Chapter 1

Computer Networks and the Internet

DATA COMMUNICATION

Communication:

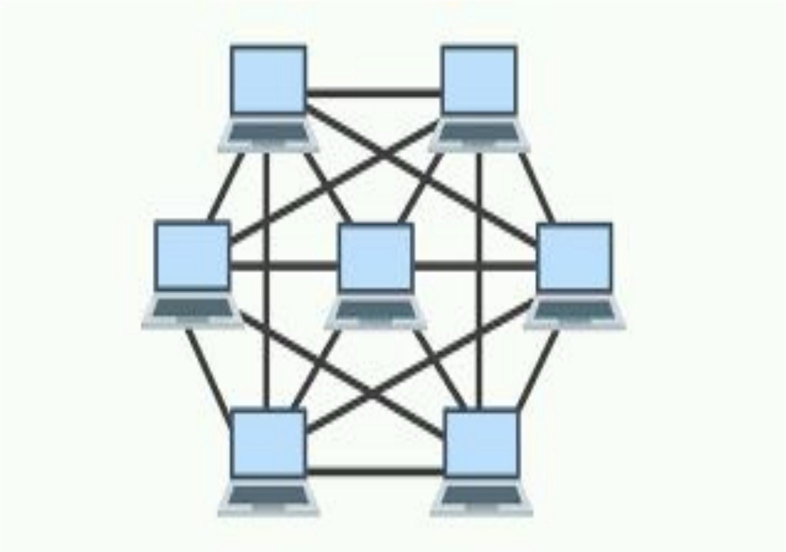
- sharing of information

Data communication:

- exchange of data between two devices via some form of transmission medium such as a wire cable.

NETWORKS

A network is a set of devices (often referred to as nodes) connected by communication links. A node can be a computer, printer, or any other device capable of sending and/or receiving data generated by other nodes on the network. A link can be a cable, air, optical fiber, or any medium which can transport a signal carrying information.



INTERNET

- Internet is a computer network that interconnects millions of computing devices around the world
- The computing devices include desktop PCs, servers, laptops, tablets, mobile phones, home electrical and security systems etc
- These computing devices are called as Hosts or End systems
- End systems are connected to the network through Communication Link. Different communication links are available with different transmission rate
- The sequence of communication links the data takes from sender to receiver is called route or path
- End systems access the Internet through Internet Service Providers(ISPs)

INTERNET(contd..)

Protocol:

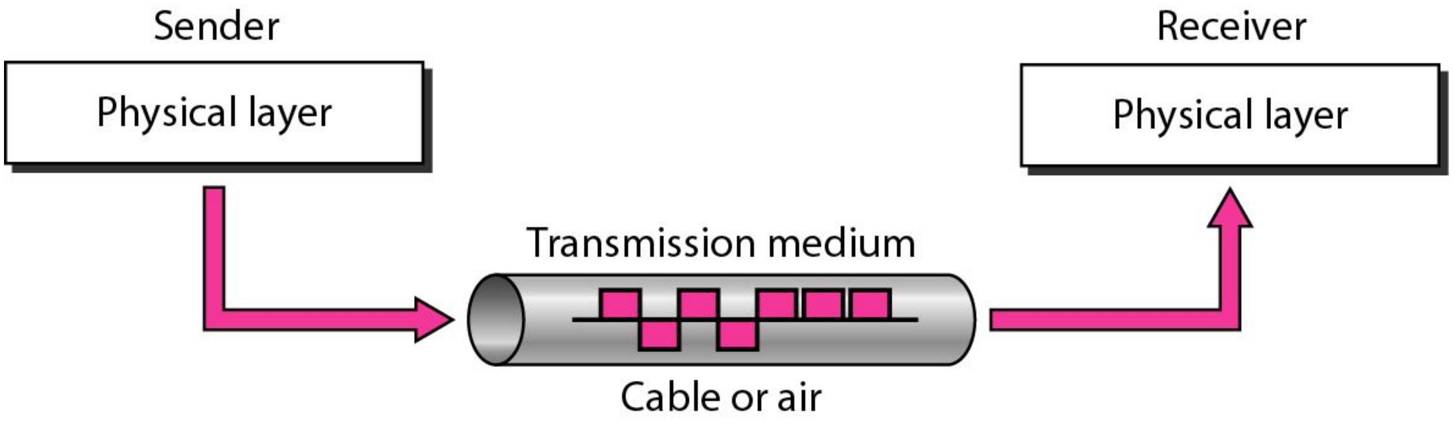
- set of rules that should be followed by the communicating devices.
- A protocol defines the format and the order of messages exchanged between two or more communicating entities as well as the actions taken on the transmission or receipt of messages

Example: one protocol rule is that the communicating devices should exchange information only in English language

THE NETWORK EDGE

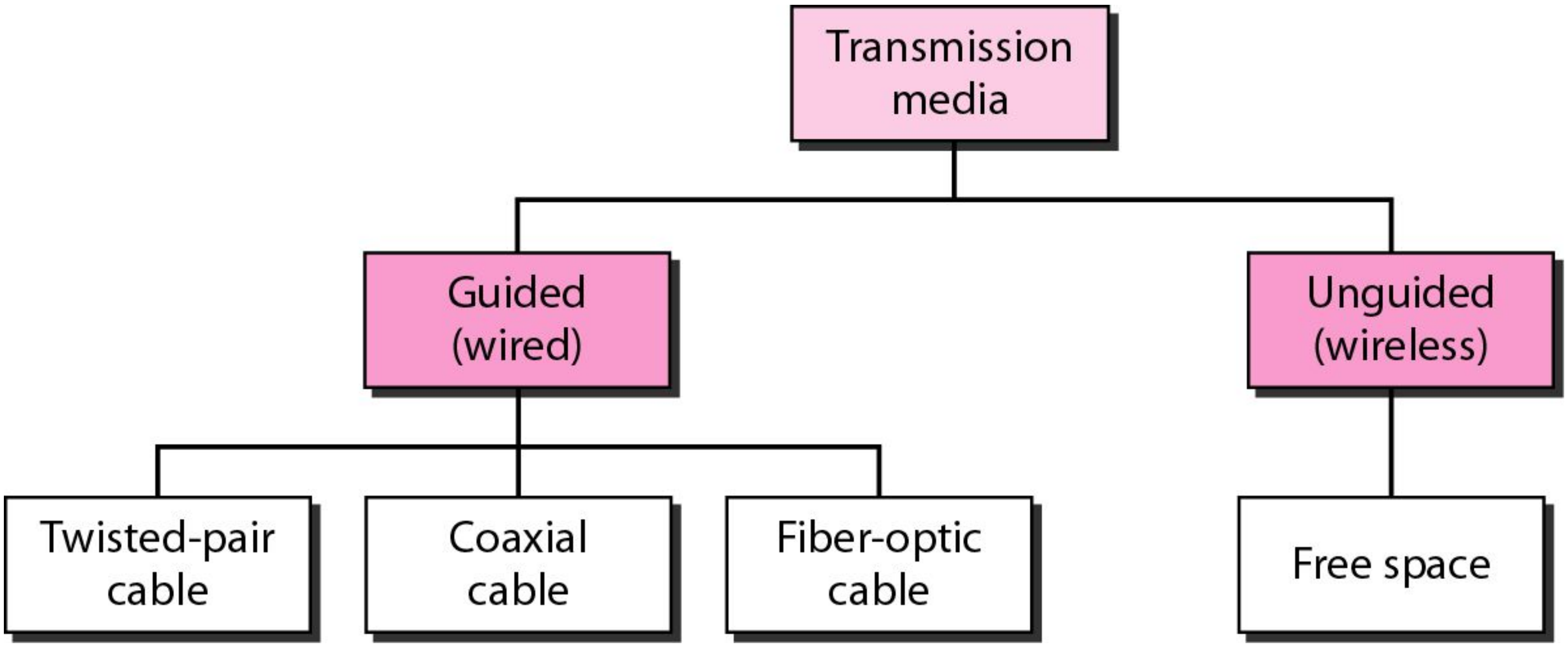
Physical media

- Physical media is also called as Transmission medium
- Transmission medium is the one which is used for transmitting data from sender to receiver



THE NETWORK EDGE (contd..)

Physical media

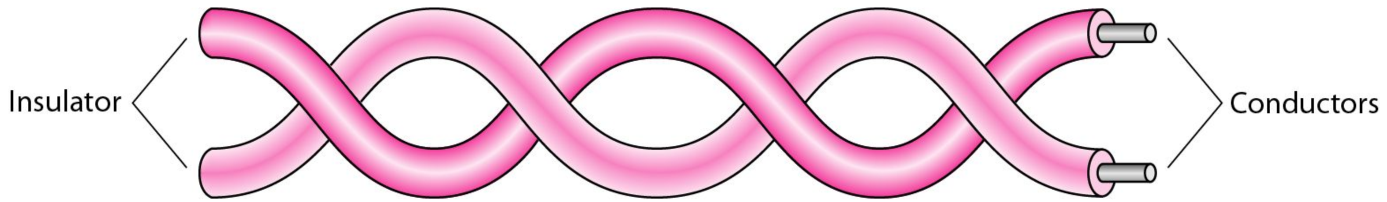


THE NETWORK EDGE (contd..)

Guided medium

1. Twisted-pair copper cable

- Least expensive and commonly used guided transmission medium
- Mostly used by Telephone networks
- Twisted pair consists of two insulated copper wires arranged in spiral pattern



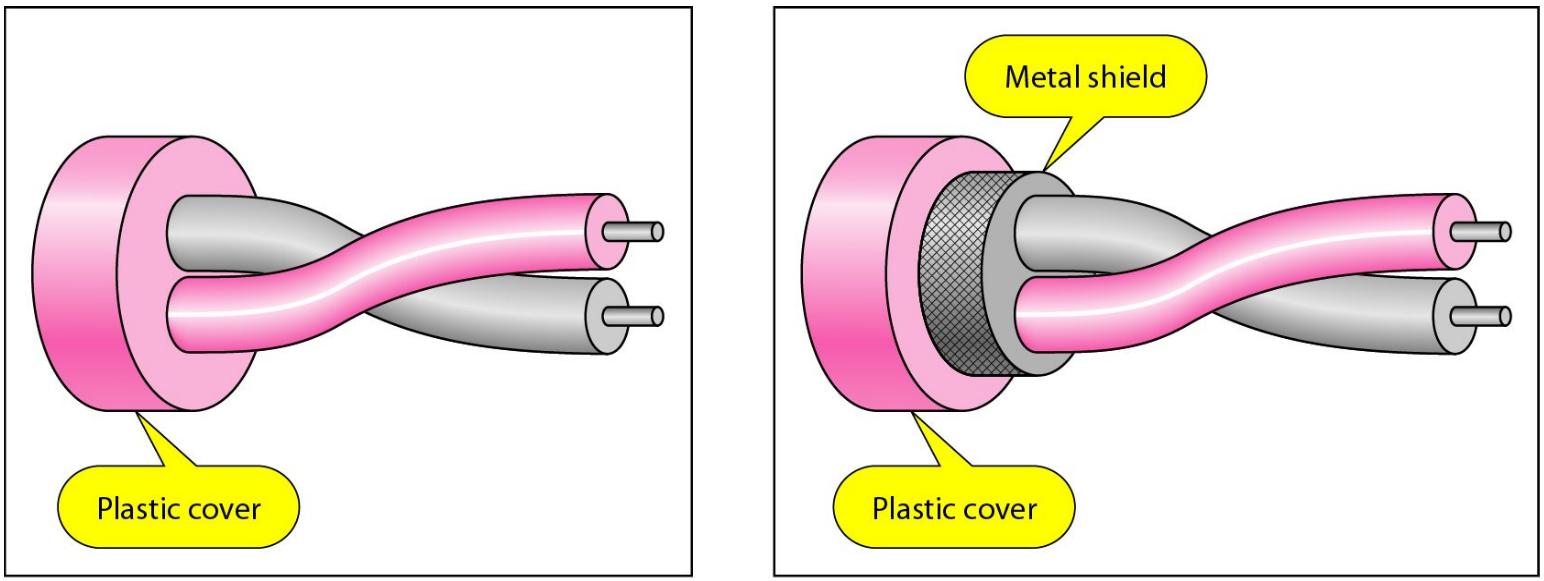
THE NETWORK EDGE (contd..)

1. Twisted-pair copper cable

- Twisted-pair cable can come in different flavors like,

  a. Unshielded Twisted Pair (UTP)

  b. Shielded Twisted Pair (STP) – contains protective shield



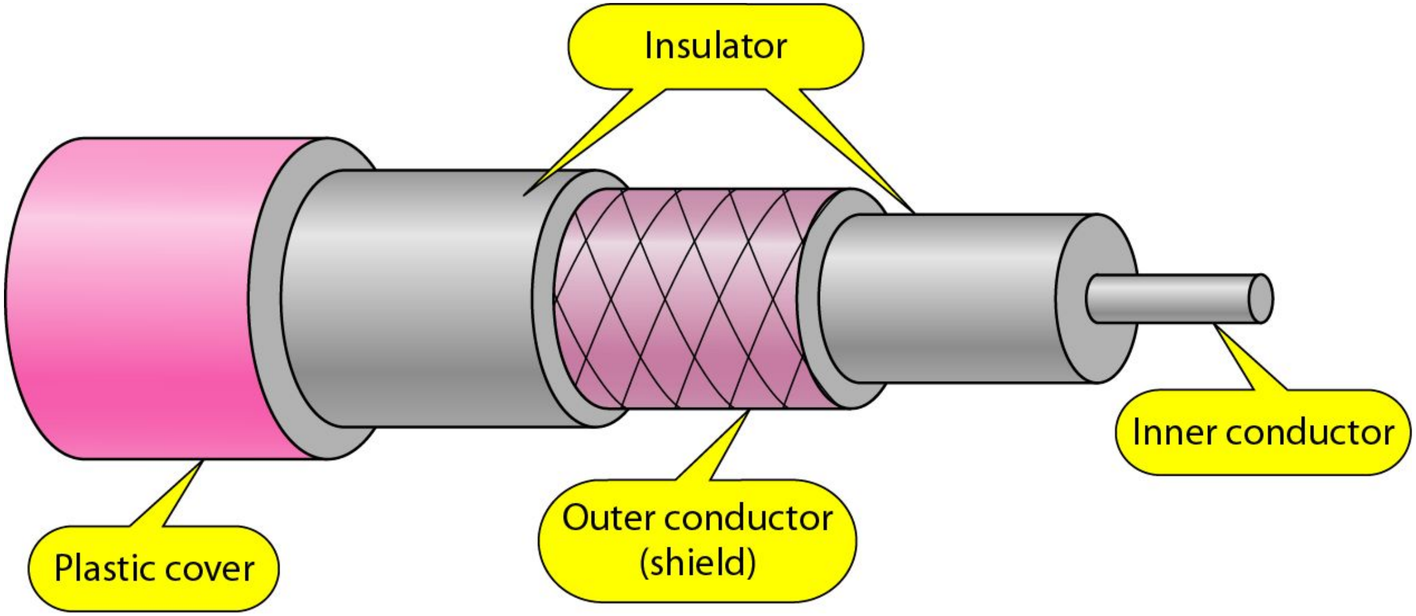
a. UTP b. STP

- UTP is commonly used in LANs

THE NETWORK EDGE (contd..)

2. Coaxial cable

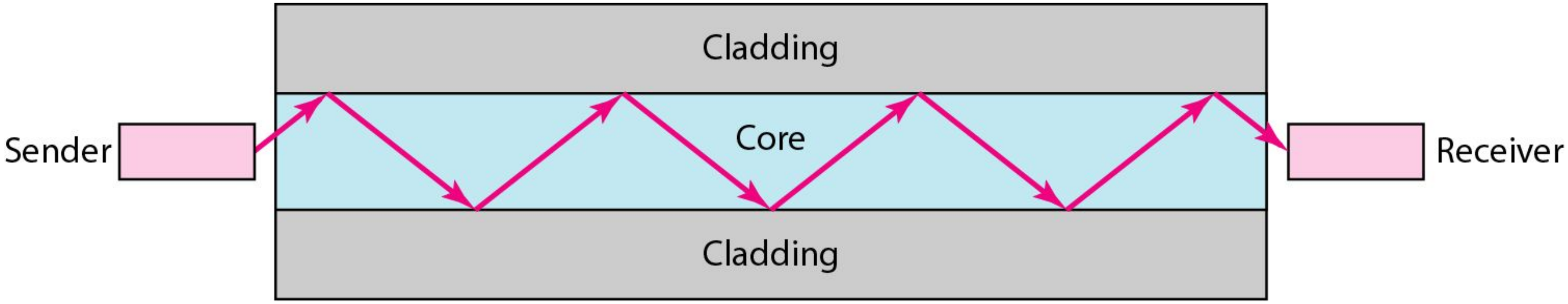
- Consists of copper conductor which are concentric in manner.
- Also contains special insulation and shielding and provides high data transmission rates
- Mostly used in cable Television systems



THE NETWORK EDGE (contd..)

3. Fiber Optics cable

- Made of glass or plastic
- Transmits signal in the form of light
- In fiber optic cable, a glass or plastic core is surrounded by cladding of less dense glass or plastic.
- Cladding is made in such a way that when light enters into it, light will be reflected



THE NETWORK EDGE (contd..)

3. Fiber Optics cable

- Fiber optic cable supports transmitting huge amount of data per second
- Fiber optic cable are useful for long distance communication
- Cost wise this cable is higher than coaxial and twisted pair cables

THE NETWORK EDGE (contd..)

Unguided medium

1.Terrestrial Radio Channels

- It is an attractive medium since it does not require any physical wire to be installed
- This type of medium provide connectivity to mobile user

3 groups:

a. channel that operate over very short distance (one or two meters)

b. channel that operate in local areas (ten or few hundred meters)

c. channel that operate in wide area (tens of kilometers)

THE NETWORK EDGE (contd..)

2.Satellite Radio Channels

- A satellite communication links two or more earth-based microwave transmitter/receivers known as ground stations
- Two types of satellites used in communications:
  - a. Geostationary satellites
  - b. Low-earth orbiting (LEO) satellites
- Geostationary satellites remain permanent above the same spot on earth. The satellite is placed at 36,000km above the earth
- LEO satellites are placed much closer to earth and do not remain permanently above one spot on Earth. They rotate around the earth and communicate with each other as well as ground stations.

The Network Core

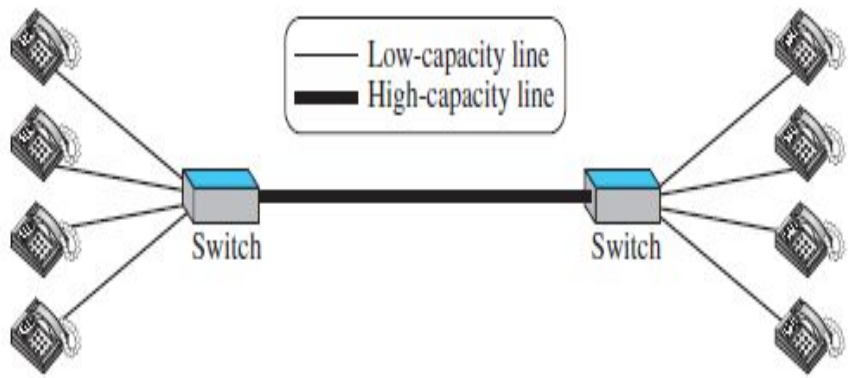
2 categories network,

1. Circuit-switched
2. Packet-switched

The Network Core (Contd..)

