# Cs601 Midterm Slides chapter 1 to 9 by ZR

Chapter 1 to 9 (topic 1 to 134)

# Introduction to the Course

The Need for Communication

Trends and Advancements

What is taught in this course?

What is NOT taught in this course?

Tips and Tricks to do well

Text and References

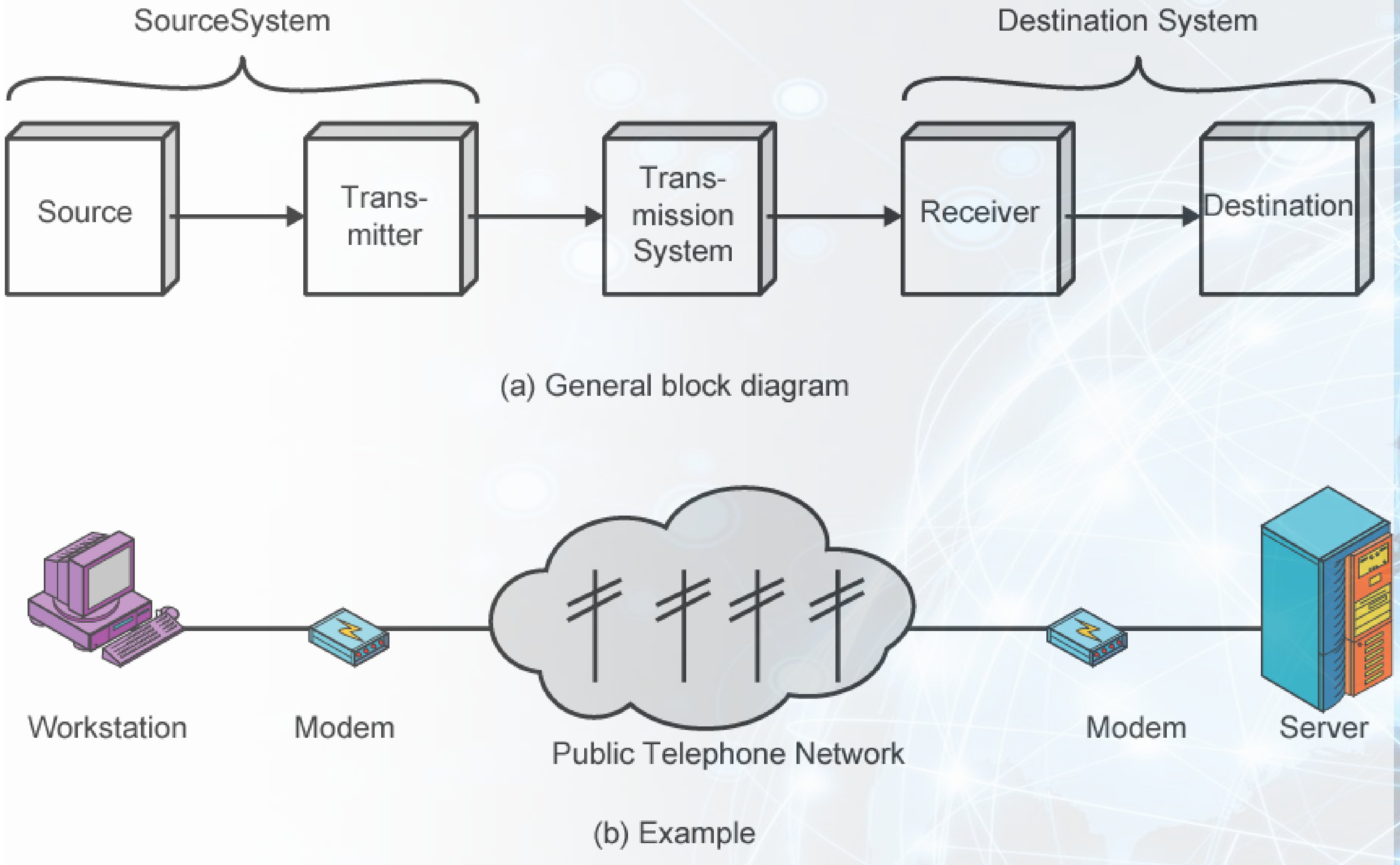
# Introduction to Data Communications

**Communication:** Sharing of Information (Local or remote)

**Telecommunications:** Communication at a Distance (includes telephony, telegraph, and television etc.)

**Data communications:** Exchange of data between two devices via some form of transmission media

# A Simple Communication Model

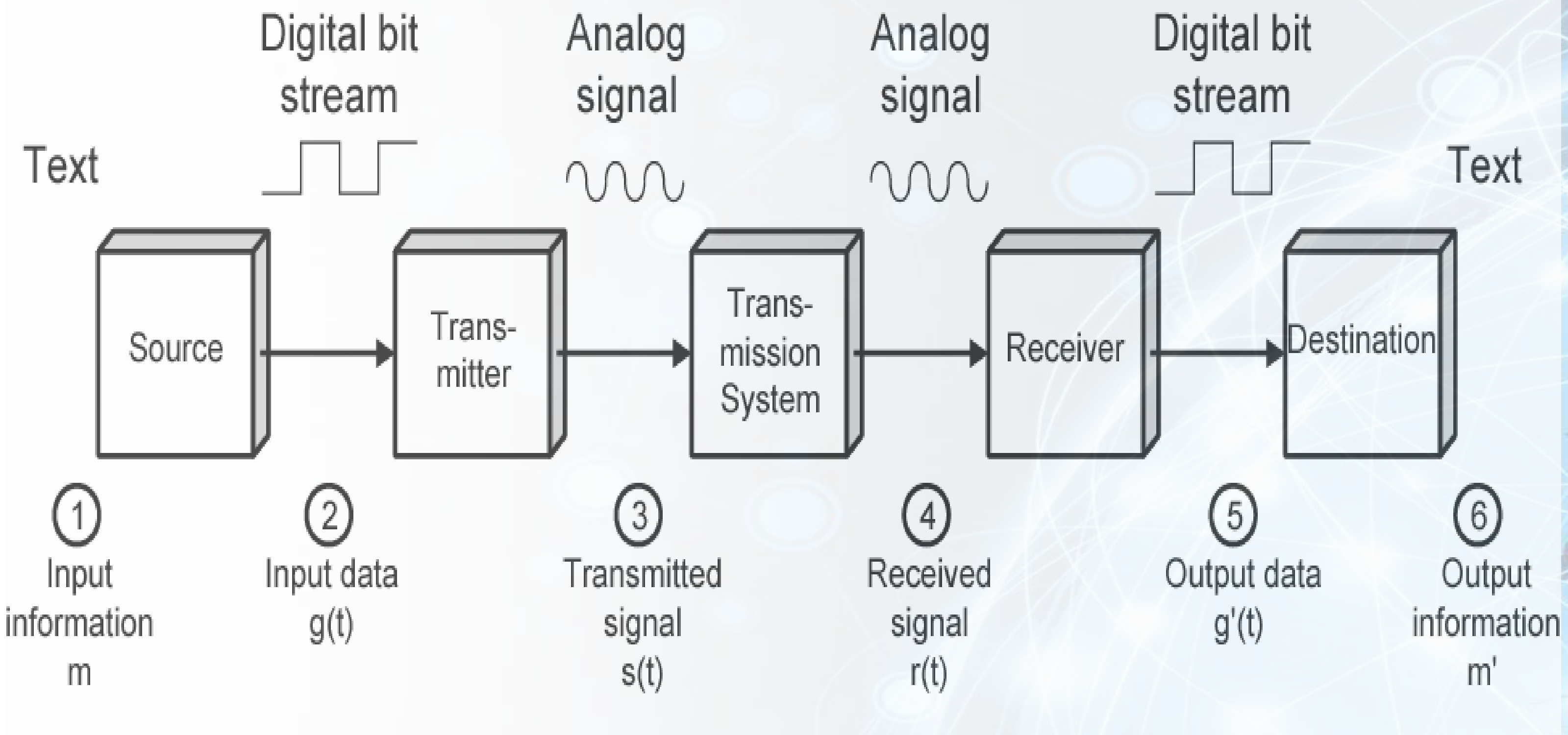


# Characteristics of a Data Communication System

**Effectiveness of a Data Communication System:**

- **Delivery**
- **Accuracy**
- **Timeliness**
- **Jitter**

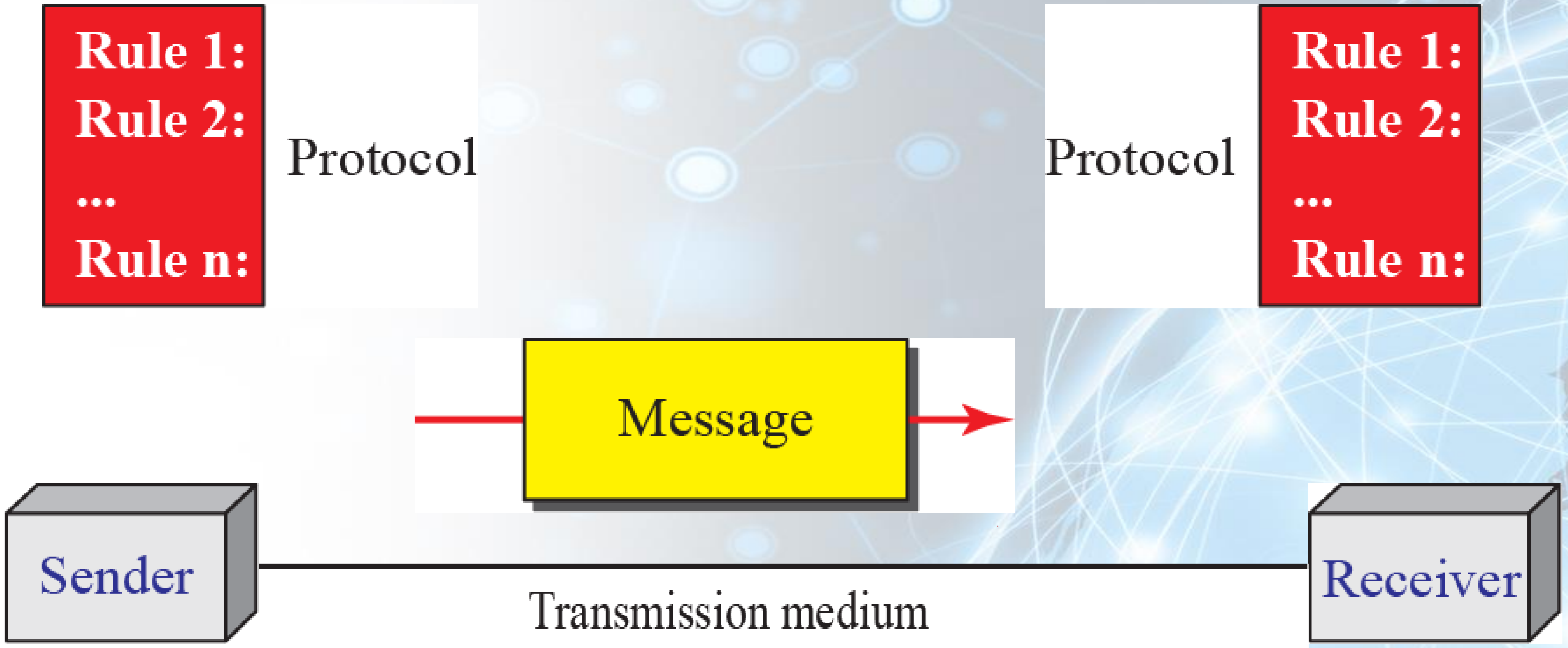
# Characteristics of a Data Communication System



# Components of a Data Communication system

**A data communications system has five components**

# Components of Data Communication system



# Data Representation and Data Flow

## Forms of Information

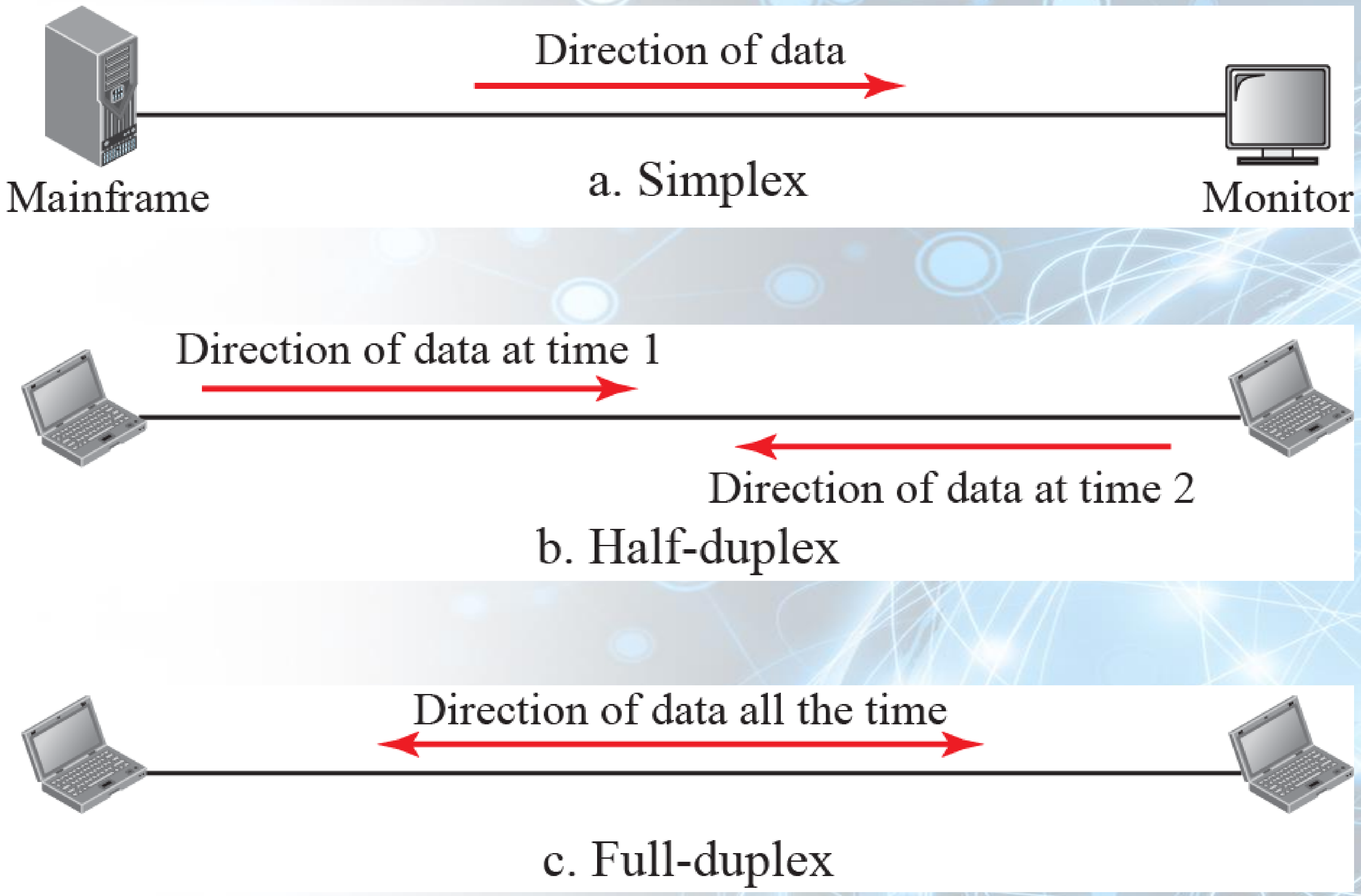
- **Text**
- **Numbers**
- **Images**
- **Audio**
- **Video**

# Data Representation and Data Flow

**Data Flow between two devices:**

- **Simplex**
- **Half-Duplex**
- **Full-Duplex**

# Data Flow


Direction of data
Mainframe
a. Simplex
Monitor
Direction of data at time 1
Direction of data at time 2
b. Half-duplex
Direction of data all the time
c. Full-duplex

# Networks

- **Network:**
  Interconnection of a set of devices capable of communication

- **Host**

- **Connecting Device**

# Network Criteria

**A network must be able to meet a certain number of criteria:**

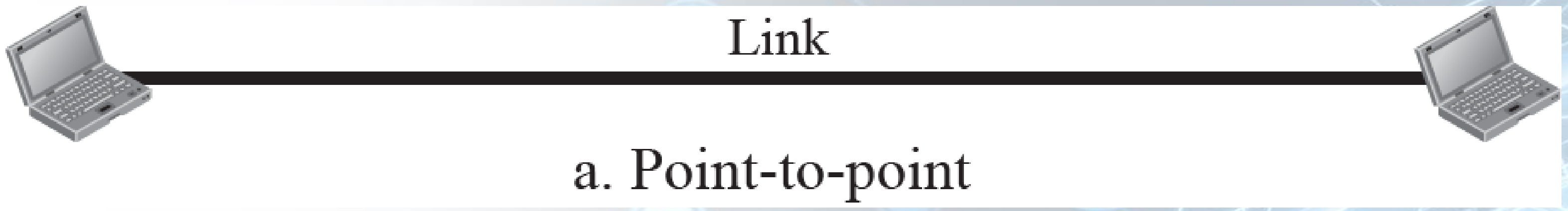
- **Performance**
  - ✓ Throughput
  - ✓ Delay
- **Reliability**
- **Security**

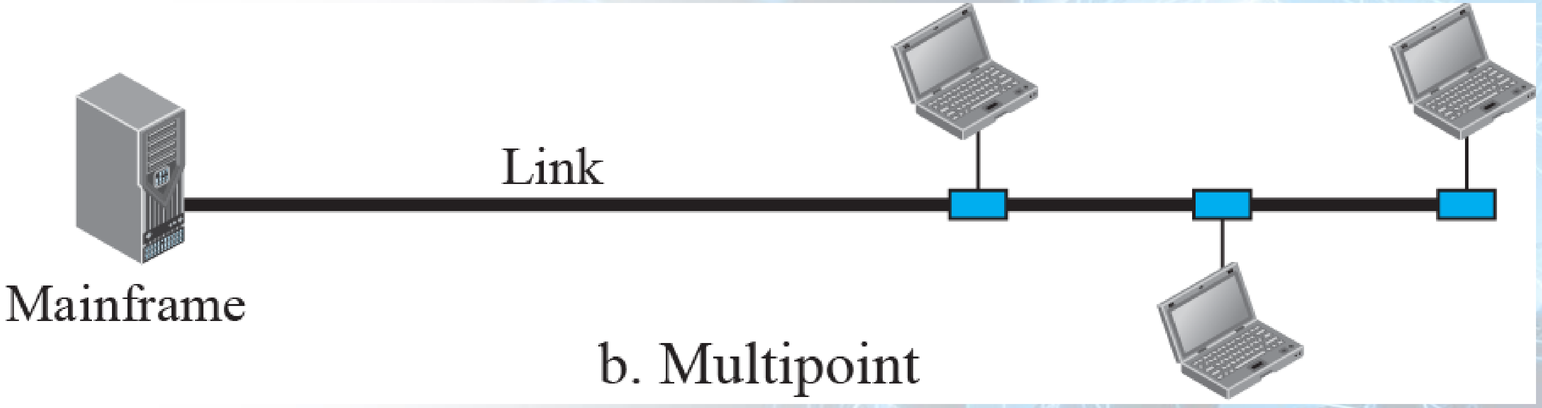
# Physical Structures

## Physical Network Attributes

- Link
- Type of Connection
  - ✓ Point-to-Point
  - ✓ Multipoint

# Physical Structures

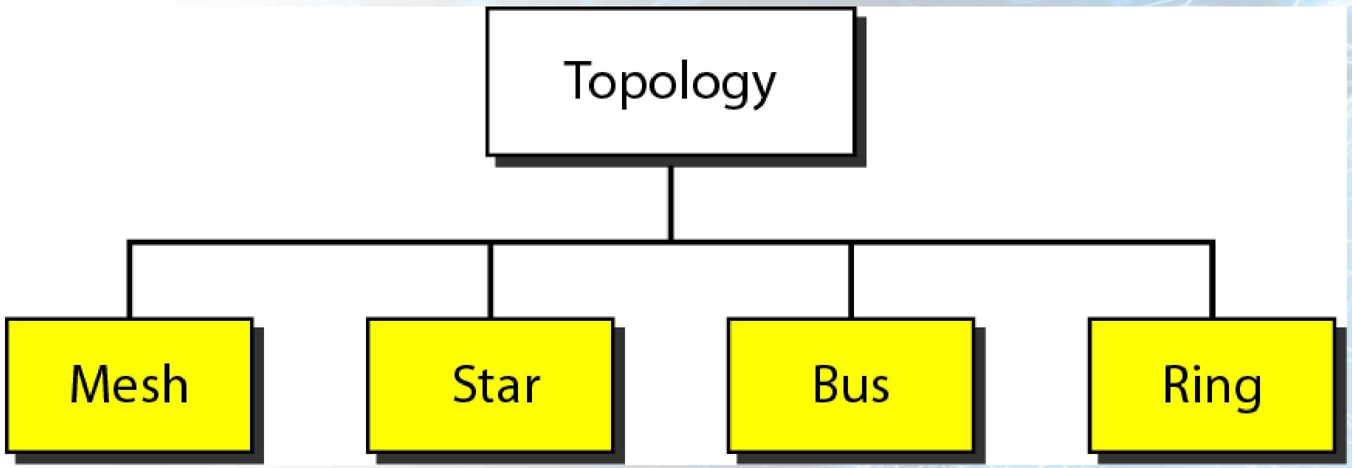


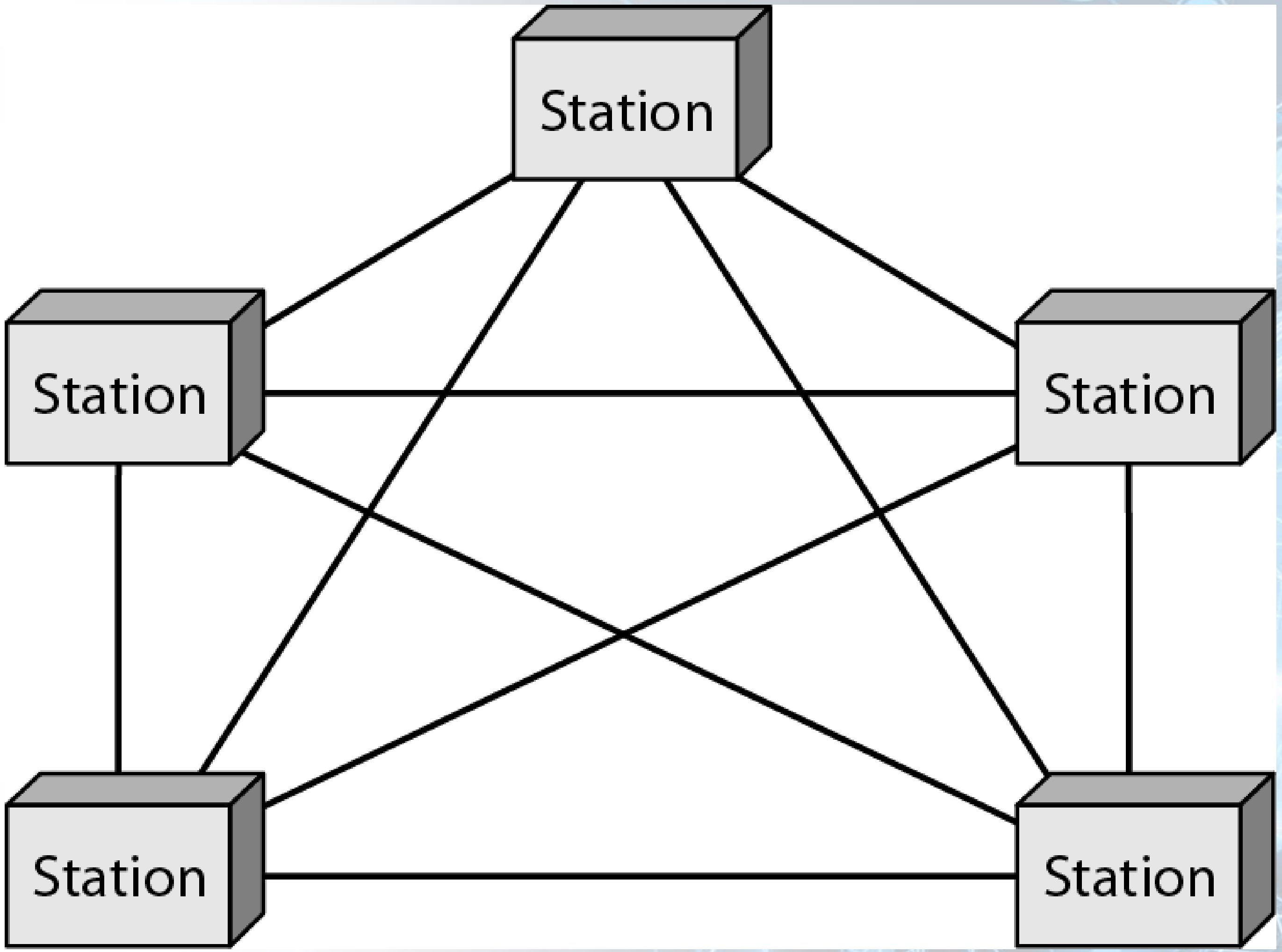
# Physical Topologies

- Physical Layout of Network
- Links + Nodes = Topology
- Physical Topologies:
  - ✓ Mesh
  - ✓ Star
  - ✓ Bus
  - ✓ Ring

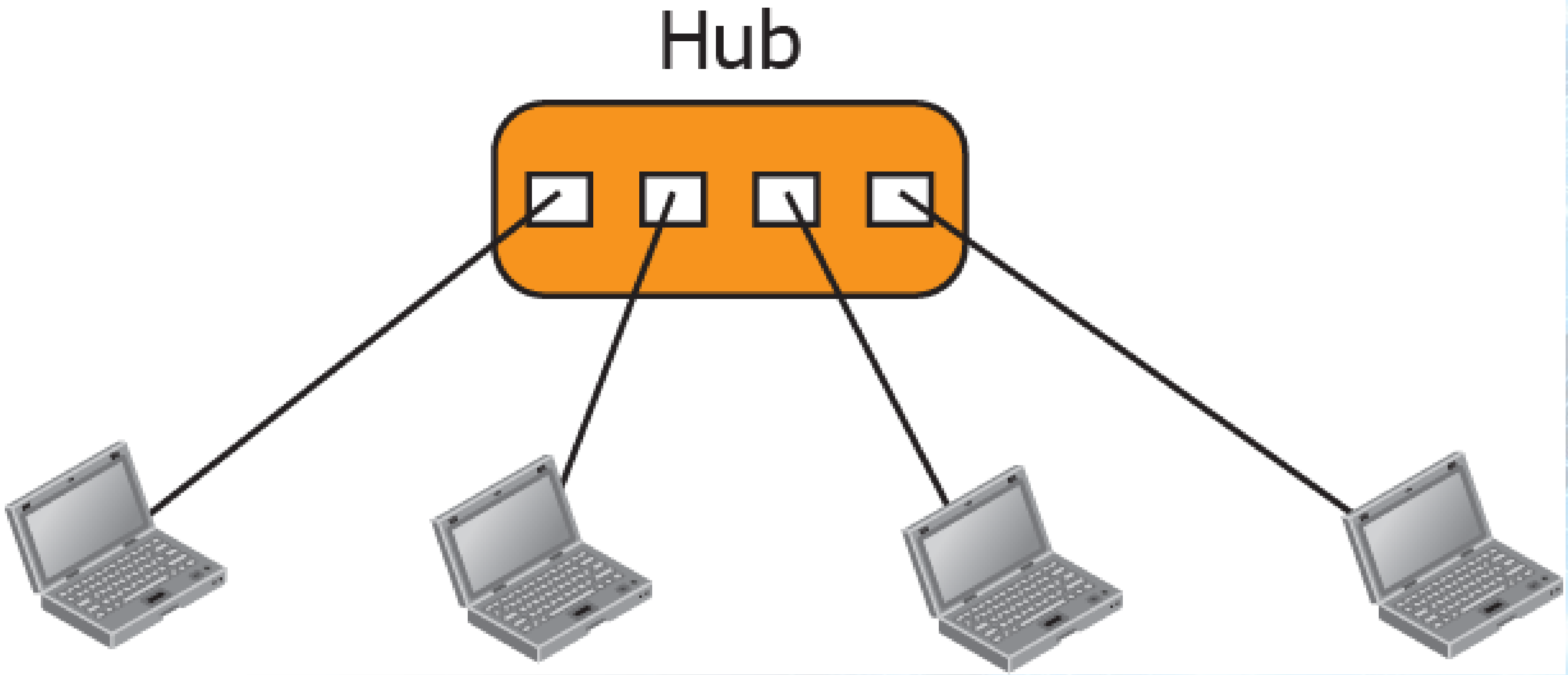
# Physical Topologies



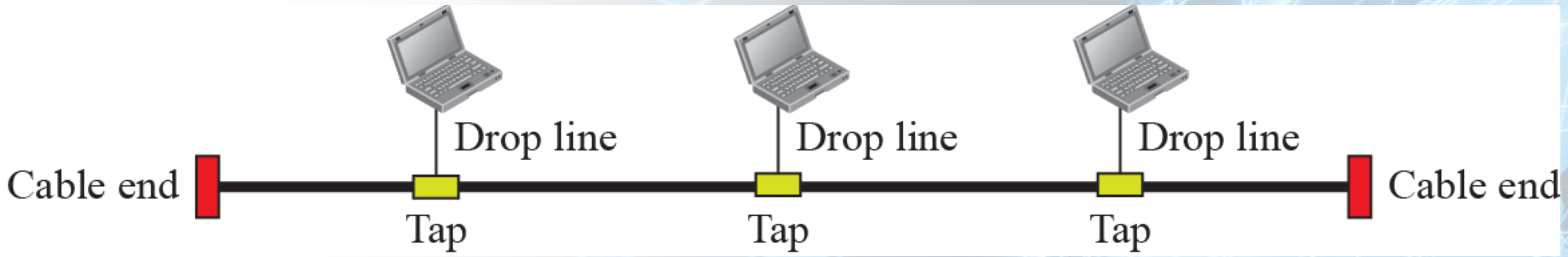
# Mesh Topology



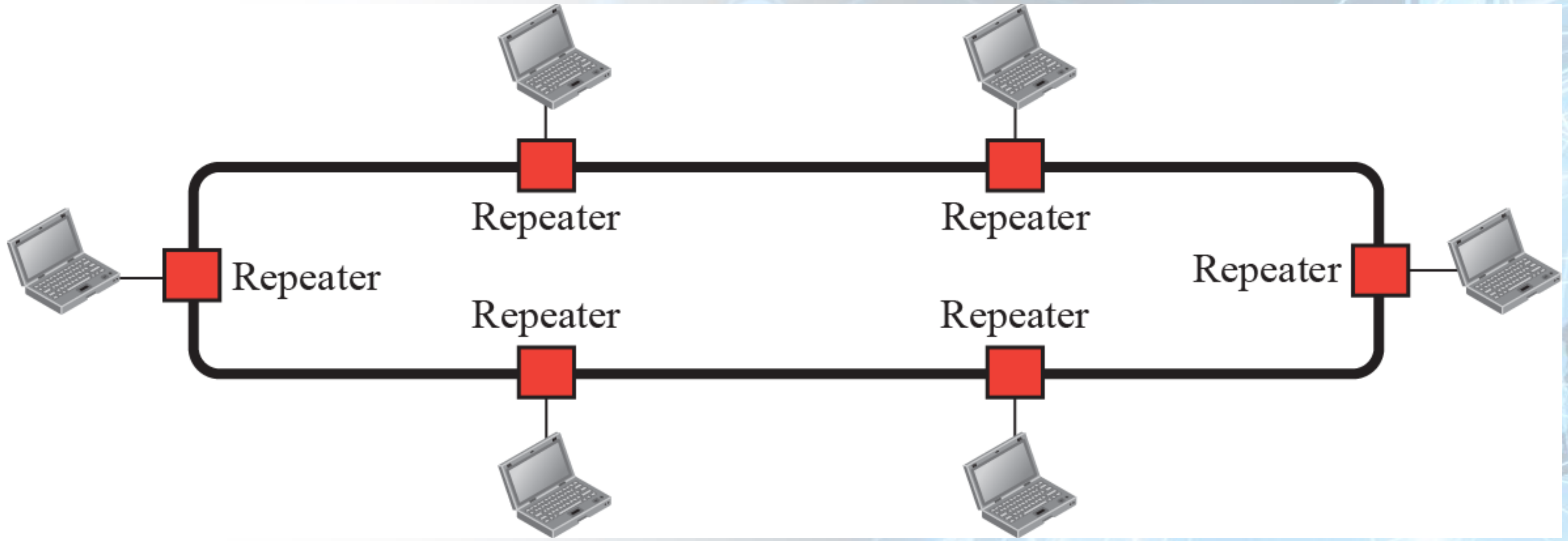
# Star Topology



# Bus Topology



# Ring Topology



# Networks Types

- **Network classification:**

  - ✓ **Size**
  - ✓ **Geographical Coverage**
  - ✓ **Ownership**

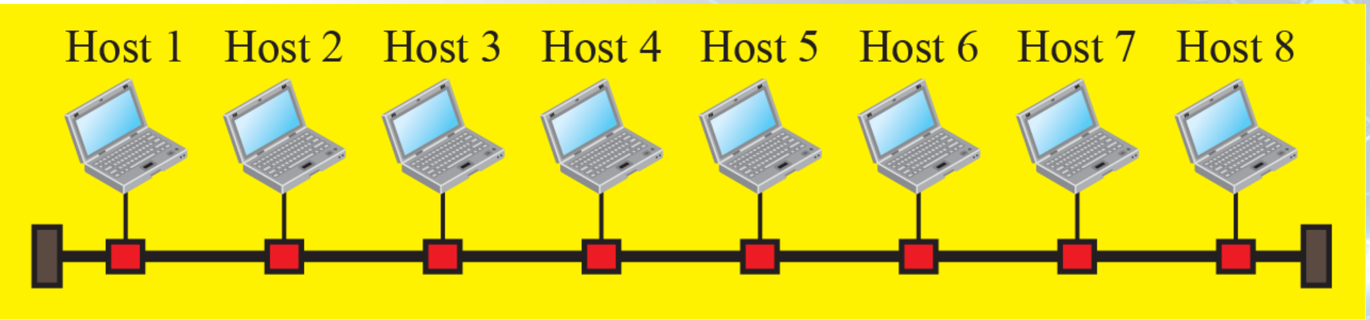
- **Local Area Networks (LANs)**

- **Wide Area Networks (WANs)**

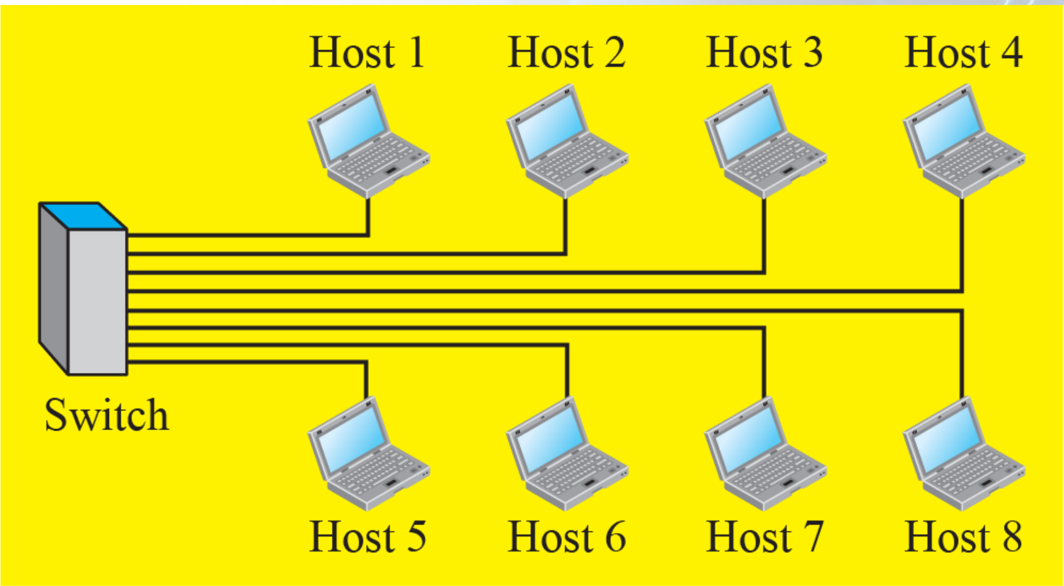
# Local Area Networks

- Usually Privately owned
- Connects some hosts in a single office, building, or campus
- Can be as simple as two PCs and a printer in someone's home office
- Can extend throughout a company
- Host Address

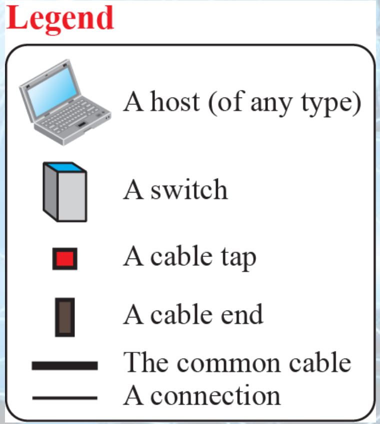
# Local Area Networks




a. LAN with a common cable (past)




b. LAN with a switch (today)



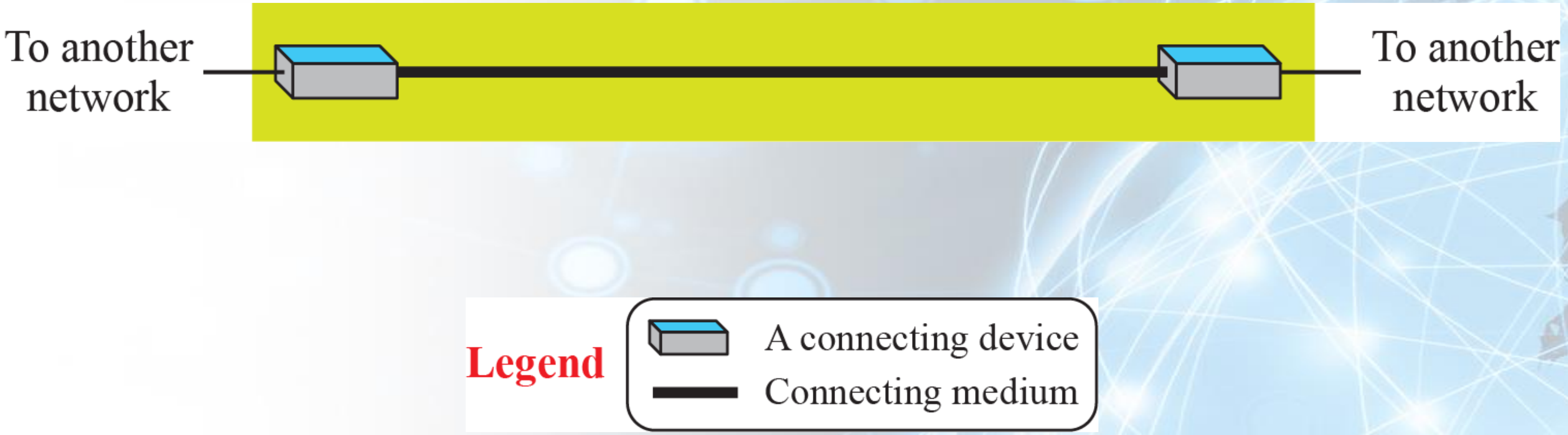
# Wide Area Network

- **Wider geographical span than a LAN**
- **Spans a town, a state, a country, or even the world**
- **Interconnects connecting devices such as switches, routers, or modems**
- **Normally created and run by communication companies**

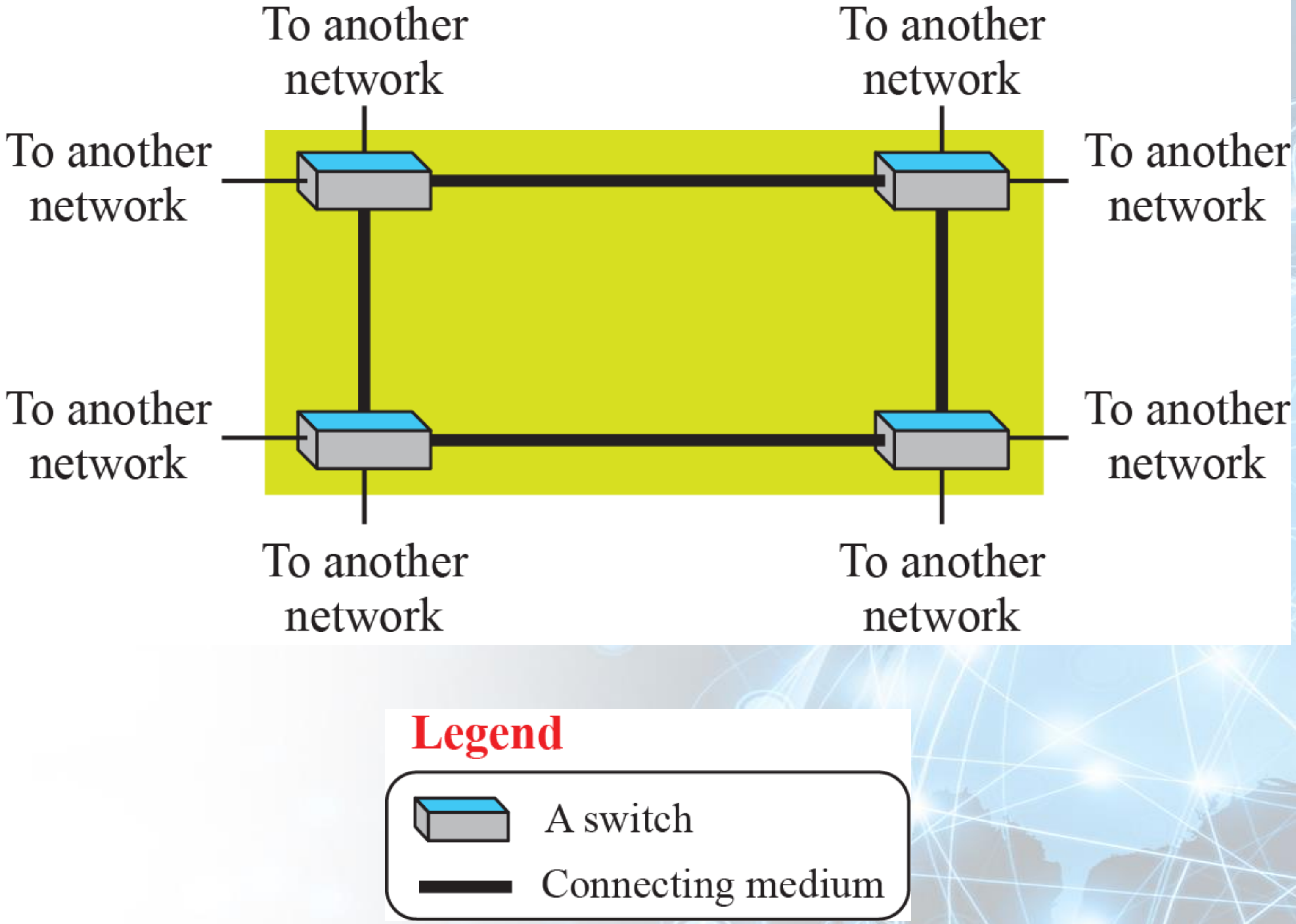
# Wide Area Network

- **Point-to-Point WAN**
- **Switched WAN**
- **Internetwork**

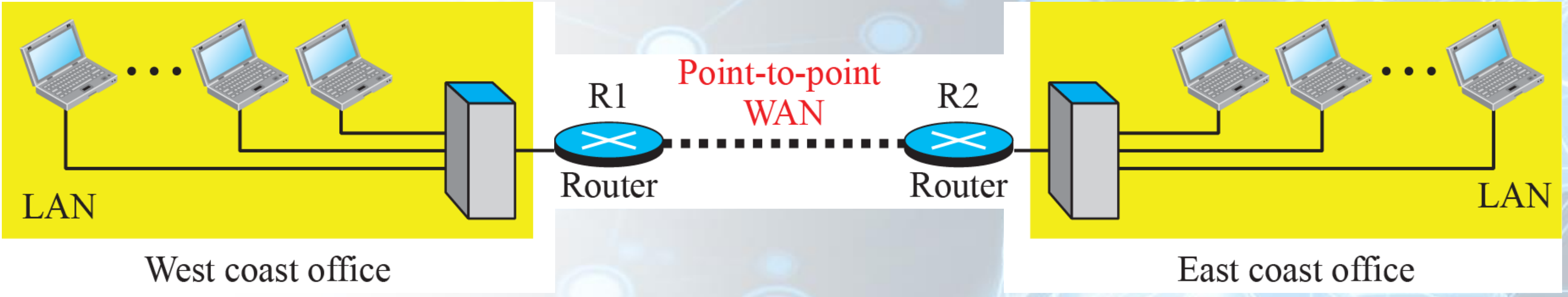
# Point-to-Point WANs



# Switched WANs



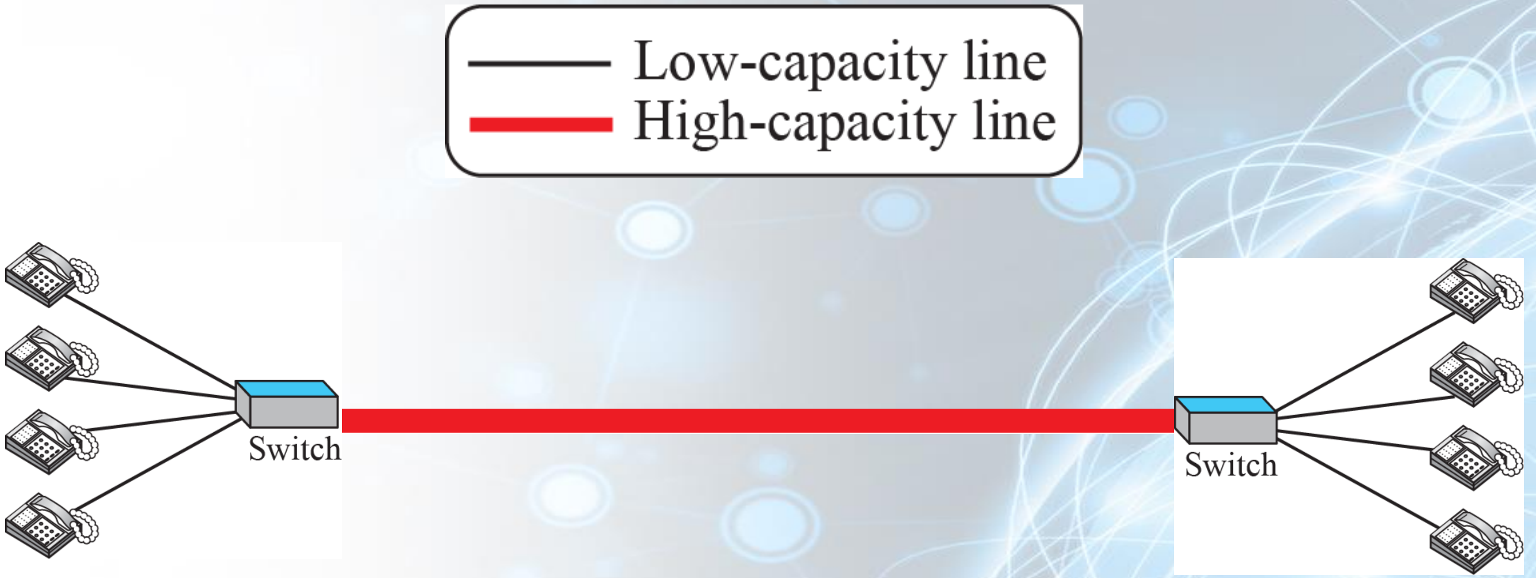
# Internetwork



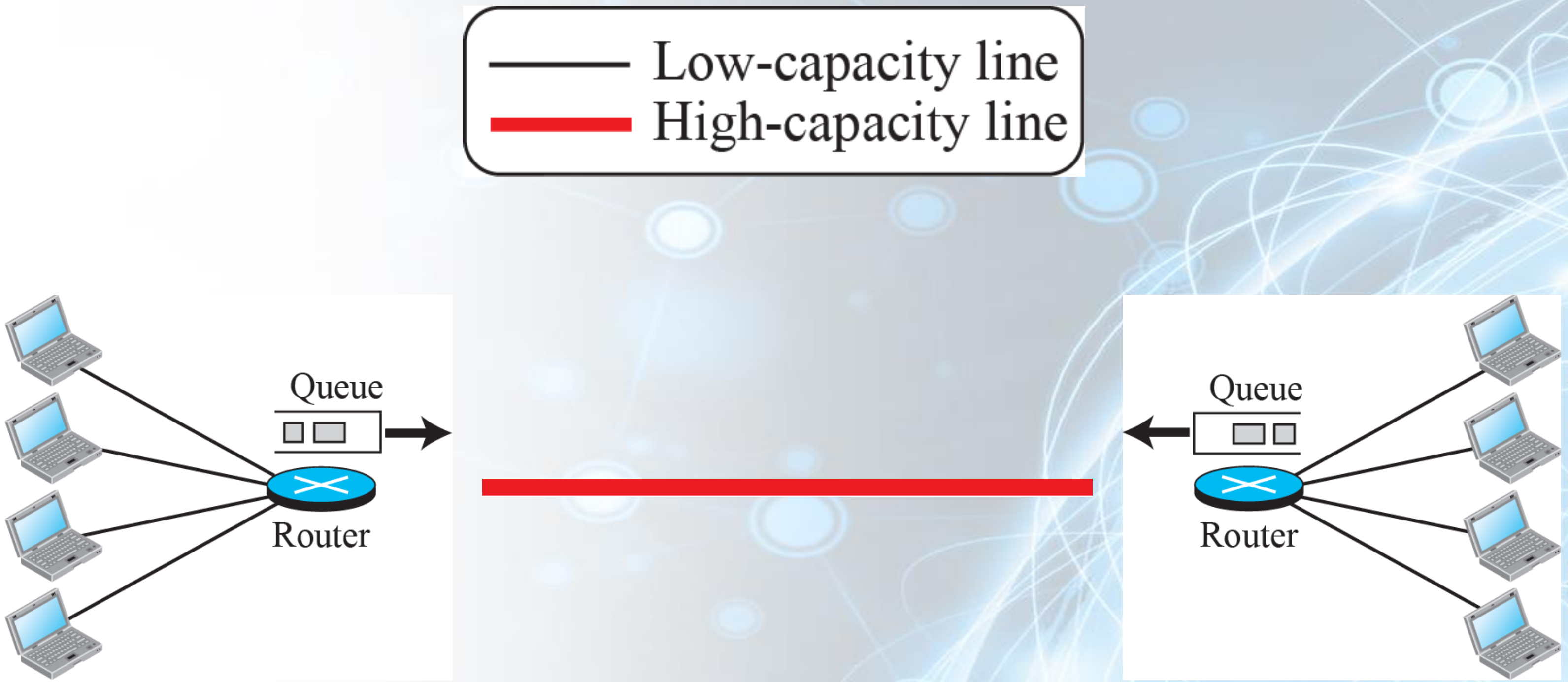
# Switching

- Switching
  - ✓ Circuit-Switched Network
  - ✓ Packet- Switched Network

# Circuit Switched Network



# Packet Switched Network



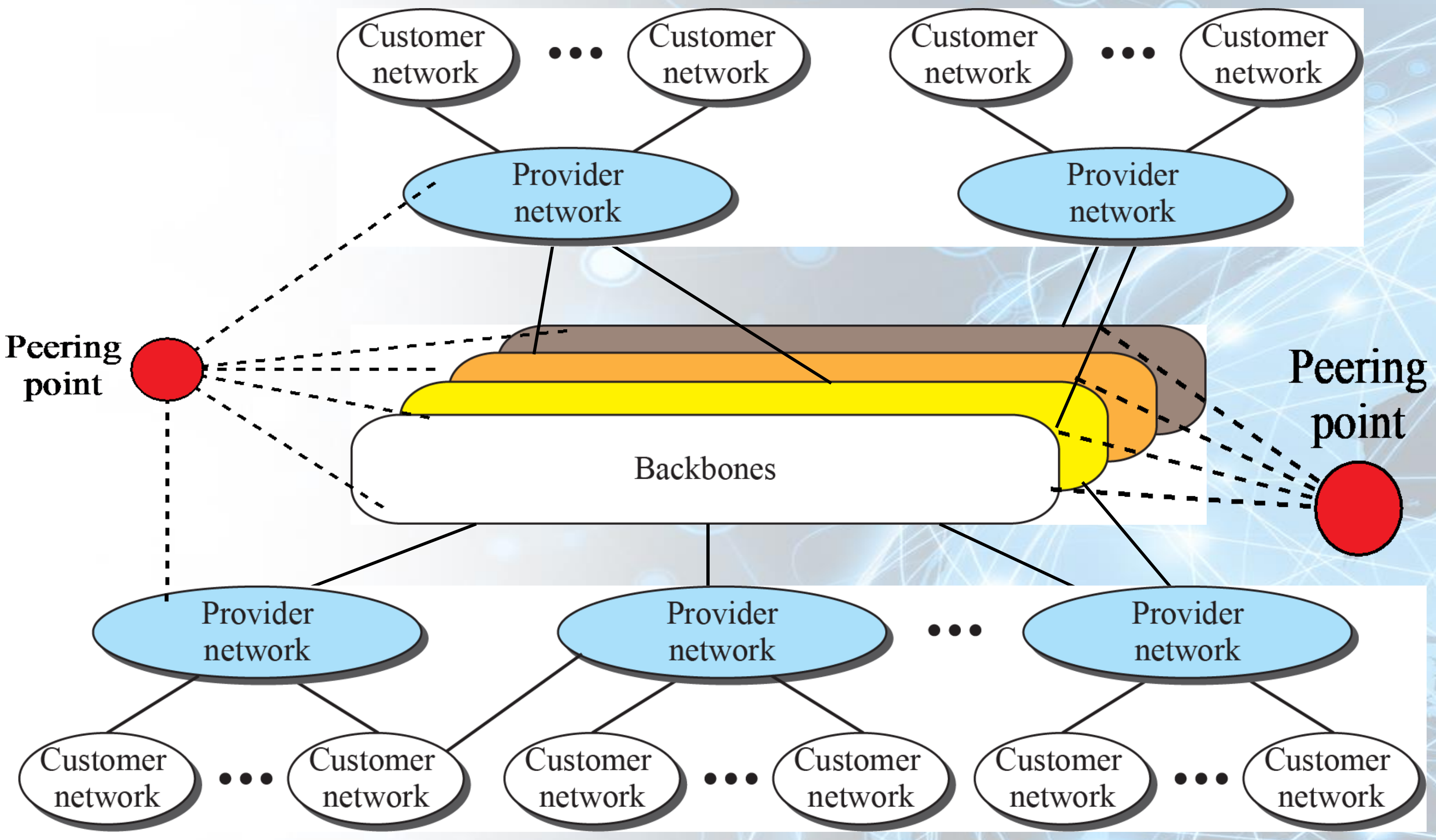
# The Internet

- **An internet (note the lowercase i) is two or more networks that can communicate with each other**

- **The Internet (uppercase I ), and is composed of thousands of interconnected networks.**

- **Accessing the Internet**

# The Internet



# Internet History

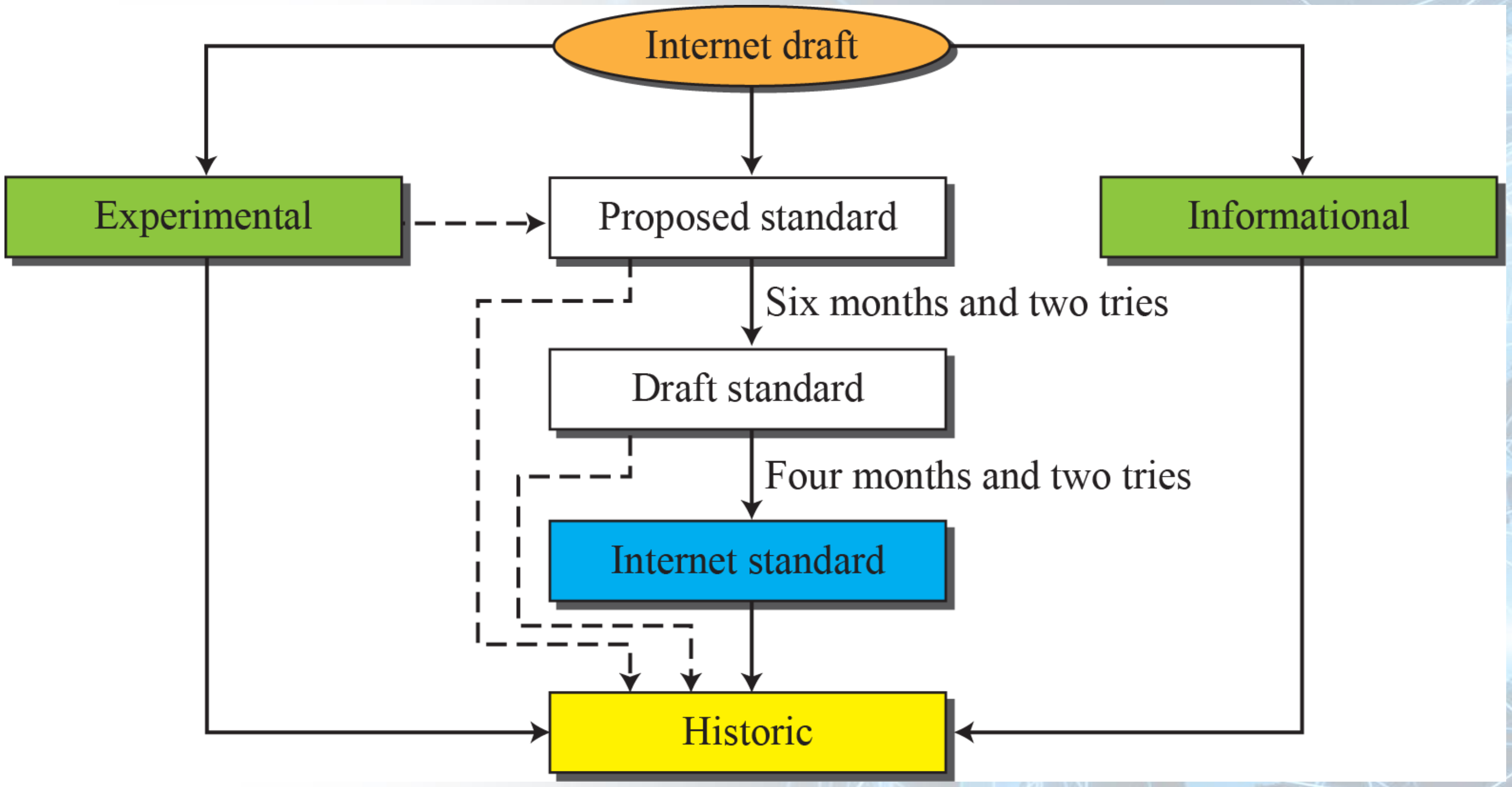
- Telegraph and Telephone networks, before 1960:
  - ✓ Constant-rate communication only
- ARPANET- Packet Switched
- Birth of the Internet &TCP/IP
- MILNET
- CSNET
- NSFNET
- Internet Today

# Internet Standards and Administration

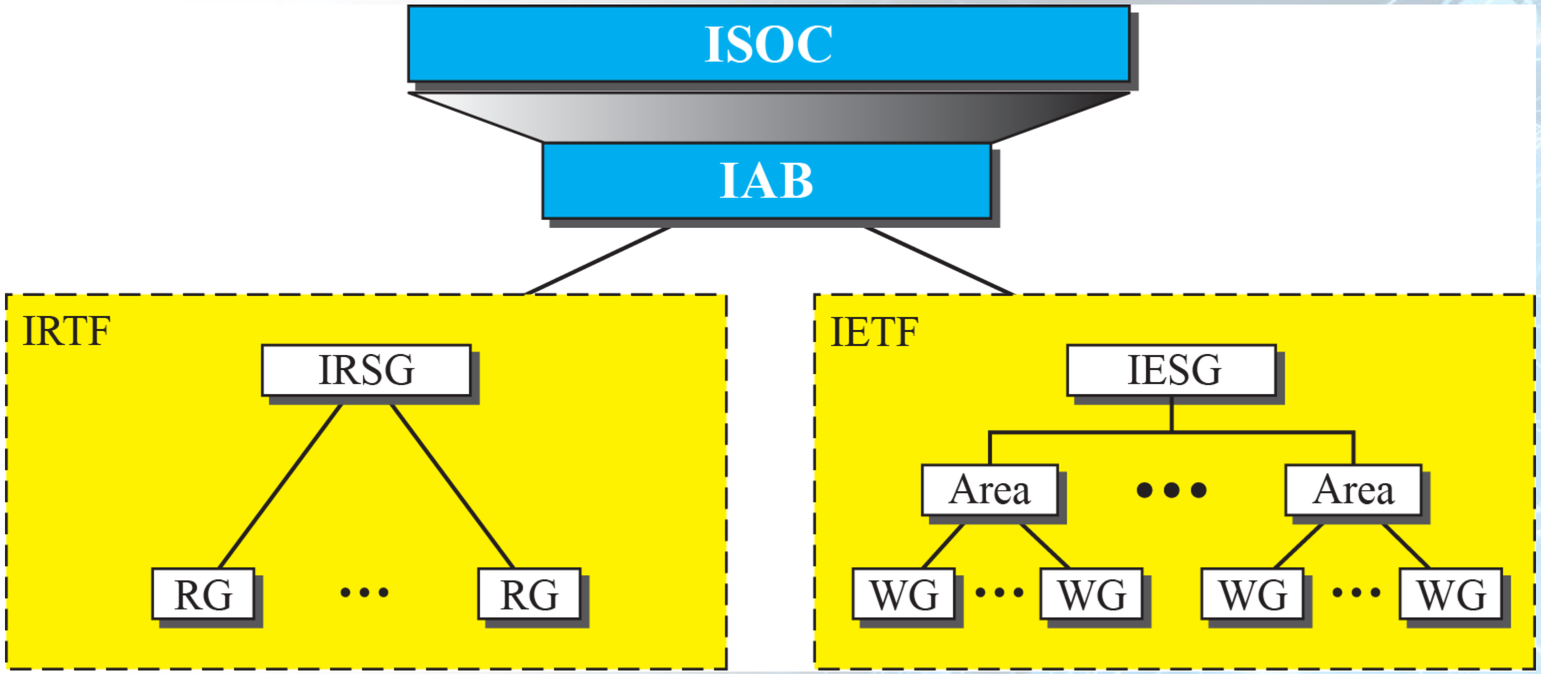
- Internet draft

- Request for Comments (RFC)
  - ✓ Proposed Standard
  - ✓ Draft Standard
  - ✓ Internet Standard
  - ✓ Historic
  - ✓ Experimental
  - ✓ Informational

# Internet Standards



# Internet Administration



# Protocol Layering - Introduction

- **Protocol**

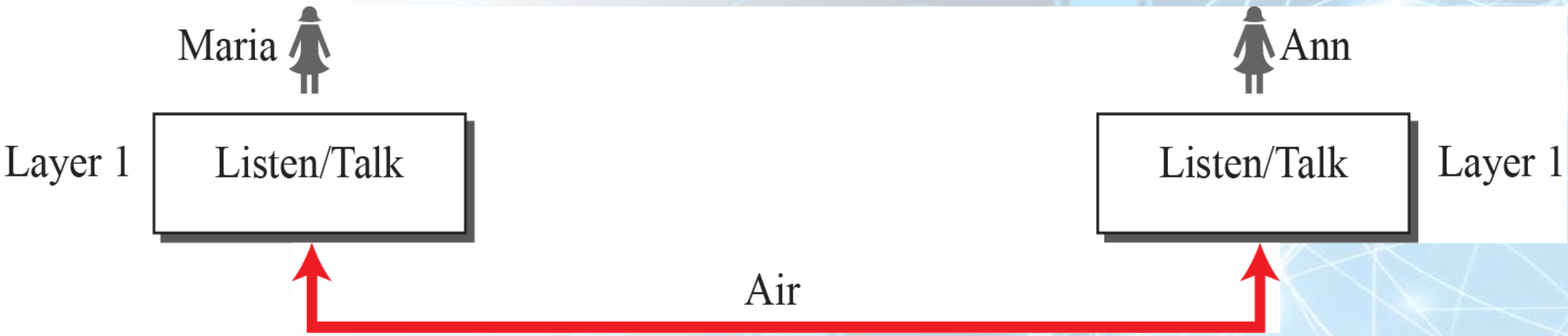
  Rules that both the sender and receiver and all intermediate devices need to follow to be able to communicate effectively

- **Protocol Layering**

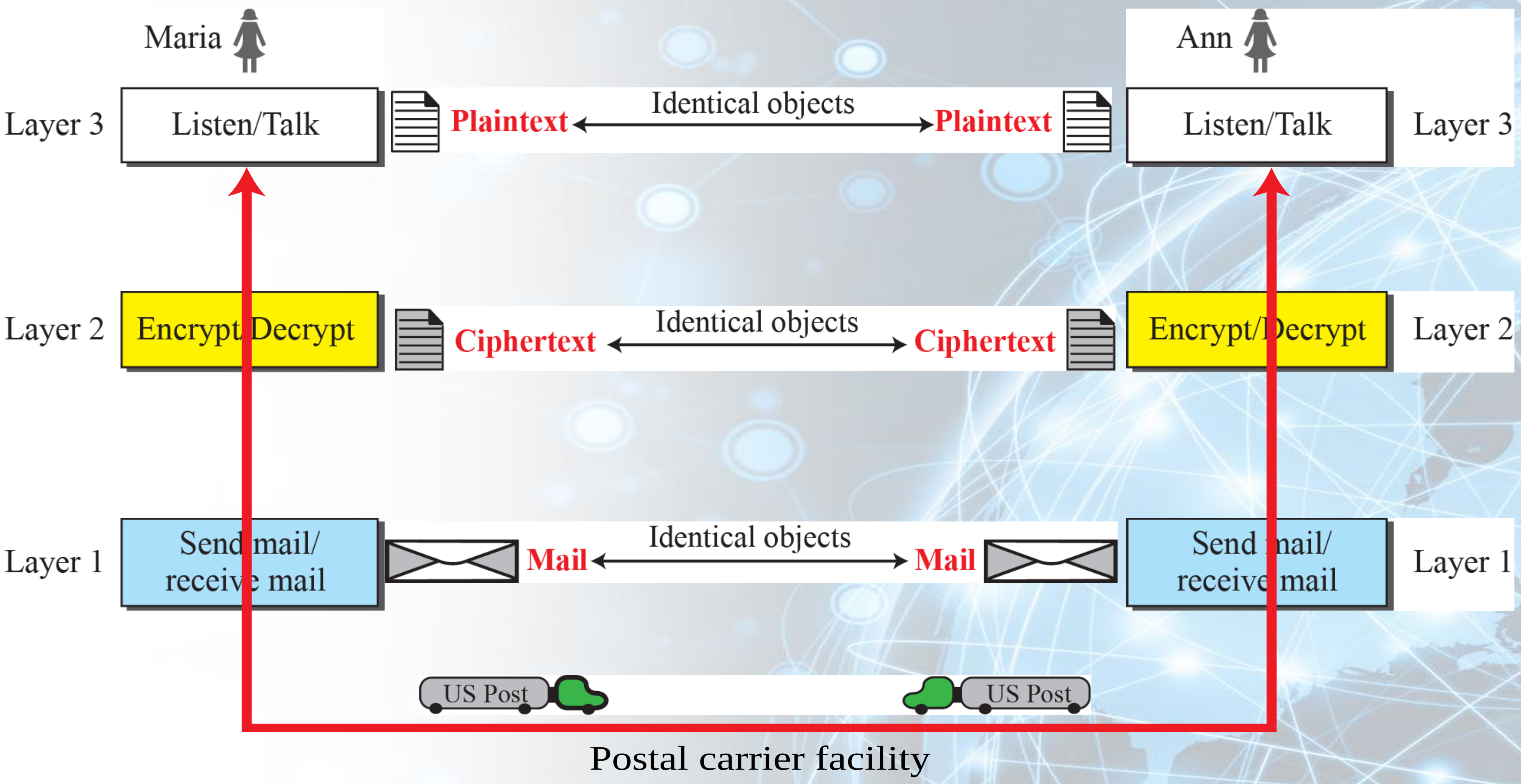
  Simple Communication: only one simple protocol

  Complex Communication, we need a protocol at each layer, or Protocol Layering

# Protocol Layering - Example Scenario 1



# Protocol Layering - Example Scenario 2



# Protocol Layering - Advantages and Disadvantages

- **Advantages**
  - ✓ Modularity
  - ✓ Separation of Service & Implementation
  - ✓ Reduced Complexity & Cost

- **Disadvantages**
  - ✓ None Really!

