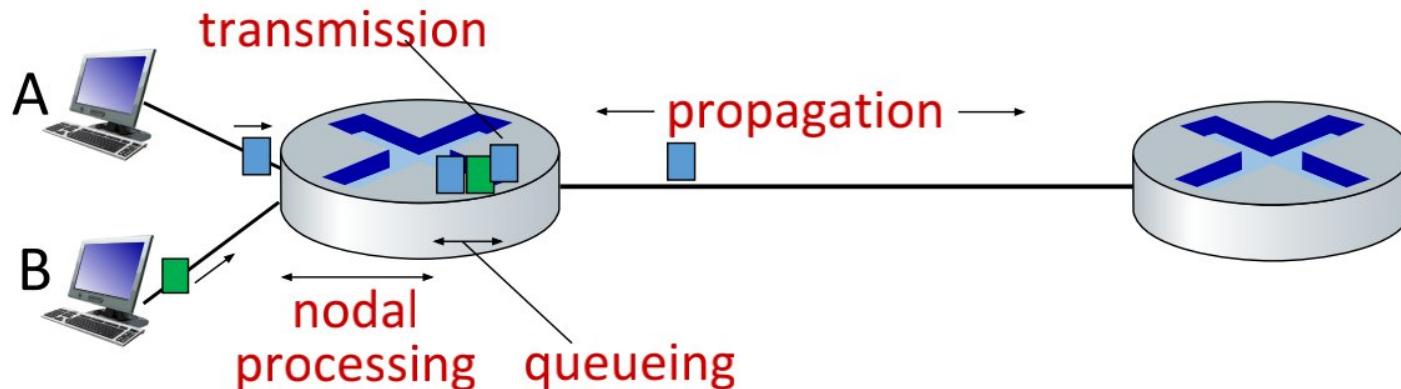
- check bit errors
- determine output link
- typically < microsecs

d_{queue} : queueing delay

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

Introduction: 1-83

Packet delay: four sources



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

d_{trans} : transmission delay:

- L : packet length (bits)
- R : link *transmission rate (bps)*

$$\boxed{\bullet d_{\text{trans}} = L/R}$$

d_{prop} : propagation delay:

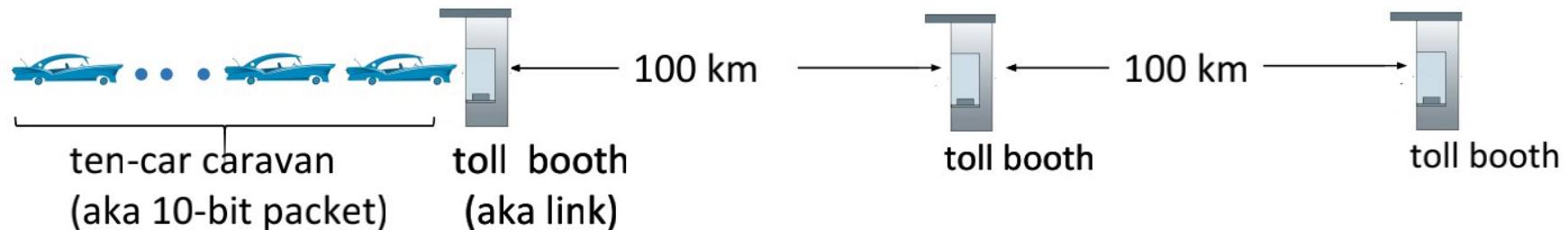
- d : length of physical link
- s : propagation speed ($\sim 2 \times 10^8$ m/sec)

$$\boxed{\bullet d_{\text{prop}} = d/s}$$

d_{trans} and d_{prop}
very different

Introduction: 1-84

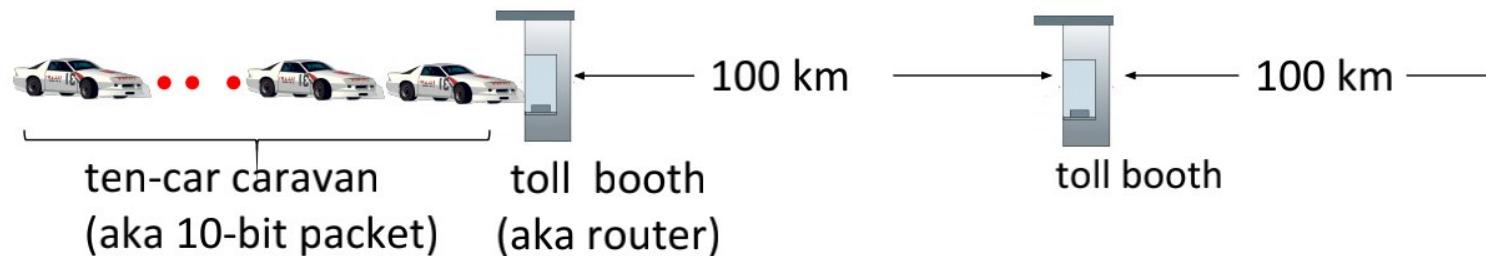
Caravan analogy



- car ~ bit; caravan ~ packet; toll service ~ link transmission
- toll booth takes 12 sec to service car (bit transmission time)
- “propagate” at 100 km/hr
- **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
- time for last car to propagate from 1st to 2nd toll booth: $100\text{km}/(100\text{km/hr}) = 1$ hr
- **A: 62 minutes**

Introduction: 1-85

Caravan analogy



- suppose cars now “propagate” at 1000 km/hr
- and suppose toll booth now takes one min to service a car
- **Q: Will cars arrive to 2nd booth before all cars serviced at first booth?**

A: Yes! after 7 min, first car arrives at second booth; three cars still at first booth

End-to-end delay

- So far we have discussed delay at a single router, but what about total delay in the journey of packet from source to destination?
- Let's suppose there are N routers between the source host and the destination host.
- With the assumption that equal delays for the sender, routers, and receiver, the total end-to-end delay (source-to-destination delay) a packet encounters can be calculated as following -

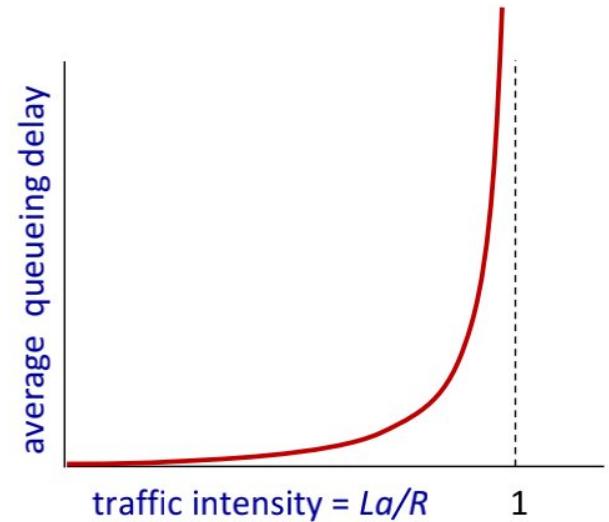
$$d_{\text{end-to-end}} = (n + 1) (d_{\text{processing}} + d_{\text{transmission}} + d_{\text{propagation}}) + n d_{\text{queuing}}$$

- Delay can have a significant impact on real-time applications such as voice and video chats, where low delay is essential to maintain smooth communication.

Packet queueing delay (revisited)

- a : average packet arrival rate
- L : packet length (bits)
- R : link bandwidth (bit transmission rate)

$$\frac{L \cdot a}{R} : \frac{\text{arrival rate of bits}}{\text{service rate of bits}} \quad \text{"traffic intensity"}$$



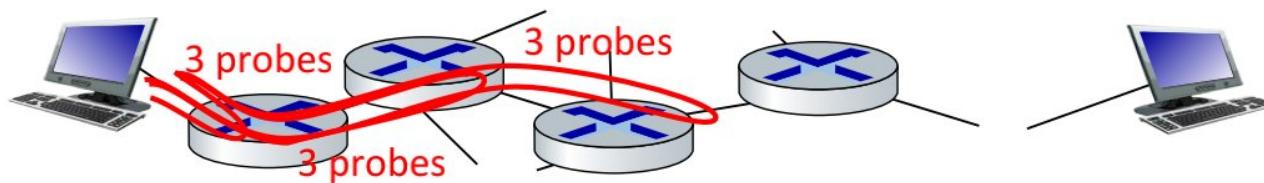
- $La/R \sim 0$: avg. queueing delay small
- $La/R \rightarrow 1$: avg. queueing delay large
- $La/R > 1$: more “work” arriving is more than can be serviced - average delay infinite!



$La/R \rightarrow 1$
Introduction: 1-88

“Real” Internet delays and routes

- what do “real” Internet delay & loss look like?
- **traceroute** program: 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 (with time-to-live field value of i)
 - router i will return packets to sender
 - sender measures time interval between transmission and reply



Introduction: 1-89

Real Internet delays and routes

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

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

3 delay measurements to border1-rt-fa5-1-0.gw.umass.edu

trans-oceanic link

looks like delays decrease! Why?

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

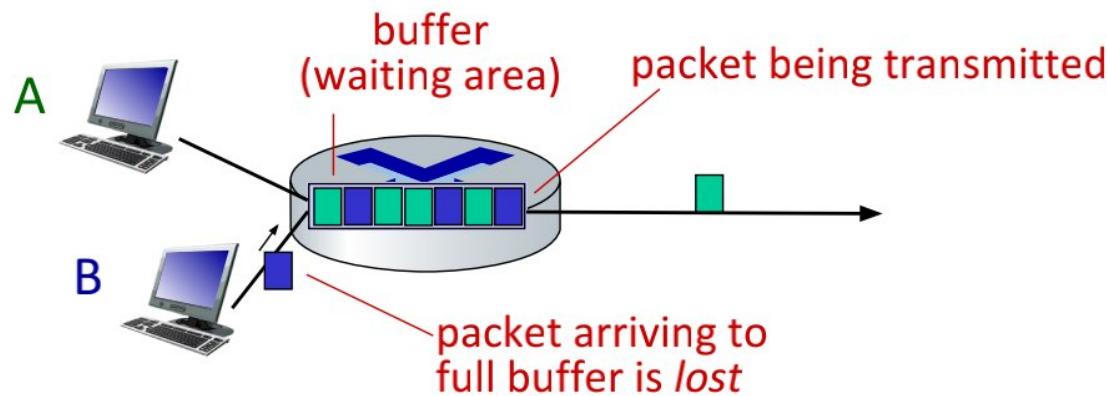
* means no response (probe lost, router not replying)

* Do some traceroutes from exotic countries at www.traceroute.org

Introduction: 1-90

Packet loss

- queue (aka buffer) preceding link in buffer has finite capacity
- packet arriving to full queue dropped (aka lost)
- lost packet may be retransmitted by previous node, by source end system, or not at all

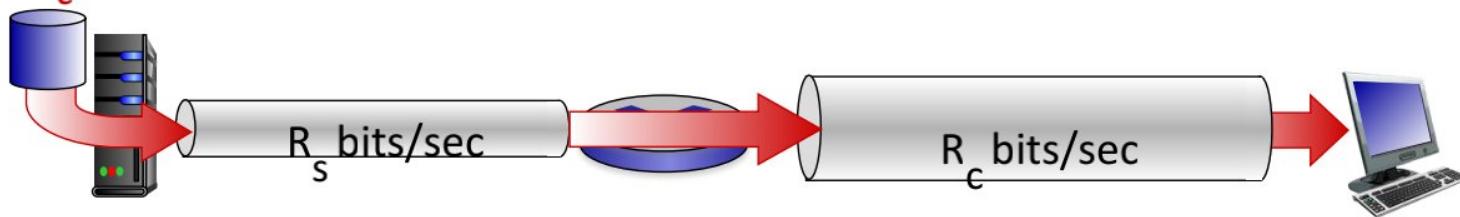


* Check out the Java applet for an interactive animation (on publisher's website) of queuing and loss

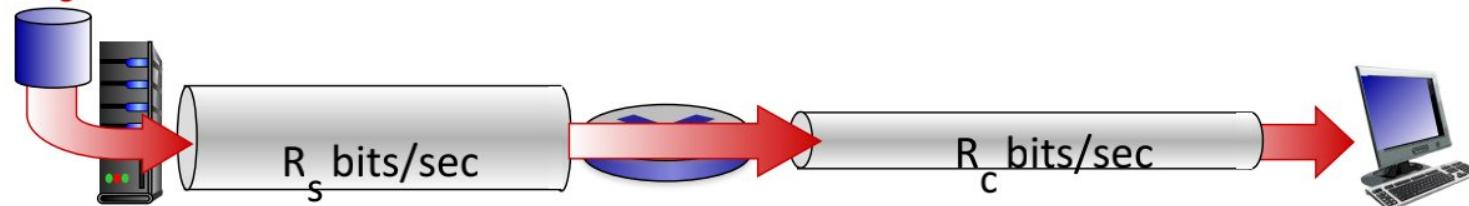
Introduction: 1-91

Throughput

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



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

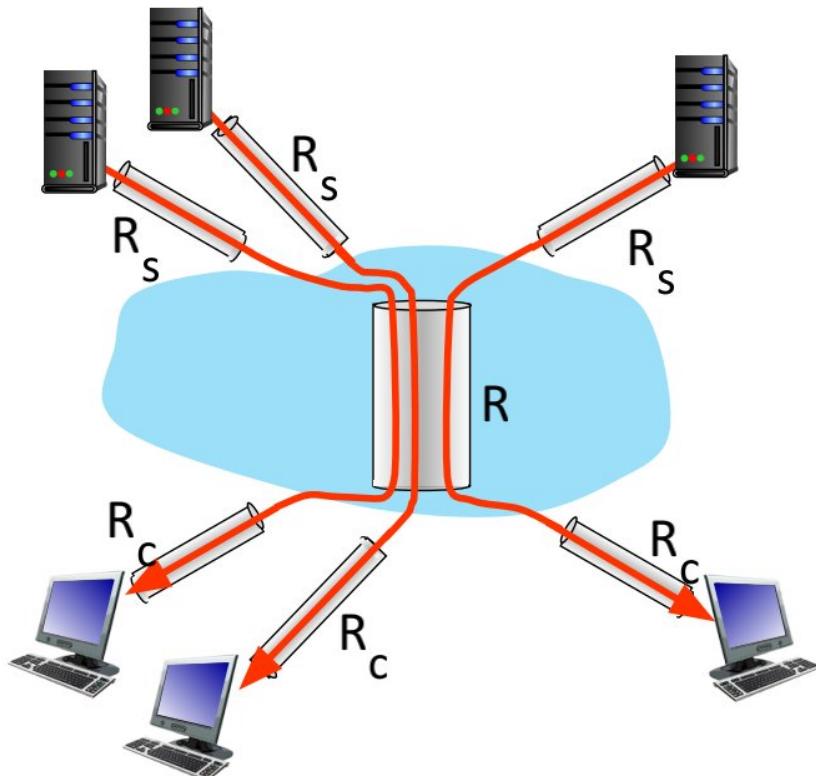


bottleneck link

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

Introduction: 1-92

Throughput: network scenario



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

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

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/

throughput

- Throughput in a packet-switched network refers to the rate at which data can be transmitted over the network link. It is usually measured in *bits per second (bps)* or *packets per second (pps)*. Throughput depends upon various factors -
- **Link Capacity** - The maximum data rate that the physical link can support. It is determined by the link's transmission rate and bandwidth.
- **Network Congestion** - High levels of network congestion can reduce throughput as packets experience more queueing delay and compete for available bandwidth.

throughput

- **Protocols Overhead** - Packet-switched networks use various protocols to manage and control data transmission. These protocols add some overhead, which can slightly reduce the actual throughput.
- **Routing Efficiency** - The efficiency of the routing algorithms and protocols used in the network can impact how quickly packets reach their destination.
- Throughput is crucial for applications that require high data transfer rates, such as file downloads, streaming, and data-intensive processes.

Chapter 2

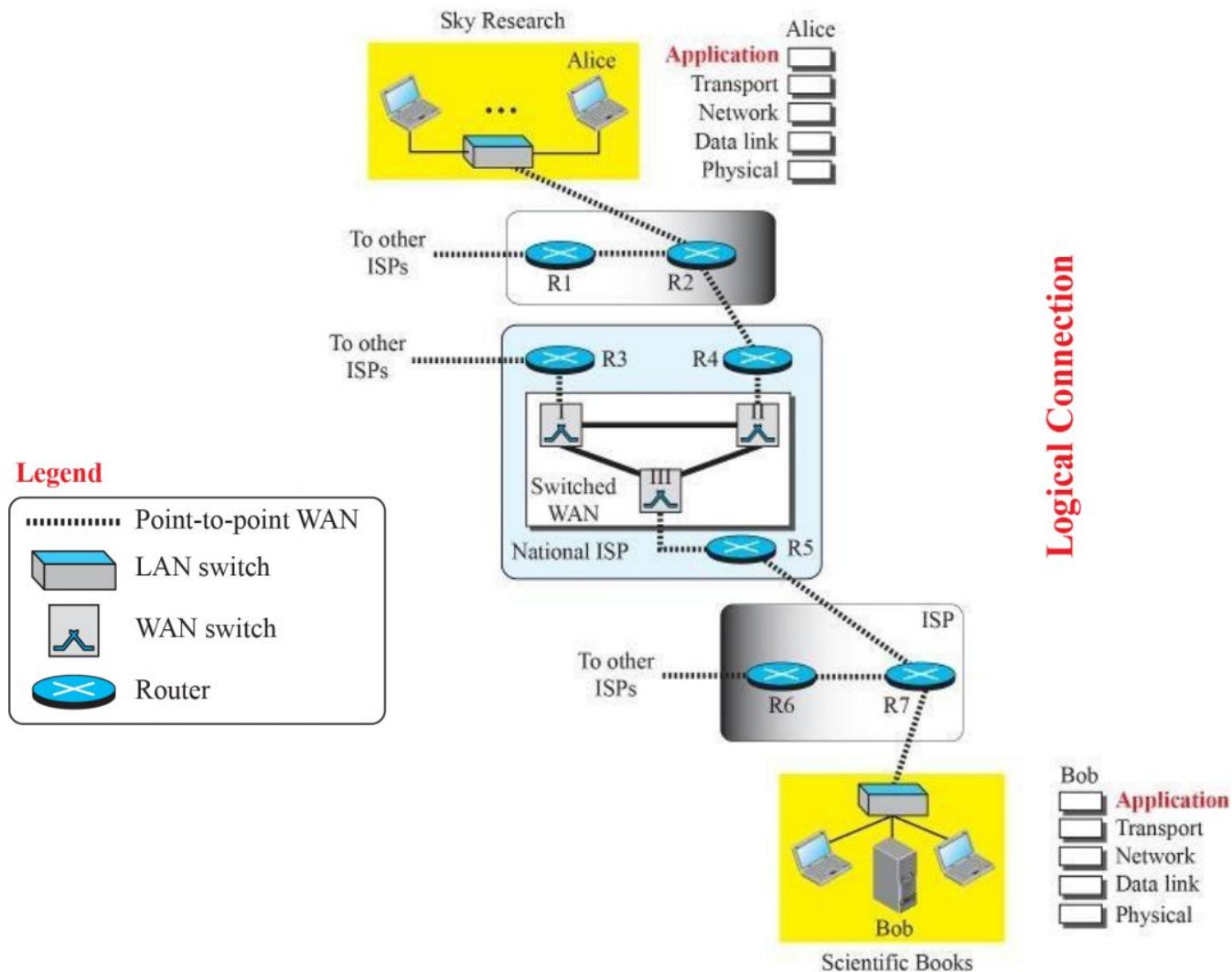
APPLICATION LAYER



Scanned with OKEN Scanner

Topics

- Domain Name Space (DNS)
- Electronic Mail
- HTTP
- Delay and throughput in Packet- switched Network



Providing services

- Internet's Original Purpose:

- Global service provision to worldwide users.