1. Circuit-switched Network:

- In the diagram four telephones at both sides connected through switch

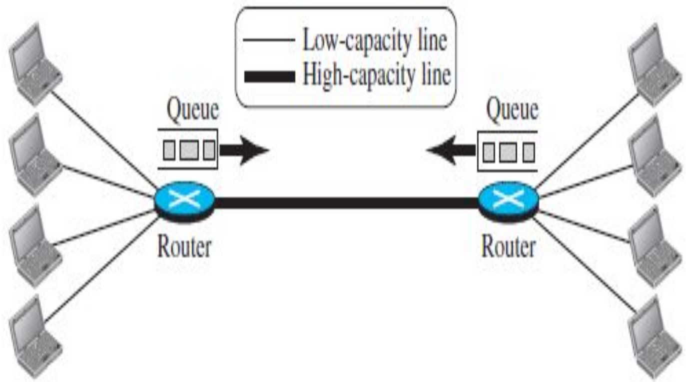


- In above diagram, capacity of the link (link connecting two switches) should be 4 times the capacity of link connecting telephone and a switch
- (ie) capacity of the link (link connecting two switches) should be in such a manner that when all 4 telephones at left hand side is communicating with all 4 telephones at the right hand side
- Circuit switch network is efficient when it is working at its full capacity. But most of the time circuit switching is inefficient because it is working at partial capacity
- **<u>Example:</u> earlier telephone networks were circuit-switched**

The Network Core (Contd..)

2. Packet-switched Network:

- In the diagram four computers at both sides is connected through routers



- Packet switching network does not require high capacity link (thick line) as like that of circuit network
- For example if suppose capacity of link connecting two routers is twice that of link connecting computers and routers then

  1. No waiting for packets when two systems at one end is communicating with two systems at other end

  2. Waiting of packets at queue when all systems in one end is communicating with all systems at other end

The Network Core (Contd..)

2. Packet-switched Network:

- Packet switched network use store and forward transmission. Store and forward mechanism means the router must receive the entire packet before it can begin to transmit the first bit of the packet onto the outbound link
- Routers have queue to store and forward packets
- **Example: Internet we using is packet-switched**

The Network Core (Contd..)

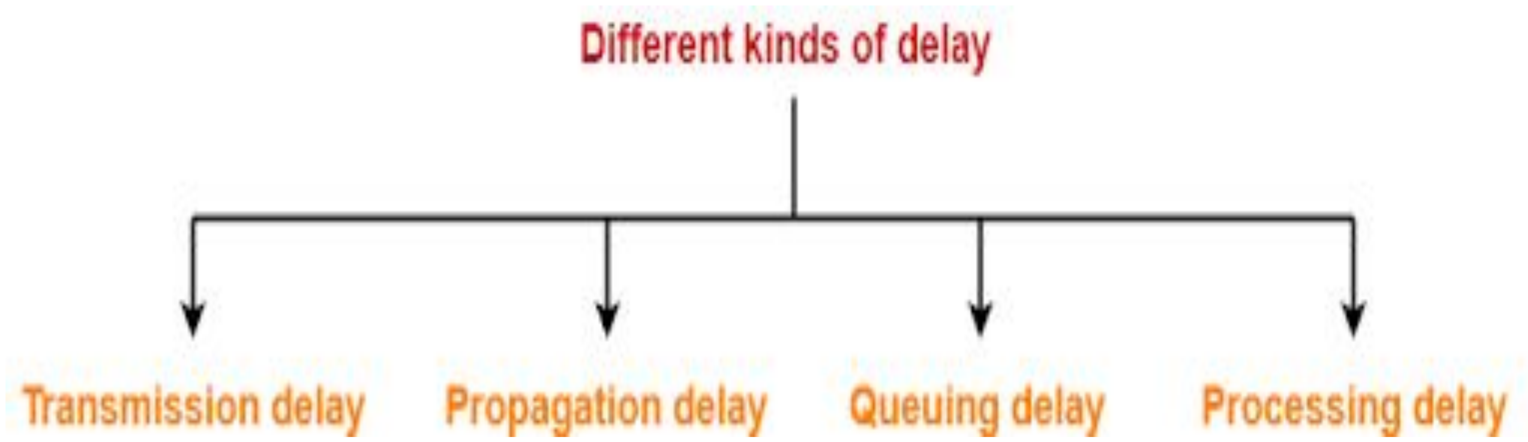
Circuit switching vs Packet switching

1. Circuit switching enables the sender to transfer the data to the receiver at guaranteed constant rate
2. Circuit switch network is efficient when it is working at its full capacity. But most of the time circuit switching is inefficient because it is working at partial capacity
3. Packet switching is simpler, more efficient and less costly than circuit switching
4. Packet switching is not suitable for real-time services like video conference calls
5. Circuit switching pre-allocates the transmission link regardless of demand from user whereas packet switching allocates link on demand

Delay, Loss and Throughput in Packet-switched Networks

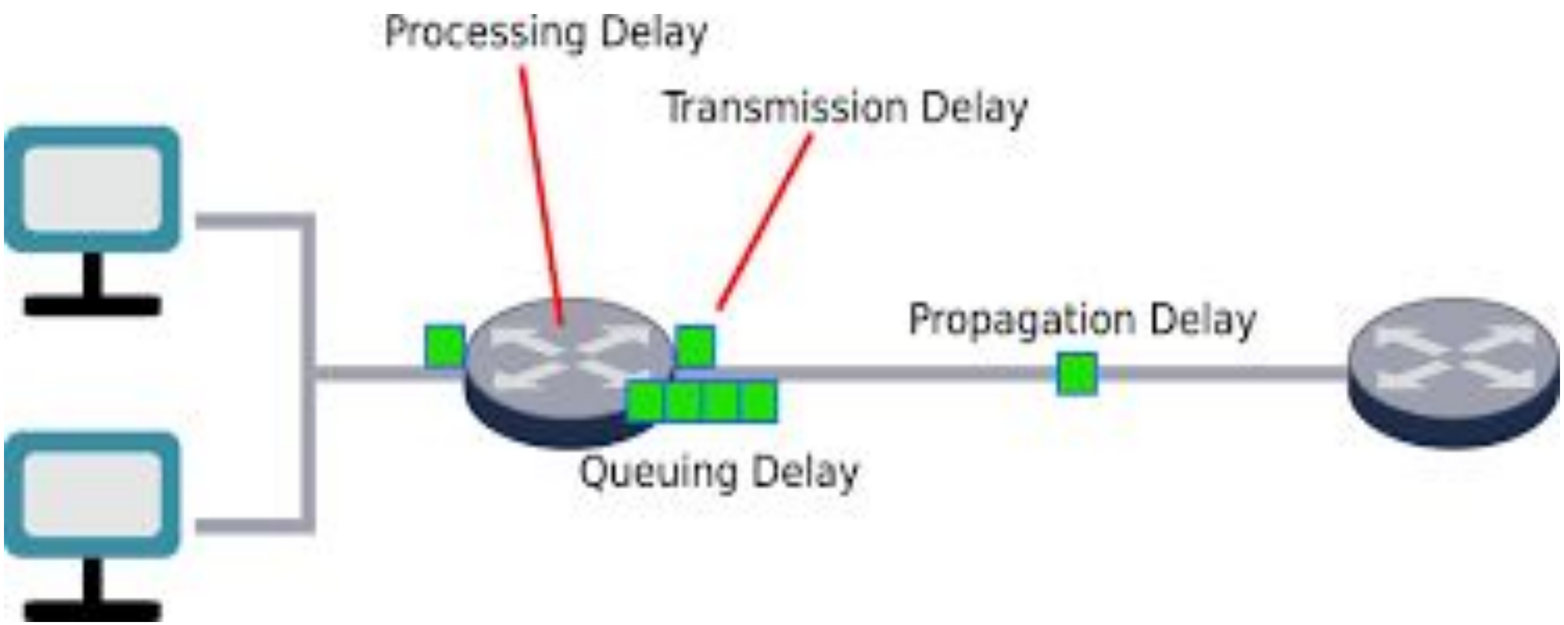
Delay

- When data is sent from source to destination, it travels through a series of nodes and routers.
- The time taken to transmit a data from source to destination is called as Delay. Delay also called Latency
- Different kinds of delay are:



- All these delays is called total delay

Delay, Loss and Throughput in Packet-switched Networks (contd..)



Delay, Loss and Throughput in Packet-switched Networks (contd..)

Processing Delay

- Time required for every intermediate node to process the message in order to move it to the intended destination
- Processing delay is in the order of microseconds or less

Queuing Delay

- There will be queue at every intermediate nodes
- The amount of time spent by a packet at the queue is called as Queuing delay
- When there is a heavy traffic in the networkand many packets are waiting to be transmitted, Queuing delay will be long
- When no packets are currently being transmitted in the link then the queuing delay is zero
- Queuing delay is in the order of microseconds to milliseconds

Delay, Loss and Throughput in Packet-switched Networks (contd..)

Transmission Delay

- Time required to push all the packet's bits into the link
- Transmission time is calculated as,

  Transmission Time = Message size / Transmission rate

- Transmission delay is in the order of microseconds or milliseconds

Propagation Delay

- Time required for a single bit in the message to travel from source to destination
- Propagation time is calculated as,

  Propagation Time = Distance / Propagation Speed

- Propagation delay is in the order of milliseconds

Delay, Loss and Throughput in Packet-switched Networks (contd..)

Example 1:

- What is the propagation time if the distance between the two points is 12,000 km? Assume the propagation speed to be 2.4×10^8 m/s in cable.

Solution:

Given, Distance = 12,000 km = 12,000 * 1000 meters (1km=1000 meters)

Propagation speed = 2.4×10^8 m/s

Propagation Time = Distance / Propagation Speed

$= (12,000 * 1000) / (2.4 * 10^8)$

$=(12 * 10^6) / (2.4 * 10^8) = 5 / 10^2$

= 0.05 sec

= 50ms

Delay, Loss and Throughput in Packet-switched Networks (contd..)

Example 2:

- What are the propagation time and the transmission time for a 2.5-kbyte message (an e-mail) if the bandwidth of the network is 1 Gbps? Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4×10^8 m/s.

Solution:

Given, Distance = 12,000 km = 12,000 * 1000 meters (1km=1000 meters)

Propagation speed = 2.4×10^8 m/s

Message size = 2.5 Kbyte = 2.5 * 1000 bytes(1 Kbyte = 1000 byte)

= 2.5 *1000 * 8 bits (1 byte = 8 bits)

Bandwidth = 1Gbps = $1 * 10^9$ bits/sec

Delay, Loss and Throughput in Packet-switched Networks (contd..)

Example 2(contd..):

Propagation Time = Distance / Propagation Speed

$= (12{,}000 * 1000) / (2.4 * 10^8)$

$= (12 * 10^6) / (2.4 * 10^8) = 5 / 10^2$

$=$ 0.05 sec = 50ms

Transmission Time = Message size / Bandwidth

$= (2.5 * 1000 * 8) / (1 * 10^9)$

$= (20{,}000) / (10^9)$

$= 2 * 10^{-5}$

Transmission Time = 0.00002 sec = 0.02 ms

Delay, Loss and Throughput in Packet-switched Networks (contd..)

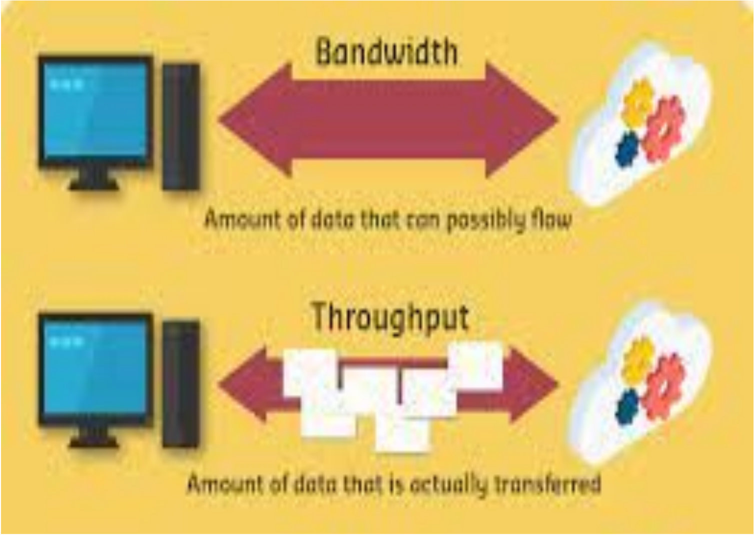
Packet Loss

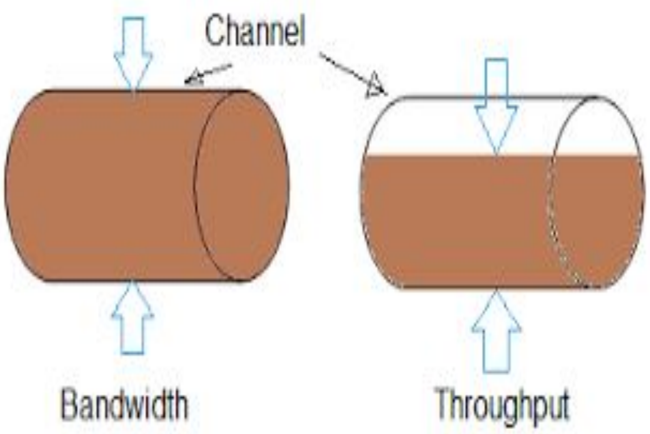
- Queue at the intermediate routers is capable of holding finite number of packets
- If packet arrives to a queue which is full then the router will drop that packet and the packet will be lost. This is called packet loss

Delay, Loss and Throughput in Packet-switched Networks (contd..)

Throughput

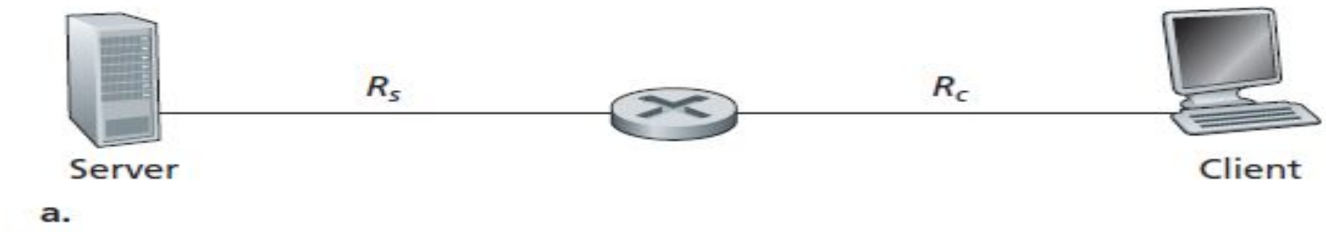
- How fast we can actually send data through a network
- Bandwidth represents maximum capacity of the channel and Throughput represents the actual speed we can be able to send the data through that channel
- Represented in bps (bits per second)
- A link can have a bandwidth of B bps but we can only send T bps (Throughput) through this link with T always less than B





Delay, Loss and Throughput in Packet-switched Networks (contd..)

Throughput



- Let R_s denote the transmission rate of the link between the server and the router and R_c denote the transmission rate of the link between the router and the client
- If $R_s < R_c$ then the bits pumped by the server will flow right through the router and arrive at the client at a rate of R_s bps. Thus the throughput in this case is R_s bps.
- If $R_c < R_s$ then the router will not be able to forward bits as quickly as it receives them. In this case, bits will only leave the router at rate R_c .Thus the end-to-end throughput in this case is R_c.

Delay, Loss and Throughput in Packet-switched Networks (contd..)

Throughput

- Thus the throughput is min{R_s, R_c} (ie) the transmission rate of the bottleneck link (the link which is having minimum transmission rate is called bottleneck link)

Delay, Loss and Throughput in Packet-switched Networks (contd..)

Throughput

Example:

1. A highway is designed to transmit 1000 cars per minute from one point to another. However if there is traffic on the road, this figure may be reduced to 100 cars per minute. The Bandwidth is 1000 cars per minute and throughput is 100 cars per minute
2. Bandwidth of a link is 1Mbps but device connected to the end can handle only 200kbps. That is we cannot send more than 200kbps through this link.

   200kbps is the throughput

Delay, Loss and Throughput in Packet-switched Networks (contd..)

Throughput

Example Problem:

- A network with bandwidth of 10 Mbps can pass only an average of 12,000 frames per minute with each frame carrying an average of 10,000 bits. What is the throughput of this network?

Solution:

Given, Number of frames passed per minute =12,000

So number of frames passed per second = 12,000 / 60 (1 sec = 1/60 minute)

Given, Bits in each frame = 10,000

Throughput = (12000*10000) / 60

= 20,00,000 bps = 2 Mbps

Throughput is one-fifth of the bandwidth in this example

Network Model

2 type of models for computer networks,

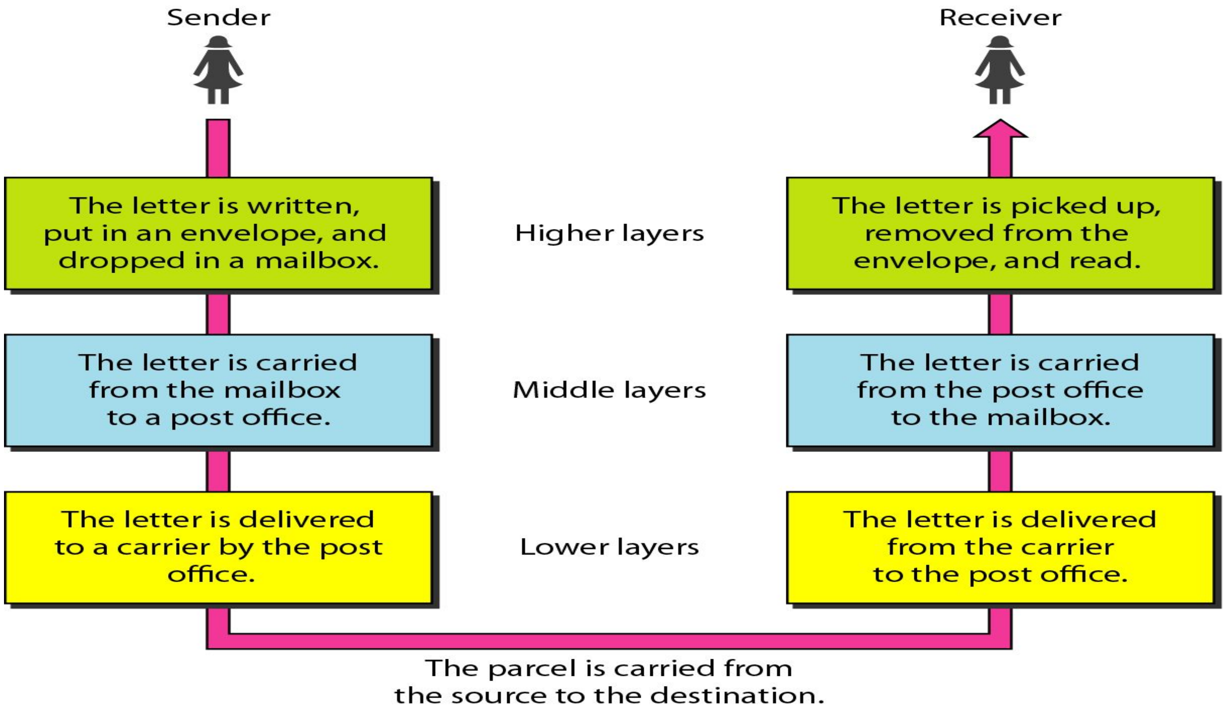
1. OSI model
2. TCP/IP model

- TCP/IP model is the model what we are using in the Internet nowadays

Protocol Layering

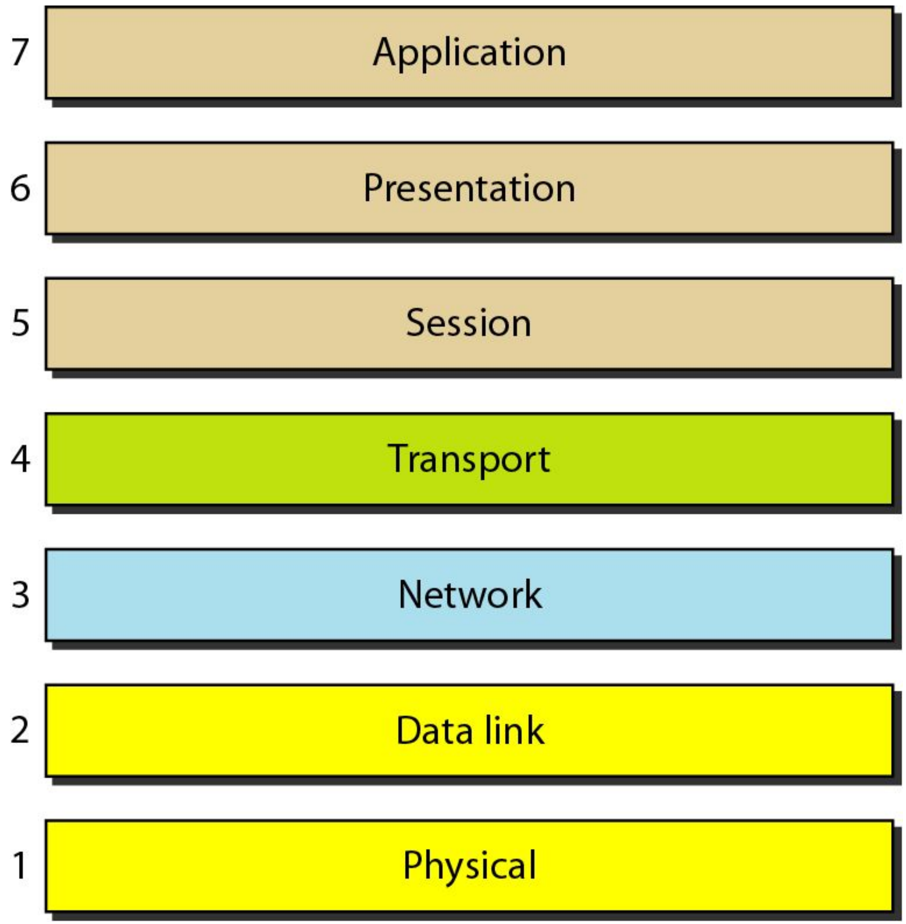
- When communication in simple we need only one protocol.
- When communication is complex we need to divide the task between layers where we need protocol for each layer
- This is called protocol layering