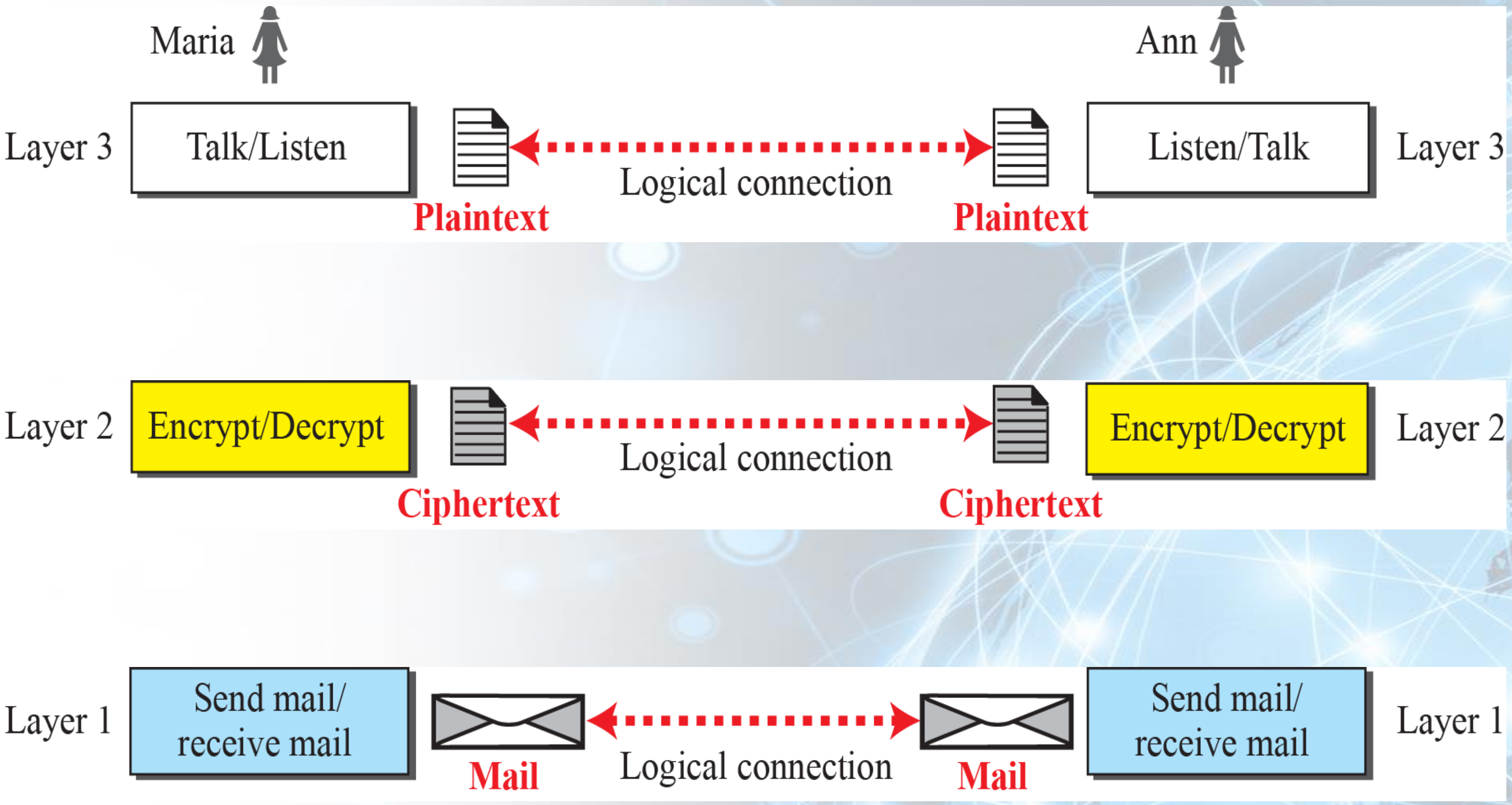
# Protocol Layering - Principles

- **Two Principles**
  - ✓ Bidirectional Communication → Each Layer performs two opposite tasks in each direction
  - ✓ Two objects under each layer at both sites should be identical

# Protocol Layering - Logical Connections

- **Logical Connections**
  - ✓ Imaginary connection between each layer

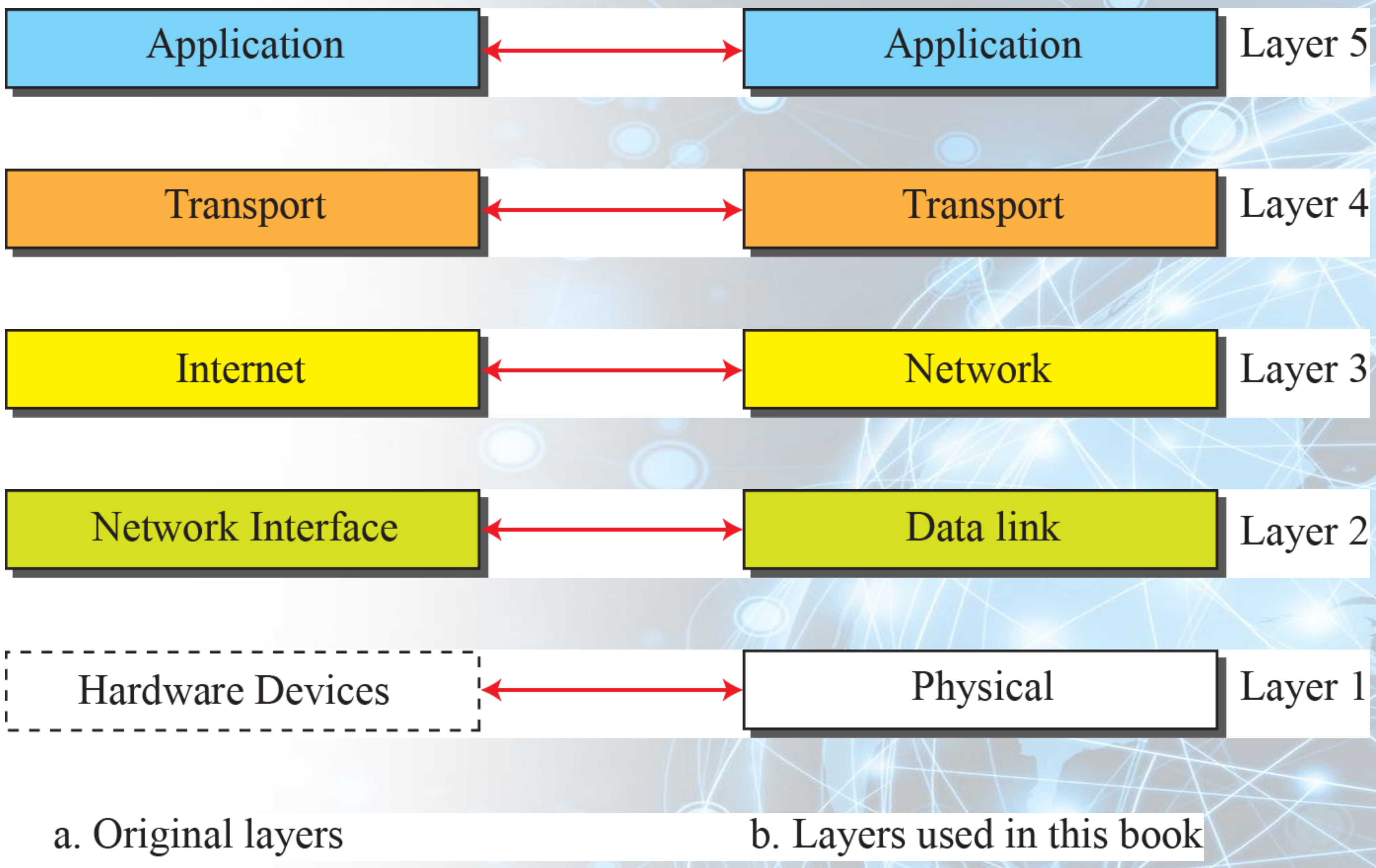
# Protocol Layering



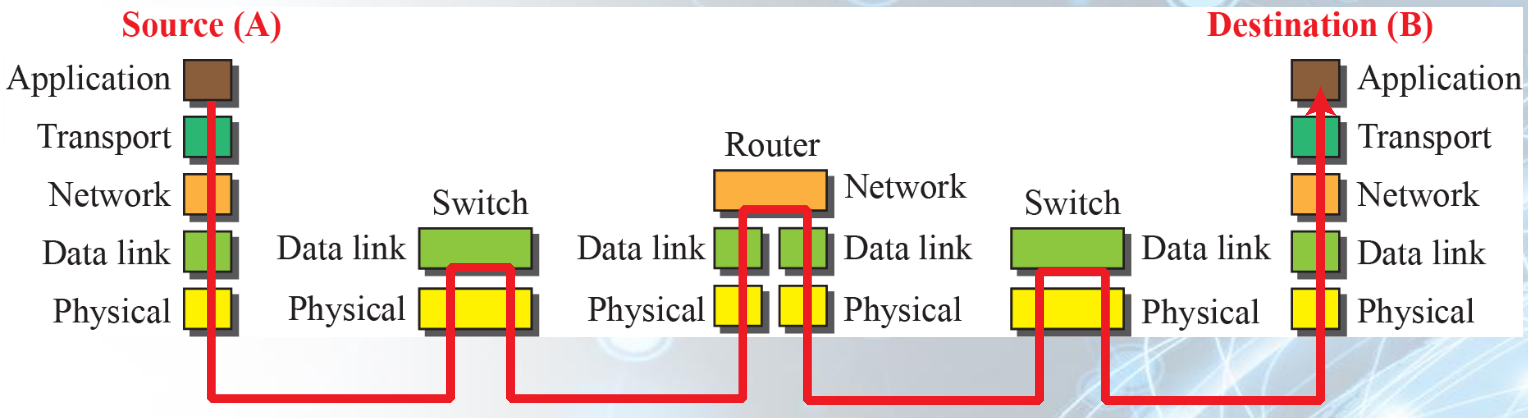
# TCP/IP Protocol Suite

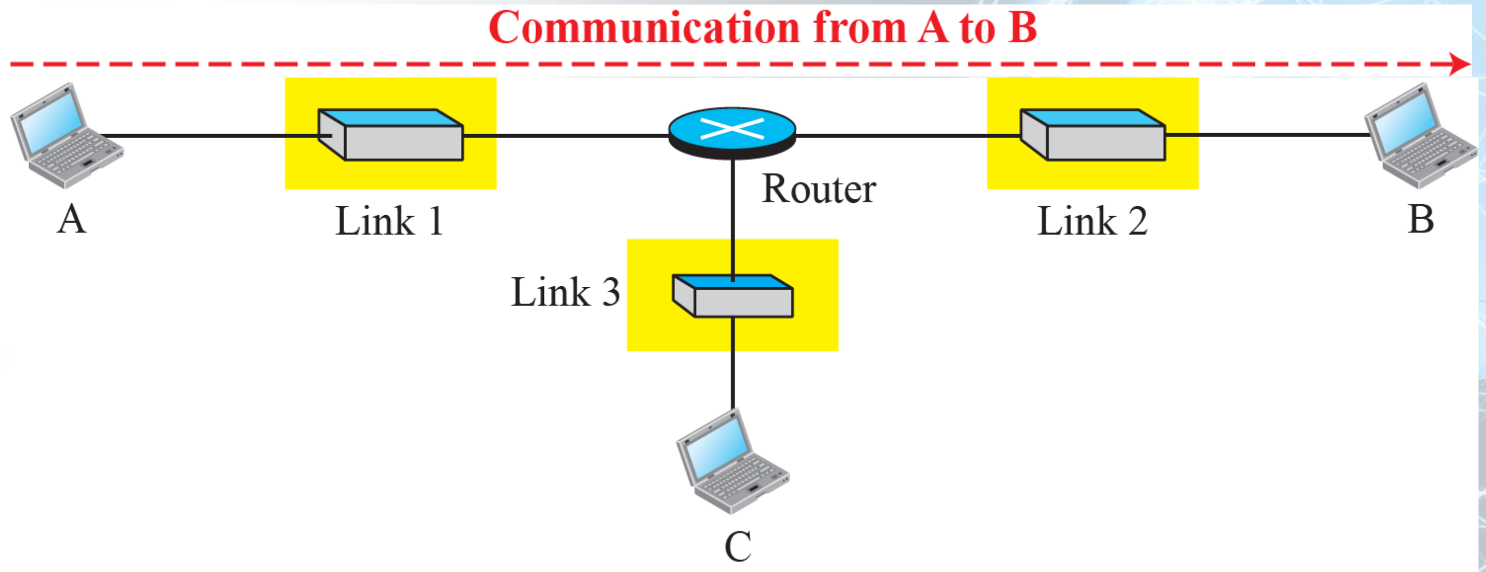
- **TCP/IP Protocol Suite**
  - ✓ Protocol suite used in Internet today
  - ✓ Each Layer provides specific functionality
  - ✓ Hierarchical Protocol
  - ✓ Presented in 1973 and chosen to be the official protocol of Internet in 1983

# TCP/IP Protocol Suite



# TCP/IP Protocol Suite - Layered Architecture



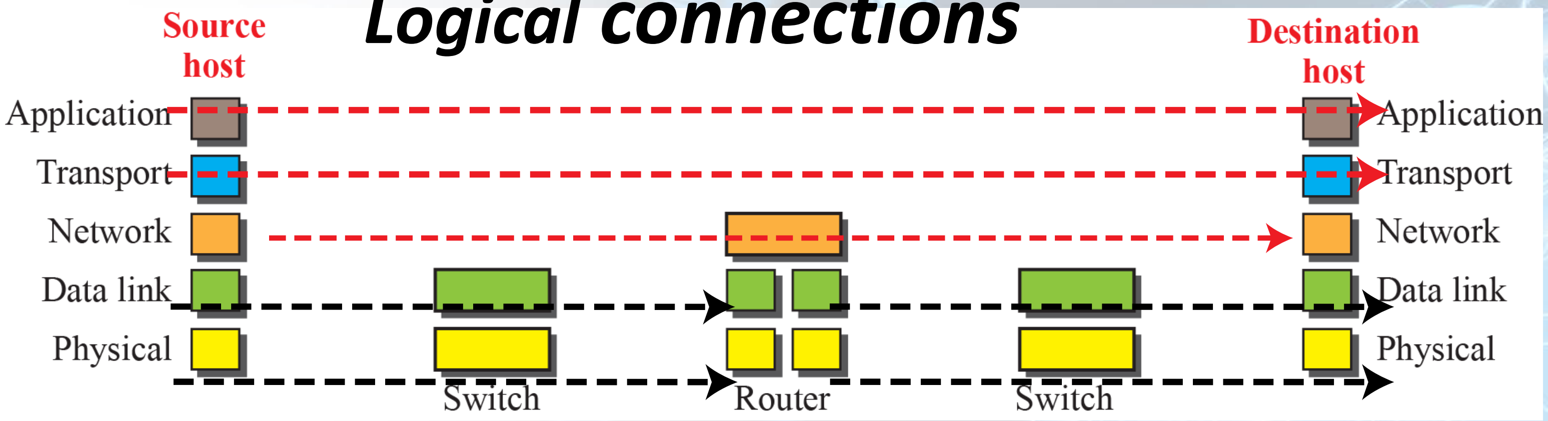



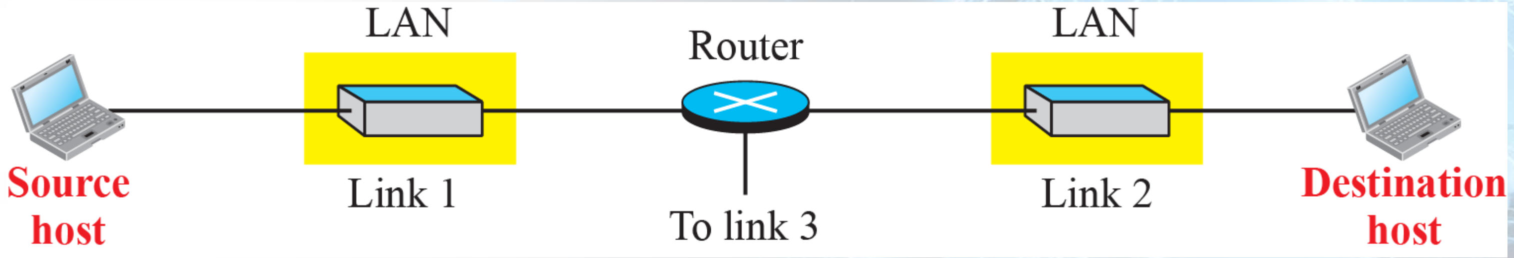
# TCP/IP Protocol Suite – Function of Layers

- **Logical Connections between TCP/IP Layers**

# TCP/IP Protocol Suite – Function of Layers

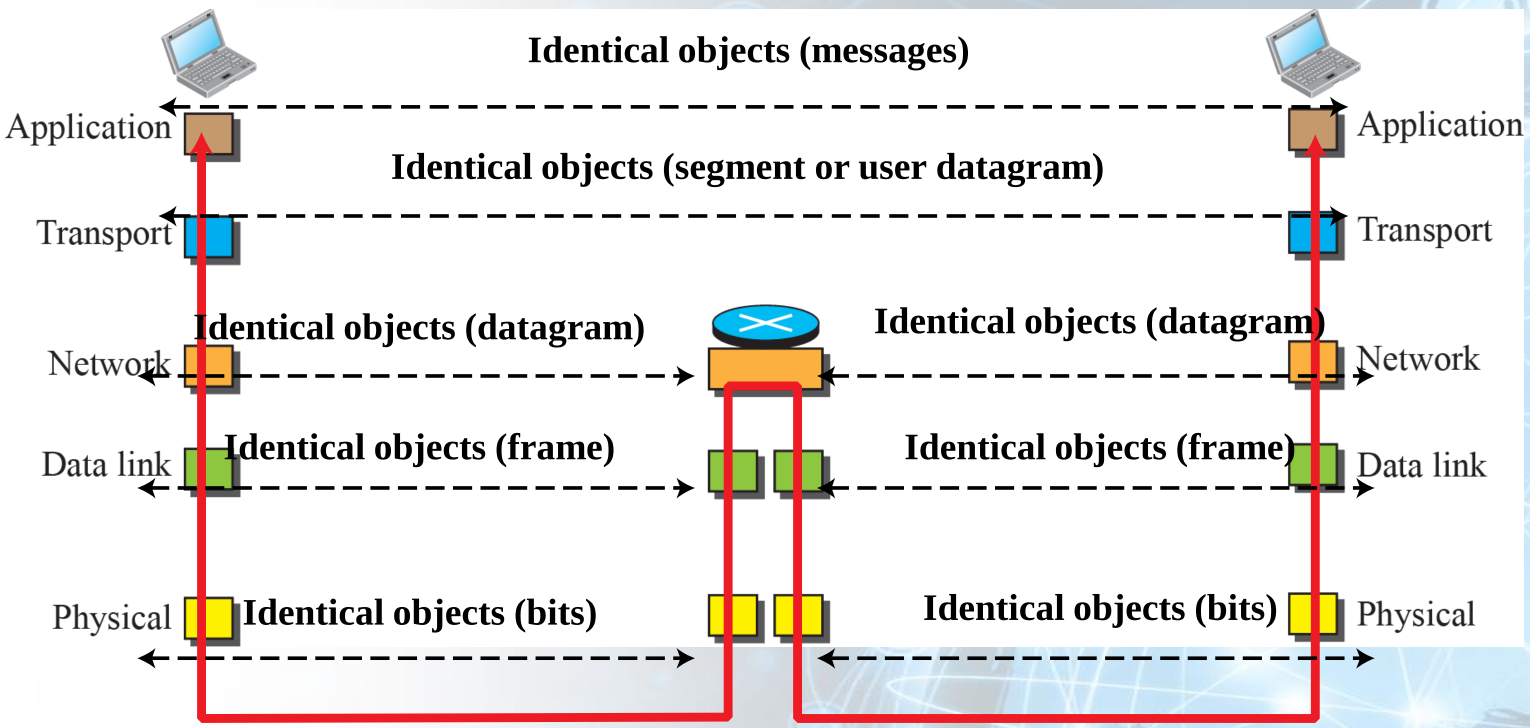
***Logical connections***



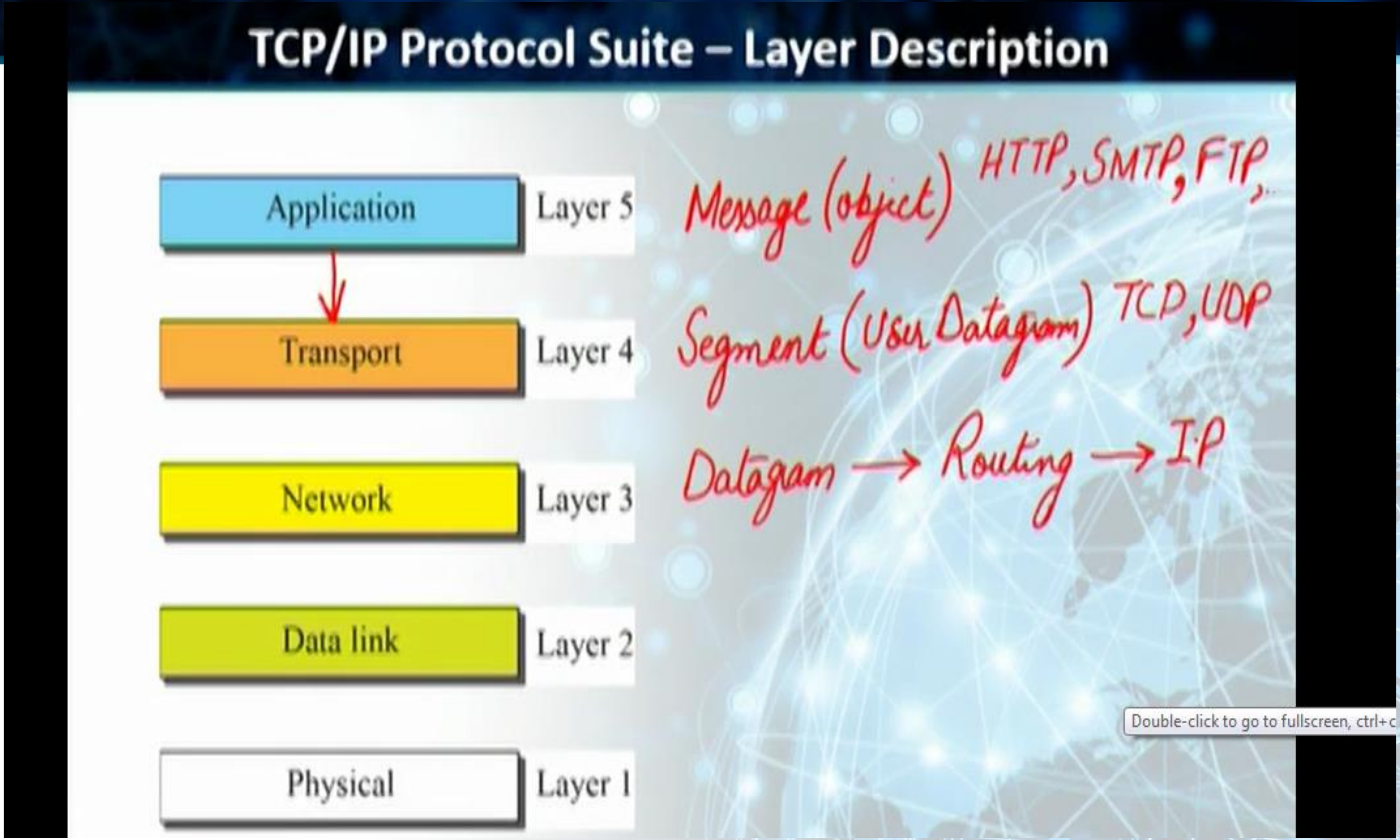
# TCP/IP Protocol Suite – Function of Layers

**Notes:** We have not shown switches because they don't change objects.

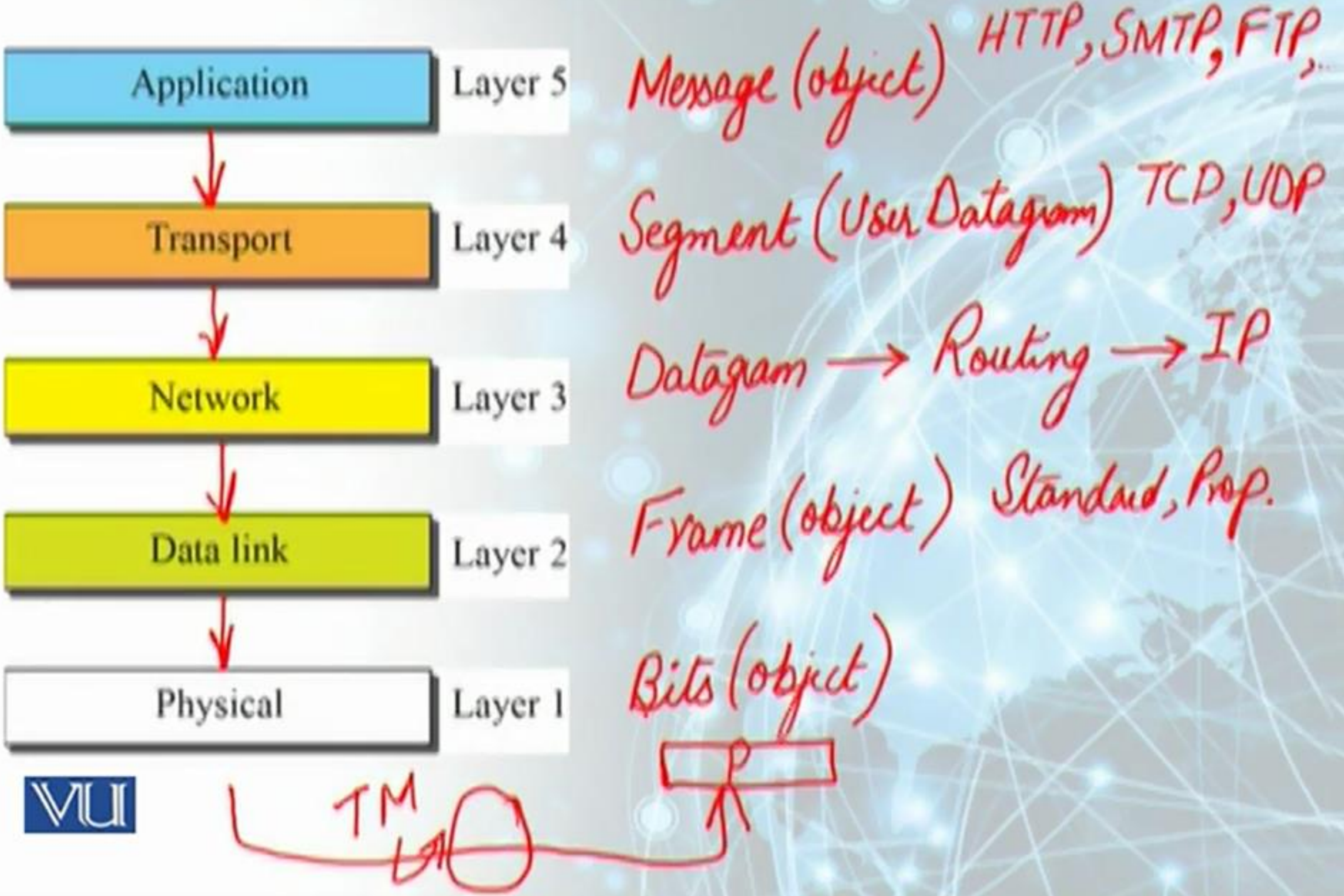


# TCP/IP Protocol Suite – Layer Description

| | |
|---|---|
| Application | Layer 5 |
| Transport | Layer 4 |
| Network | Layer 3 |
| Data link | Layer 2 |
| Physical | Layer 1 |


TCP/IP Protocol Suite – Layer Description
Application
Layer 5
Transport
Layer 4
Network
Layer 3
Data link
Layer 2
Physical
Layer 1
Message (object) HTTP, SMTP, FTP,
Segment (User Datagram) TCP, UDP
Datagram → Routing → IP
Double-click to go to fullscreen, ctrl+c

# TCP/IP Protocol Suite – Layer Description

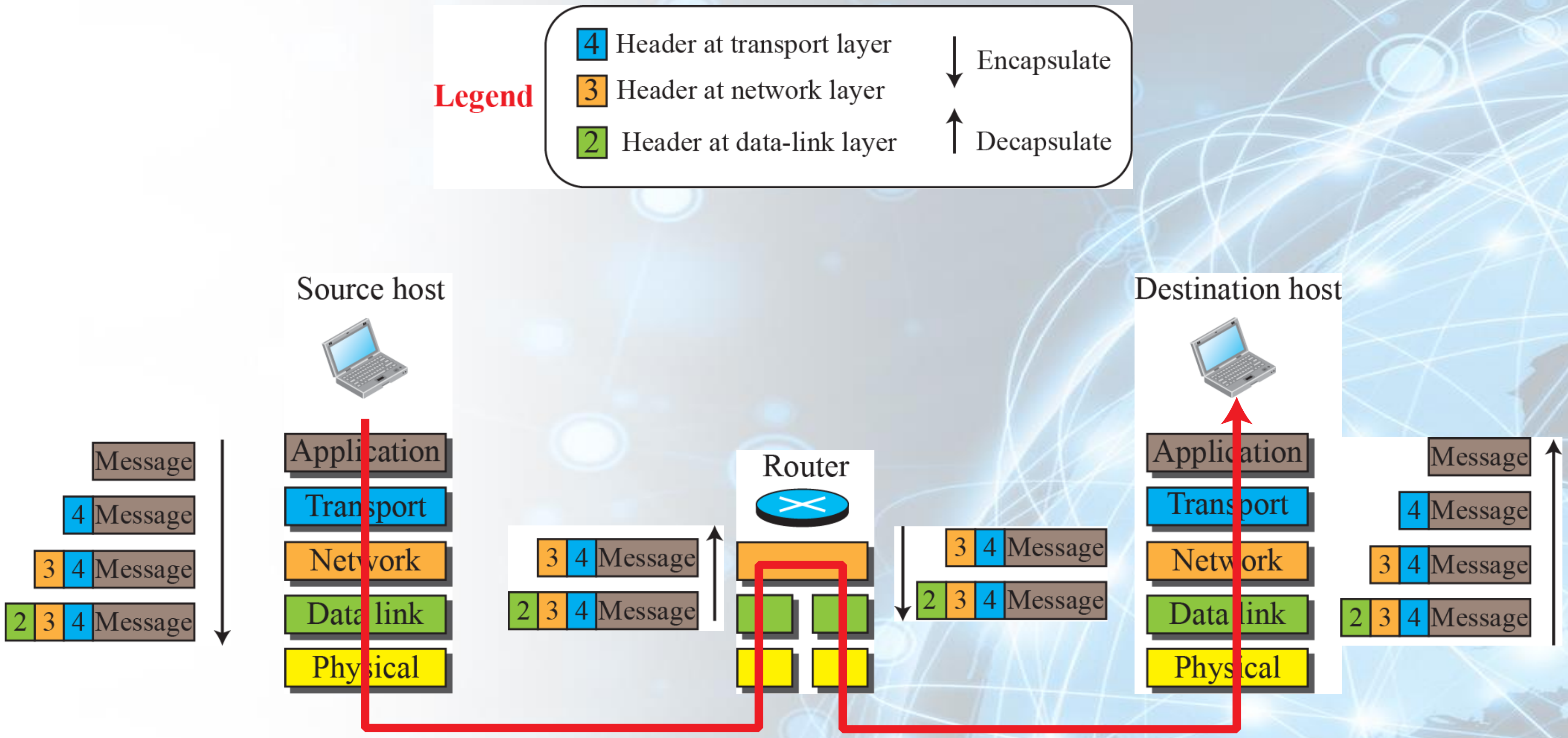


# Encapsulation & Decapsulation

- **Important Concept in Internet Protocol Layering**

- **Layer Header**

# Encapsulation & Decapsulation



# Addressing in TCP/IP Protocol Suite

- **Every communication needs at least two addresses:**
  - ✓ **Source Address &**
  - ✓ **Destination Address**
- **Addressing by Layer**
- **Physical Layer is an exception**

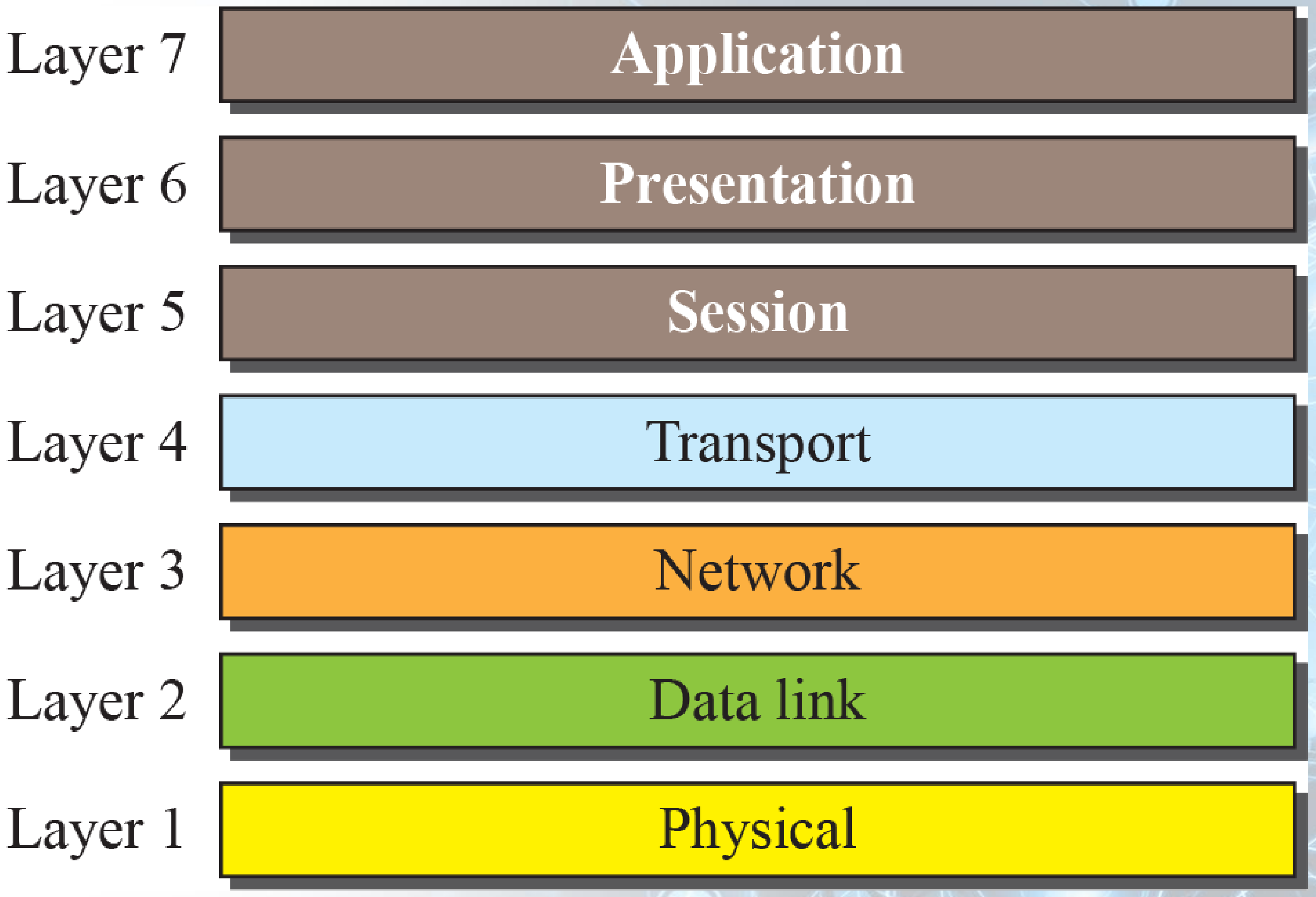
# Addressing in TCP/IP Protocol Suite

| Packet names | Layers | Addresses |
| --- | --- | --- |
| Message | Application layer | Names |
| Segment / User datagram | Transport layer | Port numbers |
| Datagram | Network layer | Logical addresses |
| Frame | Data-link layer | Link-layer addresses |
| Bits | Physical layer | |

# The Open System Interconnection (OSI) Model

- International Organization for Standardization (ISO)
- ISO established in 1947
- Close to three-fourths of countries represented
- Introduced OSI Model in late 1970s
- OSI: a 7-Layer Model

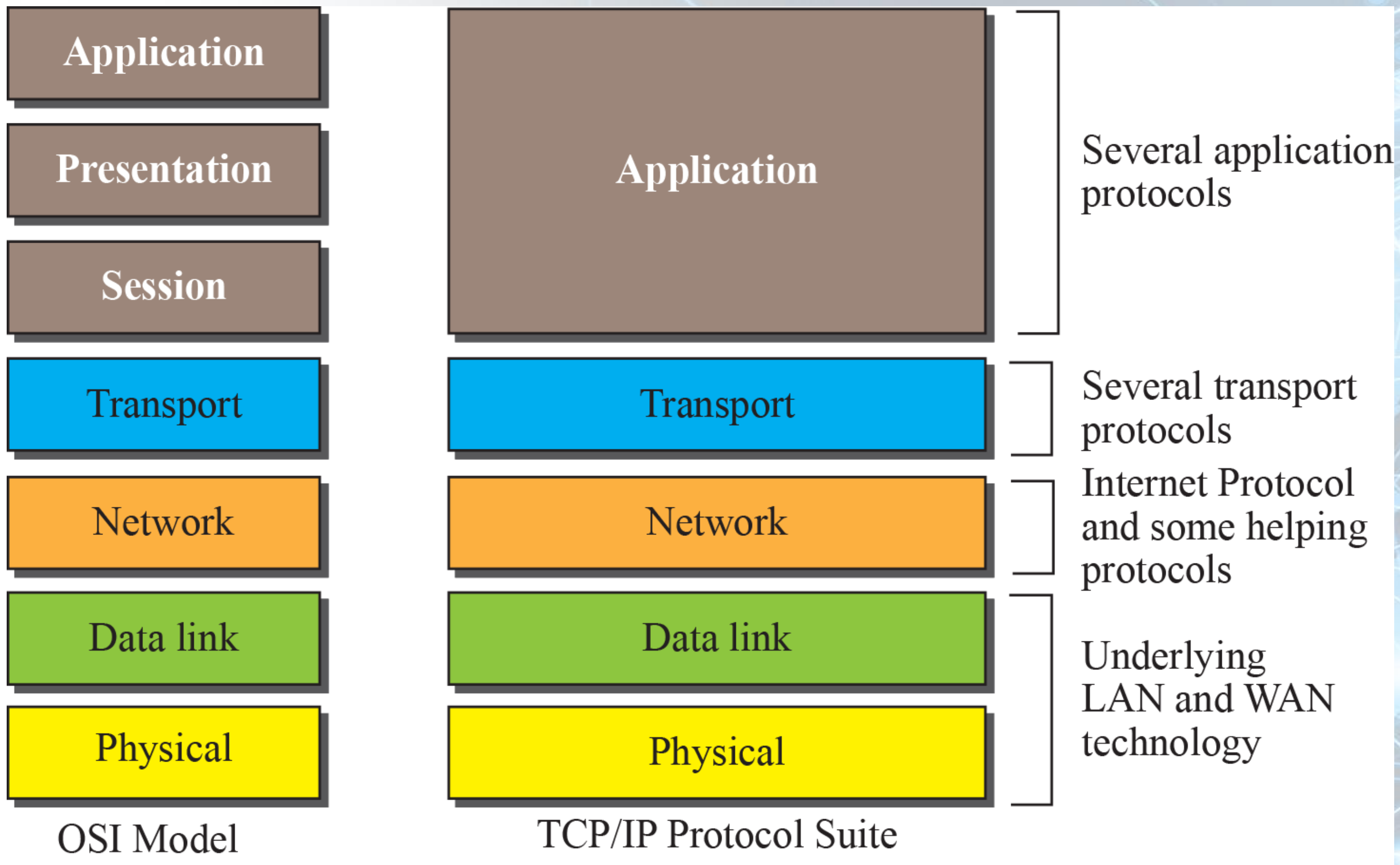
# The Open System Interconnection (OSI) Model



# OSI Model vs TCP/IP Protocol suite

- Two Layers of OSI missing from TCP/IP
- Application (TCP/IP) = Application + Presentation + Session (OSI)

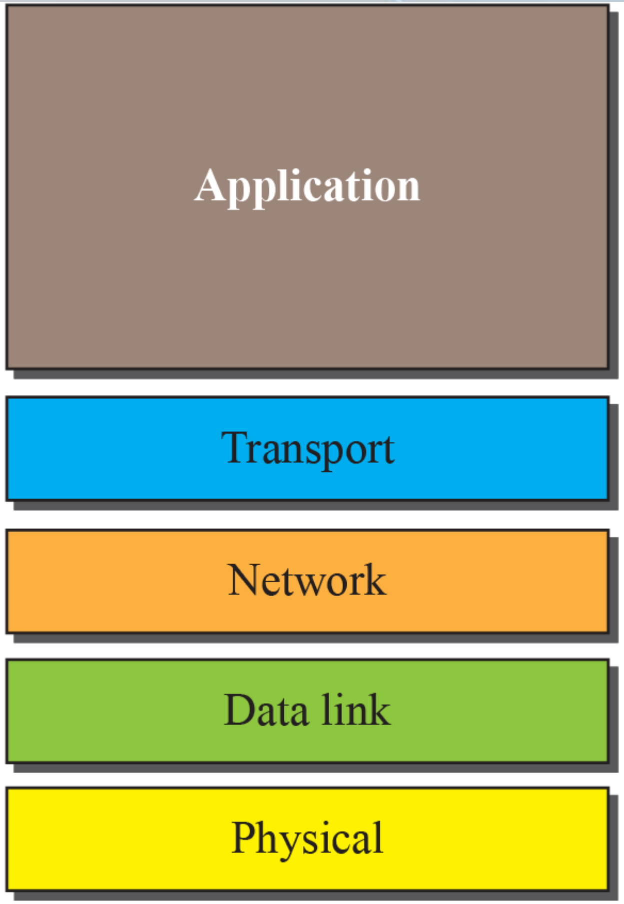
# OSI Model vs TCP/IP Protocol suite



# Lack of OSI Model's Success

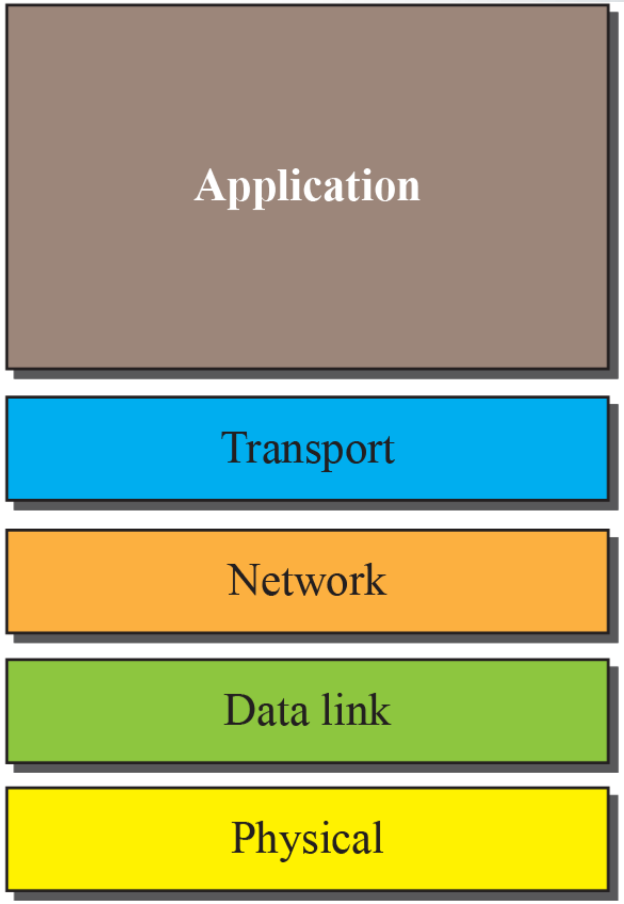
- Three reasons OSI did not replace TCP/IP:
  - ✓ OSI was completed when TCP/IP was fully in place
  - ✓ Some layers in OSI not fully defined
  - ✓ Performance of TCP/IP better than that of OSI

# Data Communication versus Computer Networks




TCP/IP Protocol Suite

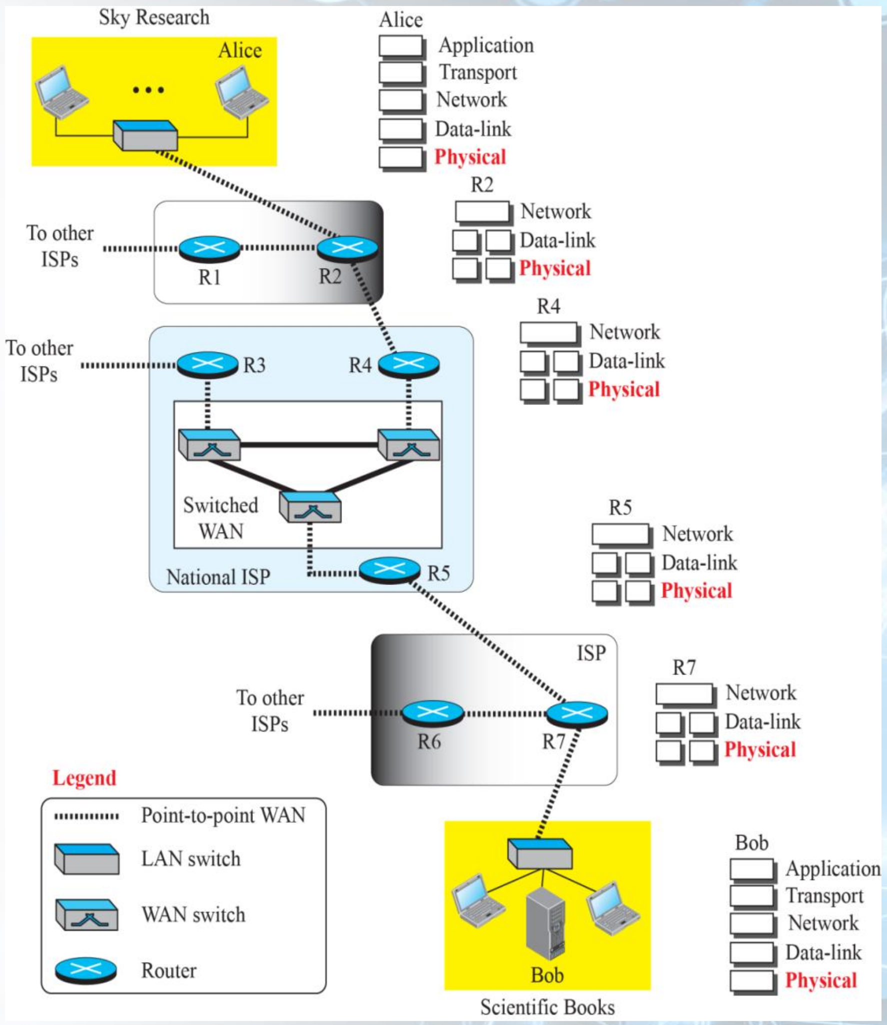
# Data Communication versus Computer Networks



TCP/IP Protocol Suite

- Analog & Digital Transmission
- Transmission Media
- Switching
- Error Detection and Correction
- Media Access and Data Link Control
- Wired and Wireless LANs

# Communication at Physical Layer



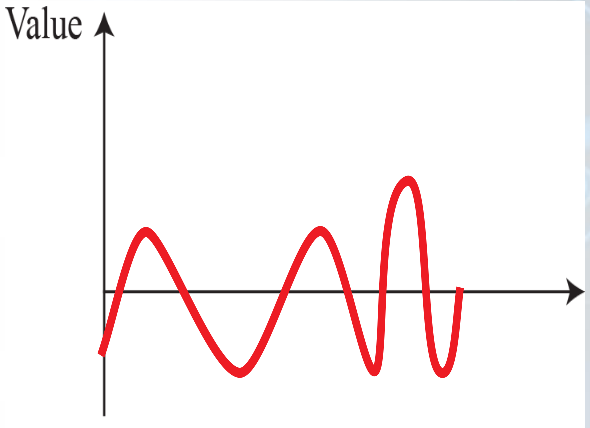
# Analog & Digital Data

- **Data → Analog or Digital**
- **Analog Data → Continuous**
- **Digital Data → Discrete**
- **Examples: Analog Clock vs. Digital Clock**
- **Human voice vs. Data in Computer**

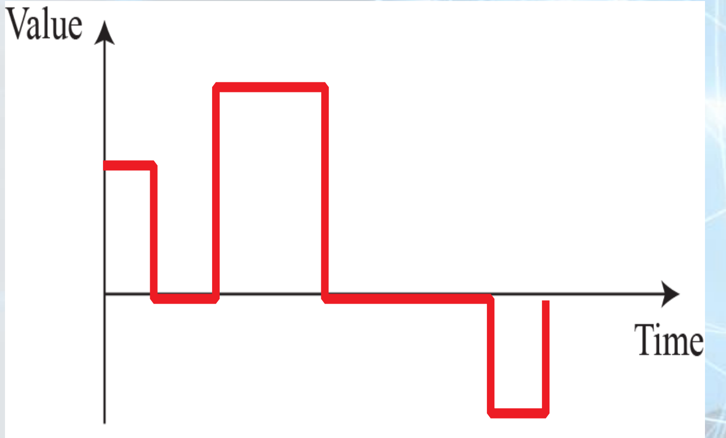
# Analog & Digital Signals

- Signals represent Data
- Signals → Analog or Digital
- Analog Signal → Infinite Levels of Intensity over time
- Digital Signal → Limited number of defined values

# Analog & Digital Signals



a. Analog signal



b. Digital signal

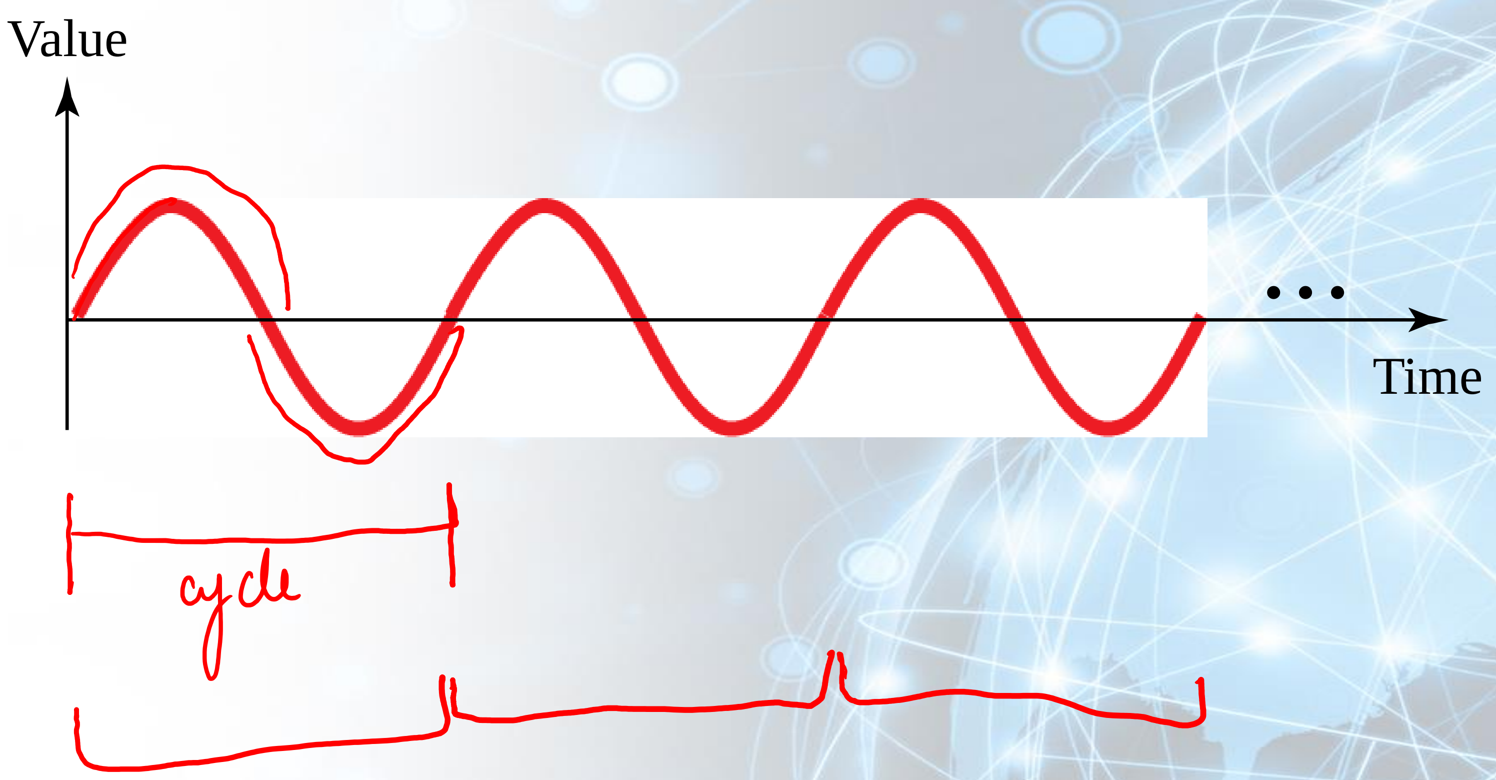
# Periodic & Non-periodic Signals

- **Analog/Digital Signal → Periodic or Non-periodic**
- **Periodic Signal → Pattern**
- **Period and Cycle**
- **Non-Periodic → No Pattern**
- **Periodic ANALOG Signals and Non-periodic DIGITAL Signals**

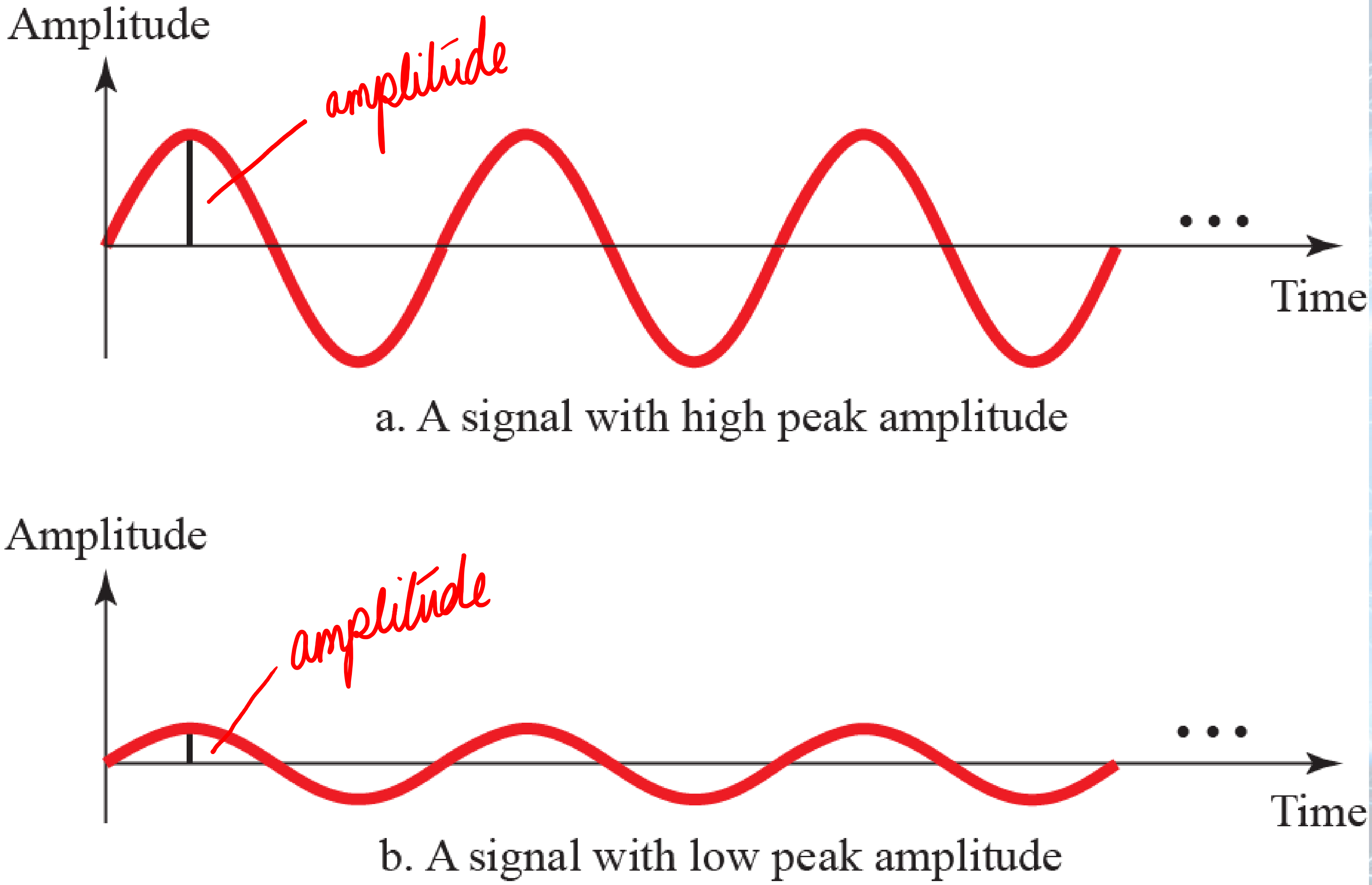
# Periodic Analog Signals

- Periodic Analog Signals → Simple or Composite
- Simple Periodic Analog signal→ Sine wave
- Composite Periodic Analog signal→ Composed of multiple sine waves

# Sine Wave



# Sine Wave – Peak Amplitude



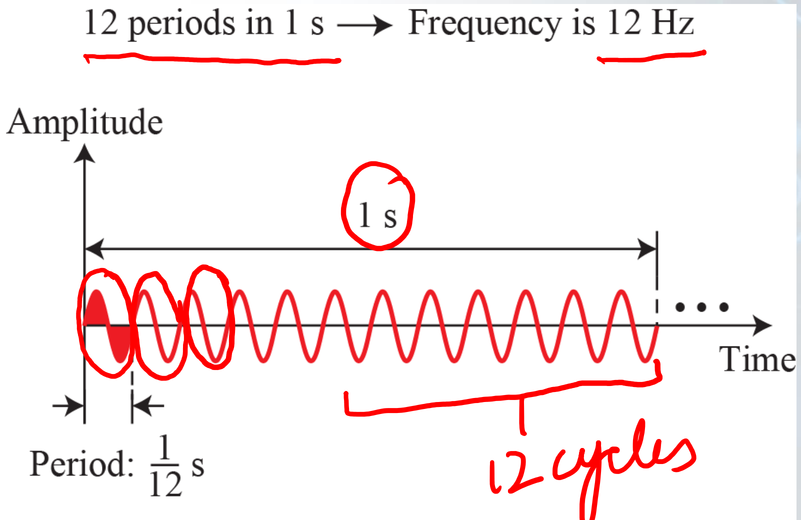
# Sine Wave –Frequency

- **Period (T) → Amount of time required to complete 1 cycle**

- **Frequency (f) → No. of Periods in 1 sec**

- **$f = 1/T$ or $T = 1/f$**

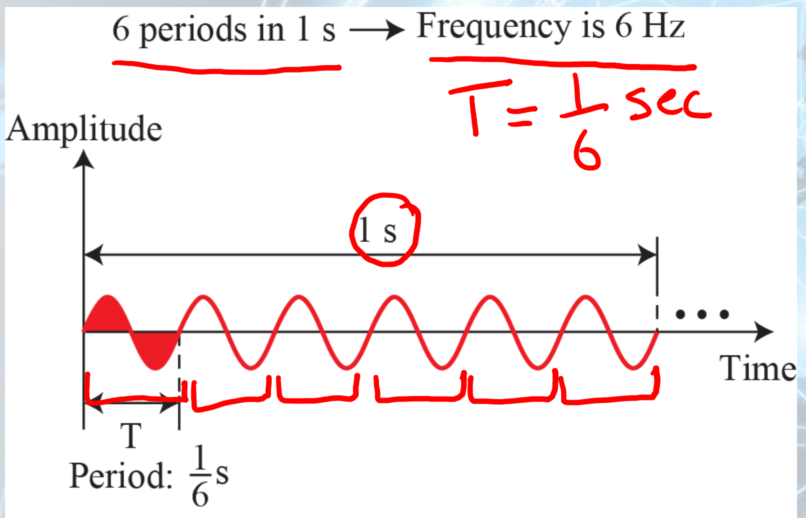
# Sine Wave –Frequency



a. A signal with a frequency of 12 Hz

$Hz = cycles/sec$

$T = \frac{1}{f} = \frac{1}{12}$ sec



b. A signal with a frequency of 6 Hz

# Sine Wave –Frequency

| *Period* | | *Frequency* | |
|---|---|---|---|
| *Unit* | *Equivalent* | *Unit* | *Equivalent* |
| Seconds (s) | 1 s | Hertz (Hz) | 1 Hz |
| Milliseconds (ms) | $10^{-3}$ s | Kilohertz (kHz) | $10^{3}$ Hz |
| Microseconds (μs) | $10^{-6}$ s | Megahertz (MHz) | $10^{6}$ Hz |
| Nanoseconds (ns) | $10^{-9}$ s | Gigahertz (GHz) | $10^{9}$ Hz |
| Picoseconds (ps) | $10^{-12}$ s | Terahertz (THz) | $10^{12}$ Hz |

# Example

The power we use at home has a frequency of 60 Hz. The period of this sine wave can be determined as follows:

$$T = \frac{1}{f} = \frac{1}{60} = 0.0166 \text{ sec}$$

$$= 16.6 \text{ msec}$$

# Example

**The period of a signal is 100 ms. What is its frequency in kilohertz?.**

$T = 100\,ms \Rightarrow 100 \times 10^{-3}\,sec = 10^{-1}\,sec$

$f = \frac{1}{T} = \frac{1}{10^{-1}} = 10\,Hz$

$10 \times 10^{-3}\,kHz$

$= 10^{-2}\,kHz$

# Phase (or Phase Shift)

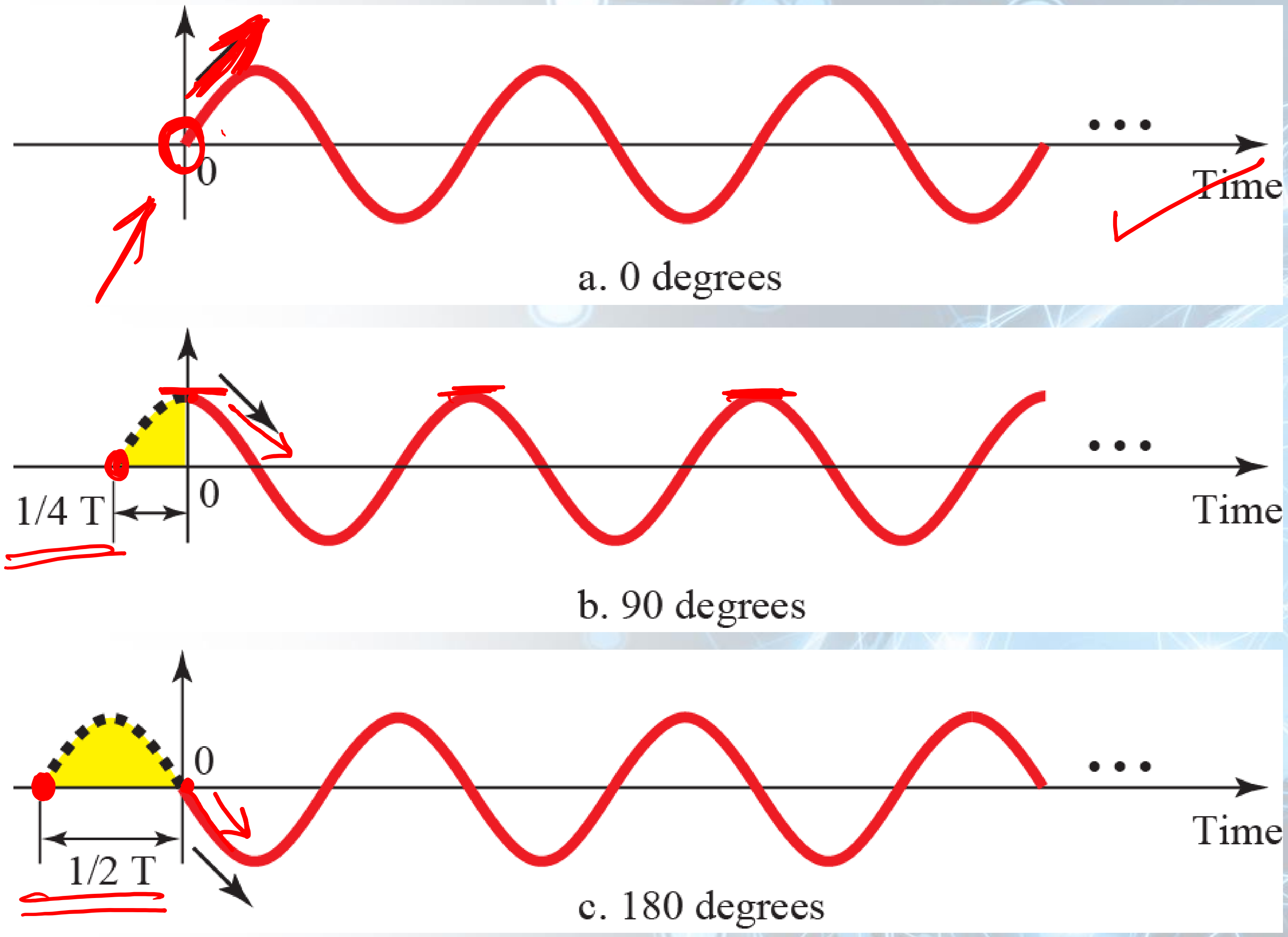
- Position of waveform relative to time 0
- Phase describes the amount of shift of the wave
- Indicates start of the first cycle

# Phase

$$360^\circ = 2\pi \text{ radians}$$

$$1^\circ = \frac{2\pi}{360} \text{ rad.}$$

# Phase



0
Time
a. 0 degrees
1/4 T
0
Time
b. 90 degrees
0
1/2 T
Time
c. 180 degrees

# Example

A sine wave is offset 1/6 cycle with respect to time 0. What is its phase in degrees and radians?

$$\frac{1}{6} \times 360^\circ = \underline{\underline{60^\circ}}$$

$$60 \times \frac{2\pi}{360} = 1.046 \text{ rad}$$

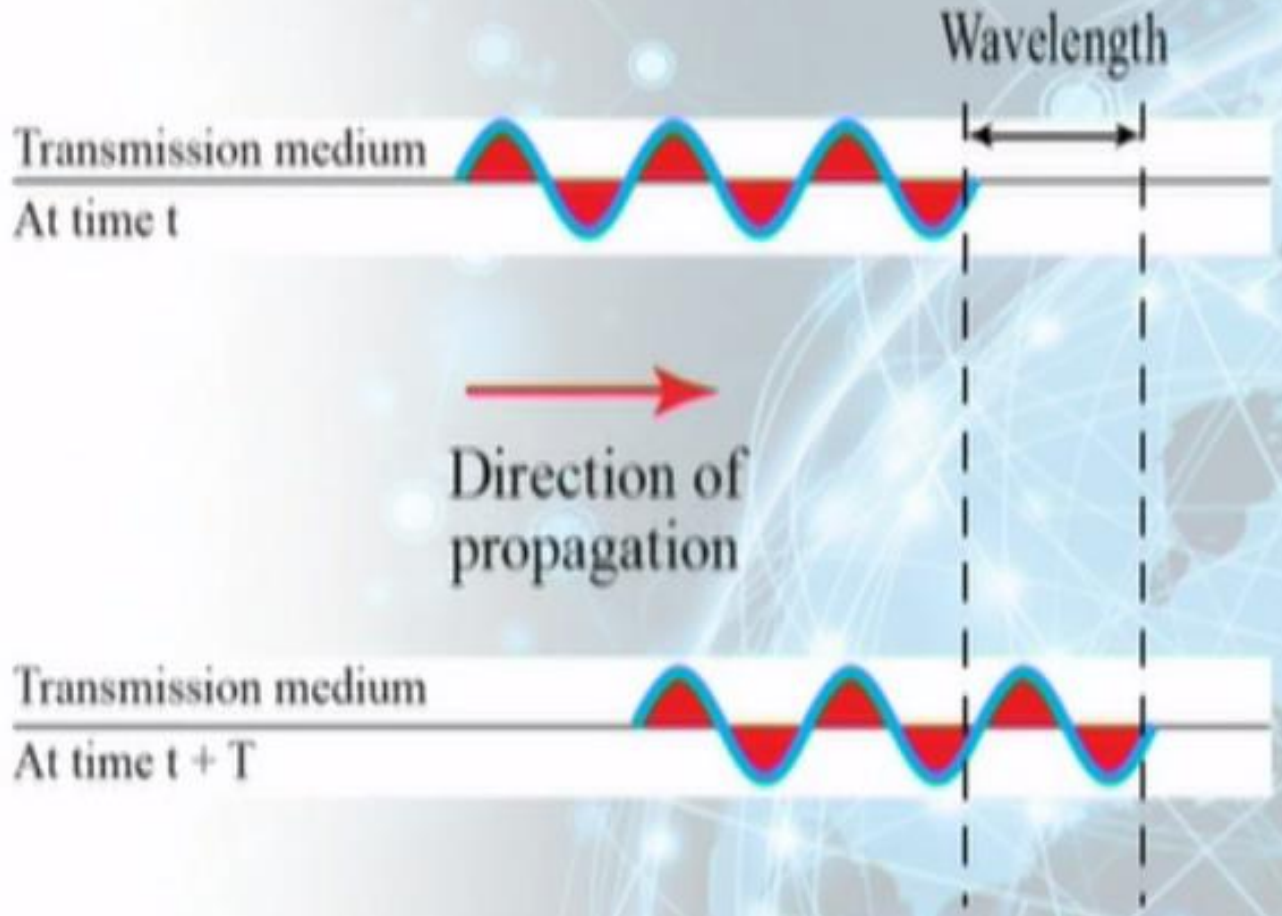
$$1^\circ = \frac{2\pi}{360} \text{ rad}$$

# Wavelength

**Wavelength is another characteristic of a signal traveling through a transmission medium. Wavelength binds the period or the frequency of a simple sine wave to the propagation speed of the medium (see Figure 3.7).**

# Wavelength

**Figure 3.7**



# Wavelength

Prop. Speed $= c =$ Light (speed)

frequency $= f$

Wavelength $= \lambda$

$$\lambda = \frac{c}{f} = \frac{3 \times 10^{8}\ m/sec}{f}$$

$$\lambda = \frac{3 \times 10^{8}}{4 \times 10^{14}}$$

# Wavelength

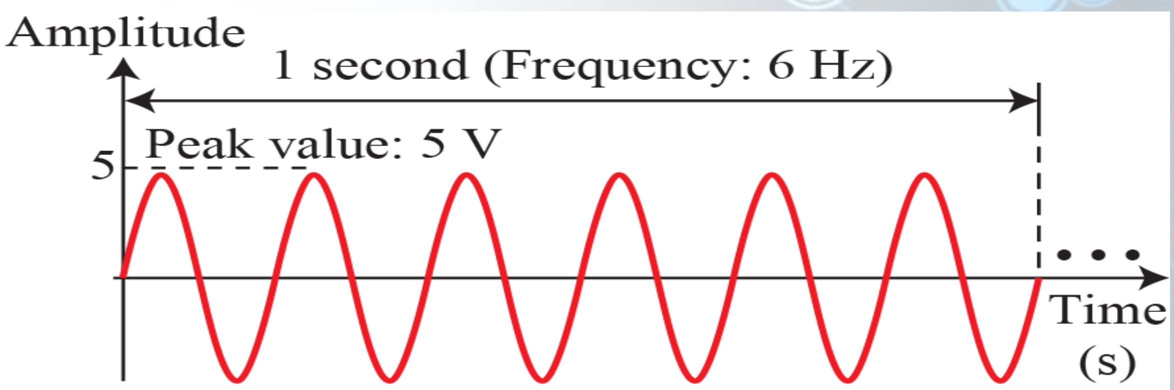
$$\lambda = 0.75 \times 10^{-6}\,m$$

$$= 0.75\,\mu m$$

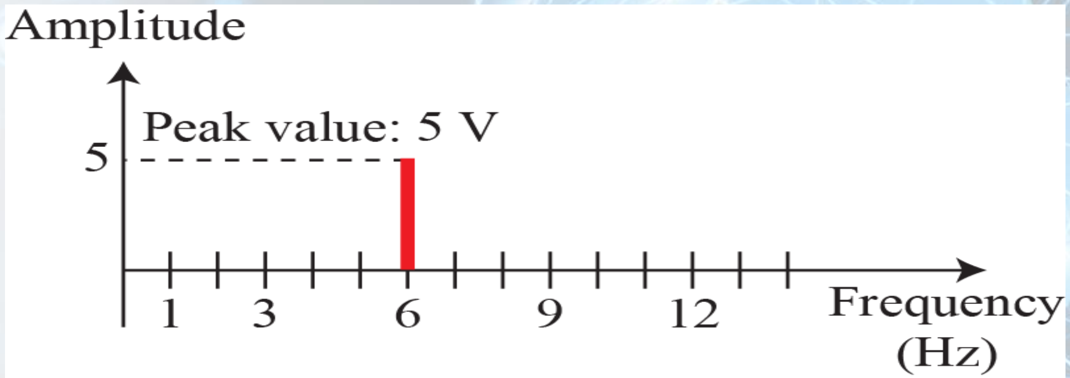
# Time & Frequency Domains

**A sine wave is comprehensively defined by its amplitude, frequency, and phase. We have been showing a sine wave by using what is called a time domain plot. The time-domain plot shows changes in signal amplitude with respect to time (it is an amplitude-versus-time plot). Phase is not explicitly shown on a time-domain plot.**

# Time & Frequency Domains




a. A sine wave in the time domain

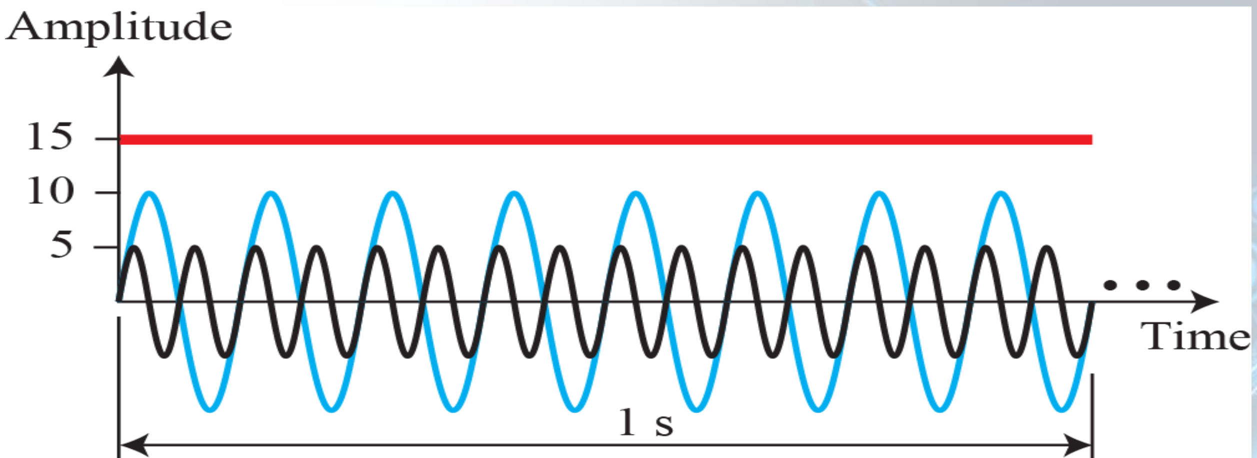



b. The same sine wave in the frequency domain

# Example 3.7

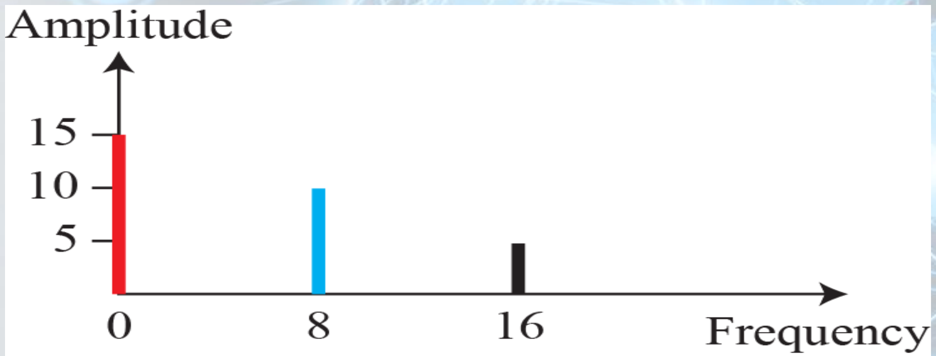
The frequency domain is more compact and useful when we are dealing with more than one sine wave. For example, Figure 3.9 shows three sine waves, each with different amplitude and frequency. All can be represented by three spikes in the frequency domain.

# Time & Frequency Domains



a. Time-domain representation

Figure 3.9



b. Frequency-domain representation

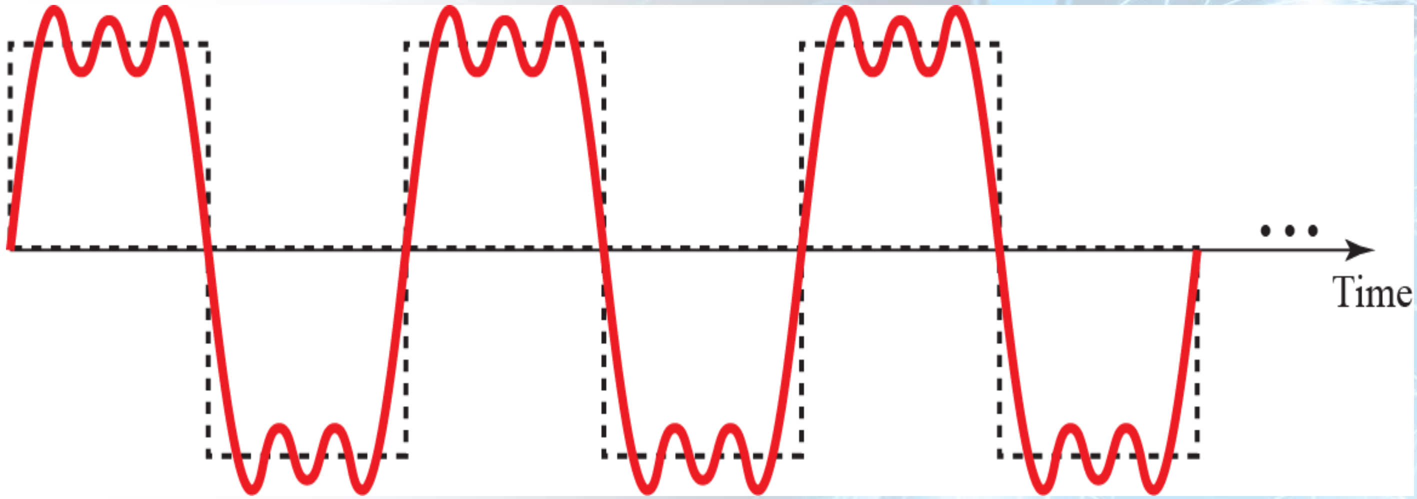
# Composite Signals

So far, we have focused on simple sine waves. Simple sine waves have many applications in daily life. We can send a single sine wave to carry electric energy from one place to another. For example, the power company sends a single sine wave with a frequency of 60 Hz to distribute electric energy to houses and businesses.

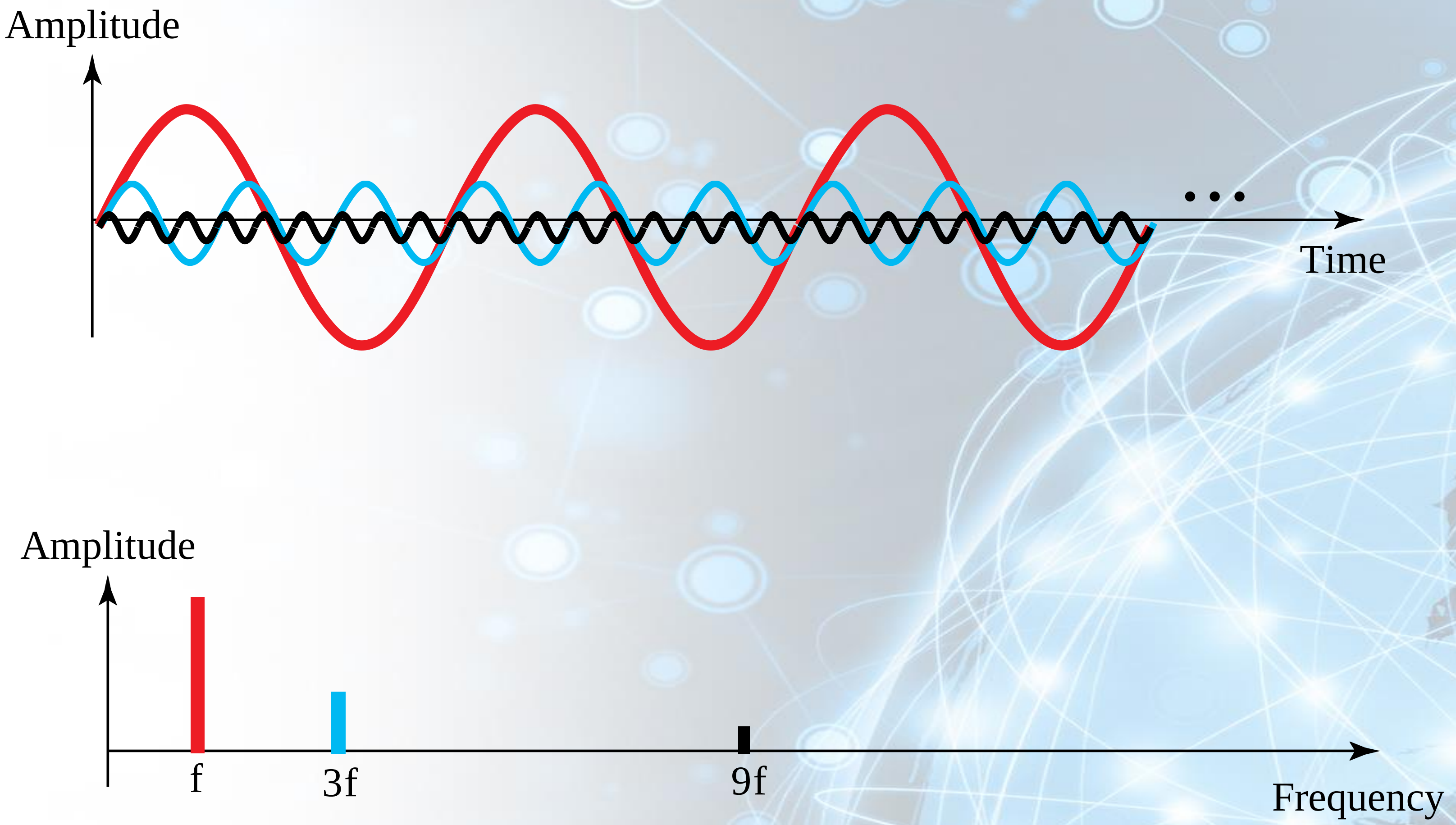
# Composite Signals

- Single Sine Wave can only carry limited information
- Composite Signal is made up of multiple simple sine waves
- Can be periodic or non-periodic

# A Composite Periodic Signal



# Decomposition of Composite Periodic Signal



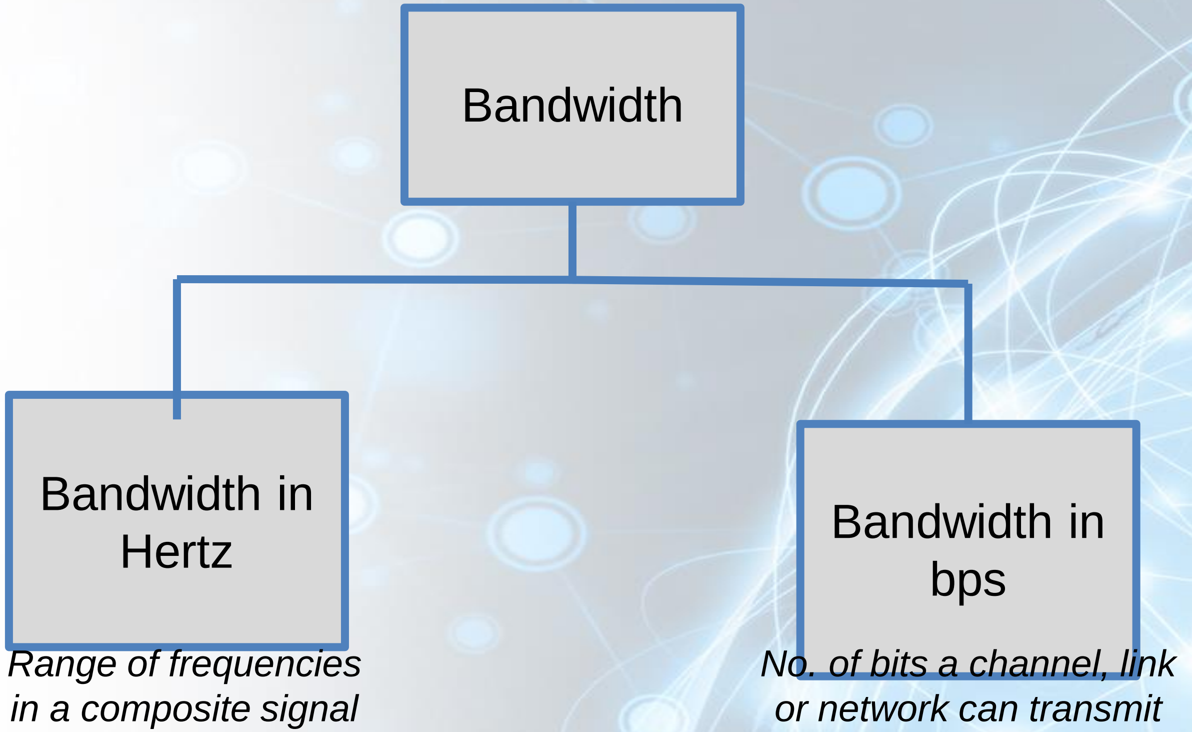

b. Frequency-domain decomposition of the composite signal

# Bandwidth

- An important characteristic that measures Network Performance

- Bandwidth can be used in two different contexts with two different measuring values:
  - Bandwidth in Hertz
  - Bandwidth in bits per second

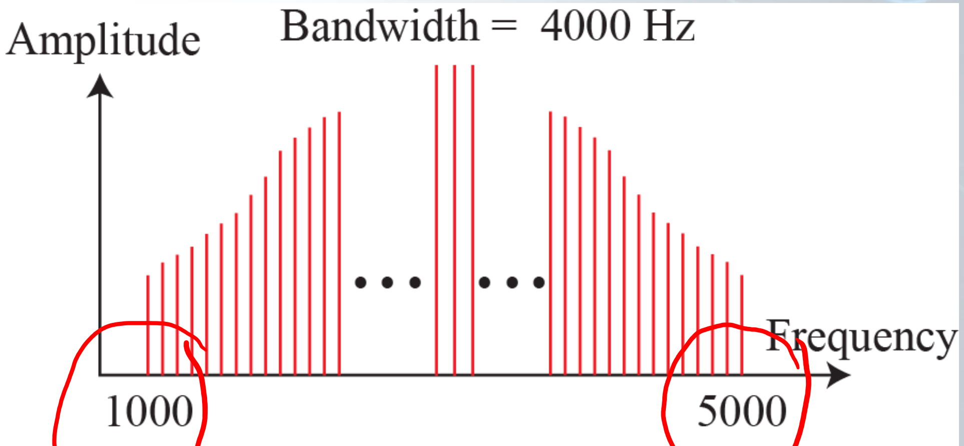
# Bandwidth


Bandwidth
Bandwidth in Hertz
Range of frequencies in a composite signal
Bandwidth in bps
No. of bits a channel, link or network can transmit

# Bandwidth

- **Range of frequencies contained in a Composite Signal**
- **The bandwidth is normally a difference between two frequencies (the highest and the lowest)**

# Bandwidth of a composite signal



a. Bandwidth of a periodic signal

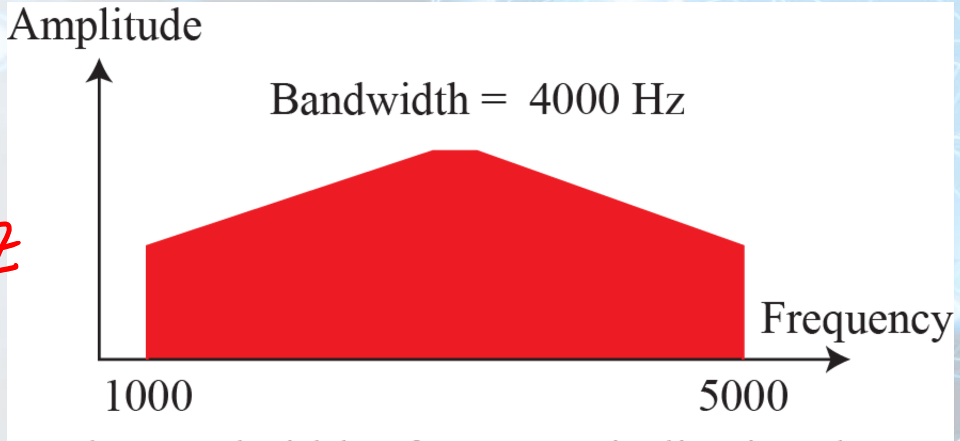
$B = f_h - f_l$

$= 5000 - 1000$

$= 4000\text{ Hz}$

$5000 - 1000$

$B = 4000\text{ Hz}$



b. Bandwidth of a nonperiodic signal

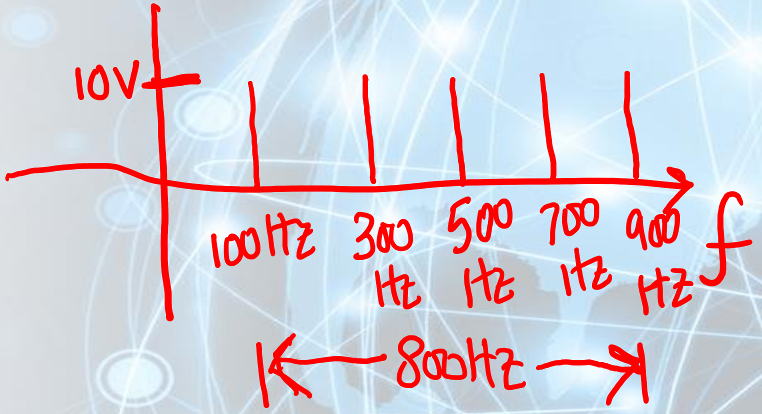
# Example

**If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is its bandwidth? Draw the spectrum, assuming all components have a maximum amplitude of 10 V.**

$B = f_h - f_l$

$= 900 - 100$

$B = 800 \text{ Hz}$



# Digital Signals

In addition to being represented by an analog signal, information can also be represented by a digital signal. For example, a 1 can be encoded as a positive voltage and a 0 as zero voltage. A digital signal can have more than two levels.