- Significance of Application Layer:

- Sole provider of services to Internet users.
 - Enables seamless addition of new application protocols.

- Evolution of Application Protocols:

- Internet's lifetime was marked by protocol expansion.
 - Initial availability of a limited number of protocols.
 - Constant addition of new protocols over time.

Functions of Application Layer

Application Layer provides a facility by which users can forward several **emails** and it also provides a **storage facility**. This layer allows users to access, retrieve and manage **files** in a remote computer. It allows users to log on as a **remote host**. It provides protocols that allow software to send and receive information and present meaningful data to users.

It handles issues such as **network transparency**, **resource allocation** and so on. The application layer is actually an **abstraction layer** that specifies the **shared protocols** and **interface methods** used by hosts in a communication network.

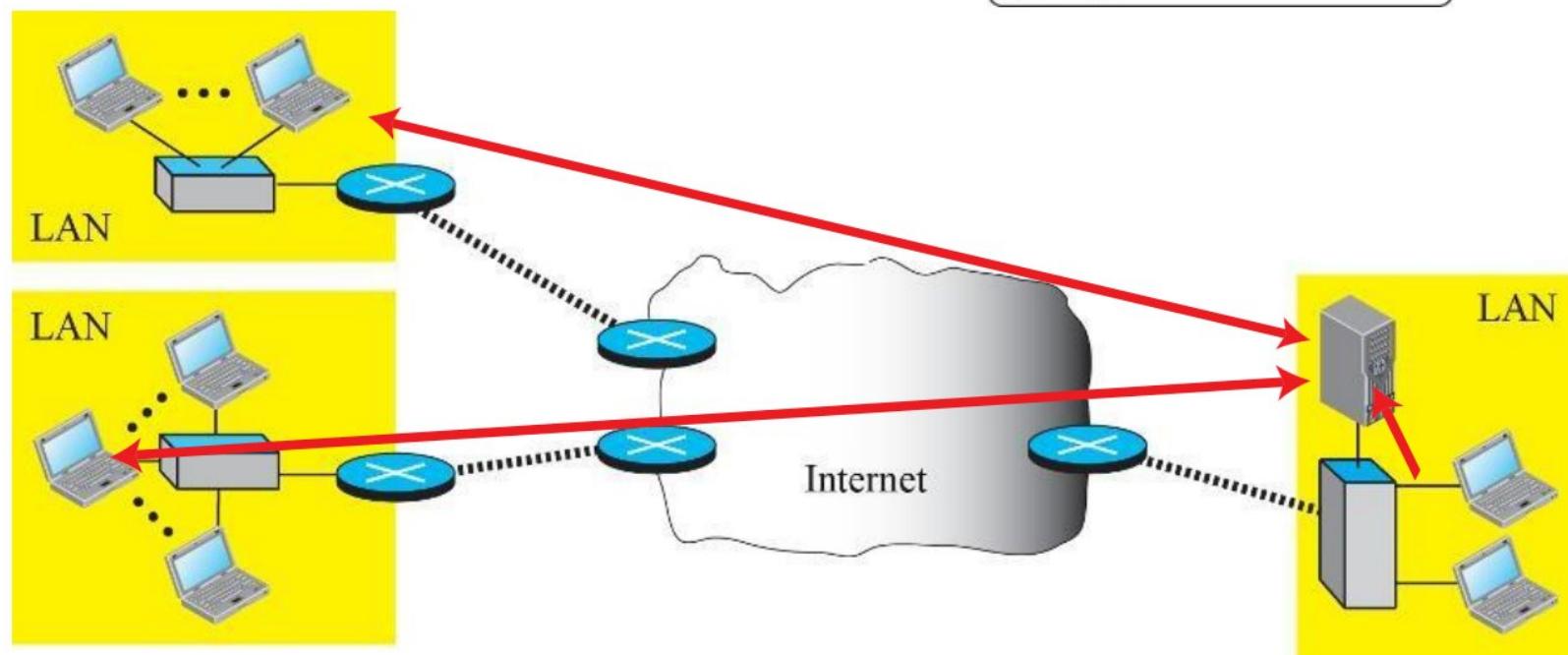
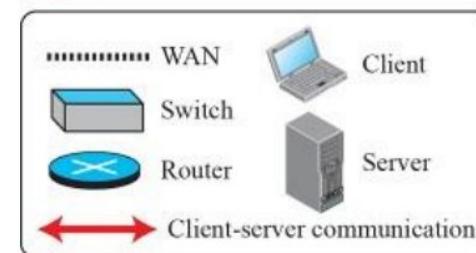
This application layer basically **interacts with Operating System (OS)** and thus further preserves the data in a suitable manner.

This layer allows users to **interact** with other **software applications**.

In this layer, data is in visual form, which makes users truly understand data rather than remembering or visualize the data in the binary format (0's or 1's).

Client-server paradigm

Legend



Client-Server Model/Architecture

The Client-server model is a distributed application structure that partitions task or workload between the providers of a resource or service, called **servers**, and service requesters called **clients**.

In the client-server architecture, when the client computer sends a request for data to the server through the internet, the server accepts the requested process and deliver the data packets requested back to the client.

Clients do not share any of their resources.

Examples of Client-Server Model are Email, World Wide Web, etc.

How the browser interacts with the servers ?

There are few steps to follow to interact client with the servers.

User enters the **URL**(Uniform Resource Locator) of the website or file. The Browser then requests the **DNS**(DOMAIN NAME SYSTEM) Server.

DNS Server lookup for the address of the **WEB Server**.

DNS Server responds with the **IP address** of the **WEB Server**.

Browser sends over an **HTTP/HTTPS** request to **WEB Server's IP** (provided by **DNS server**).

Server sends over the necessary files of the website.

Browser then renders the files and the website is displayed. This rendering is done with the help of **DOM** (Document Object Model) interpreter, **CSS** interpreter and **JS Engine** collectively known as the **JIT** or (Just in Time) Compilers.

Advantages of Client-Server model:

Centralized system with all data in a single place.

Cost efficient requires less maintenance cost and Data recovery is possible.

The capacity of the Client and Servers can be changed separately.

Disadvantages of Client-Server model:

Clients are prone to viruses, Trojans and worms if present in the Server or uploaded into the Server.

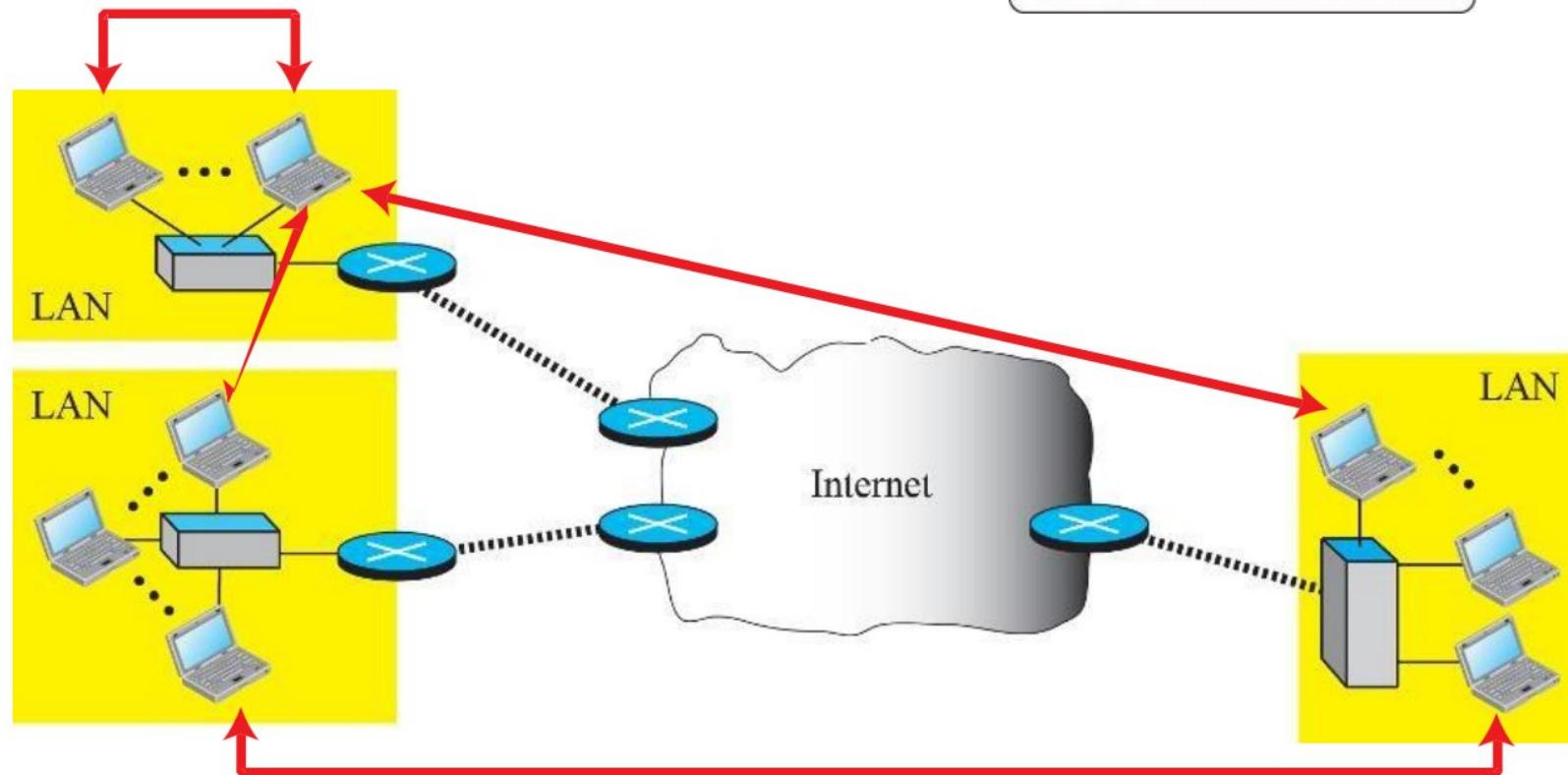
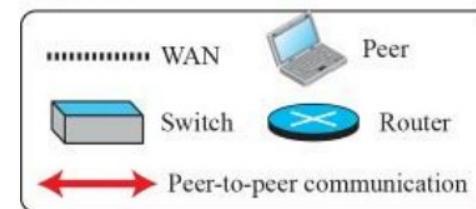
Server are prone to Denial of Service (DOS) attacks.

Data packets may be spoofed or modified during transmission.

Phishing or capturing login credentials or other useful information of the user are common and MITM(Man in the Middle) attacks are common.

Peer-to-peer Paradigm

Legend



Peer-to-Peer Architecture

A peer-to-peer network is a simple network of computers.

It first came into existence in the late 1970s.

Here each computer acts as a node for file sharing within the formed network.

Here each node acts as a server and thus there is no central server in the network.

This allows the sharing of a huge amount of data.

The tasks are equally divided amongst the nodes.

Each node connected in the network shares an equal workload.

For the network to stop working, all the nodes need to individually stop working. This is because each node works independently.

eg - Bit-torrent, Skype

Types of P2P networks

Unstructured P2P networks: In this type of P2P network, each device is able to make an equal contribution.

This network is easy to build as devices can be connected randomly in the network.

For example, Napster, Gnutella, etc.

Structured P2P networks: It is designed using software that creates a virtual layer in order to put the nodes in a specific structure.

These are not easy to set up but can give easy access to users to the content.

For example, P-Grid, Kademlia, etc.

Hybrid P2P networks: It combines the features of both P2P networks and client-server architecture.

Features of P2P network

These networks do not involve a large number of nodes, usually less than 12.

All the computers in the network store their own data but this data is accessible by the group.

Unlike client-server networks, P2P uses resources and also provides them. This results in additional resources if the number of nodes increases. It requires specialized software. It allows resource sharing among the network.

Since the nodes act as clients and servers, there is a constant threat of attack.

Almost all OS today support P2P networks.

Advantages of P2P Network

Easy to maintain: The network is easy to maintain because each node is independent of the other.

Less costly: Since each node acts as a server, therefore the cost of the central server is saved. Thus, there is no need to buy an expensive server.

No network manager: In a P2P network since each node manages his or her own computer, thus there is no need for a network manager.

Adding nodes is easy: Adding, deleting, and repairing nodes in this network is easy.

Less network traffic: In a P2P network, there is less network traffic than in a client/ server network.

Disadvantages of P2P Network

Data is vulnerable: Because of no central server, data is always vulnerable to getting lost because of no backup.

Less secure: It becomes difficult to secure the complete network because each node is independent.

Slow performance: In a P2P network, each computer is accessed by other computers in the network which slows down the performance of the user.

Files hard to locate: In a P2P network, the files are not centrally stored, rather they are stored on individual computers which makes it difficult to locate the files.

Electronic mail

At the beginning of the Internet era, the messages sent by electronic mail were short and consisted of text only. Today, electronic mail is much more complex. It allows a message to include text, audio, and video. It also allows one message to be sent to one or more recipients.

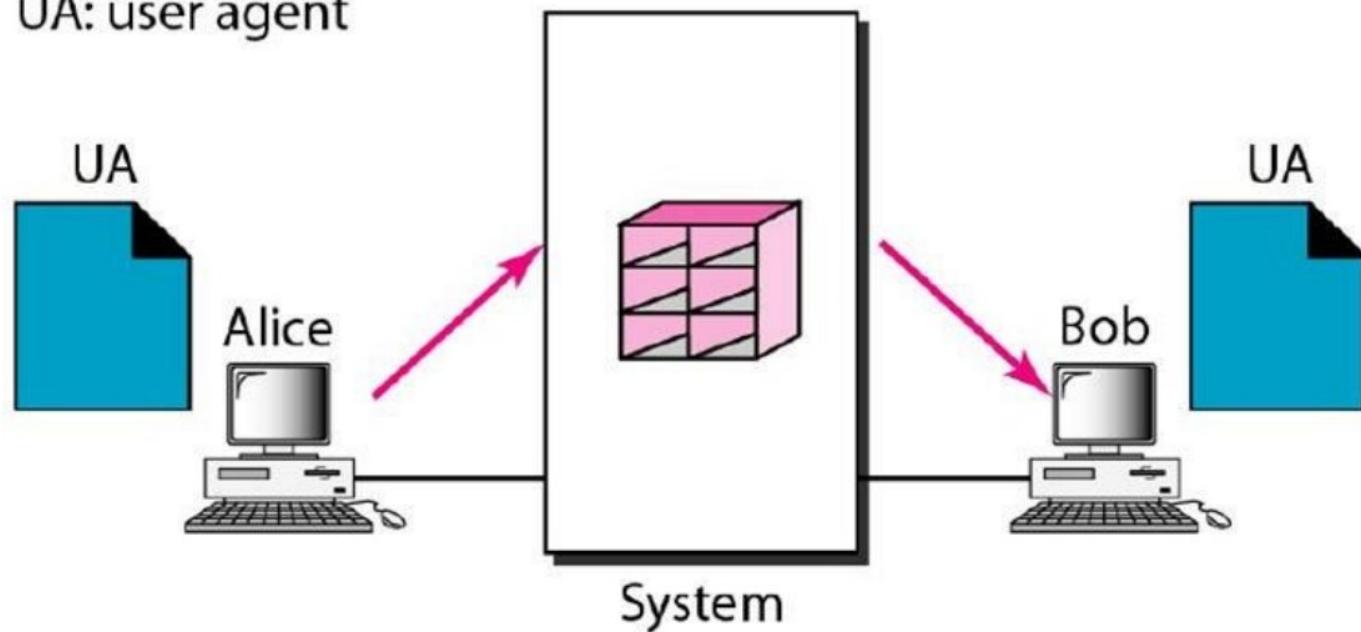
Architecture

To explain the architecture of e-mail, we give four scenarios. We begin with the simplest situation and add complexity as we proceed. The fourth scenario is the most common in the exchange of email.

First Scenario

- In the first scenario, the sender and the receiver of the e-mail are users (or application programs) on the **same system**; they are directly connected to a shared system.
- The administrator has created one **mailbox** for each user where the received messages are stored. A *mailbox* is part of a **local hard drive**, a special file with permission restrictions.
- Only the owner of the mailbox has **access** to it.
- When Alice, a user, needs to send a message to Bob, another user, Alice runs a **user agent (UA)** program to prepare the message and **UA itself** will store it in Bob's mailbox.
- The message has the sender and recipient mailbox addresses (names of files).
- Bob can retrieve and **read the contents** of his mailbox at his convenience, **using a user agent**. Figure below shows the concept.

UA: user agent

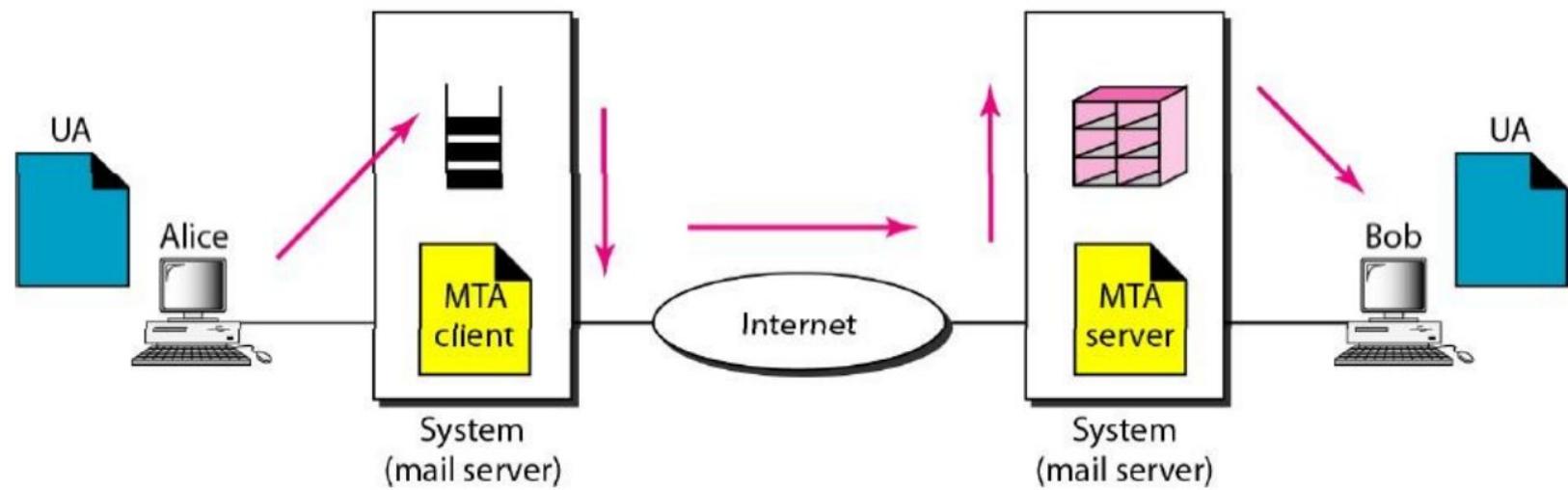


Second Scenario

- In the second scenario, the sender and the receiver of the e-mail are users (or application programs) on **two different systems**.
- So the message needs to be sent over the Internet.
- Here we need **user agents (UAs)** and **message transferagents (MTAs)**, as shown in figure below.
- Alice needs to use a **user agent** program to **send** her message to the system **at her own site**.
- The computer (sometimes called the **mail server**) at her site manages all the messages received and makes a **mail queue** to store messages waiting to be sent.
- MTA client keeps on checking the queue and when there is message then it will try to establish connection with MTA server and when connection is established then it pick the messages from queue and send them over internet to MTA server which is running at system from which bob is connected.
- MTA server after receiving messages will store them at mail box of bob.
- Like most client/server programs on the Internet, the server needs to run all the time because it does not know when a client will ask for a connection.
- Bob also needs a **user agent** program to retrieve messages stored in the mailbox of the system at his site.