Example: **Tasks involved in sending a letter**



The OSI Model

- Seven layers of the OSI model

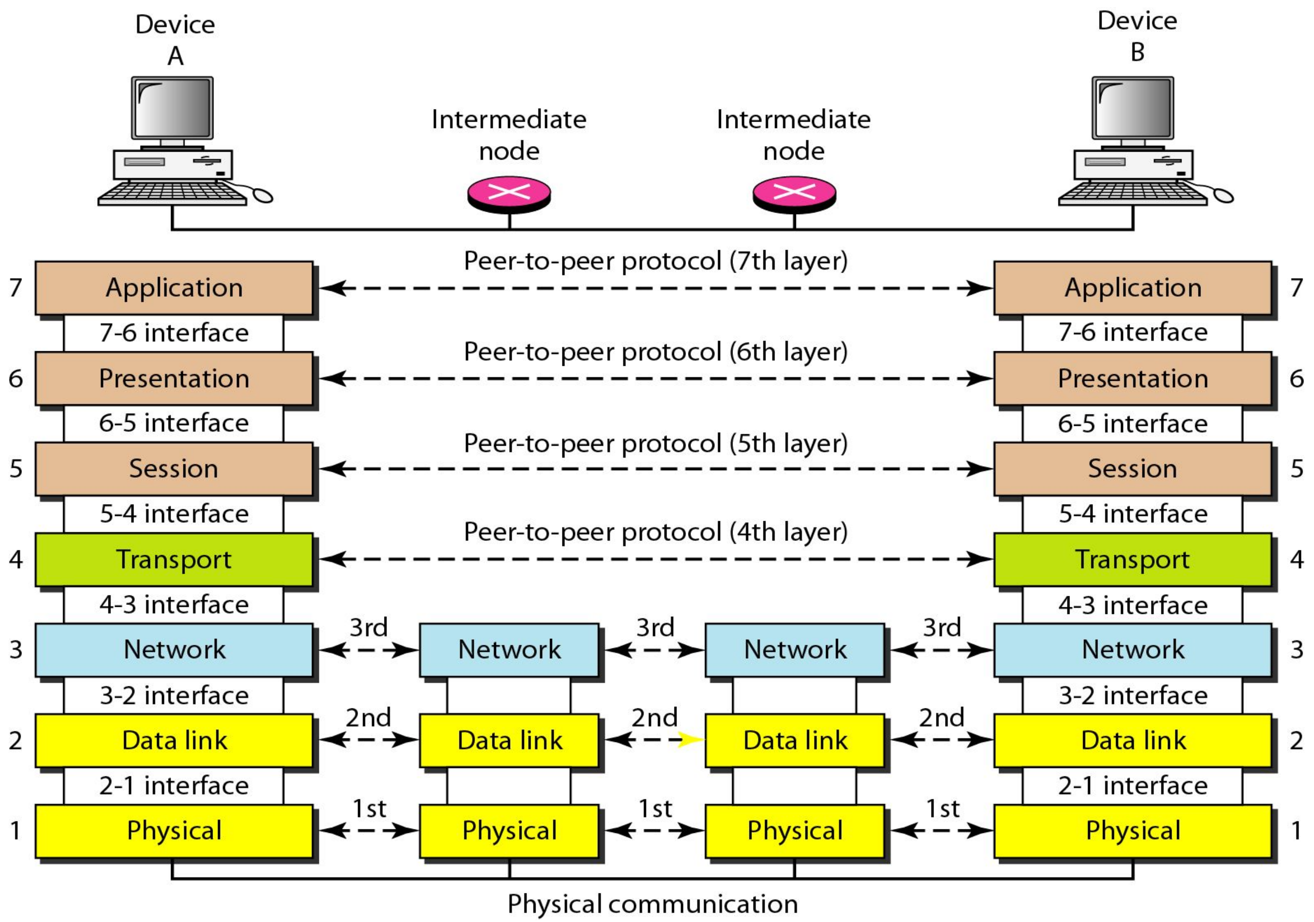


The OSI Model

- International Standards Organization (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.
- ISO is the organization and OSI is the model

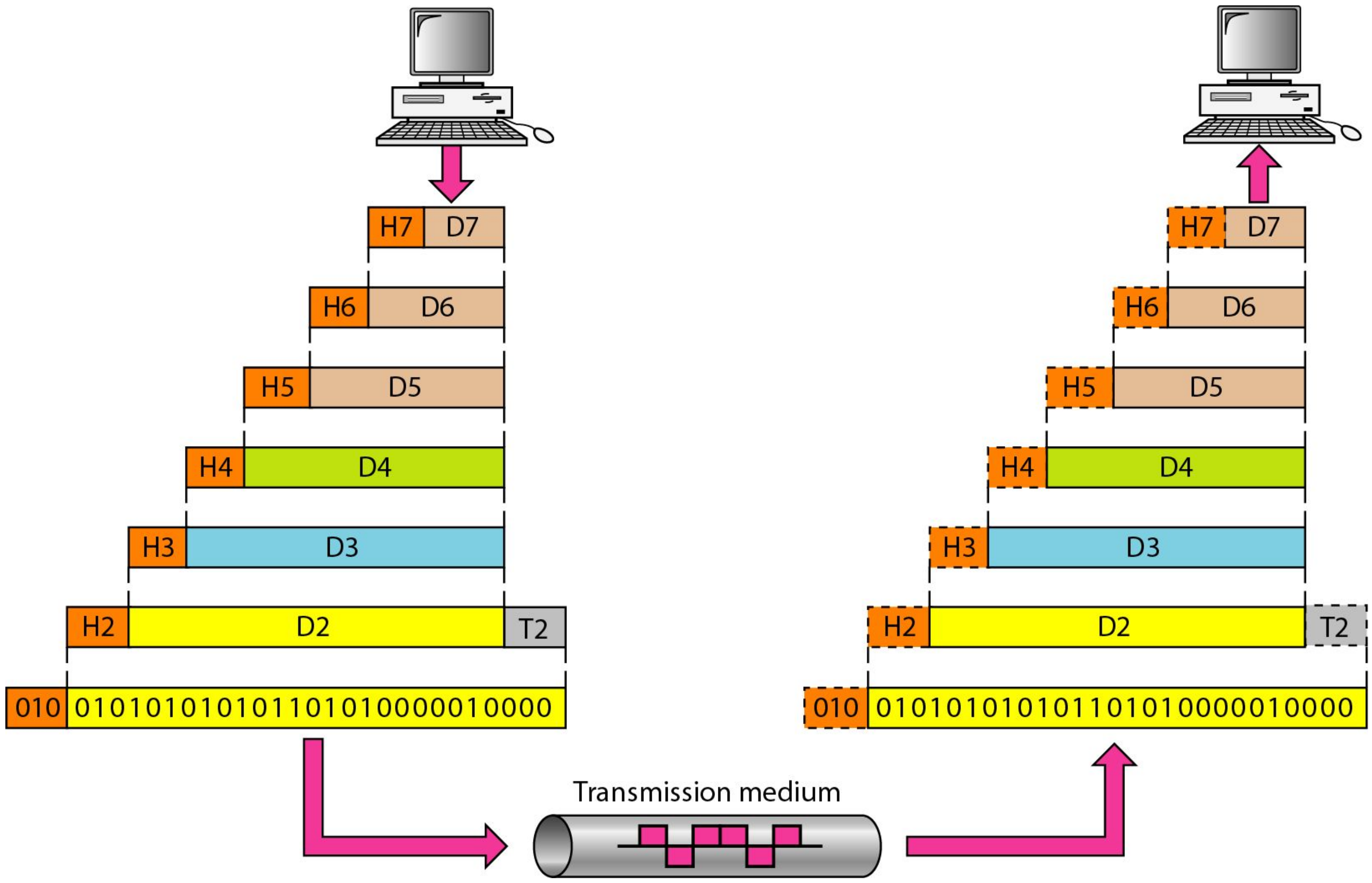
The interaction between layers in the OSI model

- Both at sender and receiver side data flow through all the 7 layers. At sender side data starts transmitting from application layers and moves down to physical layer through which it reaches the receiver. At receiver side data start moving upwards from physical to application layer

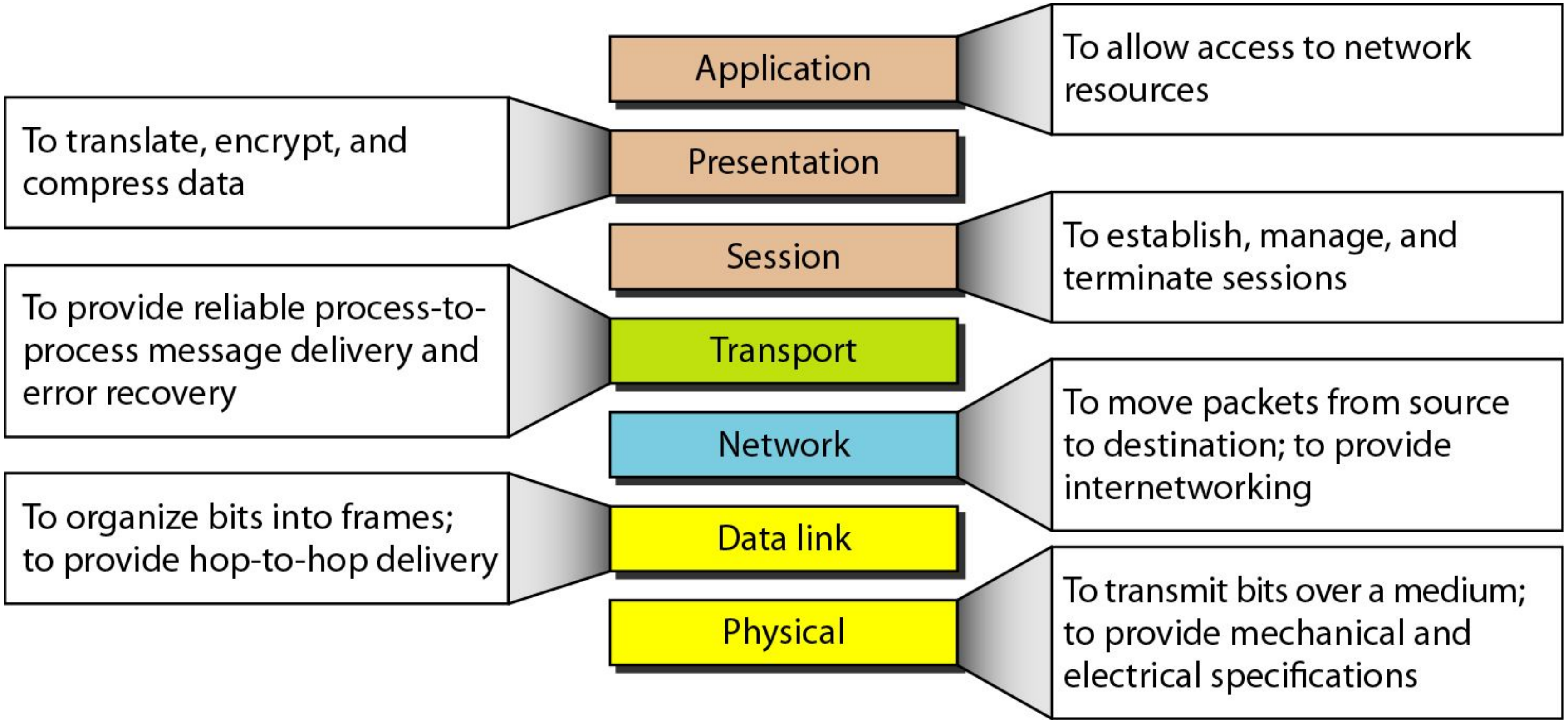


An exchange using the OSI model

- At sender side when data moves down through each layer, header is added at each layer and at receiver side header gets removed

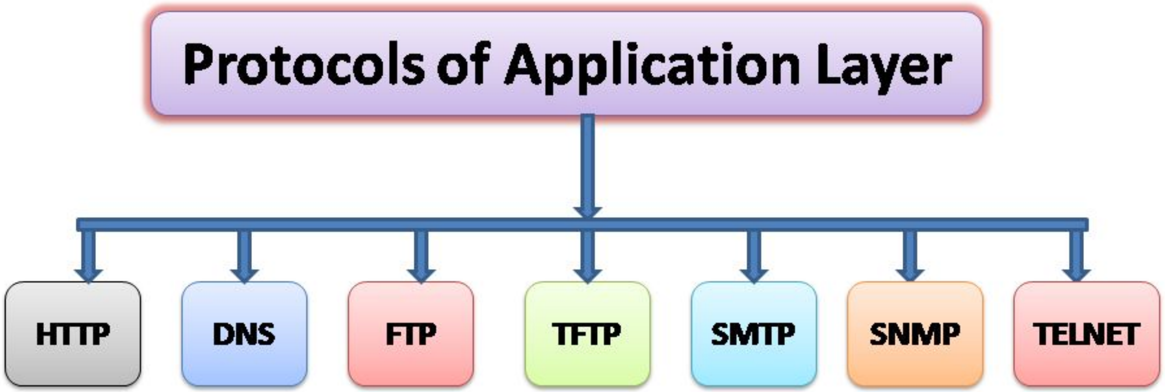


Summary of OSI layers



1.Application Layer

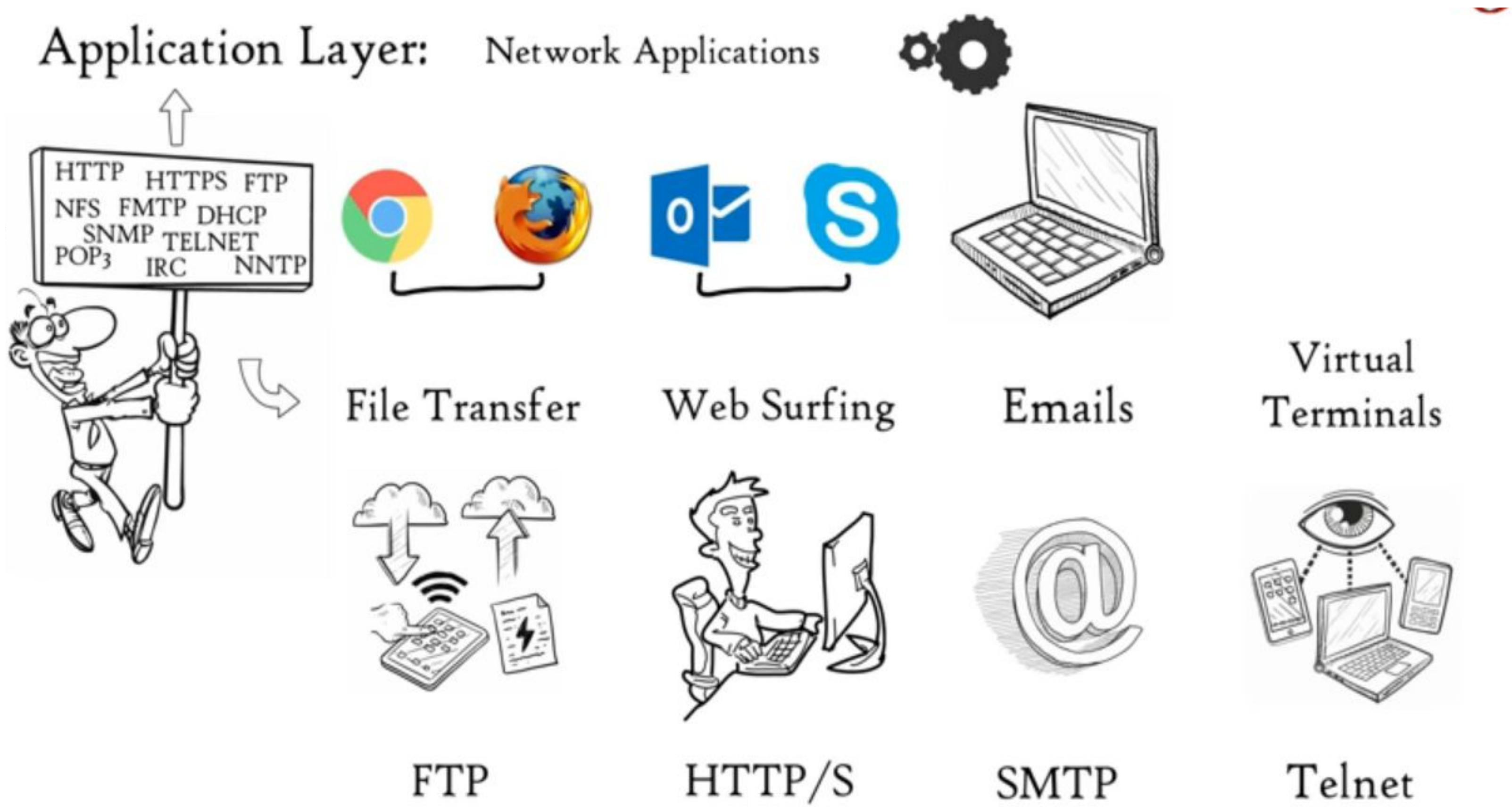
- This is the layer where user actually works
- This layer is used by computer applications like Google Chrome, Firefox etc. that use Internet
- These computer applications make use of application layer protocol to do its job
- The different application layer protocols are,



- These protocols are used for network services like Web surfing, File transfer, Emails etc.

1.Application Layer (contd..)