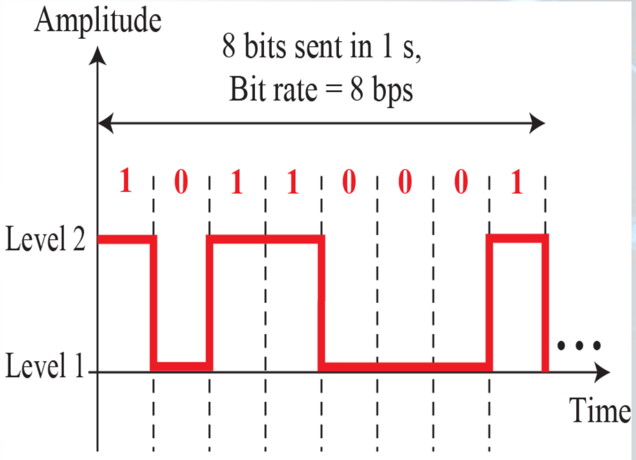
# Digital Signals

- Information can also be represented by a digital signal

- For example, a 1 can be encoded as a positive voltage and a 0 as zero voltage

- A digital signal can have more than two levels so that we can send more than one bit for each level

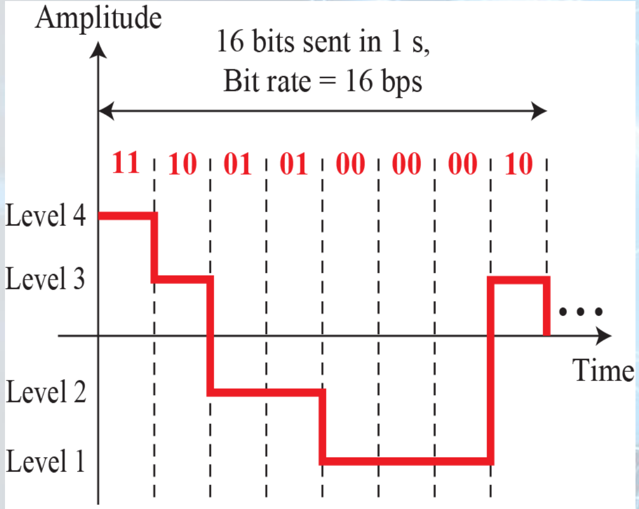
# Digital Signals




a. A digital signal with two levels

In general, if a signal has L levels, each level needs $\log_2 L$ bits. So, we can send $\log_2 2 = 1$ bit per level

$\log_2 4 = 2$ bits




b. A digital signal with four levels

# Digital Signals

In this case, we can send more than 1 bit for each level. Figure 3.17 shows two signals, one with two levels and the other with four.

# Example 3.16

A digital signal has eight levels. How many bits are needed per level? We calculate the number of bits from the following formula. Each

$$\text{Number of bits per level} = \log_2 8 = 3$$

repr … y 3 bits.

# Example

**A digital signal has eight levels. How many bits are needed pe**

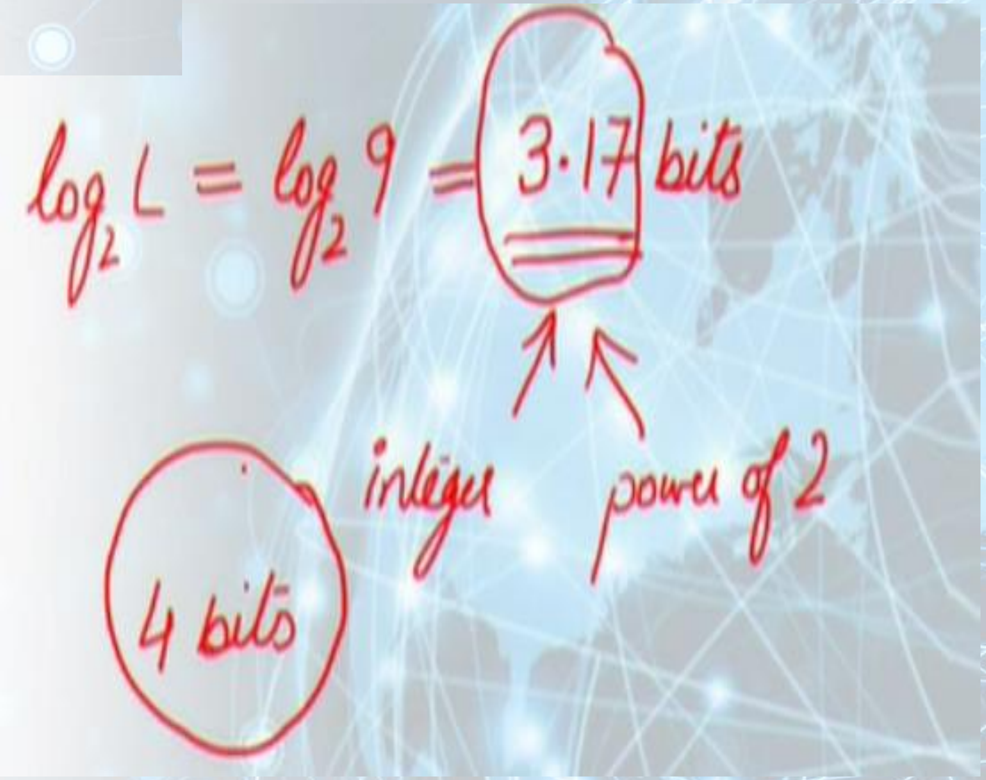
$$\text{No of bits} = \log_2 L$$
$$= \log_2 8$$
$$= 3 \text{ bits}$$

# Example 3.17

A digital signal has nine levels. How many bits are needed per level? We calculate the number of bits by using the formula. Each signal level is represented by 3.17 bits. However, this answer is not realistic. The number of bits sent per level needs to be an integer as well as a power of 2. For this example, 4 bits can represent one level.

# Example

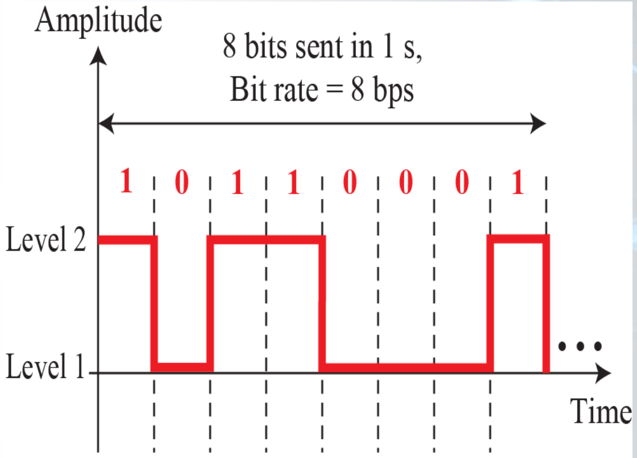
**A digital signal has nine levels. How many bits are needed per level? We calculate the number of bits by using the formula.**



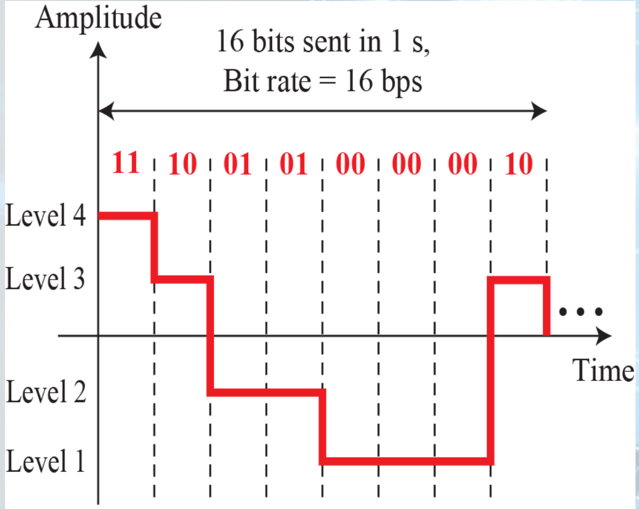
# Bit Rate

- **Number of bits sent in 1 second**
- **Bit Rate is expressed in bits per second (bps)**
- **Most digital signals are non-periodic, and thus period and frequency are not appropriate characteristics**

# Bit Rate

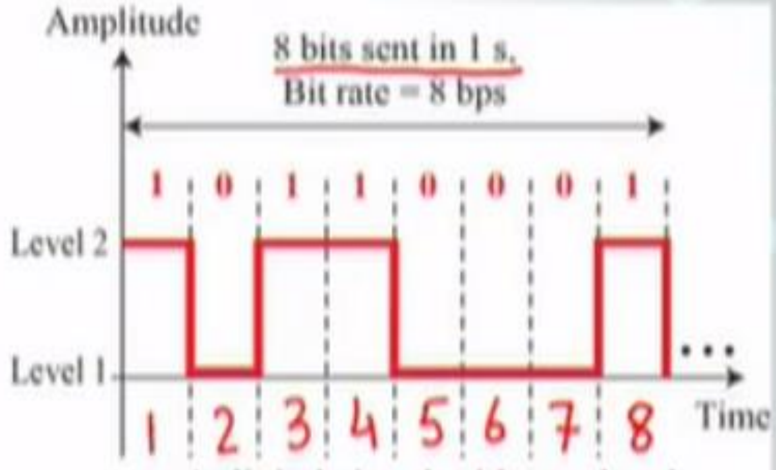



a. A digital signal with two levels




b. A digital signal with four levels

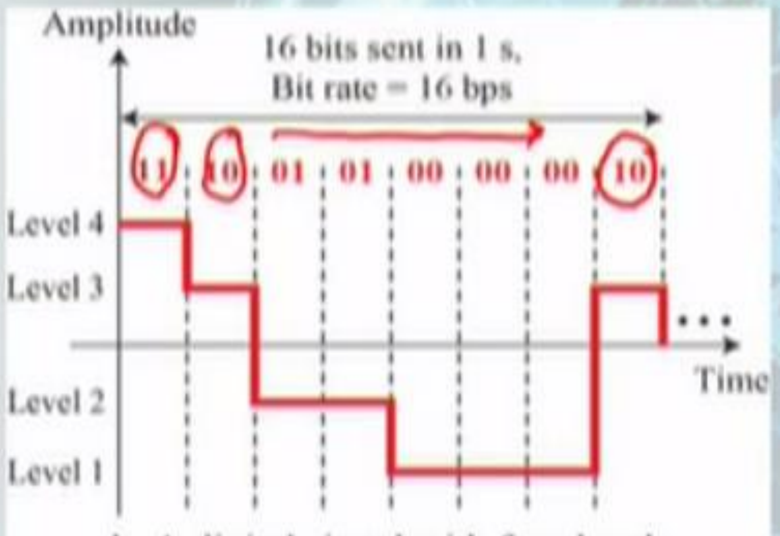
# Bit Rate




a. A digital signal with two levels

Bit Rate = 8 bps

BR = 1




b. A digital signal with four levels

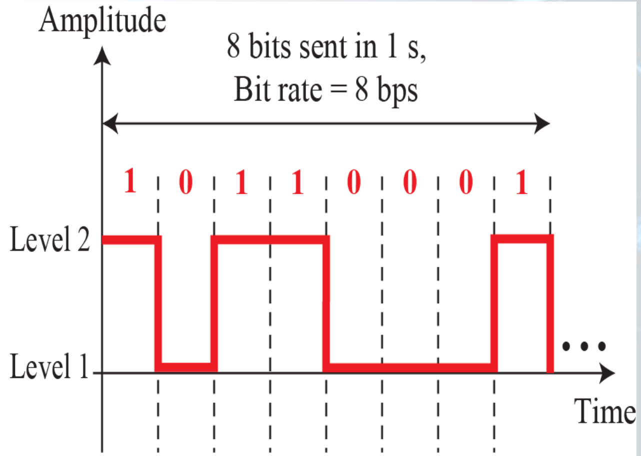
# Bit Rate

**Most digital signals are nonperiodic, and thus period and frequency are not appropriate characteristics. Another term—bit rate (instead of frequency)—is used to describe digital signals. The bit rate is the number of bits sent in 1s, expressed in bits per second (bps). Figure 3.17 shows the bit rate for two signals.**

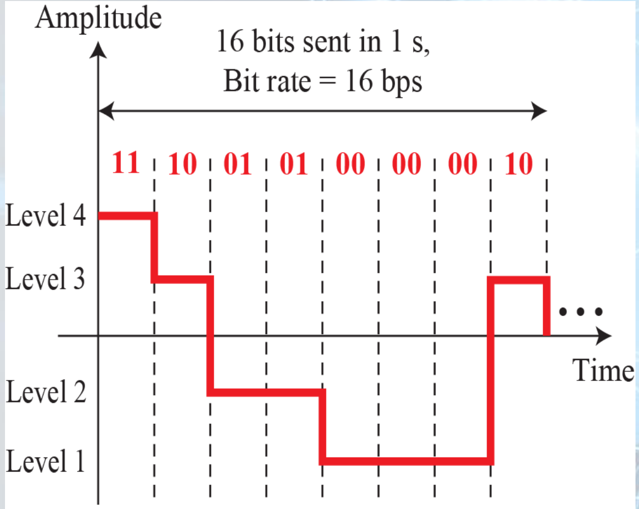
# Bit Rate

- **Number of bits sent in 1 second**
- **Bit Rate is expressed in bits per second (bps)**
- **Most digital signals are non-periodic, and thus period and frequency are not appropriate characteristics**

# Bit Rate




a. A digital signal with two levels




b. A digital signal with four levels

# Example

**Assume we need to download text documents at the rate of 100 pages per second. What is the required bit rate of the ch**

1 page = 24 lines

1 line = 80 characters

1 ch = 8 bits

Bit Rate = $100 \times 24 \times 80 \times 8$

= 1.536 Mbps

# Example 3.18

**Solution**

**From Table 3.1 we find the equivalents of 1 ms (1 ms is 10–3 s) and 1 s (1 s is 106 μs). We make the**

$100 \times 24 \times 80 \times 8 = 1{,}536{,}000$ bps

**subst** $= 1.536$ Mbps

# Example

**A digitized voice channel is made by digitizing a 4-kHz bandwidth analog voice signal. We need to sample the signal at twice the highest frequency (two samples per hertz). We assume that each sample requires 8 bits. What is the required bit rate?**

$2 \times 4000 \times 8$

$= 64$ kbps

(64,000 bps)

# Example 3.19

**Solution**

**A page is an average of 24 lines with 80 characters in each line. If we assume that one character requires**

$$2 \times 4000 \times 8 = 64{,}000 \text{ bps}$$

$$= 64 \text{ kbps}$$

# Example 3.20

What is the bit rate for high-definition TV (HDTV)?

**Solution**

HDTV uses digital signals to broadcast high quality video signals. The HDTV screen is normally a ratio of 16 : 9 (in contrast to 4 : 3 for regular TV), which means the screen is wider. There are 1920 by 1080 pixels per screen, and the screen is renewed 30 times per second.

# Example 3.20

**Solution**

Twenty-four bits represents one color pixel. We can calculate the bit rat

$$1920 \times 1080 \times 30 \times 24$$

$$= 1{,}492{,}992{,}000 \approx 1.5 \text{ Gbps}$$

The TV stations reduce this rate to 20 to 40 Mbps through compression.

# Bit Length

We discussed the concept of the wavelength for an analog signal: the distance one cycle occupies on the transmission medium. We can define something similar for a digital signal: the bit length. The bit length is the distance one bit occupies on the transmission medium.

$$\text{Bit length} = \text{propagation speed} \times \text{bit duration}$$

# Digital Signal as Composite Analog Signal

- **Based on Fourier analysis, a digital signal is a composite analog signal**

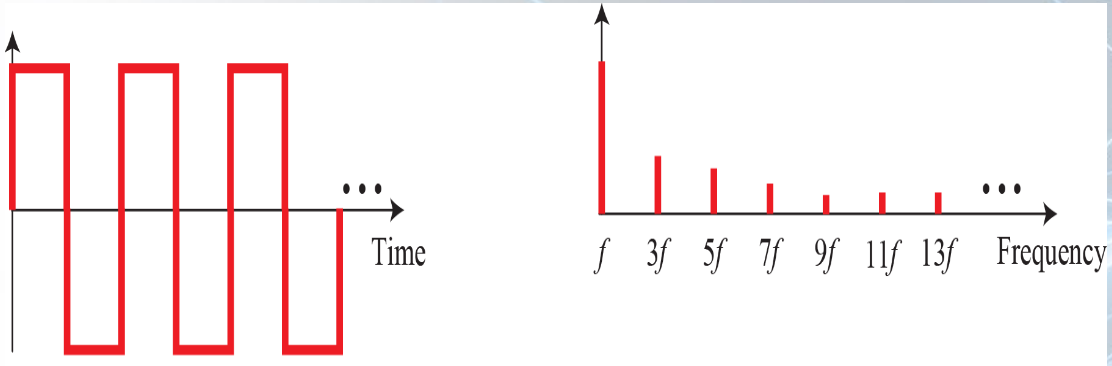
- **A digital signal, in the time domain, comprises connected vertical and horizontal line segments**

- **Infinite Bandwidth**

# Digital As Composite Analog

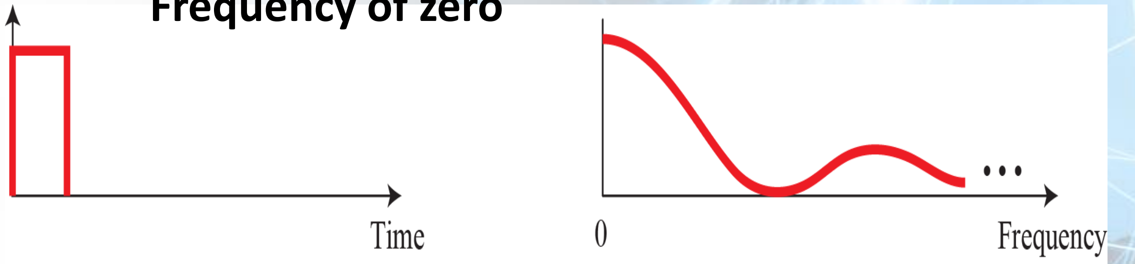
A vertical line in the time domain means a frequency of infinity: a horizontal line in the time domain means a frequency of zero. Going from a frequency of zero to a frequency of infinity implies all frequencies in between are part of the domain.

# Digital Signal as Composite Analog Signal



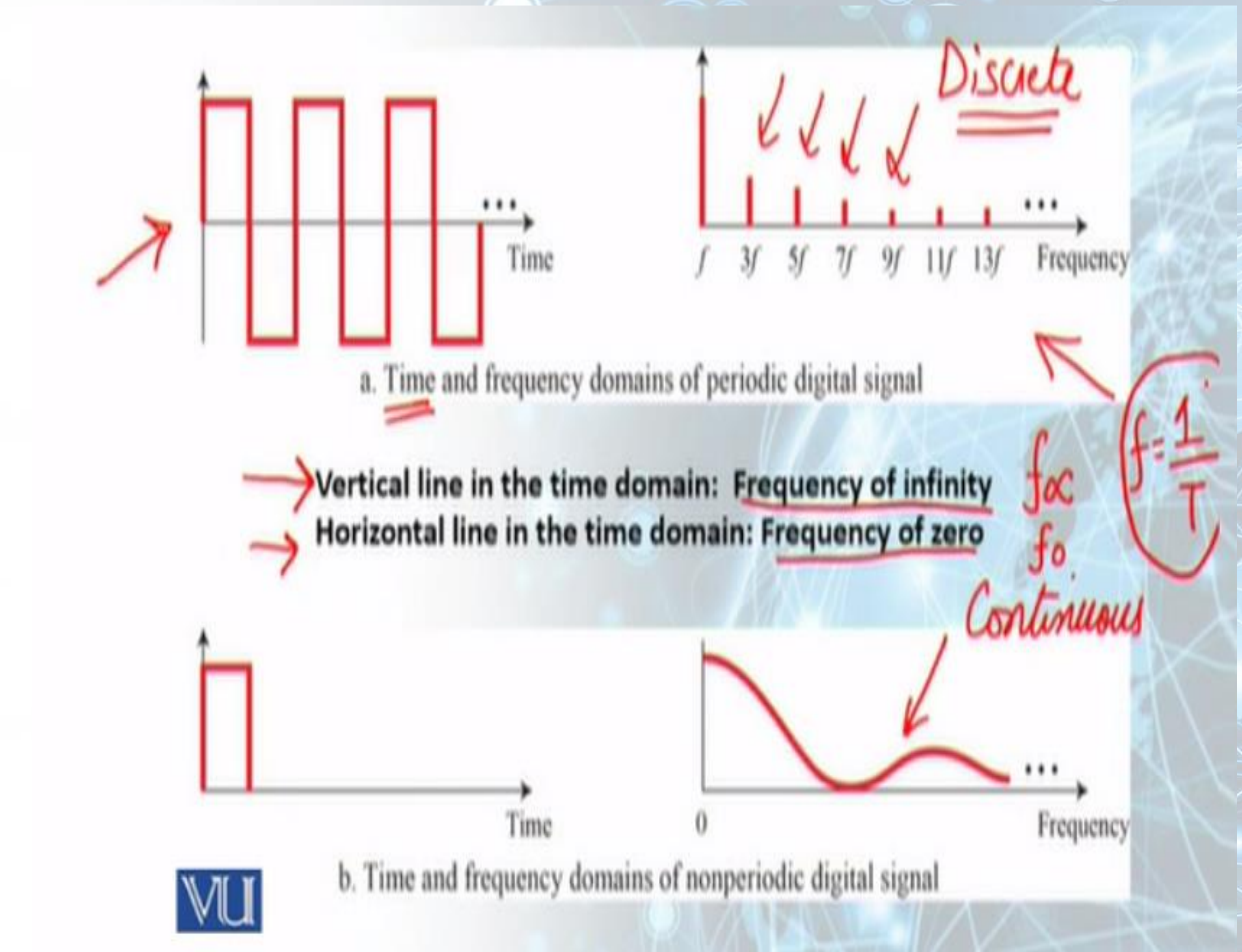

a. Time and frequency domains of periodic digital signal

**Vertical line in the time domain:**
**Frequency of infinity**
**Horizontal line in the time domain:**
**Frequency of zero**




b. Time and frequency domains of nonperiodic digital signal

# Digital Signal as Composite Analog Signal



# Transmission of Digital Signals

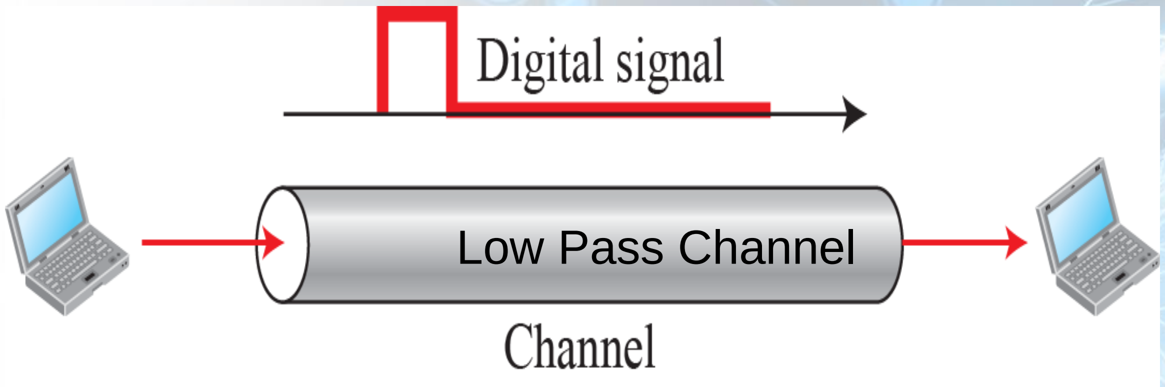
- **Digital signal, periodic or non-periodic, is a composite analog signal with frequencies between zero and infinity (Infinite Bandwidth)**

- **Two approaches for transmission:**
  - ✓ **Baseband Transmission**
  - ✓ **Broadband Transmission**

# Transmission of Digital Signals

**A vertical line in the time domain means a frequency of infinity: a horizontal line in the time domain means a frequency of zero. Going from a frequency of zero to a frequency of infinity implies all frequencies in between are part of the domain.**

# Baseband Transmission



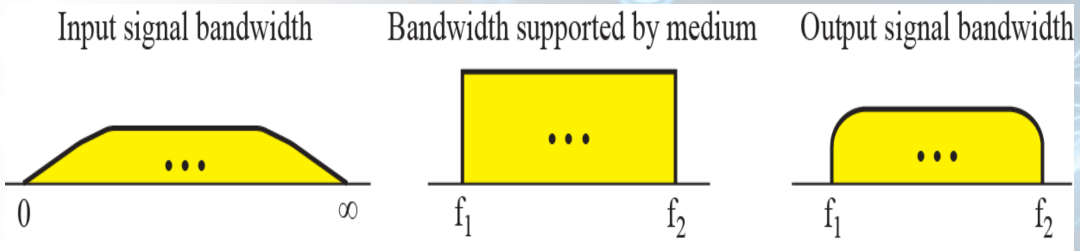

Sending a **Digital Signal** without changing it to an **Analog Signal**

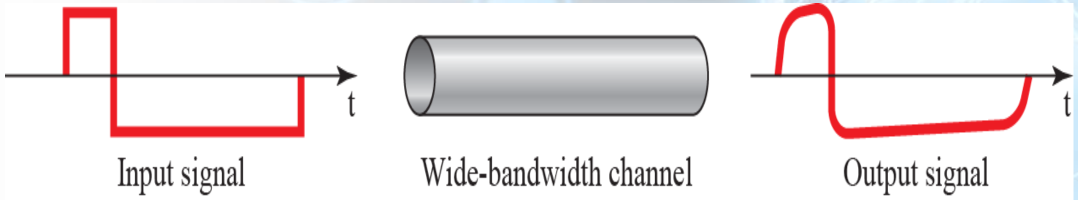
# Baseband Transmission


a. Low-pass channel, wide bandwidth

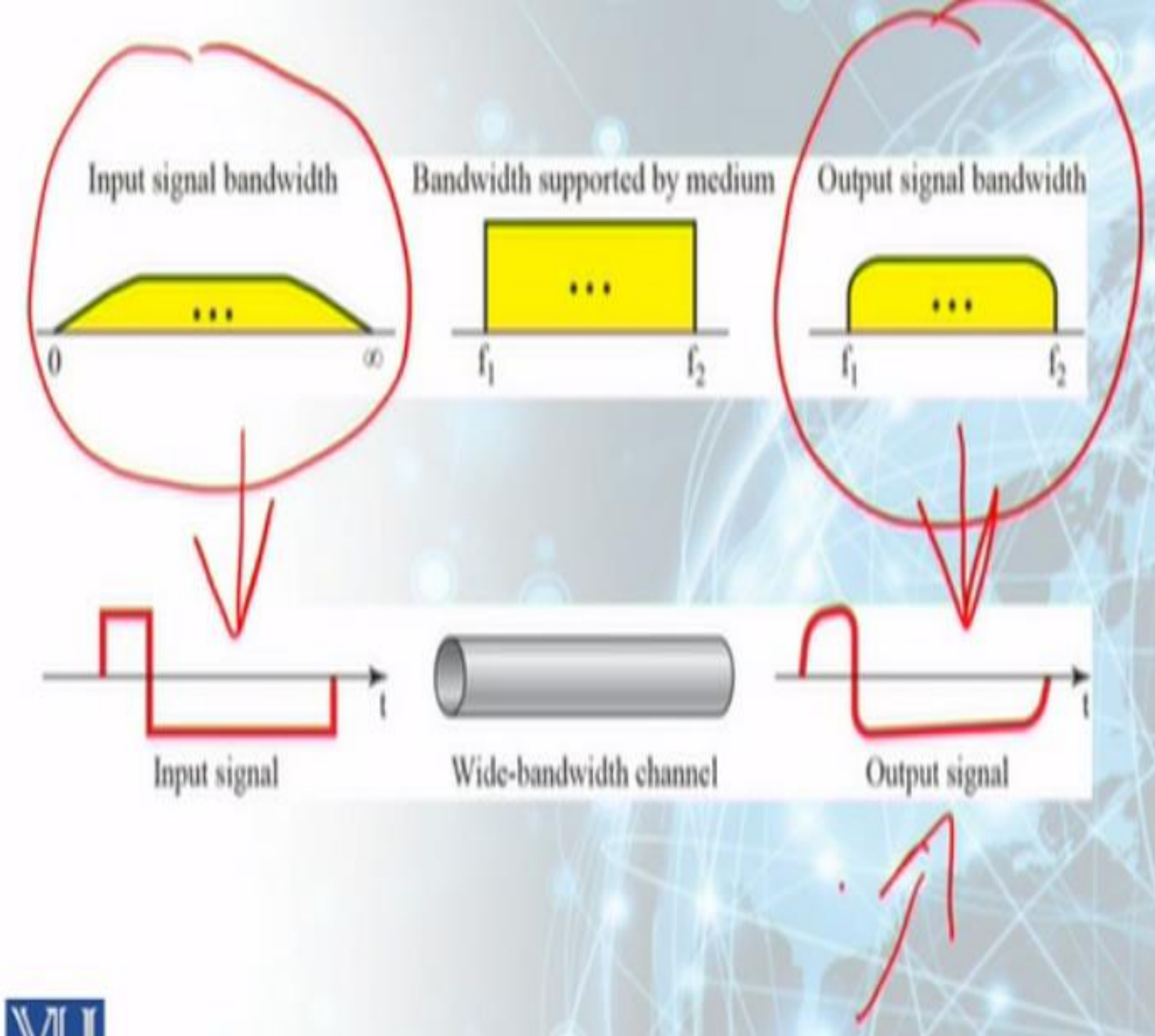

b. Low-pass channel, narrow bandwidth

# Baseband Transmission



# Baseband Transmission



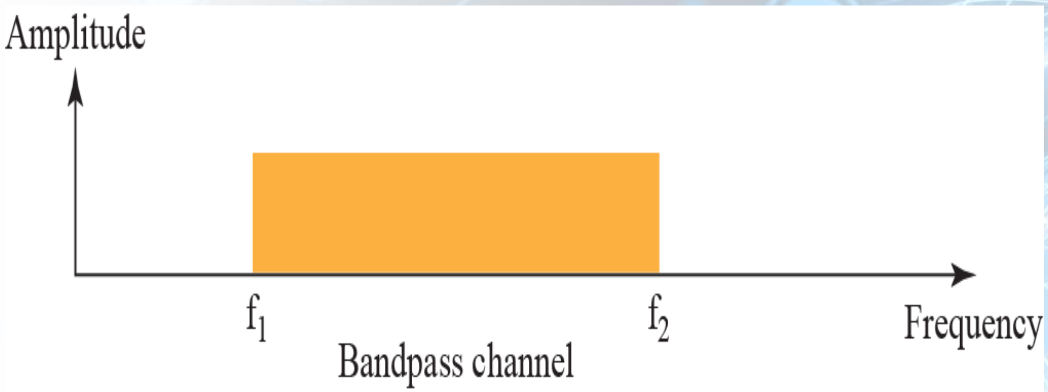
# Broadband Transmission (Modulation)

- Changing the Digital signal to an Analog signal for transmission

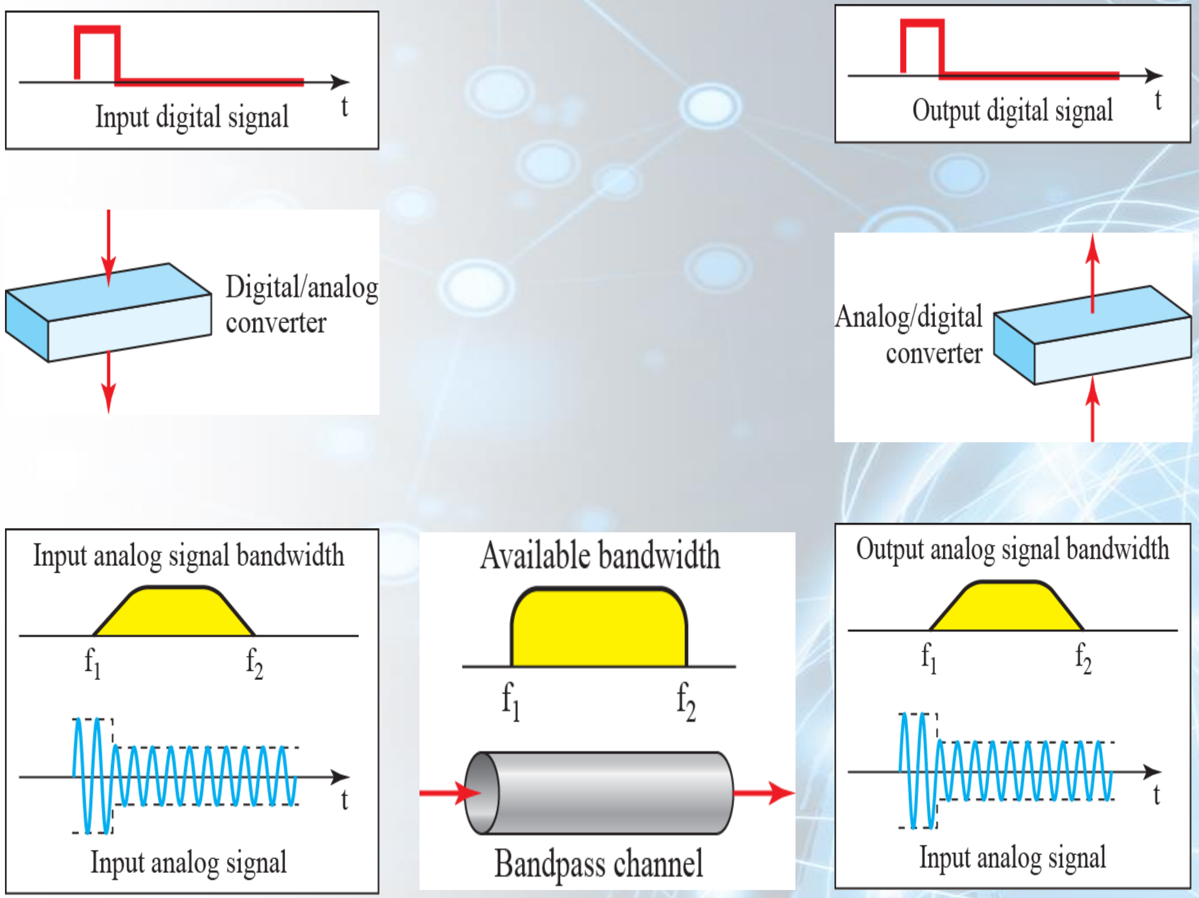
- Modulation allows us to use a bandpass channel—a channel with a bandwidth that does not start from zero

- More available than a low-pass

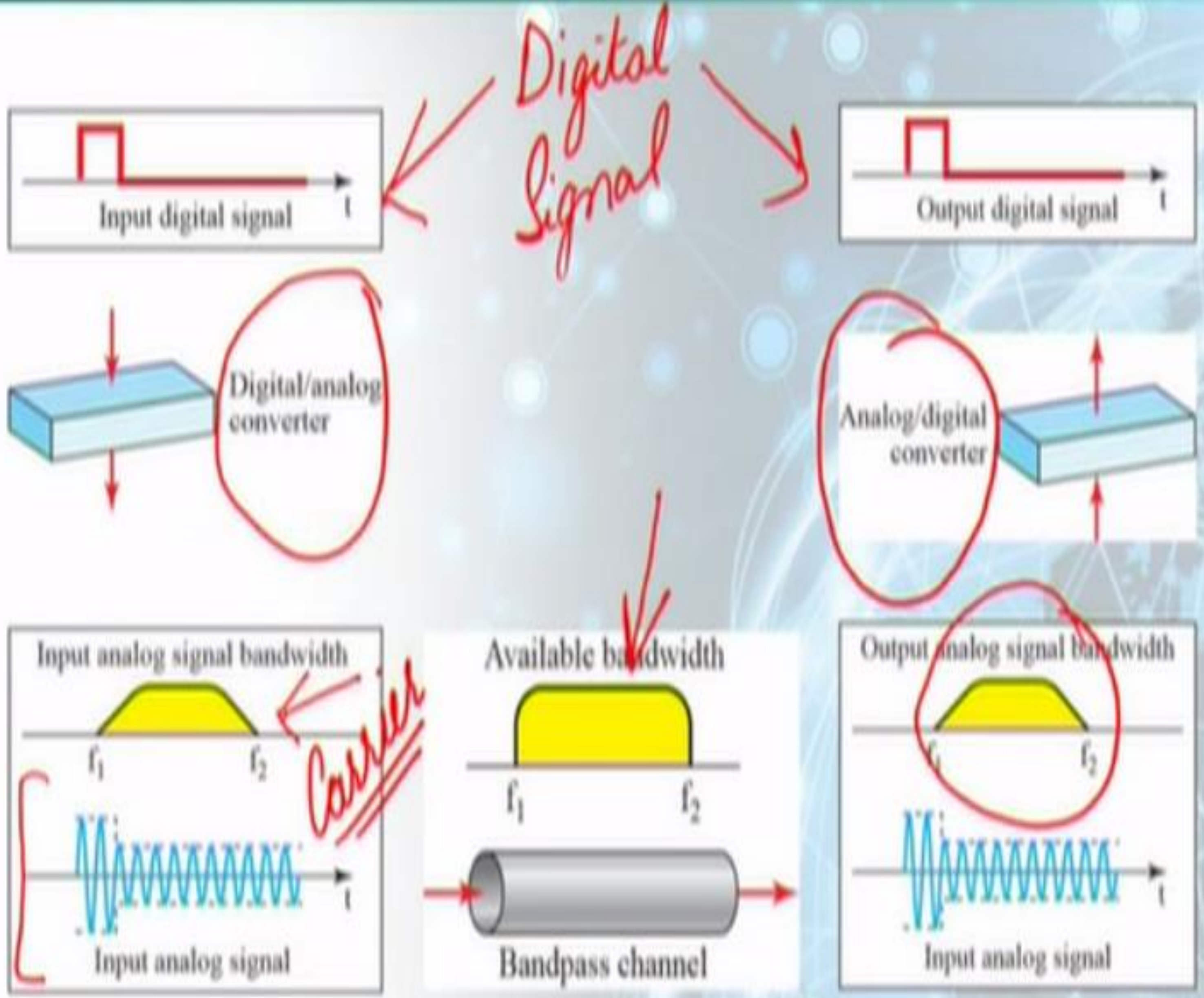
# Broadband Transmission (Modulation)



# Broadband Transmission (Modulation)



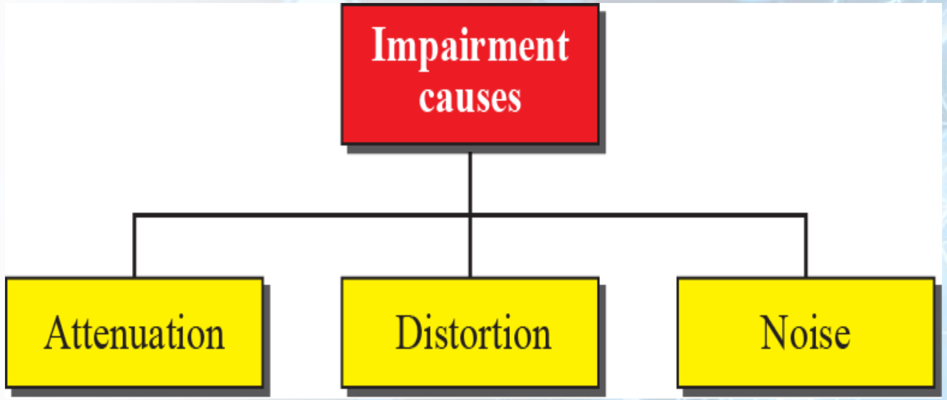
# Broadband Transmission (Modulation)



# Transmission Impairments

- Transmission media are not perfect
- Cause Signal impairments
- Signal sent is not the same as the signal received

# Causes of Transmission Impairment



# Transmission Impairment

What is sent is not what is received. Three causes of impairment are attenuation, distortion, and noise (see Figure 3.26).

# Transmission Impairment

**Signals travel through transmission media, which are not perfect. The imperfection causes signal impairment. This means that the signal at the beginning of the medium is not the same as the signal at the end of the medium.**

# Attenuation

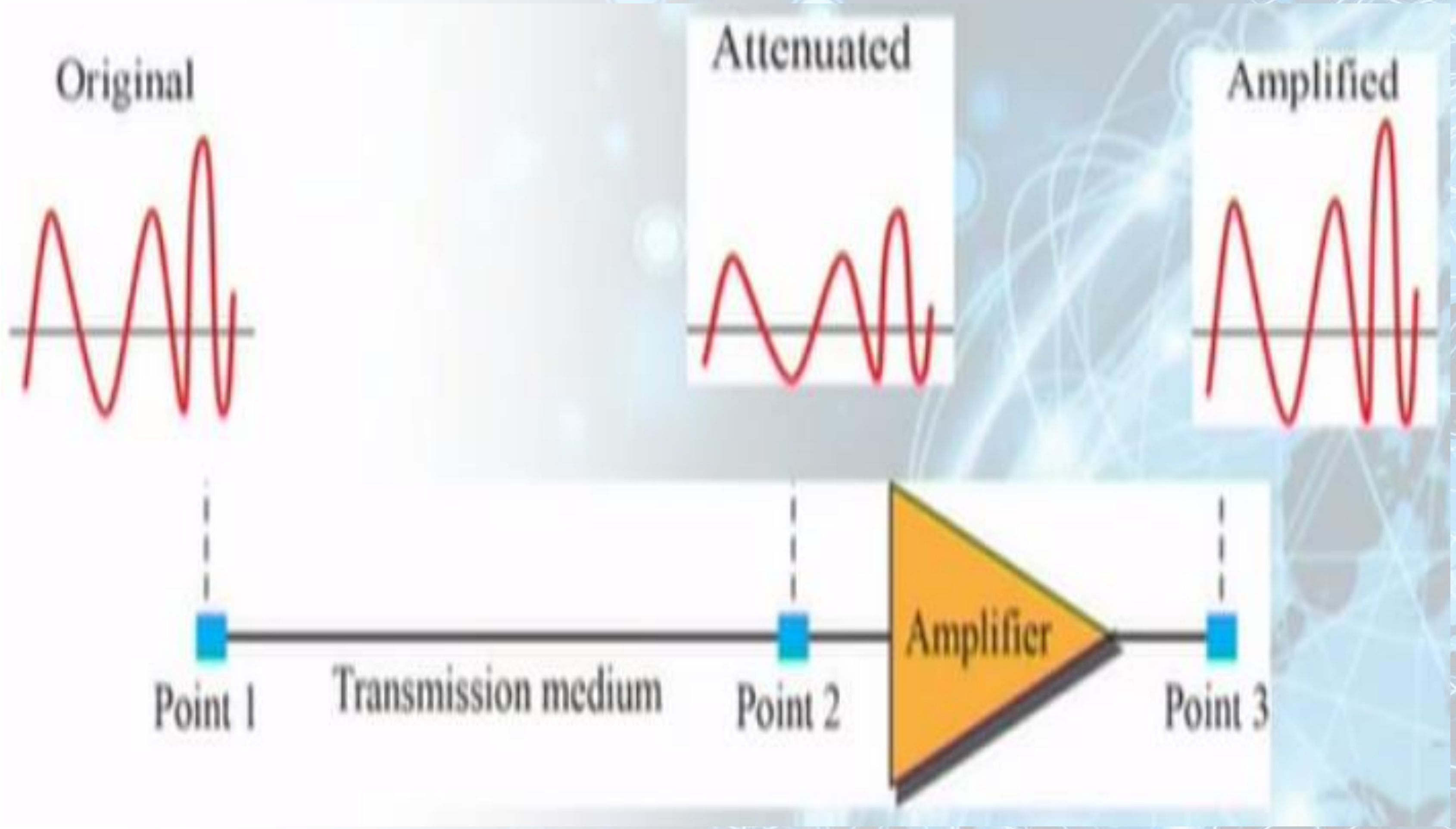
**Attenuation means a loss of energy. When a signal, simple or composite, travels through a medium, it loses some of its energy in overcoming the resistance of the medium. That is why a wire carrying electric signals gets warm, if not hot, after a while. Some of the electrical energy in the signal is converted to heat.**

# Attenuation

To compensate for this loss, amplifiers are used to amplify the signal. Figure 3.27 shows the effect of attenuation and amplification..

# Attenuation and amplification

**Figure 3.27**



# Example 3.26

Suppose a signal travels through a transmission medium and its power is reduced to one half. This means that P2 = 0.5 P1. In this case, the attenuation (loss of power) can be calculated as

$$10 \log_{10} P_2/P_1 = 10 \log_{10} (0.5\, P_1)/P_1$$

$$= 10 \log_{10} 0.5 = 10 \times (-0.3) = -3 \text{ dB}.$$

A loss of 3 dB (−3 dB) is equivalent to losing one-half the power.

# Example 3.27

**A signal travels through an amplifier, and its power is increased 10 times. This means that $P_2$ = 10P1. In this case, the amplification**

$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{10P_1}{P_1} =$$

$$10 \log_{10} 10 = 10(1) = 10 \text{ dB}$$

# Example 3.28

One reason that engineers use the decibel to measure the changes in the strength of a signal is that decibel numbers can be added (or subtracted) when we are measuring several points (cascading) instead of just two. In Figure 3.28 a signal travels from point 1 to point 4. The signal is attenuated by the time it reaches point 2.

# Example 3.28

**Between points 2 and 3, the signal is amplified. Again, between points 3 and 4, the signal is attenuated. We can find the resultant decibel value for the signal just by adding the decibel measurements between each set of points. In this case, the decibel value can be calculated as**

$$dB = -3 + 7 - 3 = +1$$

# Example 3.29

**Sometimes the decibel is used to measure signal power in milliwatts. In this case, it is referred to as $dB_m$ and is calculated as dBm = 10 log10 Pm, where Pm is the power in milliwatts. Calculate the power of a signal if its $dB_m = -30$.**

# Example 3.29

**Solution**

We can calculate the power in the signal as

$$dB_m = 10\log_{10} \longrightarrow dB_m = -30 \longrightarrow$$

$$\log_{10} P_m = -3 \longrightarrow P_m = 10^{-3}\ \text{mW}$$

# Example 3.30

**Sometimes the decibel is used to measure signal power in milliwatts. In this case, it is referred to as $dB_m$ and is calculated as dBm = 10 log10 Pm, where Pm is the power in milliwatts. Calculate the power of a signal if its $dB_m = -30$.**

# Example 3.30

**Solution**

**The loss in the cable in decibels is 5 × (−0.3) = −1.5 dB. We can**

**…er**

$$dB = 10 \log_{10} (P_2 / P_1) = -1.5$$

$$\longrightarrow \quad (P_2 / P_1) = 10^{-0.15} = 0.71$$

$$P_2 = 0.71 P_1 = 0.7 \times 2 \text{ mW} = 1.4 \text{ mW}$$

# Attenuation and Amplification - Decibel

- **Unit of Signal strength is Decibel or dB**

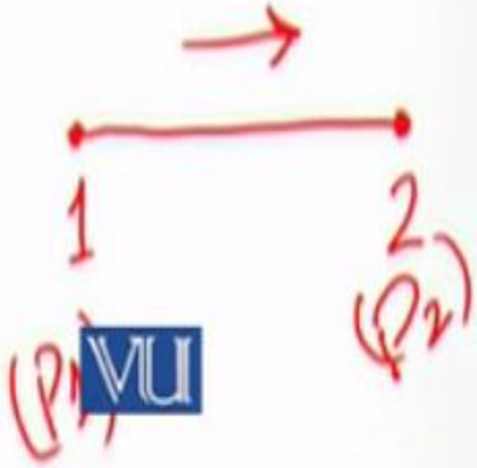
- **Decibel (dB) measures the relative strengths of two signals or one signal at two different points**

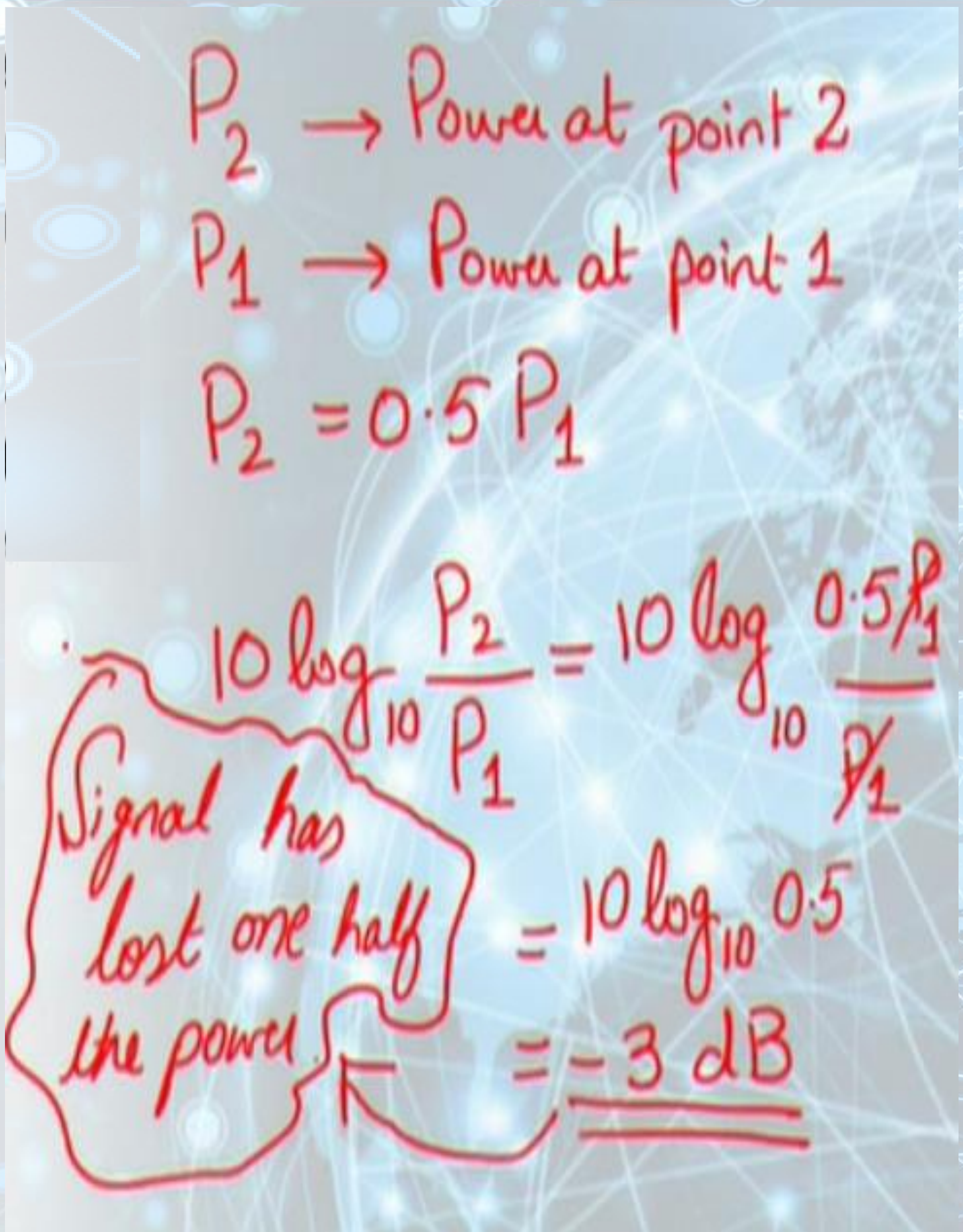
$$10 \log_{10} P_2/P_1$$

- **Decibel is negative if a signal is attenuated and positive if signal is amplified**

# Example

Suppose a signal travels through a transmission medium and its power is reduced to one half. This means that P2 = 0.5 P1. In this case, the a
p
c



# Example

A signal travels through an amplifier, and its power is increased 10 times. This means that $P_2$ = 10P1. In this case, the amplification (gain of power) can be calculated as

$$P_2 = 10 P_1$$

$$10 \log_{10} \frac{P_2}{P_1}$$

$$= 10 \log_{10} \frac{10 P_1}{P_1}$$

$$= 10 \, dB$$

# Distortion

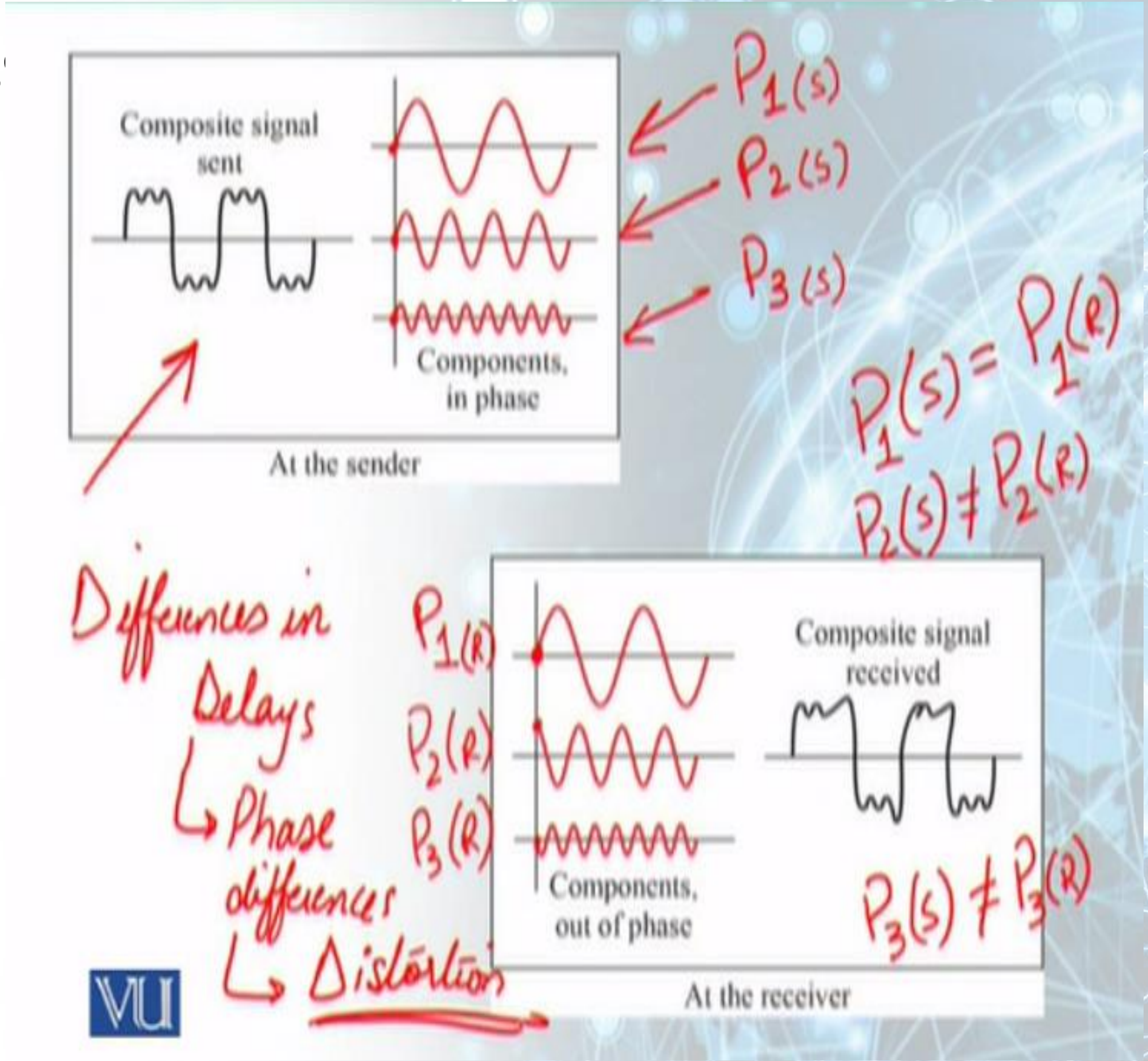
- Distortion means that the signal changes its form or shape.
- Distortion can occur in a composite signal made of different frequencies.
- Each signal component has its own propagation speed (see the next section) through a medium and, therefore, its own delay in arriving at the final destination.

# Distortion

**Differences in delay may create a difference in phase if the delay is not exactly the same as the period duration.**

# Distortion

Figure 3.2



# Noise

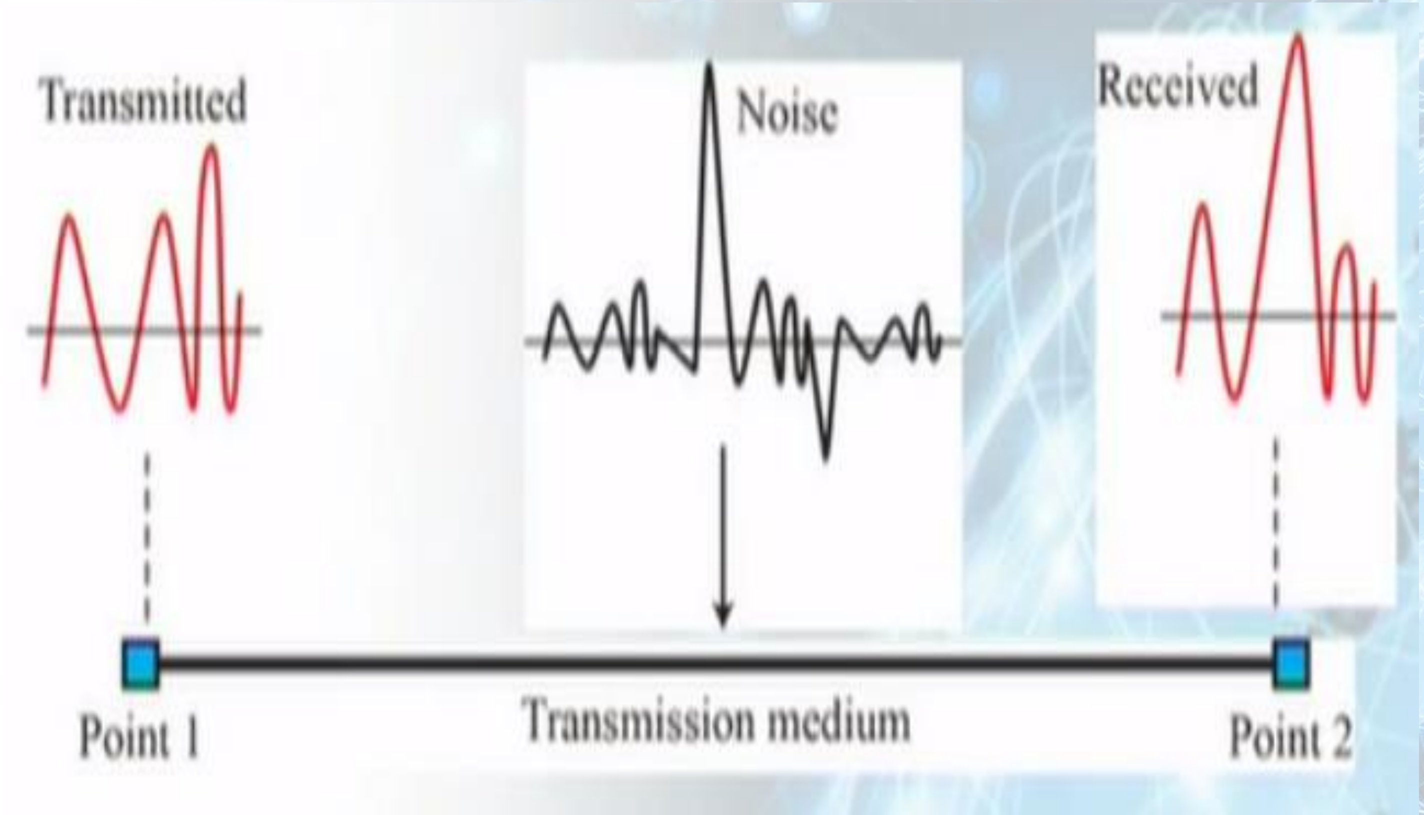
- **Noise is another cause of impairment.**
- **Several types of noise, such as thermal noise, induced noise, crosstalk, and impulse noise, may corrupt the signal.**

- **Thermal noise is the random motion of electrons in a wire, which creates an extra signal not**

# Noise

- Induced noise comes from sources such as motors.
- Crosstalk is the effect of one wire on the other.

# Noise


Transmitted
Noise
Received
Point 1
Transmission medium
Point 2

# Noise

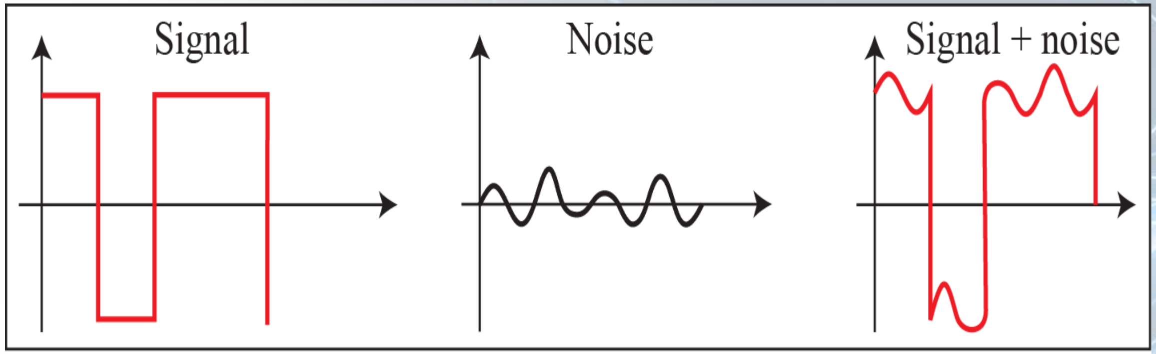
Figure 3.31

# Noise – Signal to Noise Ratio (SNR)

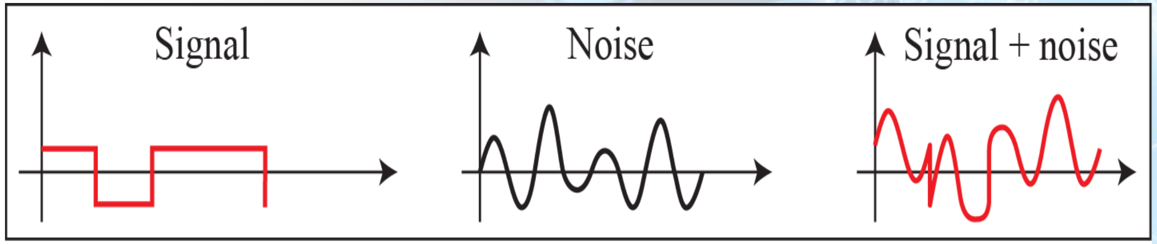
- **Signal to Noise Ratio (SNR) is used to find the theoretical bit rate limit of a signal**

$$SNR = \frac{\text{average signal power}}{\text{average noise power}}$$

# Noise – Signal to Noise Ratio (SNR)

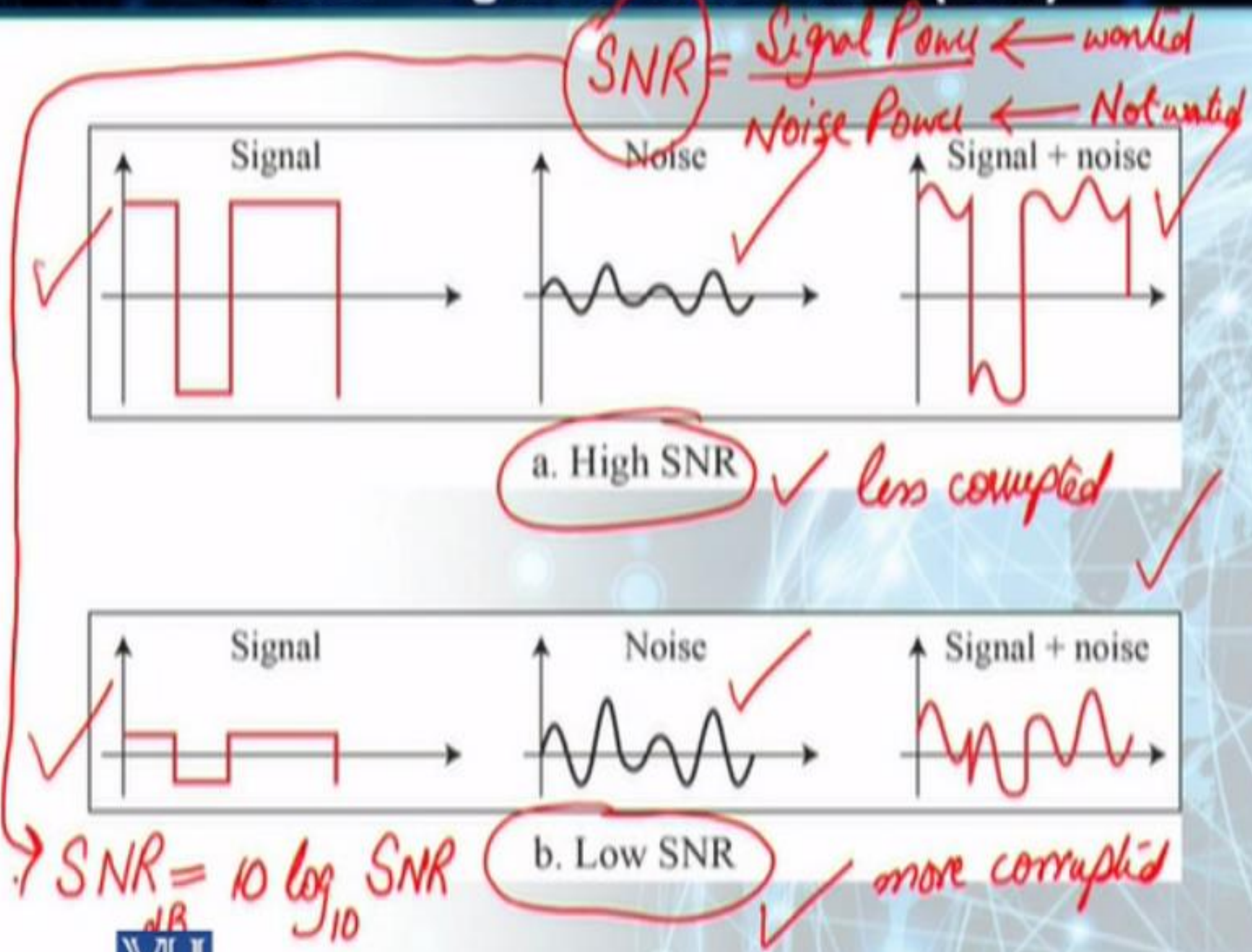



a. High SNR




b. Low SNR

# Noise – Signal to Noise Ratio (SNR)



# Example

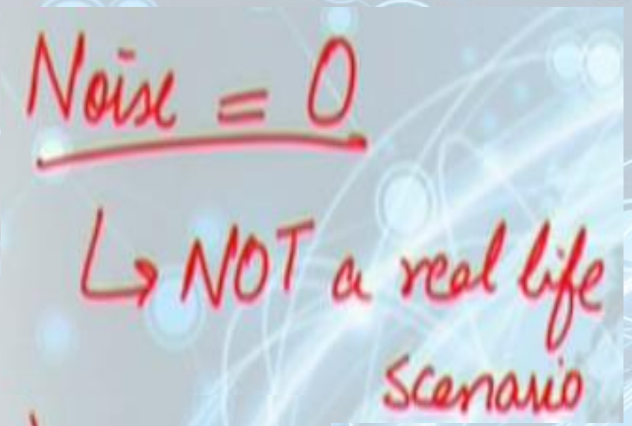
**The power of a signal is 10 mW and the power of the noise is 1 μW; what are the values of SNR and SN**

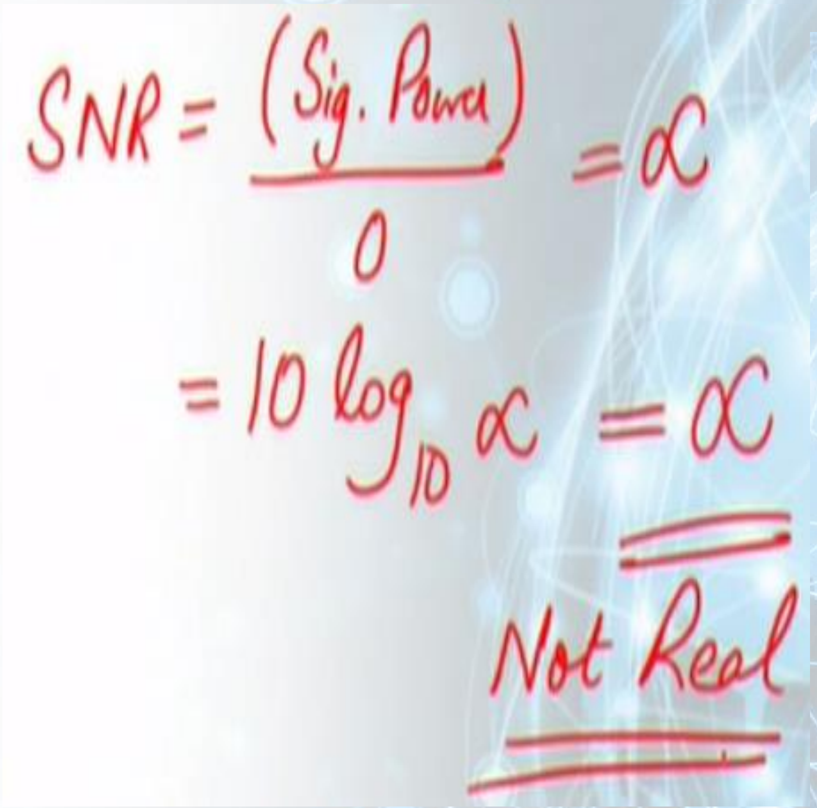
$$SNR = \frac{10\ mW}{1\ \mu W} = 10{,}000$$

$$SNR_{dB} = 10 \log_{10} 10{,}000 = 40\ dB$$

# Example

**The values of SNR and $SNR_{dB}$ for a noiseless channel are calculated as**



# Example 3.31

**The power of a signal is 10 mW and the power of the noise is 1 μW; what are the values of SNR and $SNR_{dB?}$**

**Solution**

**The values of SNR and $SNR_{dB}$ can be calculated as**

$$SNR = (10{,}000\ \mu w) / (1\ \mu w) = 10{,}000 \quad SNR_{dB}$$

$$= 10 \log_{10} 10{,}000 = 10 \log_{10} 10^4 = 40$$

# Example 3.32

**The values of SNR and $SNR_{dB}$ for a noiseless channel are**

**Solution**

**The values of SNR and SNRdB for a noiseless channel are**

$$SNR = (\text{signal power}) / 0 = \infty$$

$$\longrightarrow \quad SNR_{dB} = 10 \log_{10} \infty = \infty$$

**We can never achieve this ratio in real life; it is an ideal.**

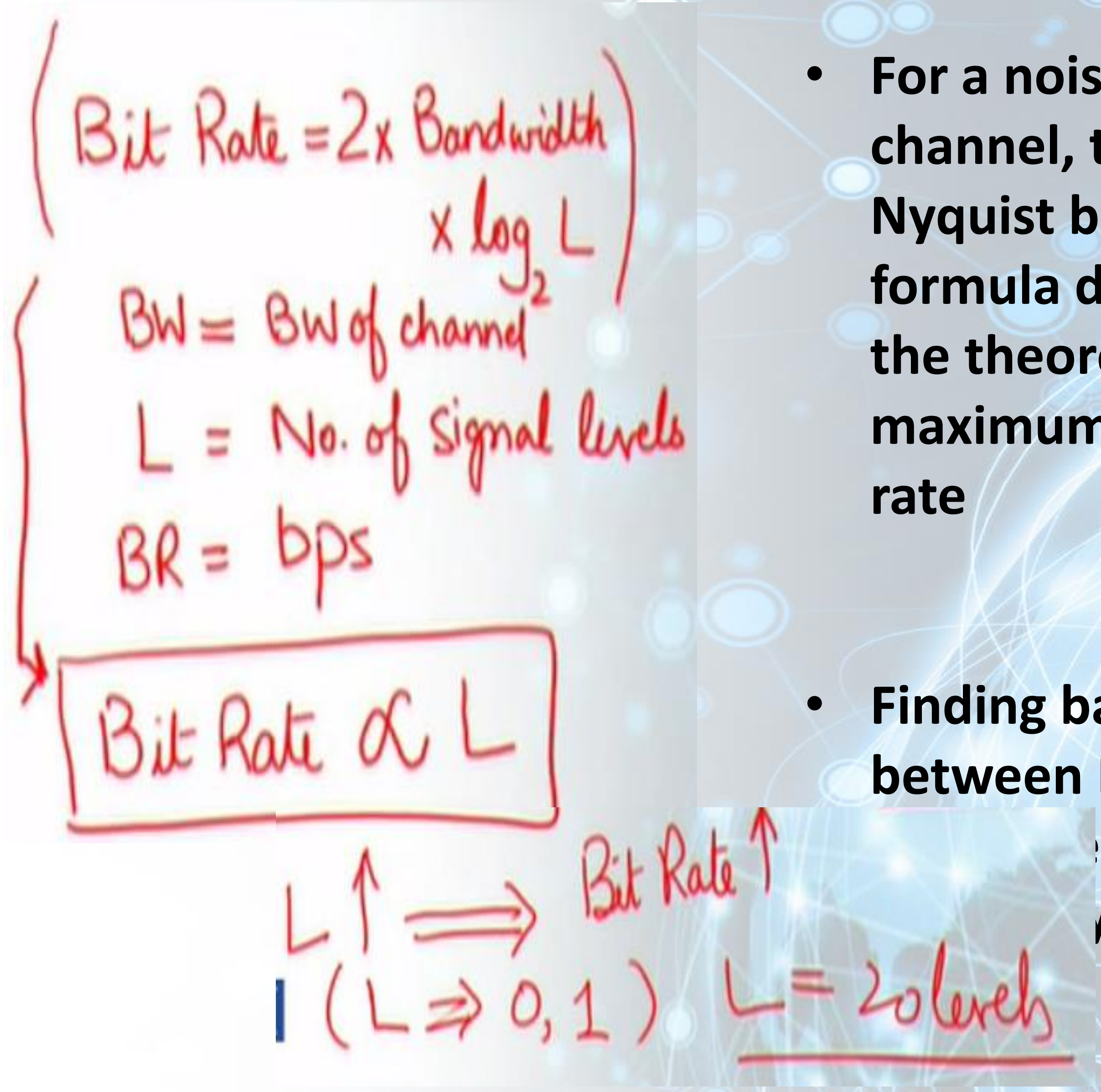
# Data Rate Limits

- How fast we can send data, in bits per second, over a channel?
- Data Rate depends on 3 factors:
  - ✓ The Bandwidth available
  - ✓ The level of the signals we use
  - ✓ The level of noise

# Data Rate Limits

- **Two theoretical formulas developed to calculate the data rate:**
  - ✓ **one by Nyquist for a noiseless channel**
  - ✓ **another by Shannon for a noisy channel**

# Noiseless Channel : Nyquist Rate




- For a noiseless channel, the Nyquist bit rate formula defines the theoretical maximum bit rate
- Finding balance between Bit rate ...em ...y

# Example

**Consider a noiseless channel with a bandwidth of 3000 Hz transmitting a signal with two signal levels. The maximum bit rate can be calculated as**

$$BR = 2 \times 3000 \times \log_2 2$$

$$= 6000 \text{ bps}$$

# Example

**Consider the same noiseless channel transmitting a signal with four signal levels (for each level, we send 2 bits). The**
**n**
**c**
**a**

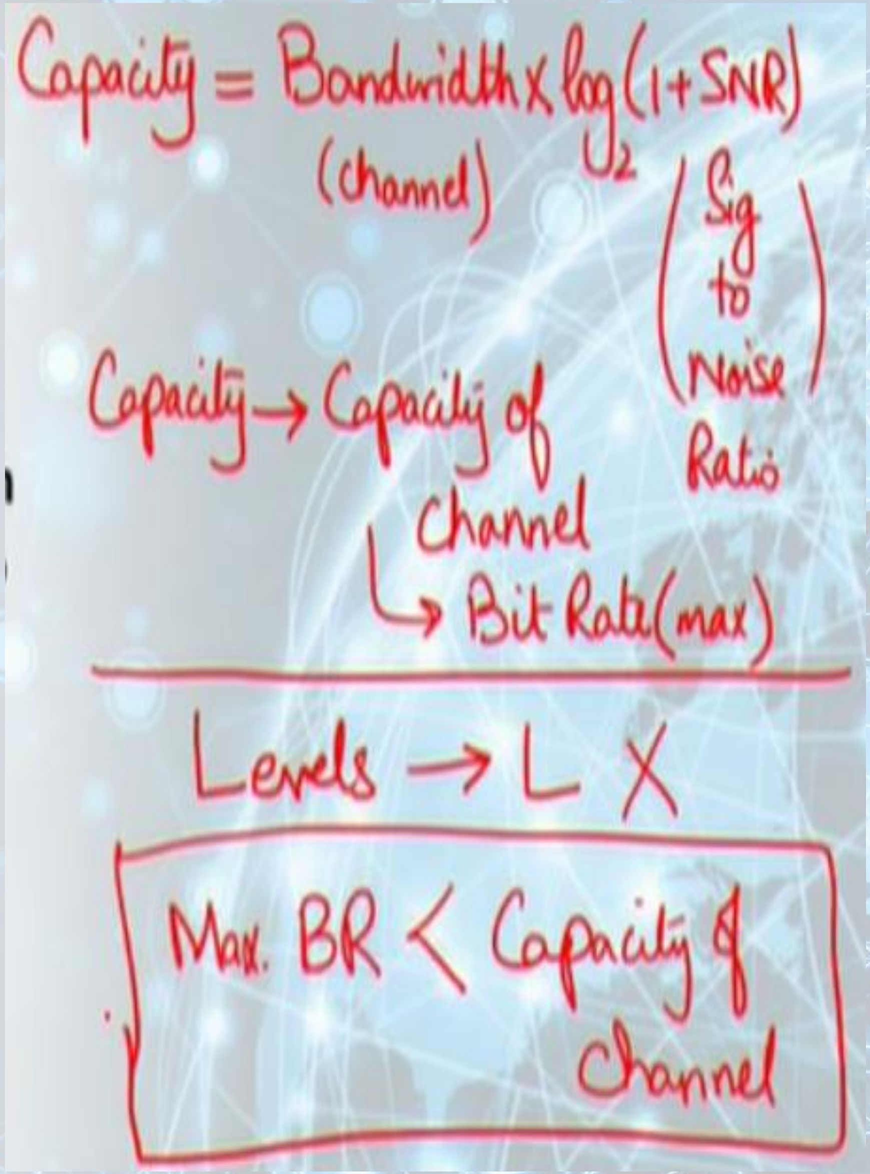
$BR \propto L$

$$BR = 2 \times 3000 \times \log_2 4$$
$$= 12{,}000 \text{ bps}$$

(Reliability)

# Noisy Channel : Shannon Capacity

- In reality, we cannot have a noiseless channel; the channel is always noisy
- In 1944, Claude Shannon introduced a formula, to determine the theoretical highest data rate for a noisy



# Example

Consider an extremely noisy channel in which the value of the signal-to-noise ratio is almost zero. In other words, the noise is so strong that the signal is faint. For this channel the capacity C is calculated as

$$SNR \simeq \text{zero}$$

$$C = B \log_2(1 + SNR)$$

$$= B \log_2 1$$

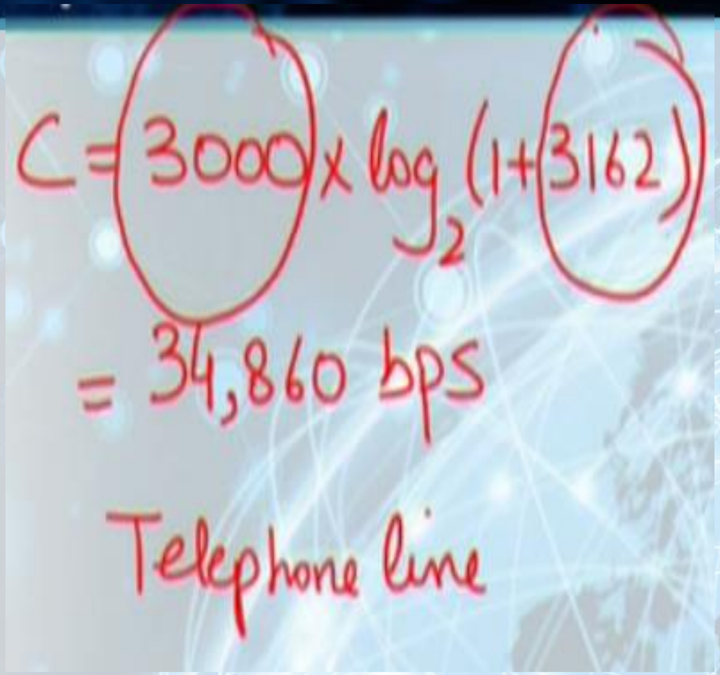
$$= B \times \text{zero}$$

$$\boxed{C = \text{zero}}$$

→ Cannot receive any data through channel.