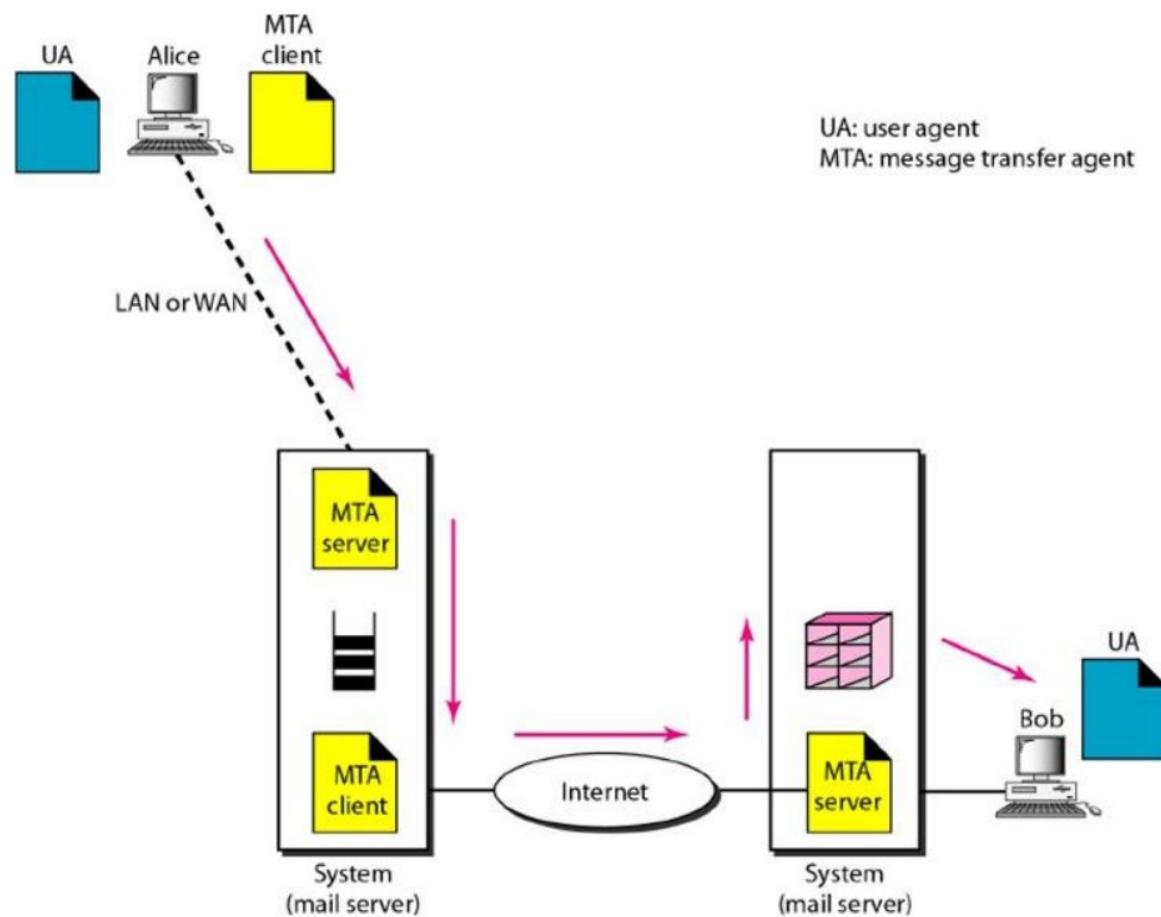
UA: user agent

MTA: message transfer agent



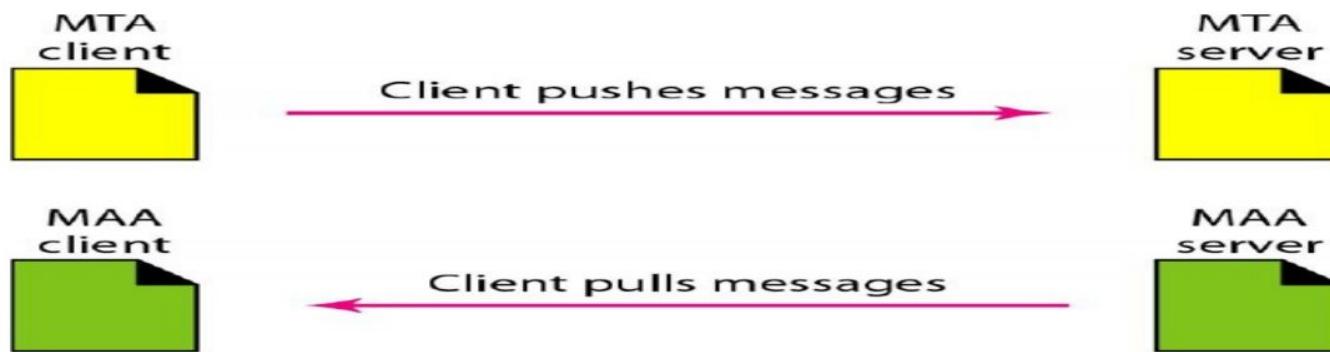
Third Scenario

- In the third scenario, Bob, as in the second scenario, is directly connected to his system.
- Alice, however, is separated from her system.
- Either Alice is connected to the system via a point-to-point WAN, such as a dial-up modem, a DSL, or a cable modem; or she is connected to a LAN in an organization that uses one mail server for handling e-mails-all users need to send their messages to this mail server. Figure below shows the situation.
- Alice still needs a user agent to prepare her message. She then needs to send the message through the LAN or WAN. This can be done through a pair of message transfer agents (client and server).
- Whenever Alice has a message to send, she calls the user agent which, in turn, calls the MTA client. The MTA client establishes a connection with the MTA server on the system, which is running all the time.
- The mail server computer at Alice's site manages all messages received and makes a mail queue. MTA client keeps on checking this queue and whenever there are messages to send it establishes a connection with MTA server at Bob's site and sends the messages. This server receives the messages and stores it in Bob's mailbox.
- At his convenience, Bob uses his user agent to retrieve the message and reads it.

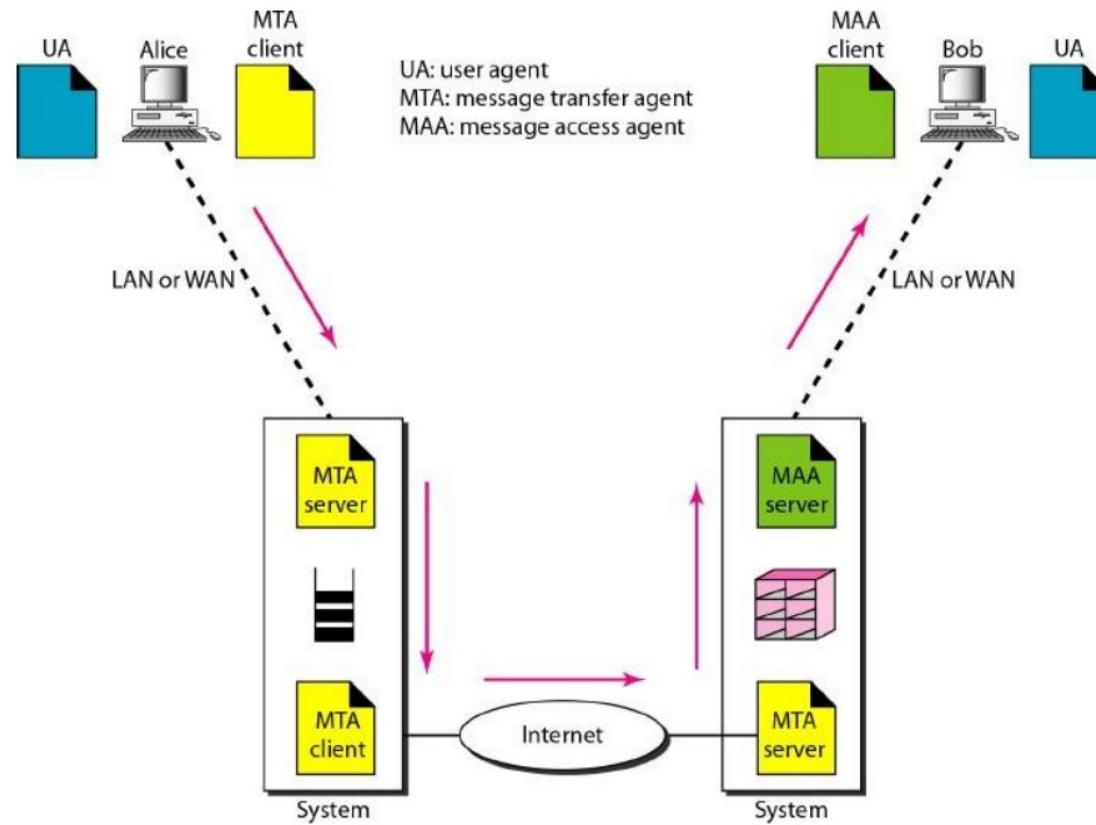


Fourth Scenario

- In the fourth and **most common scenario**, Bob is also connected to his mail server by a WAN or a LAN. After the message has arrived at Bob's mail server, Bob needs to retrieve it.
- We can't use MTA client at Bob's computer MTA server at mail server computer. This is because MTA client is a **push program** which pushes the messages to MTA server, it can't pull messages from MTA server.
- Other option is use MTA server at Bob's computer which is impossible as now Bob can't shut down her computer because she doesn't know when message will arrive.
- Hence, we need another set of client/server agents, which we call **message access agents (MAAs)**.
- Unlike MTA client, MAA client is a **pull program** and it can pull messages from MAA server.



- So Bob uses an MAA client to retrieve his messages. The client sends a request to the MAA server, which is running all the time, and requests the transfer of the messages. Figure on next page shows the situation.

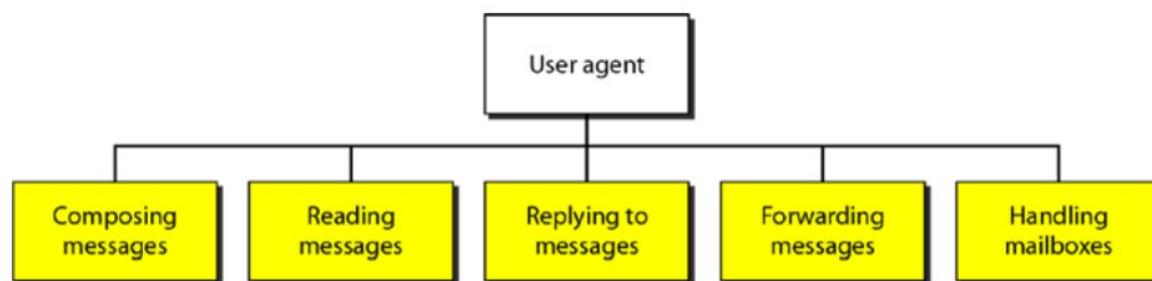


USER AGENT

The first component of an electronic mail system is the user agent (UA). It provides service to the user to make the process of sending and receiving a message easier. Best known example is Microsoft outlook.

Services Provided by a User Agent

A user agent is a software package (program) that composes, reads, replies to, and forwards messages. It also handles mailboxes. Figure below shows the services of a typical user agent.



User Agent Types

There are two types of user agents

1. Command-Driven

- Command-driven user agents belong to the early days of electronic mail. They are still present as the underlying user agents in servers.
- A command-driven user agent normally accepts a one-character command from the keyboard to perform its task. For example, a user can type the character r, at the command prompt, to reply to the sender of the message, or type the character R to reply to the sender and all recipients.
- Some examples of command-driven user agents are mail, pine, and elm.

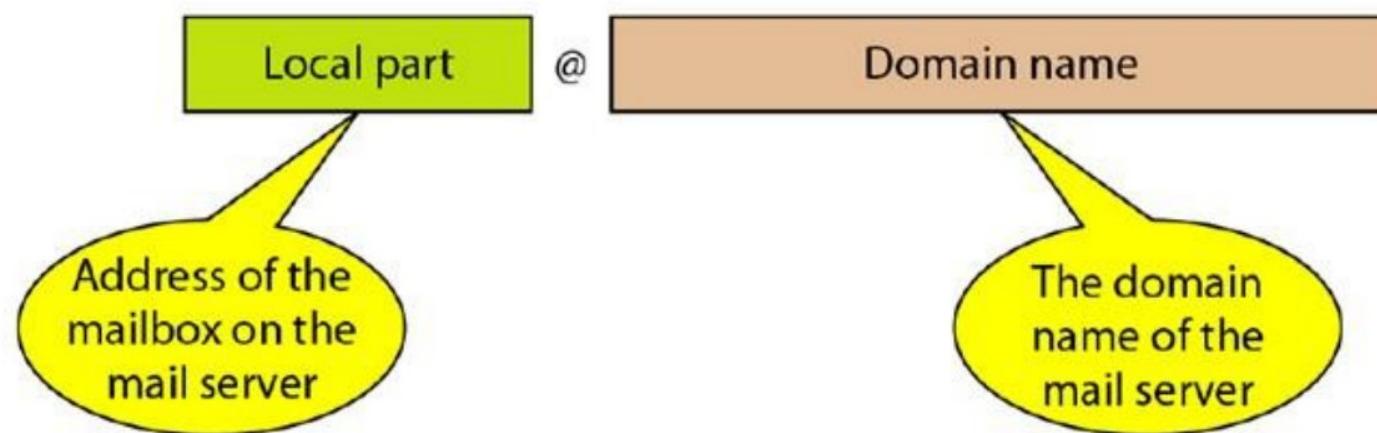
2. GUI-Based

- Modem user agents are GUI-based. They contain graphical-user interface (GUI) components that allow the user to interact with the software by using both the keyboard and the mouse.
- They have graphical components such as icons, menu bars, and windows that make the services easy to access.
- Some examples of GUI-based user agents are Eudora, Microsoft's Outlook, and Netscape.



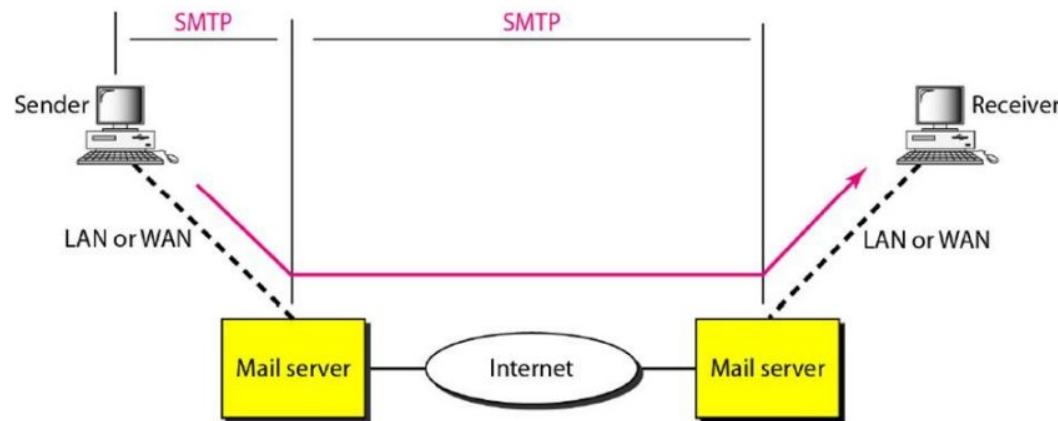
Addresses

To deliver mail, a mail handling system must use an addressing system with unique addresses. In the Internet, the address consists of two parts: a local part and a domain name, separated by an @ sign (see Figure below).

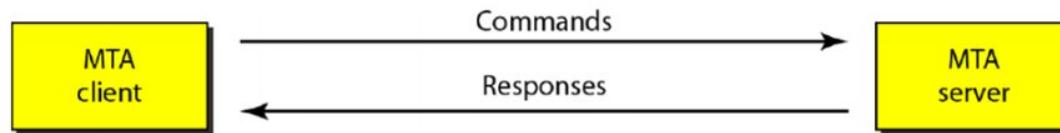


Message Transfer Agent : SMTP

- The actual mail transfer is done through message transfer agents. To send mail, a system must have the client MTA, and to receive mail, a system must have a server MTA.
- The **formal protocol that defines the MTA client and server in the Internet is called the Simple Mail Transfer Protocol (SMTP)**. As we said before, two pairs of MTA client/server programs are used in the most common situation (fourth scenario). Figure below shows the range of the SMTP protocol in this scenario.



- SMTP is used two times, between the sender and the sender's mail server and between the two mail servers.
- It is a connection-oriented protocol and uses **TCP with port number 25**.
- SMTP simply defines how commands and responses must be sent back and forth. MTA client sends the command and server sends the responses (see Figure below).



SMTP COMMANDS

HELO. This command is used by the client to identify itself.

MAIL FROM. This command is used by the client to identify the sender of the message.

RCPT TO. This command is used by the client to identify the intended recipient of the message.

DATA. This command is used to send the actual message.

QUIT. This command terminates the message.

RSET. This command aborts the current mail transaction.

VRFY. This command is used to verify the address of the recipient.

NOOP. This command is used by the client to check the status of the recipient

TURN. This command lets the sender and the recipient switch positions, whereby the sender becomes the recipient and vice versa

EXPN. This command can verify the existence of one or more mailboxes on the system.

HELP. This command asks the recipient to send information about the command sent as the argument.

SEND FROM. This command specifies that the mail is to be delivered to the terminal of the recipient, and not the mailbox.

SMOL FROM. This command specifies that the mail is to be delivered to the terminal or the mailbox of the recipient.