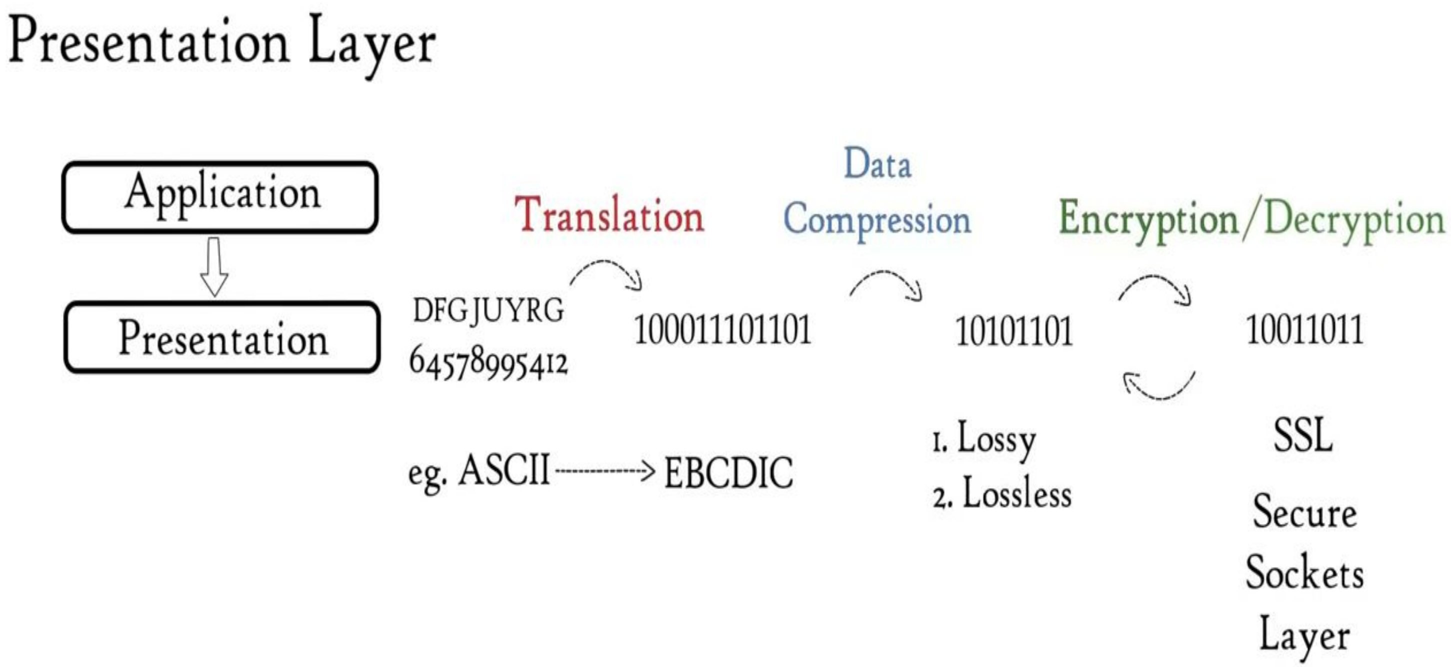
- The diagram shows the use of Application layer protocols like HTTP, FTP by network applications like browsers for file transfer, web surfing, emails etc



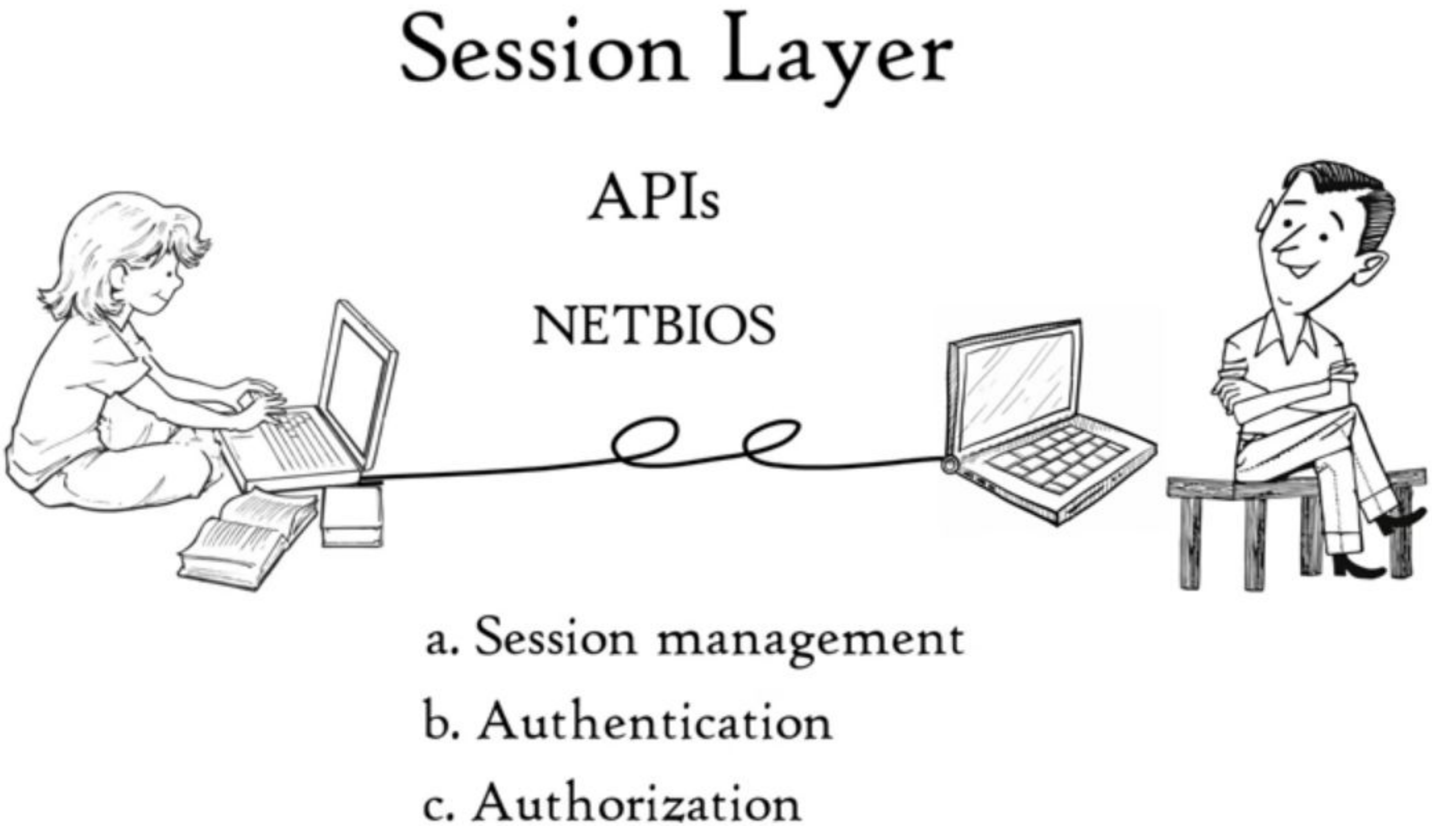
2. Presentation Layer

- This layer is responsible for 3 basic functions.

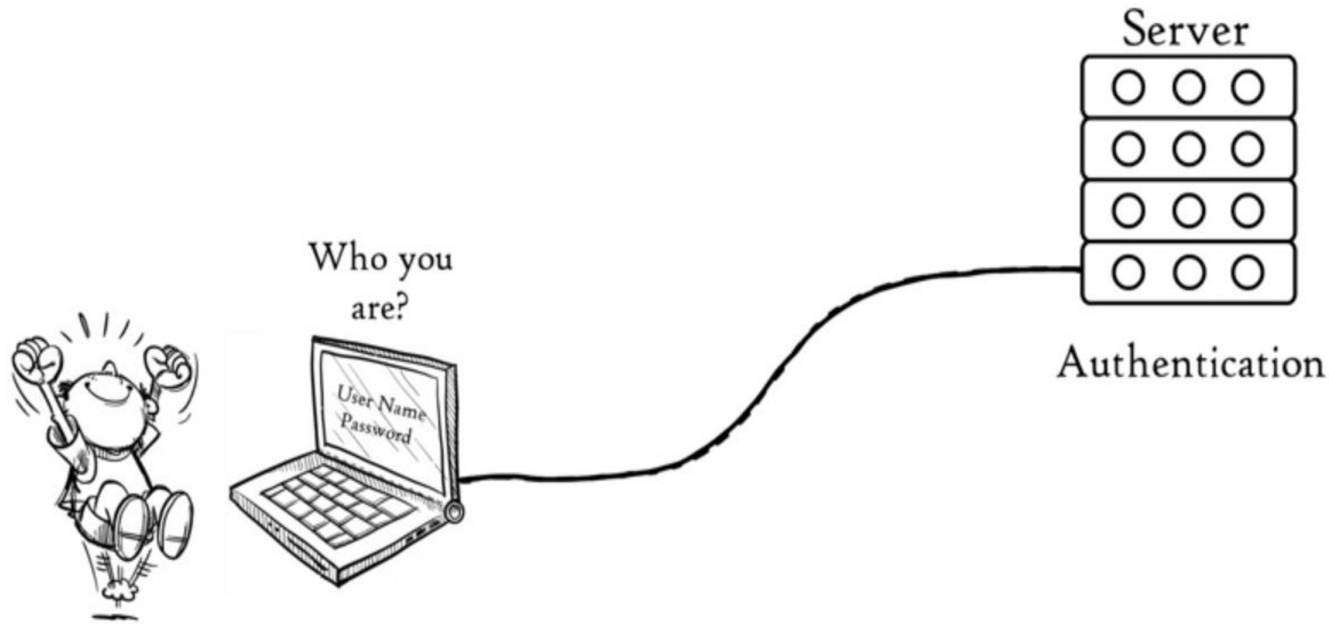
1. Translation (converting human readable form to machine understandable binary format. Eg: ASCII EBCDIC)
2. Data Compression- reducing size of the data
3. Encryption/Decryption



3. Session Layer



3.Session Layer (contd..)



4. Transport Layer

Transport Layer

Segmentation

Flow Control

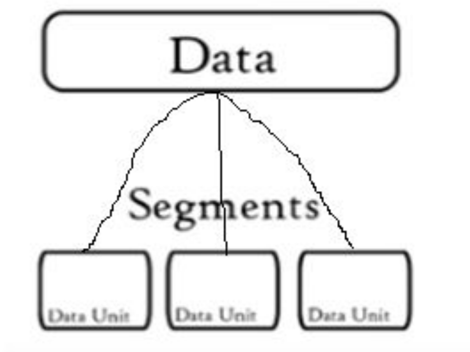
Error Control

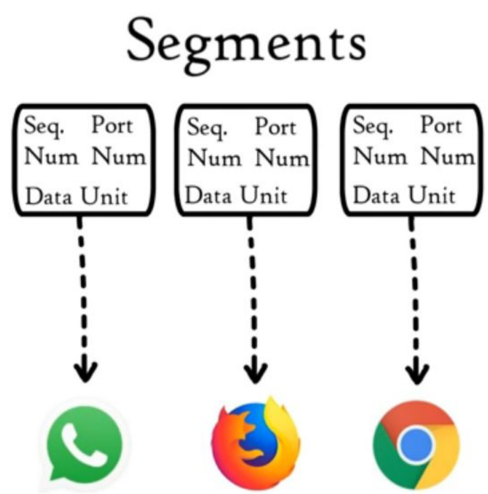
Connection and Connectionless Tx

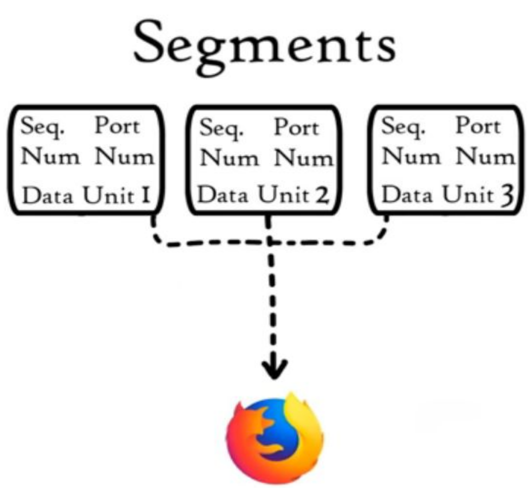
4. Transport Layer (contd..)

Segmentation:

- Segmentation means dividing data into multiple data units. Each unit called as segment
- To each segment sequence number and port number will be added
- With help of sequence number only segments will be reassembled at receiver



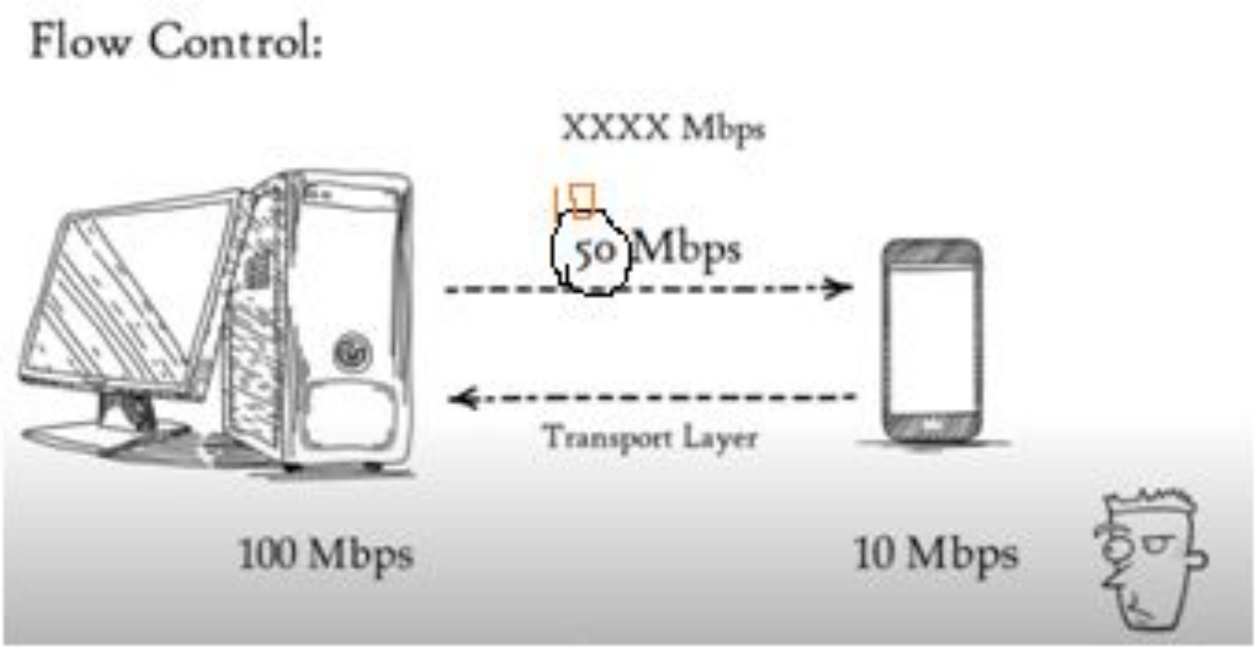




4. Transport Layer (contd..)

Flow Control

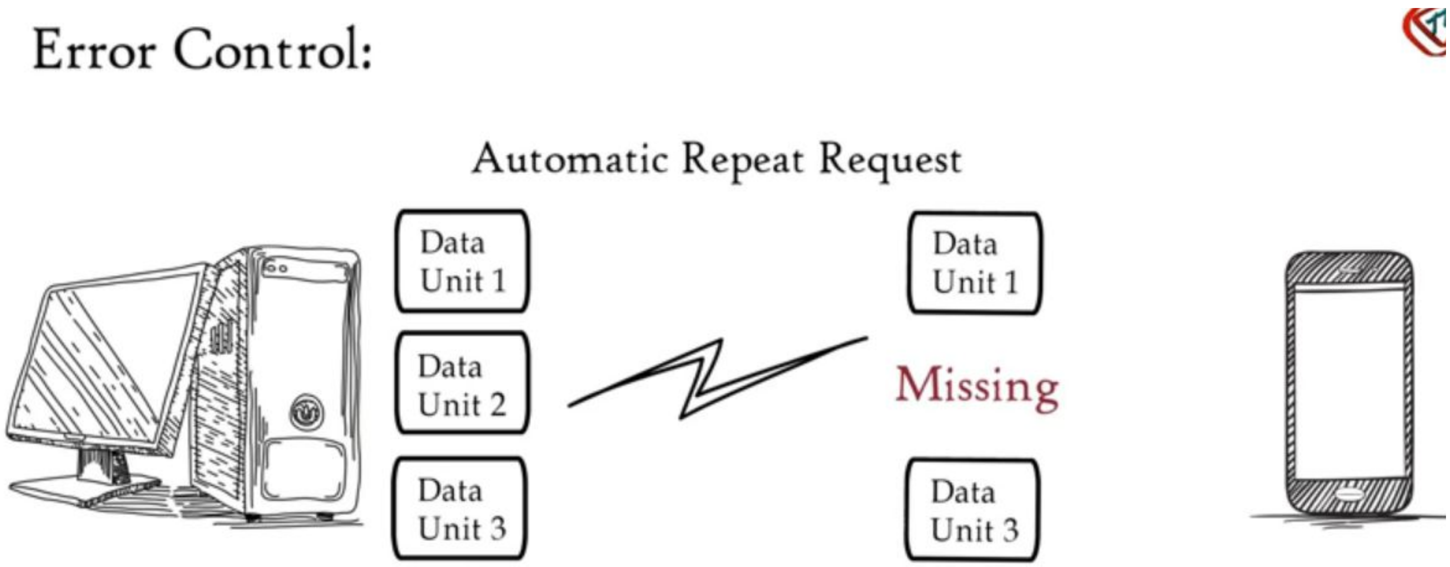
- If sender sends data at higher rate which cannot be received by the receiver then there may be loss in in data
- To overcome this problem flow control is proposed in which sender sends data at the rate acceptable by the receiver



4. Transport Layer (contd..)

Error Control

- If any data send by the sender is missing asking sender to send again



4. Transport Layer (contd..)

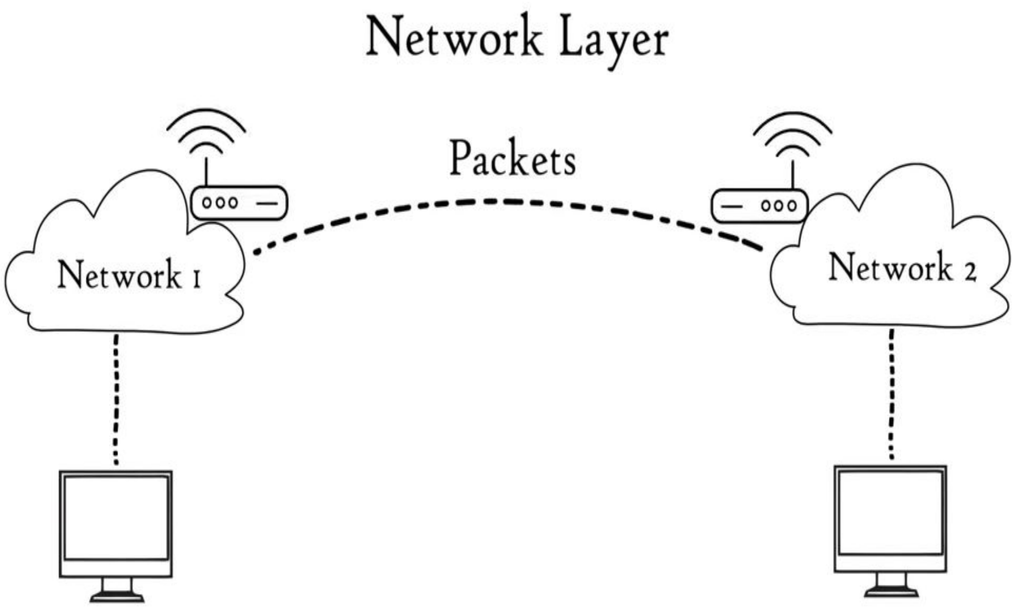
Protocols of Transport Layer

Transport Layer

Services:	Protocols:
Connection-oriented Transmission	→ Transmission Control Protocol (TCP)
Connectionless Transmission	→ User Datagram Protocol (UDP)