# Example

**Theoretical highest bit rate of a Telephone line with a Bandwidth of 3000 Hz assigned for data communication. SNR is usually 3162. The capacity is calculated as:**



# Using Both Limits

- **In practice, we need to use both methods to find the limits and signal levels**

- **Shannon's formula gives us the upper limit while the Nyquist formula gives us the signal levels**

# Example 3.37

**Consider an extremely noisy channel in which the value of the signal-to-noise ratio is almost zero. In other words, the noise is so strong that the signal is faint. For this channel, the capacity C is calculated as**

$$C = B \log_2 (1 + \text{SNR}) = B \log_2(1 + 0)$$

$$= B \log_2 1 = B \times 0 = 0$$

# Example 3.37

**This means that the capacity of this channel is zero regardless of the bandwidth. In other words, we cannot receive any data through this channel.**

# Example 3.38

**This means that the capacity of this channel is zero regardless of the bandwidth. In other words, we cannot**

**r**

**t**

**ch**

$$C = B \log_2 (1 + SNR) =$$

$$3000 \log_2(1 + 3162) =$$

$$3000 \times 11.62 = 34{,}860 \text{ bps}$$

# Example 3.38

This means that the highest bit rate for a telephone line is 34.860 kbps. If we want to send data faster than this, we can either increase the bandwidth of the line or improve the signal-to-noise ratio.

# Example 3.39

**The signal-to-noise ratio is often given in decibels. Assume that $SNR_{dB}$ = 36 and the channel bandwidth is 2 MHz. The theoretical channel capacity can be calculated as**

# Example 3.39

$$SNR_{dB} = 10 \log_{10} SNR \longrightarrow$$

$$SNR = 10^{SNR_{dB}/10} \longrightarrow$$

$$SNR = 10^{3.6} = 3981$$

$$C = B \log_2(1 + SNR) =$$

$$2 \times 10^6 \times \log_2 3982$$

$$= 24 \text{ Mbps}$$

# Example 3.40

When the SNR is very high, we can assume that SNR + 1 is almost the same as SNR. In these cases, the theoretical channel capacity can be simplified to C 5 B 3 $SNR_{dB.}$ For example, we can calculate the

$$C = 2\text{ MHz} \times (36 / 3) = 24\text{ Mbps}$$

of the previous example as

# Using Both Limits

**In practice, we need to use both methods to find the limits and signal levels. Let us show this with an example.**

# Example 3.41

**We have a channel with a 1-MHz bandwidth. The SNR for this channel is 63. What are the appropriate bit rate and signal level?**

**Solution**

**First, we use the … a to …**

$$C = B \log_2(1 + \text{SNR}) = 10^6 \log_2(1 + 63) = 10^6 \log_2 64 = 6 \text{ Mbps}$$

# Example 3.41

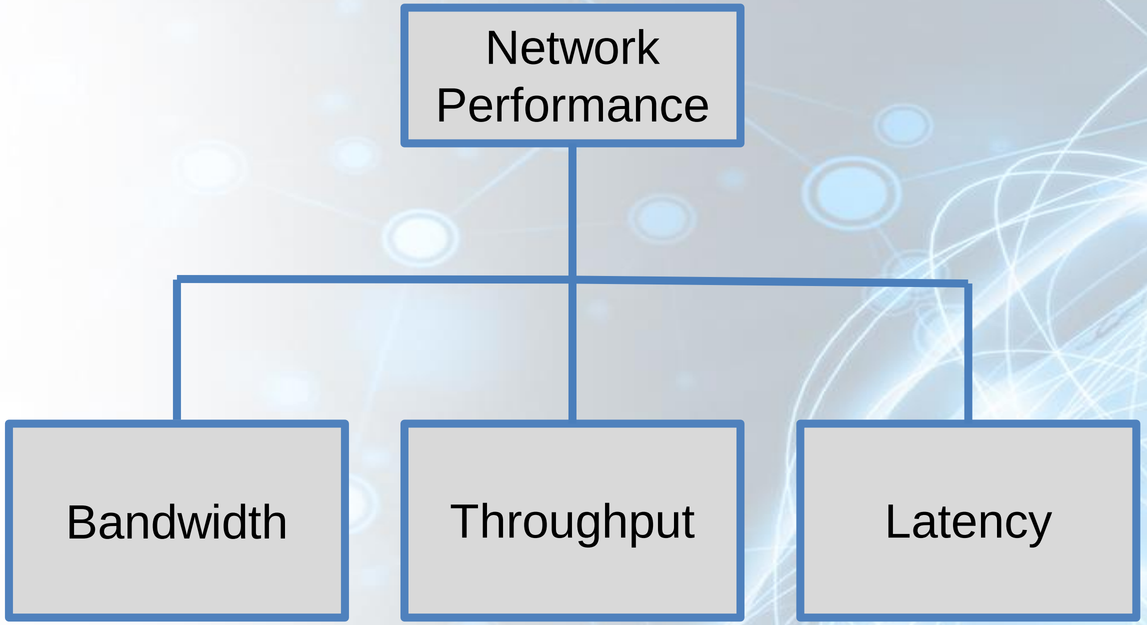
The Shannon formula gives us 6 Mbps, the upper limit. For better performance we choose something lower, 4 Mbps. Then we use the Nyquist formu... the numb... al levels

$$4 \text{ Mbps} = 2 \times 1 \text{ MHz} \times \log_2 L \longrightarrow L = 4$$

# Network Performance

- Data transmission (in form of Signal) over a network and how network behaves is important
- More important is the performance of the network
- How good is our network?

# Network Performance




- **There are 3 characteristics of network performance**

# Bandwidth

- An important characteristic that measures Network Performance

- Bandwidth can be used in two different contexts with two different measuring values:
  - Bandwidth in Hertz
  - Bandwidth in

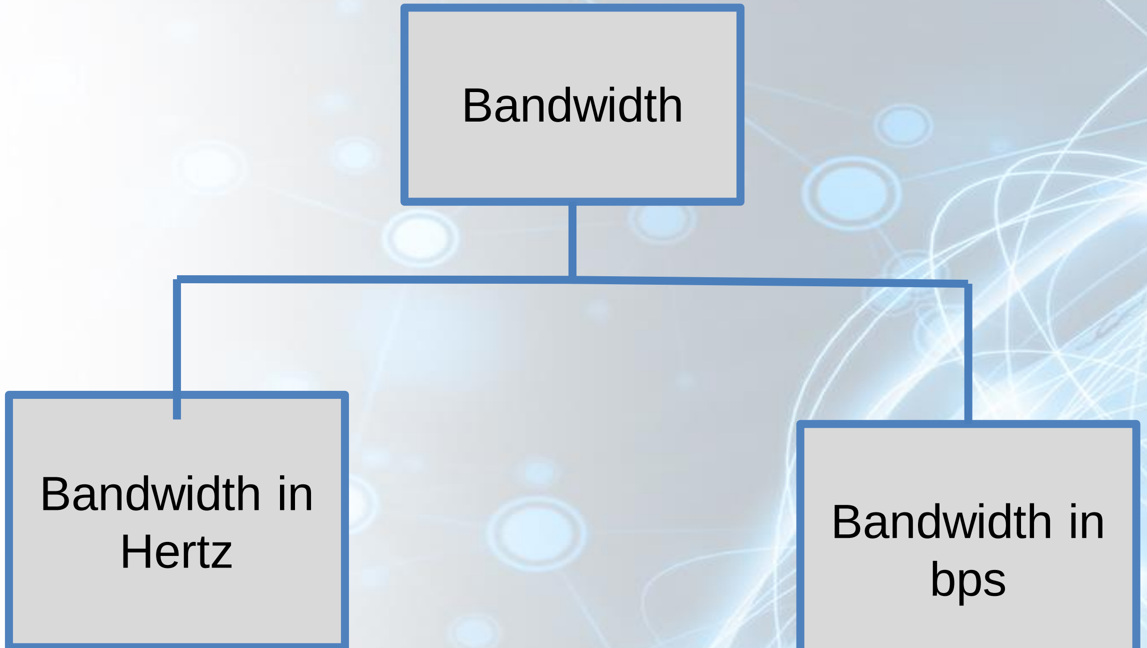
# Example 3.42

**The bandwidth of a subscriber line is 4 kHz for voice or data. The bandwidth of this line for data transmission can be up to 56,000 bps using a sophisticated modem to change the digital signal to analog.**

# Example 3.43

**If the telephone company improves the quality of the line and increases the bandwidth to 8 kHz, we can send 112,000 bps by using the same technology as mentioned in Example 3.42.**

# Bandwidth




*Range of frequencies in a composite signal*

*No. of bits a channel, link or network can transmit*

# Throughput

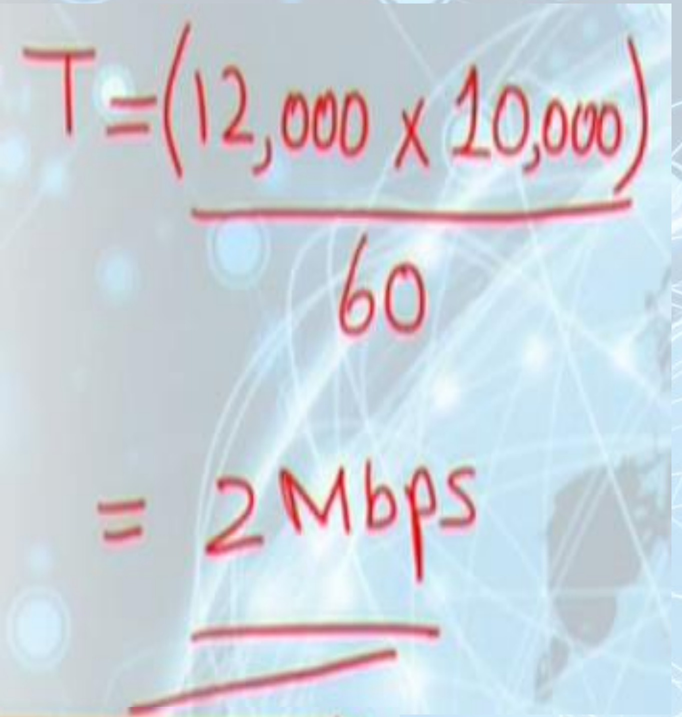
- **Measure of how fast we can actually send data through a network.**

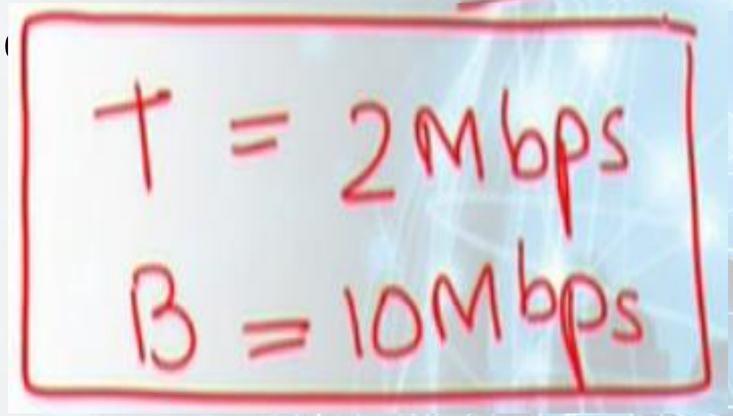
- **Bandwidth is not the same as Throughput**

- **A link may have a bandwidth of B bps, but we can only send T bps through this**

# Example

**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 network?**



# Throughput

**The throughput is a measure of how fast we can actually send data through a network. Although, at first glance, bandwidth in bits per second and throughput seem the same, they are different. A link may have a bandwidth of B bps, but we can only send T bps through this link with T always less than B.**

# Throughput

**The latency or delay defines how long it takes for an entire message to completely arrive at the destination from the time the first bit is sent out from the source.**

# Throughput

**We can say that latency is made of four components: propagation time, transmission time, queuing time and processing delay.**

**Latency = propagation time + transmission time + queuing time + processing delay**

# Example 3.44

**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?**

# Example 3.44

**Solution**

**We can calculate the throughput as Throughput =**

**(12,000X10,000)/60 = 2Mbps**

**The throughput is almost one-fifth of the bandwidth in this case.**

# Example 3.45

**What is the propagation time if the distance between the two points is 12,000 km? Assume the propagation speed to be 2.4 × 108 m/s in cable.**

**Solution**

**We can calculate the propagation time as**

***Propagation time = (12,000X10,000)/(2.4X2$^{8}$)=***

# Example 3.45

**The example shows that a bit can go over the Atlantic Ocean in only 50 ms if there is a direct cable between the source and the destination.**

# Example 3.46

**What are the propagation time and the transmission time for a 2.5-KB (kilobyte) message 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 × 108 m/s.**

# Example 3.46

**Solution**

**We can calculate the propagation and transmission time as**

***Propagation time = (12,000 X 1000)/(2.4X $10^8$) = 50 ms***

***Transmission time = (2500 X 8 ) / $10^9$ = 0.020 ms***

# Example 3.46

**Solution**

**Note that in this case, because the message is short and the bandwidth is high, the dominant factor is the propagation time, not the transmission time.**

# Example 3.47

**What are the propagation time and the transmission time for a 5-MB (megabyte) message (an image) if the bandwidth of the network is 1 Mbps? Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4 × 108**

# Example 3.47

**Solution**

**We can calculate the propagation and transmission times as**

***Propagation time = (12,000 X 1000) / (2.4 X $10^8$) = 50 ms***

***Transmission time = (5,000,000 X 8) / 106 = 40s***

**We can calculate the propagation and transmission**

# Latency or Delay

- **Latency or delay defines how long it takes for an entire message to completely arrive at the destination from the time the first bit is sent out from the source**

Latency = Propagation Time + Transmission Time + Queing Time + Processing Delay.

$$PT = \frac{\text{Distance}}{\text{Prop Speed}}$$

$$TT = \frac{\text{Message Size}}{\text{BW}}$$

QT → Time the message is held

# Example

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

$$PT = \frac{(12000 \times 1000)}{2.4 \times 10^8}$$

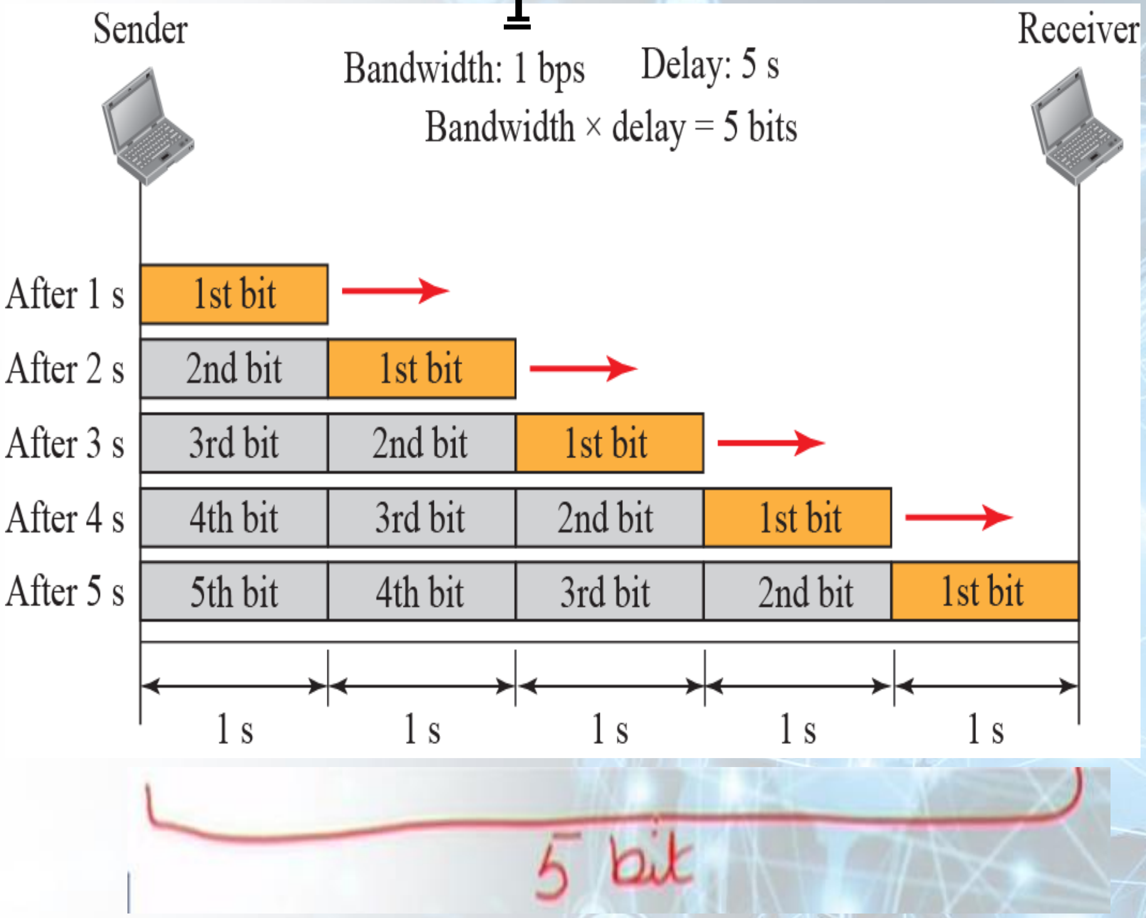
$$= 50 \text{ msec.}$$

# Delay – Bandwidth Delay Product

- **Bandwidth and delay are two performance metrics of a link**
- **Product of the two, The Bandwidth-Delay Product defines the number of bits that can fill a link**

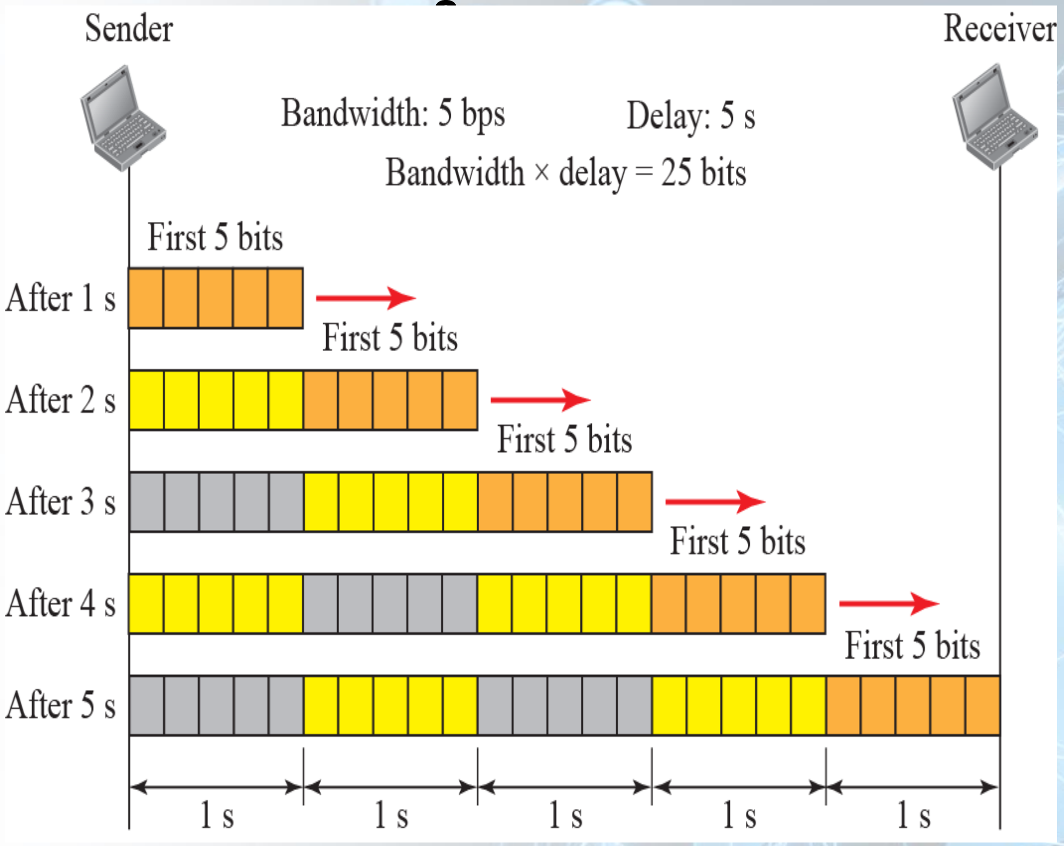
# Bandwidth-Delay Product

**Case 1**

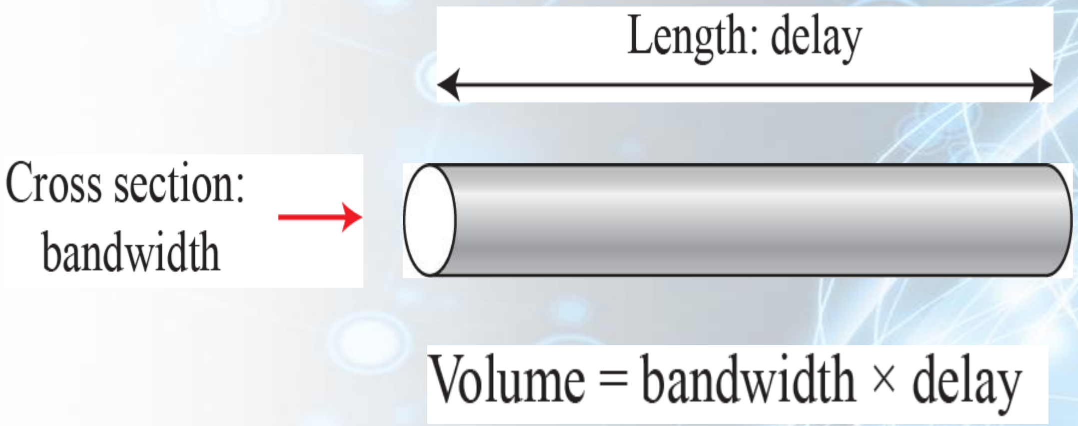


# Bandwidth-Delay Product

**Case**



# Bandwidth-Delay Product



# Example 3.48

We can think about the link between two points as a pipe. The cross section of the pipe represents the bandwidth, and the length of the pipe represents the delay. We can say the volume of the pipe defines the bandwidth-delay product, as shown in Figure 3.34.

# Delay - Jitter

- **Jitter is a problem if different packets of data encounter different delays and the application using the data at the receiver site is time-sensitive (audio and video data, for example)**

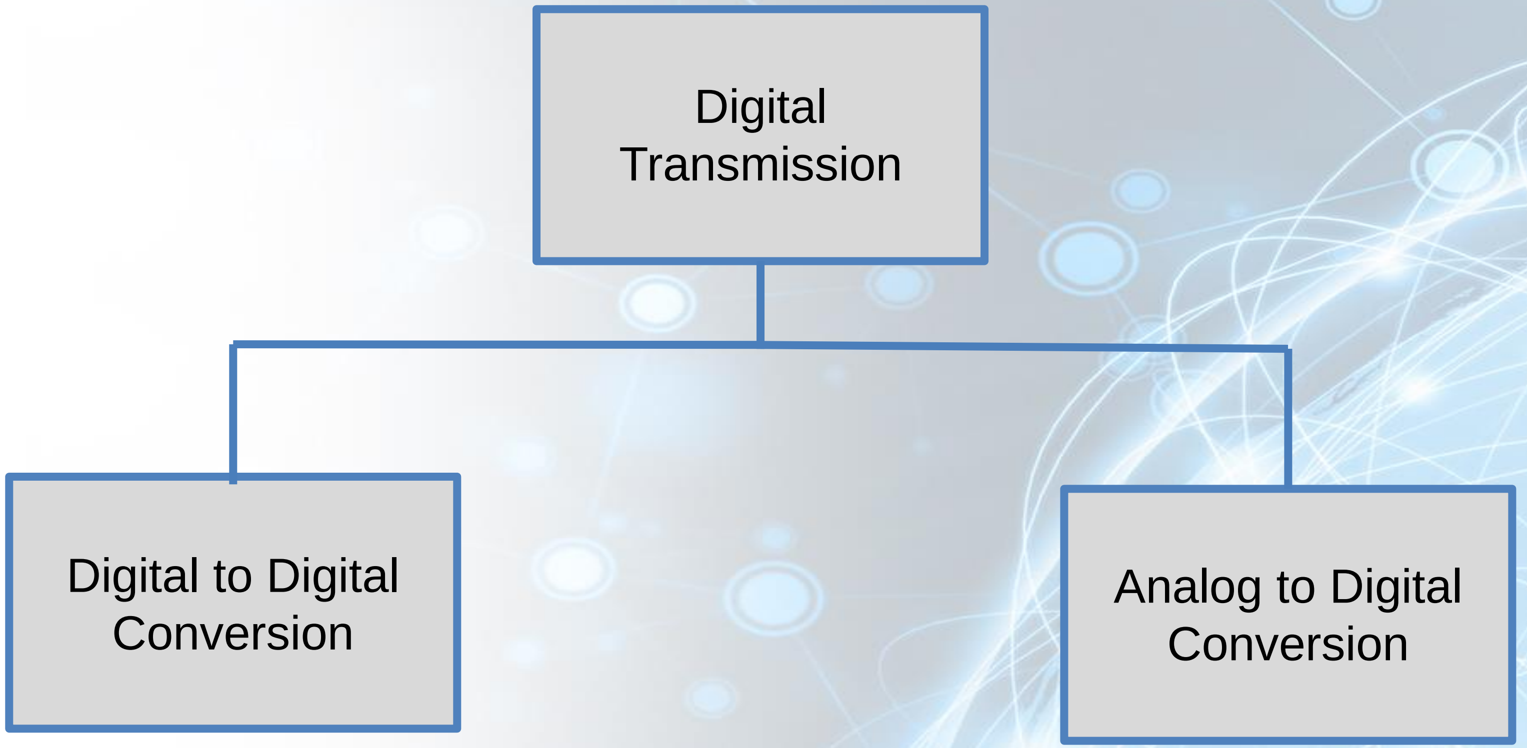
# Delay - Jitter

- **Delay for first packet is 20 ms for the second is 45 ms, and for the third is 40 ms, then the real-time application that uses the packets endures jitter**

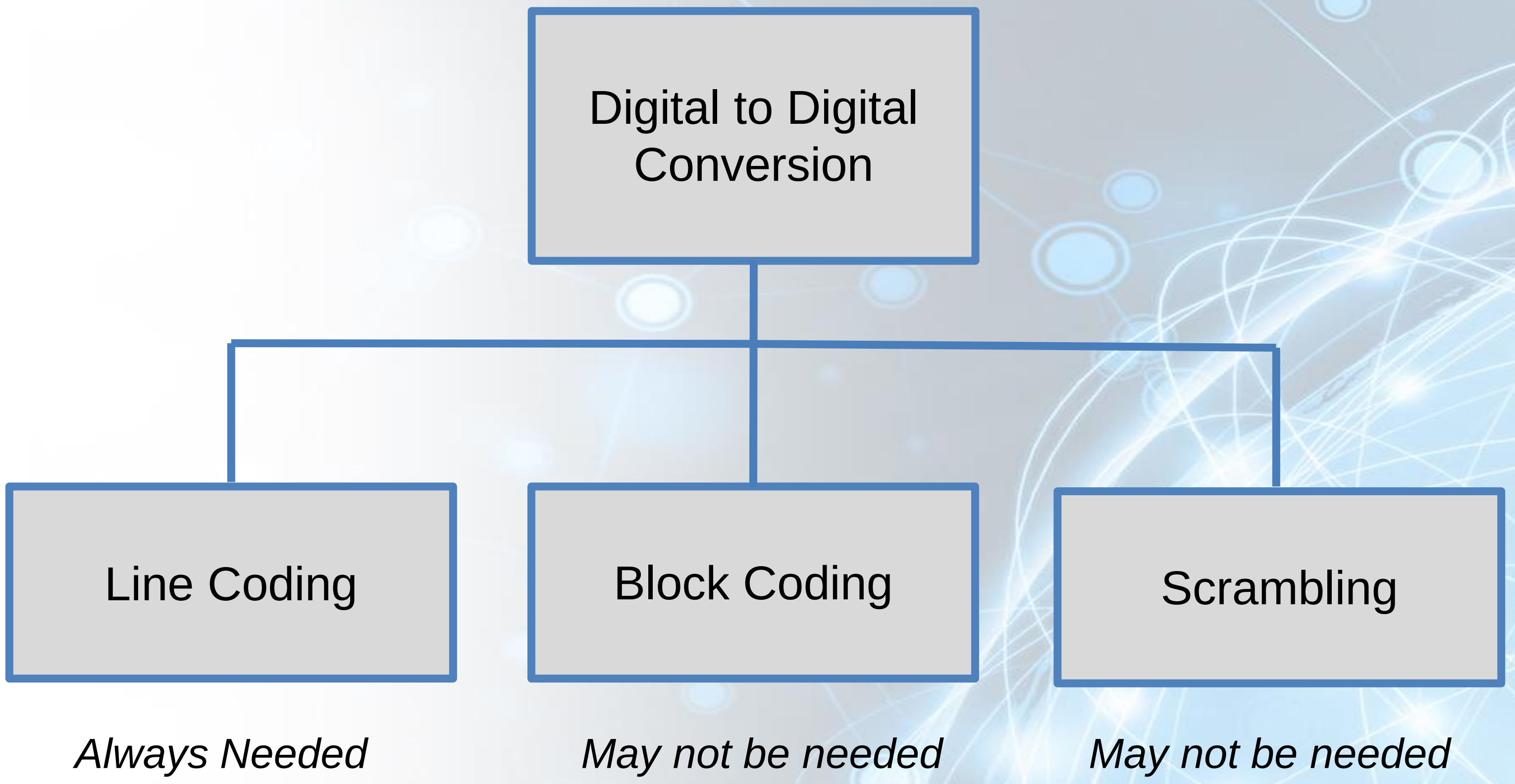
# Digital-to-digital Conversion

- **Data → Analog or Digital**
- **Signals → Analog or Digital**
- **Digital Transmission**
- **Analog Transmission**

# Digital Transmission



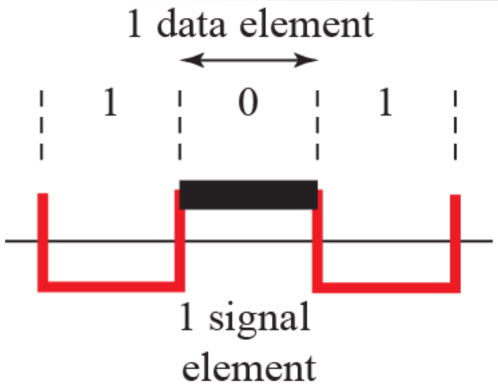
# Digital to Digital Conversion



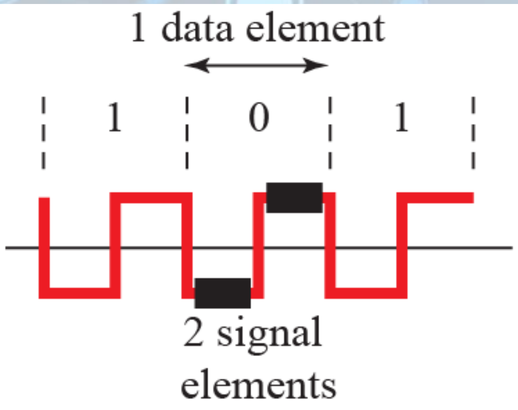
# Signal Element versus Data Element

- **A Data element is the smallest entity that can represent a piece of information → Bit**
- **A Signal element is the shortest unit of a digital signal**
- **Data Elements: Carried**
- **Signal Elements: Carriers**

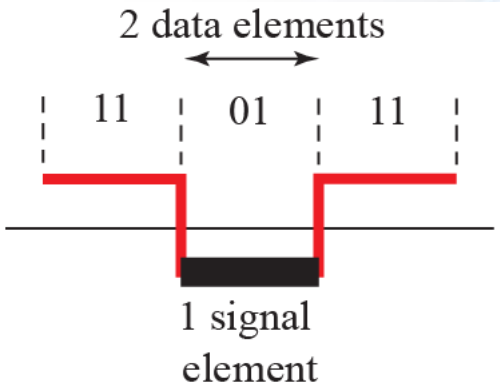
# Signal Element versus Data Element



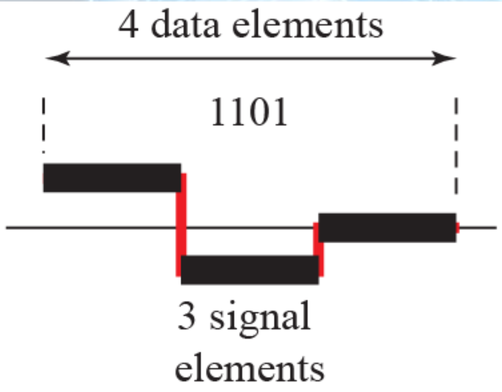

a. One data element per one signal element (r = 1)




b. One data element per two signal elements $\left(r = \frac{1}{2}\right)$




c. Two data elements per one signal element (r = 2)




d. Four data elements per three signal elements $\left(r = \frac{4}{3}\right)$

# Data Rate versus Signal Rate

S → Signal Rate

D → Data Rate

r → No. of data elements carried by signal element

$$S = \frac{D}{r}$$

- Data Rate is number of data elements sent in 1 sec (bps)
- Signal Rate is number of signal elements sent in 1 sec (baud)
- Data Rate → Bit Rate ↑
- Signal Rate → Pulse Rate, Modulation Rate or Baud Rate ↓

# Example

**A signal has a signal rate of 100 bauds. What is the Data rate if one data element is carried per signal element?**

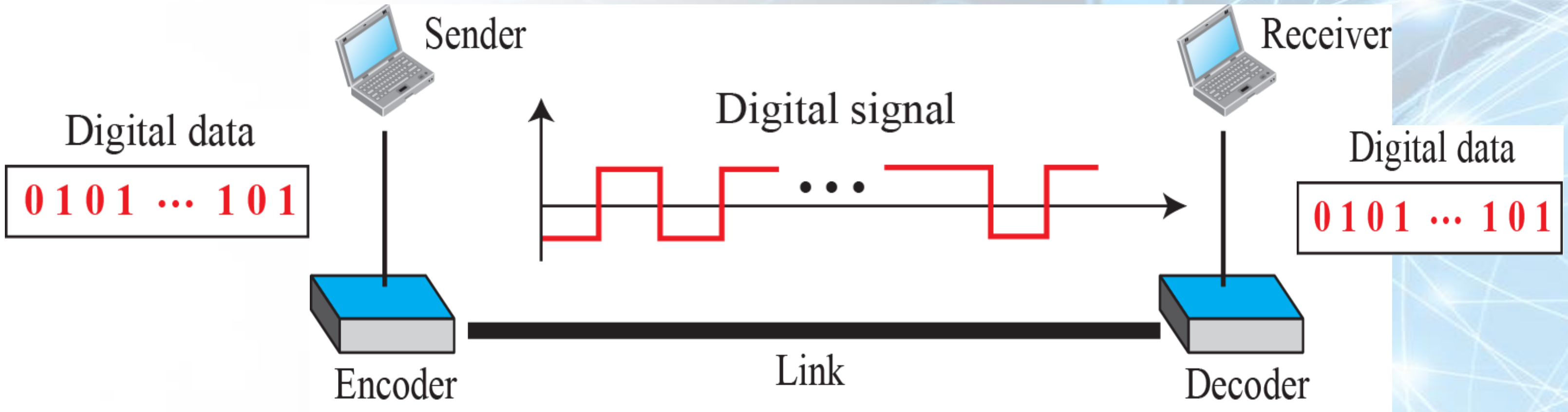
# Line Coding

- **Digital data to Digital signals**

- **Data (Text, Numbers, Pictures, Audio, or Video) is stored in computer memory as sequences of bits**

- **Line coding converts a sequence of Bits to a Digital Signal**

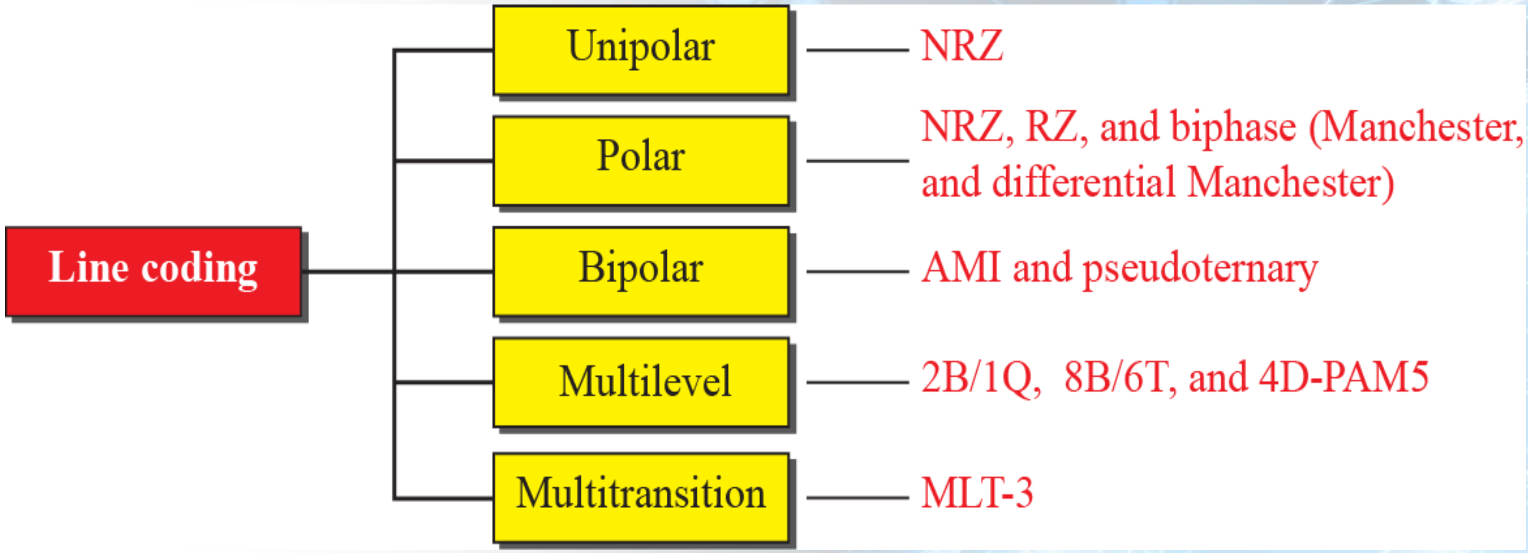
# Line Coding and Decoding



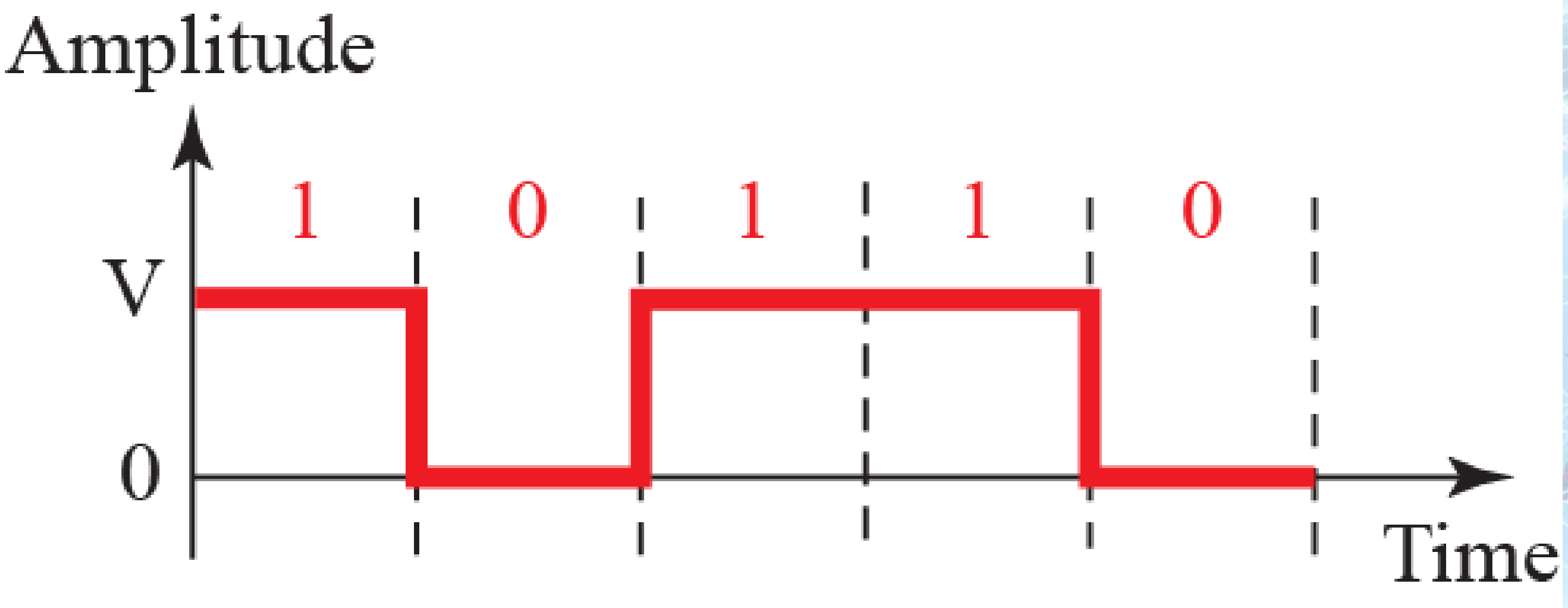
# Line Coding Schemes

- **We can roughly divide line coding schemes into five broad categories**

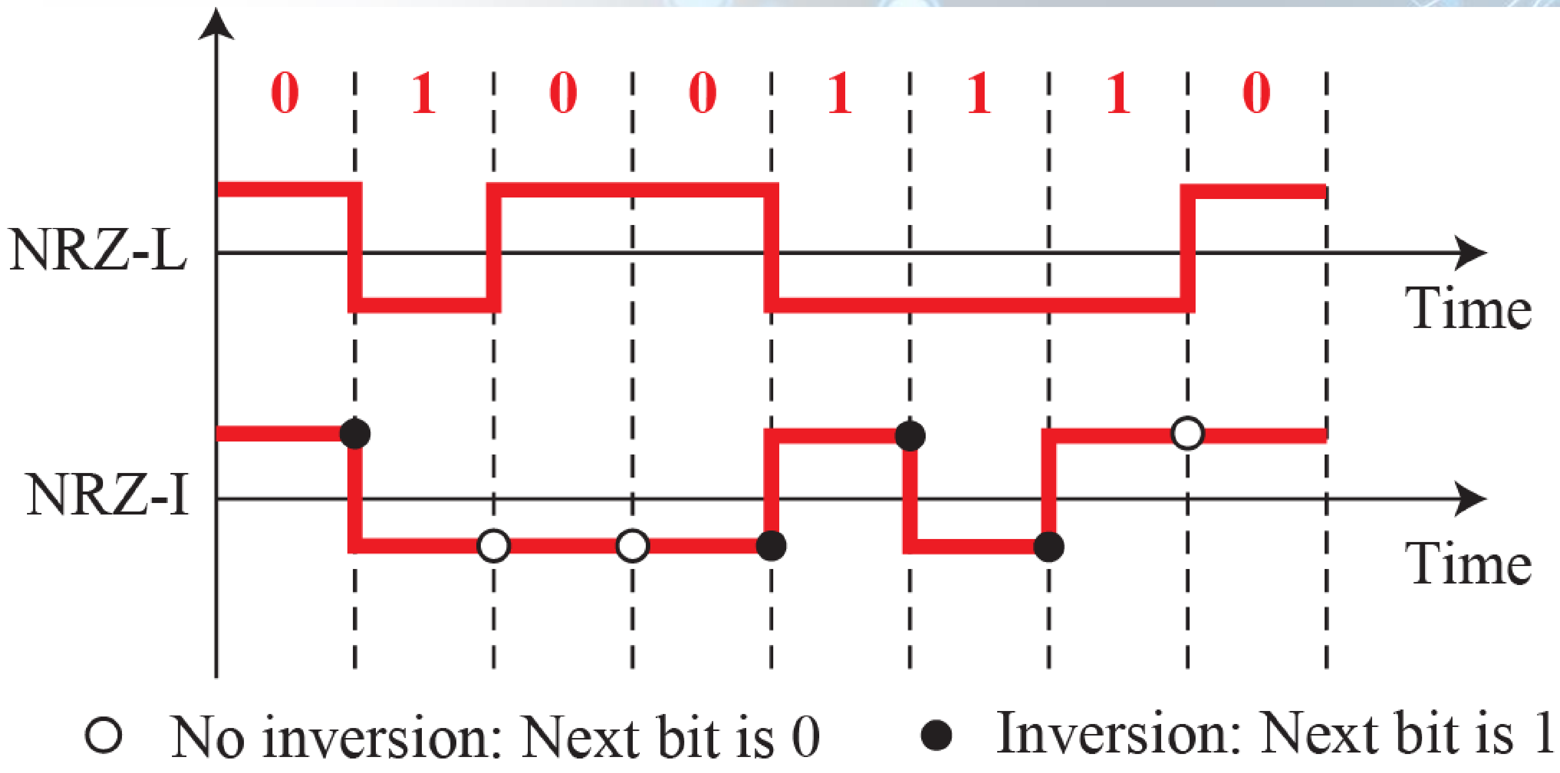
# Line Coding Schemes



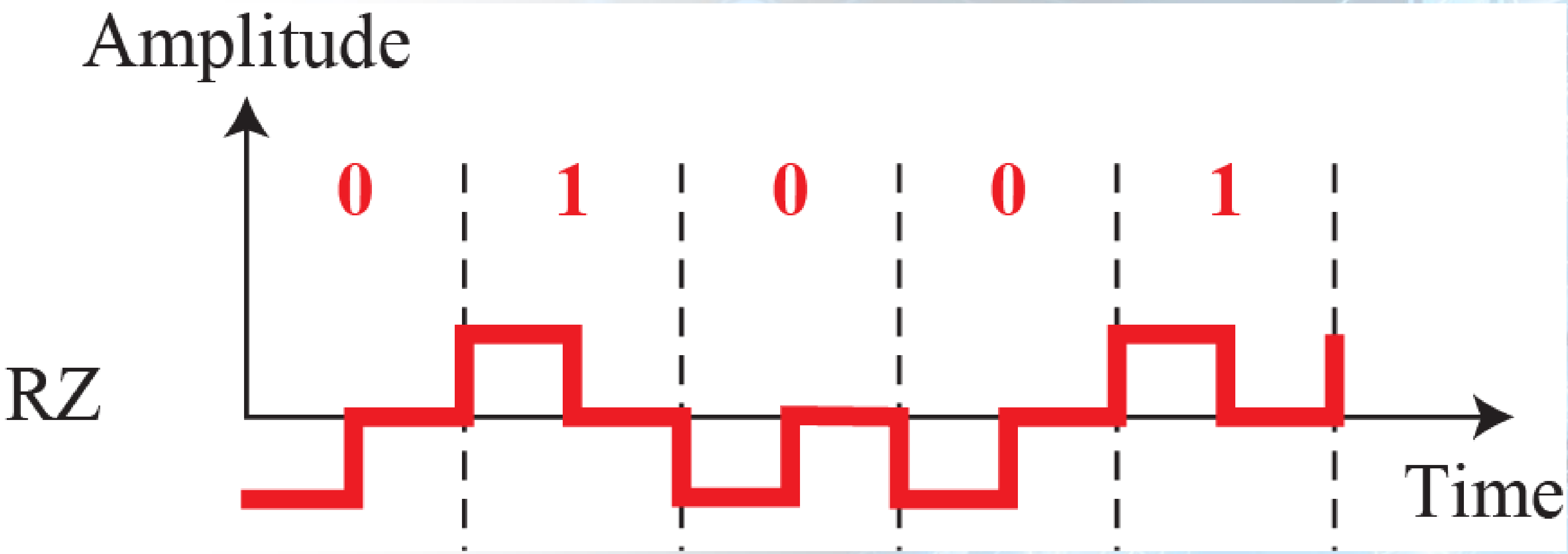
# Unipolar NRZ scheme



# Polar schemes (NRZ)



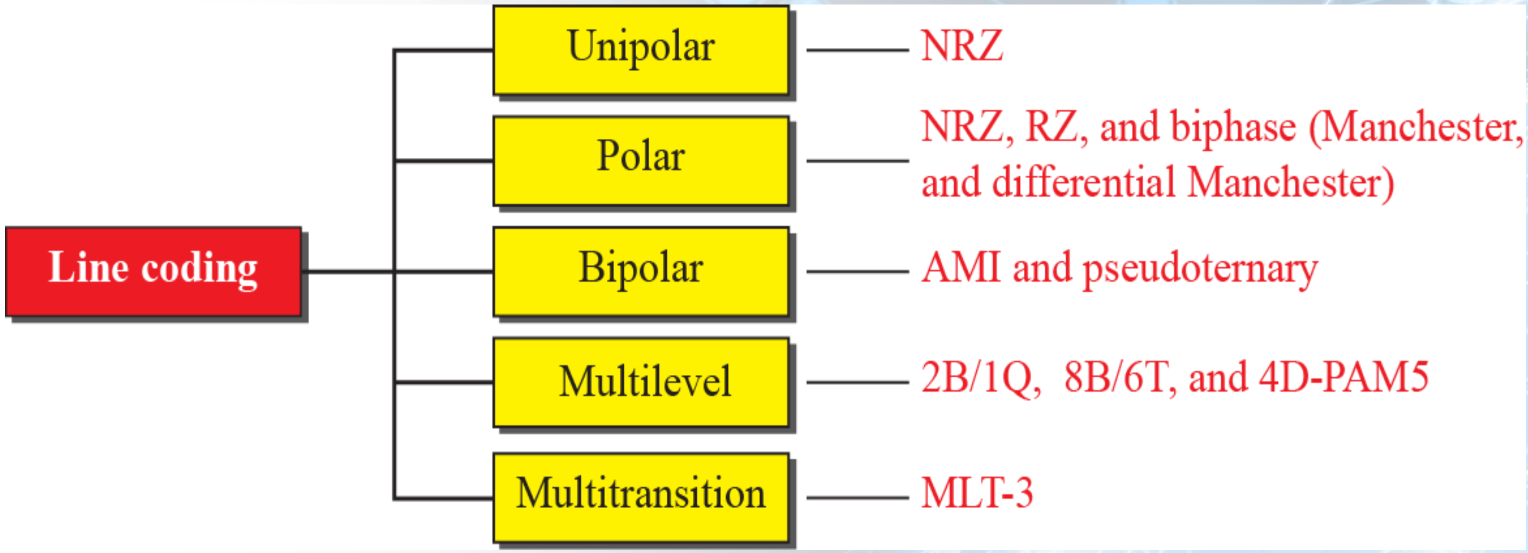
# Polar schemes (RZ)



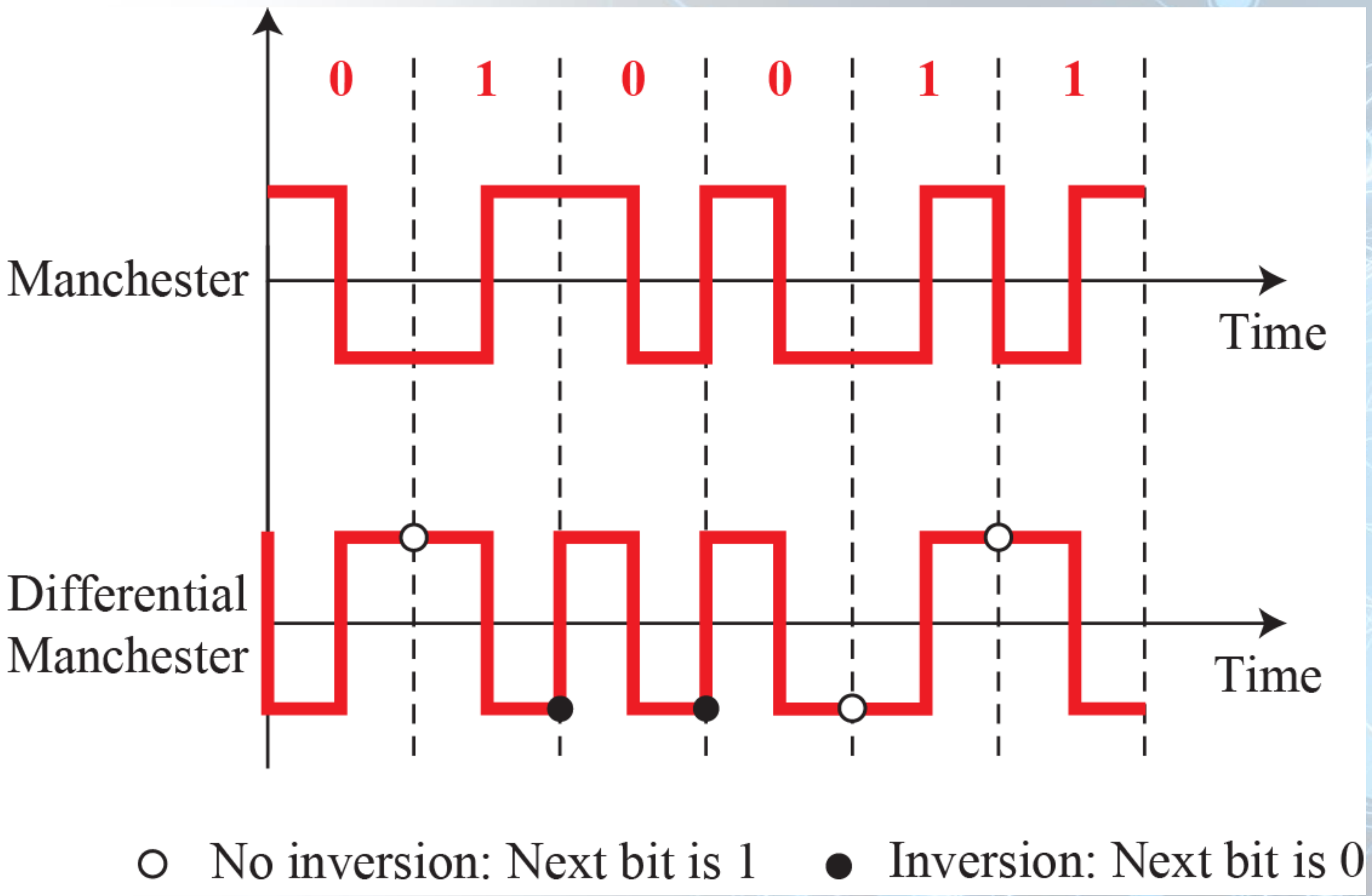
# Line Coding Schemes

- **We can roughly divide line coding schemes into five broad categories**

# Line Coding Schemes



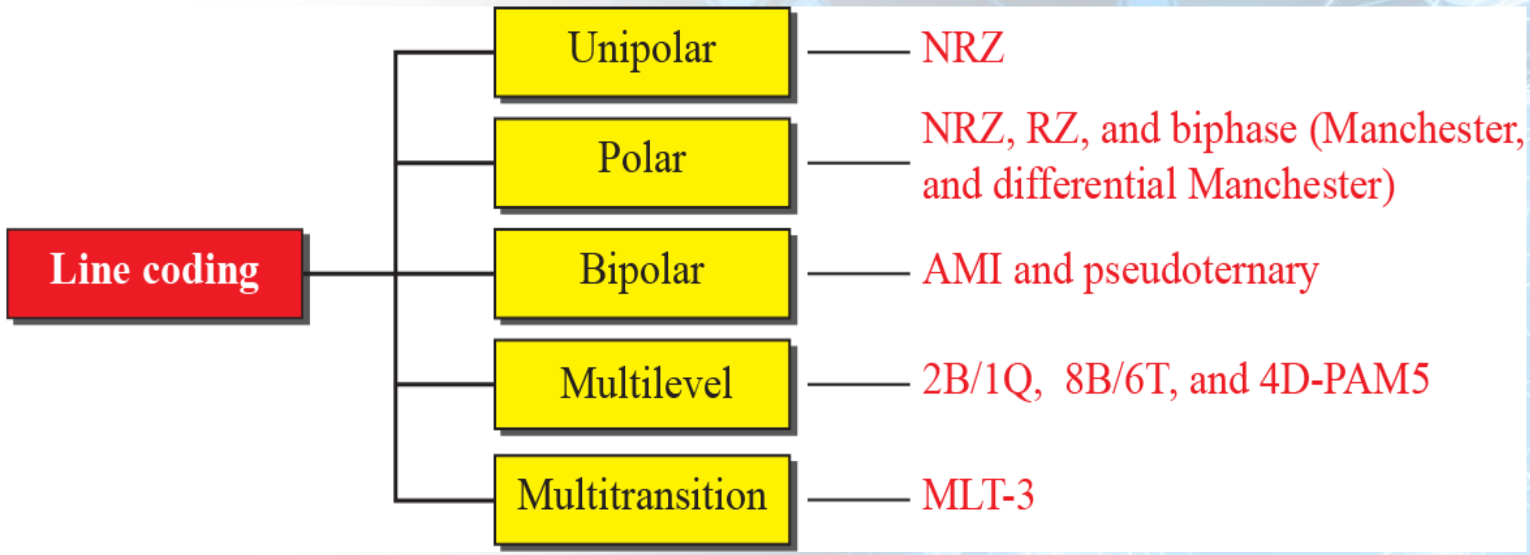
# Polar Biphase



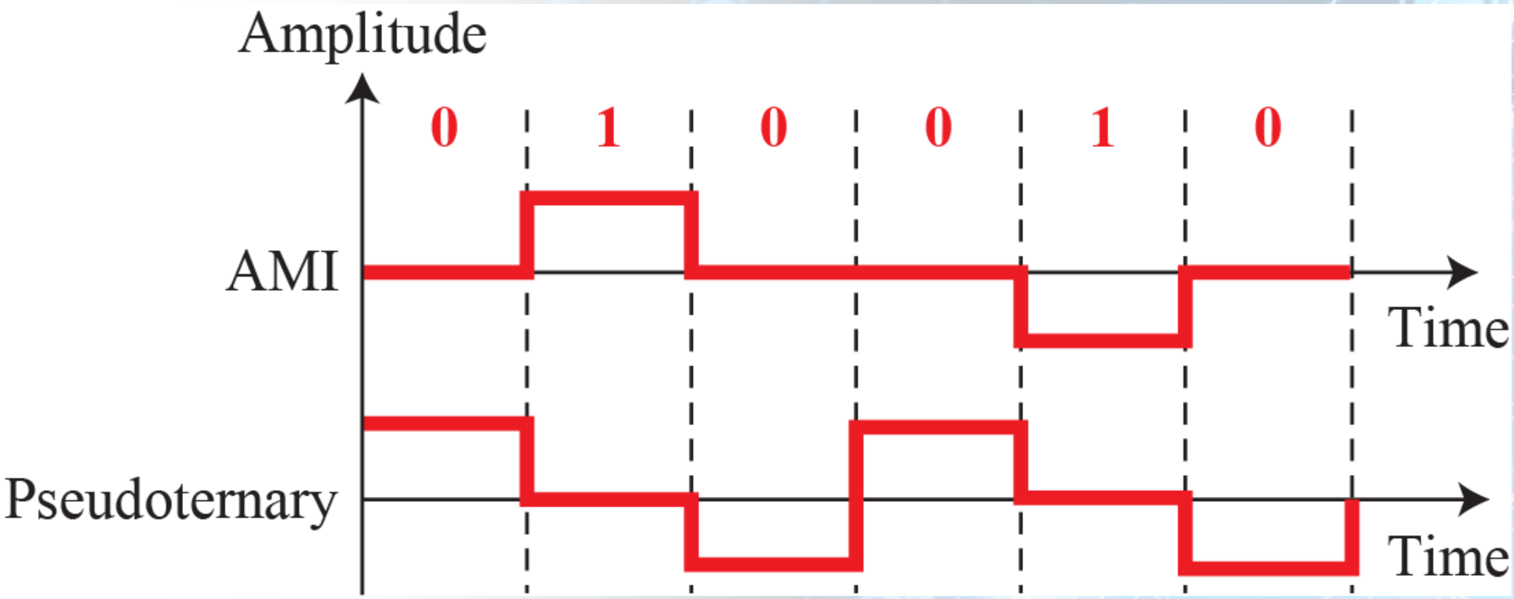
# Line Coding Schemes

- **We can roughly divide line coding schemes into five broad categories**

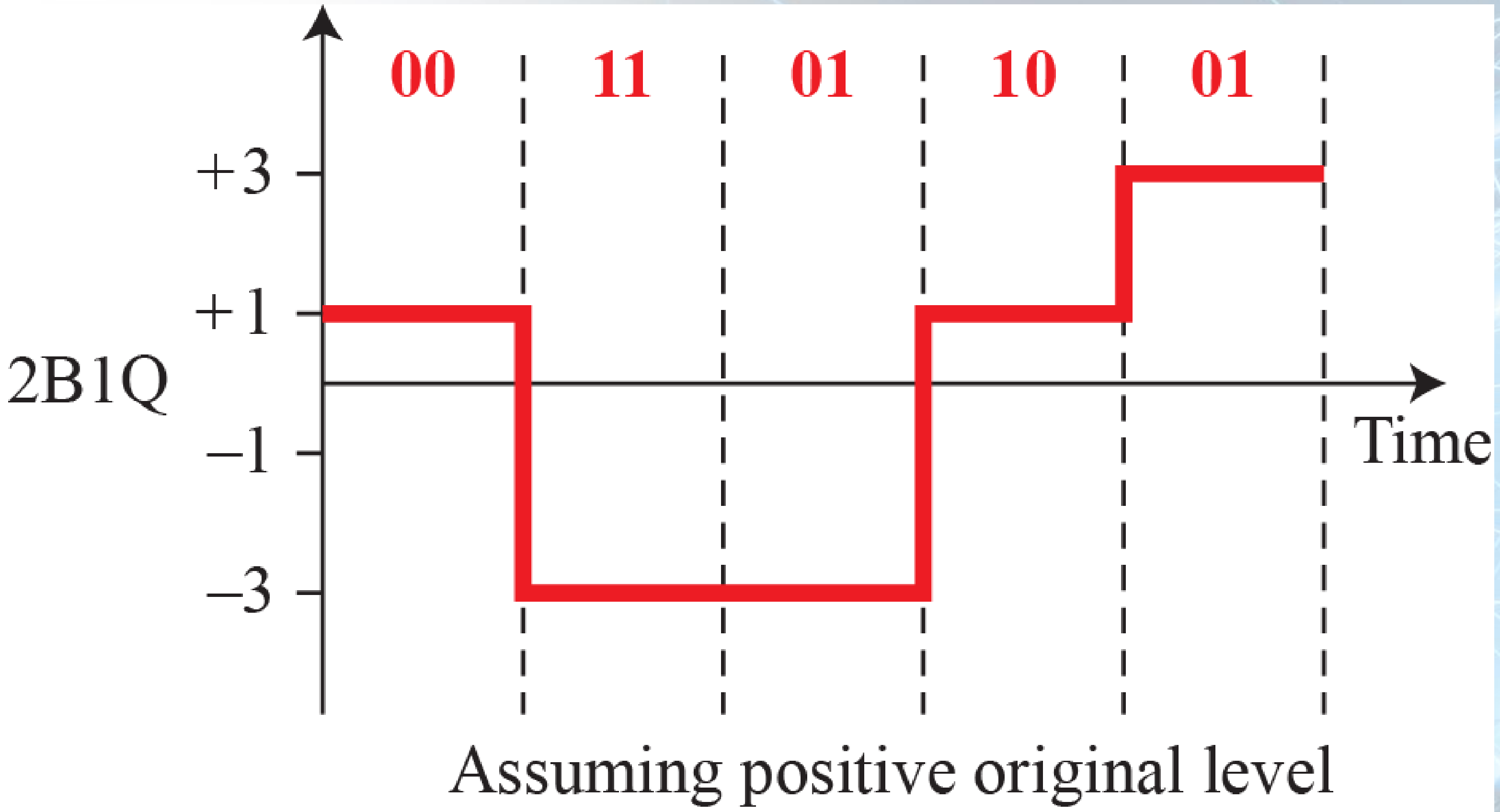
# Line Coding Schemes



# Bipolar schemes: AMI & Pseudoternary



# Multilevel: 2B1Q



# Table 4.1 : Summary of line coding schemes

| *Category* | *Scheme* | *Bandwidth (average)* | *Characteristics* |
|---|---|---|---|
| Unipolar | NRZ | $B = N/2$ | Costly, no self-synchronization if long 0s or 1s, DC |
| Polar | NRZ-L | $B = N/2$ | No self-synchronization if long 0s or 1s, DC |
| | NRZ-I | $B = N/2$ | No self-synchronization for long 0s, DC |
| | Biphase | $B = N$ | Self-synchronization, no DC, high bandwidth |
| Bipolar | AMI | $B = N/2$ | No self-synchronization for long 0s, DC |
| Multilevel | 2B1Q | $B = N/4$ | No self-synchronization for long same double bits |
| | 8B6T | $B = 3N/4$ | Self-synchronization, no DC |
| | 4D-PAM5 | $B = N/8$ | Self-synchronization, no DC |
| Multitransition | MLT-3 | $B = N/3$ | No self-synchronization for long 0s |

# Block Coding

- Block coding changes a block of ‘m’ bits into a block of ‘n’ bits (n>m)

- mB/nB encoding technique

- We need Redundancy to ensure Synchronization

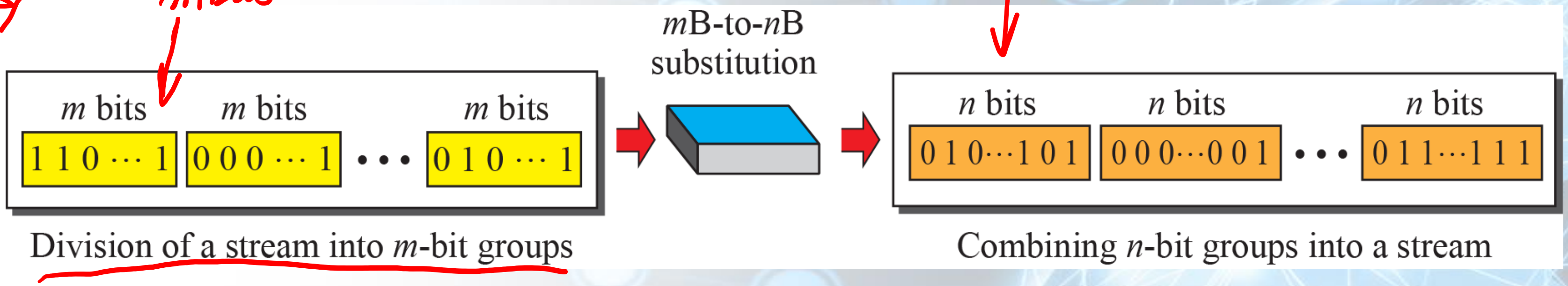
- Block coding gives us redundancy and improves line coding performance

# Block coding concept

Division Substitution Combination

Stream

m bits




mB/nB

$n > m$

Redundant bits

Redundancy

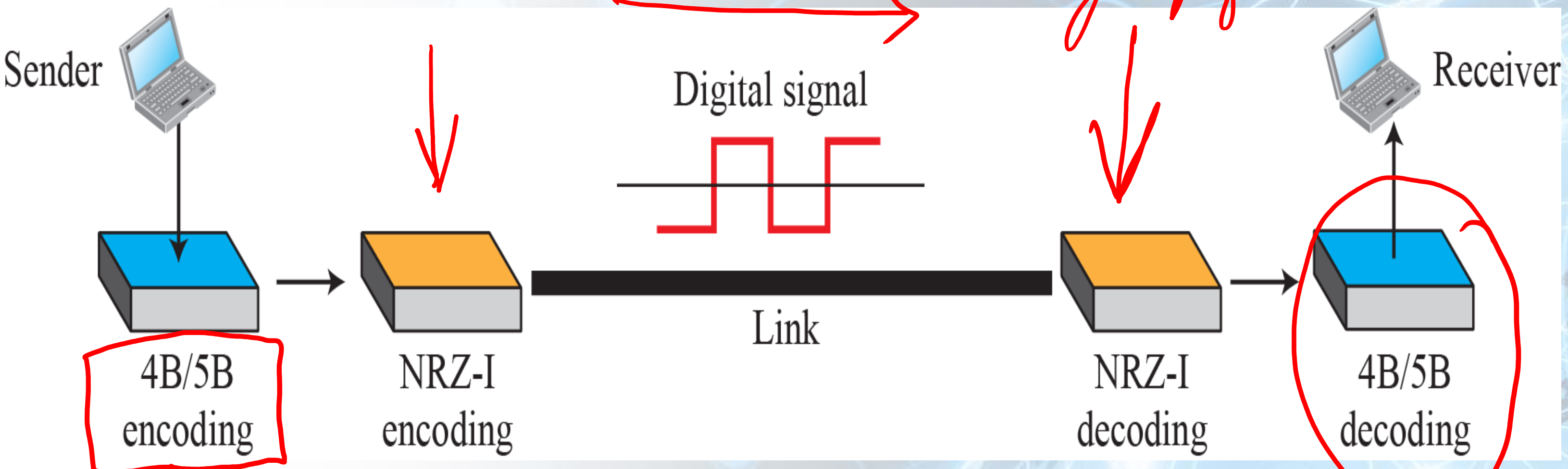
# Block Coding

- Block coding changes a block of ‘m’ bits into a block of ‘n’ bits (n>m)
- mB/nB encoding technique
- We need Redundancy to ensure Synchronization
- Block coding gives us redundancy and improves line coding performance

# Using block coding 4B/5B with NRZ-I line coding

4B/5B ⇒ $m=4$ $n=5$ $(n>m)$

long seq. of 0's




D, S & C

long seq of 0's

Decoding

Removed Redundant

# Block Coding

- **Block coding changes a block of ‘m’ bits into a block of ‘n’ bits (n>m)**
- **mB/nB encoding technique**
- **We need Redundancy to ensure Synchronization**
- **Block coding gives us redundancy and improves line coding performance**

# 4B/5B mapping codes

$2^4 = 16$ $2^5 = 32$ groups

| *Data Sequence* | *Encoded Sequence* | *Control Sequence* | *Encoded Sequence* |
|---|---|---|---|
| 0000 | 11110 | Q (Quiet) | 00000 |
| 0001 | 01001 | I (Idle) | 11111 |
| 0010 | 10100 | H (Halt) | 00100 |
| 0011 | 10101 | J (Start delimiter) | 11000 |
| 0100 | 01010 | K (Start delimiter) | 10001 |
| 0101 | 01011 | T (End delimiter) | 01101 |
| 0110 | 01110 | S (Set) | 11001 |
| 0111 | 01111 | R (Reset) | 00111 |
| 1000 | 10010 | | |
| 1001 | 10011 | | |
| 1010 | 10110 | | |
| 1011 | 10111 | | |
| 1100 | 11010 | | |
| 1101 | 11011 | | |
| 1110 | 11100 | | |
| 1111 | 11101 | | |

# Block Coding

- **Block coding changes a block of ‘m’ bits into a block of ‘n’ bits (n>m)**
- **mB/nB encoding technique**
- **We need Redundancy to ensure Synchronization**
- **Block coding gives us redundancy and improves line coding performance**

# Example

We need to send data at a 1-Mbps rate. What is the minimum required bandwidth, using a combination of 4B/5B and NRZ-I or Manchester coding?