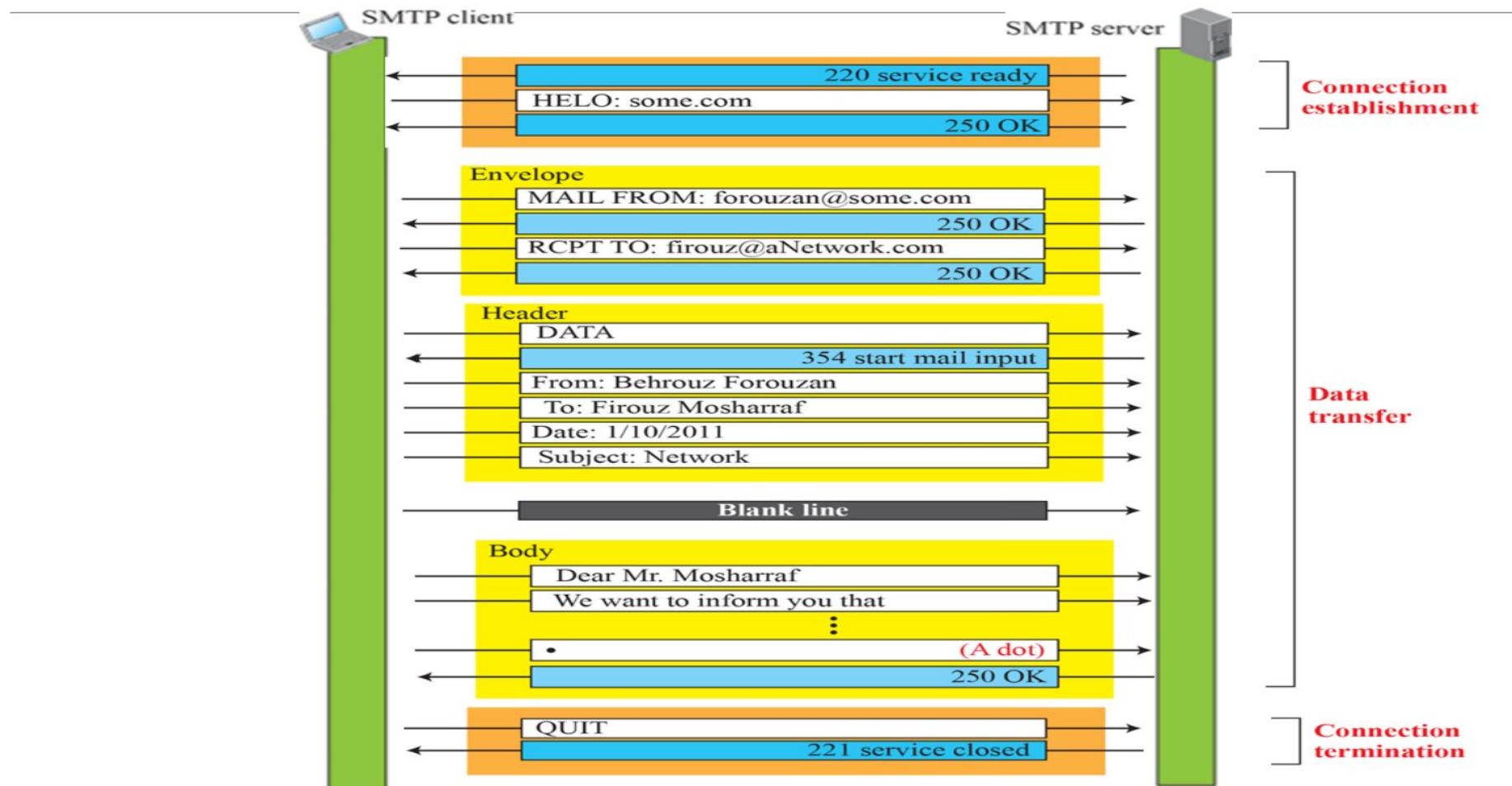
SMAL FROM. This command specifies that the mail is to be delivered to the terminal and the mailbox of the recipient.



SMTP Responses

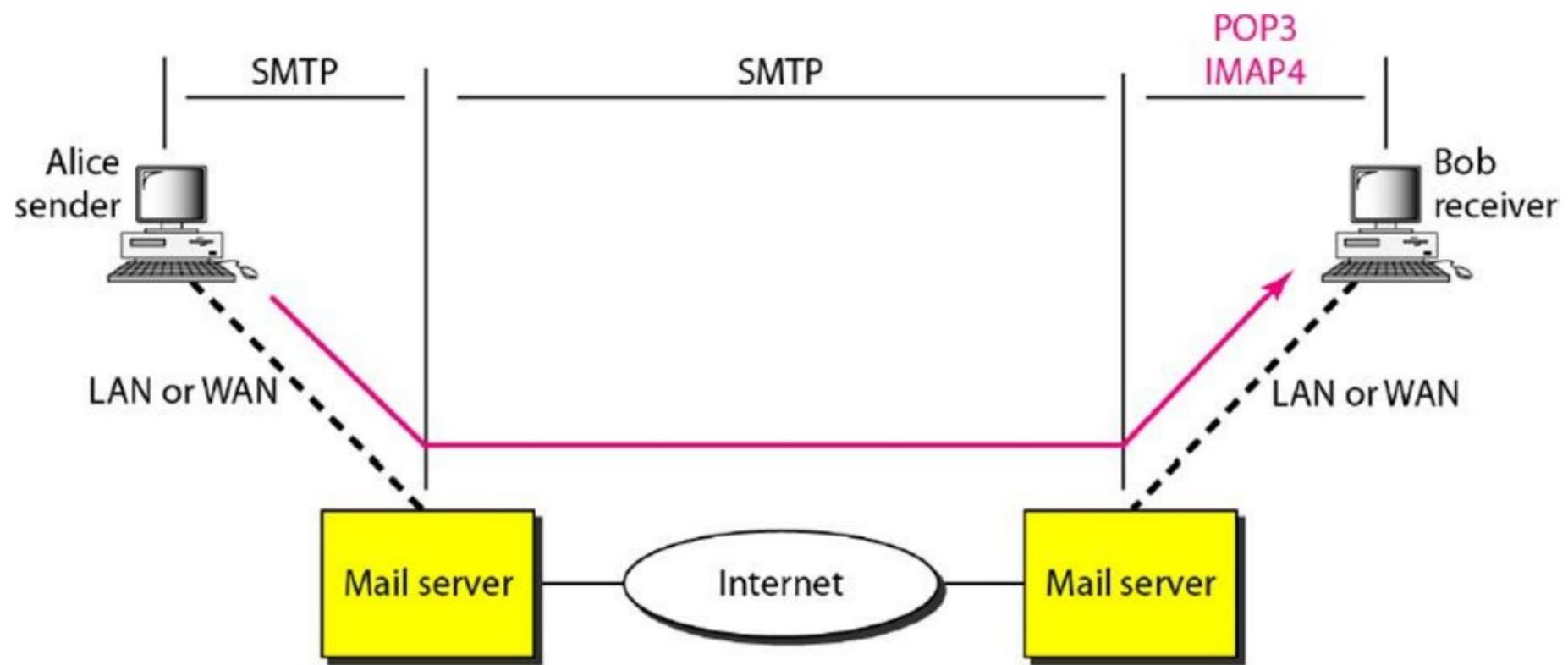
<i>Code</i>	<i>Description</i>
Positive Completion Reply	
211	System status or help reply
214	Help message
220	Service ready
221	Service closing transmission channel
250	Request command completed
251	User not local; the message will be forwarded
Positive Intermediate Reply	
354	Start mail input
Transient Negative Completion Reply	
421	Service not available
450	Mailbox not available
451	Command aborted: local error
452	Command aborted; insufficient storage

To show the three mail transfer phases, we show all of the steps described above using the information depicted in Figure 2.23. In the figure, we have separated the messages related to the envelope, header, and body in the data transfer section. Note that the steps in this figure are repeated two times in each e-mail transfer: once from the e-mail sender to the local mail server and once from the local mail server to the remote mail server. The local mail server, after receiving the whole e-mail message, may spool it and send it to the remote mail server at another time.



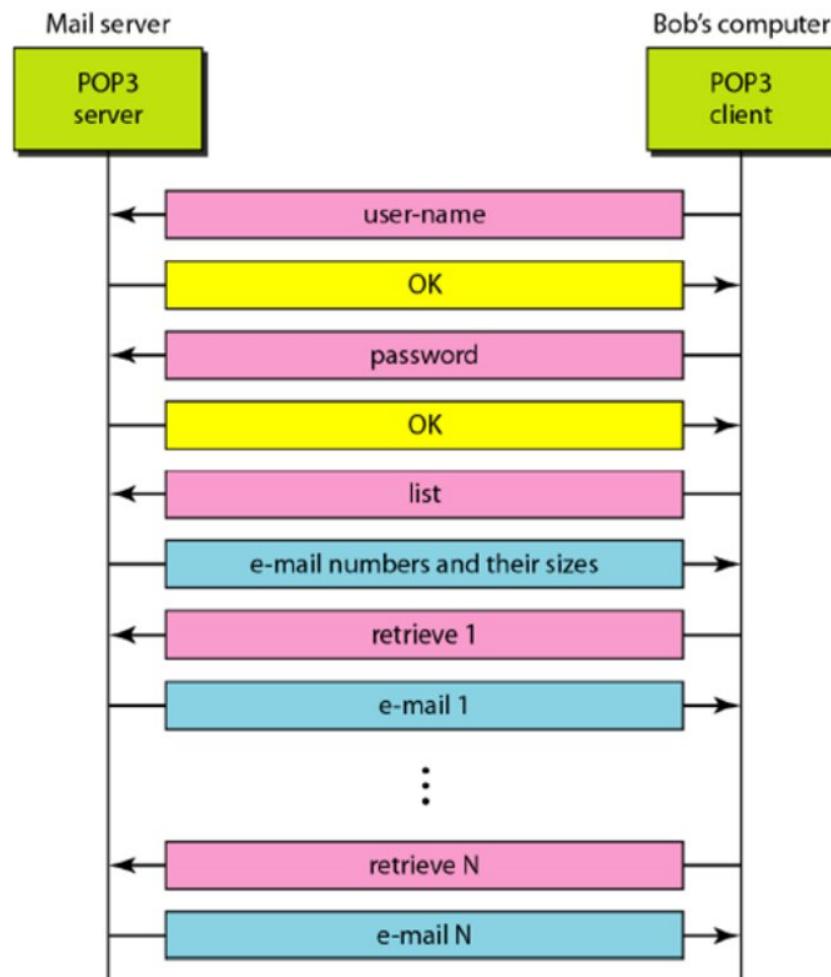
Message Access Agent: POP and IMAP

- The first and the second stages of mail delivery use SMTP. However, SMTP is not involved in the third stage because SMTP is a push protocol; it pushes the message from the client to the server. In other words, the direction of the bulk: data (messages) is from the client to the server.
- On the other hand, the third stage needs a pull protocol; the client must pull messages from the server. The direction of the bulk data is from the server to the client. The third stage uses a message access agent.
- Currently two message access protocols are available: Post Office Protocol, version 3 (POP3) and Internet Mail Access Protocol, version 4 (IMAP4). Figure below shows the position of these two protocols in the most common situation (fourth scenario).



POP3

- Post Office Protocol, version 3 (POP3) is **simple and limited in functionality**. The client POP3 software is installed on the recipient computer; the server POP3 software is installed on the mail server.
- Mail access starts with the client when the user needs to download e-mail from the mailbox on the mail server.
 - The client opens a connection to the server **on TCP port 110**.
 - It then sends its **user name and password** to access the mailbox. The user can then list and retrieve the mail messages, one by one. Figure below shows an example of downloading using POP3.



- POP3 has two modes: the **delete mode and the keep mode**.
 - In the delete mode, the mail is deleted from the mailbox after each retrieval. In the keep mode, the mail remains in the mailbox after retrieval.
 - The delete mode is normally used when the user is working at her permanent computer and can save and organize the received mail after reading or replying.
 - The keep mode is normally used when the user accesses her mail away from her primary computer (e.g., a laptop). The mail is read but kept in the system for later retrieval and organizing.

IMAP4

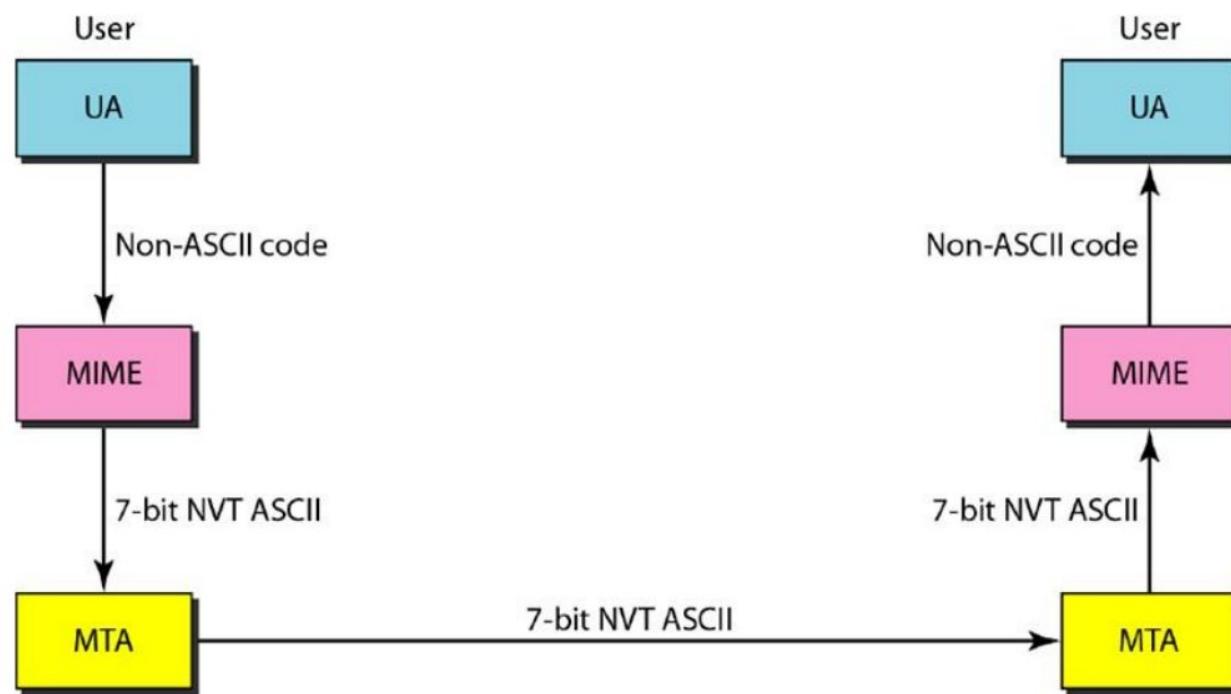
IMAP4 uses TCP port number 143 and **provides the following extra functions which are not provided by POP3**

- A user can check the e-mail header prior to downloading.
- A user can search the contents of the e-mail for a specific string of characters prior to downloading.
- A user can partially download e-mail. This is especially useful if bandwidth is limited and the e-mail contains multimedia with high bandwidth requirements.
- A user can create, delete, or rename mailboxes on the mail server.
- A user can create a hierarchy of mailboxes in a folder for e-mail storage.



MIME(multipurpose internet mail extension)

- Electronic mail has a simple structure. Its simplicity, however, comes at a price. It can **send messages only in 7-bit ASCII** format.
- In other words, it has some limitations. For example, it cannot be used for languages that are not supported by 7-bit ASCII characters (such as French, German, Hebrew, Russian, Chinese, and Japanese).
- Also, it cannot be used to send binary files or video or audio data.
- **Multipurpose Internet Mail Extensions (MIME)** is a supplementary protocol that allows non-ASCII data to be sent through e-mail.
- MIME transforms non-ASCII data at the sender site to ASCII data and delivers them to the client MTA to be sent through the Internet. The message at the receiving side is transformed back to the original data.
- We can think of MIME as a set of software functions that transforms non-ASCII data (stream of bits) to ASCII data and vice versa, as shown in Figure below
- MIME allows seven different types of data like audio, video, image etc.



MIME Headers

MIME defines five headers, as shown in Figure, which can be added to the original e-mail header section to define the transformation para

MIME headers

E-mail header	
MIME-Version: 1.1	Content-Type: type/subtype
Content-Transfer-Encoding: encoding type	
Content-ID: message ID	
Content-Description: textual explanation of nontextual contents	
E-mail body	

HTTP



Scanned with OKEN Scanner

HyperText Transfer Protocol (HTTP)

- HTTP defines client-server communication for retrieving web pages.
- Client sends requests; server returns responses.
- Server uses port 80; client uses temporary port.
- HTTP relies on TCP for connection-oriented and reliable communication.
- TCP ensures message reliability and manages errors.
- Connection establishment and termination are essential.
- No need to worry about message errors or loss due to TCP's reliability.

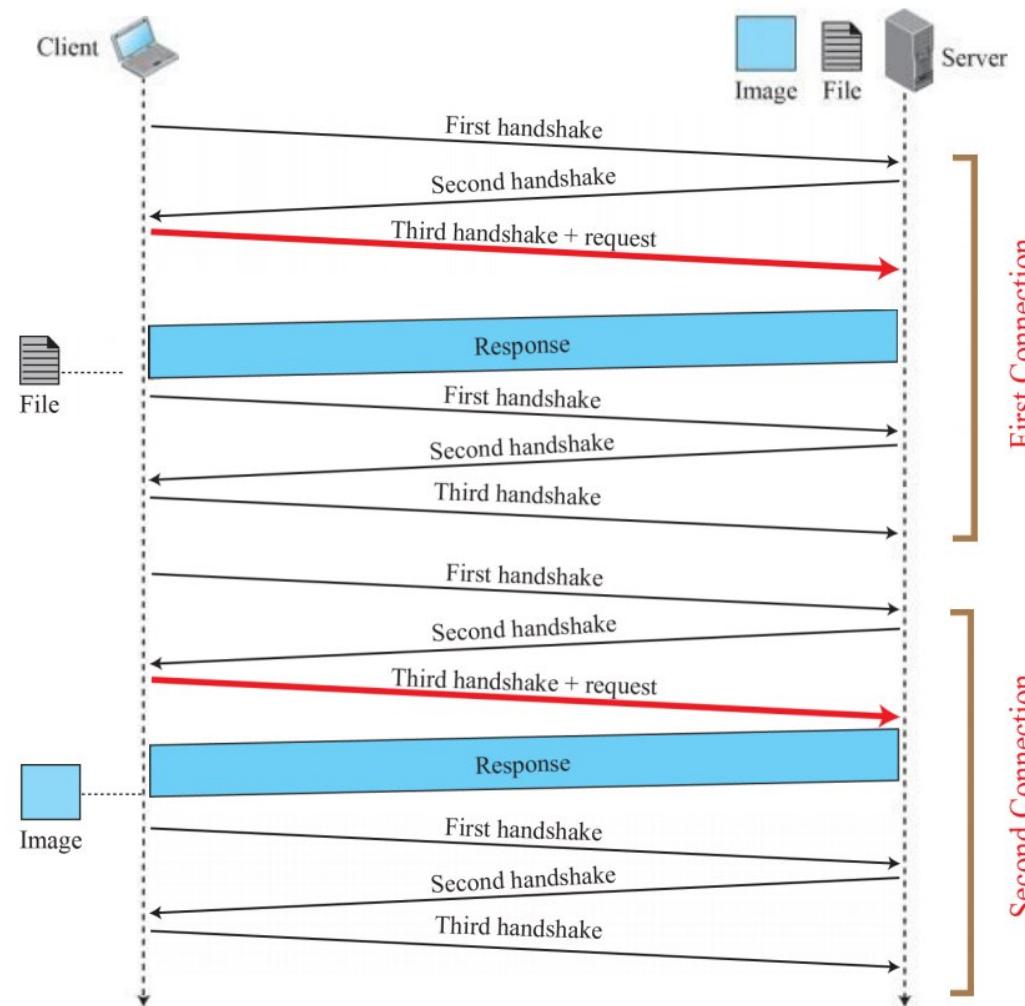
In web pages, multiple requests and responses are often needed due to embedded hypertext. When objects are on different servers, we create new TCP connections for each. If objects are on the same server, we can either use separate connections for each or one connection for all. Separate connections are 'nonpersistent,' while using one connection is 'persistent.' HTTP used to default to nonpersistent (pre-1.1), but version 1.1 made persistent default, user-changeable.

Nonpersistent Connections

In a nonpersistent connection, each request/response uses a new TCP connection:

1. Client opens a connection, sends request.
2. Server sends response, closes connection.
3. Client reads data, closes connection.