5. Network Layer

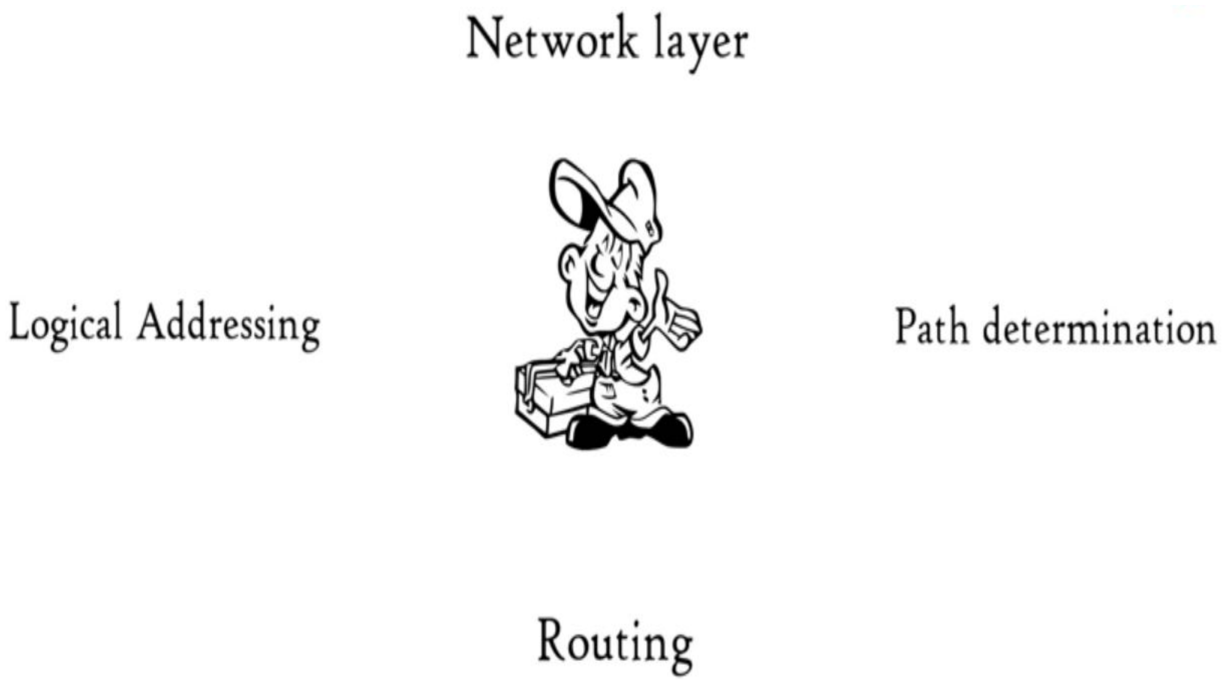
- Network Layer is responsible for transmitting data from one computer to another
- It provides system to system delivery (or) host to host delivery
- Internet Protocol (IP) is the protocol used in this layer



5. Network Layer (contd..)

<u>Functions of Network Layer:</u>

1. Logical Addressing
2. Routing
3. Path Determination

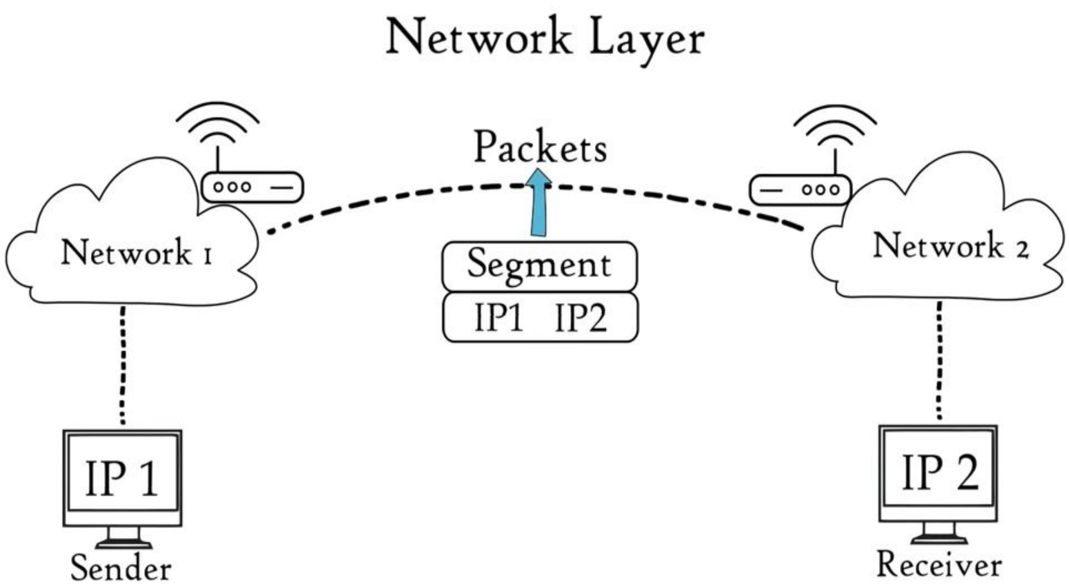


5. Network Layer (contd..)

Functions of Network Layer:

1. **Logical Addressing:**

- IP addressing done in Network Layer is called Logical addressing
- Every computer in a network is having a unique address called IP address
- Network layer puts sender and receiver IP address to the segment and form an IP packet



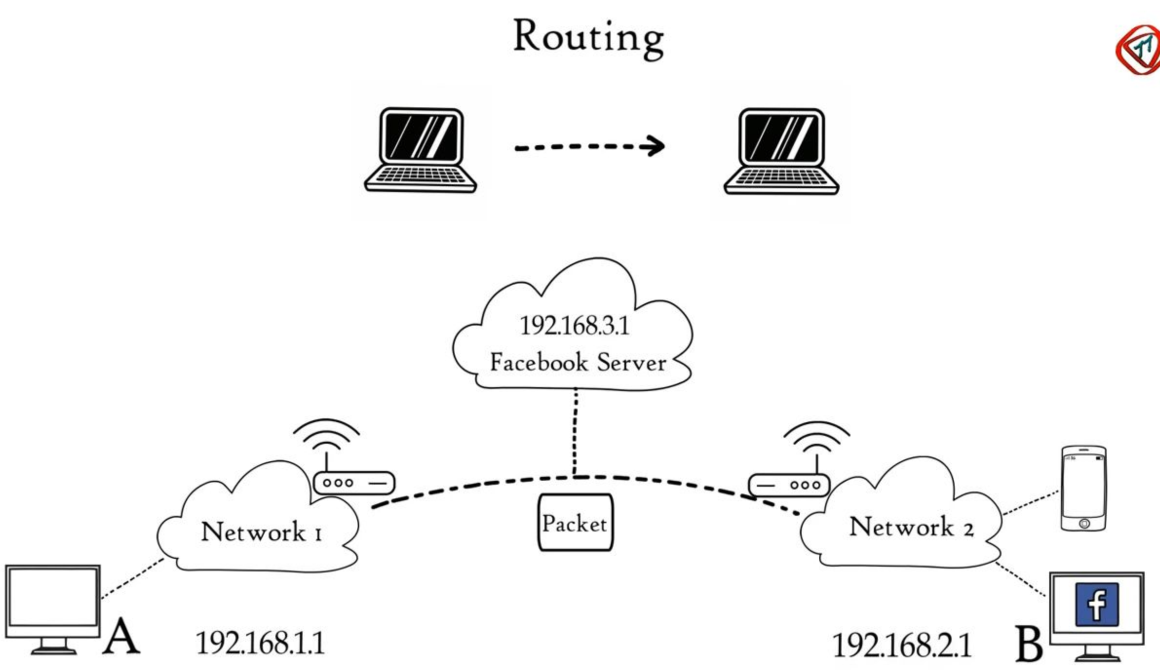
- In above diagram IP1 is sender IP address and IP2 is receiver IP address

5. Network Layer (contd..)

Functions of Network Layer:

2. **Routing:**

- Routing means moving the data from source to destination
- Routing is done with the help of IP address

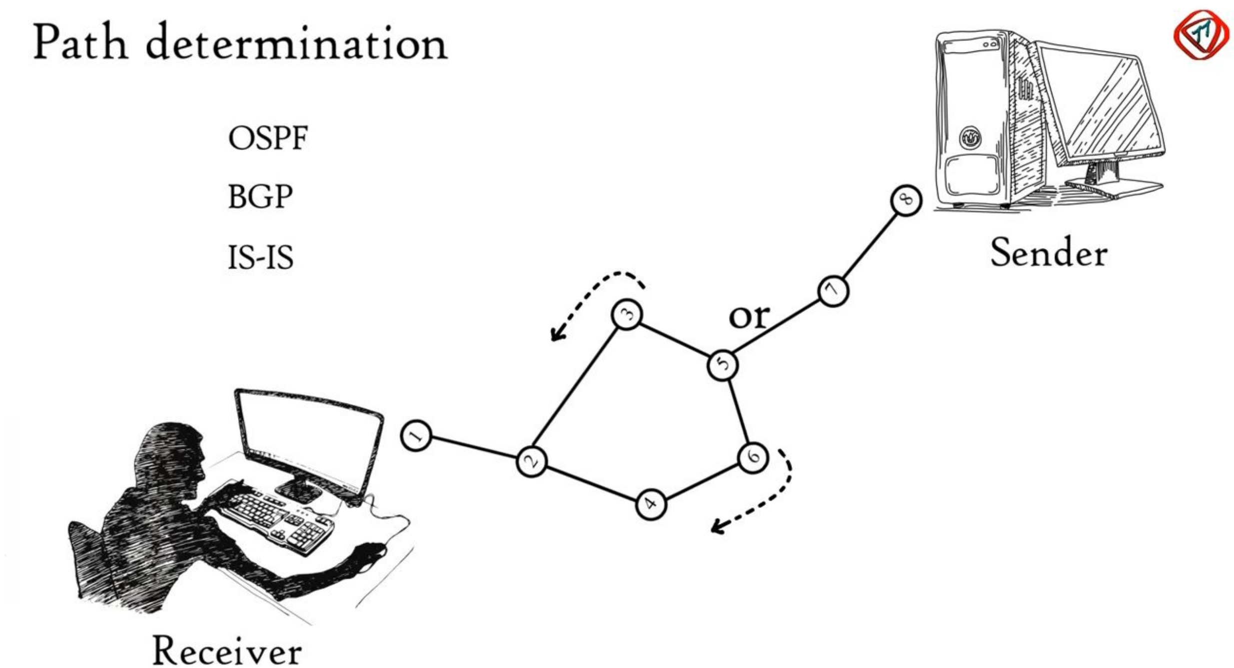


5. Network Layer (contd..)

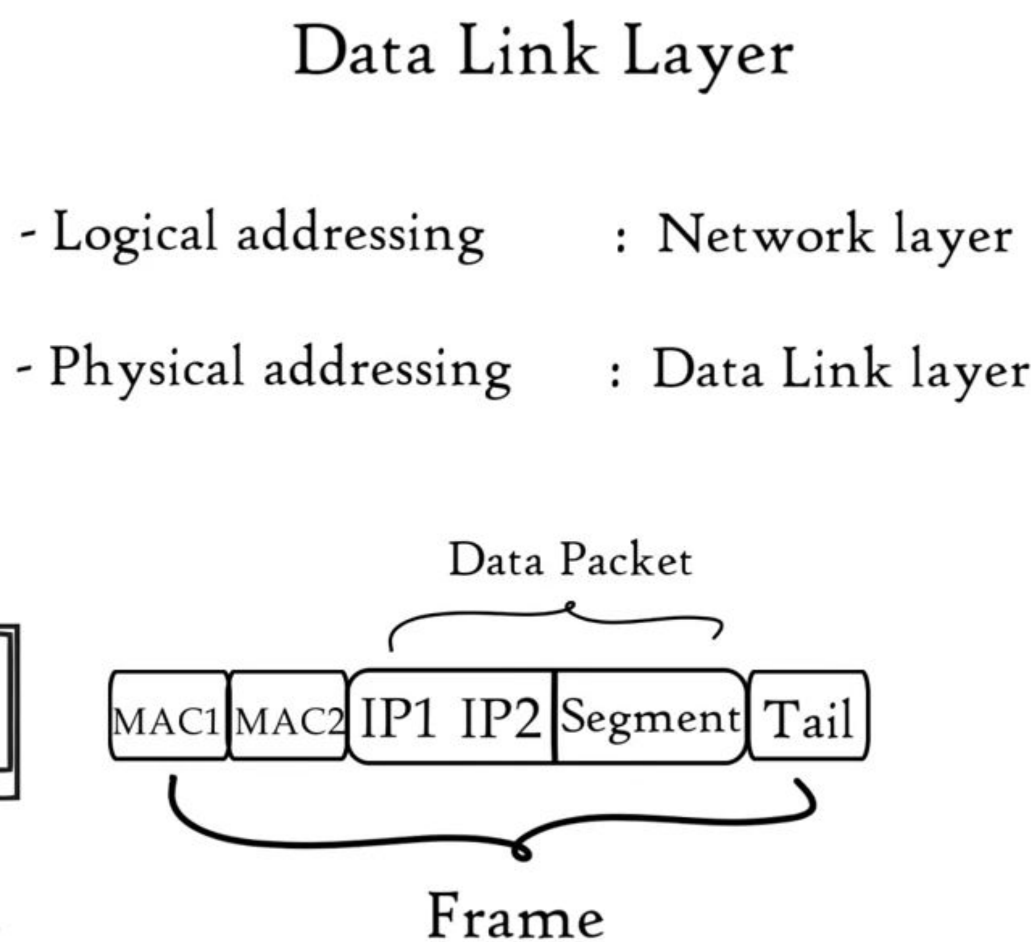
Functions of Network Layer:

3. **Path Determination:**

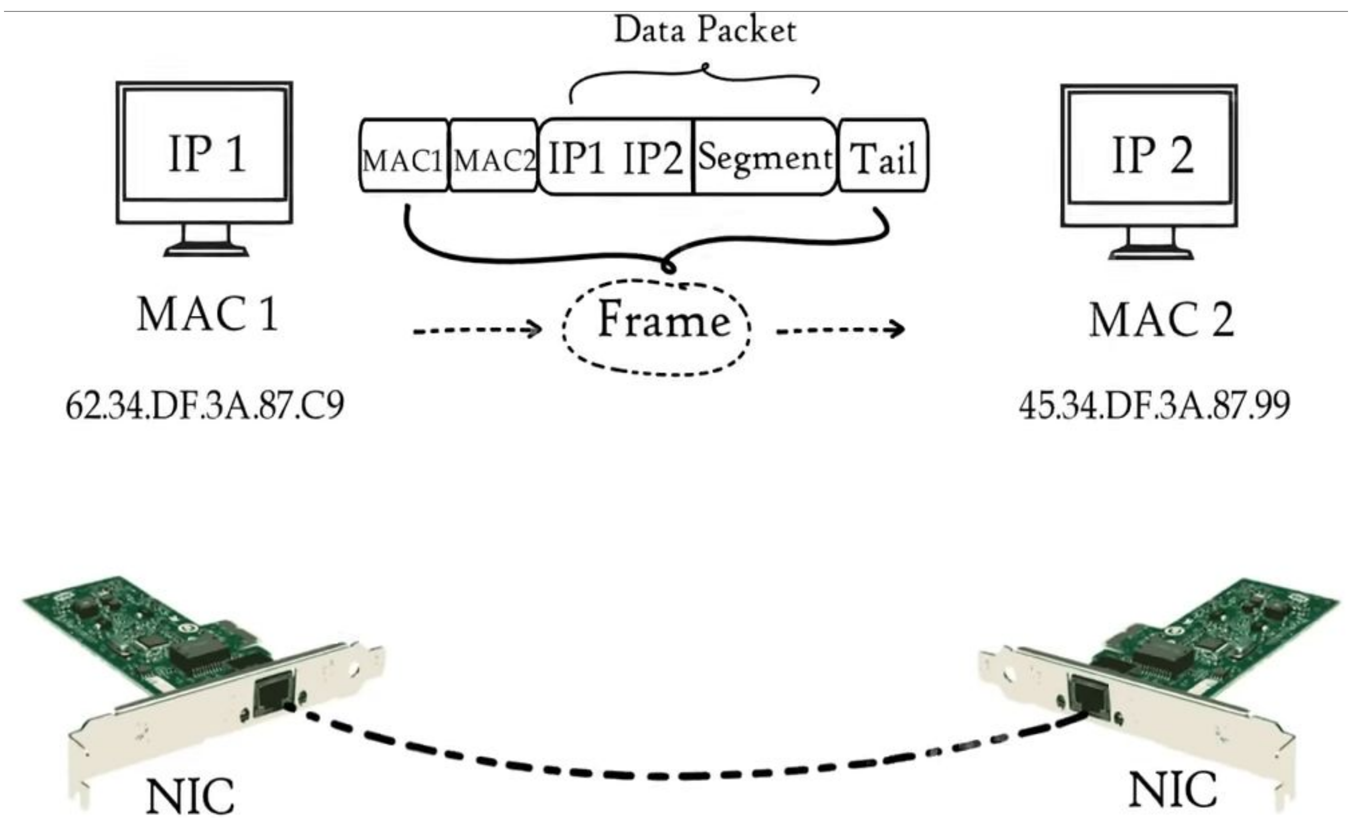
- sender can be connected to the receiver in a number of ways
- Choosing the best path for data delivery from sender to receiver is called path determination
- Protocols like OSPF, BGP, IS-IS are used for path determination



6. DataLink Layer



6. Data Link Layer (contd..)



6. Data Link Layer (contd..)

Functions of Data Link Layer:

Data Link Layer

Access the media

(Framing)

Controls how data is placed and received from the media

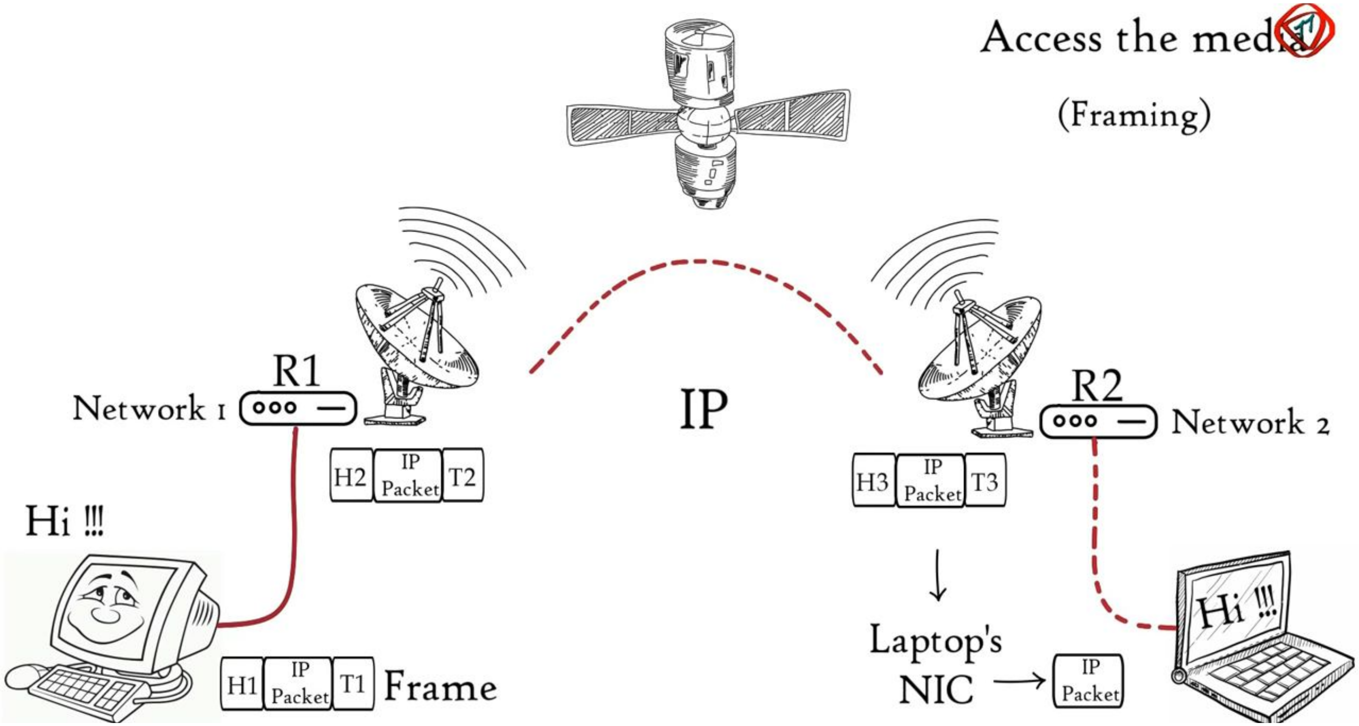
(Media Access Control)
(Error Detection)