Data Rate = 1 Mbps

4B/5B Block Coding

→ 4 bit group ⇔ 5 bit group

Data Rate = 1.25 Mbps

Signal Rate ↑

$$NRZ\text{-}I = \frac{N}{2} = \frac{1.25\,\text{Mbps}}{2} = 625\ \text{kHz}$$

Manchester ⇒ 1 MHz

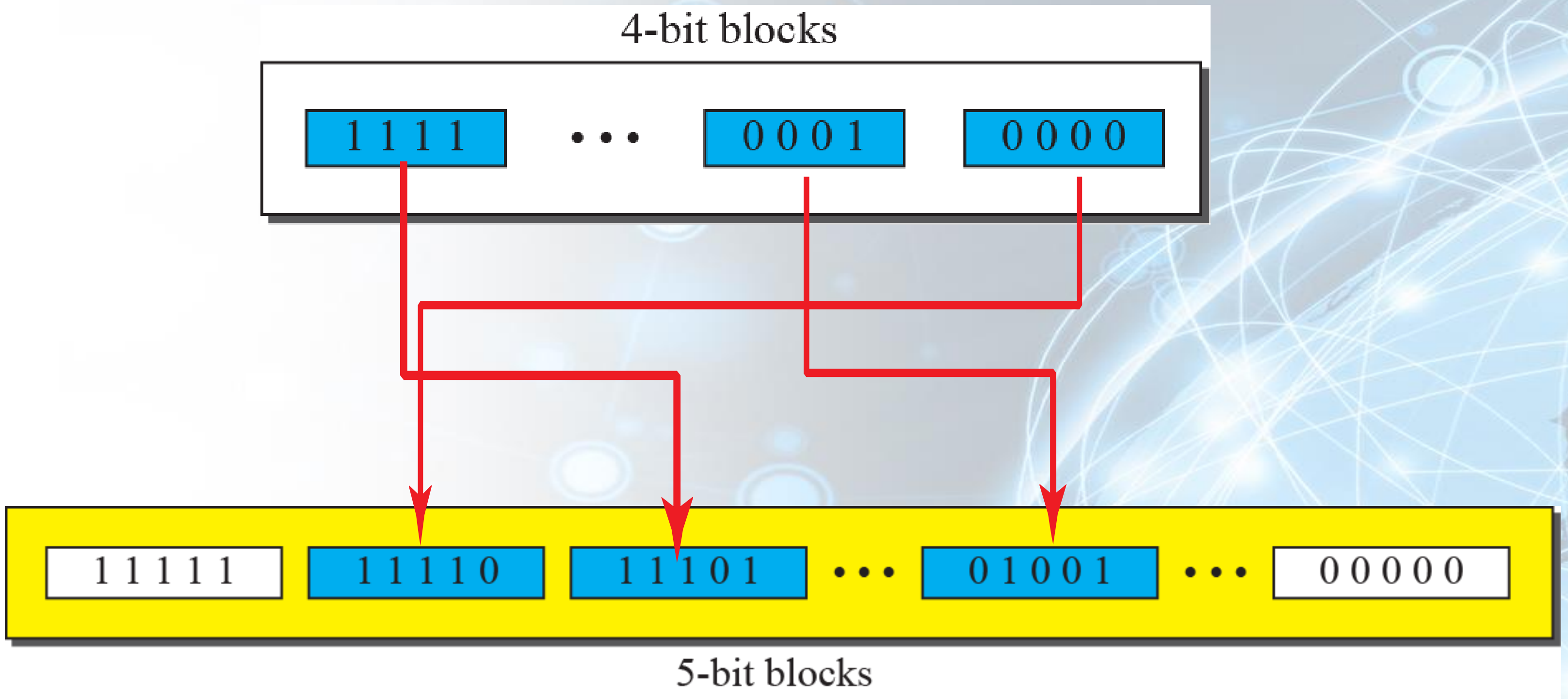
Synchronisation ⇒ ✓

Signal Rate ↑ ⇒ BW ↑ ✓

$BW_{NRZ\text{-}I} < BW_{Manchester}$

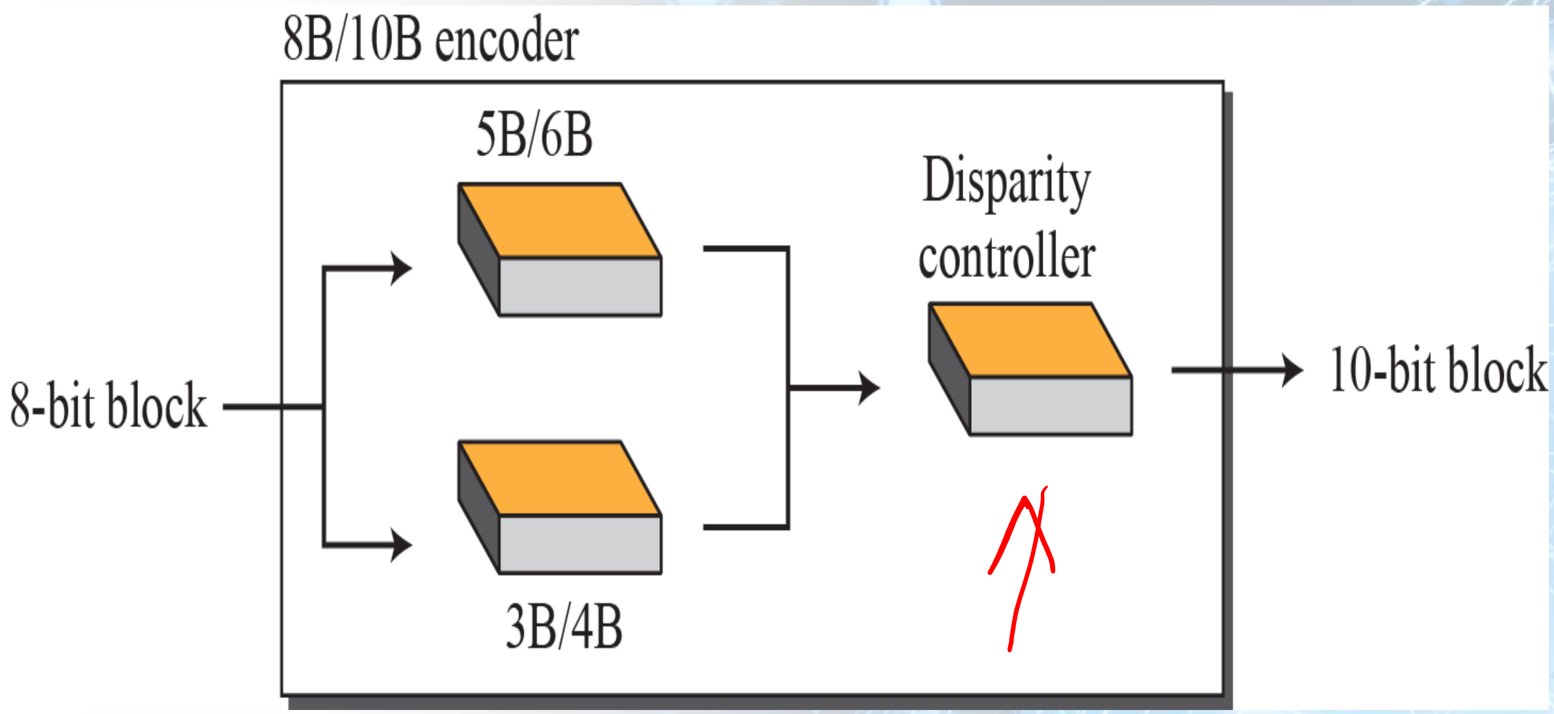
DC-component ✗

# Example


4-bit blocks
1 1 1 1
• • •
0 0 0 1
0 0 0 0
1 1 1 1 1
1 1 1 1 0
1 1 1 0 1
• • •
0 1 0 0 1
• • •
0 0 0 0 0
5-bit blocks

# 8B/10B block encoding

m=8 n=10



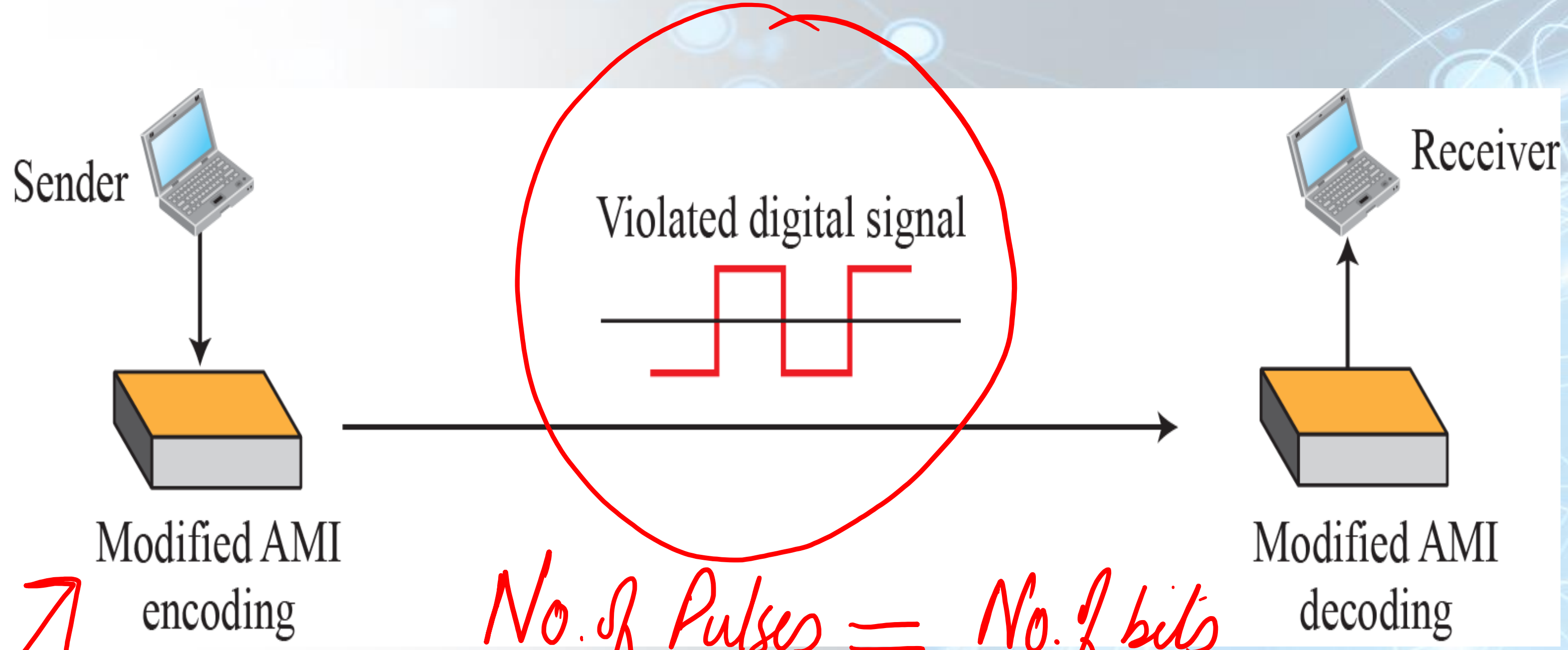
# Scrambling

- **Biphase schemes suitable for LAN but not for Long Distance**
- **Block Coding + NRZ-I solves synch issue but has DC component**
- **Bipolar AMI has a narrow bandwidth (no DC Component) but synch issue (long series of 0s)**

# Scrambling

- **The system needs to insert the required pulses based on the defined scrambling rules**

# AMI used with scrambling

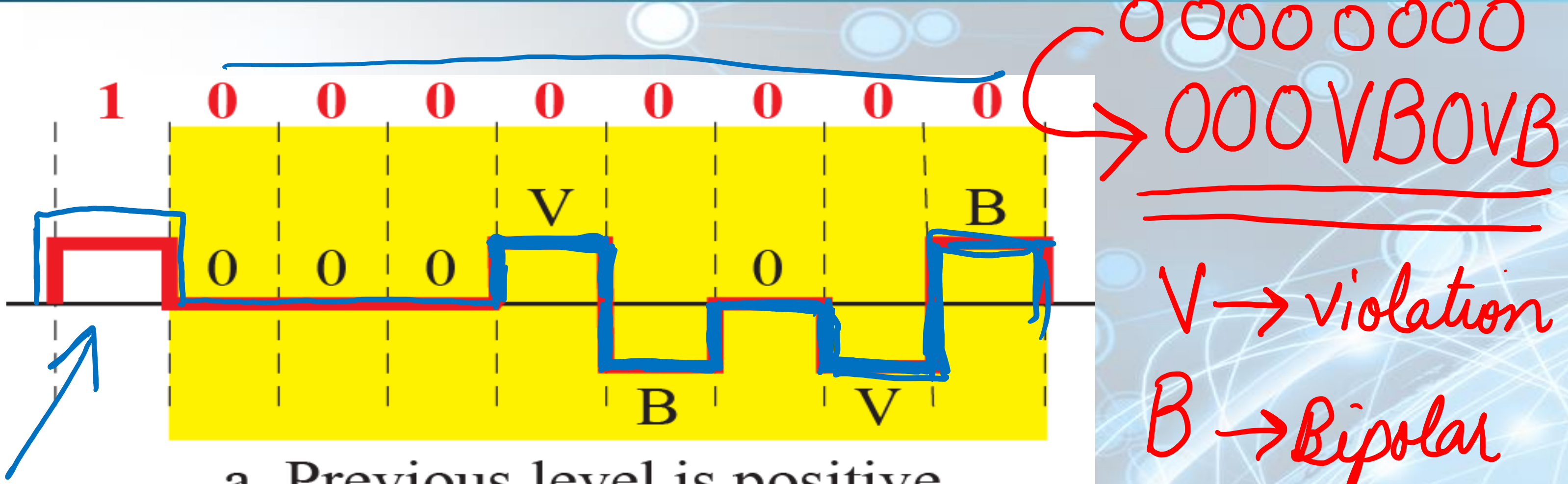



No. of Pulses = No. of bits in sequence of 0s

# Types of Scrambling Techniques

- **Two common scrambling techniques are B8ZS and HDB3**
- **Bipolar with 8-Zero Substitution (B8ZS)**
- **High-density bipolar 3-zero (HDB3)**

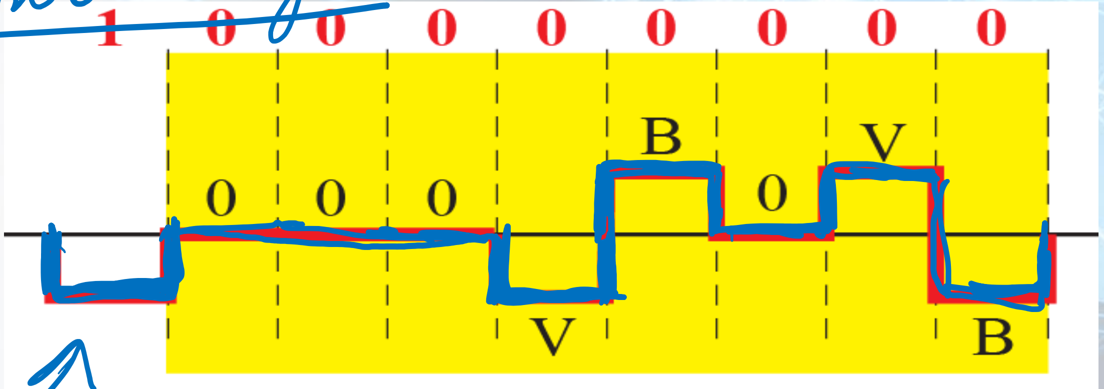
# Two cases of B8ZS scrambling technique




a. Previous level is positive.

Bit Rate doesnot change

DC Balance

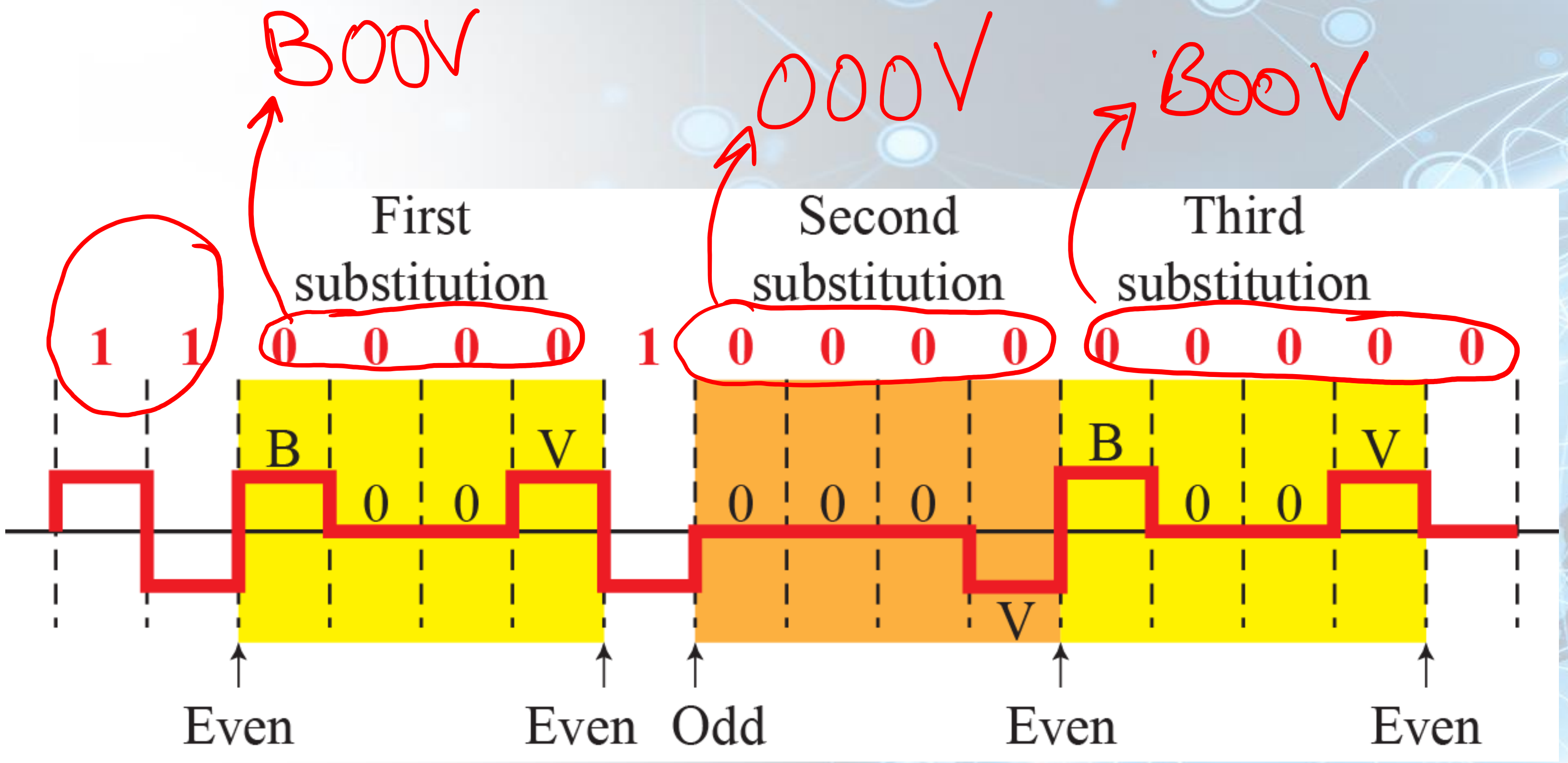



b. Previous level is negative.

# Types of Scrambling Techniques

- Two common scrambling techniques are B8ZS and HDB3
- Bipolar with 8-Zero Substitution (B8ZS)
- High-density bipolar 3-zero (HDB3)

# Different situations in HDB3 scrambling technique



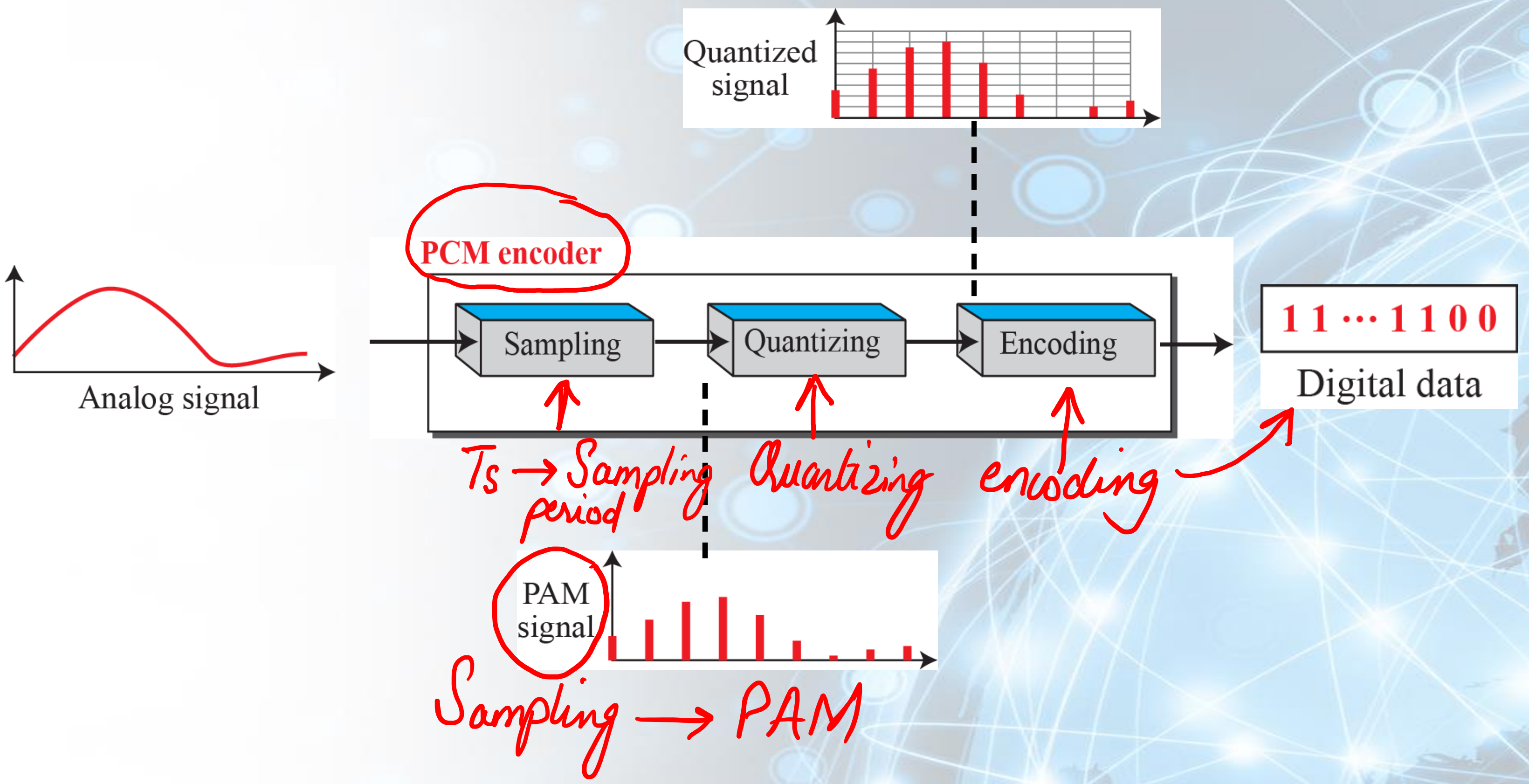

Rule 1: Non-zero pulses → odd
0000 → 000V

Rule 2: Non-zero pulses → even
0000 → B00V

# Analog-to-digital Conversion

- **Analog Data to Digital Data**
- **Process of Digitization**
- **Two techniques:**
  - ✓ **Pulse Code Modulation (PCM)**
  - ✓ **Delta Modulation (DM)**

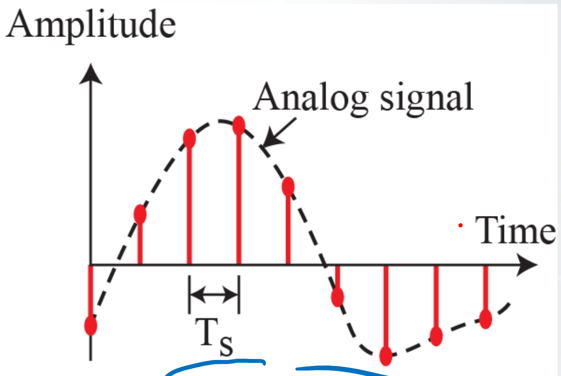
# Pulse Code Modulation (PCM)



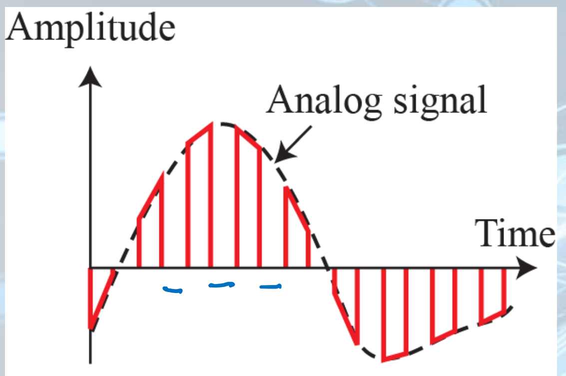
# Pulse Code Modulation (PCM)

- **Sampling**
- **Quantization**
- **Encoding**

# Three different sampling methods for PCM



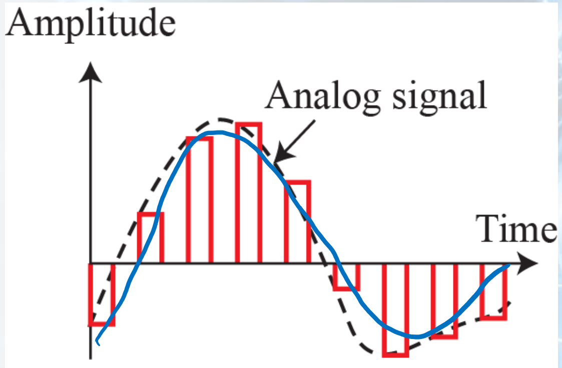

a. Ideal sampling




b. Natural sampling

Sampling
↳ Pulse Amplitude Modulation

$T_S$ → Sampled interval or Sample period




c. Flat-top sampling

Sample and Hold

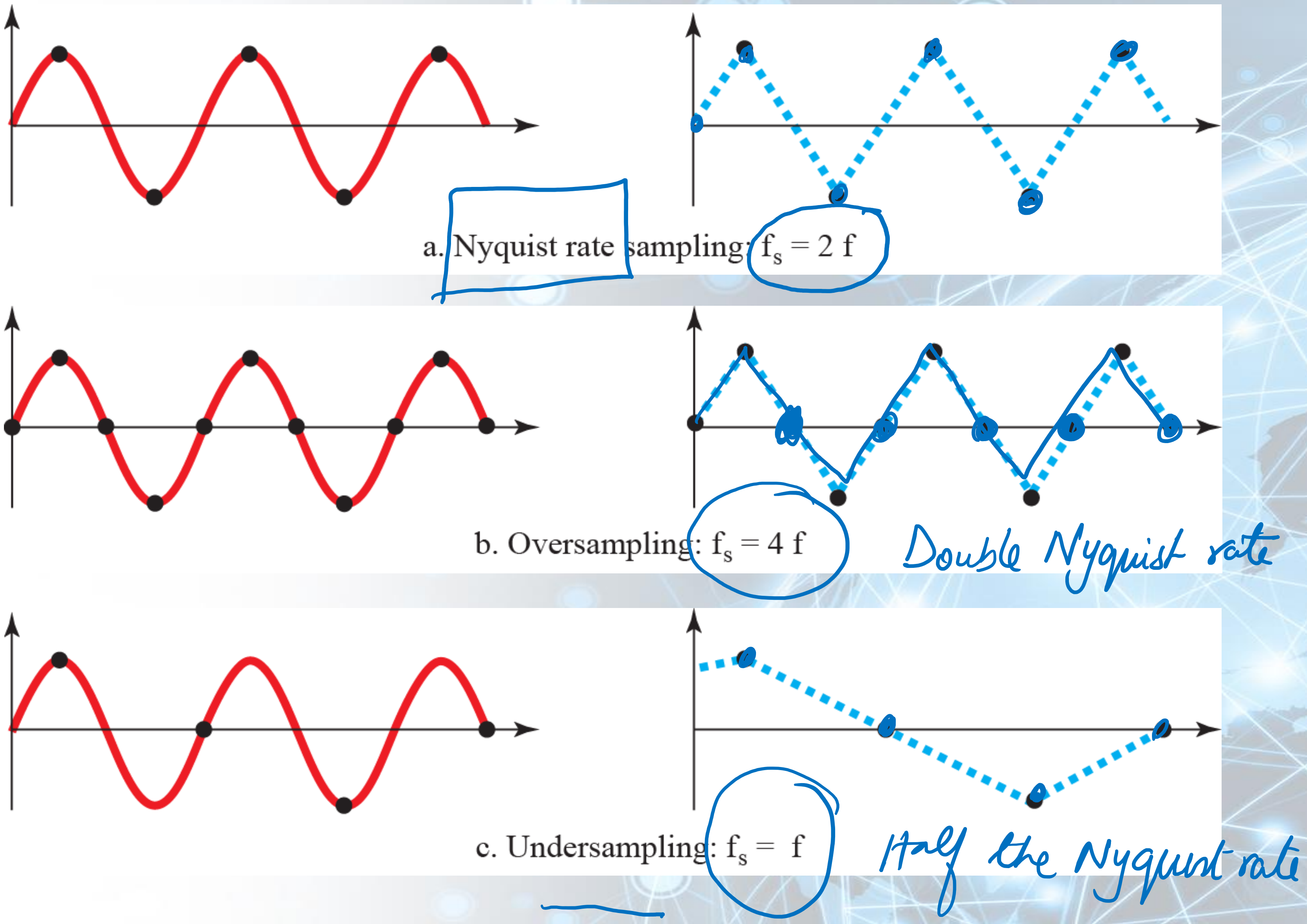
# Nyquist Sampling Rate

- **Nyquist → $f_s = 2f_h$**

- **Sampling sine wave at three sampling rates:**

  - ✓ **$f_s = 4f$ (2 times the Nyquist rate)**
  - ✓ **$f_s = 2f$ (Nyquist rate)**
  - ✓ **fs = f (one-half the Nyquist rate)**

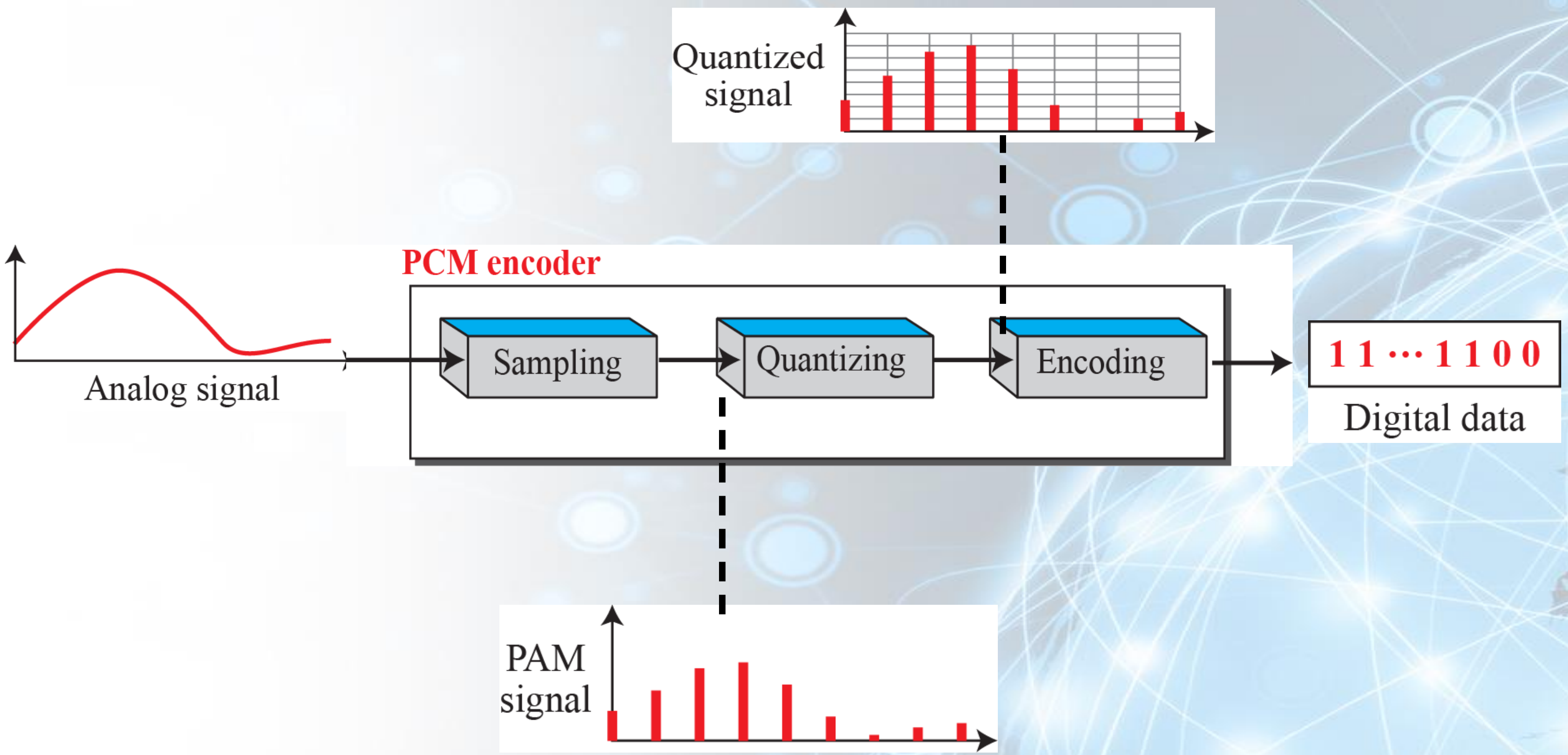
# Nyquist Sampling Rate



# Pulse Code Modulation (PCM)

- Most common technique
- Employs a PCM Encoder
- A PCM encoder has three processes:
  - ✓ Sampling
  - ✓ Quantization
  - ✓ Encoding

# Components of PCM encoder



# Pulse Code Modulation (PCM)

- **Sampling**
- **Quantization**
- **Encoding**

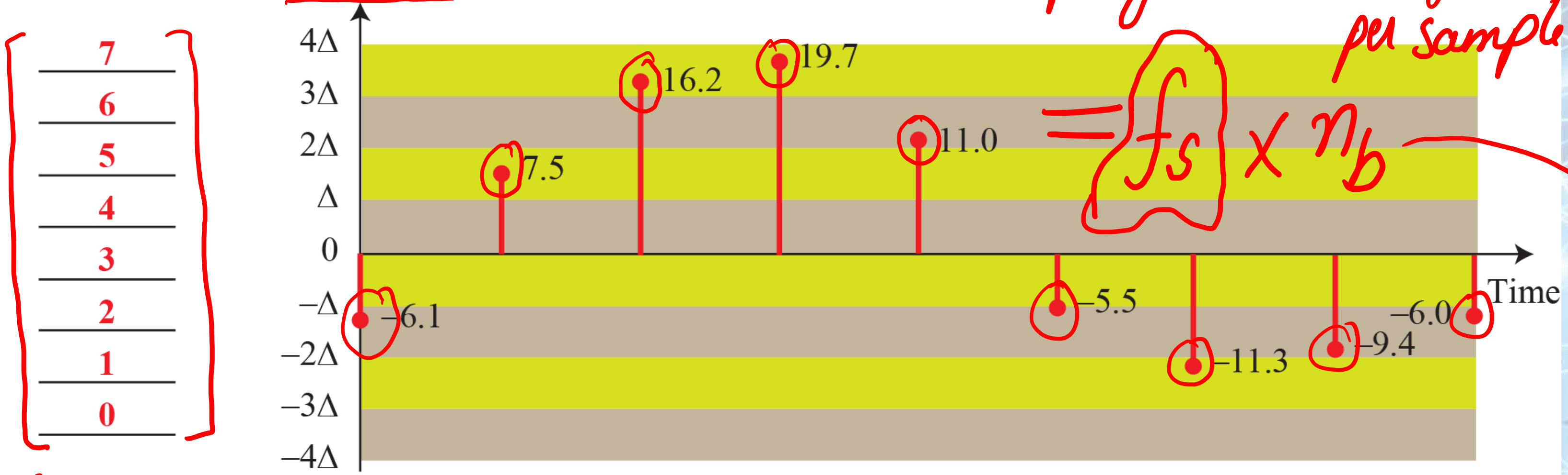
# Quantization & encoding of a sampled signal

- **Sampling → Series of pulses with amplitude values between min and max signal amplitude**
- **Infinite set with non-integral values not suitable for encoding**
- **We quantize the sampling output into certain levels based on range of amplitudes and how much accuracy is needed**

# Quantization & encoding of a sampled signal

Bit Rate = Sampling rate × No. of bits per sample

$= f_s \times n_b$




| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Normalized PAM values | –1.22 | 1.50 | 3.24 | 3.94 | 2.20 | –1.10 | –2.26 | –1.88 | –1.20 |
| Normalized quantized values | –1.50 | 1.50 | 3.50 | 3.50 | 2.50 | –1.50 | –2.50 | –1.50 | –1.50 |
| Normalized error | –0.28 | 0 | +0.26 | –0.44 | +0.30 | –0.40 | –0.24 | +0.38 | –0.30 |
| Quantization code | 2 | 5 | 7 | 7 | 6 | 2 | 1 | 2 | 2 |
| Encoded words | 010 | 101 | 111 | 111 | 110 | 010 | 001 | 010 | 010 |

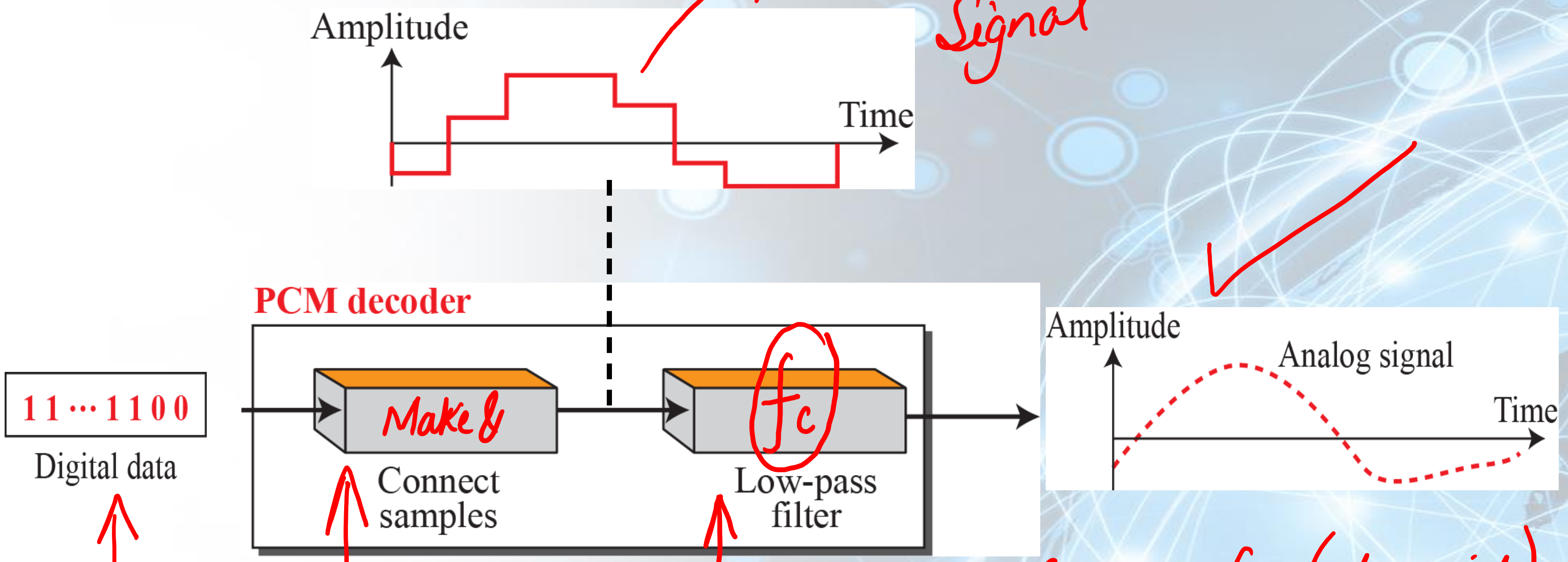
$n_b = \log_2 L$ L → Quantization Level

# Pulse Code Modulation (PCM)

- Encoding
  - ✓ Sampling
  - ✓ Quantization
  - ✓ Encoding
- Decoding

# Original Signal Recovery- PCM Decoder

Staircase Signal




✓ → $f_s = 2 f_c$ (Nyquist Rate)

✓ → L → Quantization Levels

✓ → Amplification

# Analog-to-digital Conversion

- **Analog Data to Digital Data**

- **Process of Digitization**

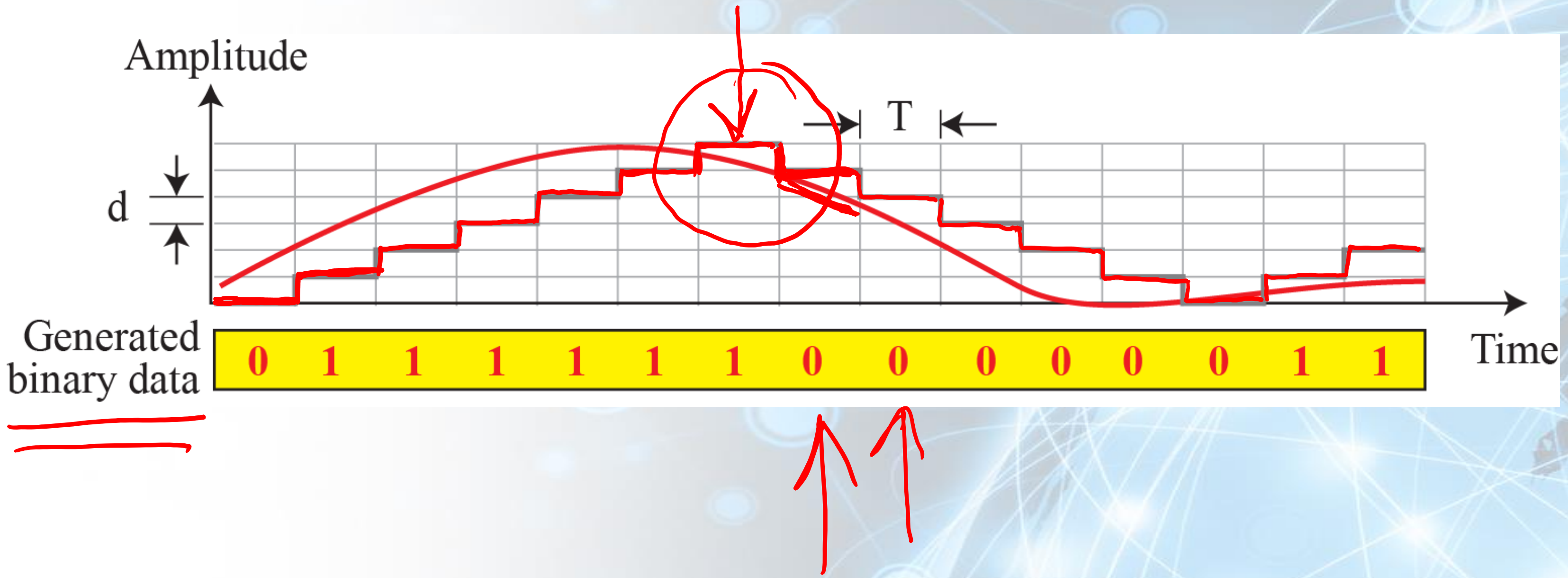
- **Two techniques:**
  - ✓ **Pulse Code Modulation (PCM)**

  - ✓ **Delta Modulation (DM)**

# Delta Modulation (DM)

- PCM is a very complex technique
- Delta modulation is a simpler technique
- PCM finds the value of the signal amplitude for each sample; DM finds the change from the previous sample
- No code words

# The process of delta modulation



# Delta Modulation (DM)

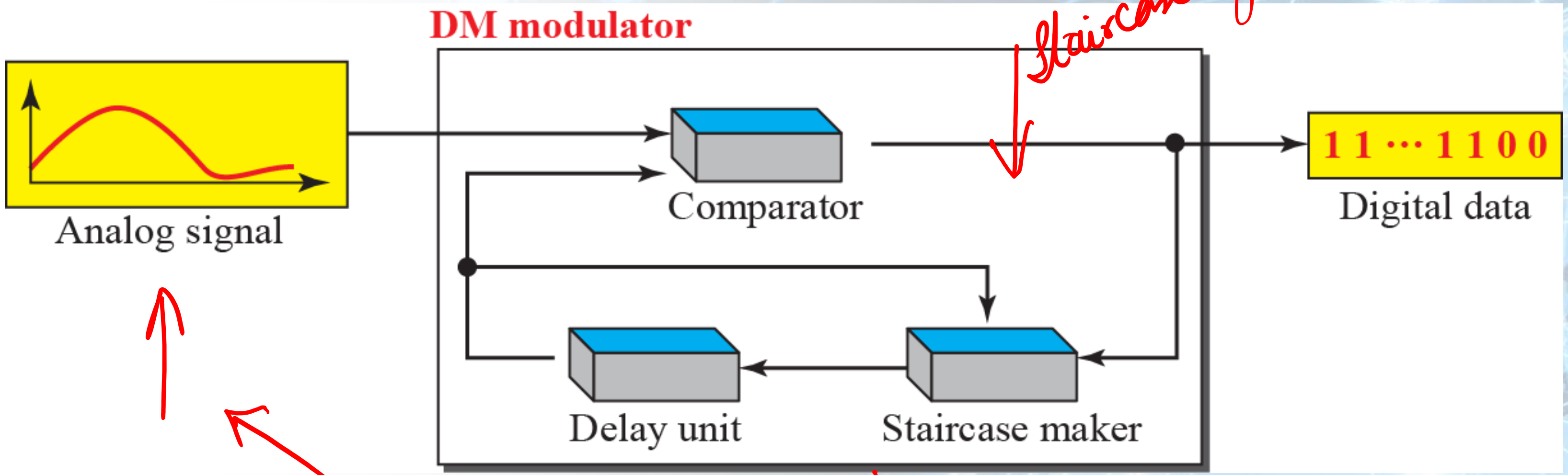
- Delta modulation is a simpler technique
- DM finds the change from the previous sample
- No code words

# Delta Modulation Components

Delta → δ

+δ → 1

−δ → 0

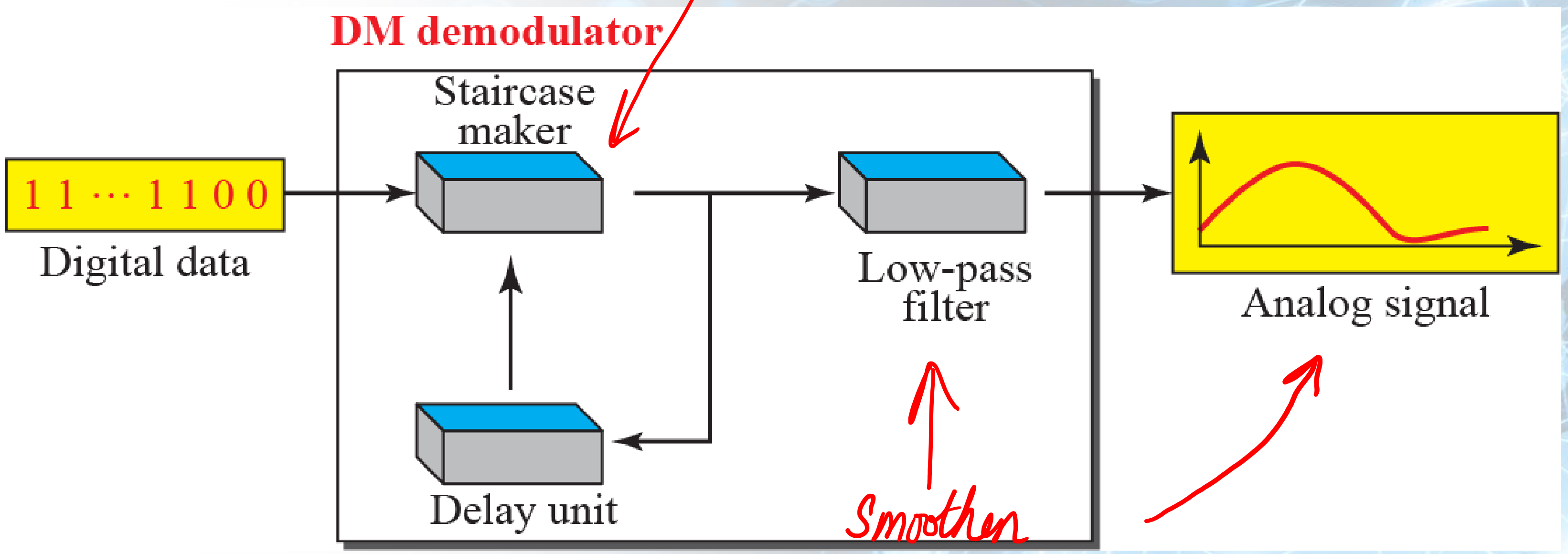



Compare → Comparator

Staircase signal

# Delta Demodulation Components

Adaptive DM → δ is not fixed → Performance ↑




Quantization Error (QE)

$QE_{DM} < QE_{PCM}$

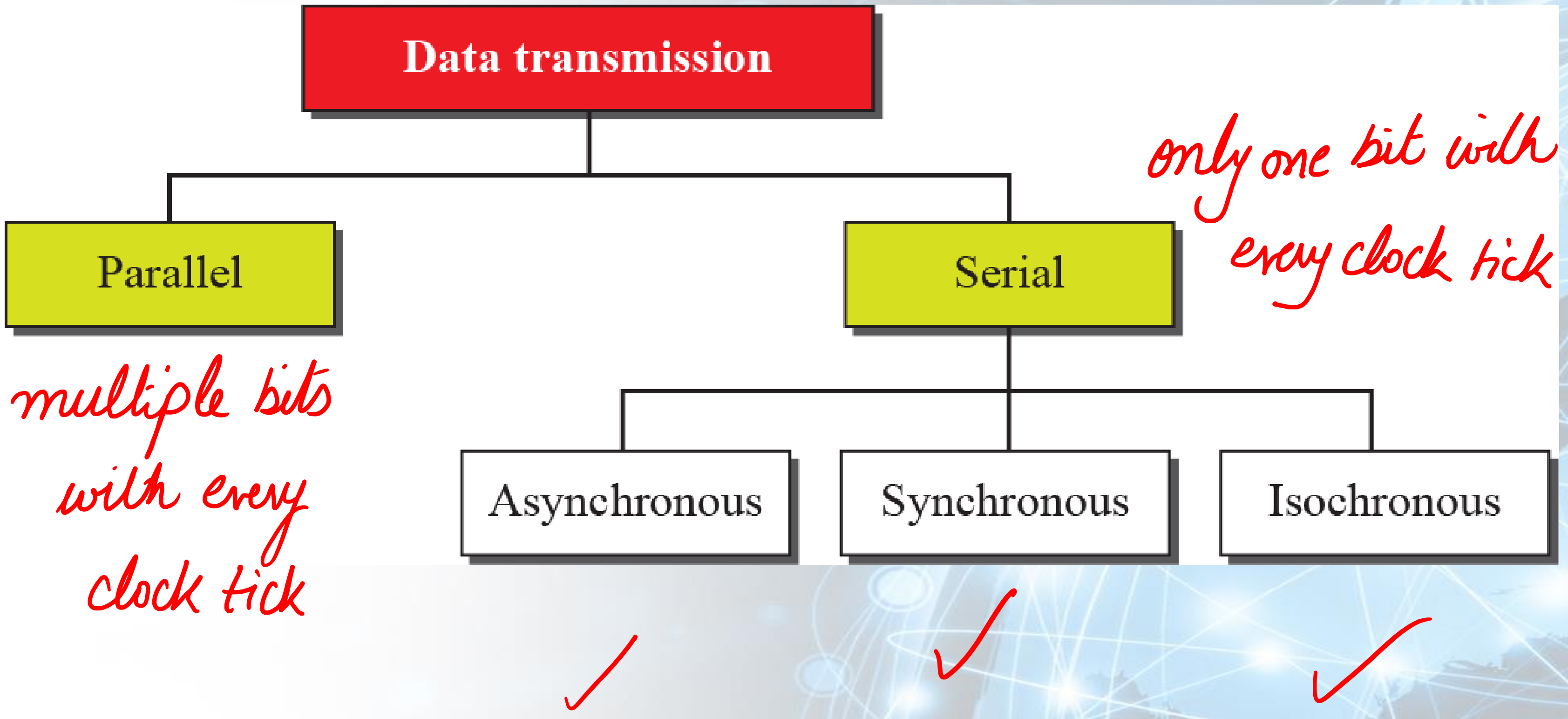
# Transmission Modes

- **Transmission of Data:**
  - ✓ **Wiring**
    - ➢ **Data Stream**

- **Do we send 1 bit at a time; or do we group bits into larger groups and, if so, how?**

- **Parallel or Serial Transmission**

# Data transmission modes

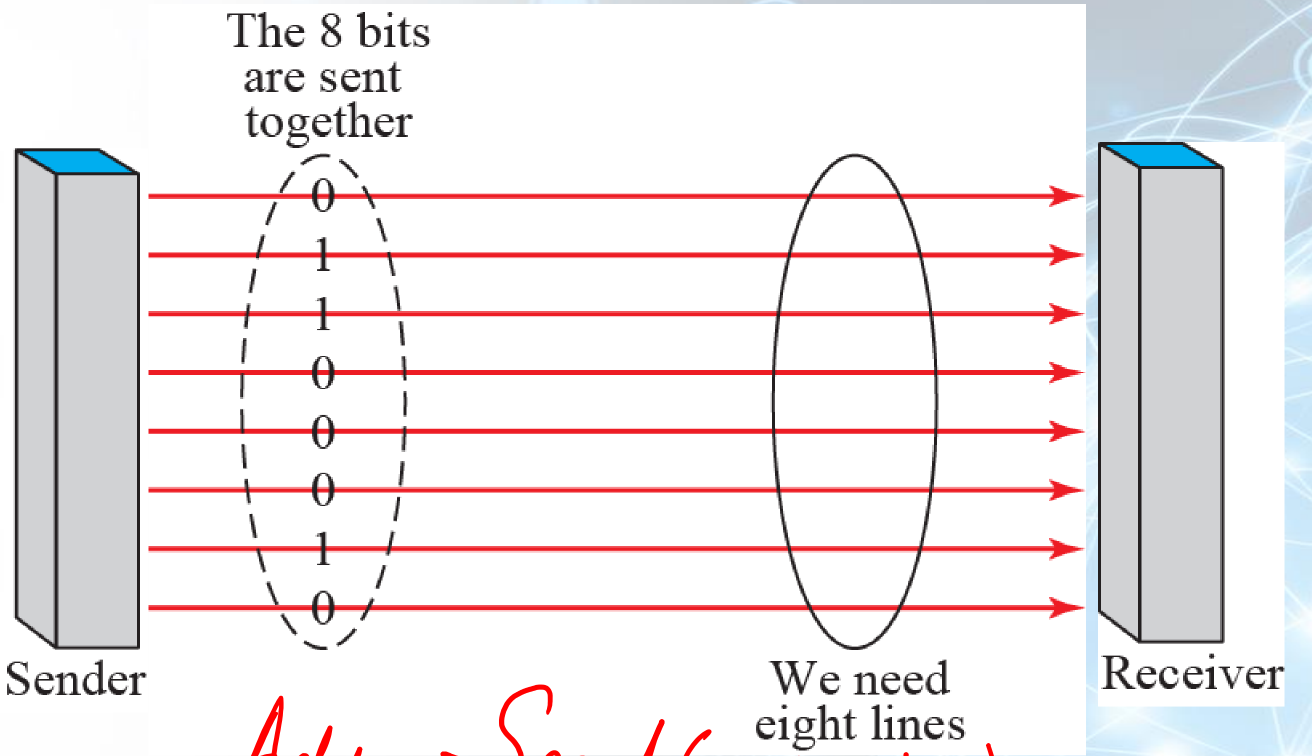


# Parallel Transmission

- Binary data (1s ad 0s) organized in groups of ‘n’ bits
- We send ‘n’ bits at a time instead of just one
- ‘n’ wires required to send ‘n’ bits at one time

# Parallel Transmission

$n = 8$




Adv → Speed (factor of n)

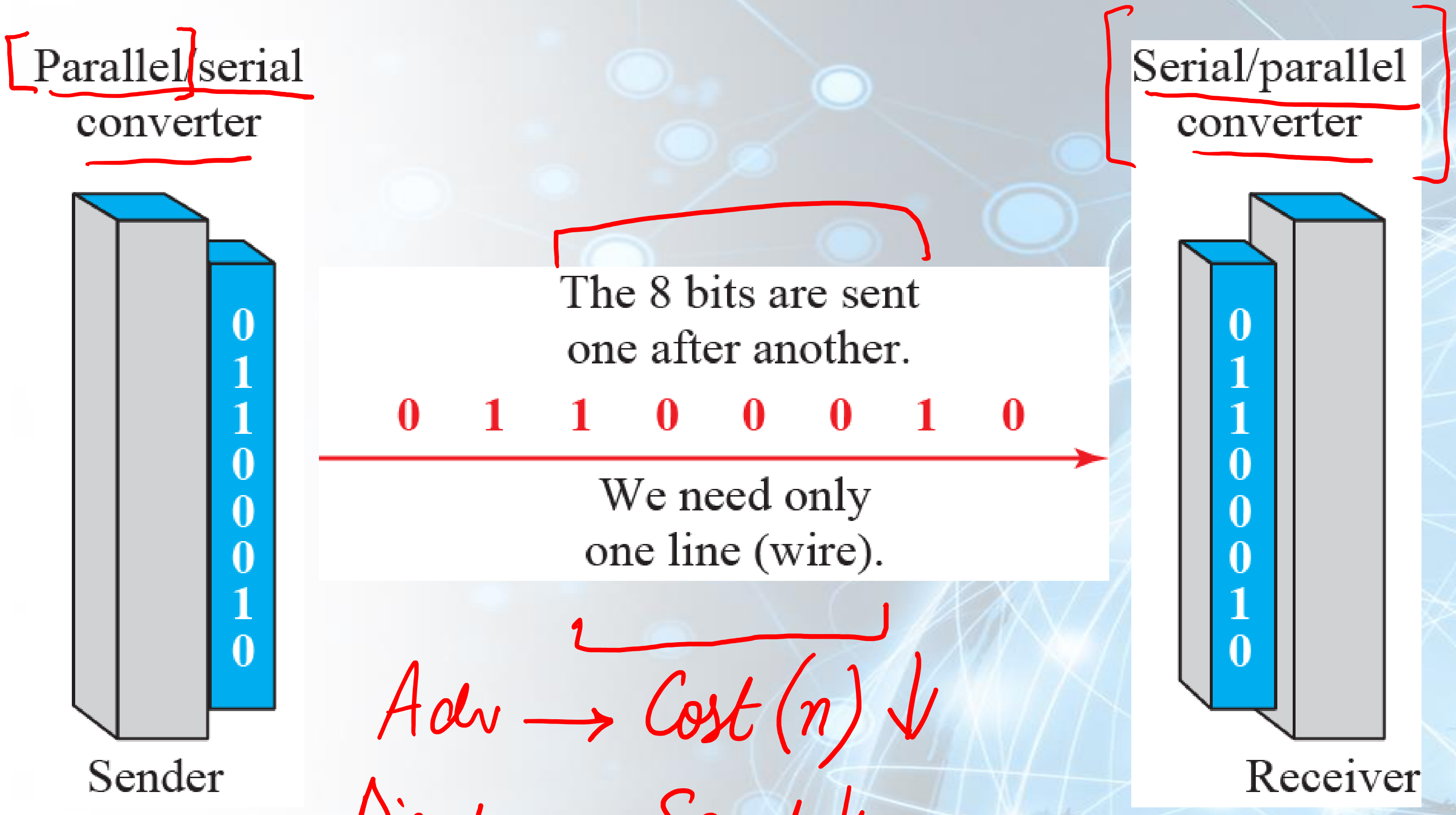
Disadv → Cost (n wires) → Short Distances

# Serial Transmission

- In serial transmission one bit follows another

- Only one communication channel rather than ‘n’ to transmit data

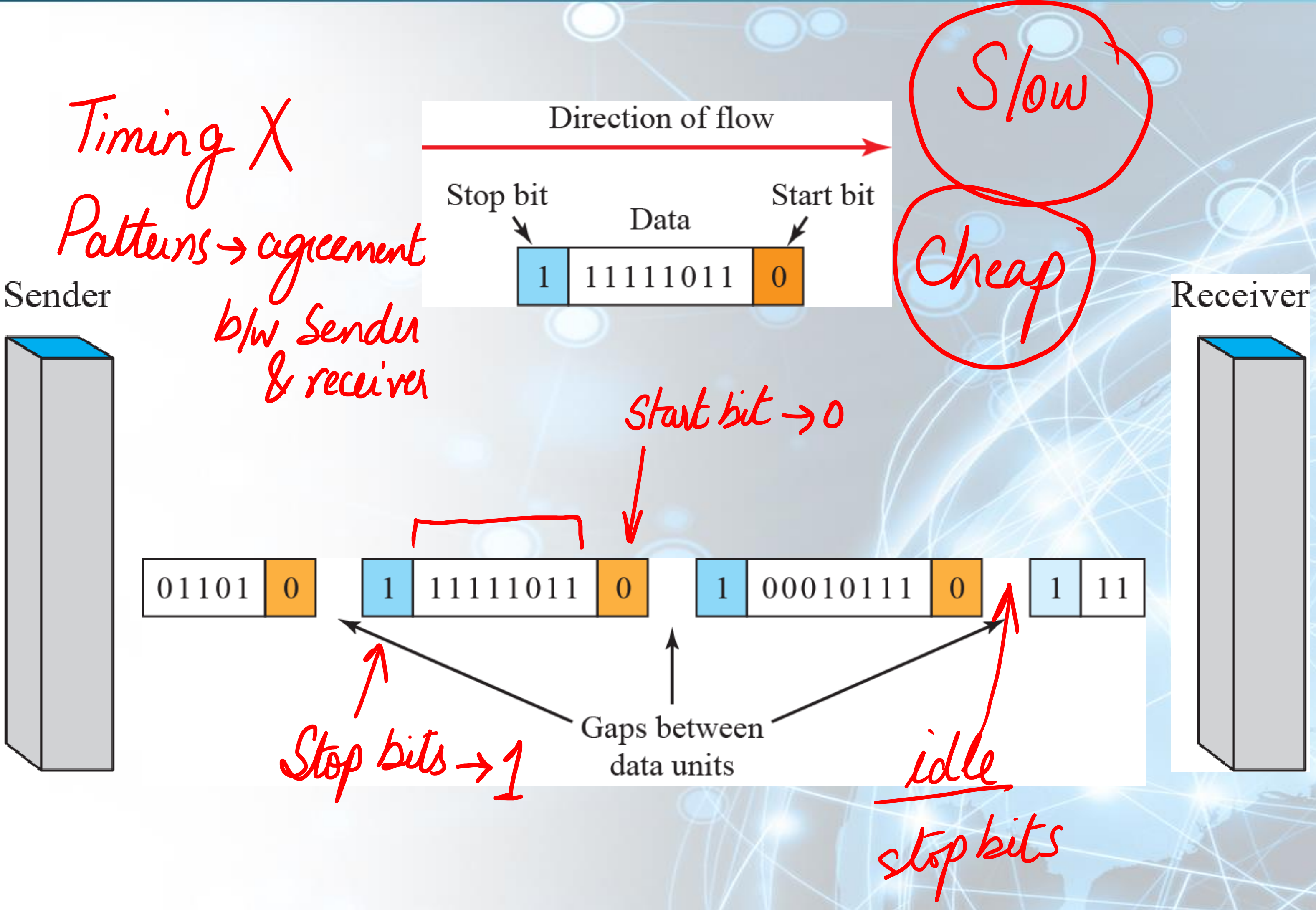
# Serial Transmission




Adv → Cost (n) ↓

Disadv → Speed ↓

# Asynchronous Transmission

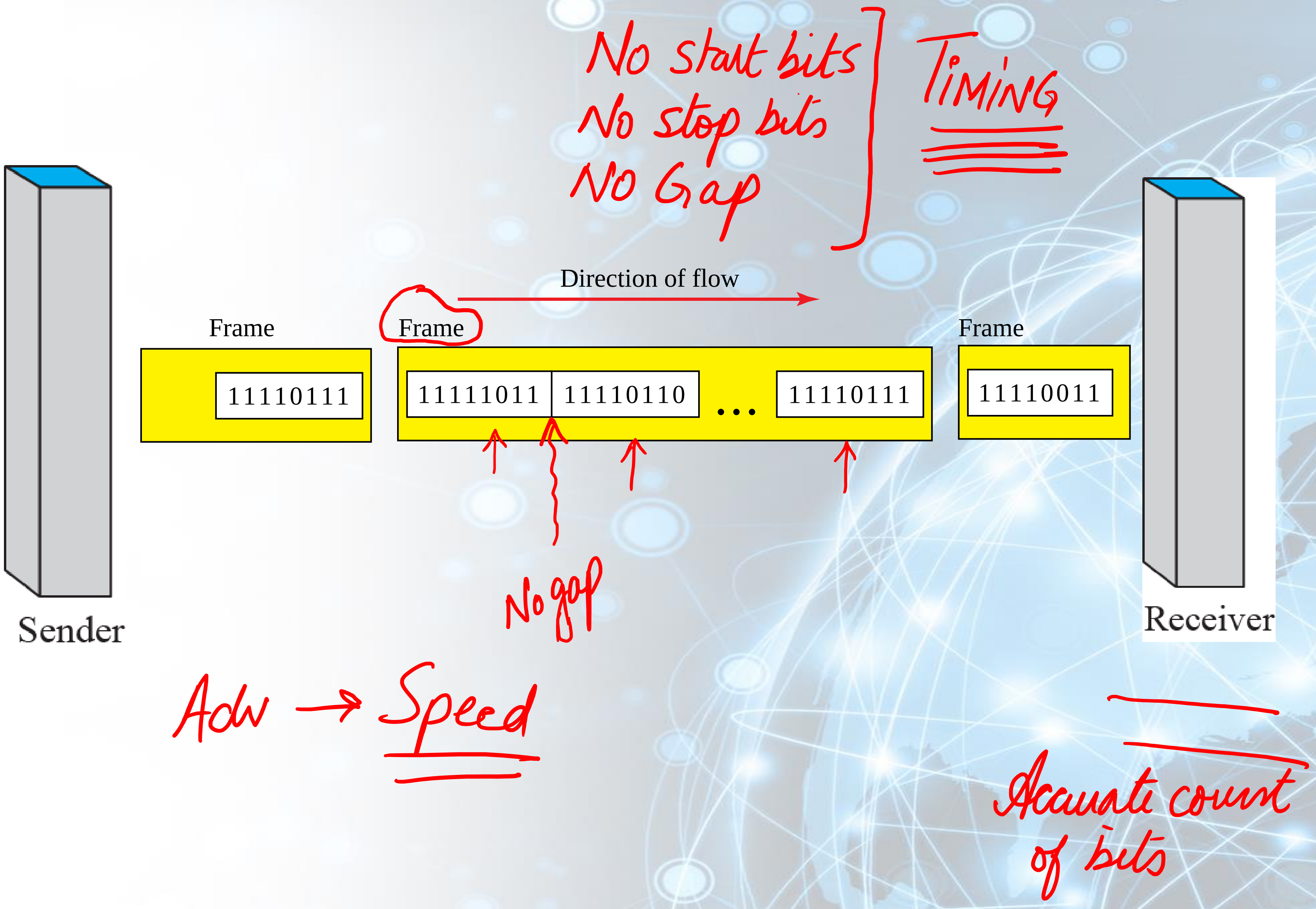


# Serial Transmission

- In serial transmission one bit follows another

- Only one communication channel rather than ‘n’ to transmit data

# Synchronous Transmission



# Isochronous Transmission

- Real time Audio and Video
- Synchronization between characters is not enough
- Entire stream should be synchronized
- Isochronous guarantees fixed rate data

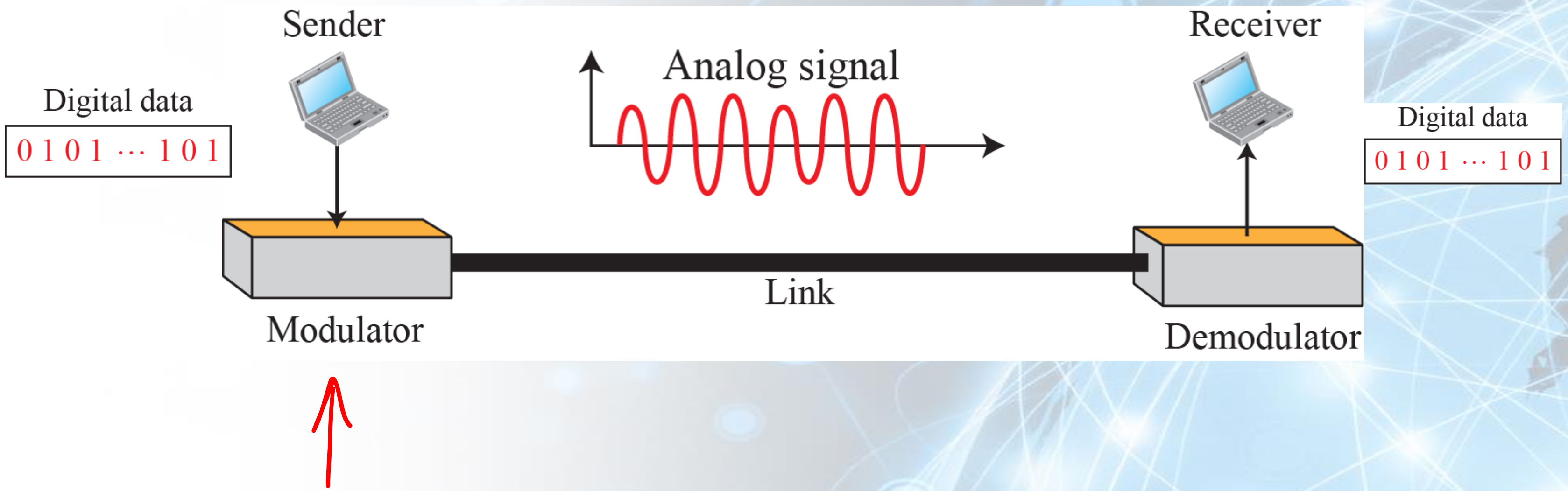
# Digital-to-Analog Conversion

- **Process of changing one of the characteristics of analog signal based on the information in digital data**

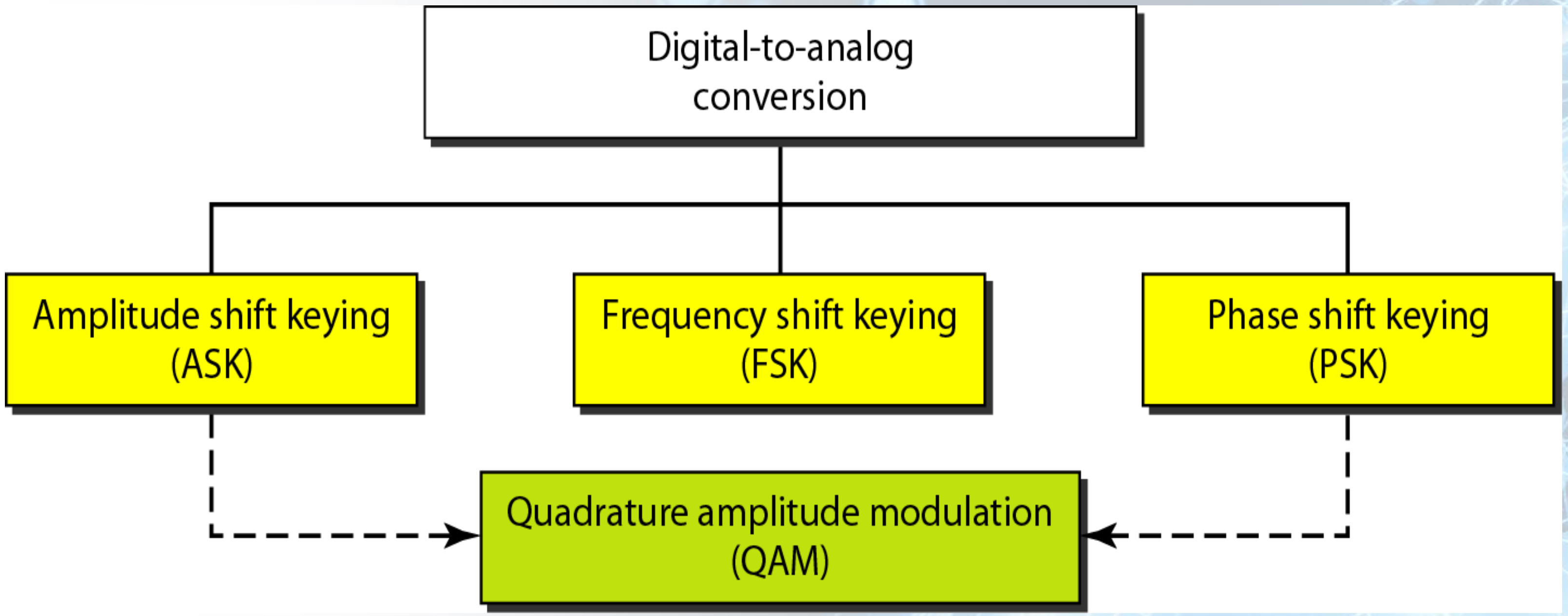
- **A sine wave is defined by 3 characteristics:**
  - ✓ **Amplitude**
  - ✓ **Frequency**
  - ✓ **Phase**

- **By changing one of these characteristics, we can use it to represent a digital signal**

# Digital-to-Analog Conversion



# Types of Digital to Analog Conversion



# Aspects of Digital to Analog Conversion

- **Before we discuss specific methods of digital-to-analog modulation, two basic issues must be reviewed:**
  - ✓ **Bit and Baud rates and**
  - ✓ **The Carrier Signal**

# Aspects of Digital to Analog Conversion

- In Analog Transmission of Digital Data, Baud Rate is less than or equal to the Bit Rate
  - ✓ Data Element vs. Signal Element ✓
  - ✓ Data Rate vs. Signal Rate
- Bandwidth Required ∝ Signal Rate (except FSK)
- Carrier Signal / Modulation (Shift Keying)

Data Element → bit

Signal Element → smallest unit of signal (constant)

$$S = \frac{N}{r} \Rightarrow r = \log_2 L$$

Carrier Signal

Sender → high freq. signal

↳ base of information signal

# Aspects of Digital to Analog Conversion

- **Before we discuss specific methods of digital-to-analog modulation, two basic issues must be reviewed:**
  - ✓ **Bit and Baud rates and**
  - ✓ **The Carrier Signal**

# Example

An analog signal carries 4 bits per signal element. If 1000 signal elements are sent per second, find the bit rate?

$r = 4 \quad S = 1000$

$N = ?$

$S = \frac{N}{r} \Rightarrow N = S \times r$

$N = 1000 \times 4$

$= 4000 bps$

# Example

An analog signal has a bit rate of 8000 bps and a baud rate of 1000 baud. How many data elements are carried by each signal element? How many signal elements do we need?