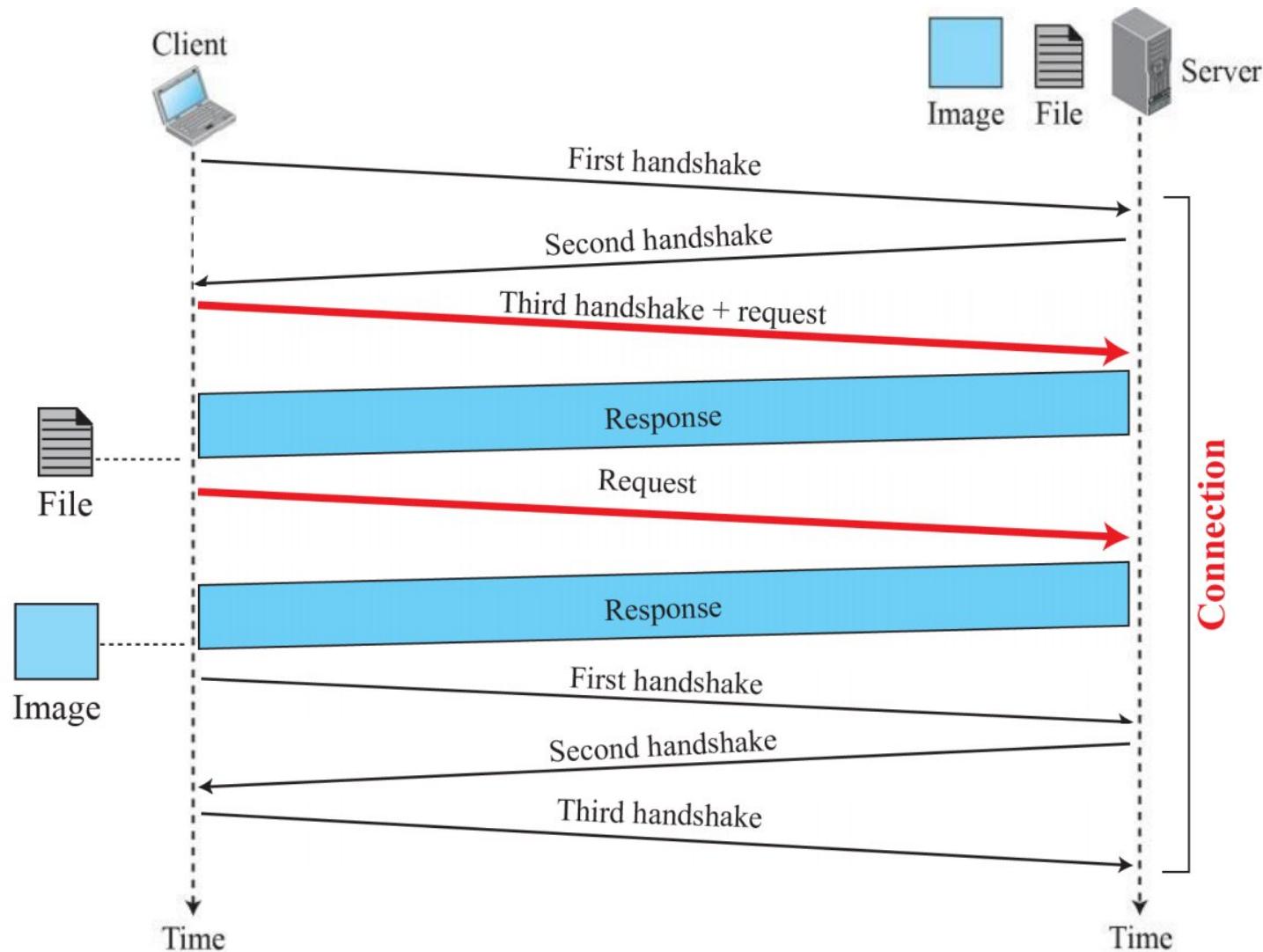
If a file has N picture links on the same server, $N + 1$ connections open and close. This method causes high server overhead due to $N + 1$ buffers needed for each connection.



Persistent Connection

HTTP 1.1 defaults to persistent connections:

- Server keeps **connection open** for more requests after responding.
- **Connection closed** if client requests or times out.
- Sender usually provides **data length** with each response.
- **Dynamic content** might not have known length. Server tells client if length is unknown, closes after sending.
- Persistent connections **save time, resources, and round trips**.
- **One set of buffers and variables needed** per connection.
- Connection setup and termination time saved.



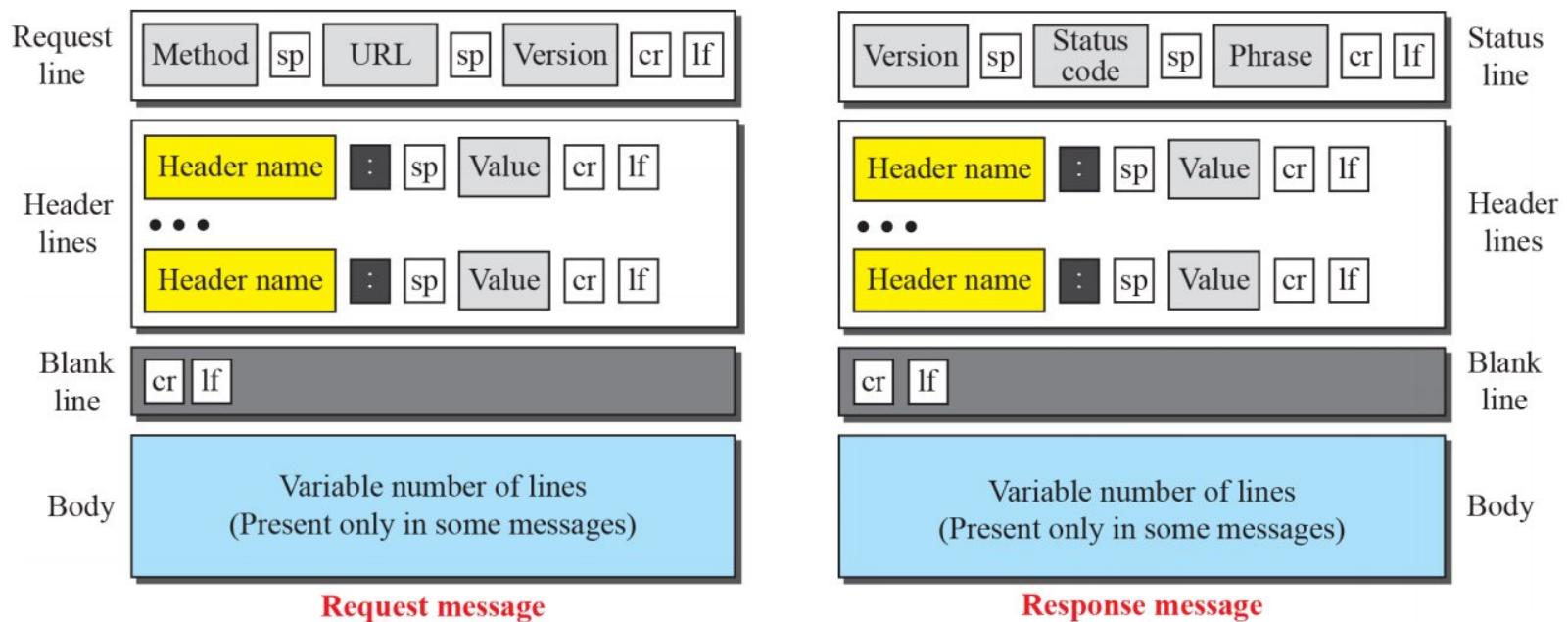
Message Formats

The first section in the request message is called the request line; the first section in the response message is called the status line. The other three sections have the same names in the request and response messages. However, the similarities between these sections are only in the names; they may have different contents.

Request message

Response message

Legend sp: Space cr: Carriage Return lf: Line Feed



Request line → **GET /somefolder/page.html HTTP/1.1**

Header lines → **Host: www.mySchool.edu**
Connection: close
User-agent: Mozilla/5.0
Accept-language: fr

Blank Line →

Entity Body →

HTTP request message

<i>Method</i>	<i>Action</i>
GET	Requests a document from the server
HEAD	Requests information about a document but not the document itself
PUT	Sends a document from the client to the server
POST	Sends some information from the client to the server
TRACE	Echoes the incoming request
DELETE	Removes the web page
CONNECT	Reserved
OPTIONS	Inquires about available options

GET: this method is used when browser request an object with the requested object identified in URL
 POST method is used when a browser send data in entity body field.

unlike GET method user-provided search term (or data does) does not concatenate with url rather it goes in the entity-body field

usually, web-based form's data go via POST method

HEAD method is like a GET method. But, when a server receives a request with HEAD method, it responds with HTTP message but it leaves out the requested object.

PUT method allows a user to upload an object to a specific path (or folder) on a web server.

DELETE method allows to delete an object on a web server.

<i>Header</i>	<i>Description</i>
User-agent	Identifies the client program
Accept	Shows the media format the client can accept
Accept-charset	Shows the character set the client can handle
Accept-encoding	Shows the encoding scheme the client can handle
Accept-language	Shows the language the client can accept
Authorization	Shows what permissions the client has
Host	Shows the host and port number of the client
Date	Shows the current date
Upgrade	Specifies the preferred communication protocol
Cookie	Returns the cookie to the server (explained later)
If-Modified-Since	If the file is modified since a specific date

Response message example

HTTP response message

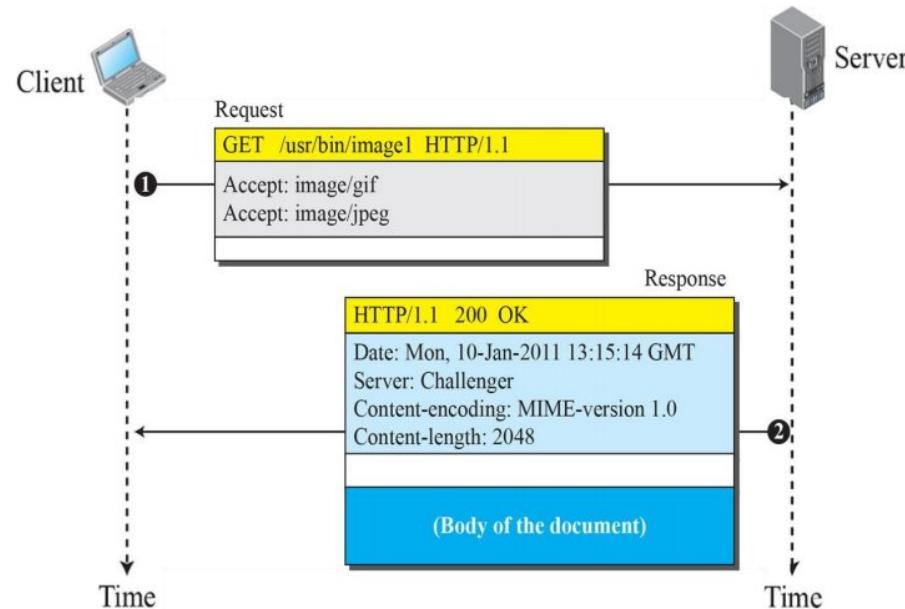
Status line	HTTP/1.1 200 OK
Header lines	Connection: close Date: Fri, 19 Jul 2019 09:25:04 GMT Server: Apache/2.2.3 (CentOS) Last-Modified: Fri, 19 Jul 2019 09:15:02 GMT Content-Length: 6821 Content-Type: text/html
Blank Line	
Entity body	(data data data data ...)

Status Codes and Phrases

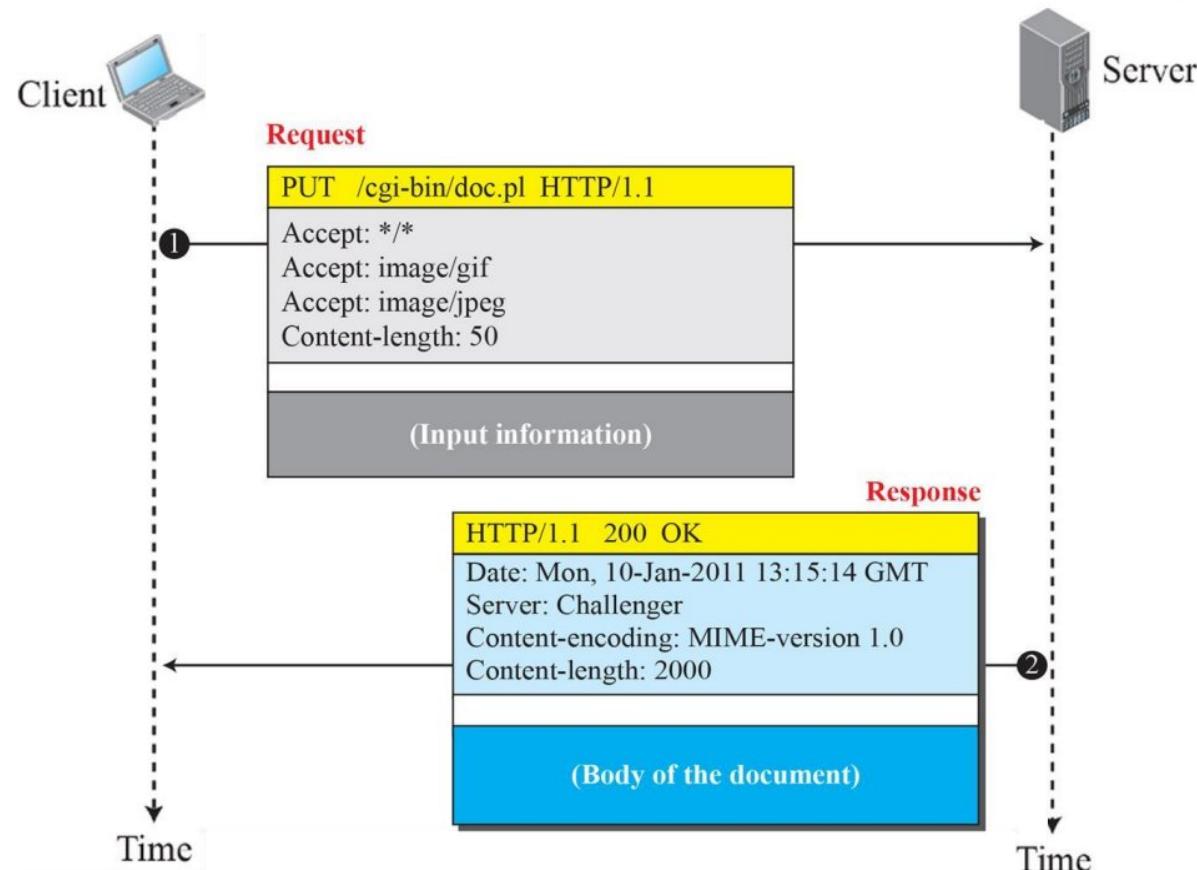
Status Code	Phrase	Description
200	OK	Request succeeded and the information is provided in the response message.
301	Moved Permanently	Requested object has been permanently moved. The new URL is given in <code>Location:</code> header field of the response message. The client software automatically retrieves the new URL.
400	Bad Request	Request could not be understood by the server.
404	Not Found	Requested object does not exist on the server.
505	HTTP Version Not Supported	Requested HTTP version is not supported by the server.

Example1- This example retrieves a document (see Figure 2.13). We use the GET method to retrieve an image with the path /usr/bin/image1. The request line shows the method (GET), the URL, and the HTTP version (1.1). The header has two lines that show that the client can accept images in the GIF or JPEG format. The request does not have a body. The response message contains the status line and four lines of header. The header lines define the date, server, content encoding and length of the document. The body of the document follows the header.

Figure 2.13: Example 2.6



Example 2- In this example, the client wants to send a web page to be posted on the server. We use the PUT method. The request line shows the method (PUT), URL, and HTTP version (1.1). There are four lines of headers. The request body contains the web page to be posted. The response message contains the status line and four lines of headers. The created document, which is a CGI document, is included as the body (see Figure 2.14).



Conditional Request

A client can add a condition in its request. In this case, the server will send the requested web page if the condition is met or inform the client otherwise. **One of the most common conditions imposed by the client is the time and date the web page is modified.** The client can send the header line If-Modified-Since with the request to tell the server that it **needs the page only if it is modified after a certain point in time.**

The following shows how a client imposes the modification data and time condition on a request.

GET http://www.commonServer.com/information/file1 HTTP/1.1

Request line

If-Modified-Since: Thu, Sept 04 00:00:00 GMT

Header line

Blank line

The status line in the response shows the file was not modified after the defined point in time. The body of the response message is also empty.

HTTP/1.1 304 Not Modified

Status line

Date: Sat, Sept 06 08 16:22:46 GMT

First header line

Server: commonServer.com

Second header line

(Empty Body)

Blank line

Empty body

Cookies

The World Wide Web was originally designed as a **stateless entity**. A client sends a request; a server responds. Their relationship is over. The original purpose of the Web, retrieving publicly available documents, exactly fits this design. Today the Web has other functions that need to remember some information about the clients

- Websites are being used as electronic stores that allow users to browse through the store, select wanted items, put them in an electronic cart, and pay at the end with a credit card.
- Some websites need to allow access to registered clients only.
- Some websites are used as portals: the user selects the web pages he wants to see.
- Some websites are just advertising agency.

Creating and Storing Cookies

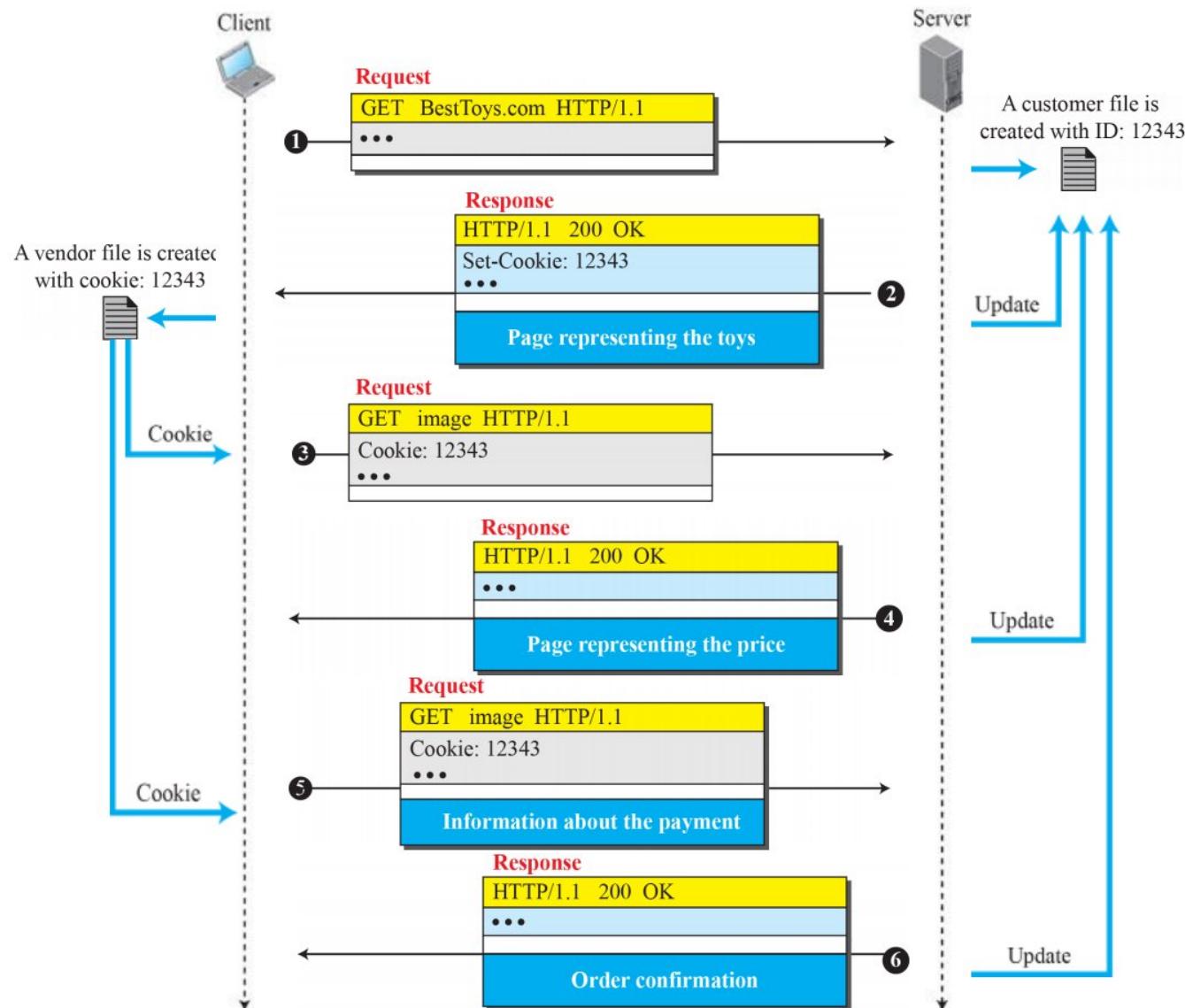
The creation and storing of cookies depend on the implementation; however, the principle is the same.