6. Data Link Layer (contd..)

Functions of Data Link Layer:

1. **Accessing the Media**

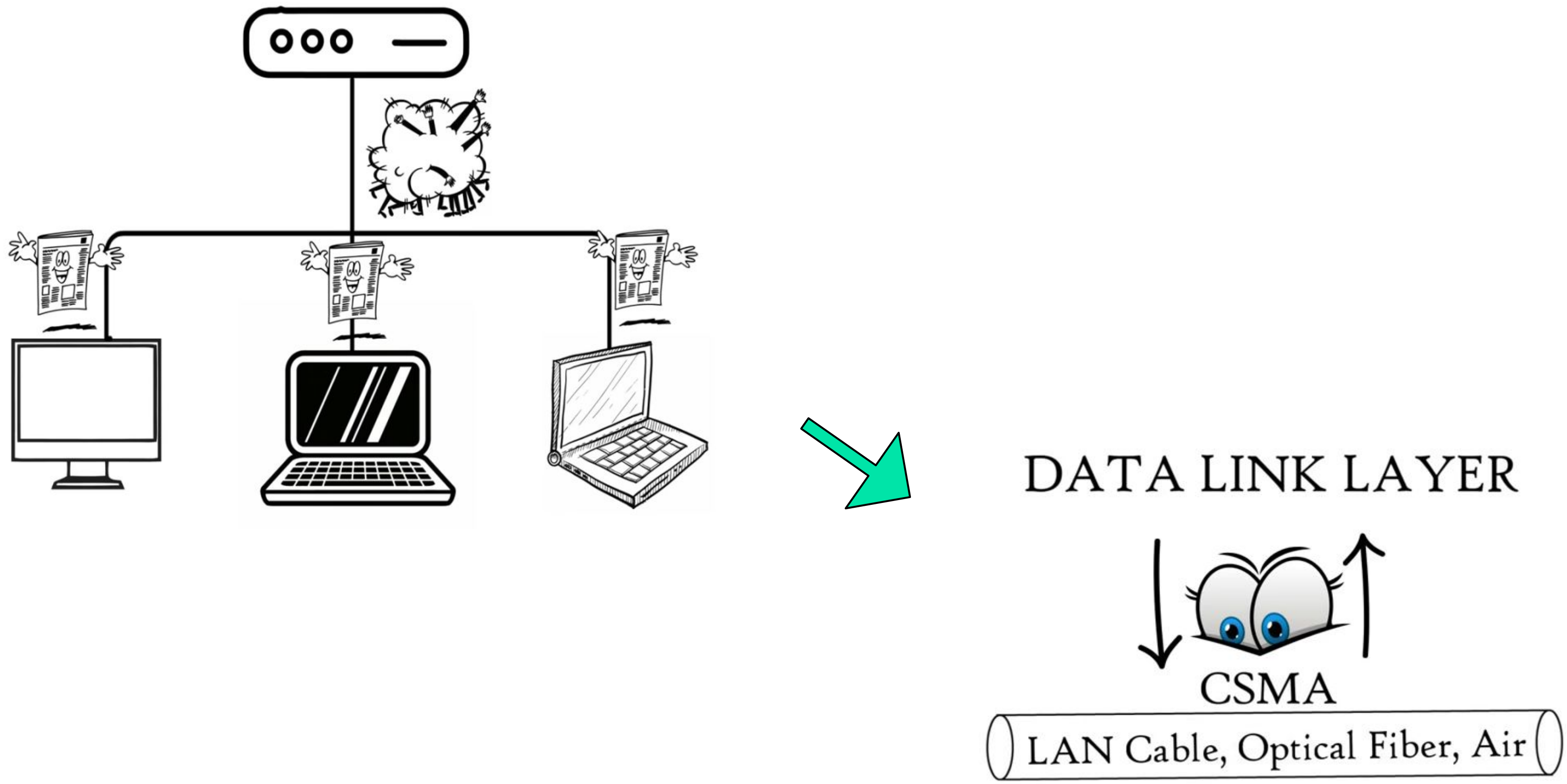
- Data will be send as frames in the data link layer



6. Data Link Layer (contd..)

Functions of Data Link Layer:

2. **Media Access Control :** Before sending data through a channel, we have check whether channel is free or not using protocol called CSMA

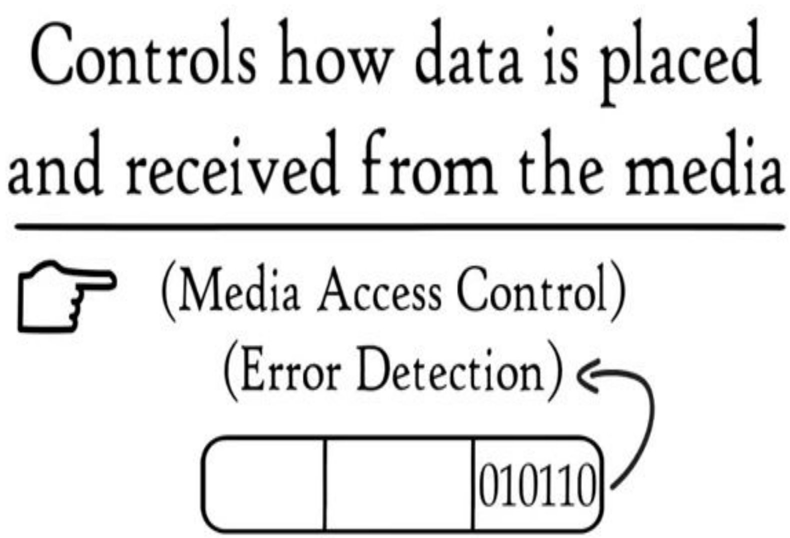


6. Data Link Layer (contd..)

Functions of Data Link Layer:

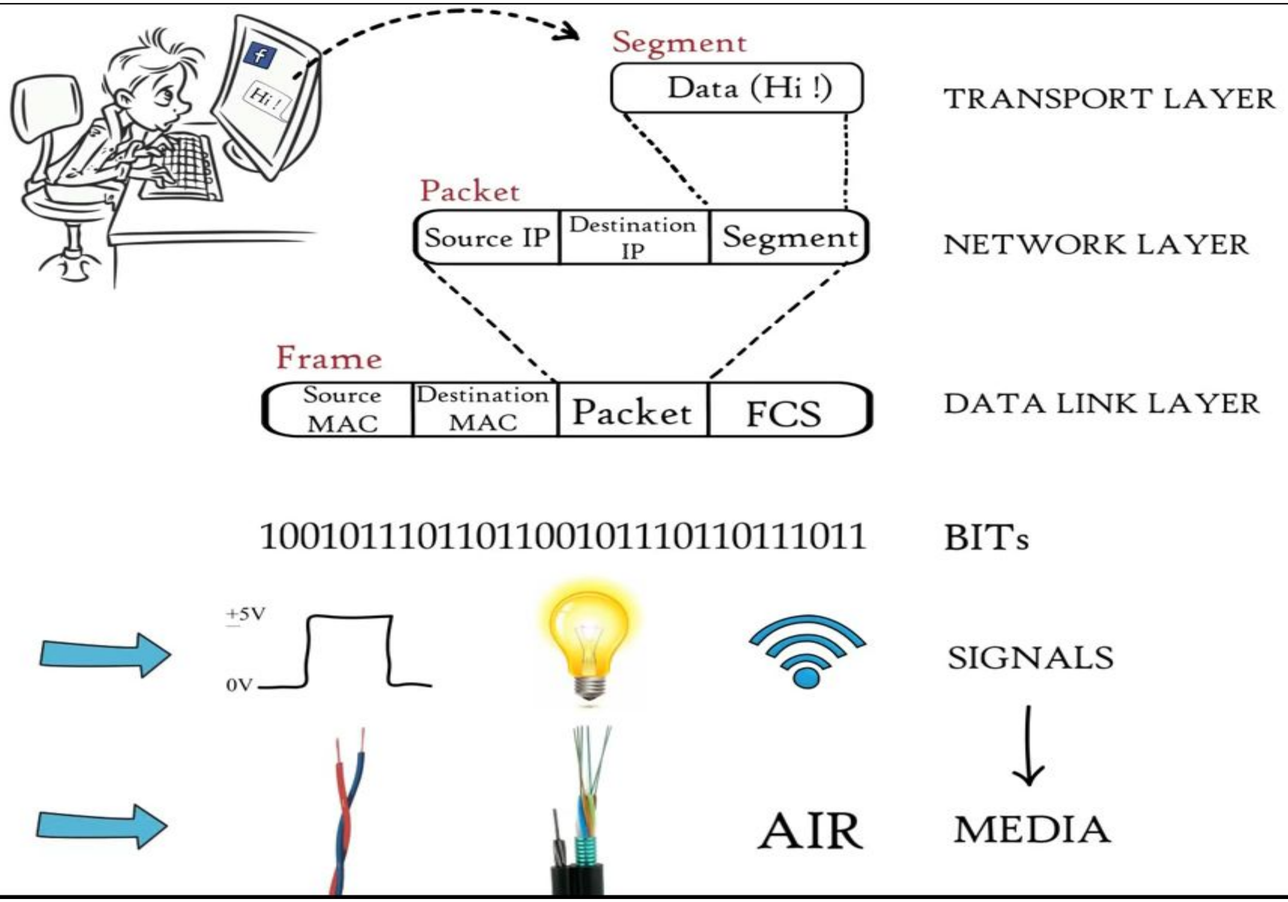
3. **Error Detection**

- In order to check whether any errors have occurred in the data during transmission, Error detection is performed at receiver side
- For this purpose some extra bits are added at the end of the data called redundant bits which are used for error detection



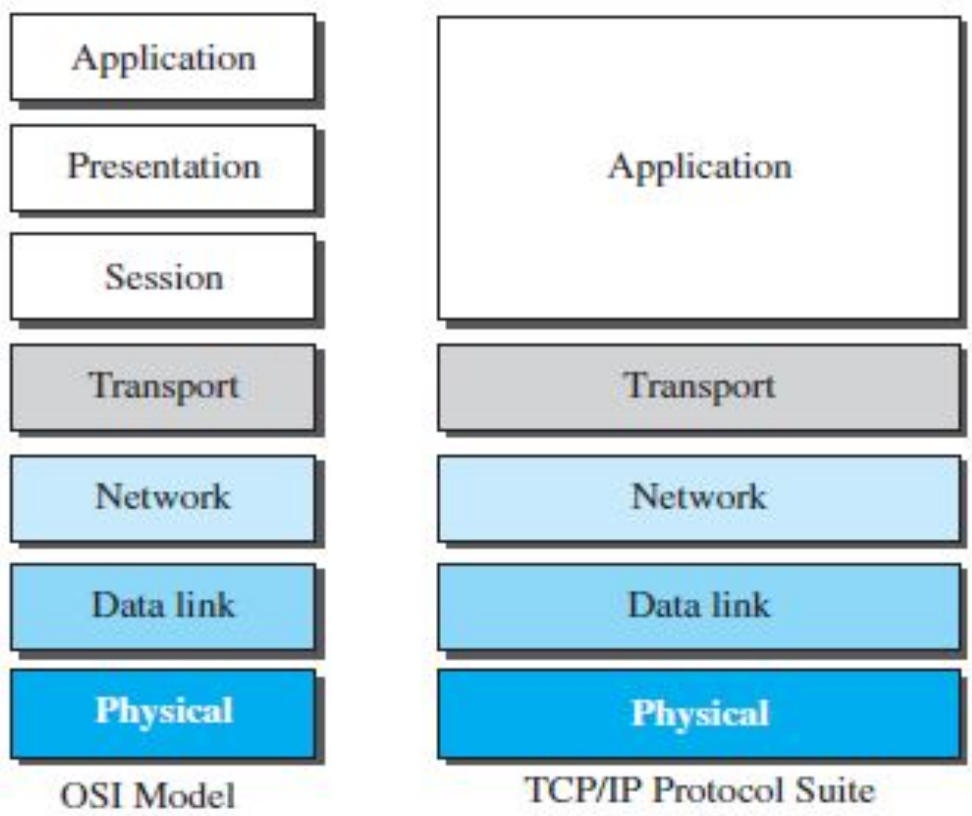
7. Physical Layer

It is the duty of the physical layer to convert data in bits to signals in order to be transmitted through the transmission medium



TCP/IP PROTOCOL SUITE

- 5 layers in the TCP/IP network model
- This TCP/IP is the model what we are using in the network nowadays

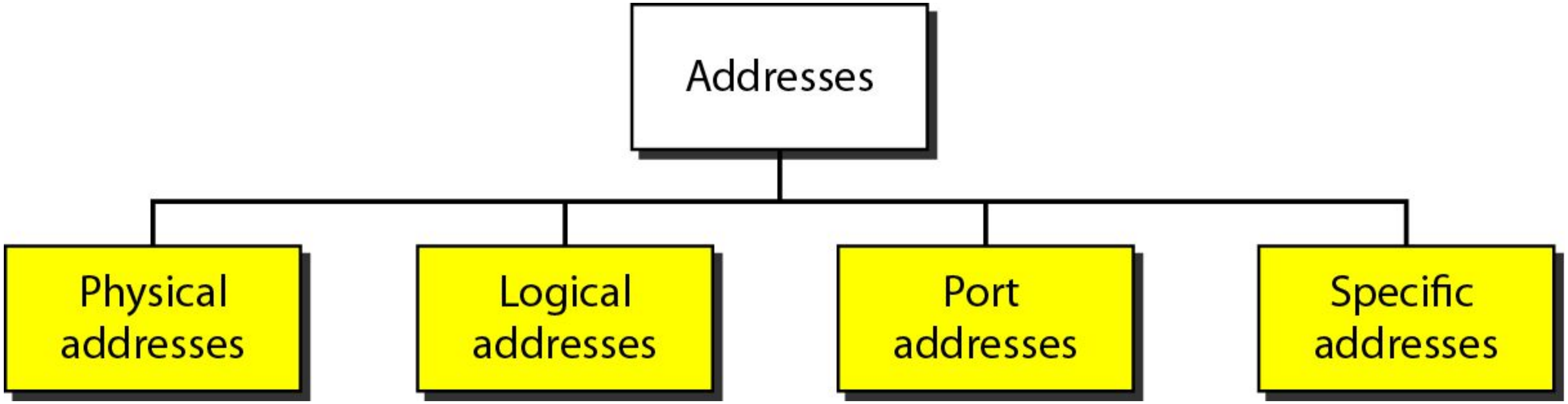


OSI model vs TCP/IP model

OSI Model	TCP/IP Model
It is developed by ISO (International Standard Organization)	It is developed by ARPANET (Advanced Research Project Agency Network)
OSI layers have seven layers	TCP/IP has four layers
Session and presentation layers are a part of the OSI model.	There is no session and presentation layer in the TCP model.
OSI is a reference model around which the networks are built. Generally it is used as a guidance tool.	TCP/IP model is, in a way implementation of the OSI model.
In the OSI model, the transport layers only connection-oriented.	A layer of the TCP/IP model is both connection-oriented and connectionless
The minimum size of the OSI header is 5 bytes	The minimum header size is 20 bytes

Addressing

- 4 types of addresses used in the network model



Network Interface Card

- A Network Interface Card (NIC) is a hardware component without which a computer cannot be connected over a network.
- It is a circuit board installed in a computer that provides a dedicated network connection to the computer.
- It is also called network interface controller, network adapter or LAN adapter.

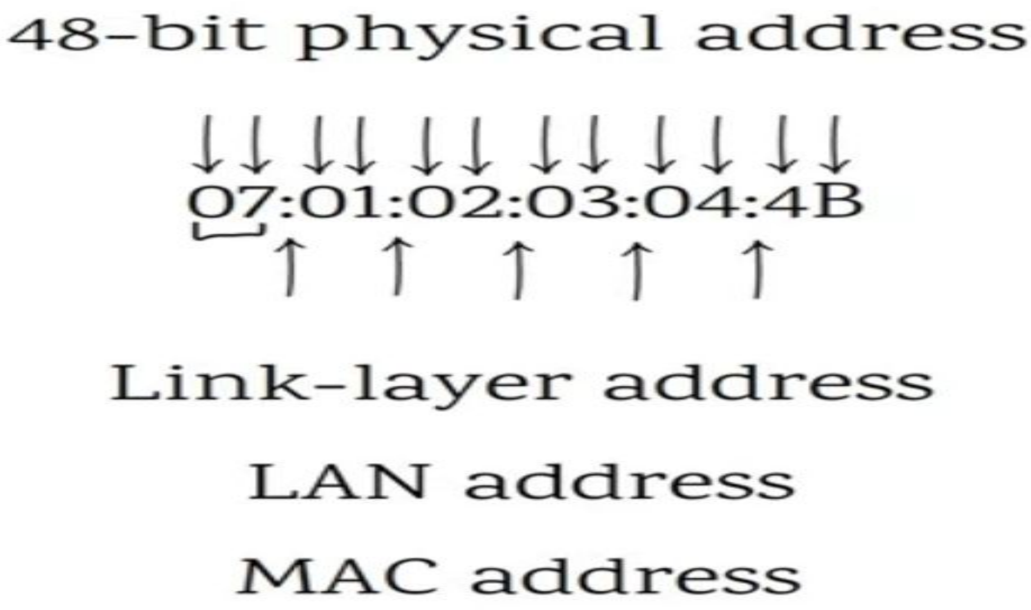
Physical Address/MAC Address

- Physical address is a globally unique address assigned to every Network Interface Card (NIC) in a system
- This address is used to uniquely identify a system in a network
- This address is provided by the manufacturer who manufactures the card and is embedded in the card itself
- This address is a permanent address . Even though we are moving a system from one network to another network this address remains same
- Physical address is mostly referred as called Media Access Control (MAC) address
- Also referred in other ways like Link Layer address (or) LAN address
- Useful for local communications

Physical Address/MAC Address (contd..)

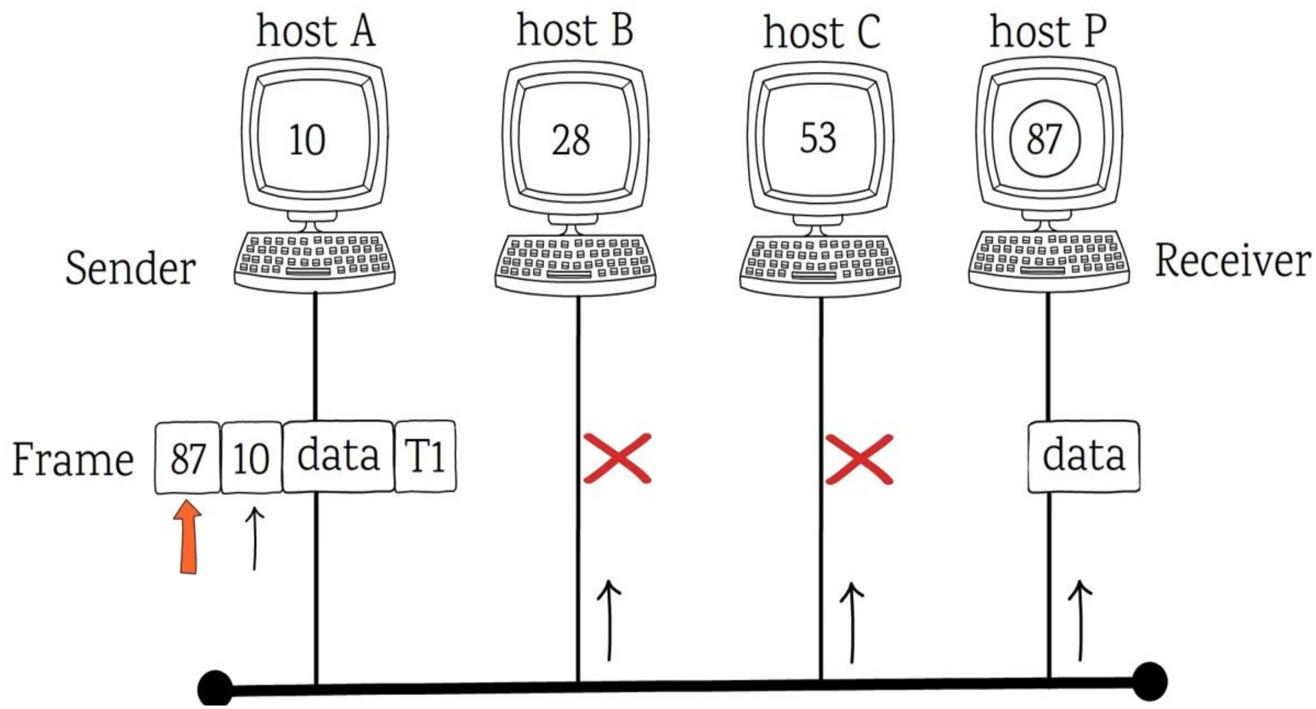
Format of MAC address:

- Every MAC address is of 48 bits which is written in hexadecimal format as shown below
- Every byte is separated by colon



Physical Address/MAC Address (contd..)