$N = 8000$ bps

$S = 1000$ baud

$L = ?$

$r = ?$

$S = \frac{N}{r} \Rightarrow r = \frac{N\ (bits)}{S\ (bauds)}$

→ $r = 8$ bits/baud

$r = \log_2 L$

→ $L = 2^r = 2^8 = 256$

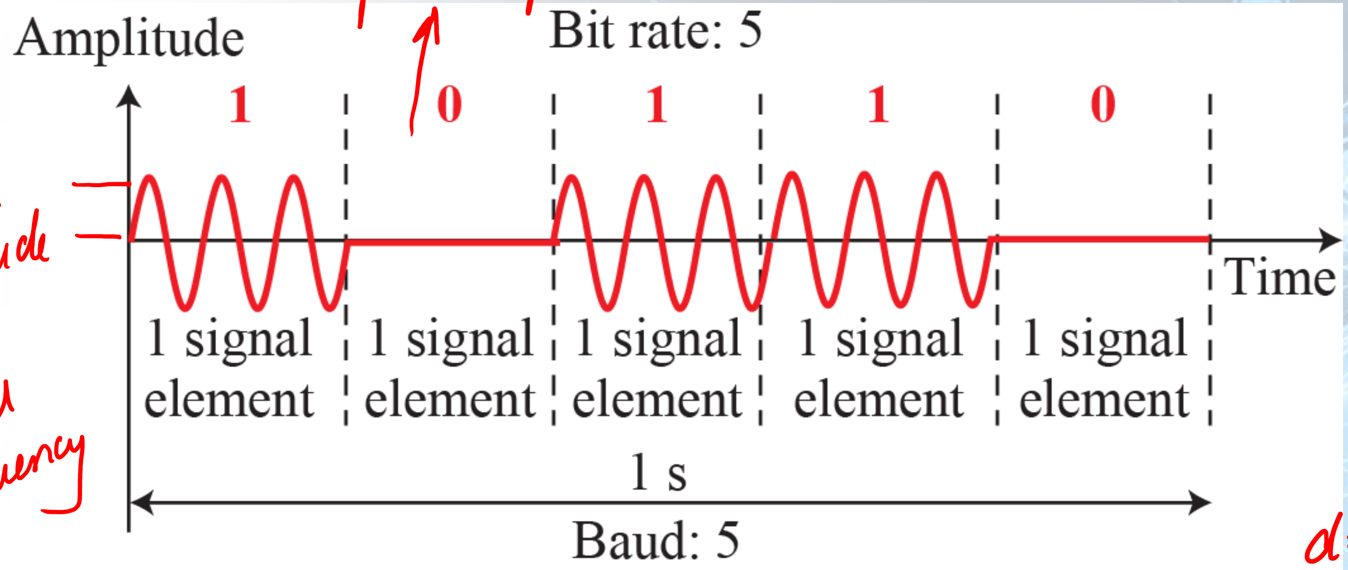
# Amplitude Shift Keying (ASK)

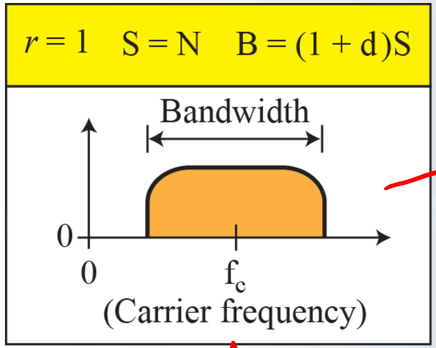
- The amplitude of the carrier signal is varied to create signal elements

- Both frequency and phase remain constant while the amplitude changes

- Binary ASK or On-Off Keying (OOK)

# Binary Amplitude Shift Keying (Binary ASK)




peak amplitude is zero

Same amplitude as carrier frequency

non periodic composite signal

BW ∝ Signal Rate

$d = 0 \rightarrow min$

$d = 1 \rightarrow max$

$B = (1+d)S$

$d \rightarrow$ modulation & filtering process $(0 \rightarrow 1)$

# Amplitude Shift Keying (ASK)

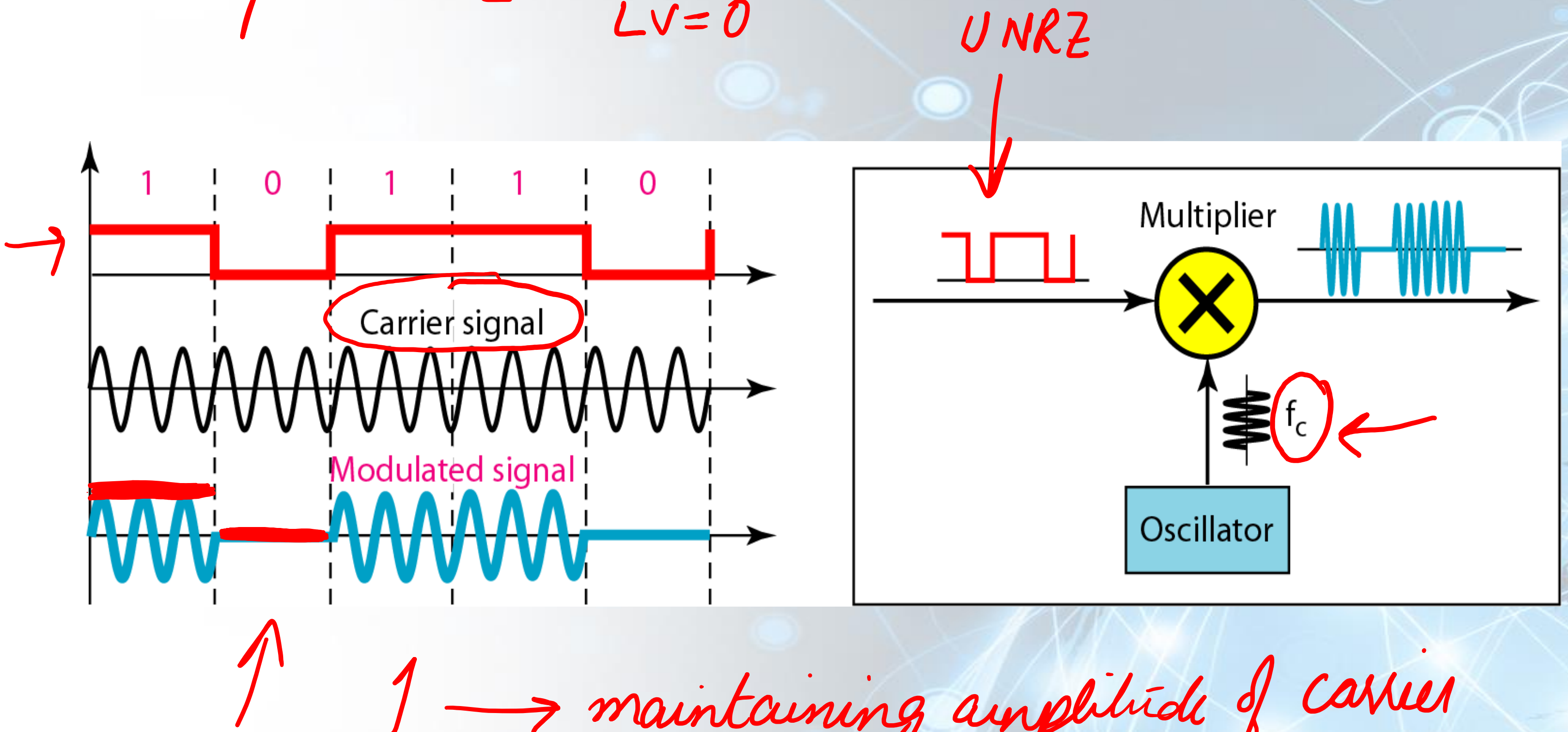
- **The amplitude of the carrier signal is varied to create signal elements**

- **Both frequency and phase remain constant while the amplitude changes**

- **Binary ASK or On-Off Keying (OOK)**

# Implementation of Binary ASK

Unipolar NRZ → HV = 1
LV = 0




1 → maintaining amplitude of carrier
0 → zero amplitude

# Example

We have an available bandwidth of 100 kHz which spans from 200 to 300 kHz. What are the carrier frequency and the bit rate if we modulated our data by using ASK with d = 1?

$r = 1$

$f_c = 250\ kHz$

$B = (1+d)S$

$B = (1+1)S$

$B = 2S$

$B = 2\left(\frac{N}{r}\right)$

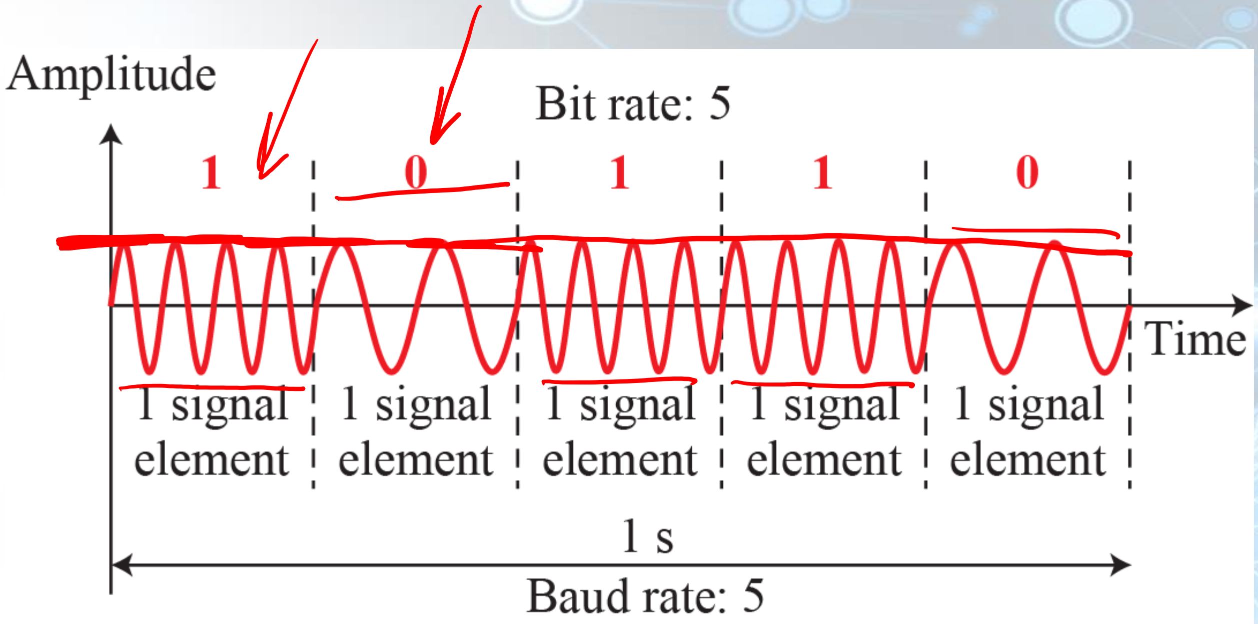
$B = 2N \quad (r = 1)$

$N = \frac{B}{2} = \frac{100\ kHz}{2} = 50\ kbps$

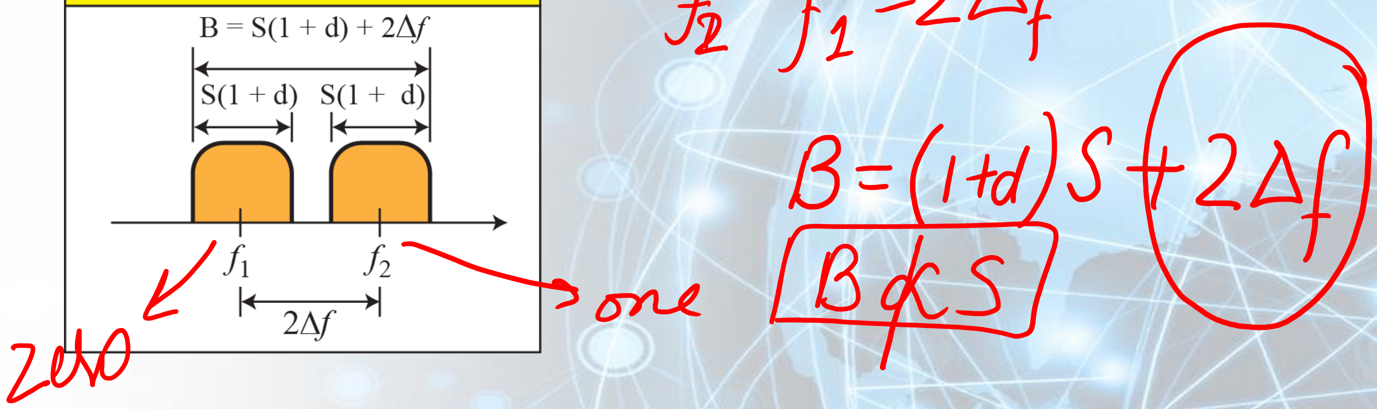
# Frequency Shift Keying (FSK)

- The frequency of the carrier signal is varied to represent data
- The frequency of the modulated signal is constant for the duration of one signal element, but changes for the next signal element if the data element changes
- Both peak amplitude and phase remain constant

# Binary Frequency Shift Keying




$r = 1 \quad S = N \quad B = (1 + d)S + 2\Delta f$



# Frequency Shift Keying (FSK)

- **The frequency of the carrier signal is varied to represent data**
- **Both peak amplitude and phase remain constant**

# Example

We have an available bandwidth of 100 kHz which spans from 200 to 300 kHz. What should be the carrier frequency and the bit rate if we modulated our data by using FSK with d = 1?

$$B = (1+d) \times S + 2\Delta f$$

$$\Delta f = 50 kHz$$

$$B = 2S + 50$$

$$2S + 50 = 100$$

$$2S = 50 kHz$$

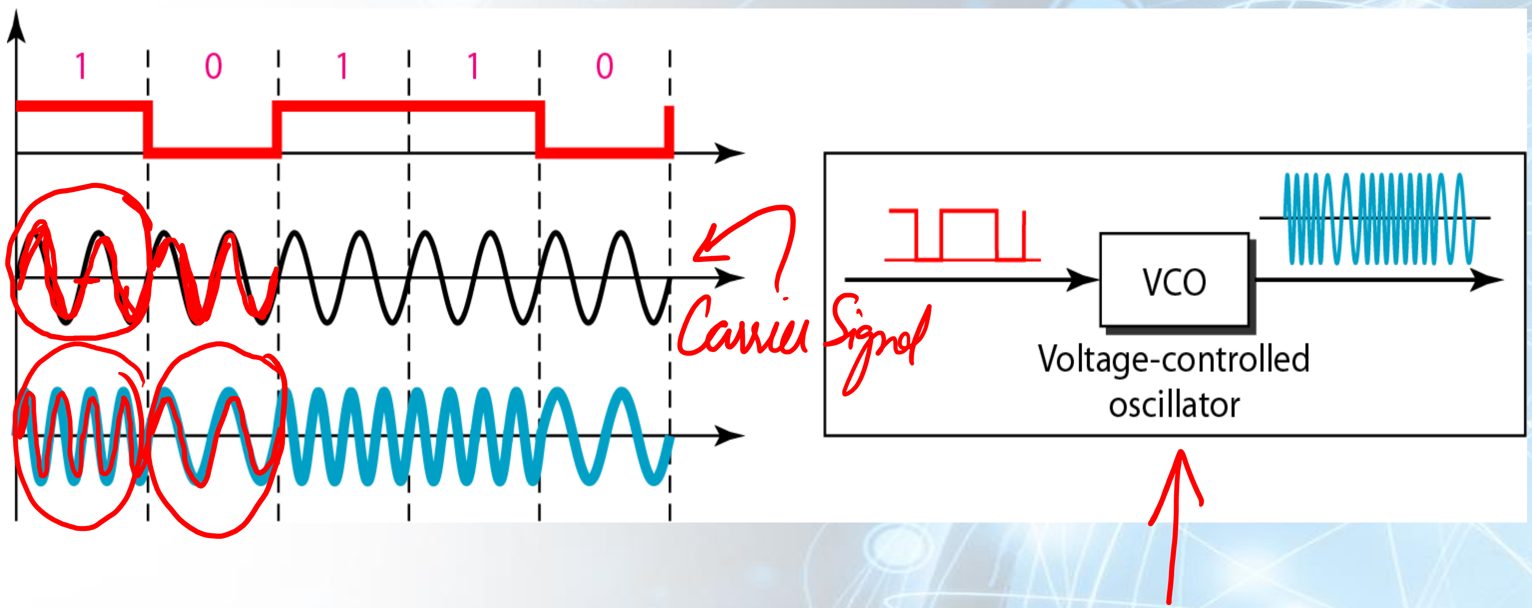
$$S = 25 kbaud$$

$$N = S$$

$$N = 25 kbps$$

# Implementation of BFSK

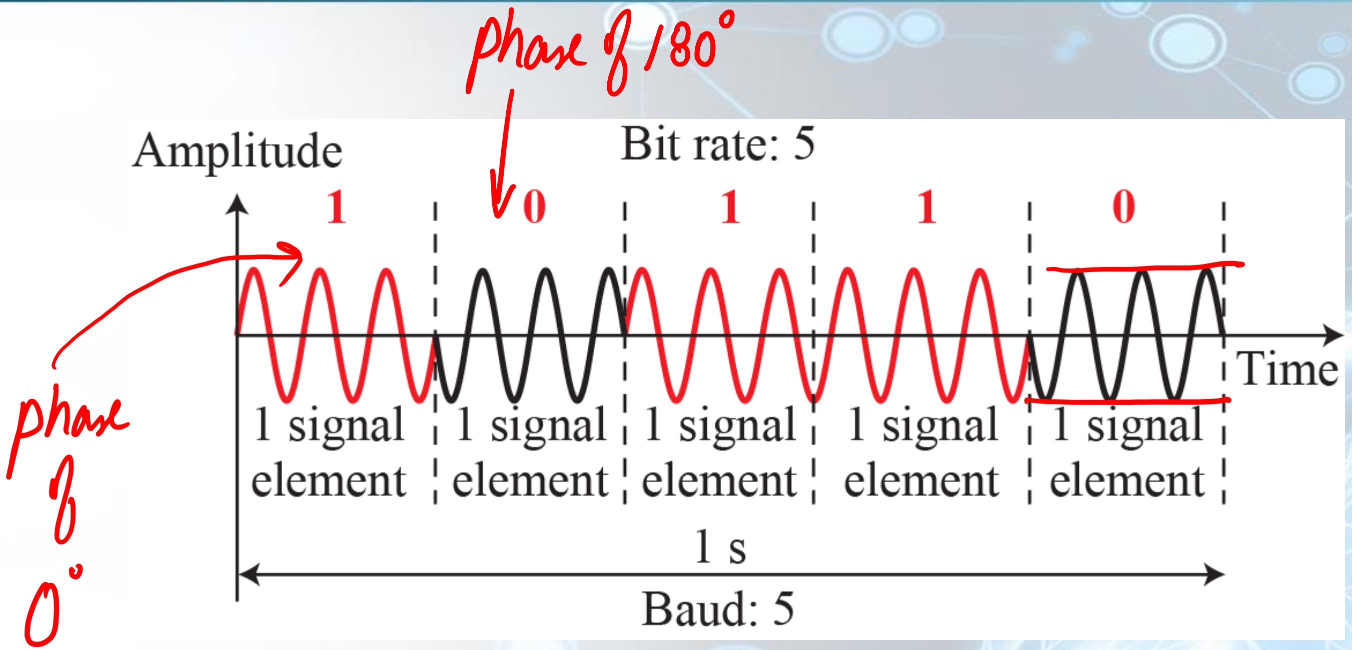
Unipolar NRZ

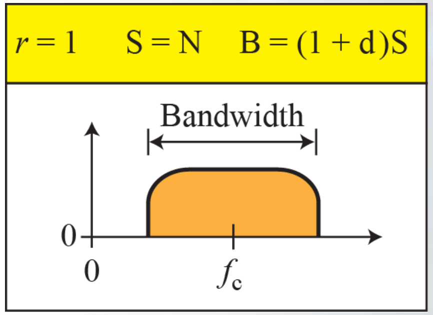


# Phase Shift Keying (PSK)

- The phase of the carrier is varied to represent two or more different signal elements
- Both peak amplitude and frequency remain constant
- PSK is relatively common than ASK or FSK

# Binary Phase Shift Keying



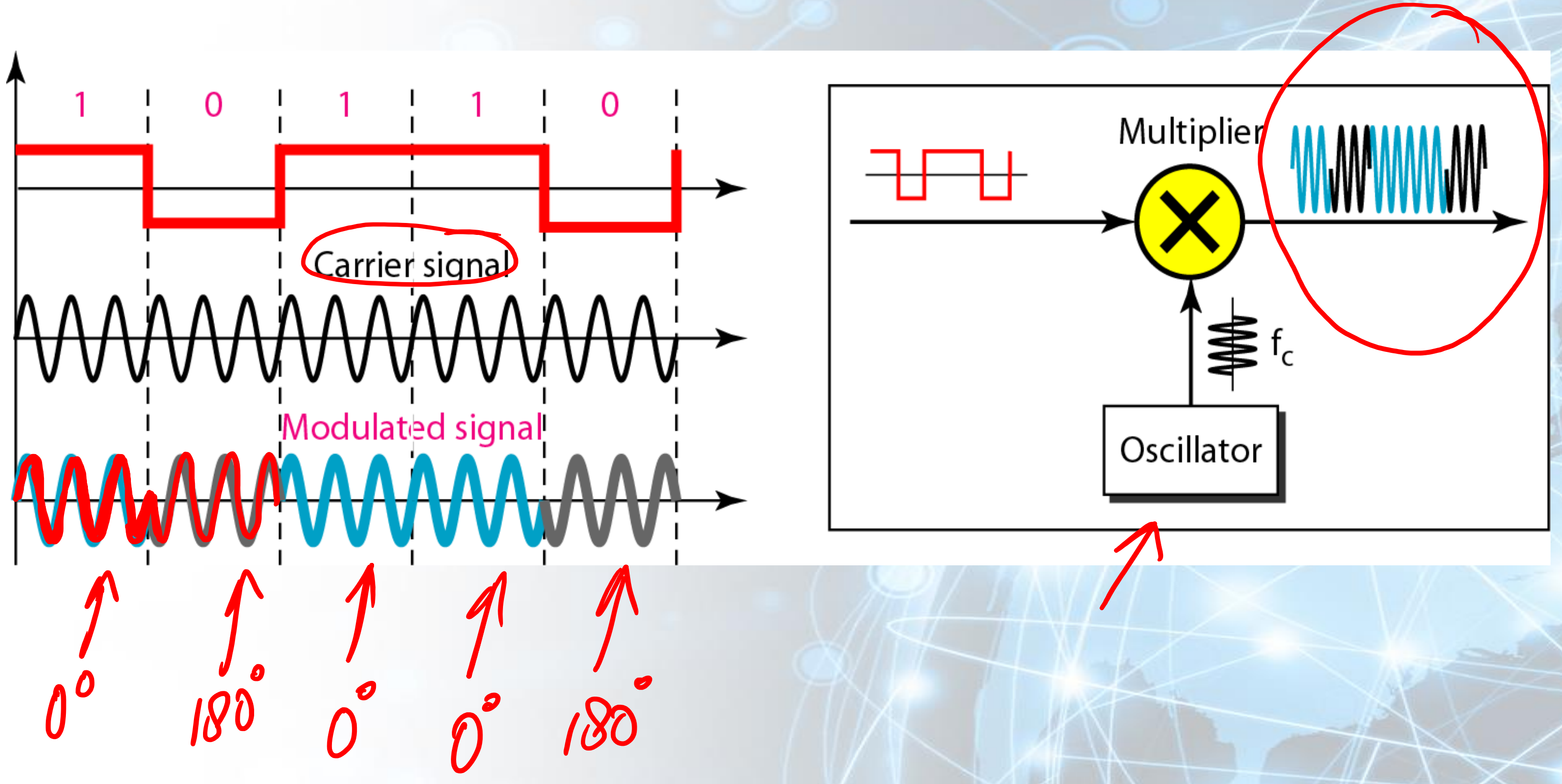




$B = (1+d)S$

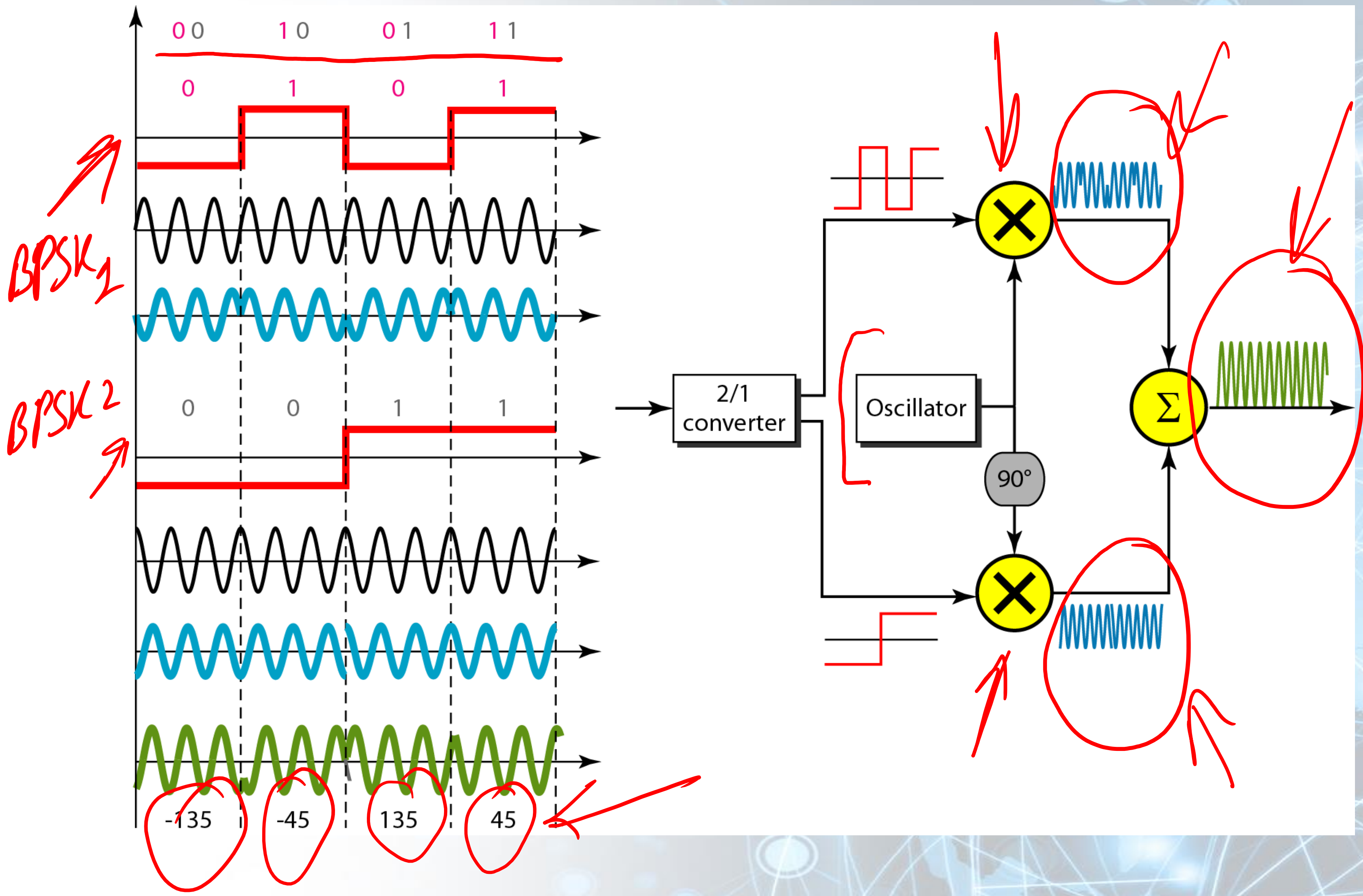
$B_{PSK} = B_{ASK}$

# Implementation of BPSK

Polar NRZ



# QPSK and its Implementation



# Example

**Find the bandwidth for a signal transmitting at 12 Mbps for QPSK. The value of d = 0.**

$r = 2$

$S = \frac{N}{r}$

$= \frac{12\text{ Mbps}}{2}$

$= 6\text{ Mbaud}$

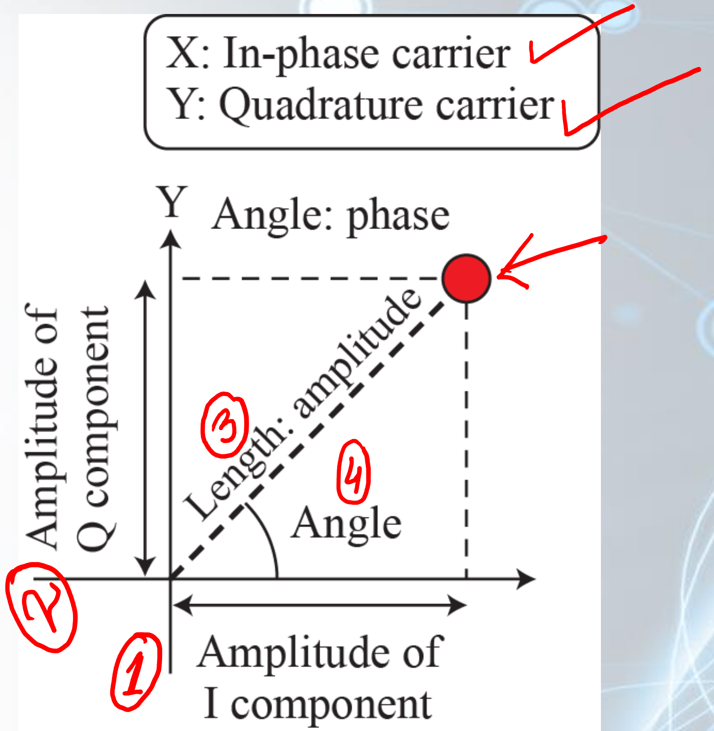
$d = 0 \rightarrow B = S = \underline{6\text{ MHz}}$

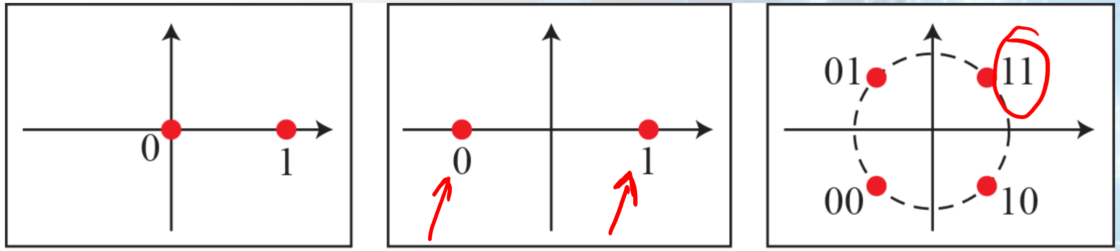
# Constellation Diagram

- Helps us define the phase and amplitude of a signal element when we are using two carriers (one in phase and other in quadrature)

- Signal element is represented as a dot

# Constellation Diagram



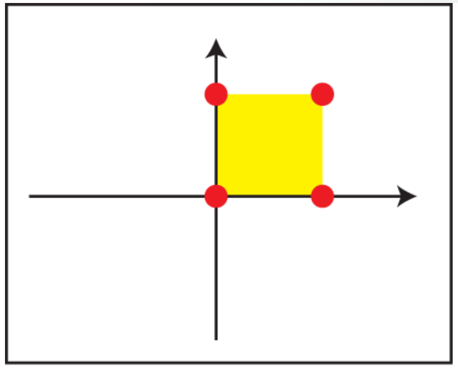




a. BASK (OOK) b. BPSK c. QPSK

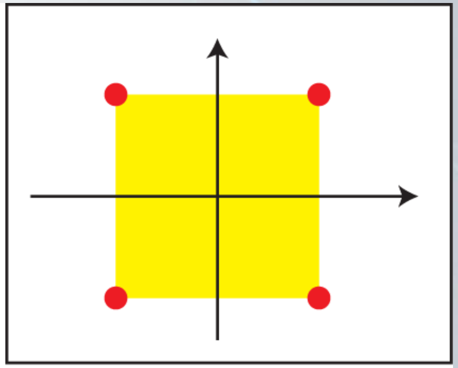
# Quadrature Amplitude Modulation (QAM)

- **PSK is limited by the ability of the equipment to distinguish small differences in phase which limits its potential bit rate**
- **We have been altering only one of the three characteristics of a sine wave at a time; but what if we alter two?**
- **Why not combine ASK and PSK?**

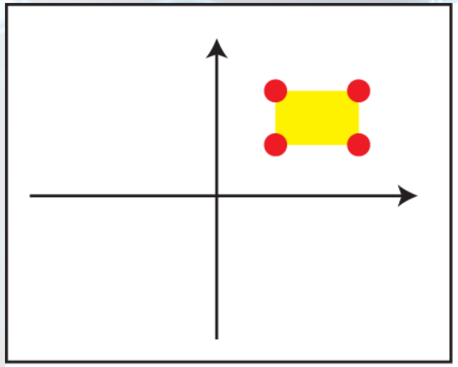
# Constellation diagrams for some QAMs



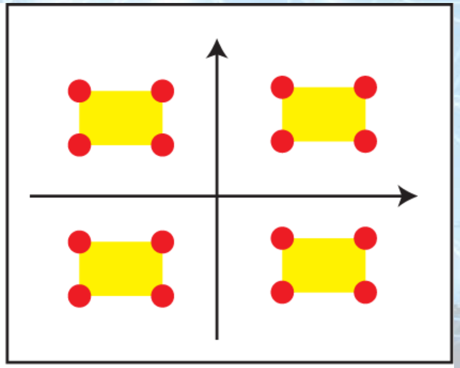
a. 4-QAM



b. 4-QAM



c. 4-QAM

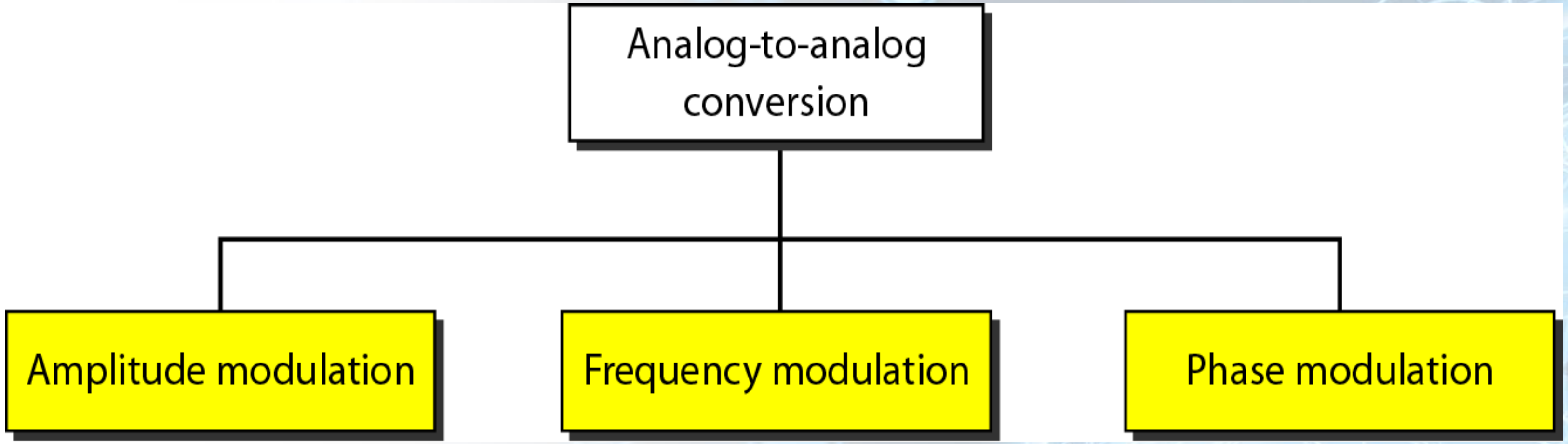


d. 16-QAM

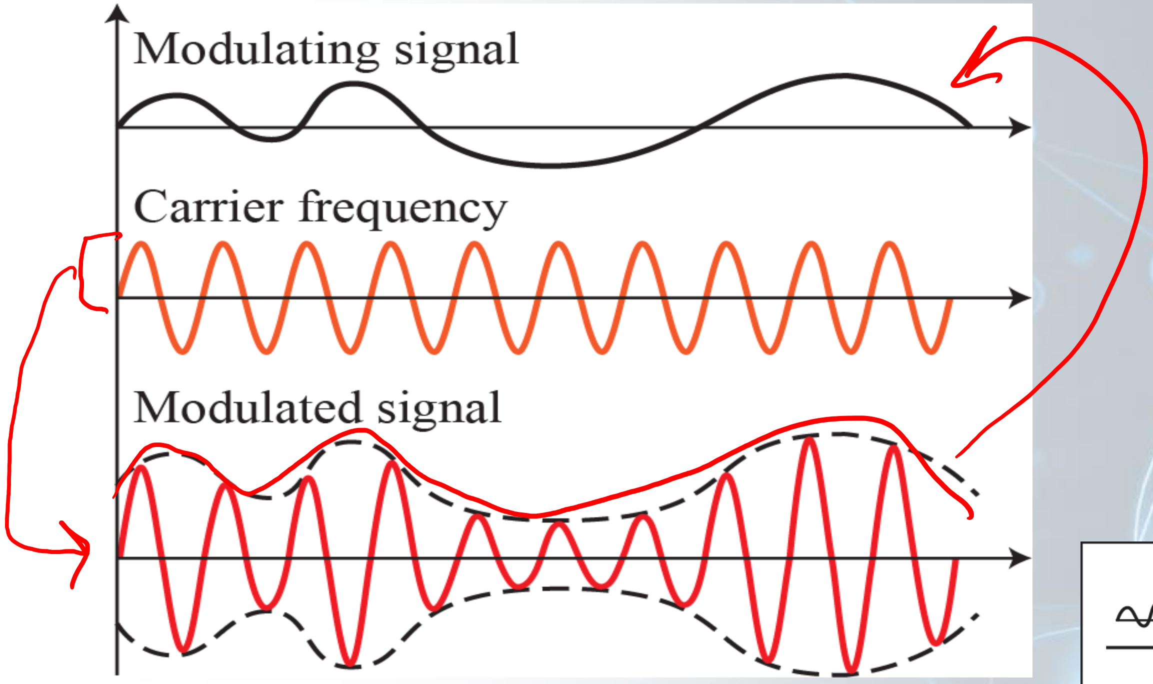
# Analog-to-Analog Conversion

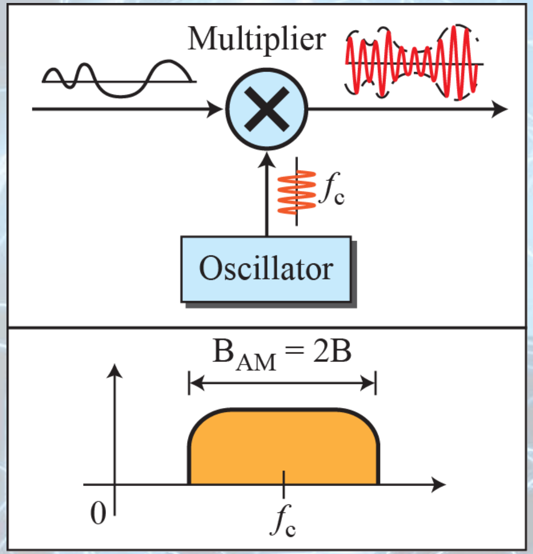
- Representation of Analog information by an Analog signal
- Amplitude Modulation (AM)
- Frequency Modulation (FM)
- Phase Modulation (PM)

# Types of Analog-to-Analog Modulation



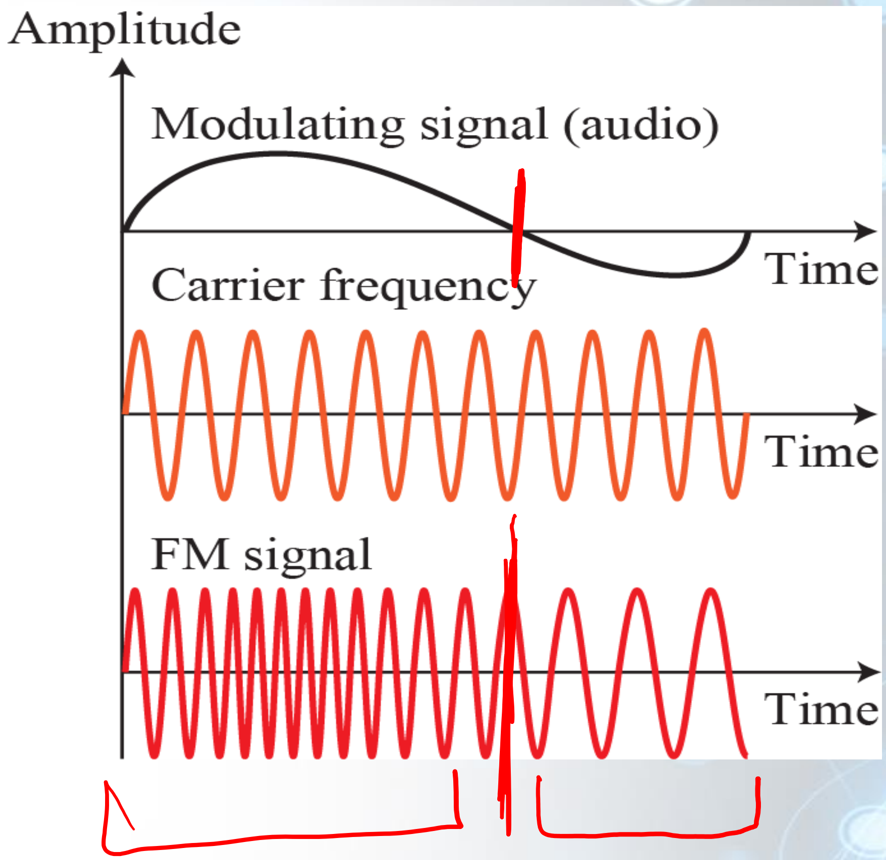
# Amplitude modulation



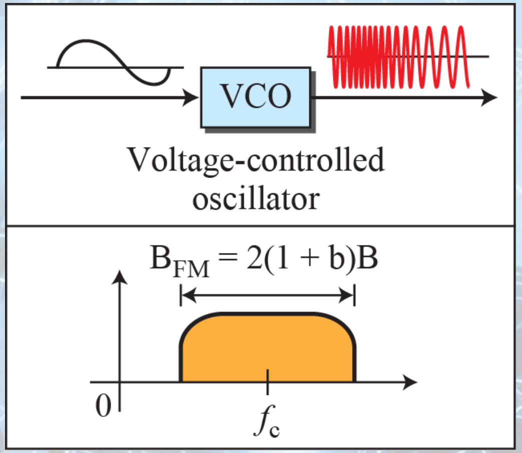

$B_{AM} = 2B$
$f_c$

# Frequency Modulation




$B_{FM} = 2(1+\beta)B$

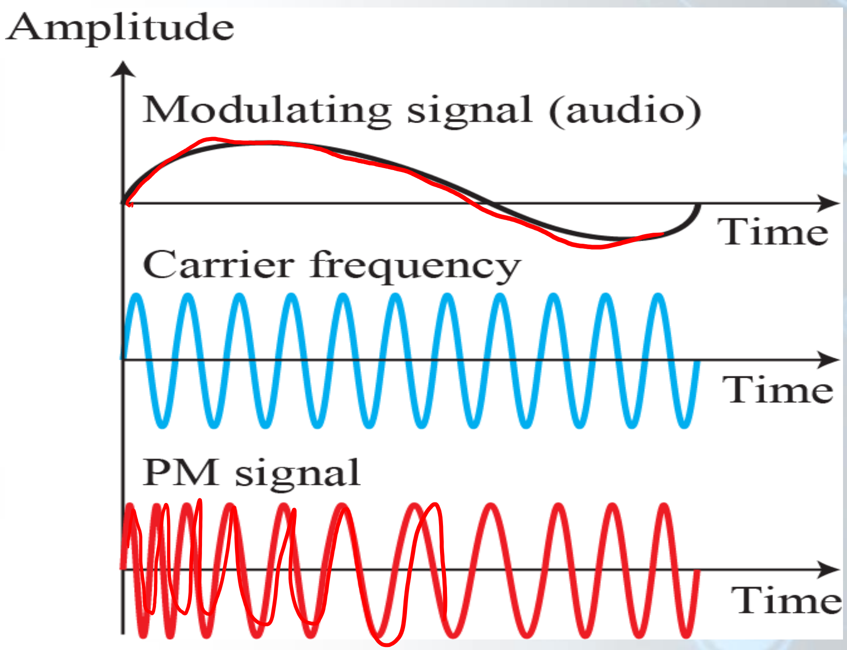
↳ Beta = 4



# Analog-to-Analog Conversion

- **Representation of Analog information by an Analog signal**
- **Amplitude Modulation (AM)**
- **Frequency Modulation (FM)**
- **Phase Modulation (PM)**

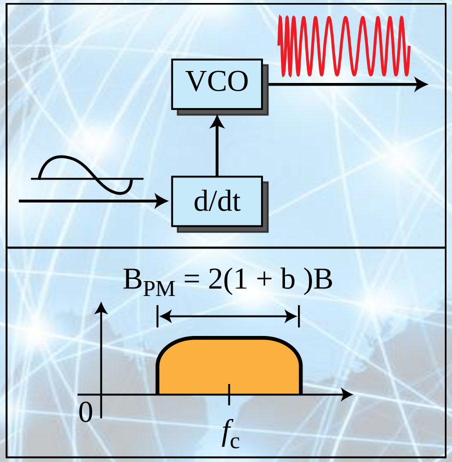
# Phase Modulation




$$B_{PM} = 2(1+\beta)B$$

$\beta = 1$ narrowband

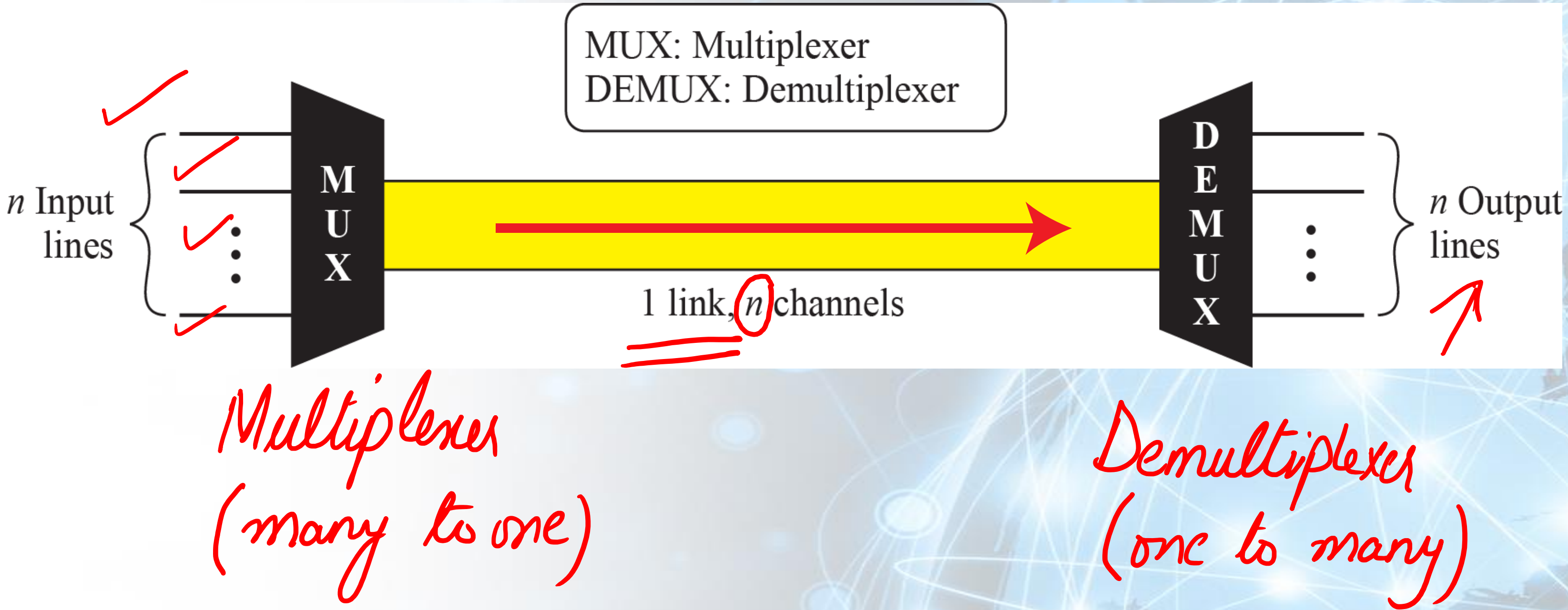
$\beta = 3$ wideband



# Multiplexing

- Simultaneous transmission of multiple signals across a single data link
- As data & telecomm use increases, so does traffic
  - ✓ Add individual links each time a new channel is needed
  - ✓ Install higher-bandwidth links and use each to carry multiple signals

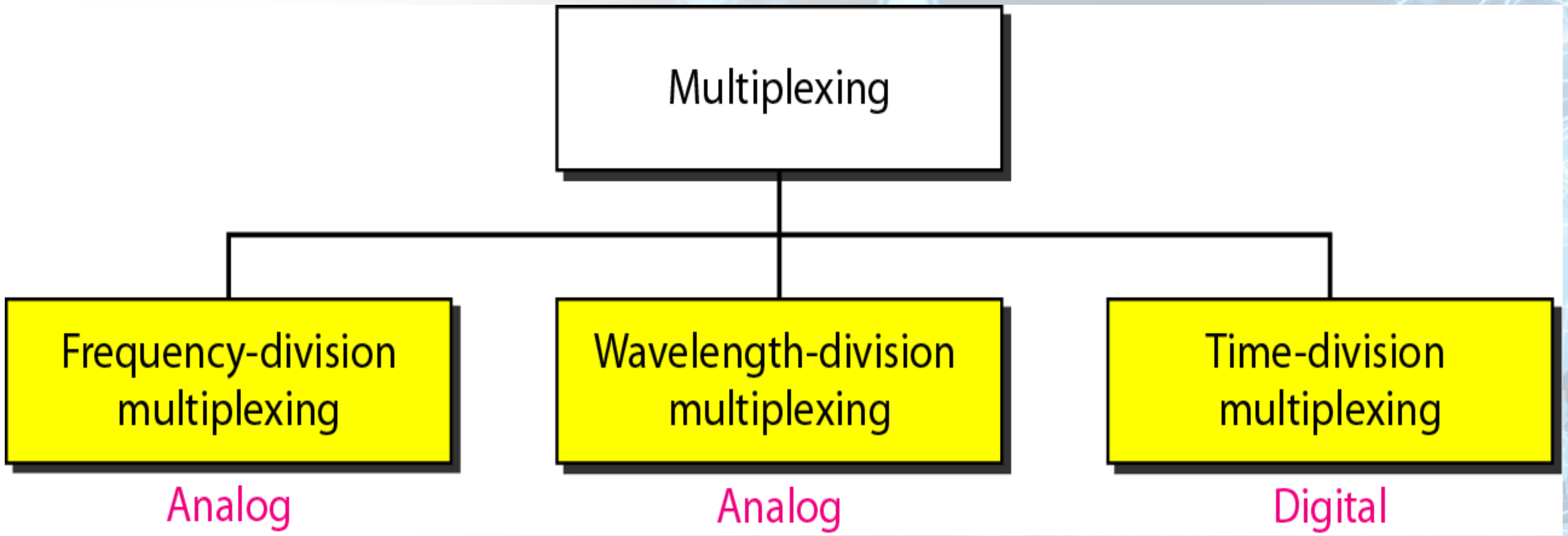
# Dividing a Link into Channels



# Multiplexing

- **Simultaneous transmission of multiple signals across a single data link**

# Categories of Multiplexing



# Frequency-Division Multiplexing

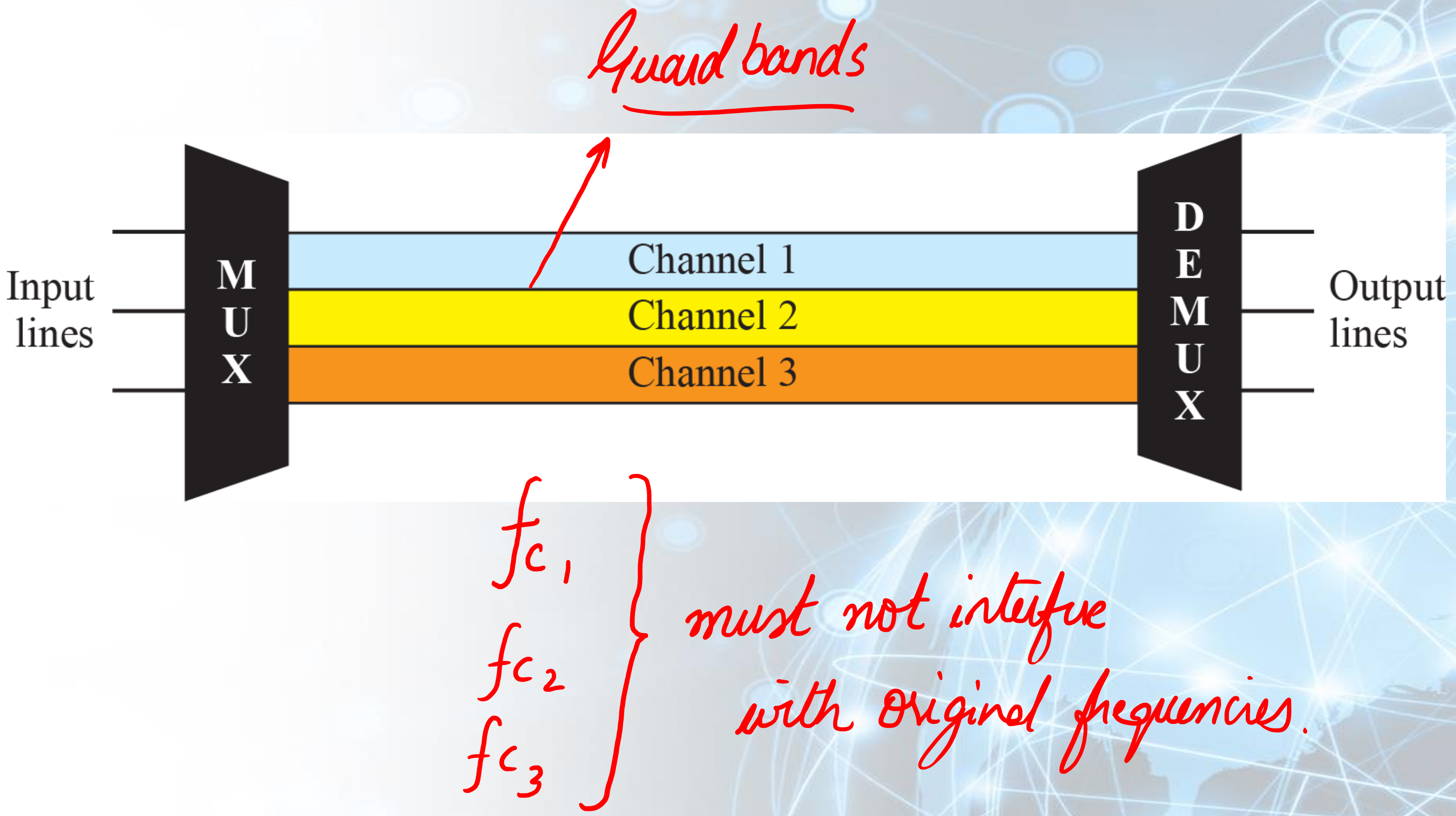
- **An analog technique that can be applied when the bandwidth of a link (in hertz) is greater than the combined bandwidths of the signals to be transmitted**

- **Signals generated by each sending device modulate different carrier frequencies**

# Frequency-Division Multiplexing

**These modulated signals are then combined into a single composite signal that can be transported by the link**

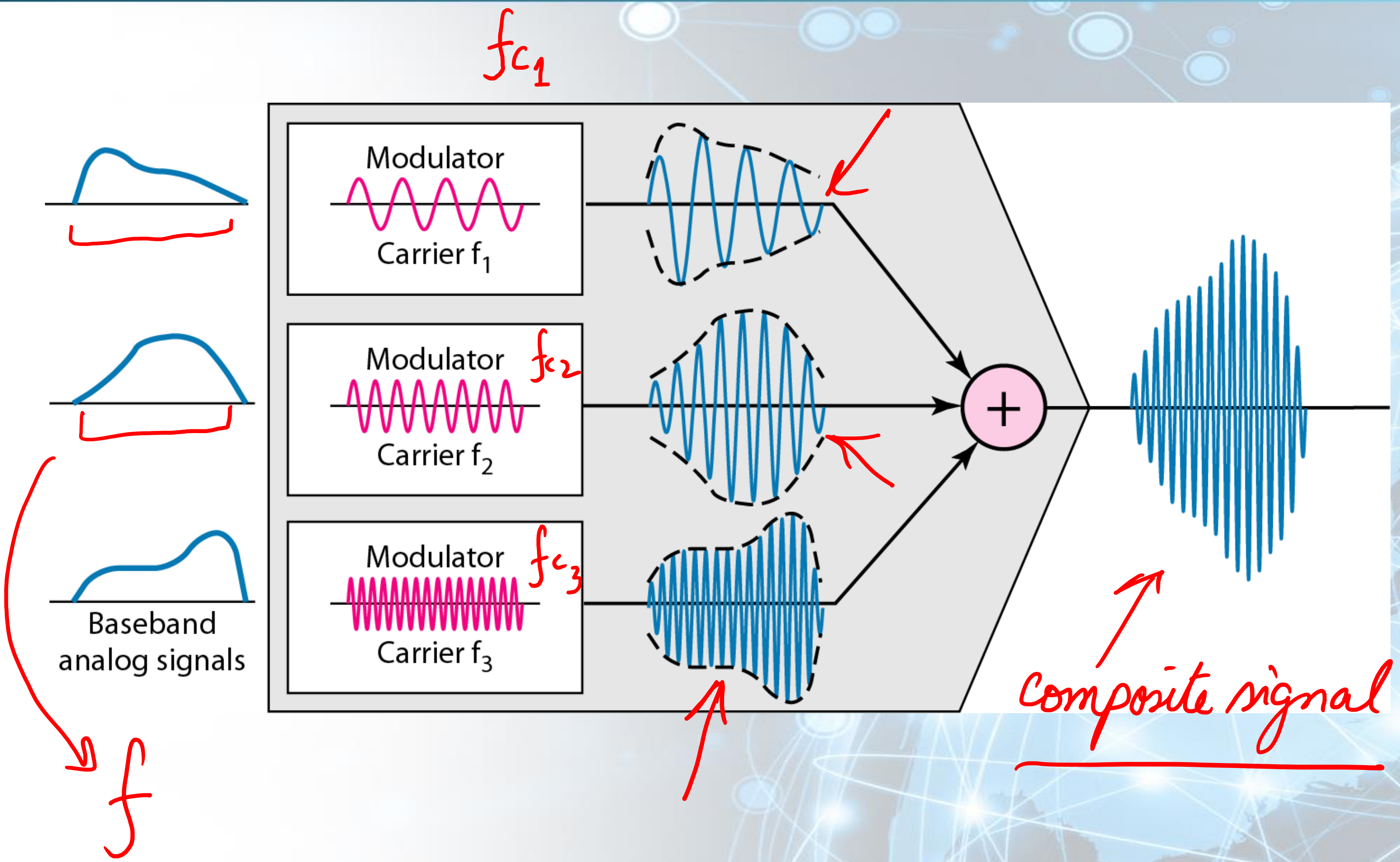
# Frequency-Division multiplexing



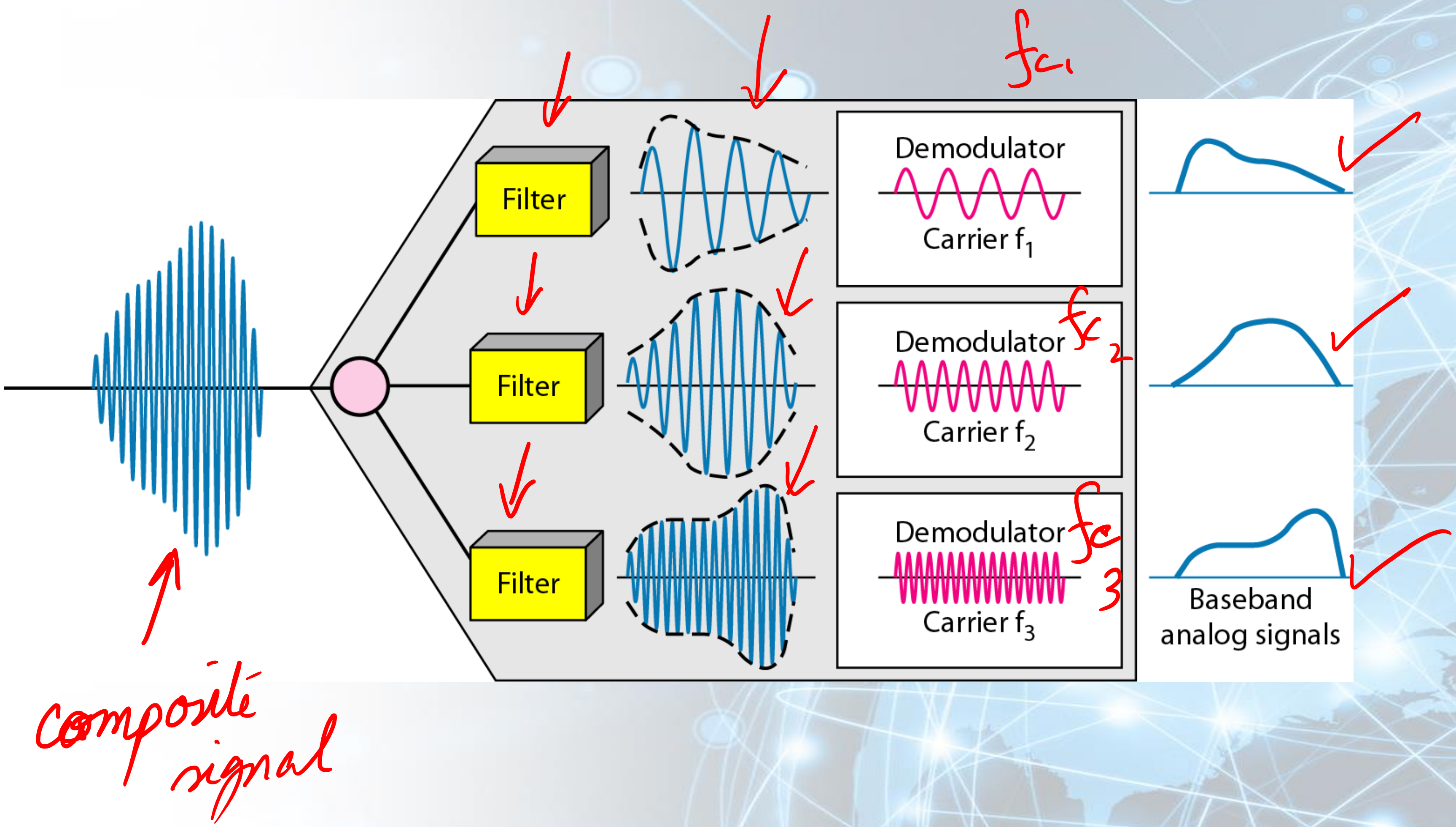
# Frequency-Division Multiplexing

- An analog technique that can be applied when the bandwidth of a link (in hertz) is greater than the combined bandwidths of the signals to be transmitted

# FDM Multiplexing

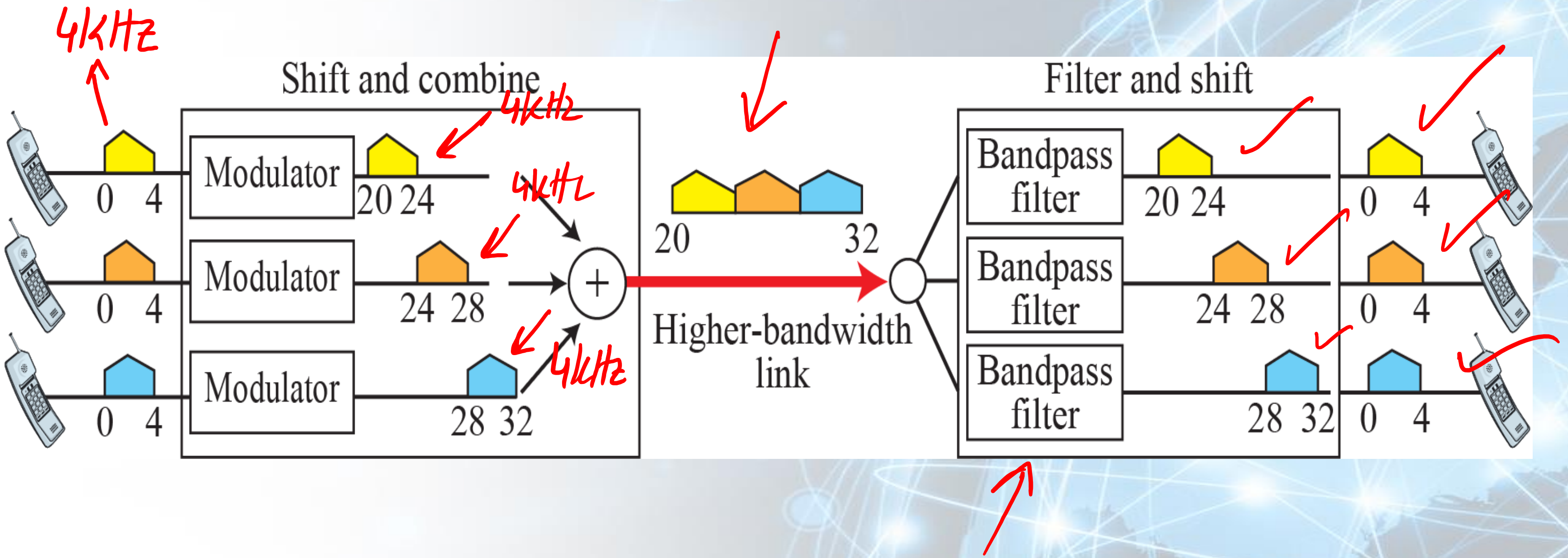


# FDM De-Multiplexing



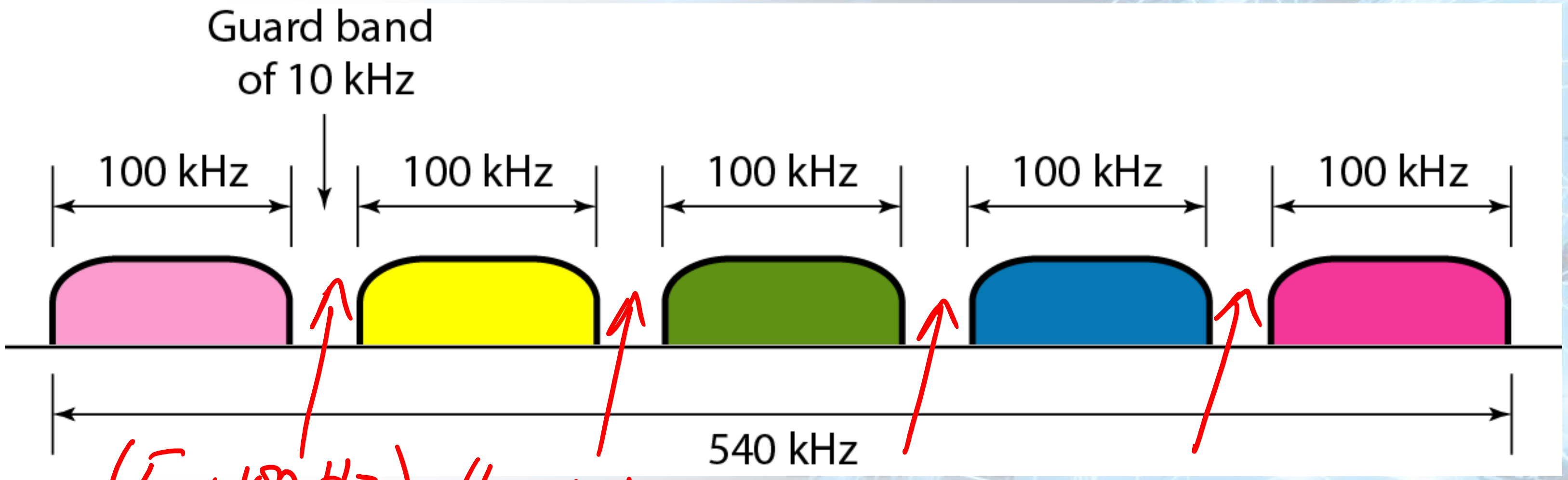
# Example

**Assume that a voice channel occupies a bandwidth of 4 kHz. We need to combine three voice channels into a link with a bandwidth of 12 kHz, from 20 to 32 kHz. Show the configuration, using the frequency domain. Assume there are no guard bands.**



# Example

**Five channels, each with a 100-kHz bandwidth, are to be multiplexed together. What is the minimum bandwidth of the link if there is a need for a guard band of 10 kHz between the channels to prevent interference?**



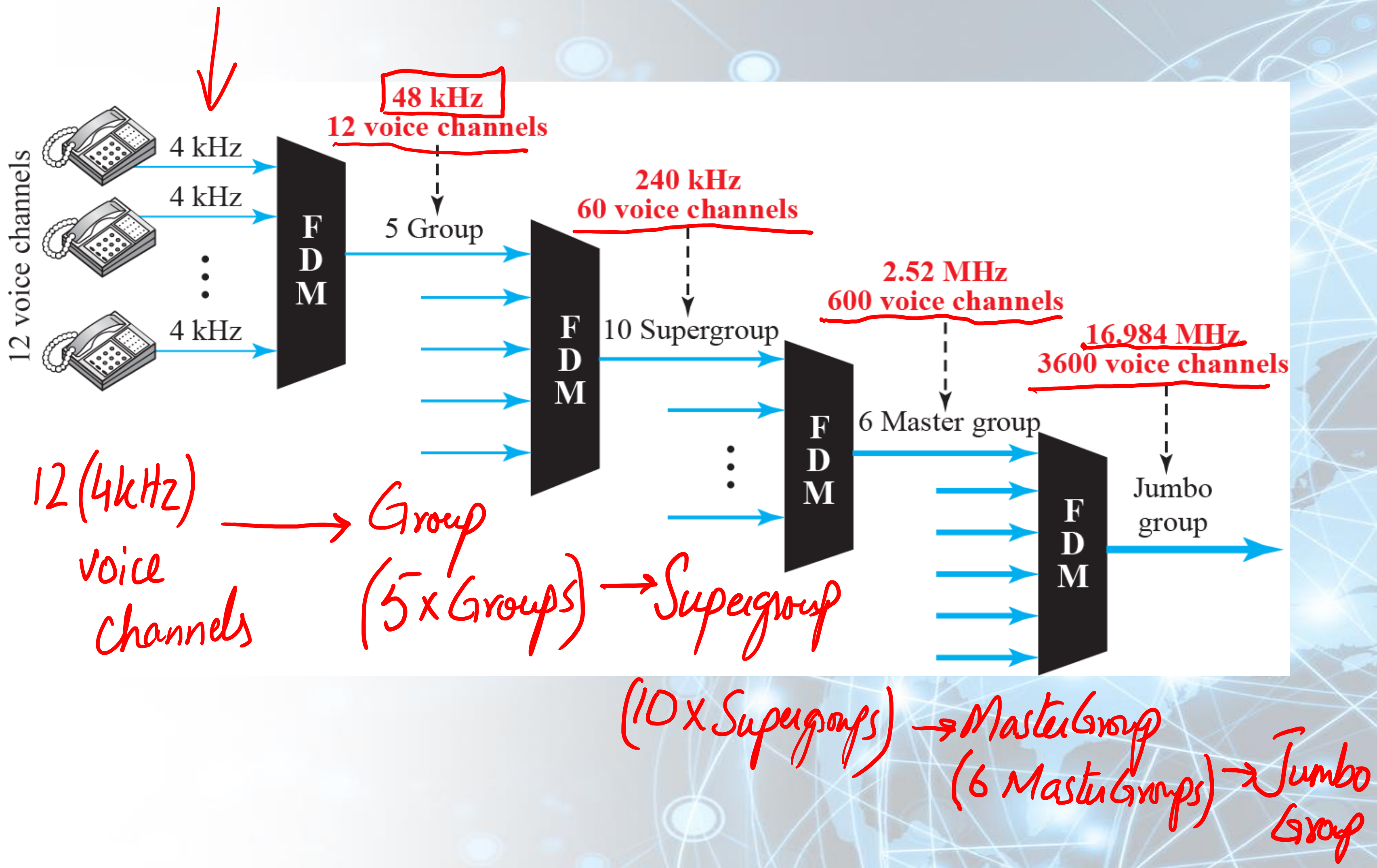

(5 x 100 Hz) + (4 x 10 kHz) = 540 KHZ

# The Analog Carrier System

- Telephone companies multiplex signals from lower-bandwidth lines on to higher-bandwidth lines

- For Analog, FDM is used

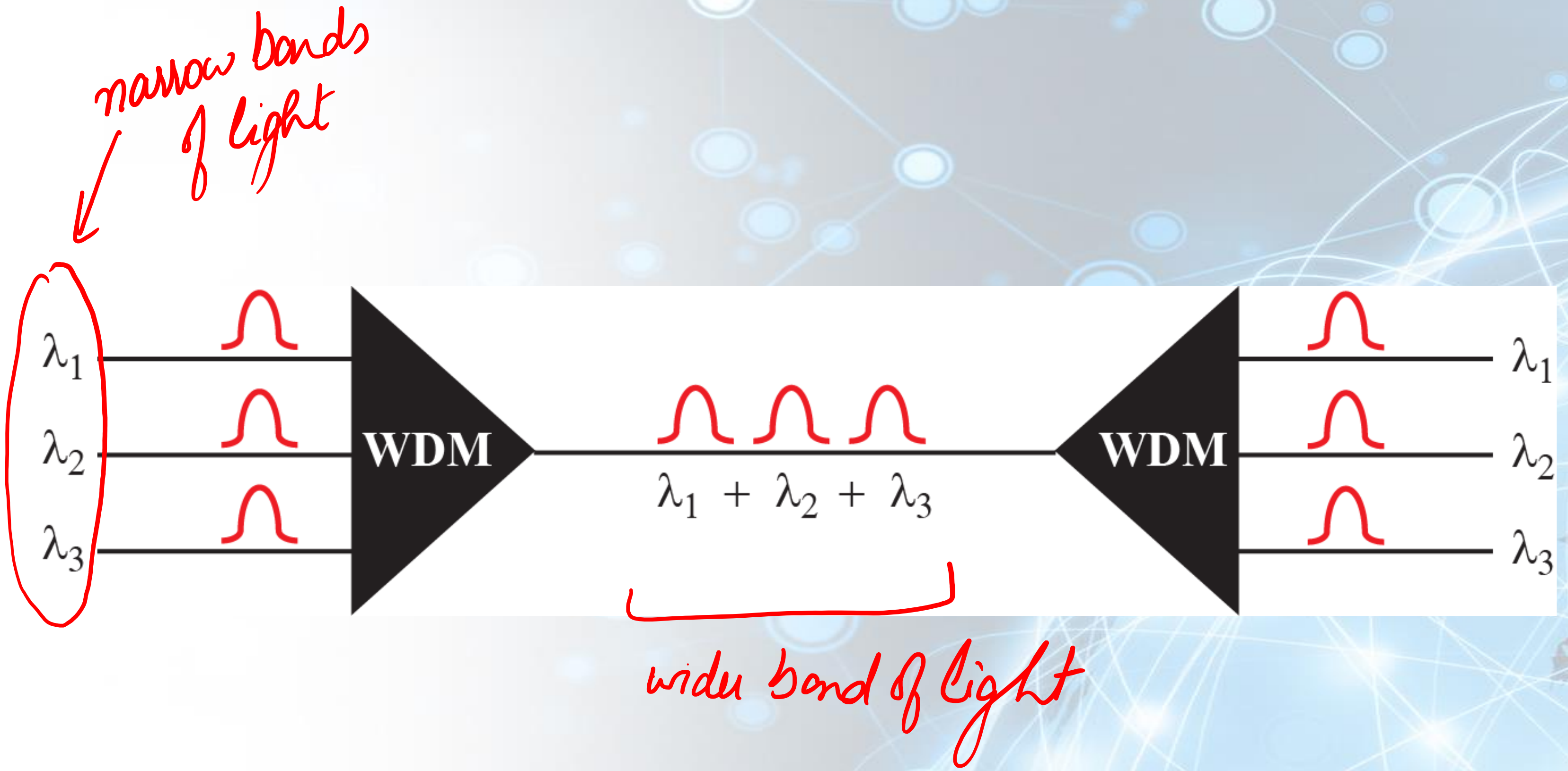
# Analog Hierarchy



# Wavelength-Division Multiplexing

- **Designed to use the high-data-rate capability of fiber-optic cable**
- **Fiber data rate is higher than the data rate of metallic transmission cable**
- **Using a fiber-optic cable for a single line wastes the available bandwidth**
- **Multiplexing allows us to combine several lines into one**

# Wavelength-Division Multiplexing (WDM)

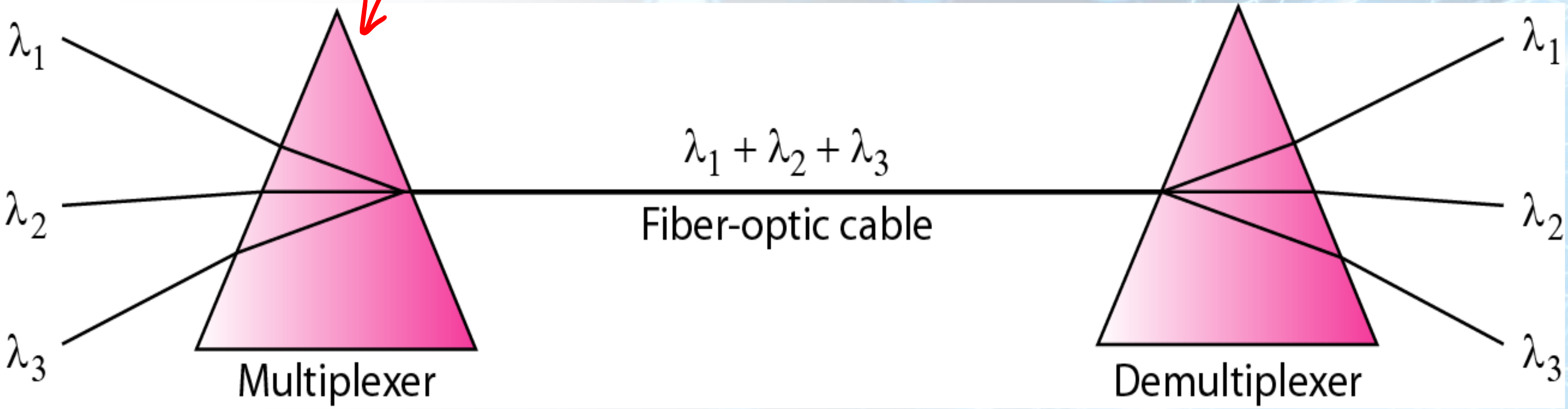


# Prisms in Wave-Length Division Multiplexing

SONET

Prism

Prism




DWDM → Efficient than WDM

Dense

# Time-Division Multiplexing

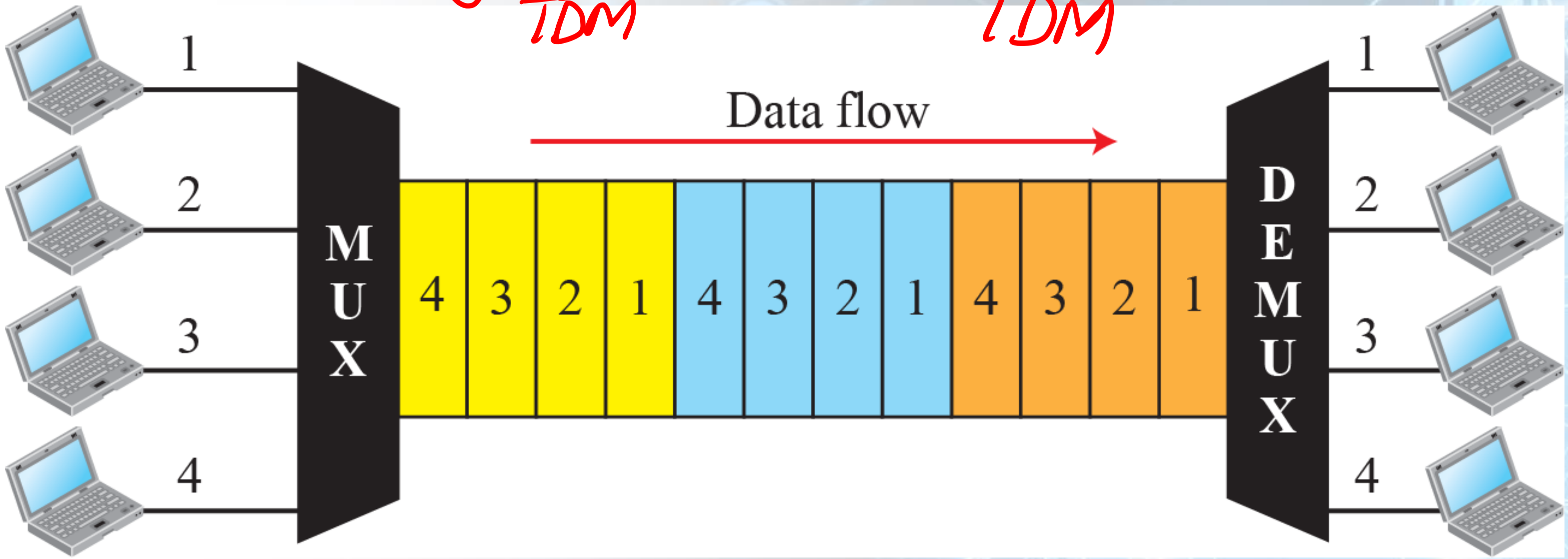
- **Digital process that allows several connections to share the high bandwidth of a link**

- **Time is shared i.e. each connection occupies a portion of time in the link**

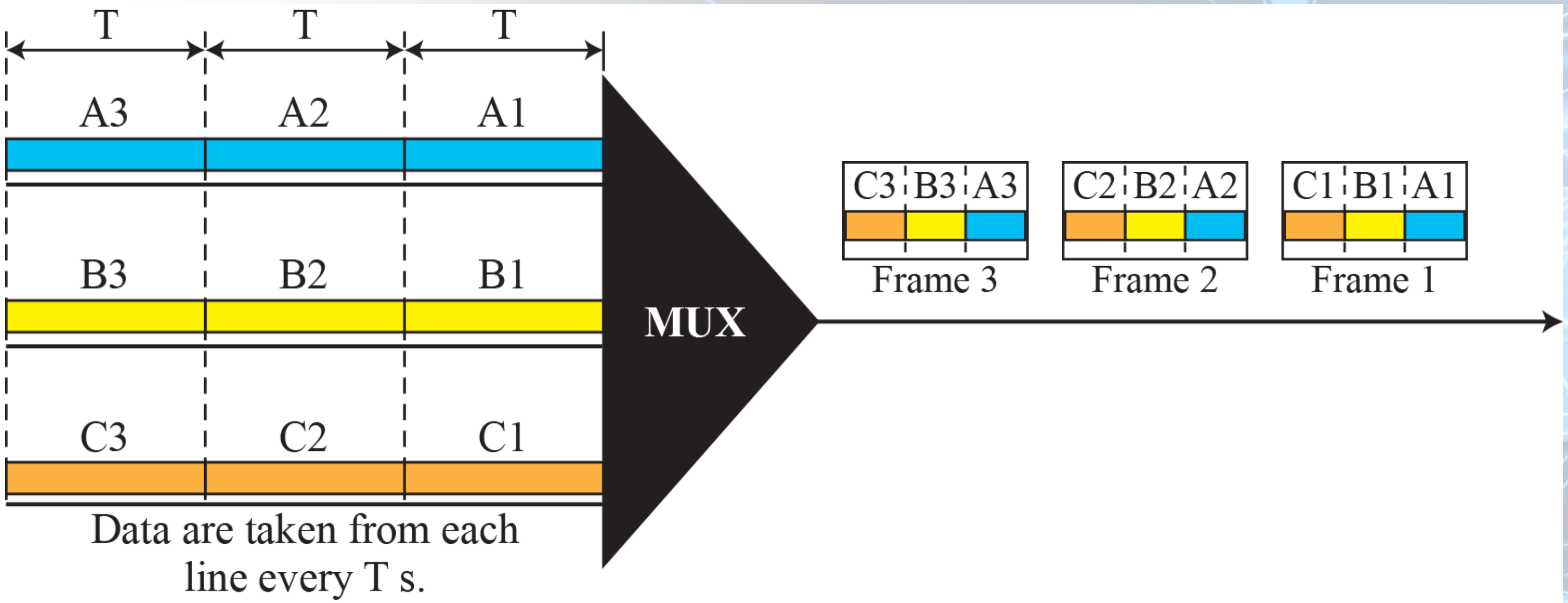
# TDM

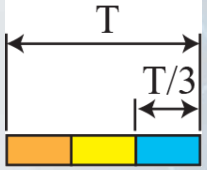
Synchronous TDM

Statistical TDM



# Synchronous Time-Division Multiplexing




Each frame is 3 time slots.
Each time slot duration is T/3 s.