1. When a server receives a request from a client, it stores information about the client in a file or a string. The information may include the domain name of the client, the contents of the cookie (information the server has gathered about the client such as name, registration number, and so on), a timestamp, and other information depending on the implementation.
2. The server includes the cookie in the response that it sends to the client.
3. When the client receives the response, the browser stores the cookie in the cookie directory, which is sorted by the server domain name.

Using Cookies

- 1. E-commerce Cookie Usage:** An online store uses cookies for shoppers. When a shopper adds an item to their cart, a cookie with item details like number and price is sent. If they add more items, the cookie updates. At checkout, the last cookie calculates the total charge.
- 2. Registered Clients Cookie:** Some websites allow only registered users. A first-time registered client gets a cookie. Later visits require the right cookie to access.
- 3. Web Portal Cookie:** A web portal uses cookies similarly. A user's favorite pages are saved in a cookie. Returning to the site sends the cookie to show the user's preferences.
- 4. Advertising Agency Cookie:** Advertising agencies also use cookies. They place ads on popular sites, sending only a URL. Clicking the ad sends a request to the agency with a cookie containing the user's ID. This builds a profile of the user's web behavior for targeted advertising, which has sparked privacy concerns.

Figure 2.15 shows a scenario in which an electronic store can benefit from the use of cookies. Assume a shopper wants to buy a toy from an electronic store named BestToys. The shopper browser (client) sends a request to the BestToys server. The server creates an empty shopping cart (a list) for the client and assigns an ID to the cart (for example, 12343). The server then sends a response message, which contains the images of all toys available, with a link under each toy that selects the toy if it is being clicked. This response message also includes the Set-Cookie header line whose value is 12343. The client displays the images and stores the cookie value in a file named BestToys.



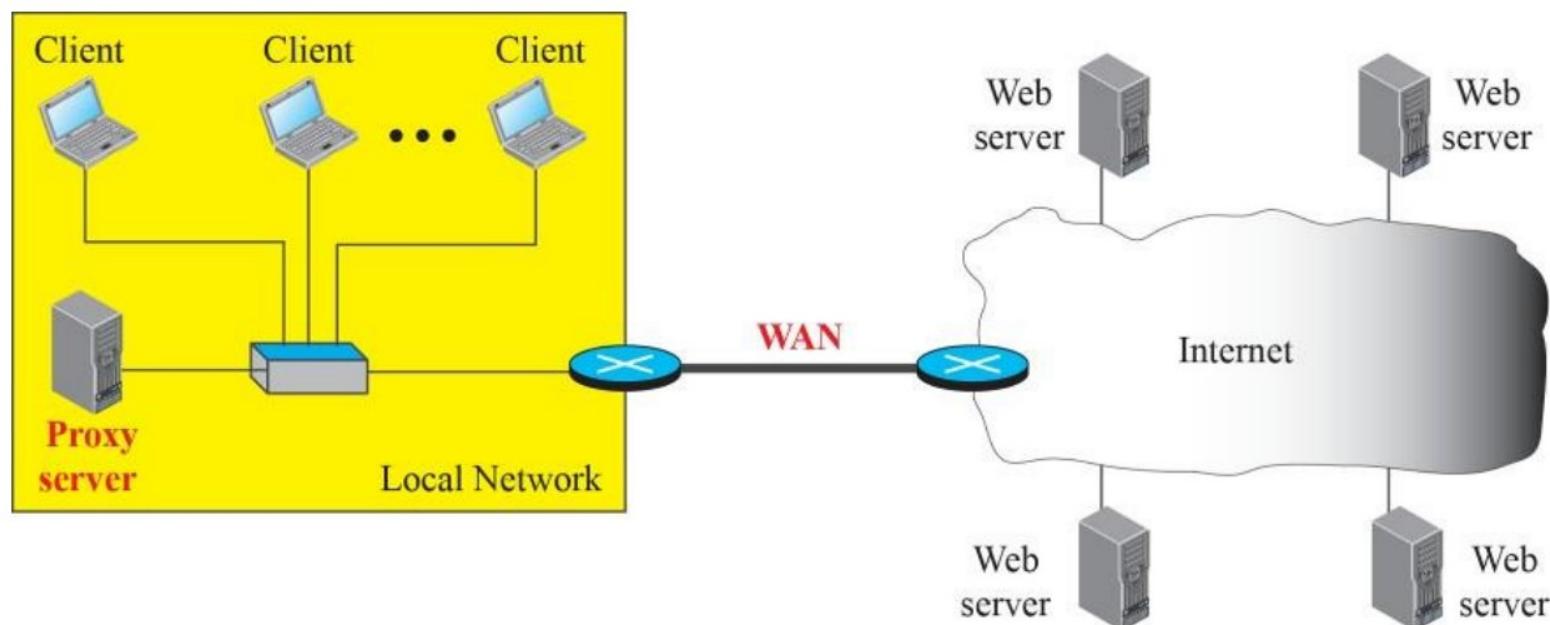
Web Caching: Proxy Server

- HTTP has a feature for proxy servers. These servers store recent response copies. The client sends a request to the proxy server, which checks if the response is cached. If not, it sends the request to the main server. Incoming responses are stored by the proxy server for future requests from other clients.
- The **proxy server lessens the load on the original server, cuts down on traffic, and improves speed**. However, clients must be configured to use the proxy server instead of the main server.
- It's important to know that the proxy server acts as both a server and a client. It **serves responses to clients** when it has them, but it **also acts as a client** to get responses from the main server when it doesn't have them.

Proxy servers are often placed at the client's location, creating a hierarchy:

1. Clients themselves can work as small proxy servers, storing frequently requested responses.
2. Within a company, a proxy server on the LAN reduces incoming and outgoing load.
3. Internet Service Providers (ISPs) with many customers can use proxy servers to ease network load.

Figure 2.16 shows an example of a use of a proxy server in a local network, such as the network on a campus or in a company. The proxy server is installed in the local network. When an HTTP request is created by any of the clients (browsers), the request is first directed to the proxy server. If the proxy server already has the corresponding web page, it sends the response to the client. Otherwise, the proxy server acts as a client and sends the request to the web server in the Internet. When the response is returned, the proxy server makes a copy and stores it in its cache before sending it to the requesting client.



Cashe Update

An important question is how long a response should stay in the proxy server before being removed and replaced. Different strategies are used for this. One idea is to keep a list of websites that don't change often. For example, **a news site might update its news each morning. So, a proxy could get the news in the morning and keep it until the next day.** Another suggestion is to **add headers that show when the information was last changed.** The proxy can use this information to guess how long the data will stay valid.

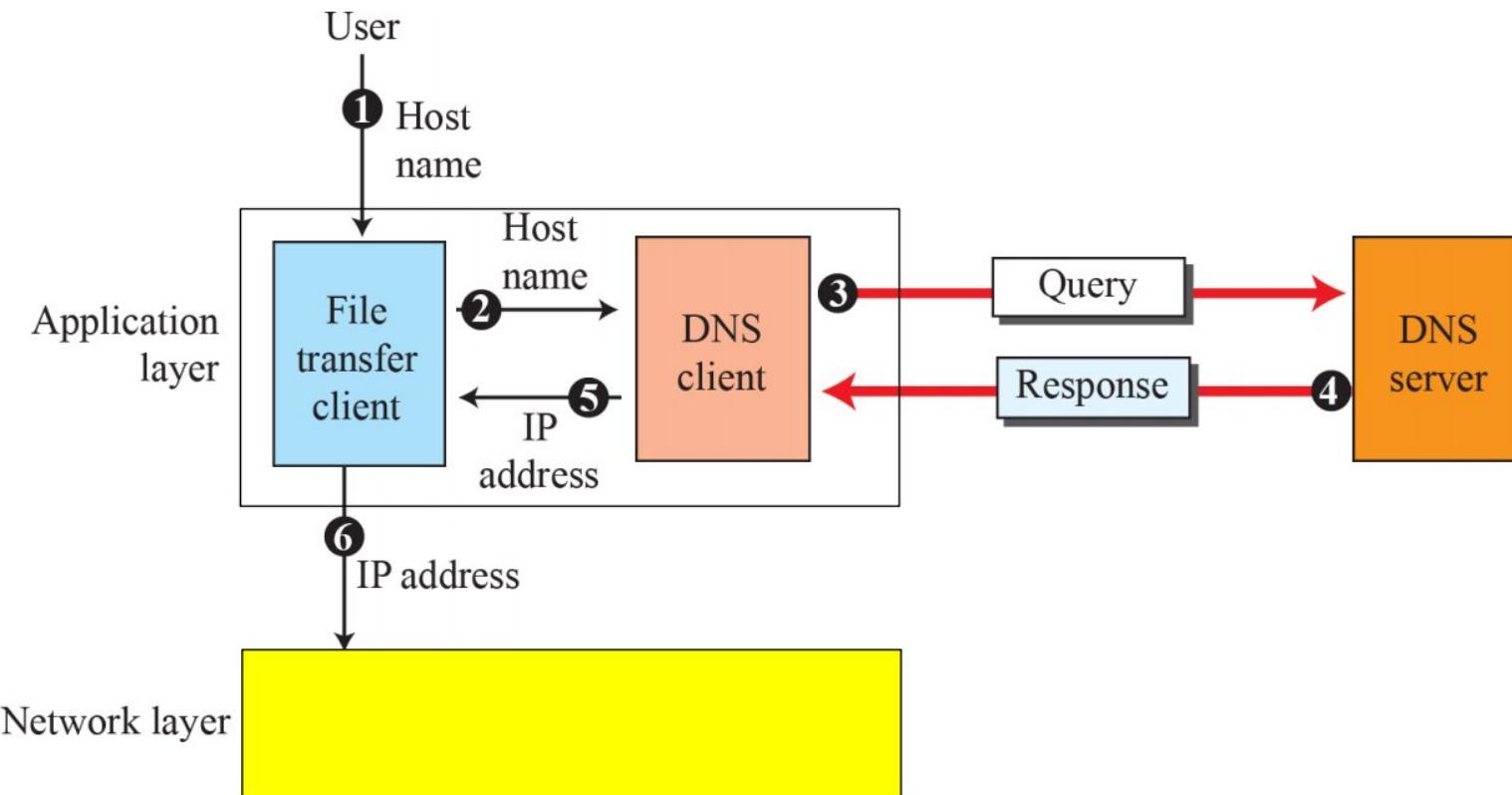
DNS

Domain name system

Domain Name System (DNS)

1. The client/server programs can be divided into two categories: those that can be directly used by the user, such as e-mail, and those that support other application programs.
2. The Domain Name System (DNS) is a supporting program that is used by other programs such as e-mail.
3. A user of an e-mail program may know the e-mail address of the recipient; however, the IP protocol needs the IP address.
4. The DNS client program sends a request to a DNS server to map the e-mail address to the corresponding IP address.
5. To identify an entity, TCP/IP protocols use the IP address, which uniquely identifies the connection of a host to the Internet.
6. However, people prefer to use names instead of numeric addresses. Therefore, we need a system that can map a name to an address or an address to a name.

Purpose of DNS



NAME SPACE

- To be unambiguous, the names assigned to machines must be carefully selected from a name space with complete control over the binding between the names and IP addresses.
- In other words, the **names must be unique because the addresses are unique.**
- A name space that maps each address to a unique name can be organized in two ways:
 - 1.flat name space
 - 2.hierarchical.

Flat Name Space

In a flat name space, a name is assigned to an address. A name in this space is a sequence of characters without structure.

The main disadvantage of a flat name space is that it cannot be used in a large system such as the Internet because it must be centrally controlled to avoid ambiguity and duplication.

Hierarchical Name Space

In a hierarchical name space, each name is made of several parts.

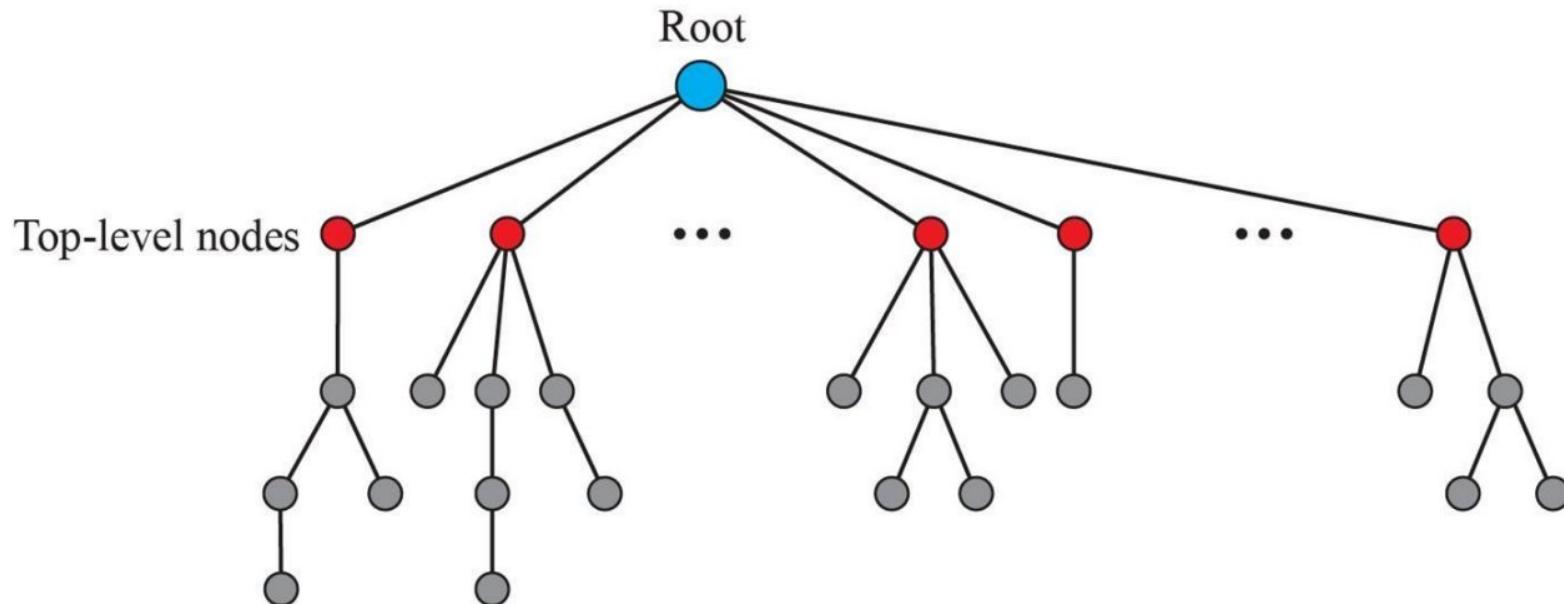
The first part can define the nature of the organization, the second part can define the name of an organization, the third part can define departments in the organization, and so on.

DOMAIN NAME SPACE

To have a hierarchical name space, a domain name space was designed.

In this design the names are defined in an inverted-tree structure with the root at the top.

The tree can have only 128 levels: level 0 (root) to level 127.



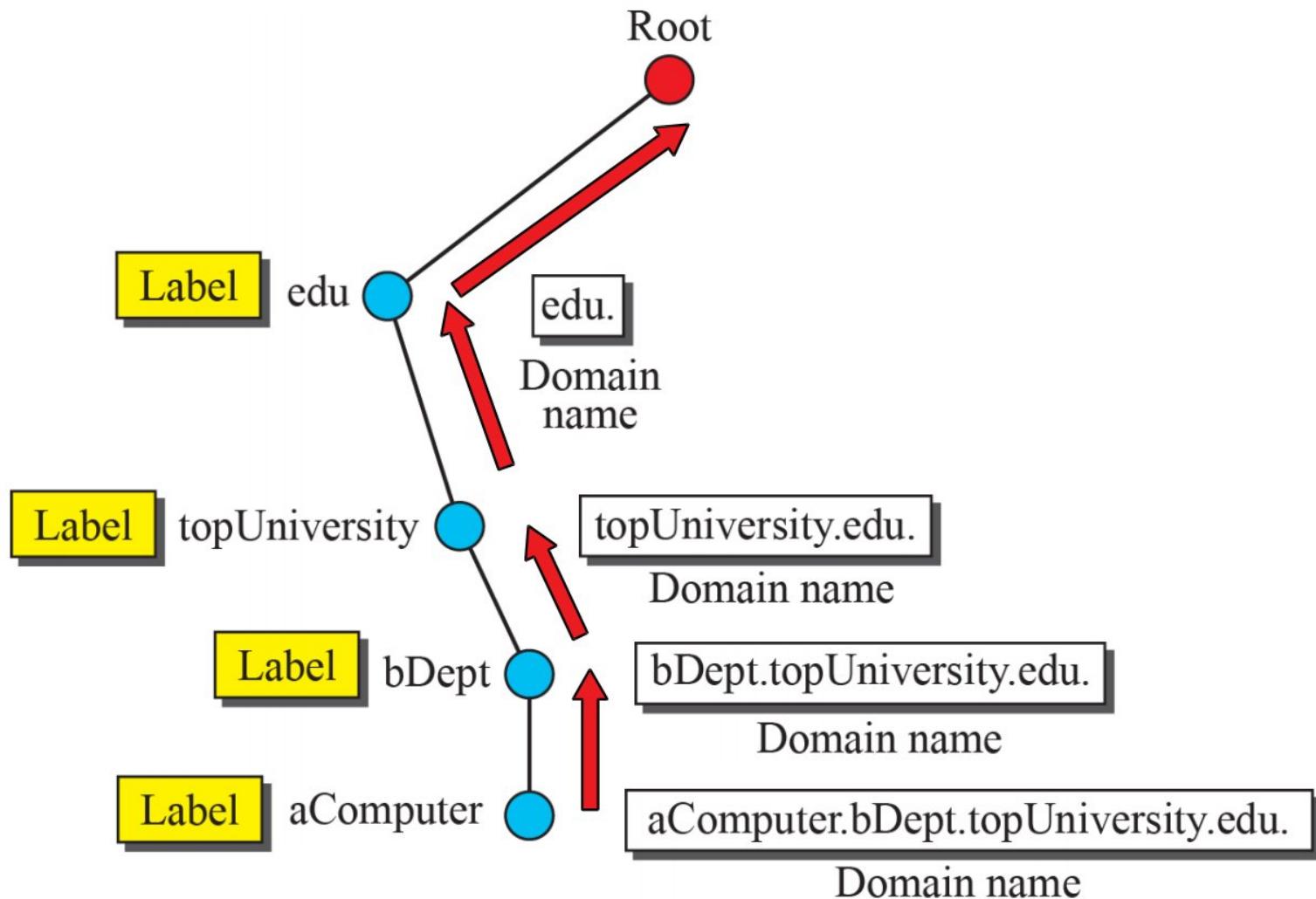
Each node in the tree has a label, which is a string with a maximum of 63 characters.

The root label is a null string (empty string).

DNS requires that children of a node (nodes that branch from the same node) have different labels, which guarantees the uniqueness of the domain names.