- If we are sending data within a network then MAC address alone is necessary to send the data. Assume MAC address of sender and receiver as 10 and 87

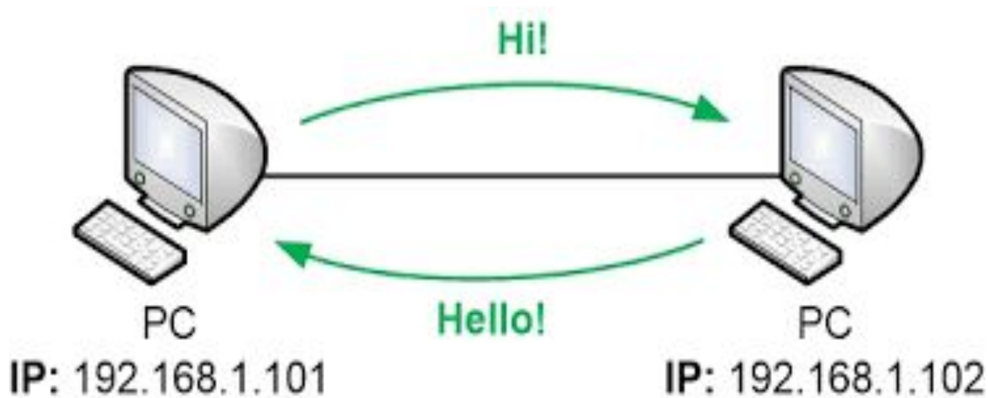


Logical Address/IP Address

- Logical address/IP address is a unique address assigned to each device in a network
- When a system comes in a network an IP address is assigned to the system
- This IP address is not a fixed address. Whenever a system moves from one network to another network this address is going to be changed.

Example:

- IP Address is similar to address that every house is having which is used by the postal service for delivering letters



Logical Address/IP Address(contd..)

Format of IP address:

- Every IP address is of 32 bits which is written in dotted decimal format as shown below
- Every byte is separated by dot(.)

IP: 192.168.1.101

Why both MAC and IP Addresses are needed for a system?

What happens if MAC Address alone is maintained for a system?

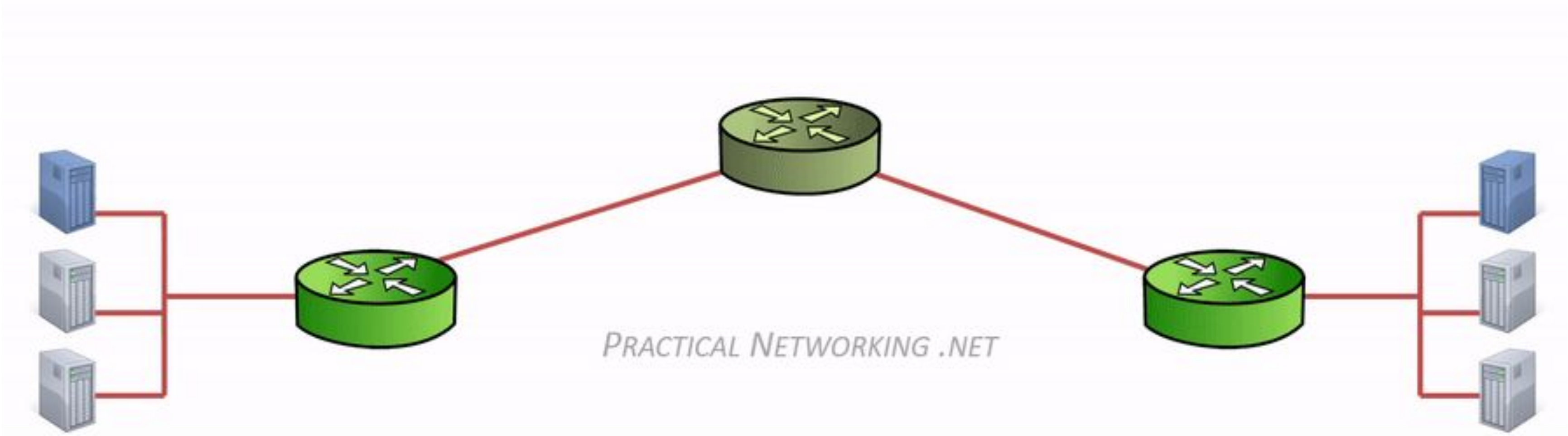
- Assume in the world every people is going to have a unique name and no address is maintained about where that person present in the world. If one person wants to send a message to the someone then that person has to go to every house and verify where that person wants to deliver the message and finally reach the destination. Doing this job is a very tedious one. Consider that unique name as the MAC address of system in network. MAC address is like a name for a system. Having MAC address (name) alone it is not enough to reach destination. We have to now in which location (ie) in which network the destination resides. For finding out that location of destination, IP address is used

Why both MAC and IP Addresses are needed for a system?

What happens if IP Address alone is maintained for a system?

- Every data send from source to destination is going to have the source and destination system IP address. If source and destination are present in two different networks then where the source has to forward the packet next by having the source and destination IP address alone in the data is a question mark. This is the place where MAC address is used. The source will forward the data to the router with the help of router MAC address. Router after getting the data will now change source MAC as its MAC address and destination MAC address as next router MAC address. This is how forwarding of data happens with the help of both IP and MAC Address

Animation representing changing of MAC address at intermediate nodes (Put in slideshow and see)

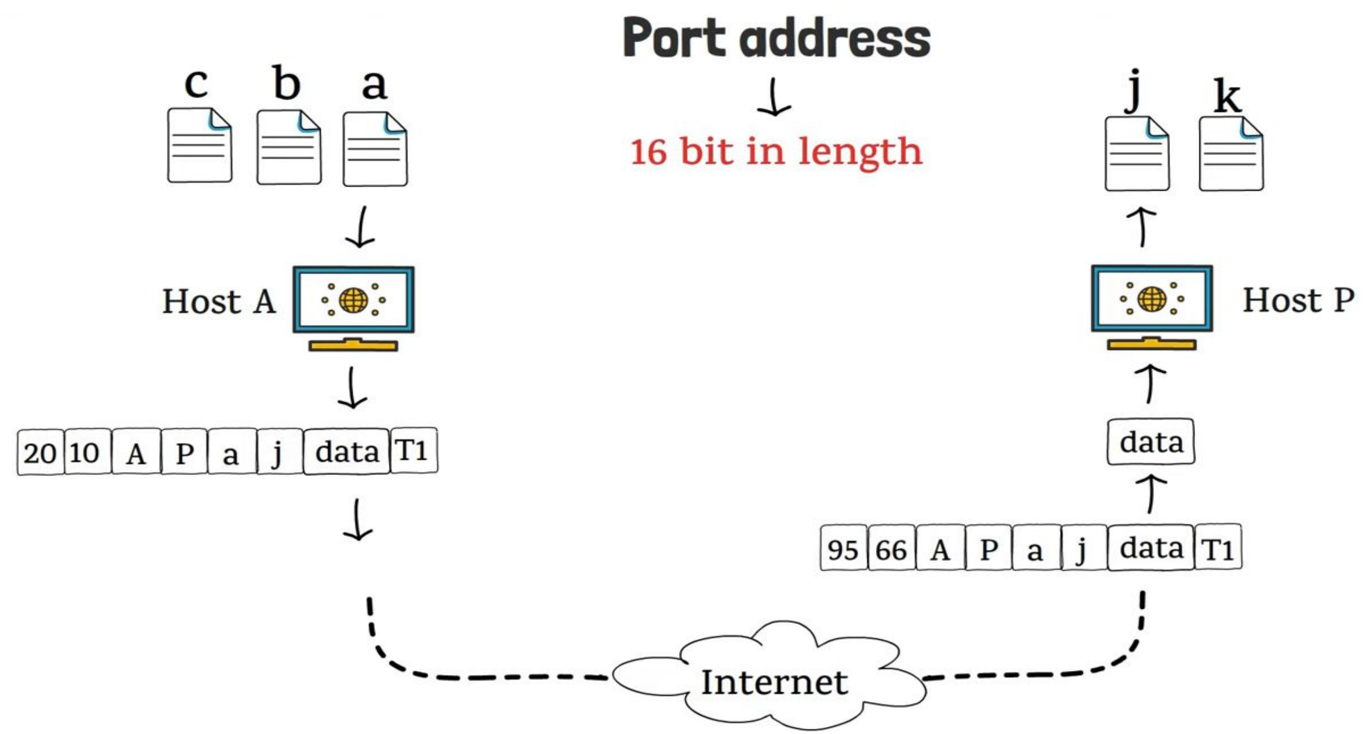


Port Numbers

- Every process running in a computer is going to have a unique number called Port numbers
- Port Number is of 16 bit in length

Example:

- In below example a, b and c are the port number of applications at sender side and j and k are the port number of applications at receiver side



Specific Address

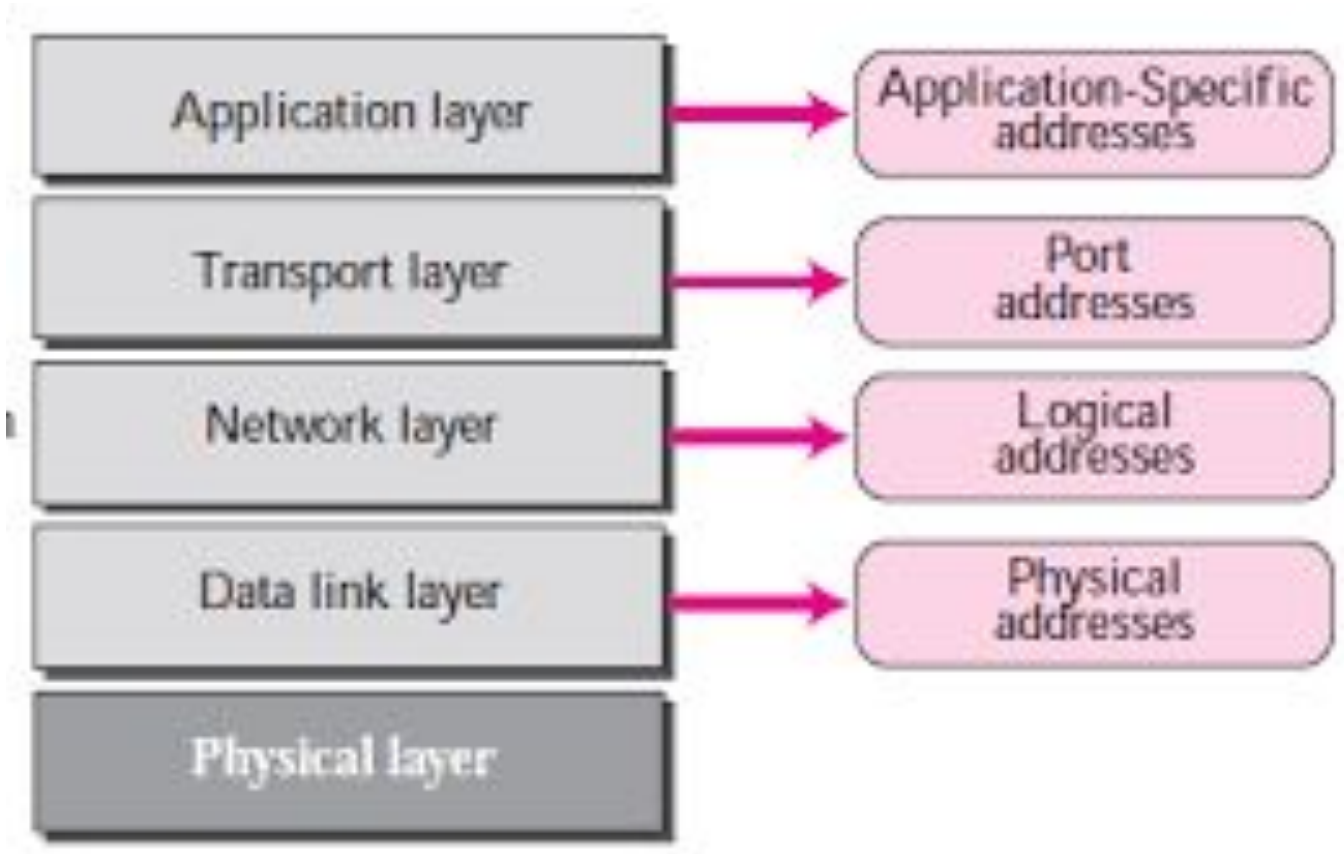
- Addresses like emails, URL are referred as specific addresses
- These specific address are converted to port numbers and IP address with the help of DNS(Domain Name Service)

Examples:

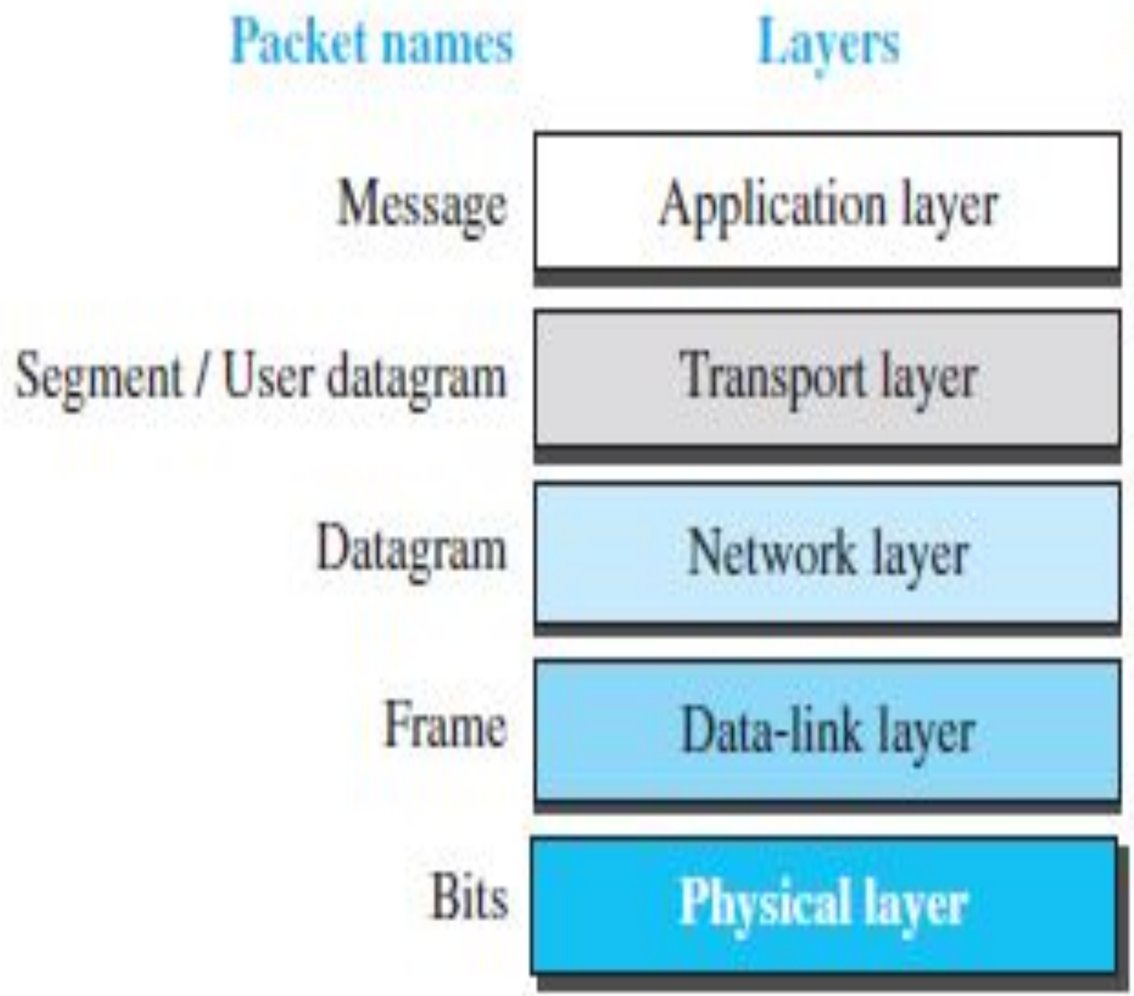
URL : www.google .com

Email: abc@gmail.com

Relationship of layers and addresses in TCP/IP



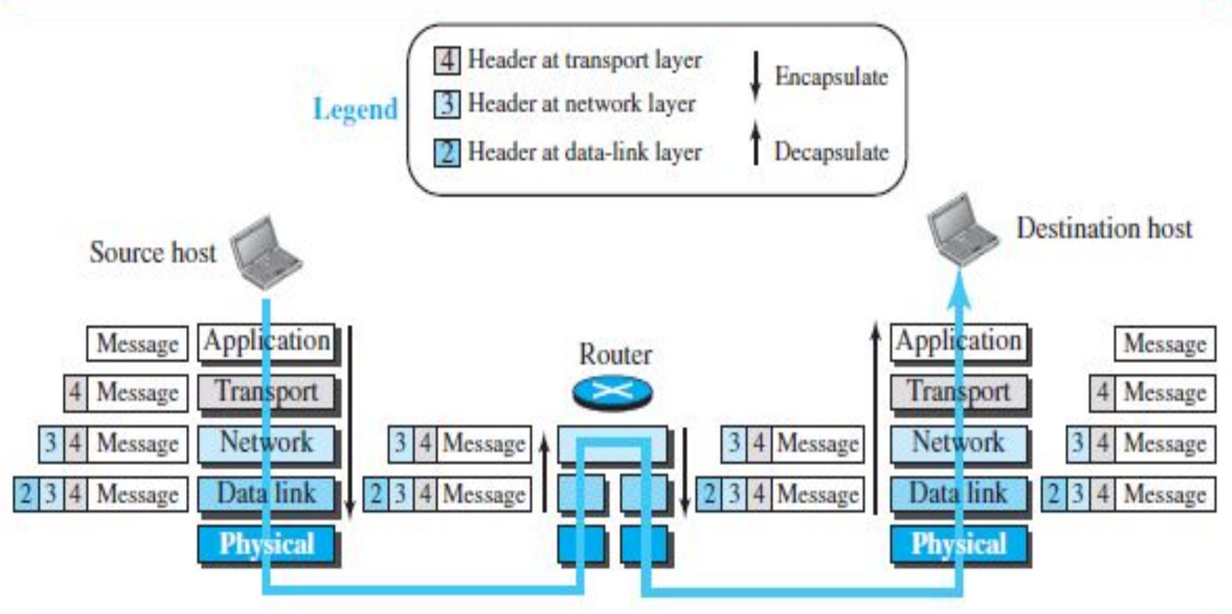
Different terms used for data in TCP/IP model layers



Encapsulation and Decapsulation

Encapsulation at sender side:

- At sender side encapsulation is done
- Encapsulation means adding of headers in each layer to the data.
- In transport layer source and destination port addresses are added. In network layer source and destination IP addresses are added. In Data Link layer source and destination Mac addresses are added.



Encapsulation and Decapsulation (contd..)