# Time-Division Multiplexing

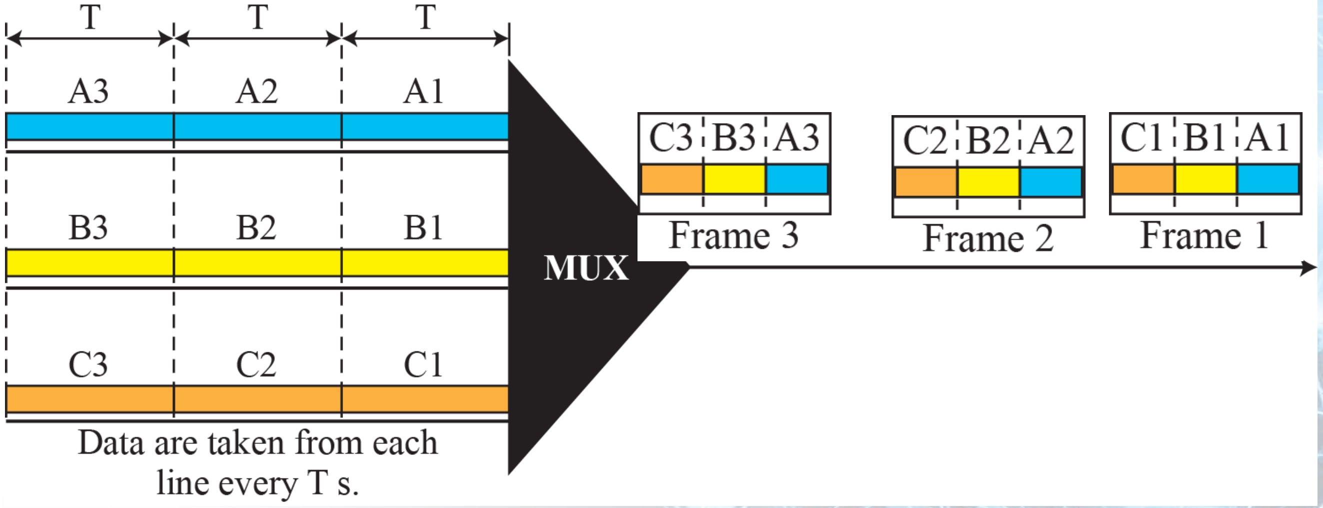
- **Digital process that allows several connections to share the high bandwidth of a link**

- **Time is shared i.e. each connection occupies a portion of time in the link**

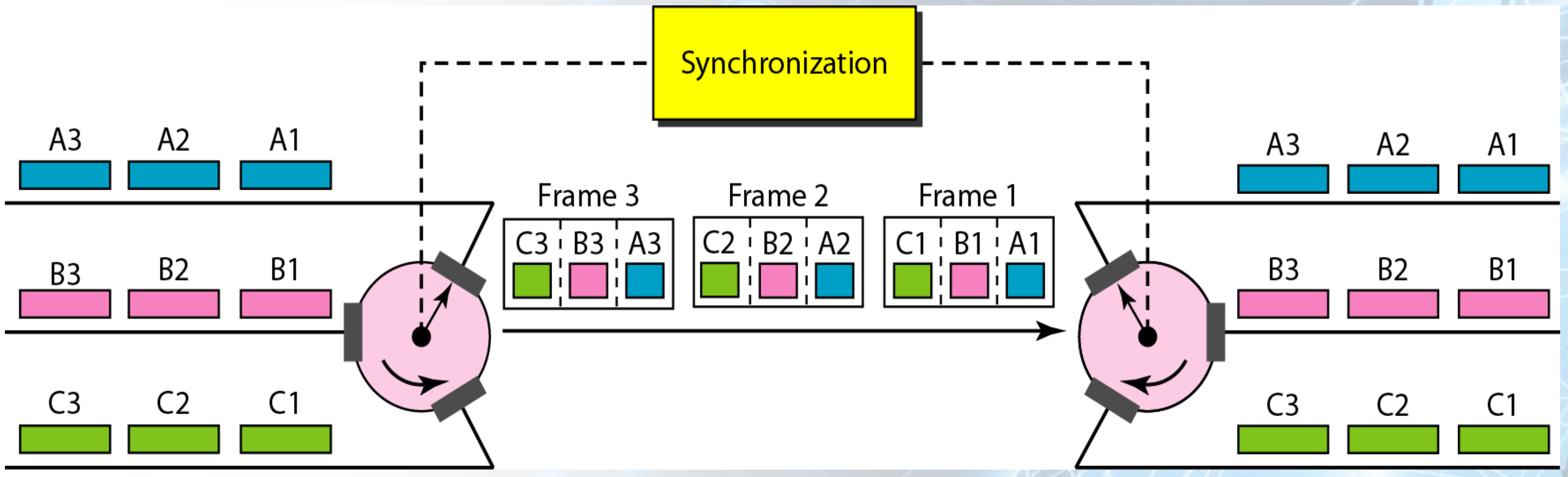
# Example

In Figure the data rate for each input connection is 1 kbps. If 1 bit at a time is multiplexed (a unit is 1 bit), what is the duration of

- each input slot,
- each output slot, and
- each frame?



# Interleaving

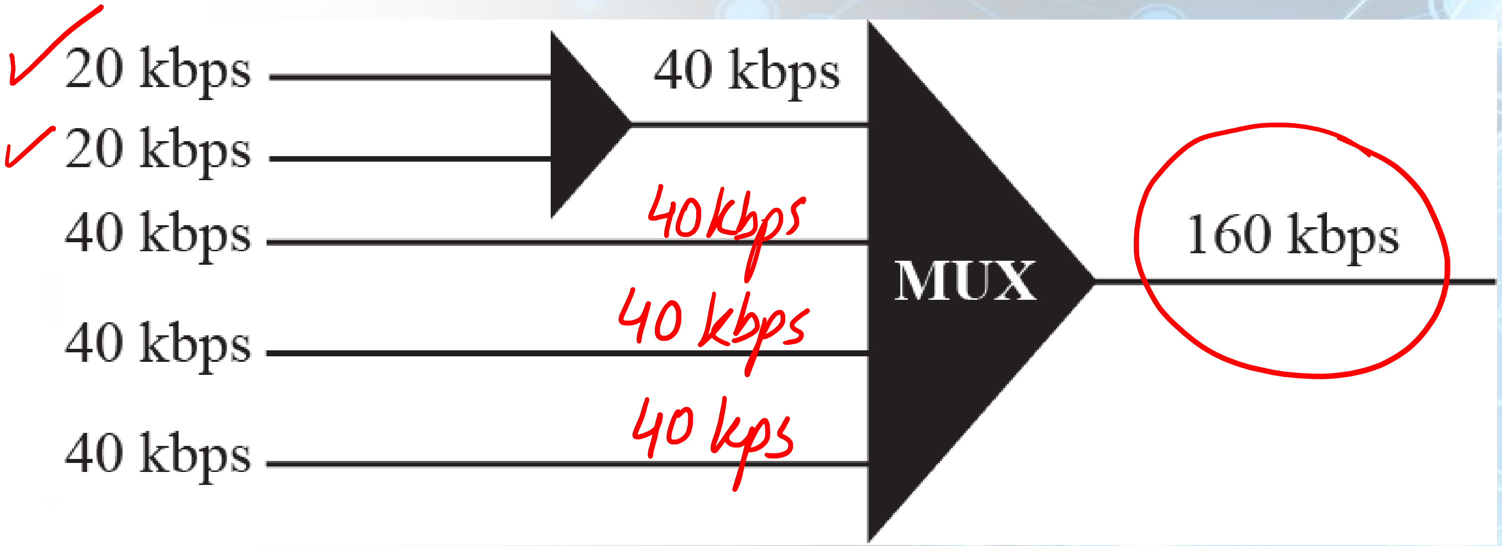


# Time-Division Multiplexing

- Digital process that allows several connections to share the high bandwidth of a link

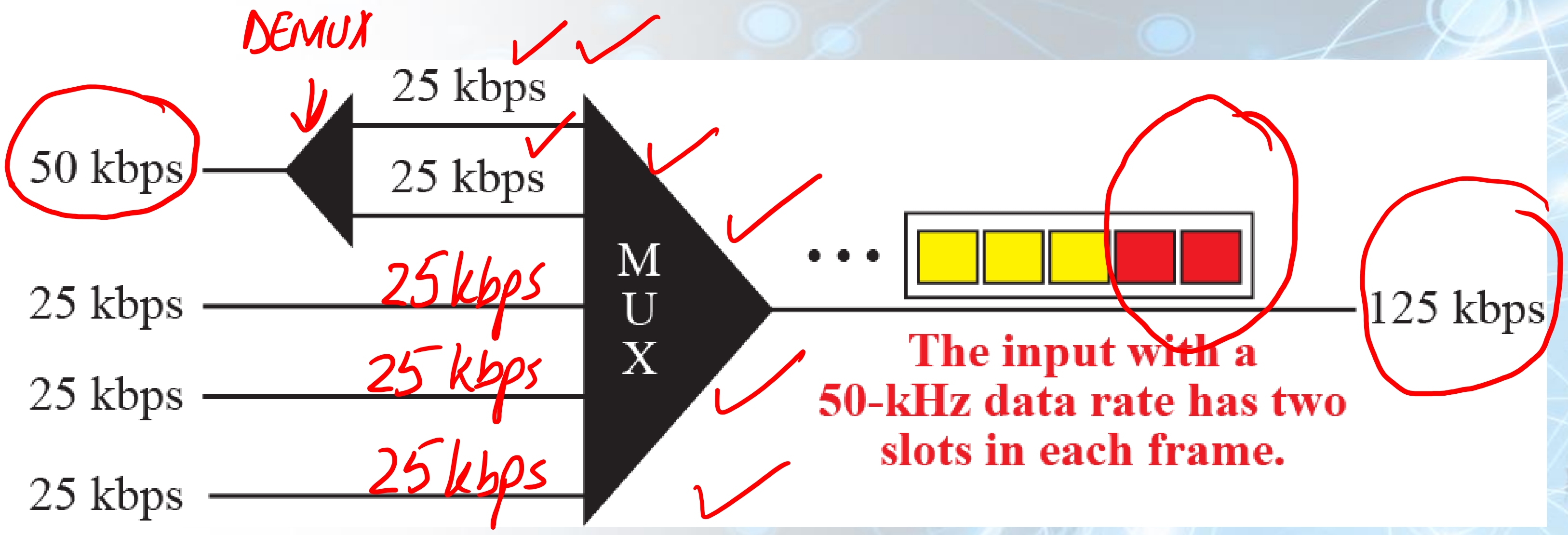
- Time is shared i.e. each connection occupies a portion of time in the link

# Multilevel Multiplexing

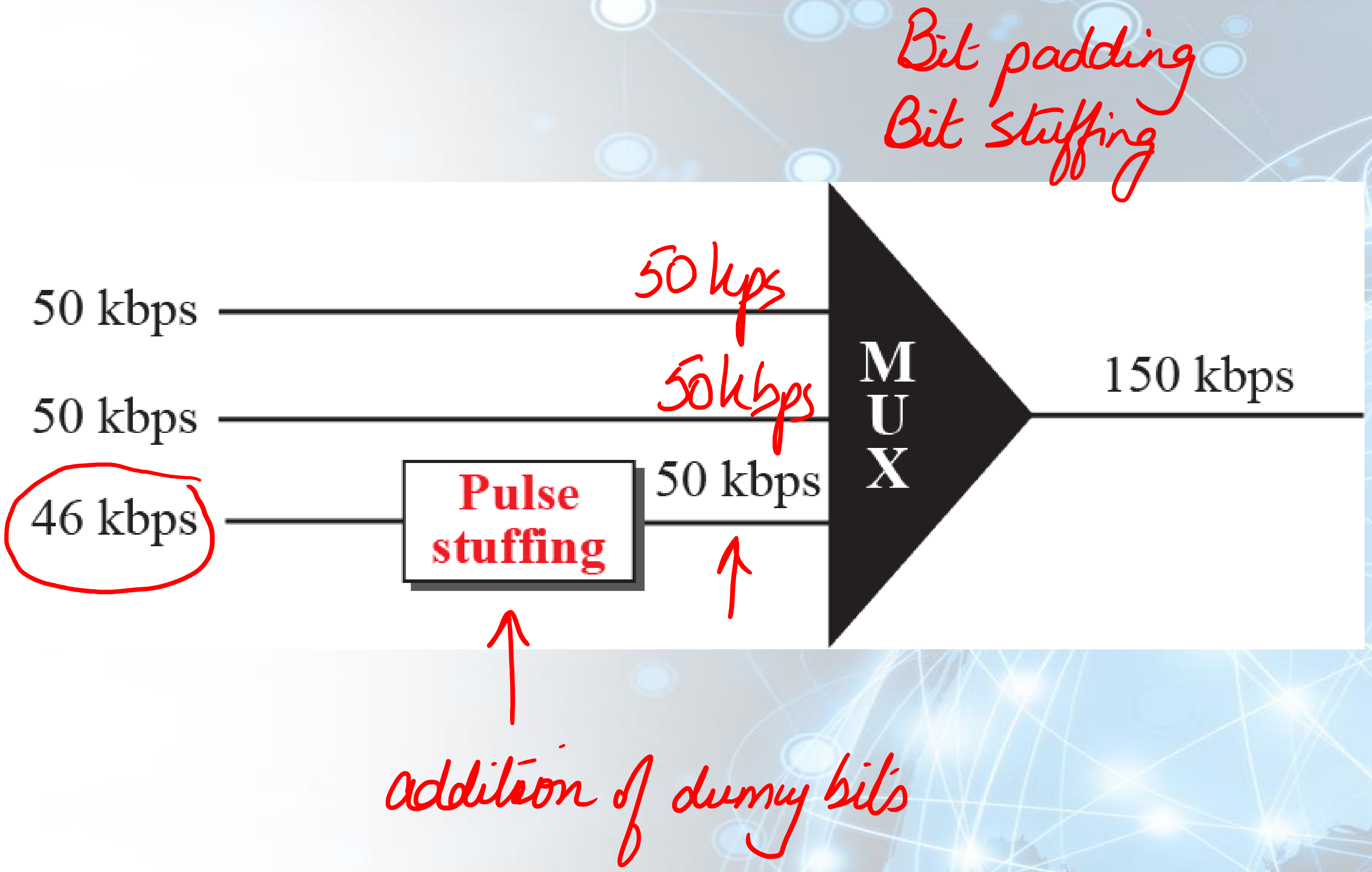



20 is a multiple of 40

# Multiple-SLot Multiplexing



# Pulse Stuffing

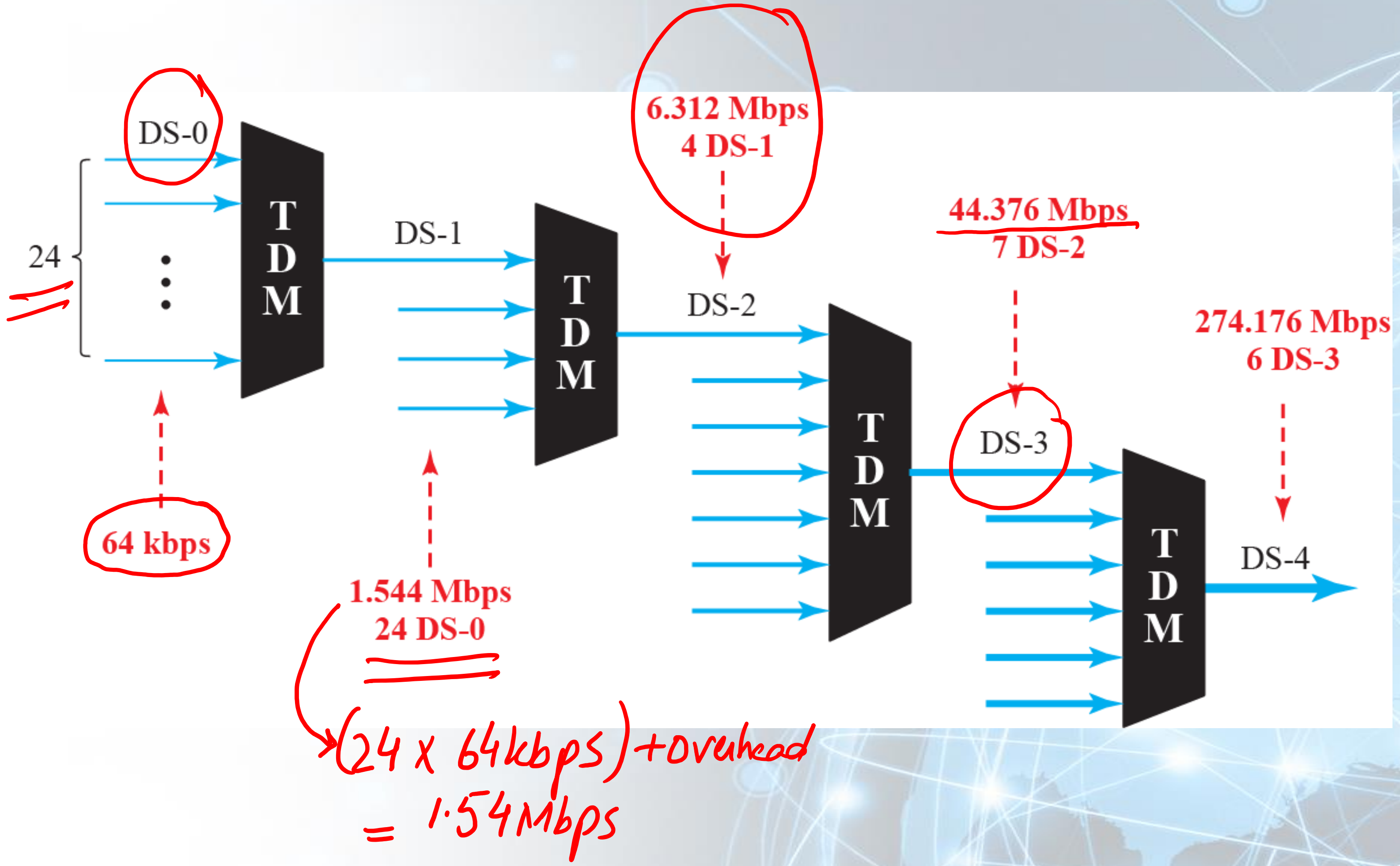


# Time-Division Multiplexing

- **Digital process that allows several connections to share the high bandwidth of a link**

- **Time is shared i.e. each connection occupies a portion of time in the link**

# Digital Hierarchy

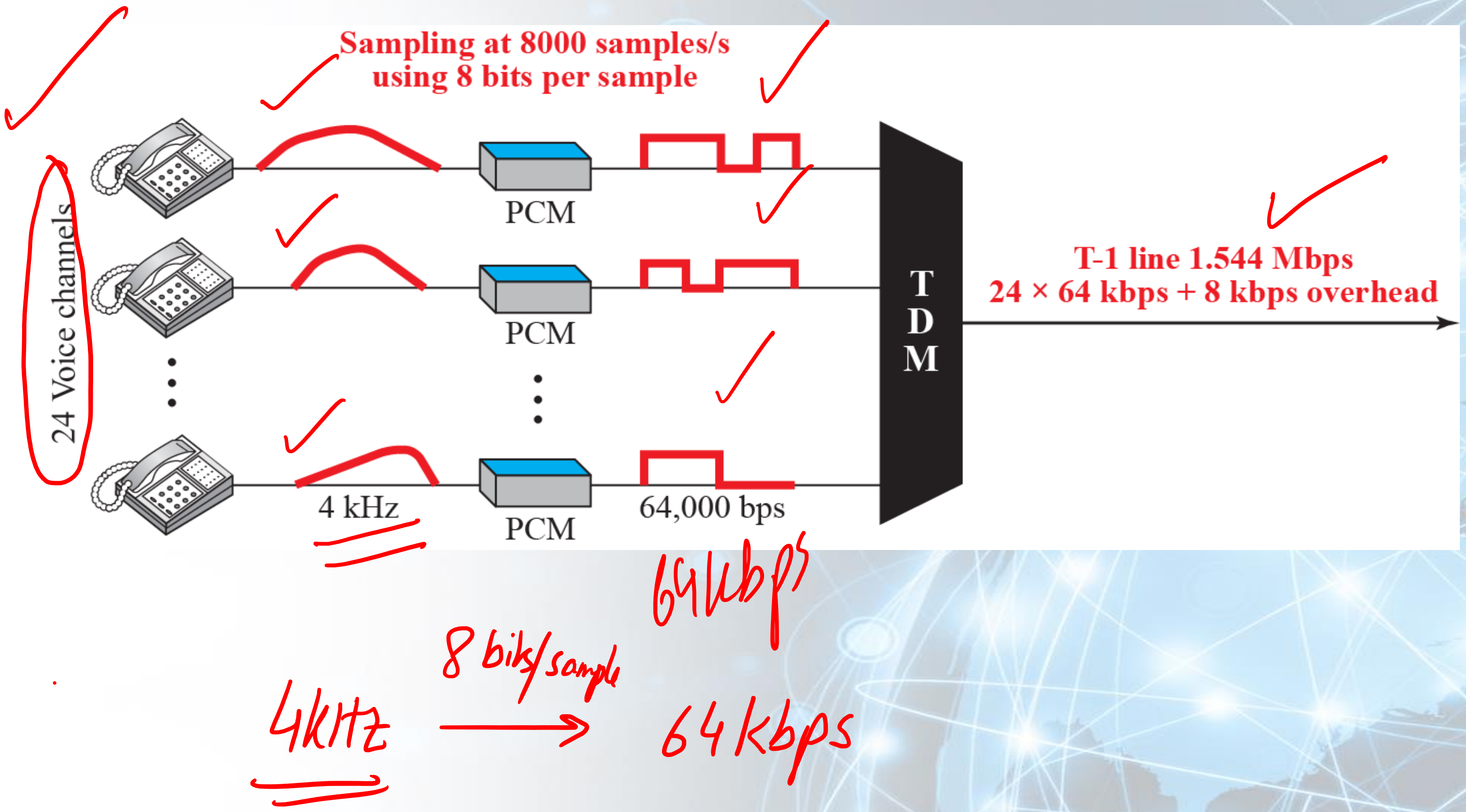


# DS and T Line Rates

| Service | Line | Rate (Mbps) | Voice Channels |
|---|---|---|---|
| DS-1 | T-1 | 1.544 | 24 |
| DS-2 | T-2 | 6.312 | 96 |
| DS-3 | T-3 | 44.736 | 672 |
| DS-4 | T-4 | 274.176 | 4032 |

DS0

# T-1 Line



Sampling at 8000 samples/s
using 8 bits per sample
24 Voice channels
PCM
PCM
PCM
4 kHz
64,000 bps
T
D
M
T-1 line 1.544 Mbps
24 × 64 kbps + 8 kbps overhead
64kbps
8 bits/sample
4kHz
64 kbps

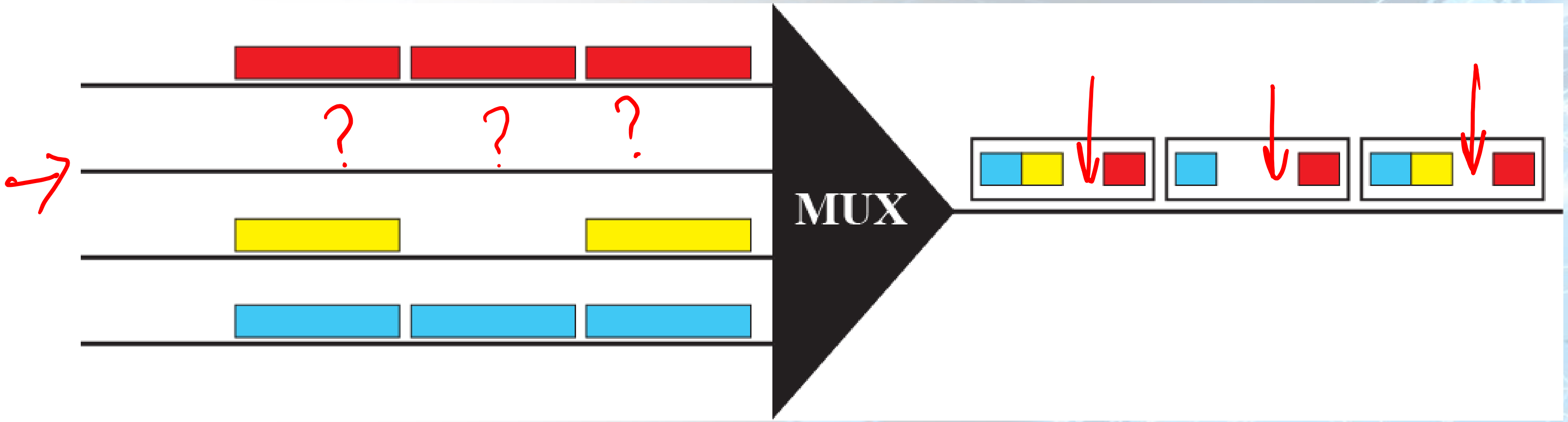
# E Line Rates

| *Line* | *Rate (Mbps)* | *Voice Channels* |
|---|---|---|
| E-1 | 2.048 | 30 |
| E-2 | 8.448 | 120 |
| E-3 | 34.368 | 480 |
| E-4 | 139.264 | 1920 |

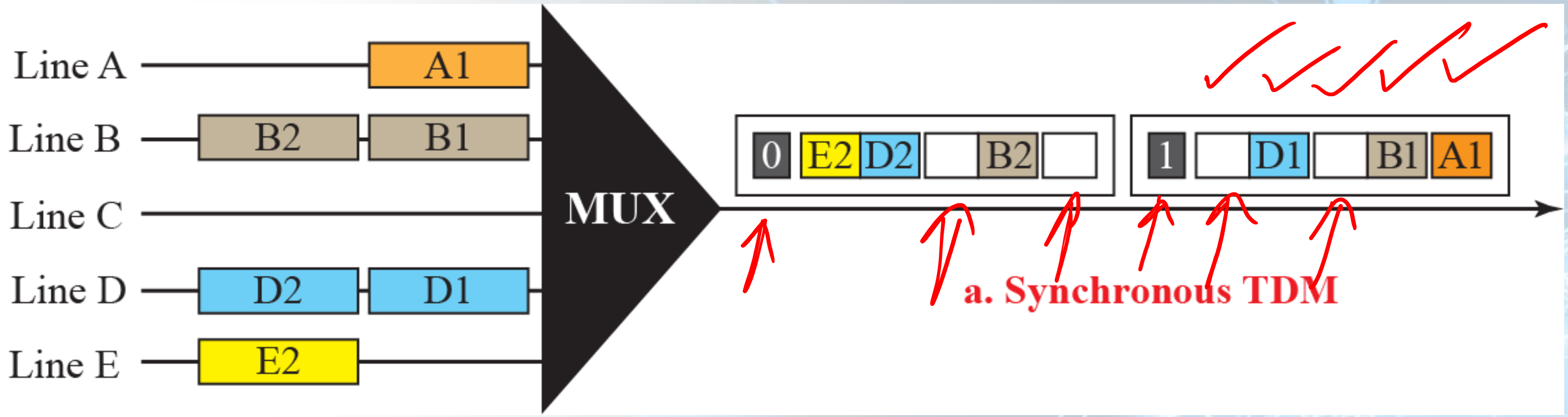
# Time-Division Multiplexing

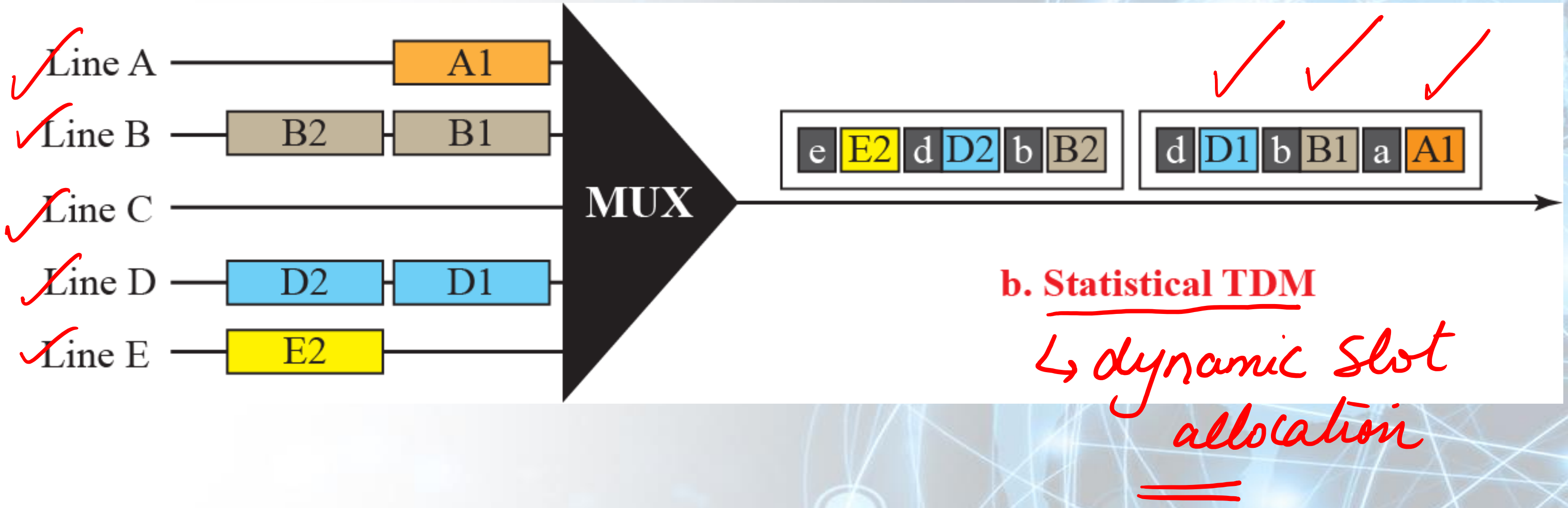
- Synchronous TDM
- Statistical TDM

# Empty slots



# Statistical TDM



# SPREAD SPECTRUM

- **In wireless applications, stations must be able to share the medium without interception by an eavesdropper and without being subject to jamming from a malicious intruder**

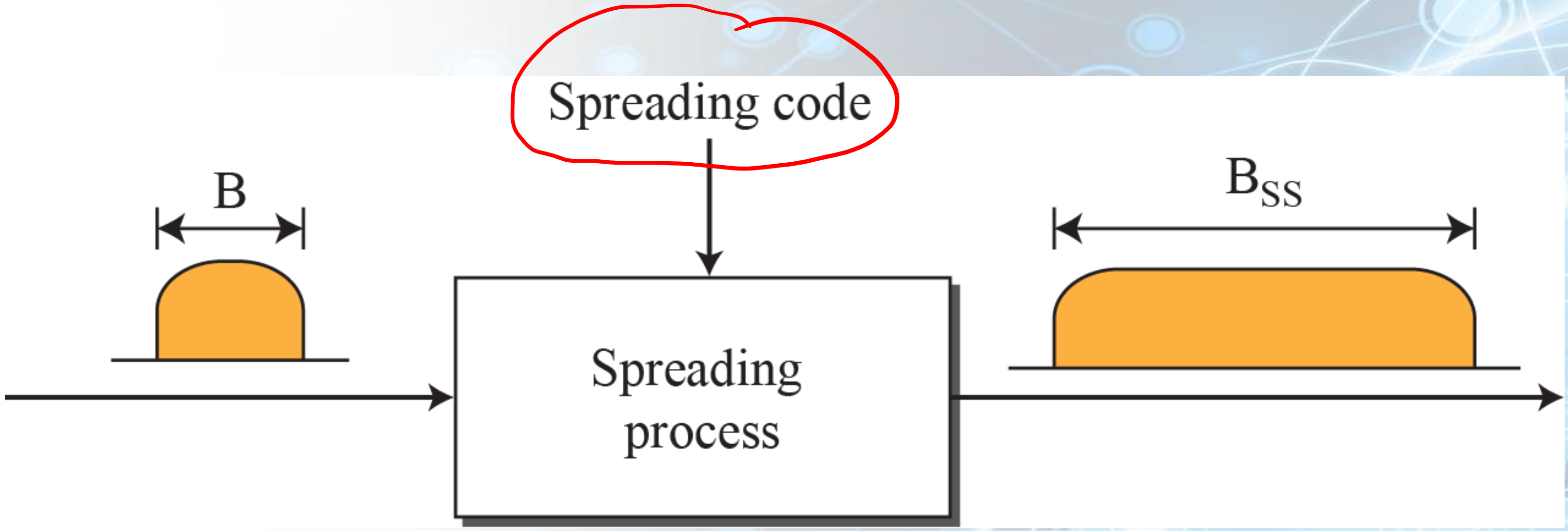
- **To achieve these goals, spread spectrum adds redundancy and spread original spectrum needed for each station**

# SPREAD SPECTRUM - Principles

- **Bandwidth allocated to each station needs to be larger than what is needed to allow Redundancy**

- **Spreading process should be independent of the original signal**

# Spread Spectrum




$B_{ss} > B$

# SPREAD SPECTRUM TECHNIQUES

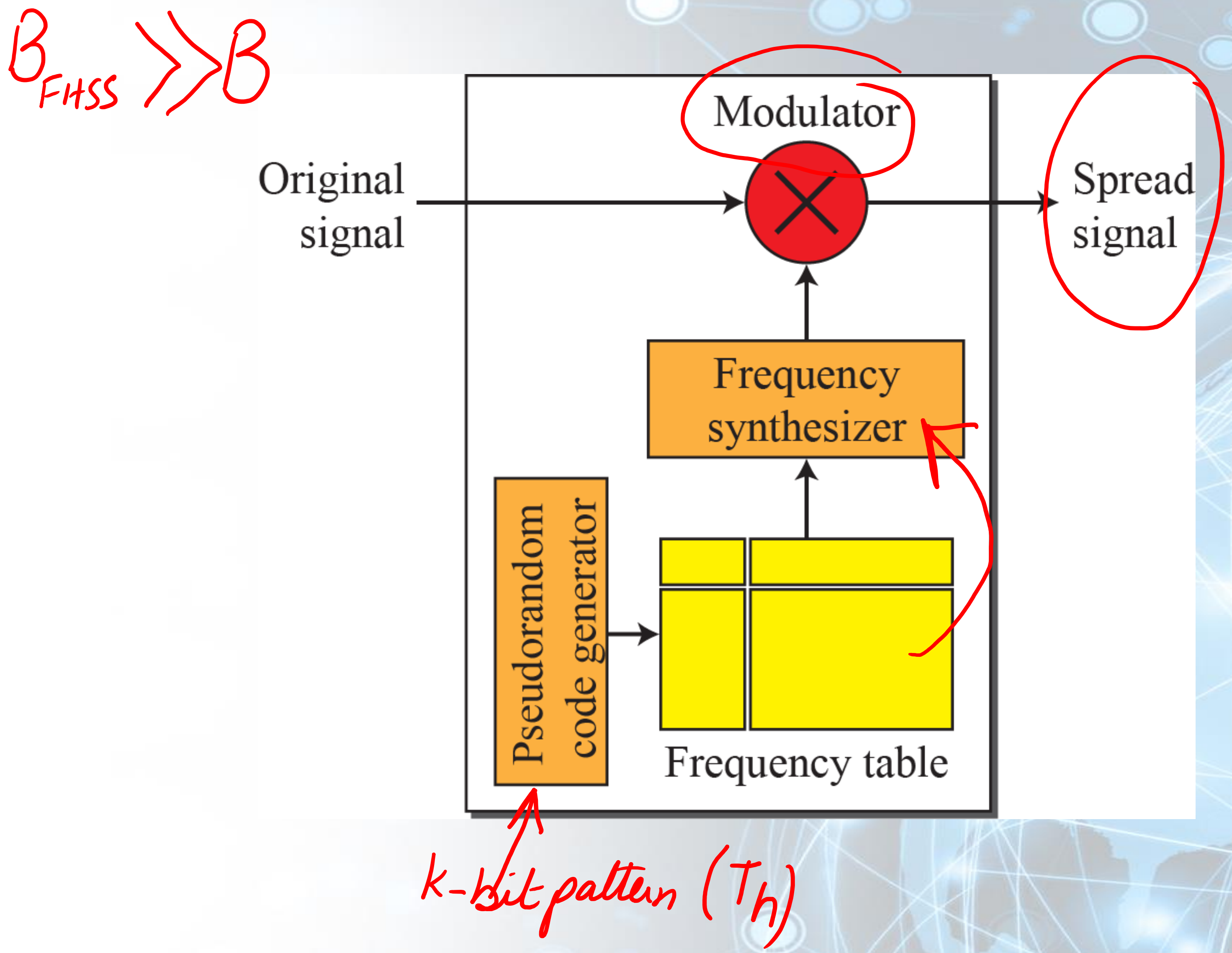
- **Frequency Hopping Spread Spectrum (FHSS)**
- **Direct Sequence Spread Spectrum (DSSS)**

# Frequency Hopping Spread Spectrum (FHSS)

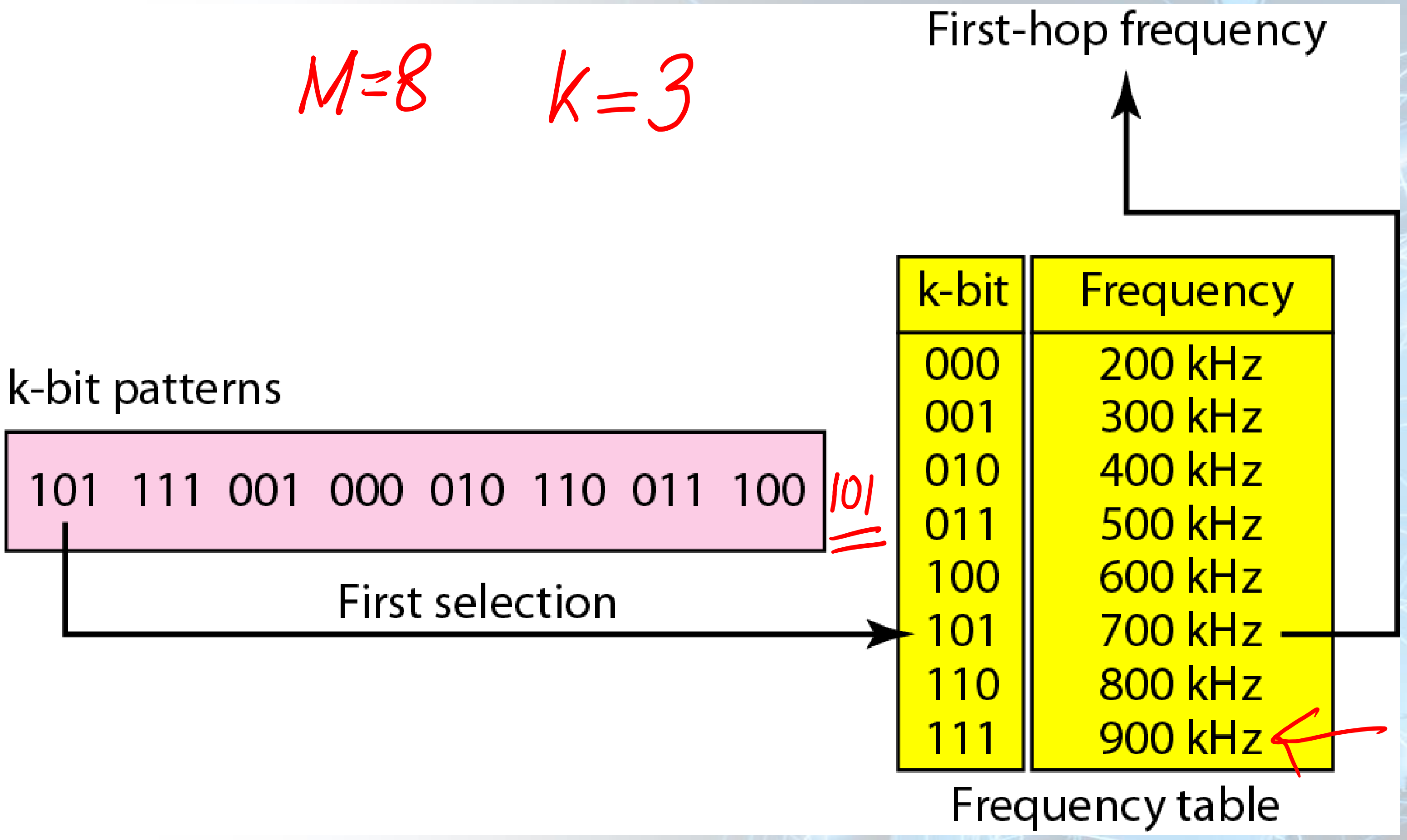
- **‘M’ different carrier frequencies that are modulated by the source signal**

- **At one moment, signal modulates one carrier frequency and at next moment, it modulates another**

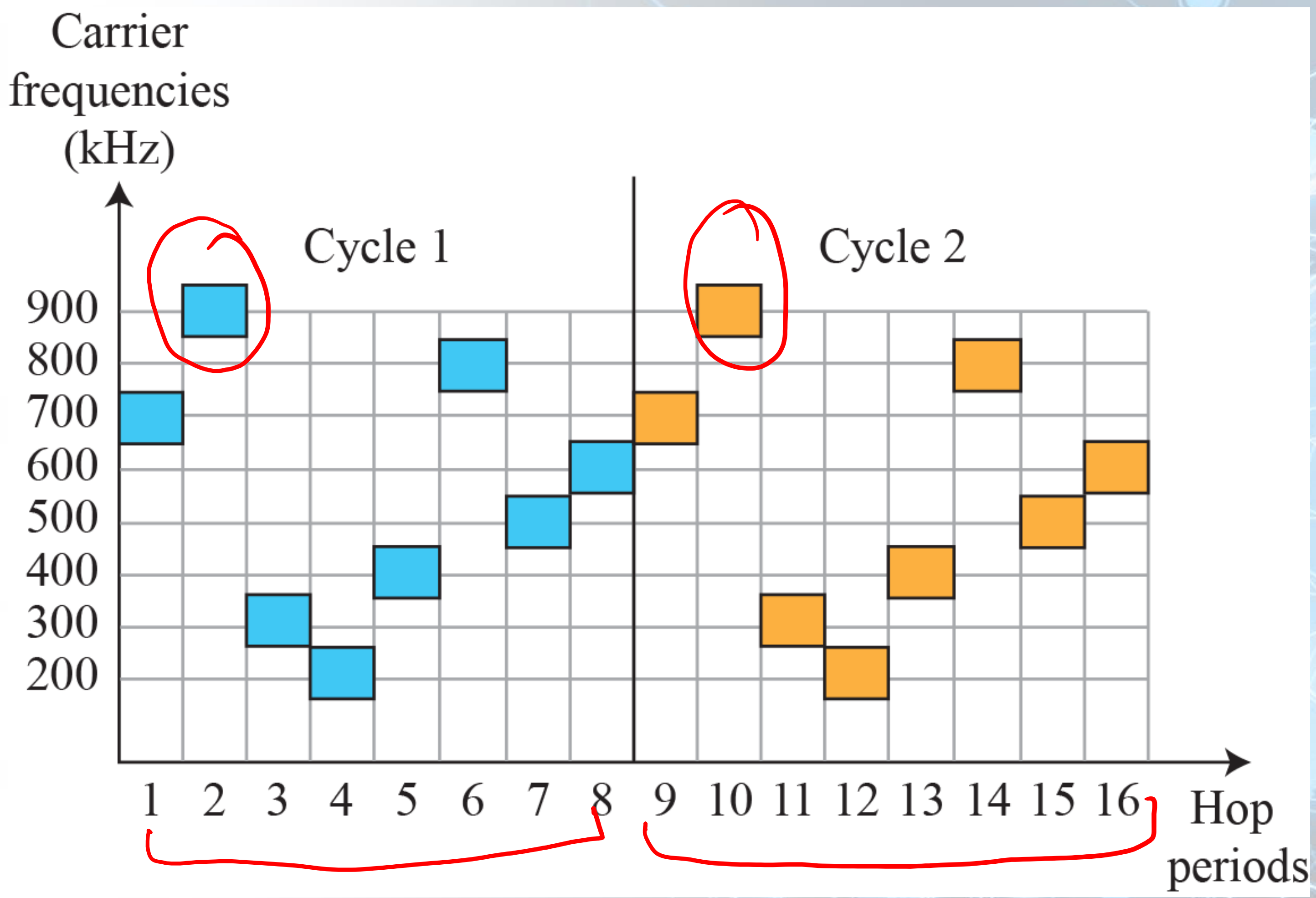
# Frequency Hopping Spread Spectrum (FHSS)



# Frequency Selection in FHSS

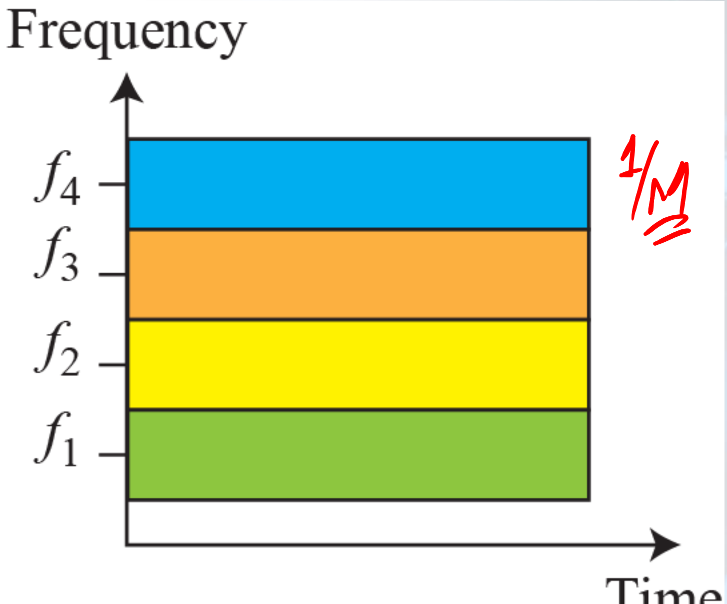


# FHSS Cycles

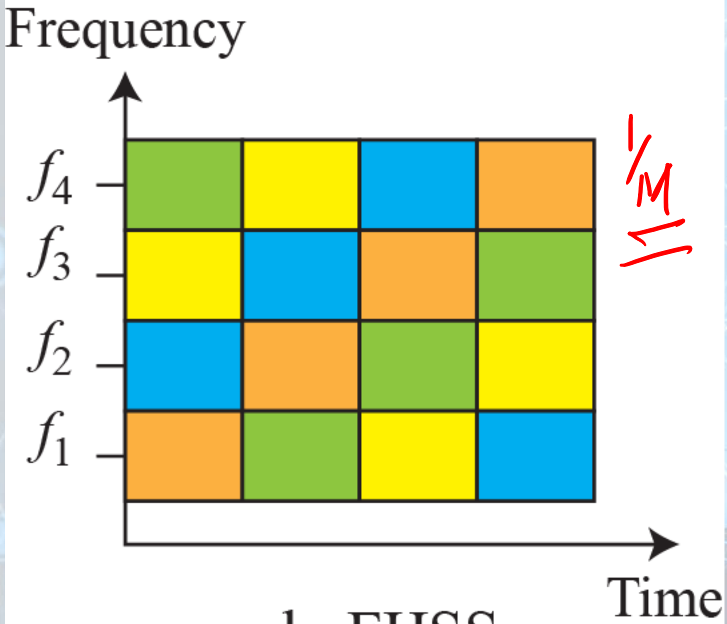


Carrier frequencies (kHz)
Cycle 1
Cycle 2
900
800
700
600
500
400
300
200
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Hop periods

# Bandwidth Sharing



a. FDM



b. FHSS

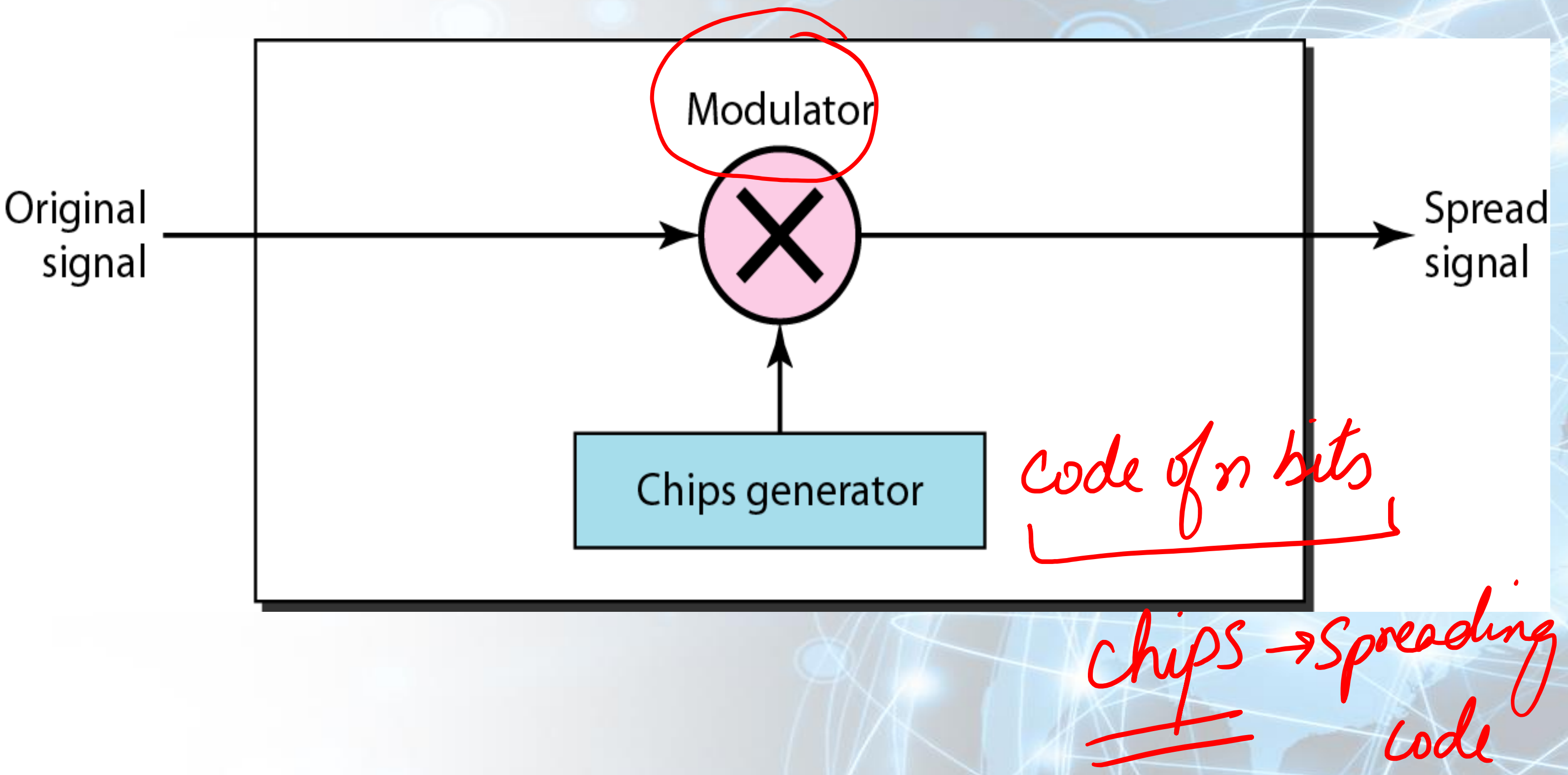
# DSSS

- DSSS also expands the bandwidth of the original signal, but the process is different

- We replace each data bit with ‘n’ bits using a spreading code

- Each bit is assigned a code of ’n’ bits, called chips, where the chip rate is ‘n’ times that of the data bit

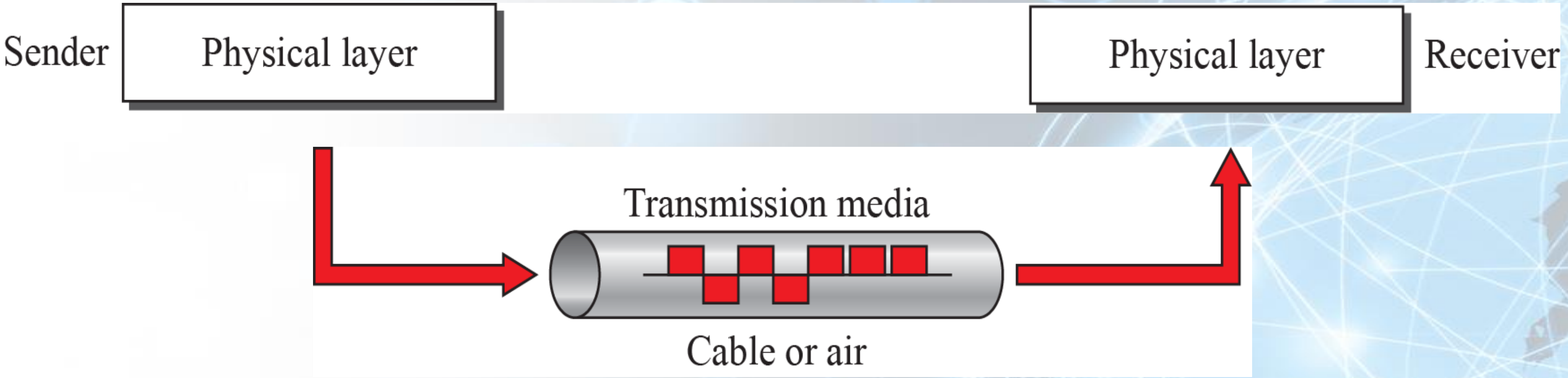
# DSSS


Modulator
Original signal
Spread signal
Chips generator
code of n bits
chips → spreading code

# Transmission Media

- **Located below the physical layer and are directly controlled by the physical layer**
- **Belong to layer zero**
- **Metallic Media i.e. Twisted pair and Coaxial Cable**
- **Optical Fiber Cable**
- **Free Space i.e. Air, Vaccum**

# Transmission Media & Physical Payer



# Transmission Media

- **Located below the physical layer and are directly controlled by the physical layer**

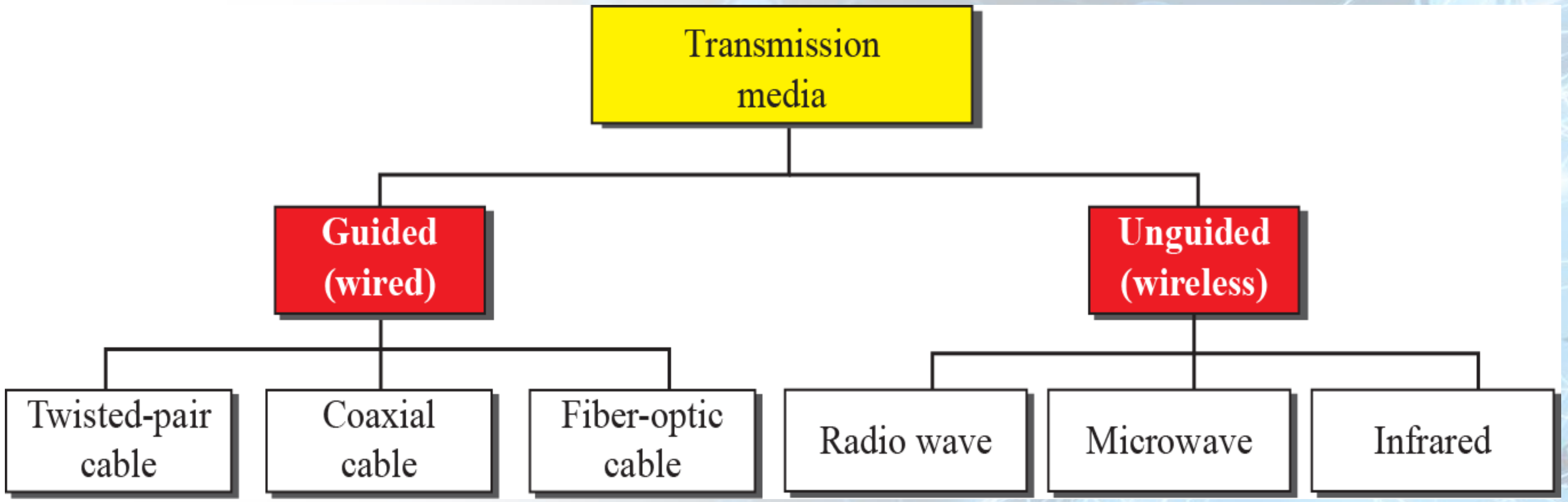
- **Belong to layer zero**

- **Metallic Media i.e. Twisted pair and Coaxial Cable**

- **Optical Fiber Cable**

- **Free Space i.e. Air, Vaccum**

# Classes of Transmission Media



# Guided Media

- Media that provides a conduit from one device to another

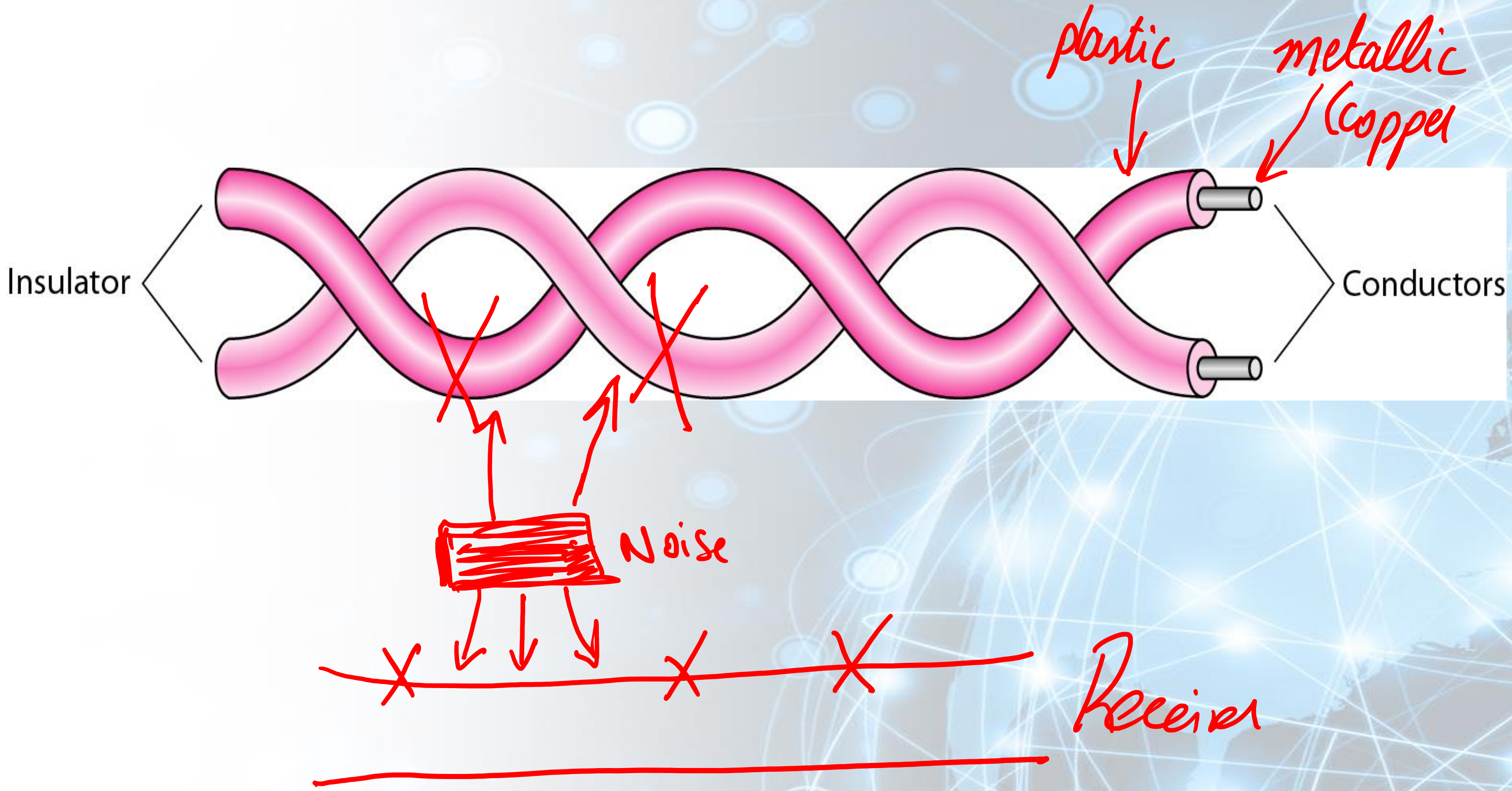
- Twisted-pair cable, coaxial cable, and fiber-optic cable

- Signal traveling along any of these media is directed and contained by the physical limits of the medium

# Twisted-Pair Cable

- Consists of 2 copper conductors, each with its own plastic insulation, twisted together
- One wire carries signals and other is ground reference
- Receiver uses difference between the two
- Interference (Noise) & Crosstalk

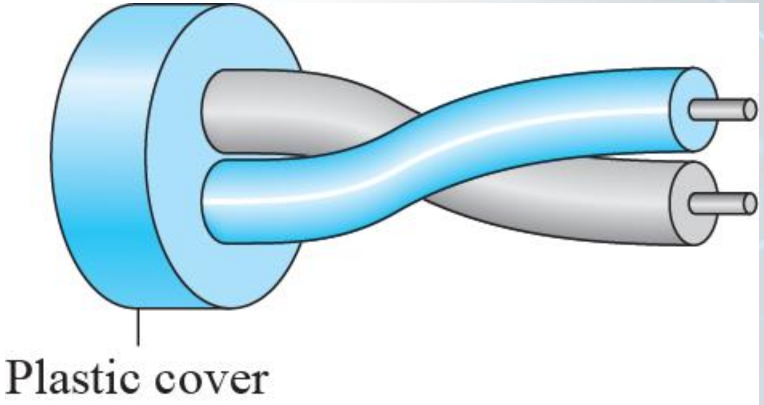
# Twisted-Pair Cable



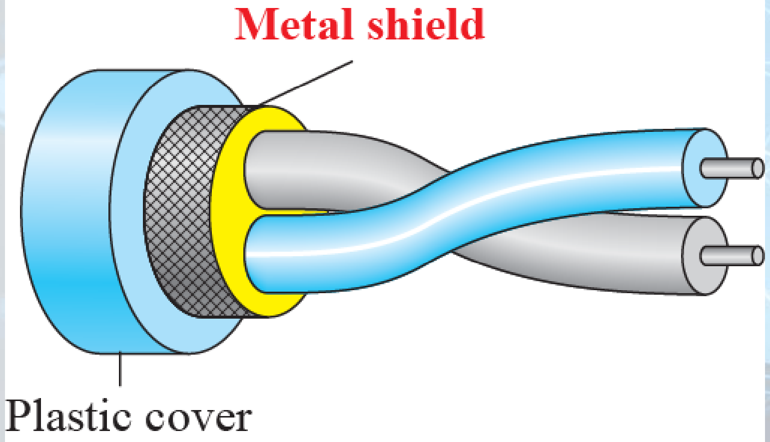
# Twisted-Pair Cable

- **UTP**
- **STP**

# Unshielded vs. Shielded Twisted Pair Cable




a. UTP




b. STP

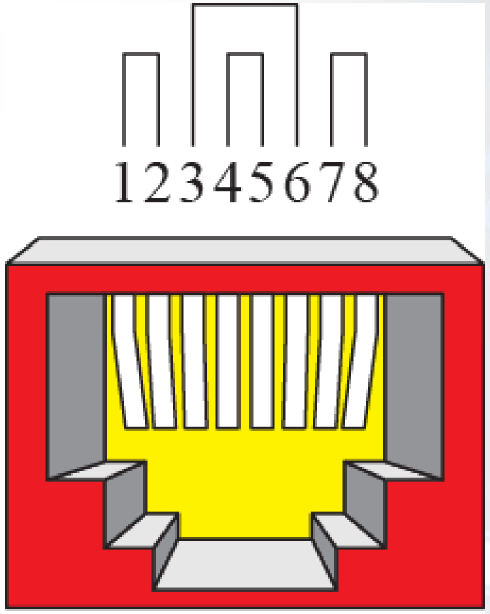
# Categories of Unshielded Twisted-Pair Cables

| *Category* | *Specification* | *Data Rate (Mbps)* | *Use* |
|---|---|---|---|
| 1 | Unshielded twisted-pair used in telephone | < 0.1 | Telephone |
| 2 | Unshielded twisted-pair originally used in T lines | 2 | T-1 lines |
| 3 | Improved CAT 2 used in LANs | 10 | LANs |
| 4 | Improved CAT 3 used in Token Ring networks | 20 | LANs |
| 5 | Cable wire is normally 24 AWG with a jacket and outside sheath | 100 | LANs |
| 5E | An extension to category 5 that includes extra features to minimize the crosstalk and electromagnetic interference | 125 | LANs |
| 6 | A new category with matched components coming from the same manufacturer. The cable must be tested at a 200-Mbps data rate. | 200 | LANs |
| 7 | Sometimes called *SSTP (shielded screen twisted-pair)*. Each pair is individually wrapped in a helical metallic foil followed by a metallic foil shield in addition to the outside sheath. The shield decreases the effect of crosstalk and increases the data rate. | 600 | LANs |

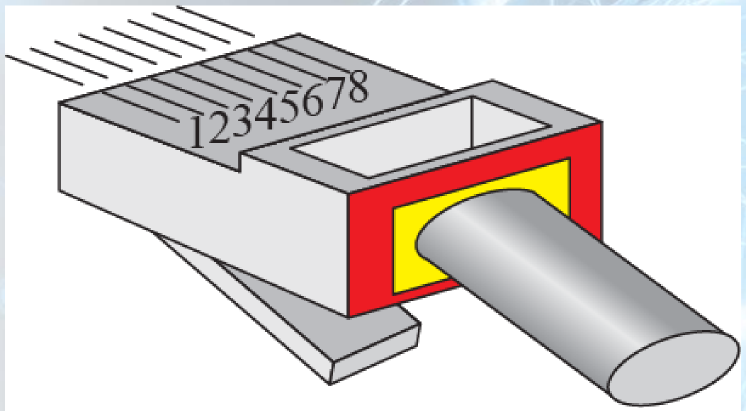
# UTP Connectors

Registered Jack

Keyed

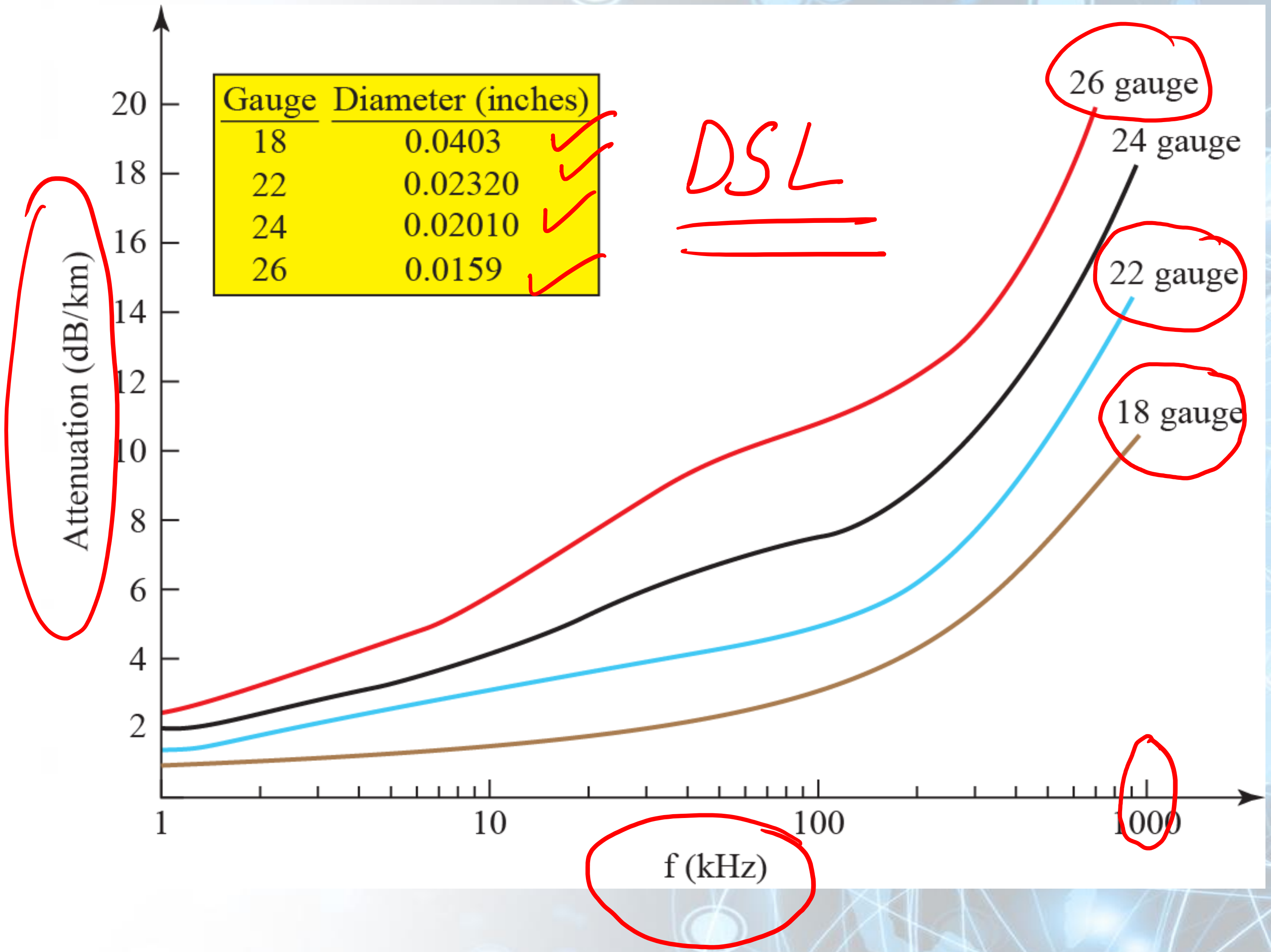



RJ-45 Female




RJ-45 Male

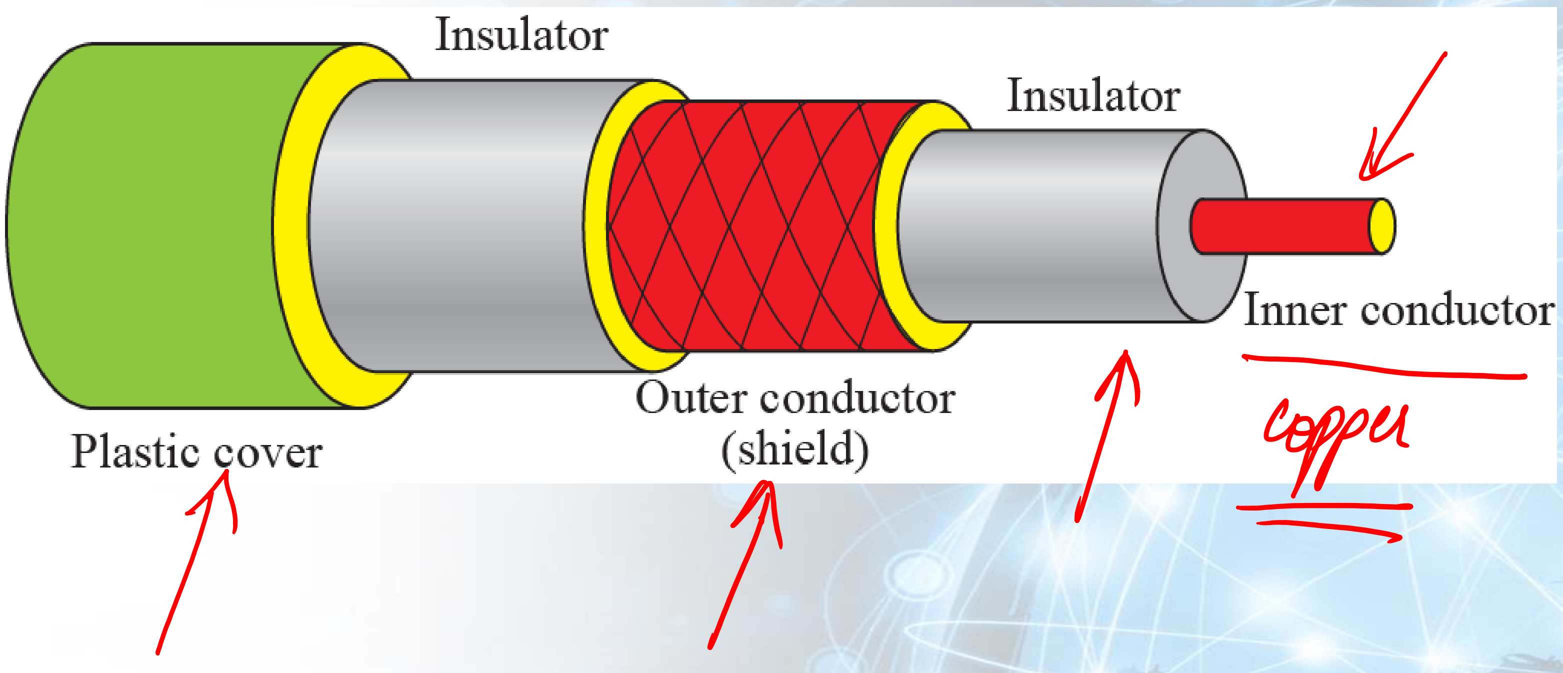
# UTP Performance



# Coaxial Cable

- Carries signals of higher frequency ranges than those in twisted pair cable

# Coaxial Cable



# Categories of Coaxial Cables

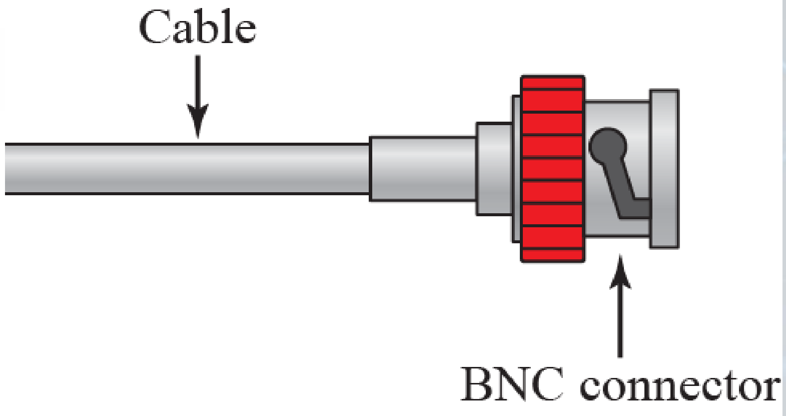
ohms

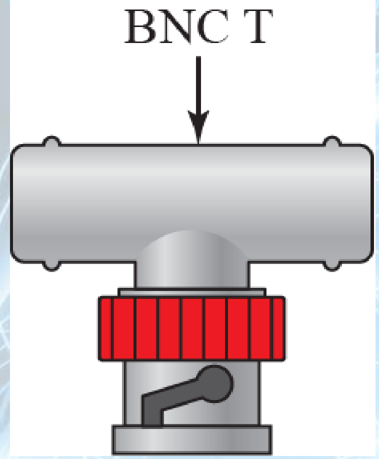
| *Category* | *Impedance* | *Use* |
|---|---|---|
| RG-59 | 75 Ω | Cable TV |
| RG-58 | 50 Ω | Thin Ethernet |
| RG-11 | 50 Ω | Thick Ethernet |