Domain Name

- Each node in the tree has a domain name.
- A full domain name is a sequence of labels separated by dots (.).
- The domain names are always read from the node up to the root.
- The last label is the label of the root (null). This means that a full domain name always ends in a null label



Fully Qualified Domain Name:

- If a label is terminated by a null string, it is called a fully qualified domain name (FQDN). An FQDN is a domain name that contains the full name of a host.
- It contains all labels, from the most specific to the most general, that uniquely define the name of the host. For example, the domain name
 - challenger.atc.tbda.edu.
- is the FQDN of a computer named challenger installed at the Advanced Technology Center (ATC)
- at De Anza College.
- A DNS server can only match an FQDN to an address.
- Note that the name must end with a null label, but because null means nothing, the label ends with a dot (.)

Partially Qualified Domain Name:

If a label is not terminated by a null string, it is called a partially qualified domain name (PQDN).

A PQDN starts from a node, but it does not reach the root.

It is used when the name to be resolved belongs to the same site as the client.

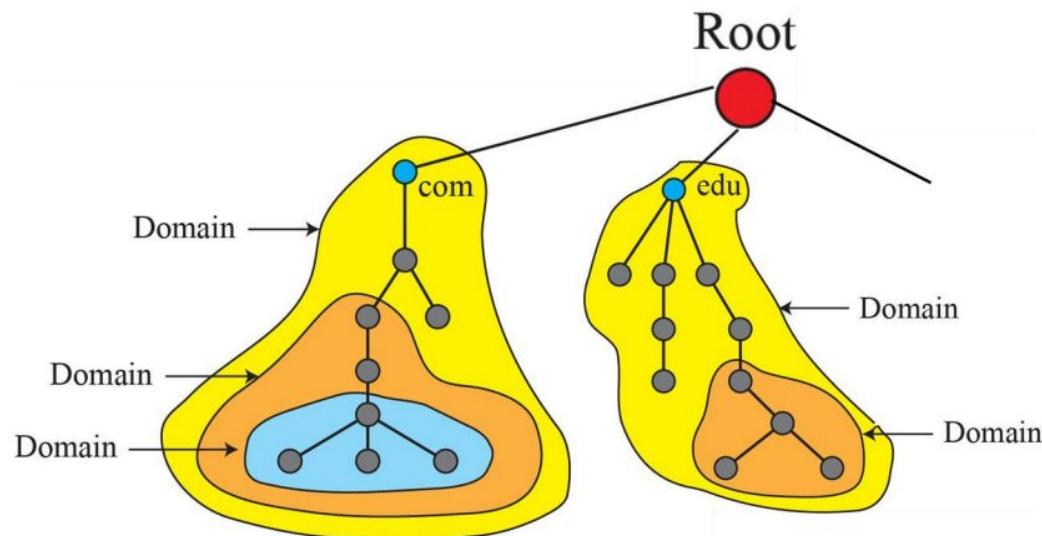
Here the resolver can supply the missing part, called the suffix, to create an FQDN. For example, if a user at the jhda.edu. site wants to get the IP address of the challenger computer, he or she can define the partial name

challenger

The DNS client adds the suffix atc.jhda.edu. before passing the address to the DNS server.

Domain:

1. A domain is a sub-tree of the domain name space.
2. The name of the domain is the domain name of the node at the top of the sub-tree.
3. Note that a domain may itself be divided into domains (or sub-domains).



DISTRIBUTION OF NAME SPACE

The information contained in the domain name space must be stored.

However, it is very inefficient and also unreliable to have just one computer store such a huge amount of information.

It is inefficient because responding to requests from all over the world places a heavy load on the system.

It is not unreliable because any failure makes the data inaccessible.

Hierarchy of Name Servers

The solution to these problems is to distribute the information among many computers called DNS servers.

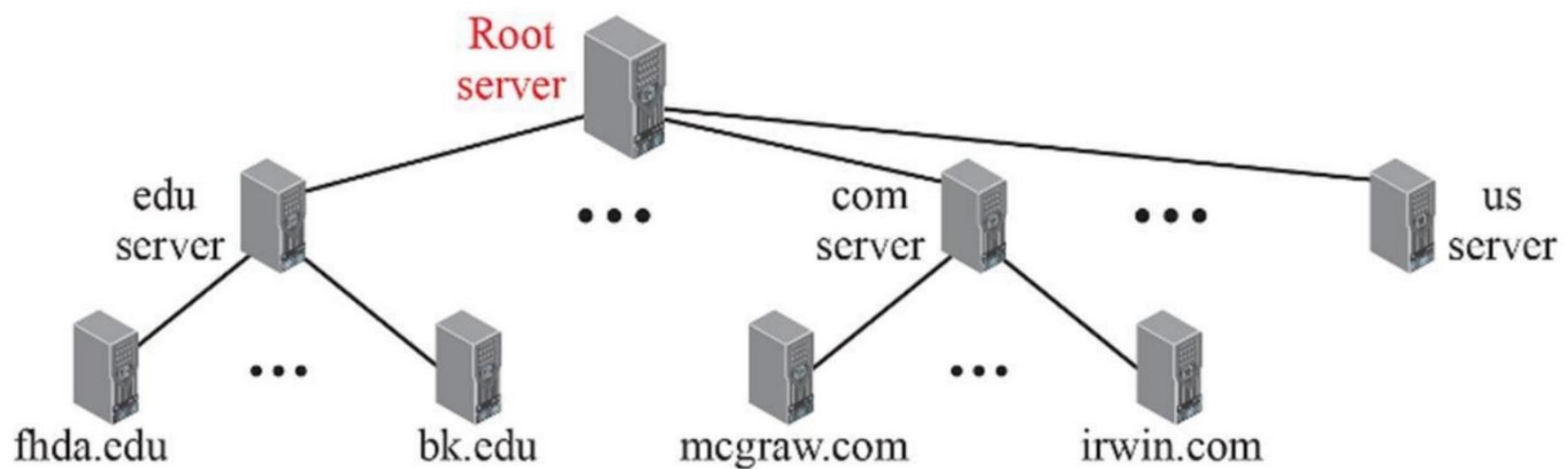
One way to do this is to divide the whole space into many domains based on the first level.

In other words, we let the root stand alone and create as many domains (sub-trees) as there are first-level nodes.

Because a domain created in this way could be very large, DNS allows domains to be divided further into smaller domains (sub-domains).

Each server can be responsible (authoritative) for either a large or a small domain.

In other words, we have a **hierarchy of servers in the same way that we have a hierarchy of names**.



Zone:

Since the complete domain name hierarchy cannot be stored on a single server, it is divided among many servers.

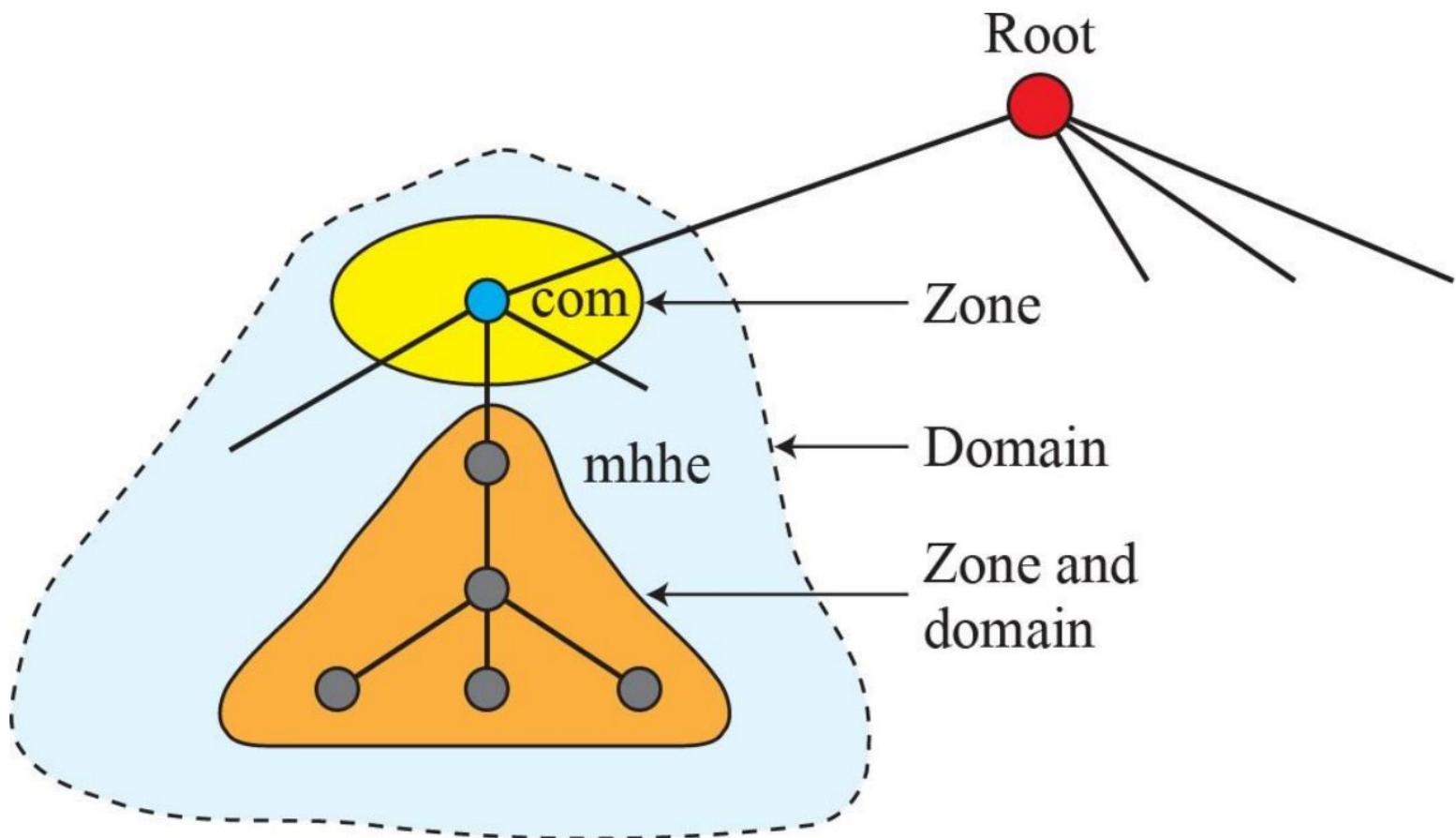
What a server is responsible for or has authority over is called a zone.

If a server accepts responsibility for a domain and does not divide the domain into smaller domains, the domain and the zone refer to the same thing.

The server makes a database called a zone file and keeps all the information for every node under that domain.

However, if a server divides its domain into sub-domains and delegates part of its authority to other servers, domain and zone refer to different things.

The information about the nodes in the sub-domains is stored in the servers at the lower levels, with the original server keeping some sort of reference to these lower-level servers.



Root Server

- A root server is a server whose zone consists of the whole tree.
- **A root server usually does not store any information** about domains but delegates its authority
- to other servers, **keeping references** to those servers.
- There are several root servers, each covering the whole domain name space. The servers are distributed all around the world.

Primary and Secondary Servers:

- DNS defines two types of servers: primary and secondary.
- A primary server is a server that stores a file about the zone for which it is an authority. It is responsible for creating, maintaining, and updating the zone file.
- It stores the zone file on a local disk.
- A **secondary server** is a server that transfers the complete information about a zone from another server (primary or secondary) and stores the file on its local disk.
- The secondary server neither creates nor updates the zone files. If updating is required, it must be done by the primary server, which sends the updated version to the secondary.
- Note also that a server can be a primary server for a specific zone and a secondary server for another zone

DNS IN THE INTERNET

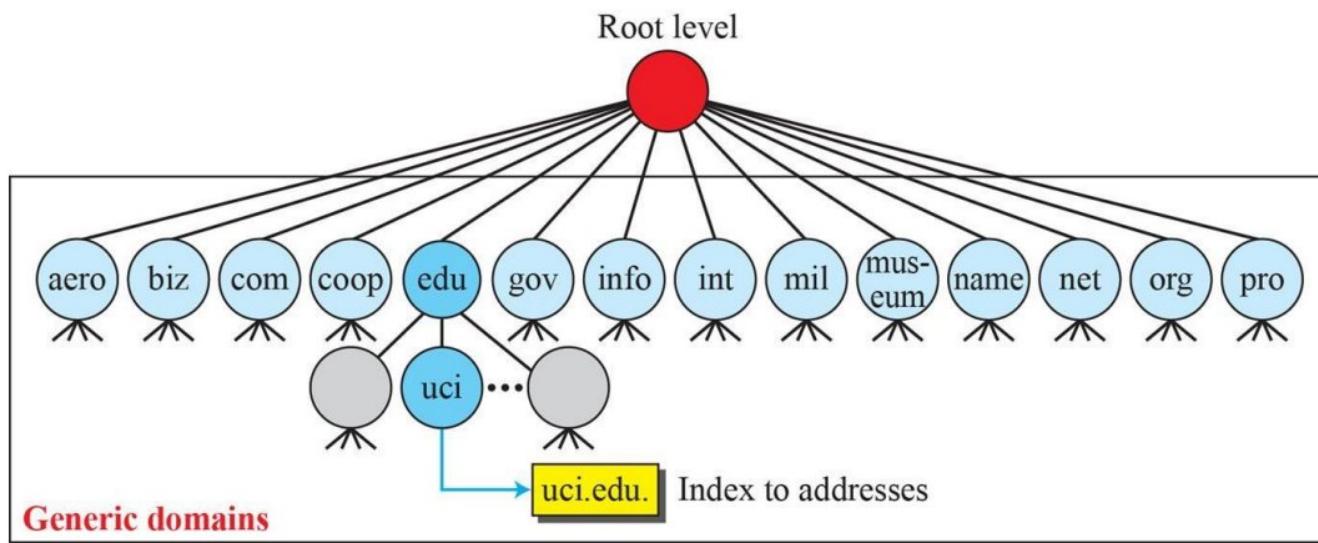
DNS is a protocol that can be used in different platforms. In the Internet, the domain name space (tree) is divided into three different sections: **generic domains, country domains, and the inverse domain.**

Generic Domains:

It defines the registered hosts according to their generic behavior.

Each node in a tree defines the domain name, which is an index to the DNS database.

It uses three-character labels, and these labels describe the **organization type**.



Cont..

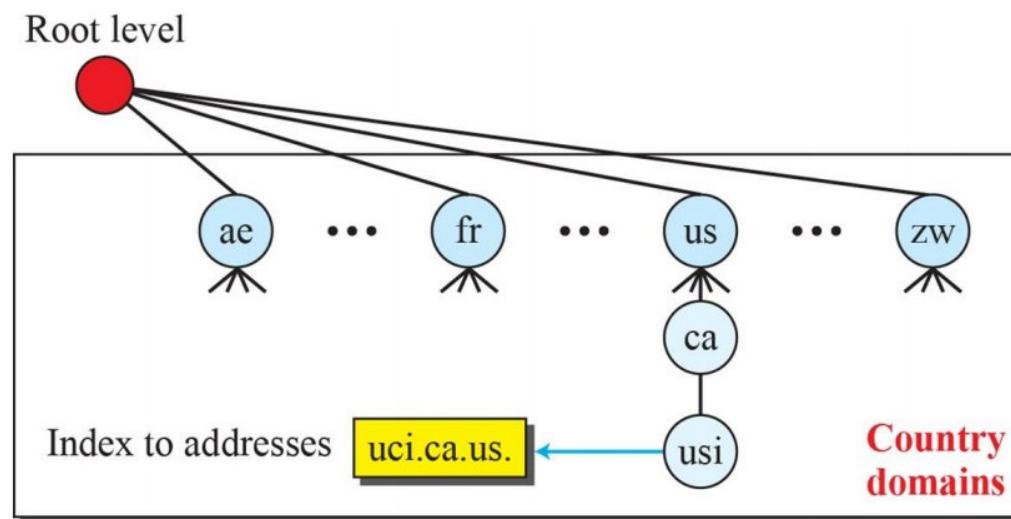
<i>Label</i>	<i>Description</i>
aero	Airlines and aerospace companies
biz	Businesses or firms (similar to "com")
com	Commercial organizations
coop	Cooperative business organizations
edu	Educational institutions
gov	Government institutions
info	Information service providers
int	International organizations
mil	Military groups
museum	Museums and other nonprofit organizations
name	Personal names (individuals)
net	Network support centers
org	Nonprofit organizations
pro	Professional individual organizations

Generic domain labels

Country Domains:

The country domains section uses two-character **country abbreviations** (e.g., us for United States).

Second labels can be organizational, or they can be more specific, national designations. The United States, for example, uses state abbreviations as a subdivision of us (e.g., ca.us.).



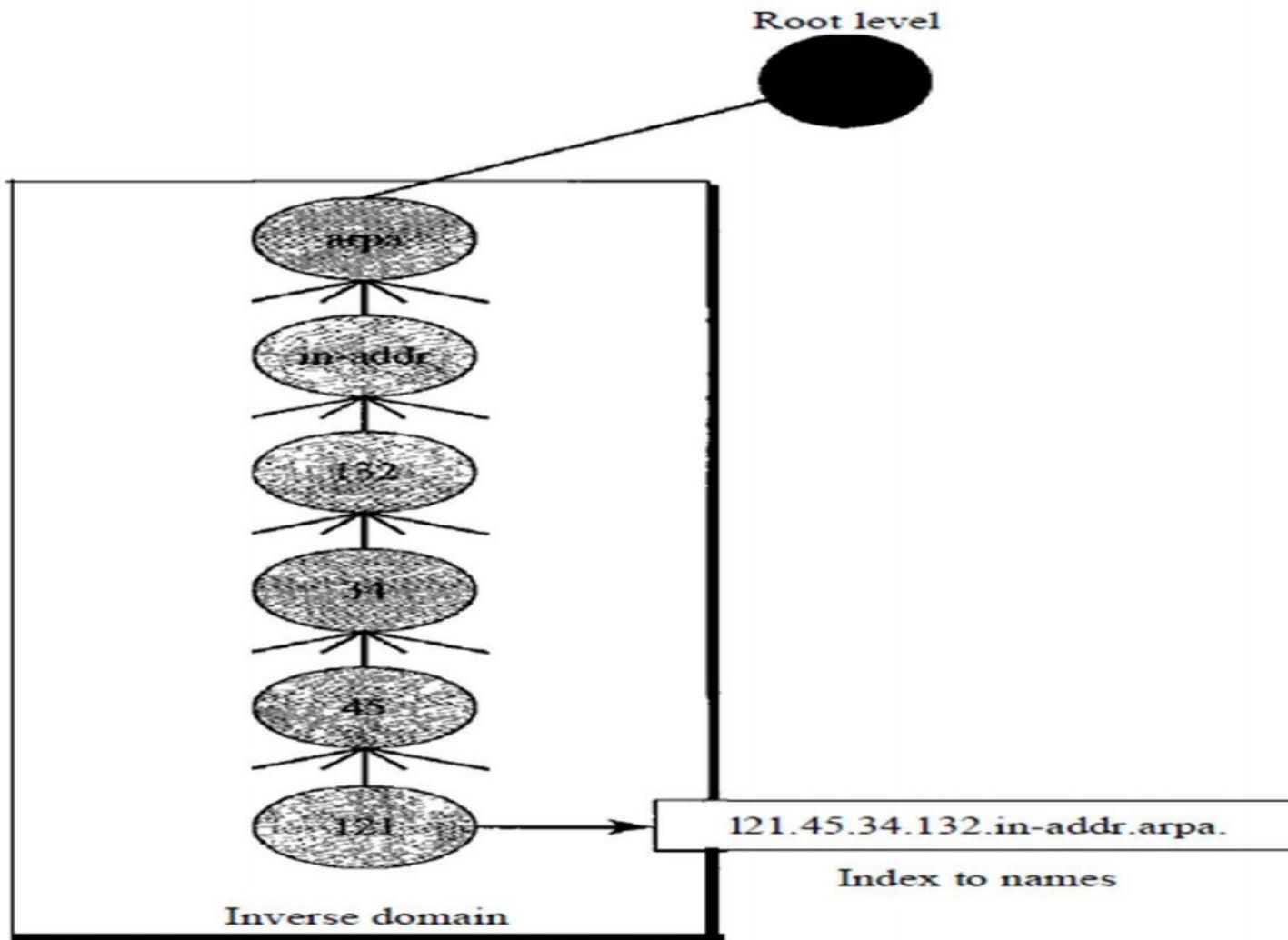
Inverse Domain

It is used for mapping an address to a name.