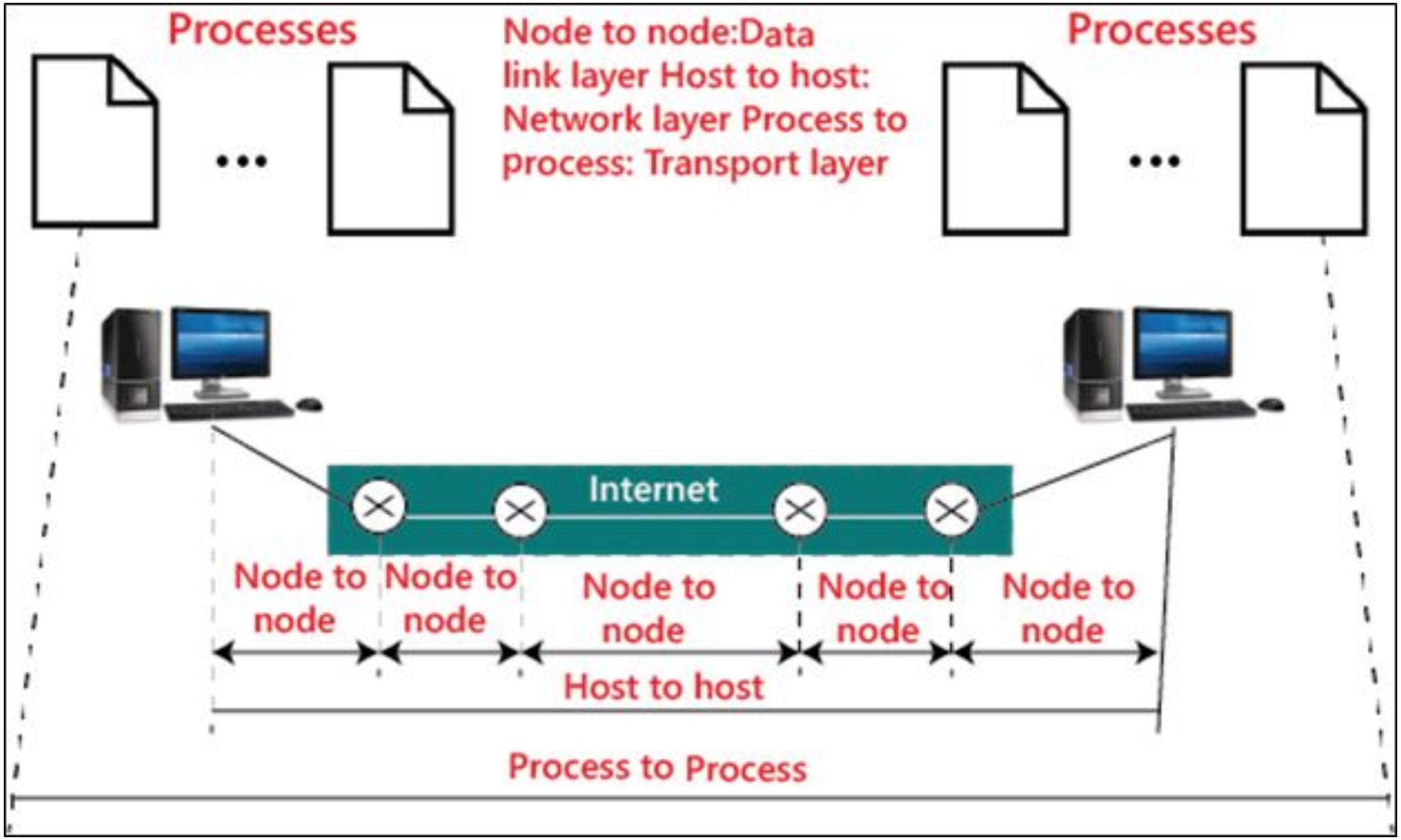
Encapsulation and Decapsulation at router:

- Router performs decapsulation followed by encapsulation

Decapsulation at receiver :

- Decapsulation is done at receiver side
- After the data reaches the receiver every header is removed in each layer and finally the data is given to the application layer

Types of Data Delivery



End of Chapter 1

Number of intermediate routers = 10

Propagation time = Distance / Speed = $(2000 * 10^3) / 2 \times 10^8 = 1 * 10^{-2}$ s

Transmission time = Message size / Bandwidth

$= 50,00,000 / 5 * 10^6 = 1$ s

Queuing Time = $2 * 10^{-6}$ s

Queuing Time at 10 routers = $10 * 2 * 10^{-6}$ s = $2 * 10^{-5}$ s

Processing Time = $1 * 10^{-6}$ s

Processing Time at 10 routers = $10 * 1 * 10^{-6}$ s = $1 * 10^{-5}$ s

Latency (Delay) = Propagation time + Transmission time + Queuing Time + Processing Time

$= 1 * 10^{-2} + 1 + 2 * 10^{-5} + 1 * 10^{-5}$

Latency (Delay) = 1.01000030 s

15. What is the total delay (latency) for a frame of size 5 million bits that is being sent on a link with 10 routers each having a queuing time of 2 μs and a processing time of 1 μs. The length of the lin k is 2000 Km. The speed of light inside the link is 2 × 108 m/s. The link has a bandwidth of 5 Mbps. Which component of the total delay is dominant? Which one is negligible?

Solution:

Given, Message size = 50,00,000 bits

Length of the link (distance) = 2000 Km = $2000 * 10^3$ meters

Speed = 2×10^8 m/s

Bandwidth = 5Mbps = $5 * 10^6$ bps

15. What is the total delay (latency) for a frame of size 5 million bits that is being sent on a link with 10 routers each having a queuing time of 2 μs and a processing time of 1 μs. The length of the lin k is 2000 Km. The speed of light inside the link is 2 × 108 m/s. The link has a bandwidth of 5 Mbps. Which component of the total delay is dominant? Which one is negligible?

Solution:

Given, Message size = 50,00,000 bits

Length of the link (distance) = 2000 Km = $2000 * 10^3$ meters

Speed = 2×10^8 m/s

Bandwidth = 5Mbps = $5 * 10^6$ bps

END-to-END DELAY:

- Suppose there are N-1 routers between the source host and the destination host

- Assume that the network is uncongested, the processing delay at each router and at source host is d_{proc}, the transmission rate out of each router and out of the source is R bits/sec and the propagation on

queuing delay is negligible

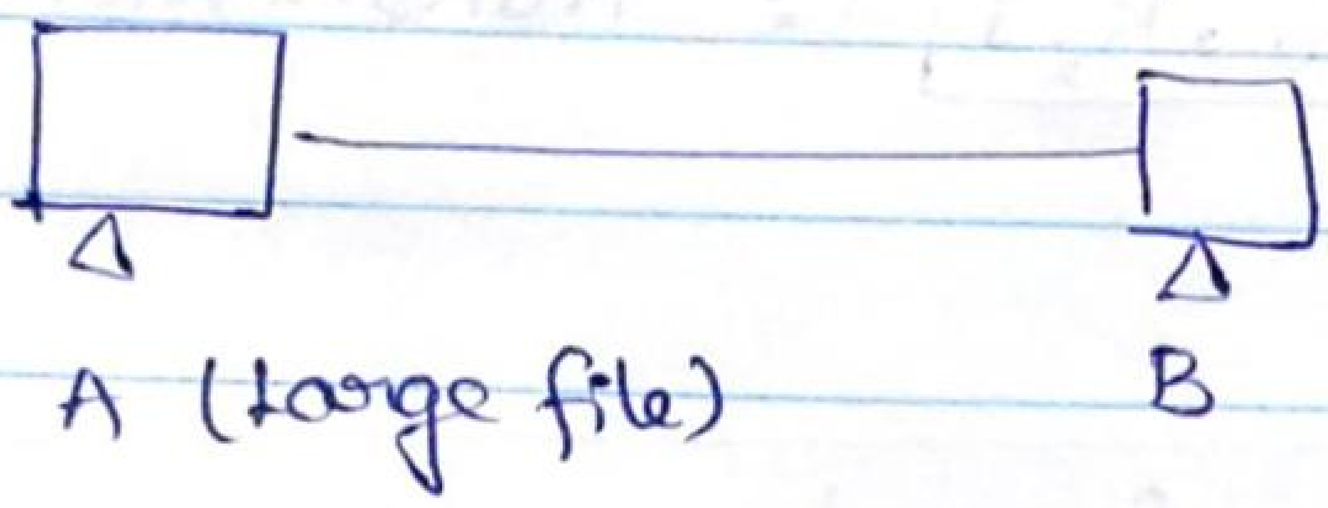
http://www.traceroute.org
Pingplotter

each link is d_{prop}. The nodal delays accumulate and give an end-to-end delay.

$$\boxed{d_{end-end} = N\left(d_{proc} + d_{trans} + d_{prop}\right)}$$

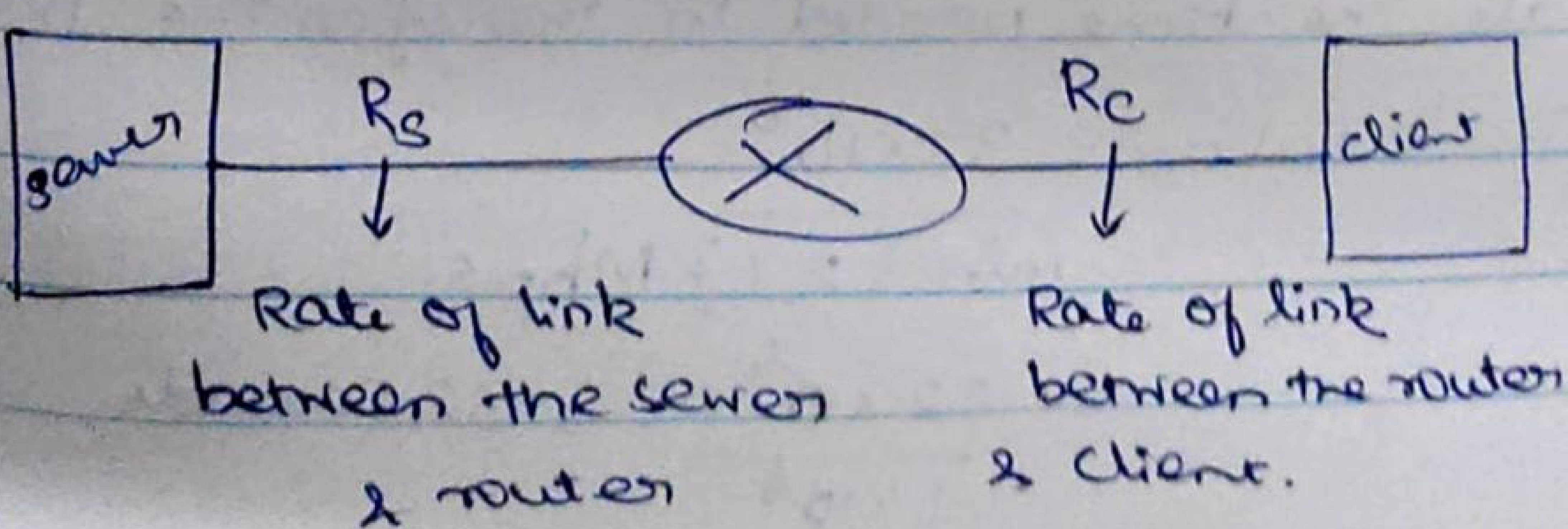
$$d_{trans} = \frac{L}{R} \rightarrow$$ L is the packet size.

THROUGHPUT IN COMPUTER NETWORKS:



- The $\boxed{\text{instaneous throughput}}$ at any instant of time is the rate at which host B is receiving the file.
- If the file consists of F bits and the transfer takes T seconds for Host B to receive all F bits, then the

$$\boxed{\text{average throughput} = \frac{F}{T} \text{ bits/sec}}$$



$\boxed{R_s < R_c}$, bits pumped by the server will flow right through the router and arrive at the client at a rate of R_s bps, giving a throughput of R_s bps.

$\boxed{R_c < R_s}$ In this case, bits will only leave the router at rate R_c giving an end-to-end throughput of R_c.

$\boxed{\text{Throughput} = \min\{R_c, R_s\}}$ i.e Transmission rate of bottleneck link

$$\boxed{\text{Time taken to transfer a large file of F bits from server to client} = \frac{F}{\min(R_s, R_c)}}$$

Example:

Suppose MP3 file is downloaded which consists of 32 million bits, the server has transmission rate of 2 Mbps and the access link of you is 1Mbps. Calculate the time needed to transfer the file.

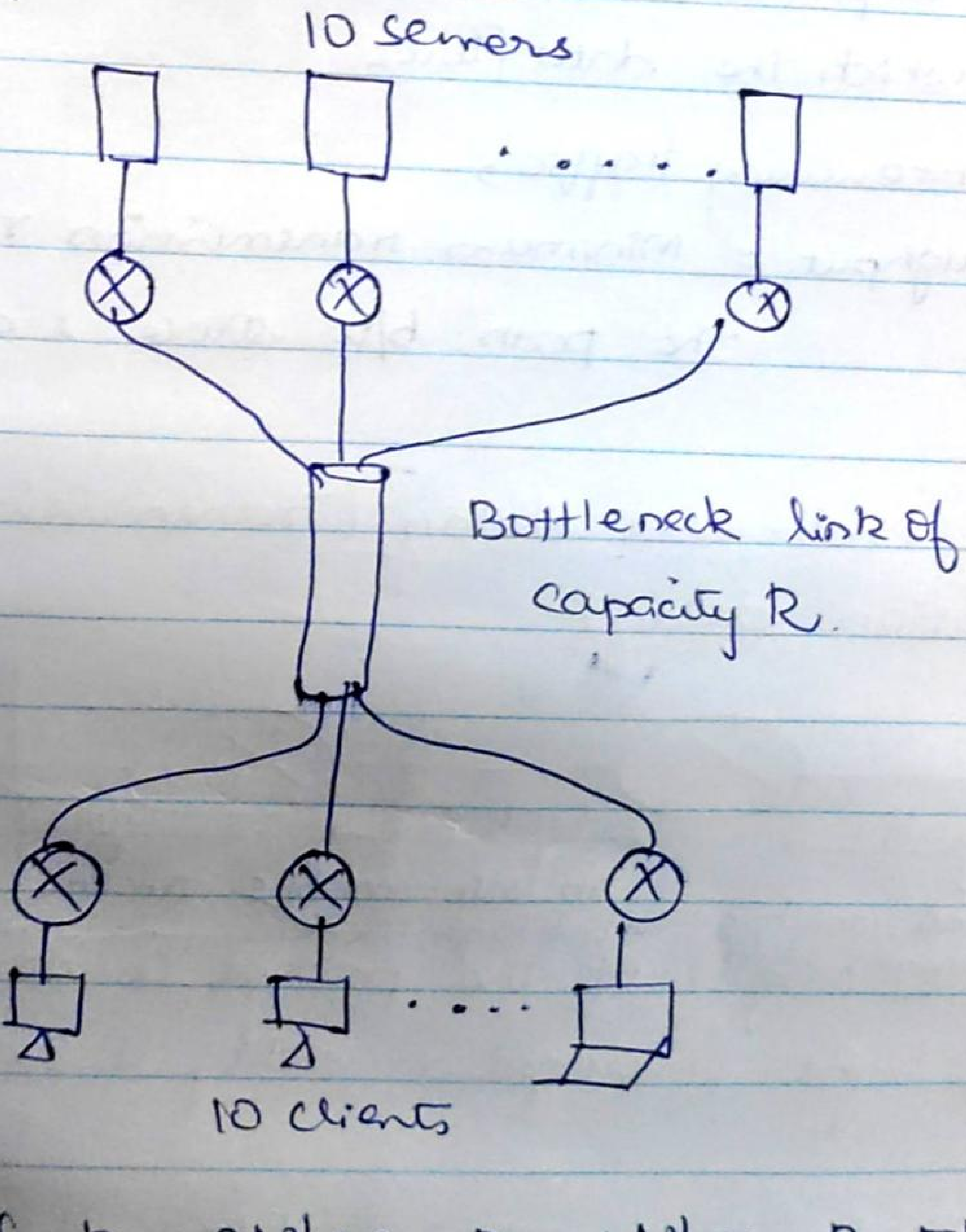
$$\text{Time taken} = \frac{32 \times 10^6}{\min\{2,1\} \text{ Mbps}}$$

$$= \frac{32 \times 10^6}{1 \times 10^6} = 32 \text{ seconds}$$

- If there is a n/w with N links between the server and the client, with the transmission rates of N links being $R_1, R_2, \ldots R_N$

Throughput for a file $= \min \{R_1, R_2, \ldots R_N\}$

Suppose;



$ If $R_s = 2$ Mbps, $R_c = 1$ Mbps, $R = 5$ Mbps and the common link divides its transmission rate equally among 10 downloads

Each download will have throughput $= \frac{5 \times 10^3 \times 10^{\cancel{8}\,2}}{\cancel{10}} = 500\,kbps$

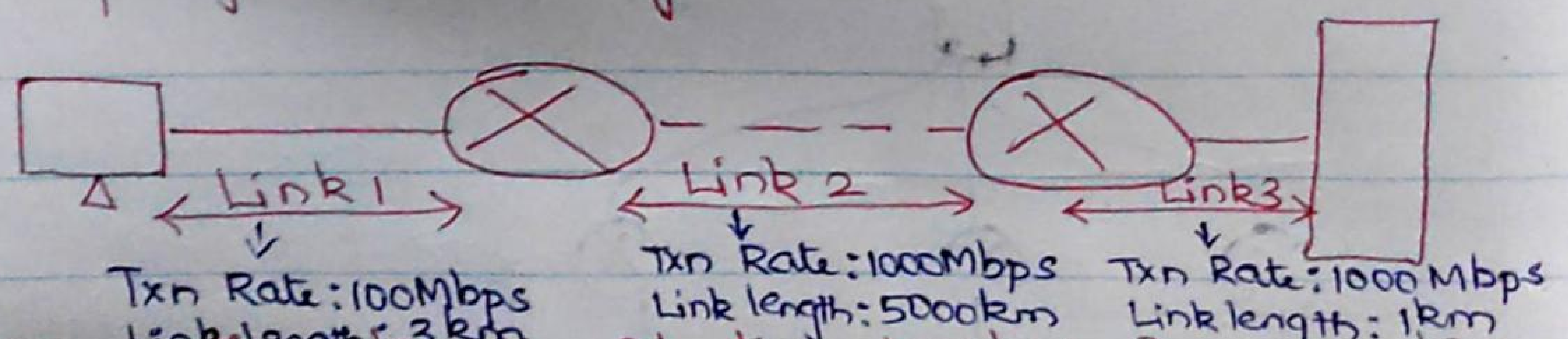
End-to-end throughput for each download is reduced to <u>500kbps</u>

★ <u>Throughput</u> depends on the <u>transmission</u> <u>rate</u> of the links over which the data flows

★ No other intervening traffic,

Throughput = Minimum transmission rate along the path b/w source & destination.

1) Computing end-end delay (Transmission and Propagation delay)



Assume the length of the packet is 4000 bits. The speed of light propogation delay is 3×10^8 m/sec.

1) What is the transmission delay of Link 1?

Transmission delay $= \frac{L}{R}$

$= \frac{4000}{100 \times 10^6} = \frac{4 \times 10^3}{1 \times 10^8} = 4 \times 10^{-5}$ sec

2) What is the propagation delay of Link1?

Propagation delay $= \frac{d}{s}$

$= \frac{3 \times 10^3}{3 \times 10^8}$

$= \frac{\cancel{3} \times 10^3}{\cancel{3} \times 10^8} = 1 \times 10^{-5}$ sec

3) What is the total delay of Link1?

Total delay of link1 $= 4 \times 10^{-5} + 1 \times 10^{-5}$ sec

$= \underline{5 \times 10^{-5}}$ sec.

4) What is the transmission delay of Link2?

5) What is the propagation delay of Link2?

6) What is the total delay of Link 2?

7) Txn delay of Link3?

8) Prop delay of Link3?

9) Total delay of Link3?

10) What is the total delay?