When a client requests to the server, **the server has a list of authorized clients.**

The server asks its resolver to send the query to the DNS server to verify the client belongs to the list of authorized clients and sends a query to the DNS server to map an address to the name.

This type of query is called an inverse or pointer (PTR) query. To handle a pointer query, the inverse domain is added to the domain name space with the first-level node called arpa. The second level is also one single node named in-addr (for inverse address). The rest of the domain defines IP addresses.



RESOLUTION

Mapping a name to an address or an address to a name is called name-address resolution.

Resolver:

1. DNS is designed as a client/server application. A host that needs to map an address to a name or a name to an address calls a DNS client or a resolver.
2. The resolver accesses the **closest DNS server with a mapping request**.
3. If the server has the information, it satisfies the resolver; otherwise, it either refers the **resolver to other servers** or **asks other servers to provide** the information.
4. After the resolver receives the mapping, it interprets the response to **see if it is a real resolution or an error**, and finally delivers the result to the process that requested it.

Mapping Names to Addresses

Most of the time, the resolver gives a domain name to the server and asks for the corresponding address.

In this case, the server checks the generic domains or the country domains to find the mapping.

In both the cases, the query is sent by the resolver to the local DNS server for resolution. If the local server cannot resolve the query, it either refers the resolver to other servers or asks other servers directly.

Mapping Addresses to Names:

A client can send an IP address to a server to be mapped to a domain name. As mentioned before, this is called a PTR query.

To answer queries of this kind, DNS uses the inverse domain. However, in the request, the IP address is reversed and the two labels in-addr and arpa are appended to create a domain acceptable by the inverse domain section.

For example, if the resolver receives the IP address 132.34.45.121, **the resolver first inverts the address** and then adds the two labels before sending.

The domain name sent is "121.45.34.132.in-addr.arpa." which is received by the local DNS and resolved.

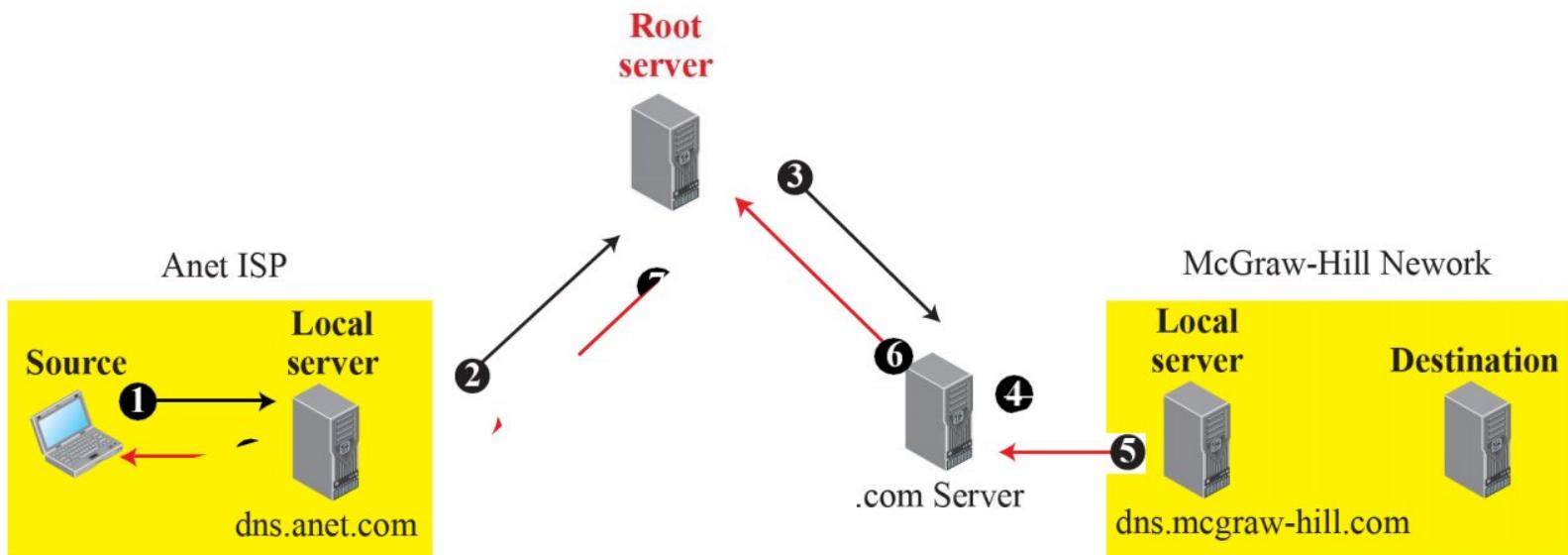
Recursive Resolution

The client (resolver) can ask for a recursive answer from a name server. This means that the resolver expects the server to supply the final answer.

If the server is the authority for the domain name, it checks its database and responds. If the server is not the authority, it sends the request to another server (the parent usually) and waits for the response.

If the parent is the authority, it responds; otherwise, it sends the query to yet another server.

When the query is finally resolved, the response travels back until it finally reaches the requesting client. This is called recursive resolution



Source: some.anet.com
Destination: engineering.mcgraw-hill.com

Iterative Resolution

If the client does not ask for a recursive answer, the mapping can be done iteratively.

If the server is an authority for the name, it sends the answer. If it is not, it returns (to the client) the IP address of the server that it thinks can resolve the query.

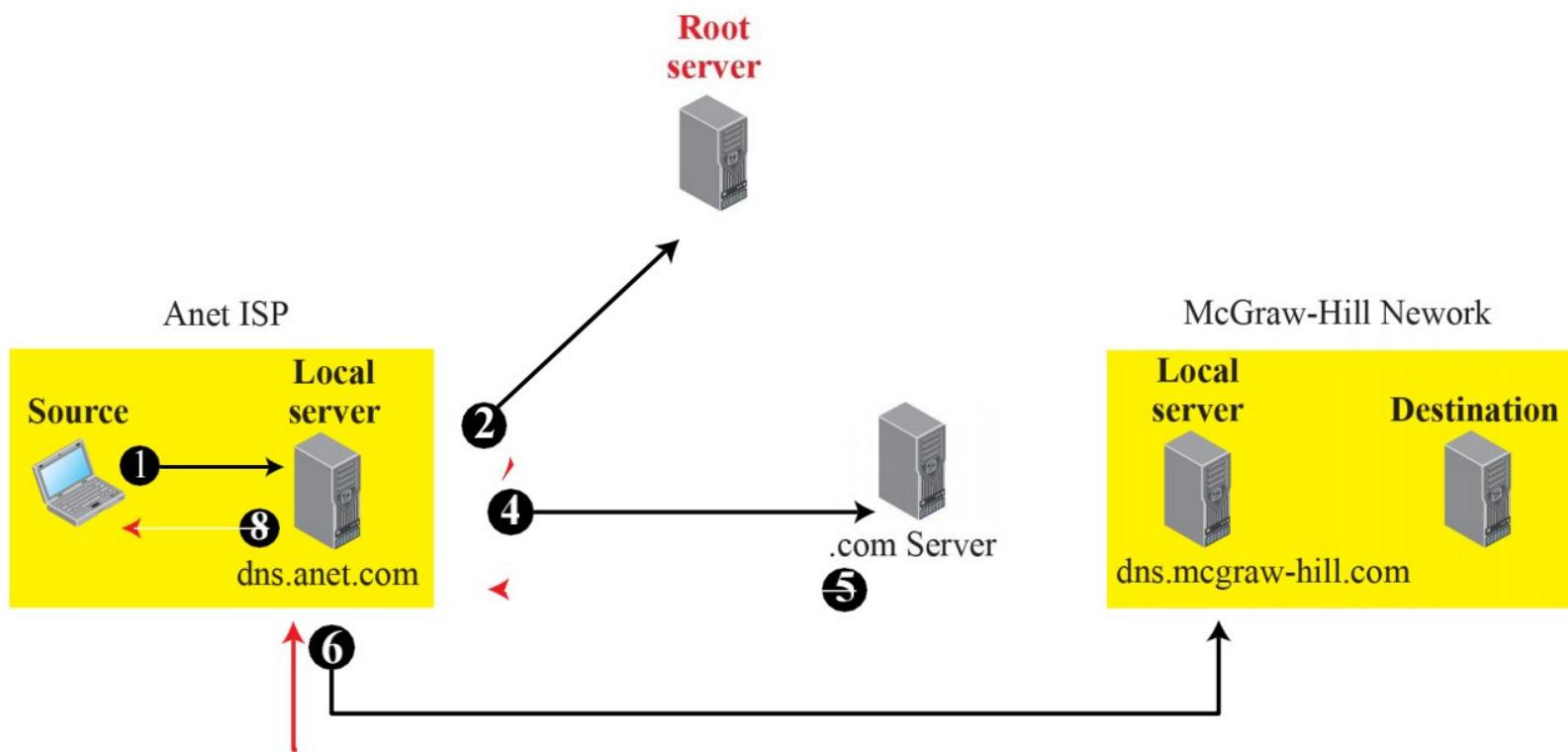
The client is responsible for repeating the query to this second server.

If the newly addressed server can resolve the problem, it answers the query with the IP address; otherwise, it returns

the IP address of a new server to the client.

Now the client must repeat the query to the third server.

This process is called iterative resolution because the client repeats the same query to multiple servers.



Source: some.anet.com
Destination: engineering.mcgraw-hill.com

Caching

Each time a server receives a query for a name that is not in its domain, it needs to search its database for a server IP address.

Reduction of this search time would increase efficiency.

DNS handles this with a mechanism called caching.

Caching is used to speeds up resolution.

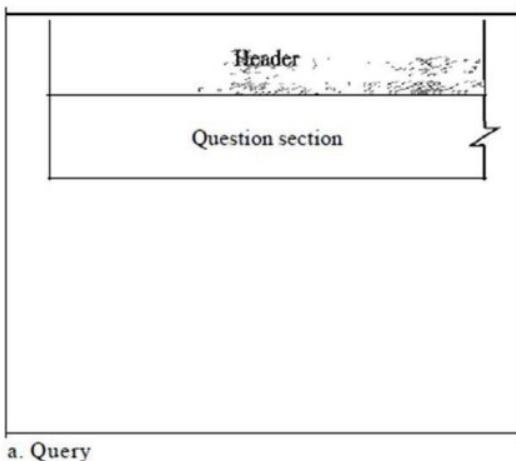
When a server asks for a mapping from another server and receives the response, it stores this information in its cache memory before sending it to the client.

If the same or another client asks for the same mapping, it can check its cache memory and solve the problem.

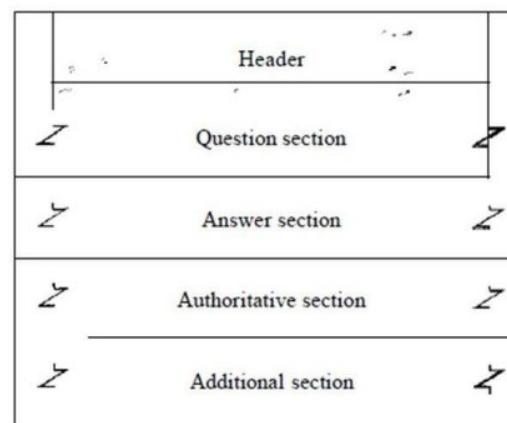
However, to inform the client that the response is coming from the cache memory and not from an authoritative source, the server marks the response as unauthoritative.

DNS MESSAGES

- DNS has two types of messages: **query and response**. Both types have the same format. The **query message** consists of a **header and question records**.
- The **response message** consists of a **header, question records, answer records, authoritative records, and additional records**.



a. Query



b. Response

Question Section:

This is a section consisting of one or more question records.

It is present on both query and response messages.

A question record is **used by the client to get information from a server**. This contains the domain name.

Answer Section:

This is a section consisting of one or more resource records.

It is present only on response messages.

This section includes the **answer from the server to the client** (resolver).

Each domain name (each node on the tree) is associated with a record called the resource record. The server database consists of resource records. Resource records are also what is returned by the server to the client.

Authoritative Section:

This is a section consisting of one or more resource records.

It is present only on response messages.

This section **gives information** (domain name) **about one or more authoritative servers** for the query.

Additional Information Section:

This is a section consisting of one or more resource records.

It is present only on response messages.

This section provides **additional information that may help the resolver**.

For example, a server may give the domain name of an authoritative server to the resolver in the authoritative section, and include the IP address of the same authoritative server in the additional information section.

Header

The **identification** subfield is used by the client to match the response with the query.

The **client uses a different identification number each time it sends a query**. The server duplicates this number in the corresponding response.

Identification	Flags
Number of question records	Number of answer records (all Os in query message)
Number of authoritative records (all Os in query message)	Number of additional records (all Os in query message)

The **flags** subfield is a collection of subfields that define the type of the message, the type of answer requested, **the type of desired resolution (recursive or iterative)**, and so on.

The **number of question records** subfield contains the number of queries in the question section of the message. The **number of answer** records subfield contains the number of answer records in the answer section of the response message. Its value is zero in the query message.

The number of authoritative records subfield contains the number of authoritative records in the authoritative section of a response message. Its value is zero in the query message.

Finally, the **number of additional records** subfield contains the number additional records in the additional section of a response message.

DNS Record types

DNS record types are records that provide important information about a hostname or domain.

These records include the current IP address for a domain.

Also, DNS records are stored in text files (zone files) on the authoritative DNS server.



1. A record

The A record is the most important DNS record type. The "A" in A record stands for "address." An A record shows the IP address for a specific hostname or domain

For example, a DNS record lookup for the domain example.com returns the following result:

Type	Domain Name	IP Address	TTL
A	example.com	93.184.216.34 Verizon Business (AS15133)	24 hrs

The A record only supports IPV4 addresses.

The main use of A record is for IP address lookup. Using an A record, a web browser is able to load a website using the domain name. As a result, we can access websites on the internet without knowing their IP addresses.

Another use of A record is in the domain name system-based blackhole list (DNSBL). Here, the A record is **used to block mail from known spam sources**.

2. AAAA record

AAAA record, just like A record, point to the IP address for a domain. However, this DNS record type is different in the sense that it **points to IPV6 addresses**.

3. CNAME record:

A CNAME (Canonical Name) **points one domain or sub-domain to another domain name**, allowing you to update one A Record each time you make a change, regardless of how many Host Records need to resolve to that IP address.

These records point to www.example.com to example.com, imap.example.com to mail.example.com, and docs.example.com to ghs.google.com.

The first record allows the domain to resolve to the same server with or without the www sub-domain. The second record allows you to use an alternative sub-domain for email hosting and delivery. The third record allows you to use the docs.example.com sub-domain with G Suite, where you can use Google's document management system.

Delay and throughput in Packet-switched Network

Delay in Packet- switched Network

Delay in a packet-switched network refers to the time it takes for a packet of data to travel from the source to the destination. There are several components of delay:

- Transmission Delay
- Propagation Delay
- Processing Delay
- Queueing Delay
- Total Delay

- Transmission Delay: This is the time taken to transmit the entire packet onto the communication medium. It depends on the packet's size and the transmission rate of the link.
 - $Delay_{tr} = (\text{Packet length}) / (\text{Transmission rate})$.
- Propagation Delay: This is the time it takes for a signal to travel from the source to the destination. It is determined by the physical distance between the two points and the speed of the signal through the transmission medium.
 - $Delay_{pg} = (\text{Distance}) / (\text{Propagation speed})$.
- Processing Delay: When a packet arrives at a router or a network device, there is a small processing delay as the device inspects the packet headers and makes forwarding decisions.
 - $Delay_{pr} = \text{Time required to process a packet in a router or a destination host}$

- Queueing Delay: If there are other packets ahead of the current packet waiting to be transmitted on the same link, the packet will experience a delay in the queue before it gets its turn for transmission.
 - $Delay_{qu}$ = The time a packet waits in input and output queues in a router
- Total Delay: assuming equal delays for the sender, routers, and receiver, the total delay (source-to-destination delay) a packet encounters can be calculated if we know the number of routers, n, in the whole path.

$$\text{Total delay} = (n + 1) (Delay_{tr} + Delay_{pg} + Delay_{pr}) + (n) (Delay_{qu})$$

- Delay can have a significant impact on real-time applications such as voice and video, where low delay is essential to maintain smooth communication.

Throughput in Packet- switched Network

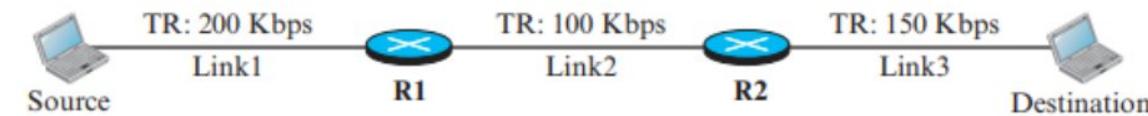
Throughput in a packet-switched network refers to the rate at which data can be transmitted over the network link. It is usually measured in bits per second (bps) or packets per second (pps). Throughput depends on various factors:

- Link Capacity
- Network Congestion
- Protocol Overheads
- Routing Efficiency

- **Link Capacity:** The maximum data rate that the physical link can support. It is determined by the link's transmission rate and bandwidth.
- **Network Congestion:** High levels of network congestion can reduce throughput as packets experience more queueing delay and compete for available bandwidth.
- **Protocol Overheads:** Packet-switched networks use various protocols to manage and control data transmission. These protocols add some overhead, which can slightly reduce the actual throughput.

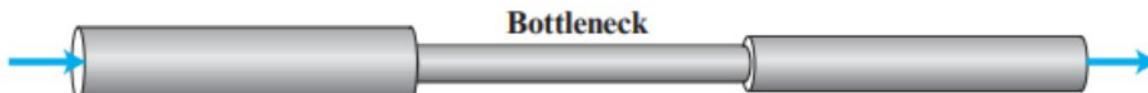
- **Routing Efficiency:** The efficiency of the routing algorithms and protocols used in the network can impact how quickly packets reach their destination.
- **Throughput** is crucial for applications that require high data transfer rates, such as file downloads, streaming, and data-intensive processes.

Figure 4.10 **Throughput in a path with three links in a series**



a. A path through three links

TR: Transmission rate



b. Simulation using pipes

In this figure, the data can flow at the rate of 200 Kbps in Link1. However, when the data arrives at router R1, it cannot pass at this rate. Data needs to be queued at the router and sent at 100 Kbps. When data arrives at router R2, it could be sent at the rate of 150 Kbps, but there is not enough data to be sent. In other words, the average rate of the data flow in Link3 is also 100 Kbps. We can conclude that the average data rate for this path is 100 Kbps, the minimum of the three different data rates. The figure also shows that we can simulate the behavior of each link with pipes of different sizes; the average throughput is determined by the bottleneck, the pipe with the smallest diameter. In general, in a path with n links in series, we have

$$\text{Throughput} = \min \{TR_1, TR_2, \dots, TR_n\}.$$