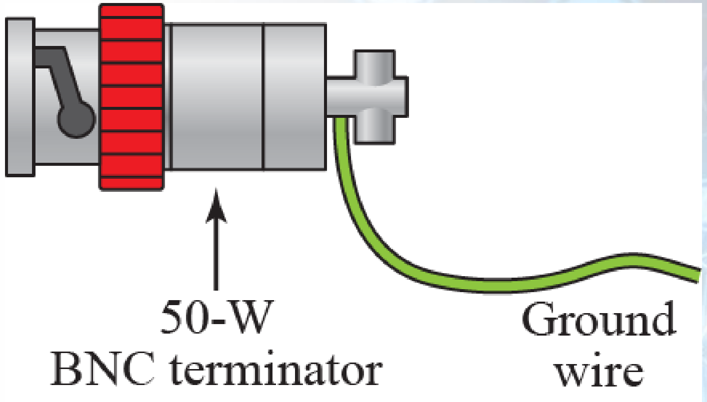
# Coaxial Cable

- Carries signals of higher frequency ranges than those in twisted pair cable

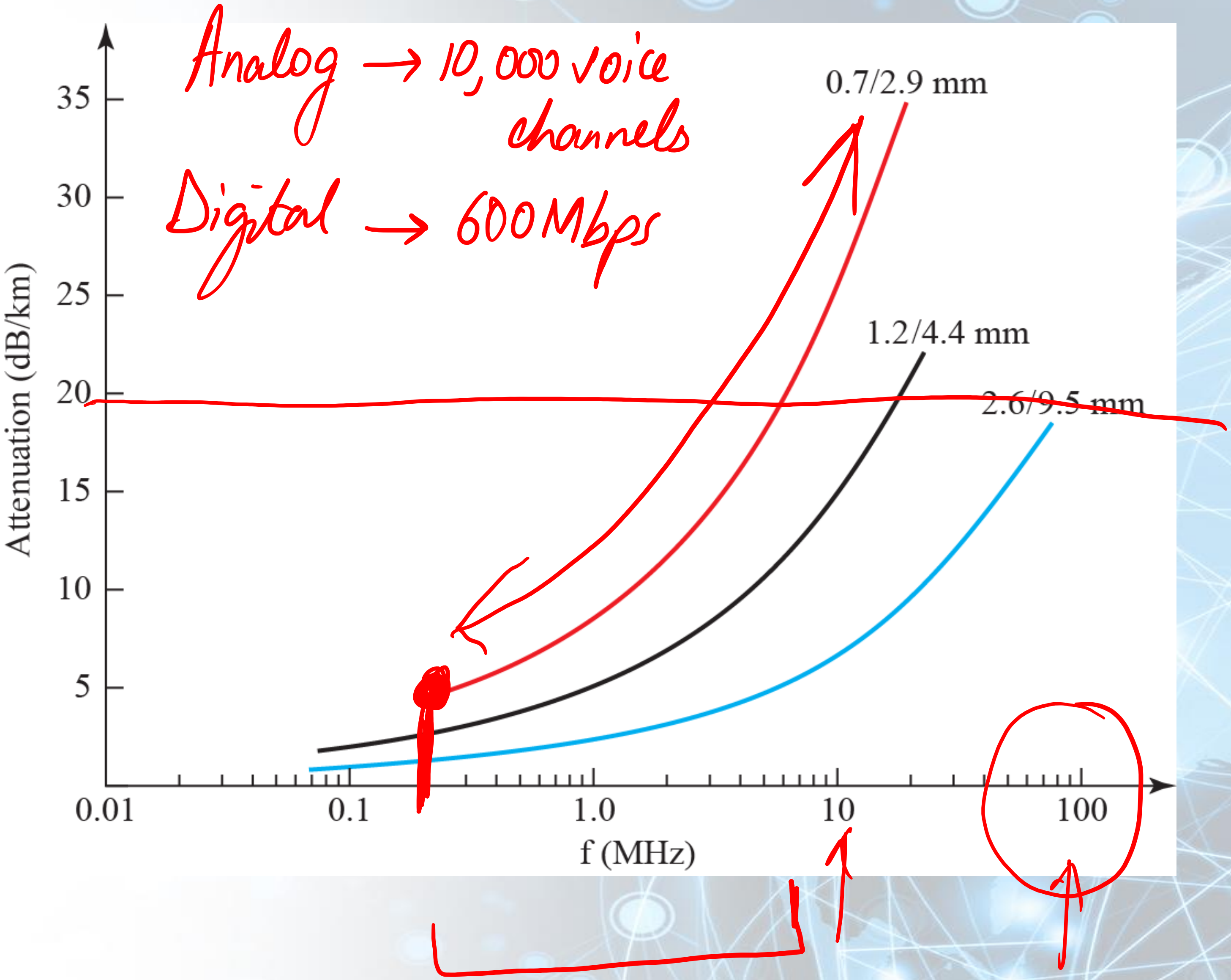
# BNC Connectors



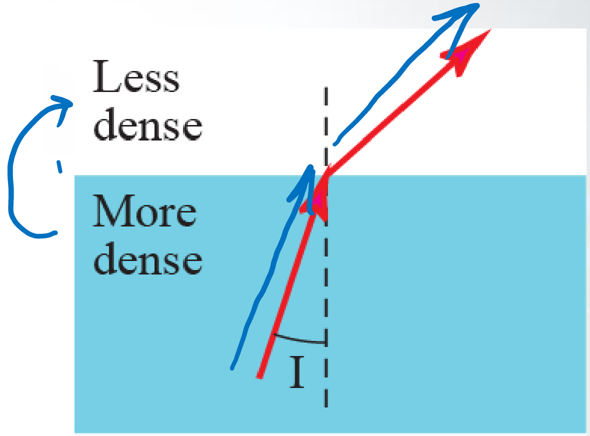
# Coaxial Cable Performance



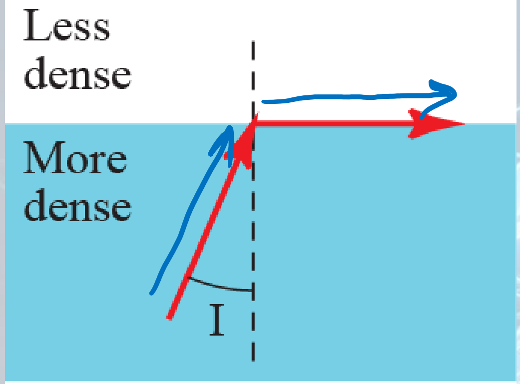
# Fiber-Optic Cable

- Made of glass or plastic and transmits signals in the form of light
- Light travels in a straight line as long as it is moving through a single uniform substance
- If a ray of light traveling through one substance suddenly enters another substance (of a different density), the ray changes direction

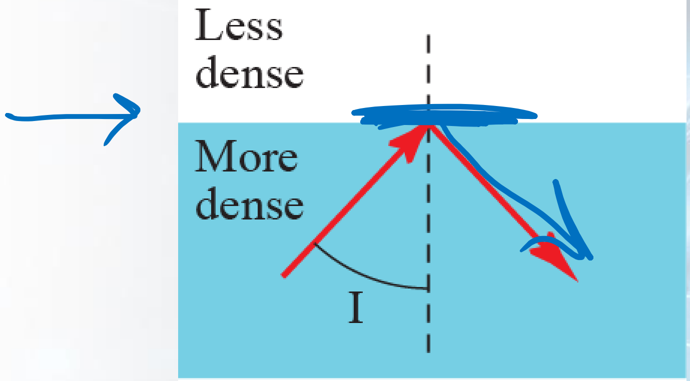
# Bending of Light Ray




I < critical angle, refraction




I = critical angle, refraction



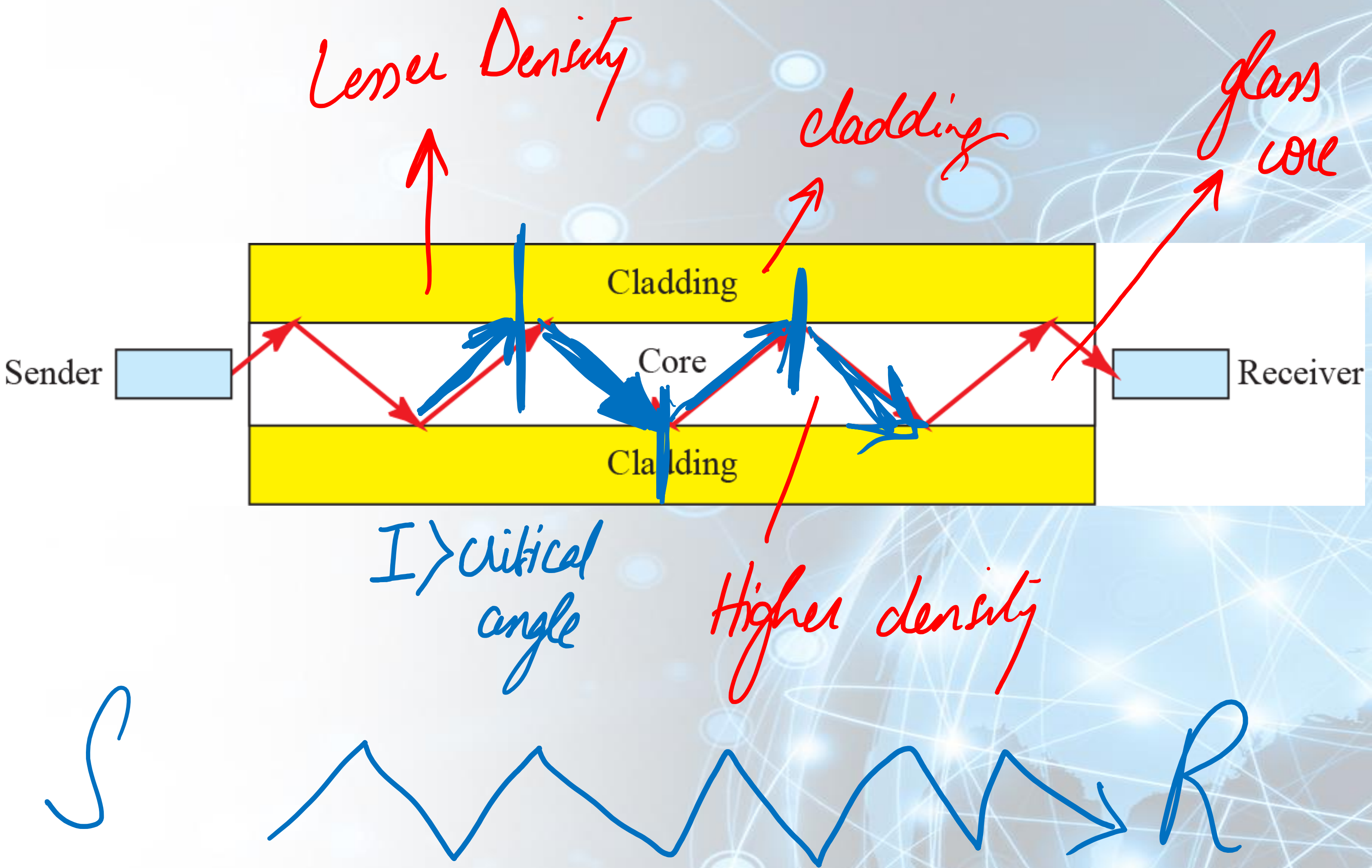

I > critical angle, reflection

reflected

# Fiber-Optic Cable

- **Made of glass or plastic and transmits signals in the form of light**

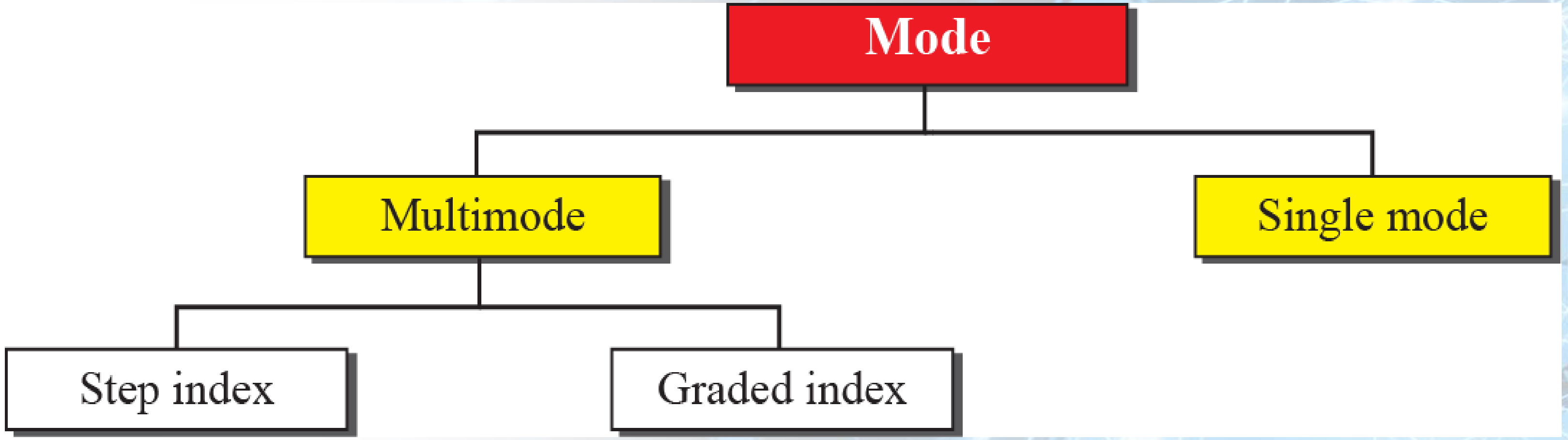
# Optical Fiber



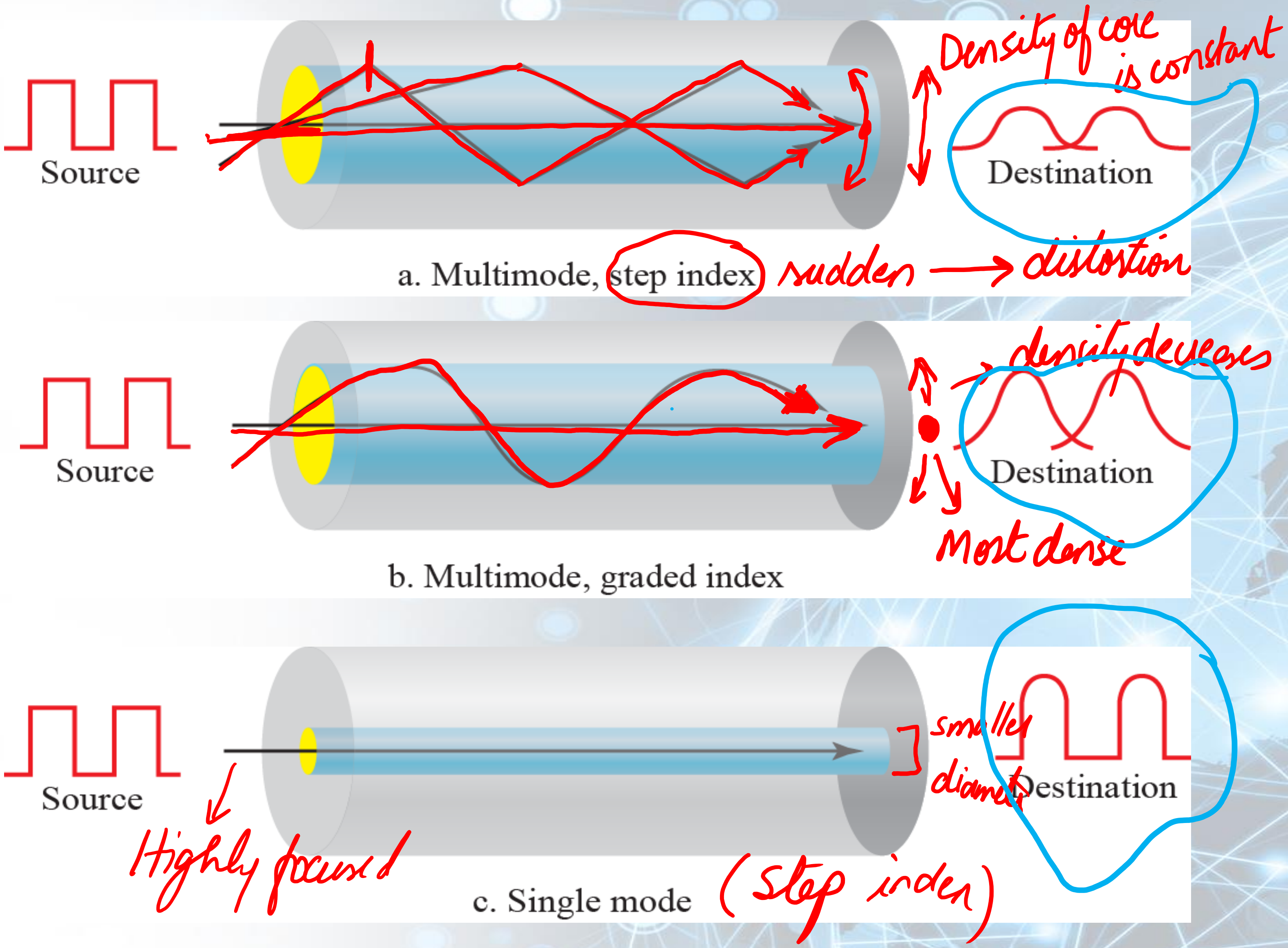
# Fiber-Optic Cable

- Made of glass or plastic and transmits signals in the form of light

# Propagation Modes



# Modes




a. Multimode, step index

b. Multimode, graded index

c. Single mode

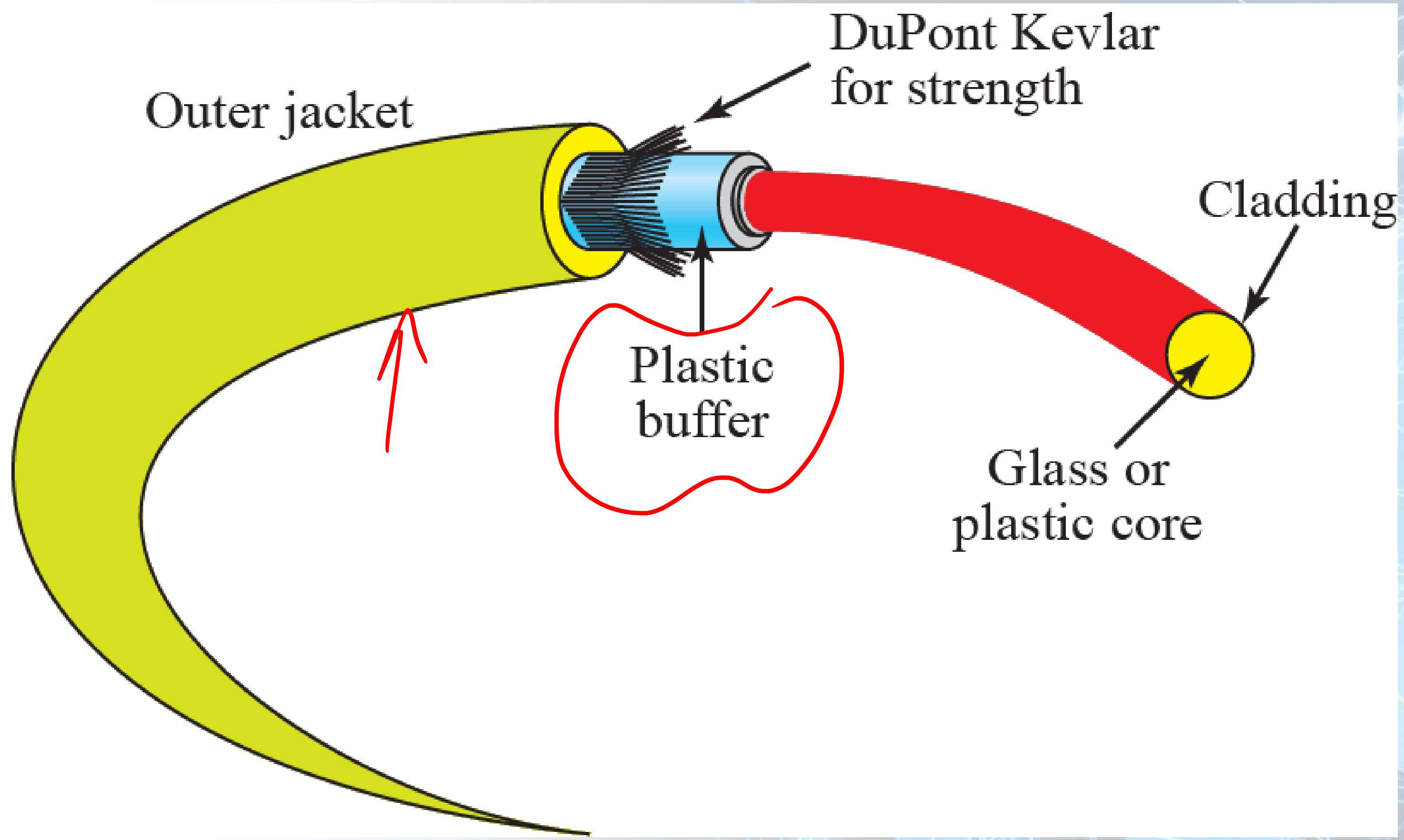
# Fiber-Optic Cable

- **Made of glass or plastic and transmits signals in the form of light**

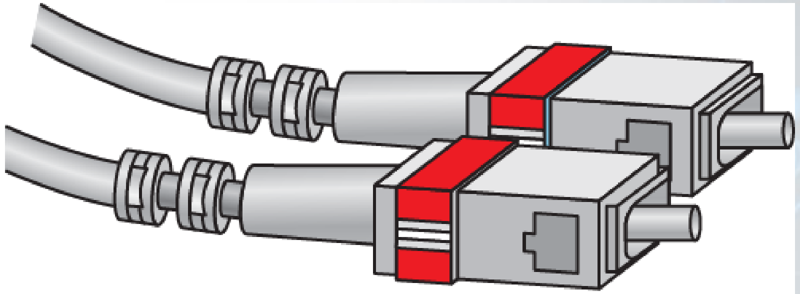
# Fiber Types

| *Type* | *Core (μm)* | *Cladding (μm)* | *Mode* |
|---|---|---|---|
| 50/125 | 50.0 | 125 | Multimode, graded index |
| 62.5/125 | 62.5 | 125 | Multimode, graded index |
| 100/125 | 100.0 | 125 | Multimode, graded index |
| 7/125 | 7.0 | 125 | Single mode |

# Fiber Composition

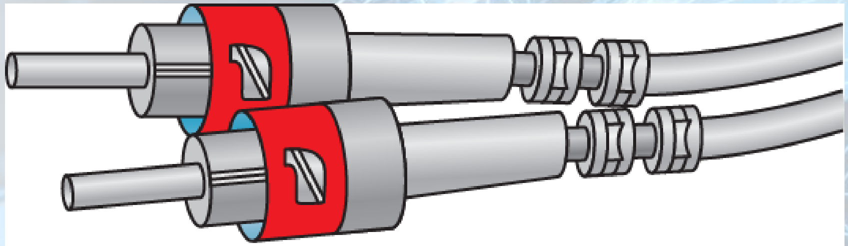


# Fiber-Optic Cable Connector



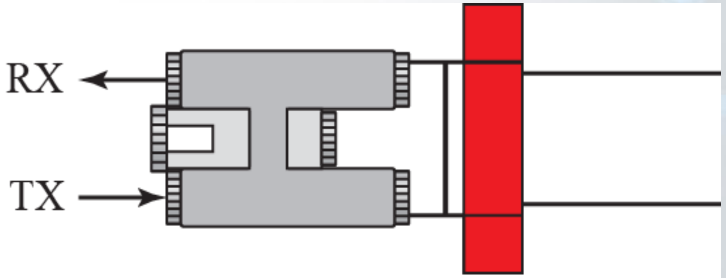
SC connector

Cable TV



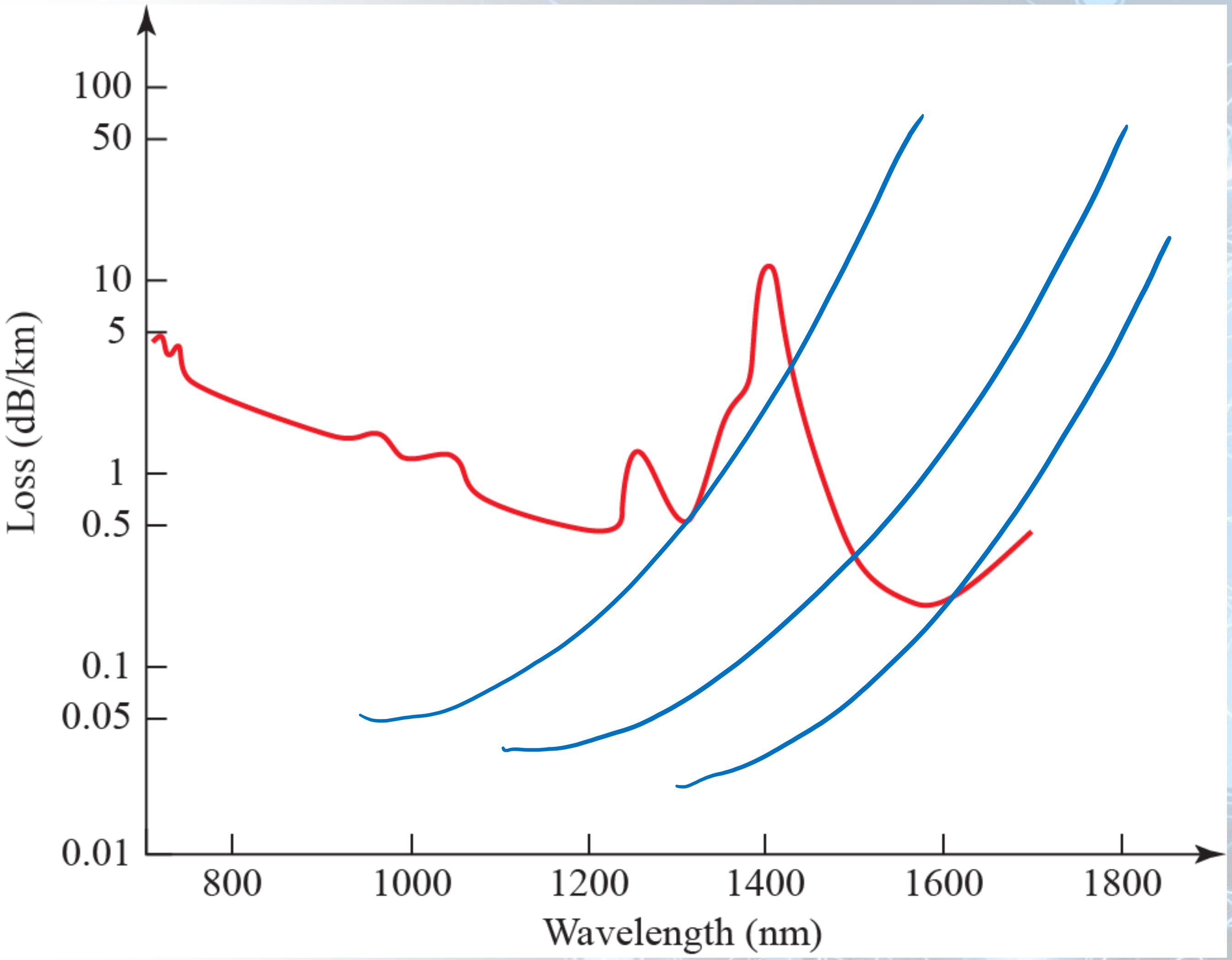
ST connector

Networking Routers




MT-RJ connector

# Optical Fiber Performance



# Advantages & Disadvantages

- **Higher Bandwidth**
- **Less Attenuation**
- **Less EM Interference**
- **Light Weight**
- **Less corrosive than copper**

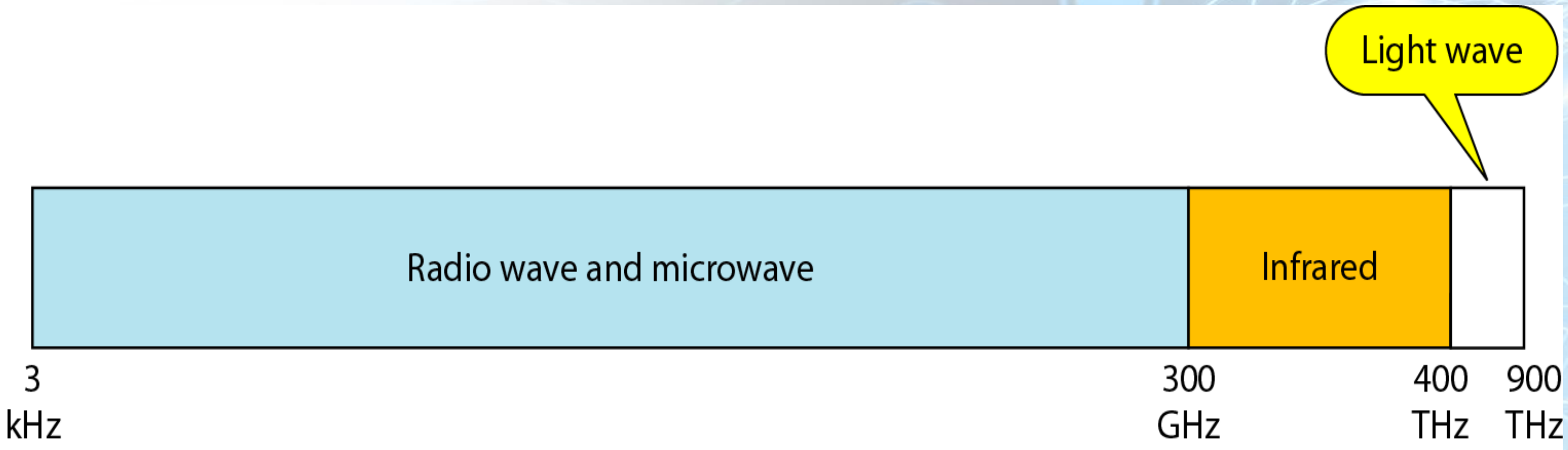
---

- **Installation/Maintenance**
- **Unidirectional**
- **Cost**

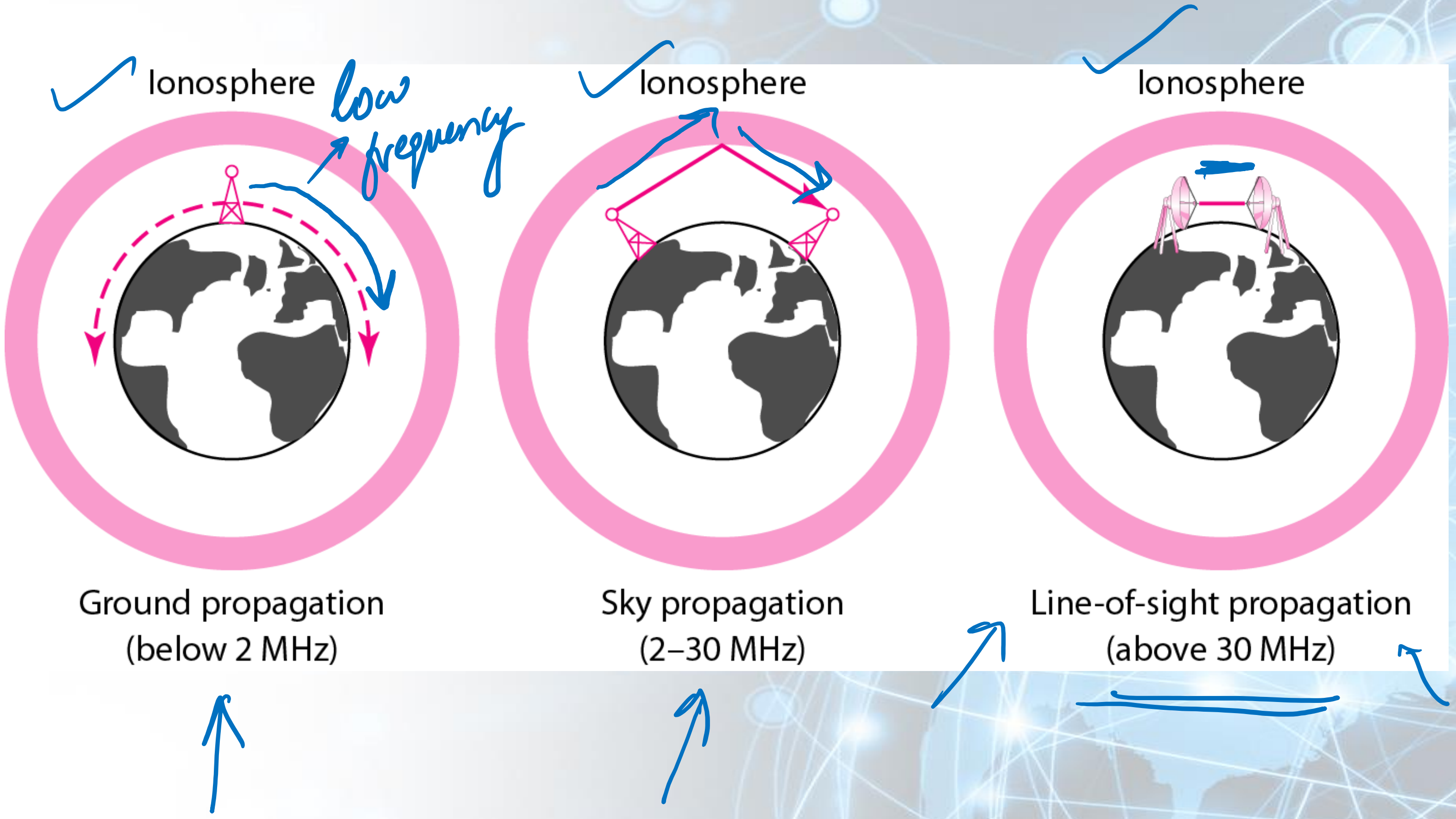
# Unguided Media

- Unguided medium transport waves without using a physical conductor
- Often referred to wireless communication
- Signals are normally broadcast through free space and thus are available to anyone who has a device capable of receiving them

# Electromagnetic Spectrum



# Propagation Methods



# Bands

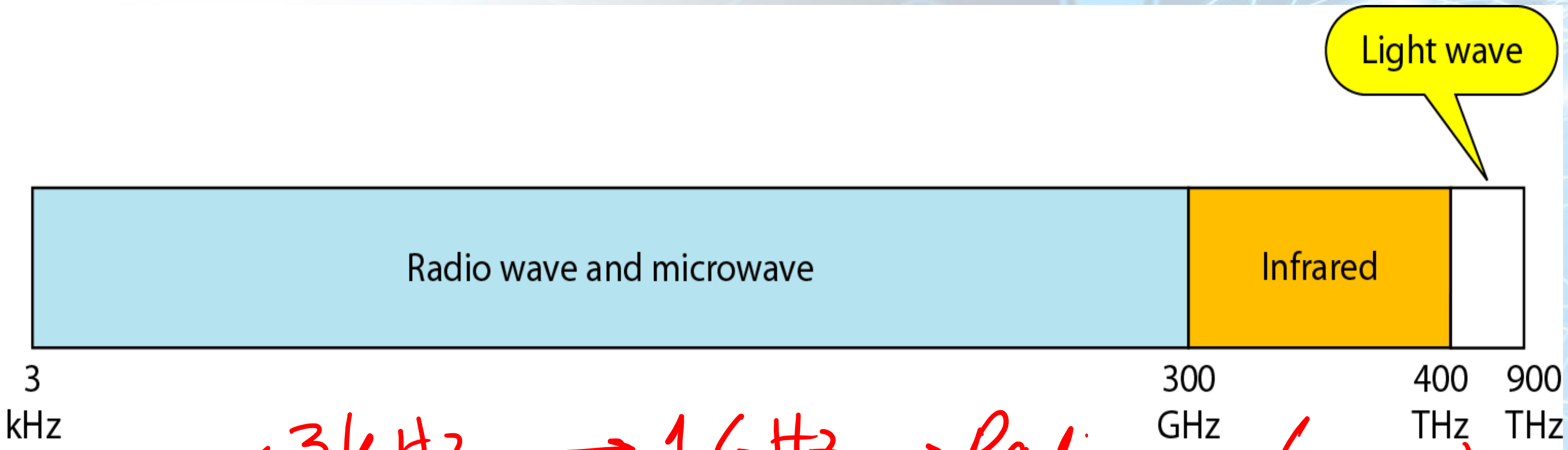
| *Band* | *Range* | *Propagation* | *Application* |
|---|---|---|---|
| very low frequency (VLF) | 3–30 kHz | Ground | Long-range radio navigation |
| low frequency (LF) | 30–300 kHz | Ground | Radio beacons and navigational locators |
| middle frequency (MF) | 300 kHz–3 MHz | Sky | AM radio |
| high frequency (HF) | 3–30 MHz | Sky | Citizens band (CB), ship/aircraft |
| very high frequency (VHF) | 30–300 MHz | Sky and line-of-sight | VHF TV, FM radio |
| ultrahigh frequency (UHF) | 300 MHz–3 GHz | Line-of-sight | UHF TV, cellular phones, paging, satellite |
| superhigh frequency (SF) | 3–30 GHz | Line-of-sight | Satellite |
| extremely high frequency (EHF) | 30–300 GHz | Line-of-sight | Radar, satellite |

# Radio Waves

- Electromagnetic waves ranging in frequencies between 3 kHz and 1 GHz are normally called radio waves

- Electromagnetic waves ranging in frequencies between 1 and 300 GHz are called microwaves

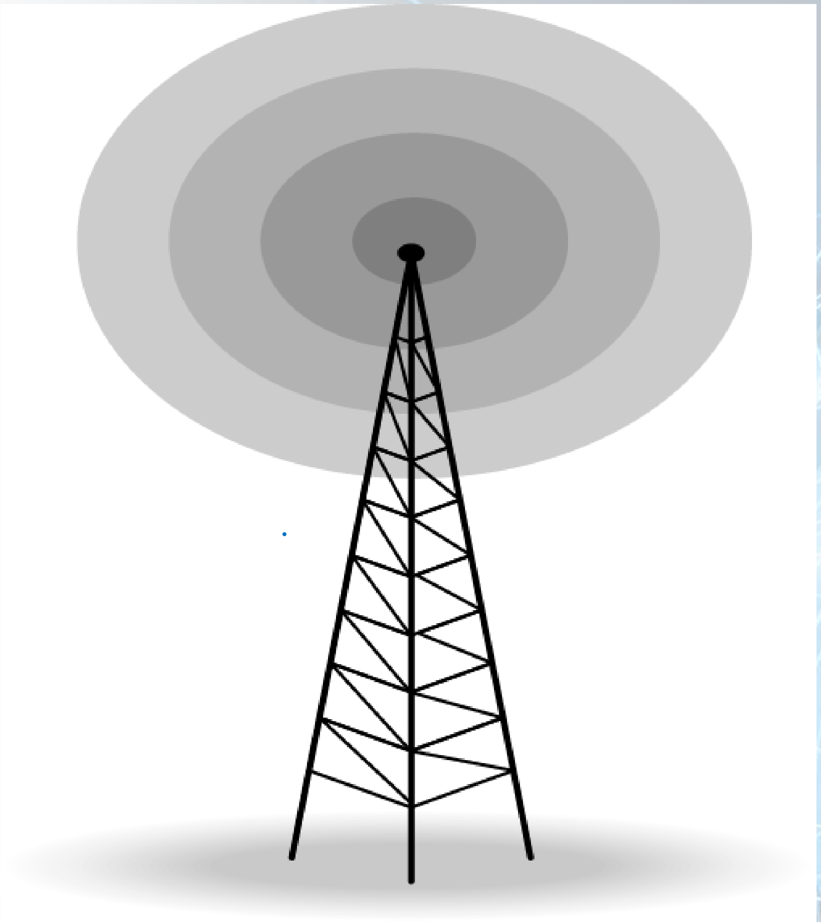
# Electromagnetic Spectrum




3kHz → 1GHz → Radio waves (narrow)

Sub-bands 1GHz → 3GHz → Microwaves

# Omnidirectional Antenna



AM
FM
} Radio

TV
cordless phones
pagers

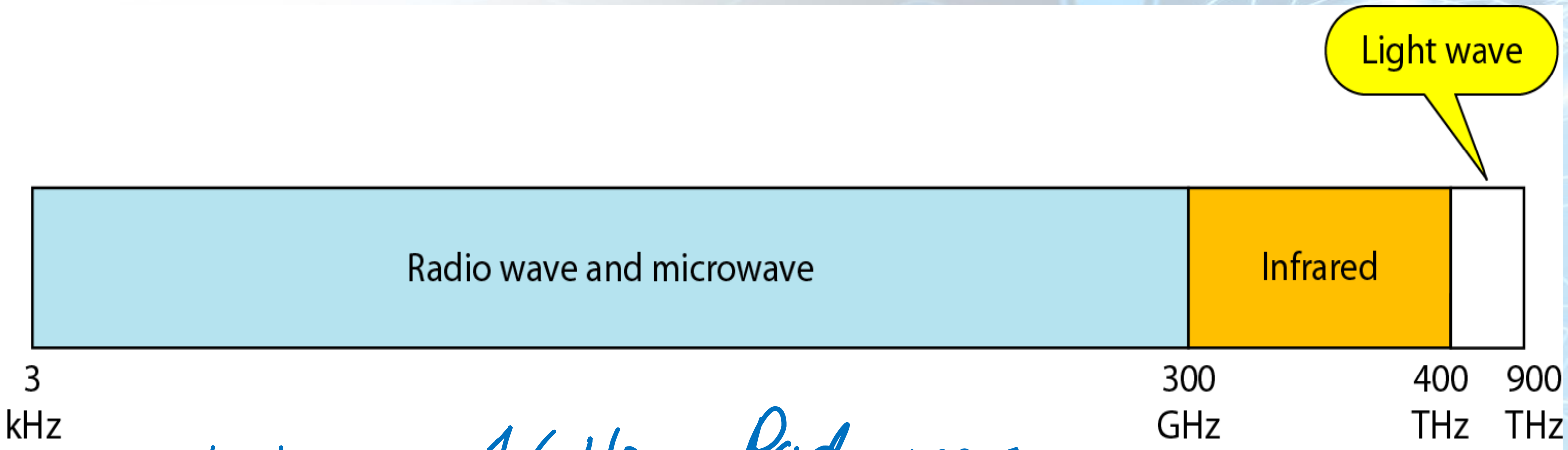
# Microwaves

- **Electromagnetic waves having frequencies between 1 and 300 GHz are called microwaves**

- **Microwaves are unidirectional**

- **When an antenna transmits microwaves, they can be narrowly focused**

# Electromagnetic Spectrum



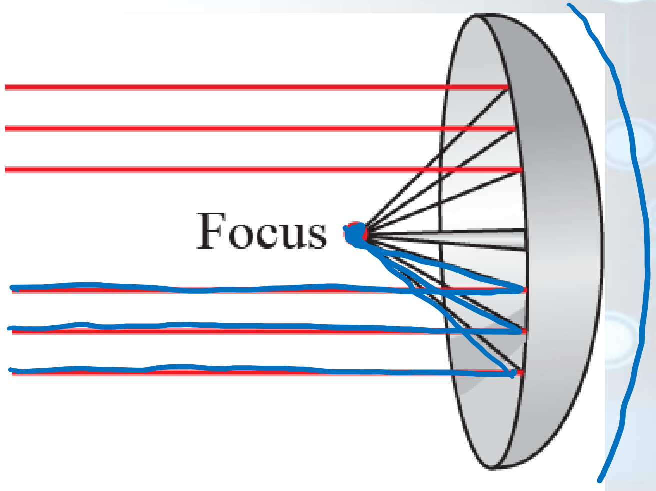

3kHz — 1GHz Radio waves

1GHz — 300GHz Microwaves (unidirectional) (line of sight)

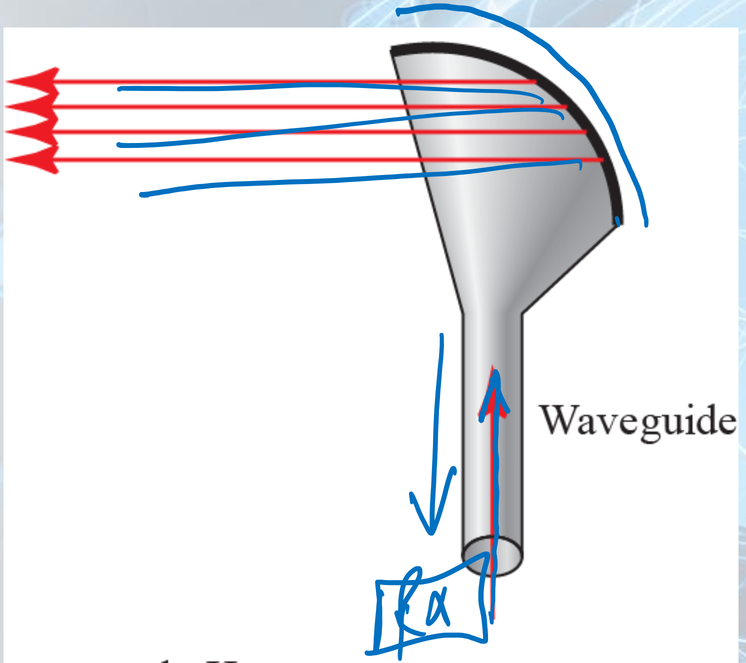
↓

299GHz → High data rates

# Unidirectional Antennas




a. Parabolic dish antenna




b. Horn antenna

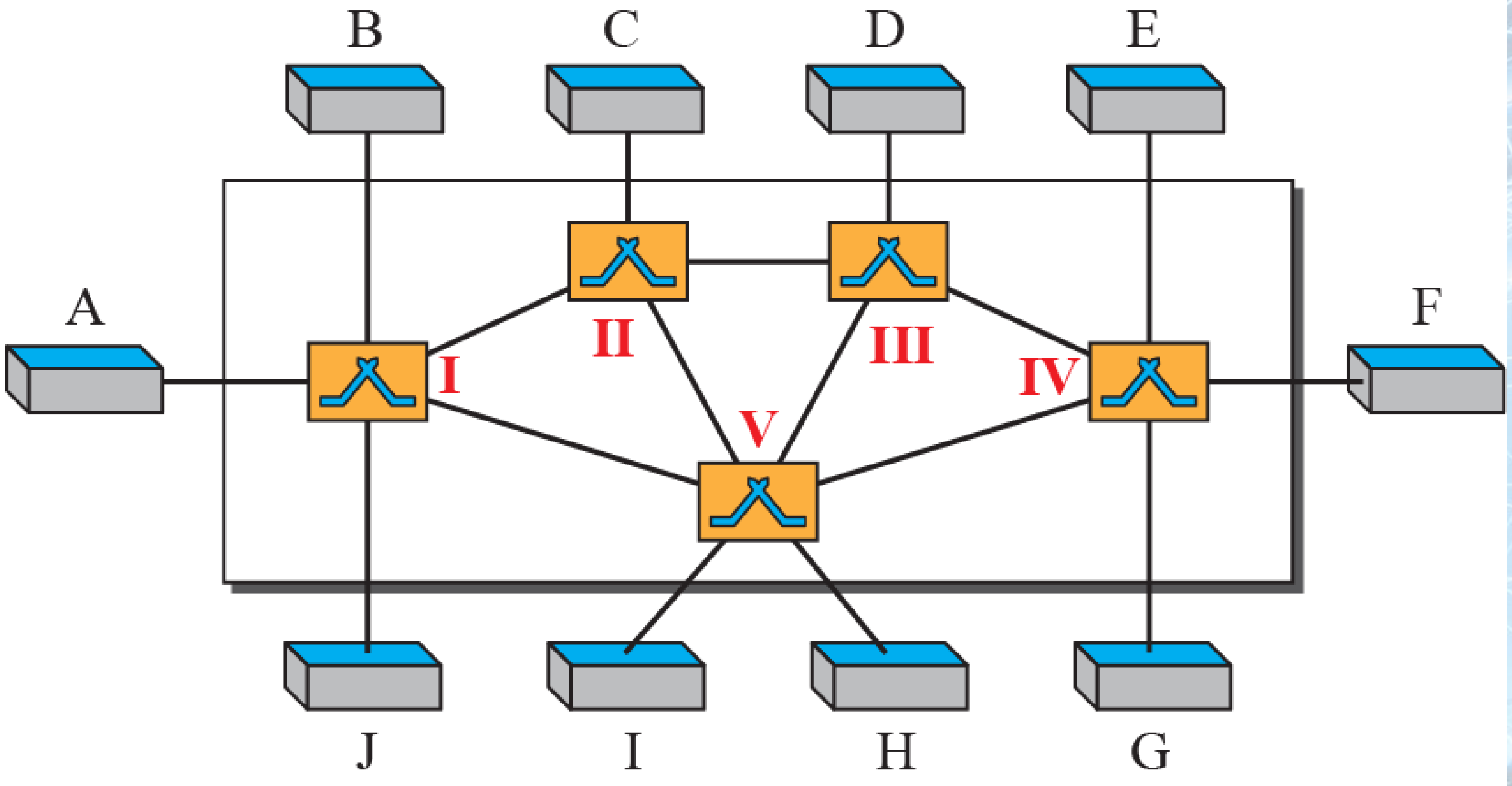
# Infrared

- **Infrared waves, with frequencies from 300 GHz to 400 THz (wavelengths from 1 mm to 770 nm), can be used for short-range communication**
- **Infrared waves, having high frequencies, cannot penetrate walls**
- **Prevents interference between one system and another**

# Switching

- A network is a set of connected devices
- Problem of how to connect multiple devices to make one-to-one communication possible
- The solution is Switching
- Switched network consists of a series of switches

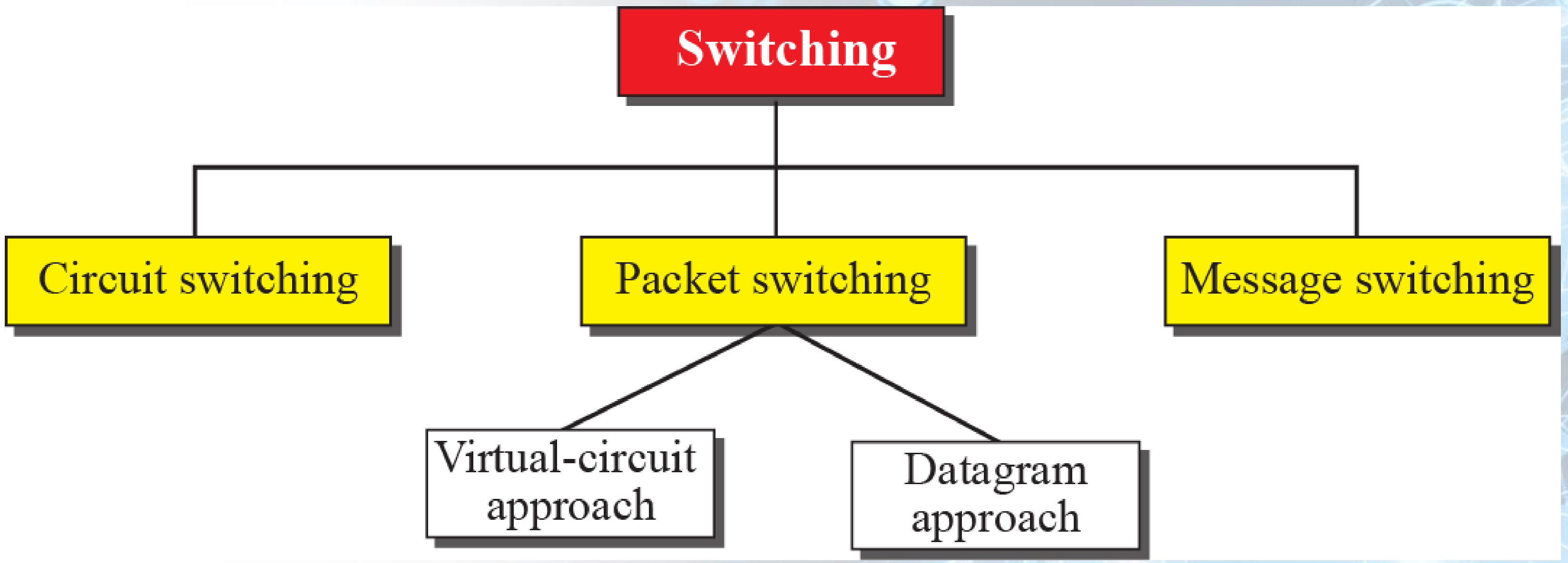
# Switched Network



# Three Methods of Switching

- **Three Methods:**
  - ✓ **Circuit Switching**
  - ✓ **Packet Switching**
  - ✓ **Message switching**
- **The first two are commonly used today**
- **The third has been phased out in general communications**

# Taxonomy of Switched Networks



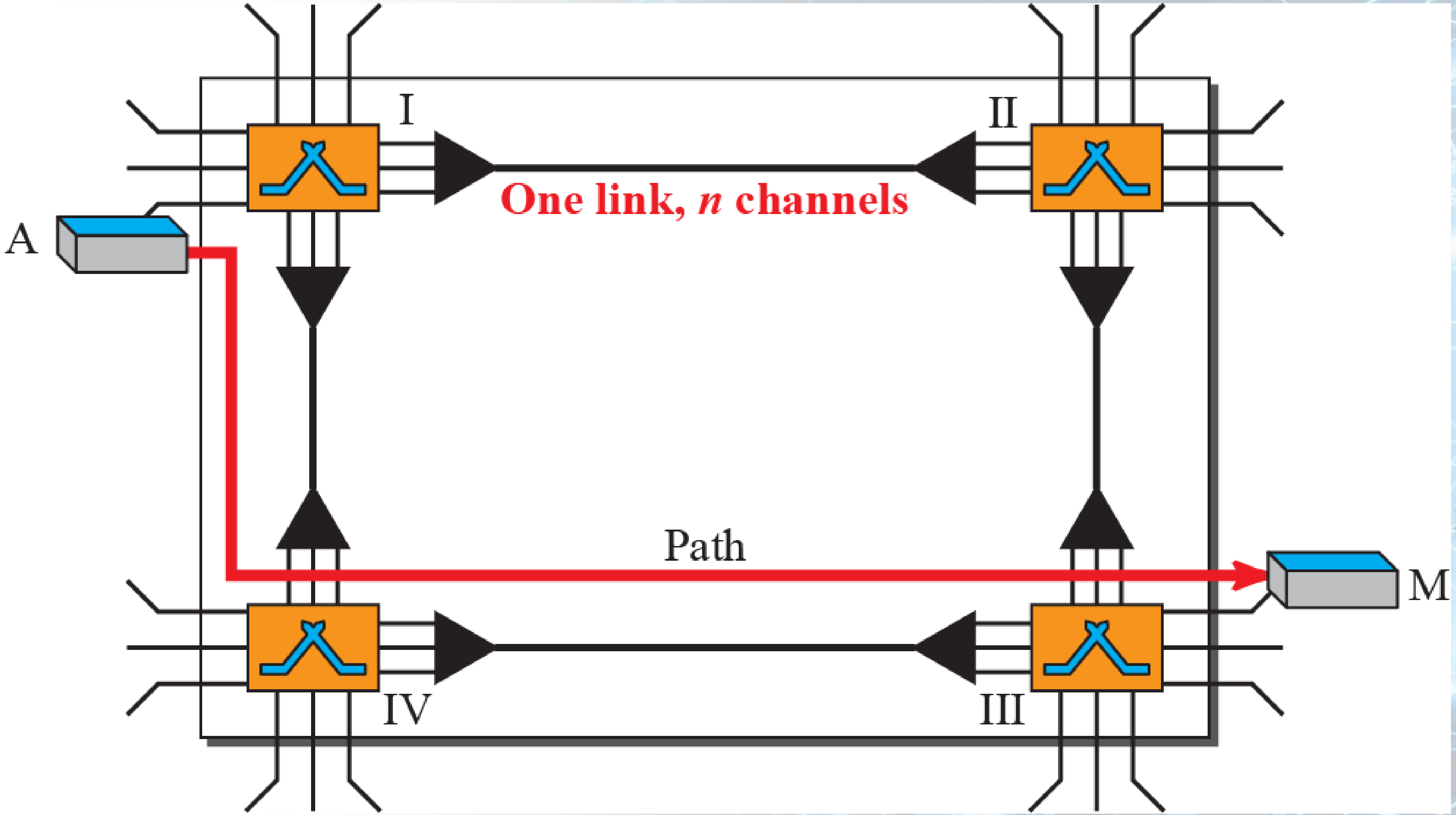
# Circuit-switched Networks

- **A set of switches connected by physical links**
- **A connection between two stations is a dedicated path made of one or more links**
- **Each connection uses only one dedicated channel on each link**
- **Each link is normally divided into n channels by using FDM or TDM**

# Circuit-switched Networks

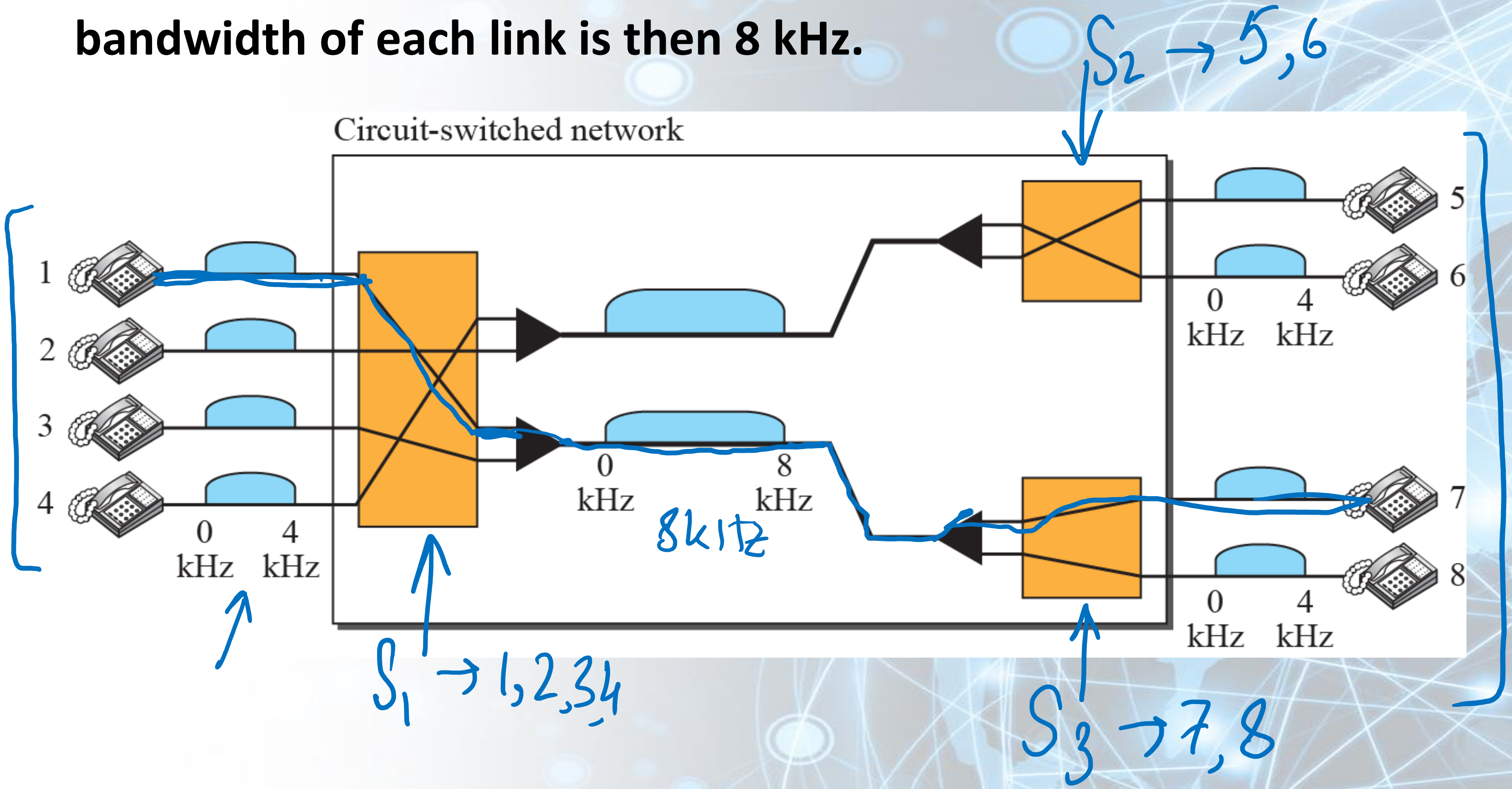
- **A set of switches connected by physical links**

# A Circuit-Switched Network



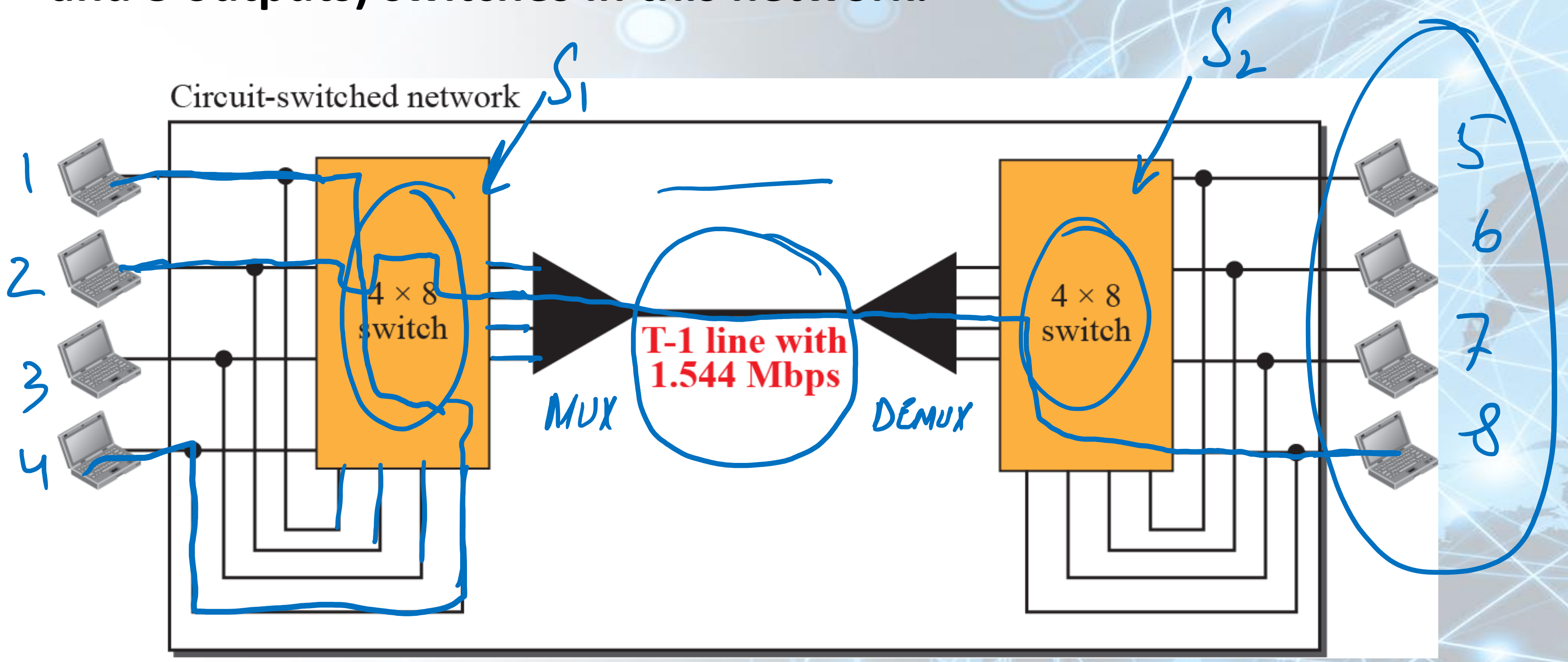
# Example

As a trivial example, let us use a circuit-switched network to connect eight telephones in a small area. Communication is through 4-kHz voice channels. We assume that each link uses FDM to connect a maximum of two voice channels. The bandwidth of each link is then 8 kHz.



# Example

As another example, consider a circuit-switched network that connects computers in two remote offices of a private company. The offices are connected using a T-1 line leased from a communication service provider. There are two 4 × 8 (4 inputs and 8 outputs) switches in this network.

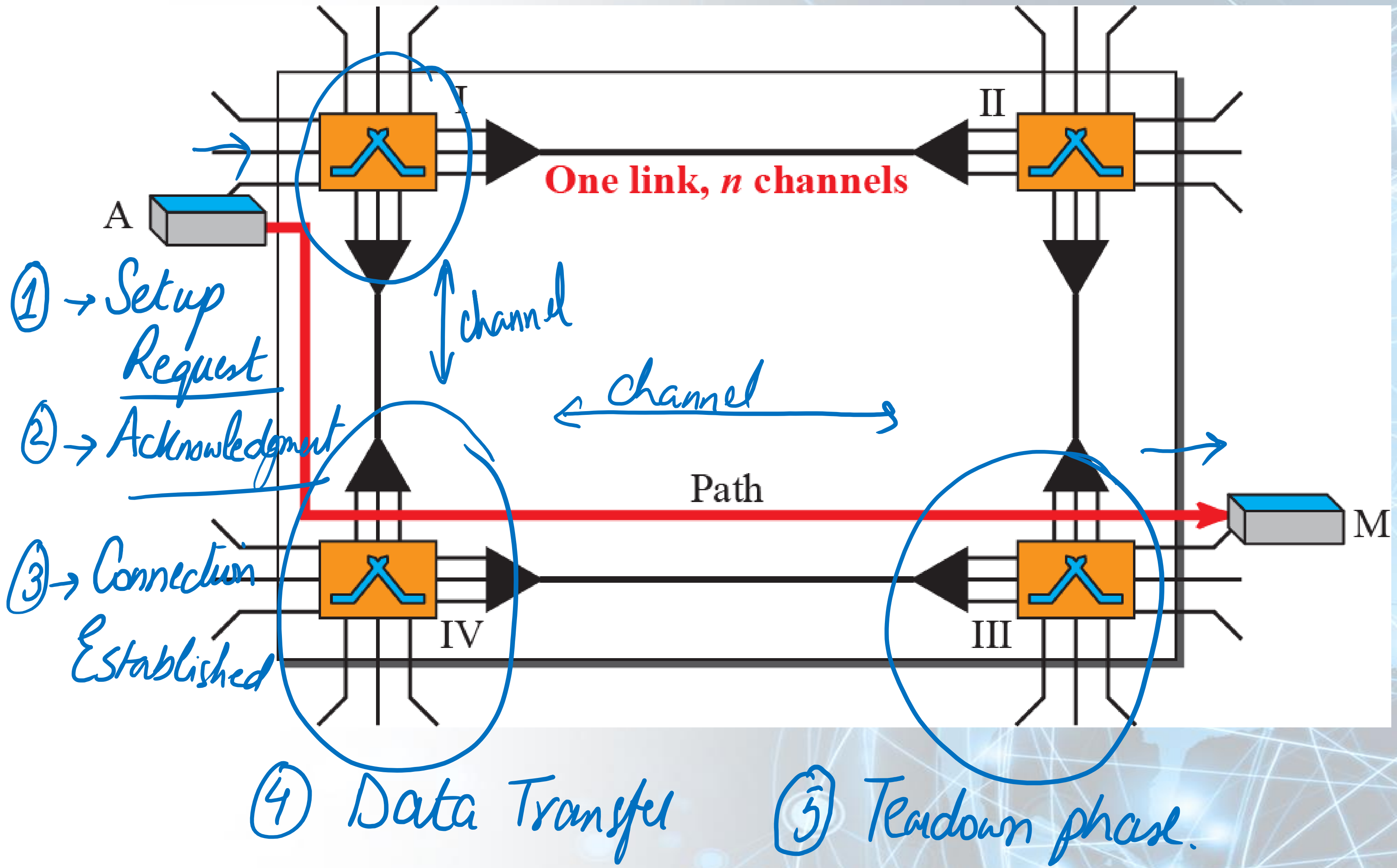


# Three Phases in a Circuit Switched Network

- **The actual communication in a circuit-switched network requires 3 phases:**
  - ✓ **Connection Setup**
  - ✓ **Data Transfer**
  - ✓ **Connection Teardown**

# Three Phases in a Circuit Switched Network

Dedicated Circuit → Link with channels



# Efficiency of a Circuit-Switched Network

- **Not as efficient as packet switching because resources are allocated during the entire duration of the connection and these resources are unavailable to other connections**

# Efficiency of a Circuit-Switched Network

- In a telephone network, people normally terminate the communication when they have finished their conversation

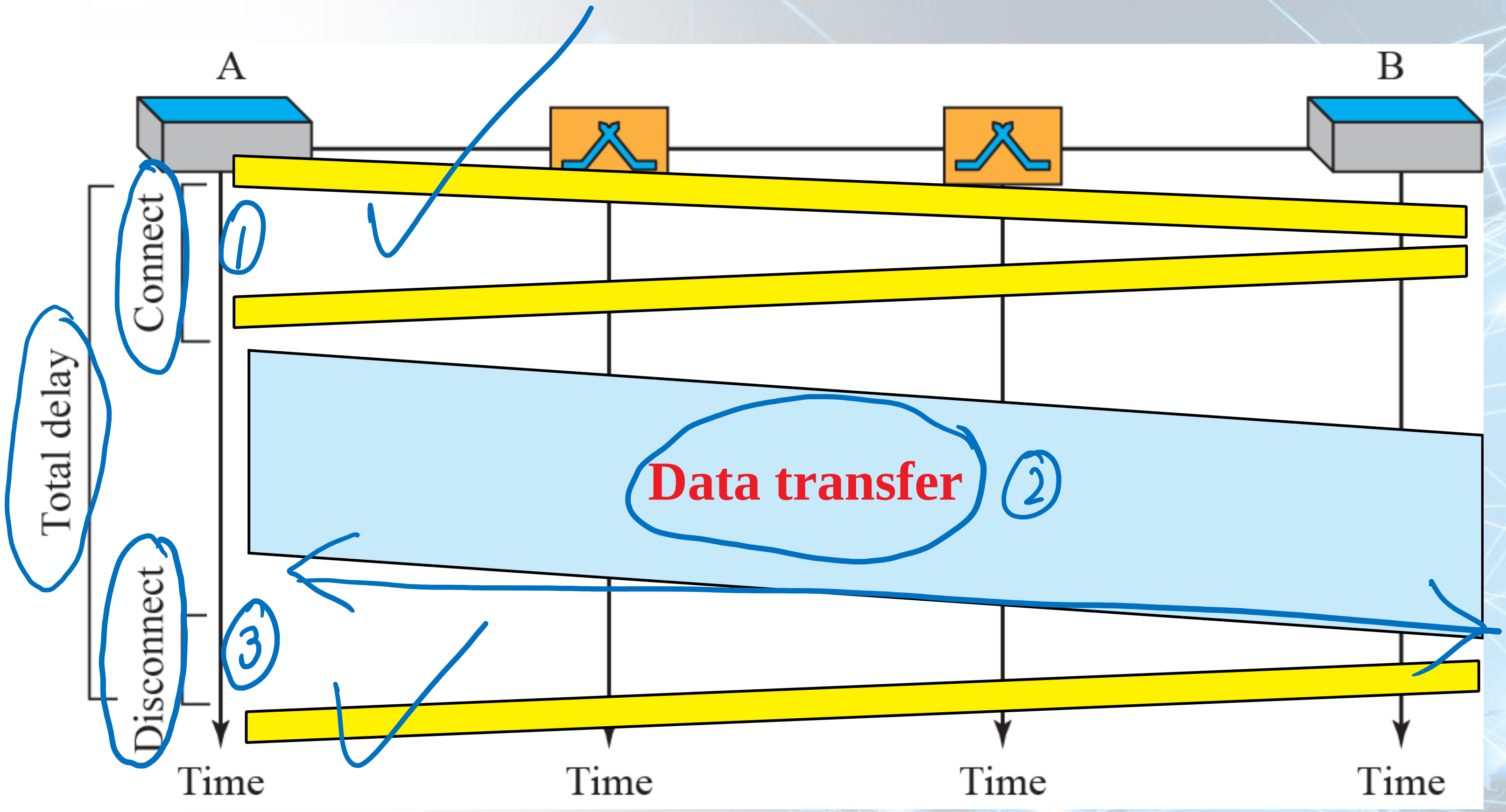
- Data Network is an issue

# Delay in a Circuit-Switched Network

- **Circuit switched networks have low efficiency but minimal delay**

- **Data is not delayed at each switch; the resources are allocated for the duration of the connection**

# Delay in a Circuit-Switched Network



# Packet Switching

- If the message is going to pass through a packet-switched network, it needs to be divided into packets of fixed or variable size

- The size of the packet is determined by the network and the governing protocol

# Datagram Networks

- Each packet is treated independently of all others.
- Even if a packet is part of a multi-packet transmission, the network treats it as though it existed alone
- Packets are referred to as datagrams

# Virtual-Circuit Networks

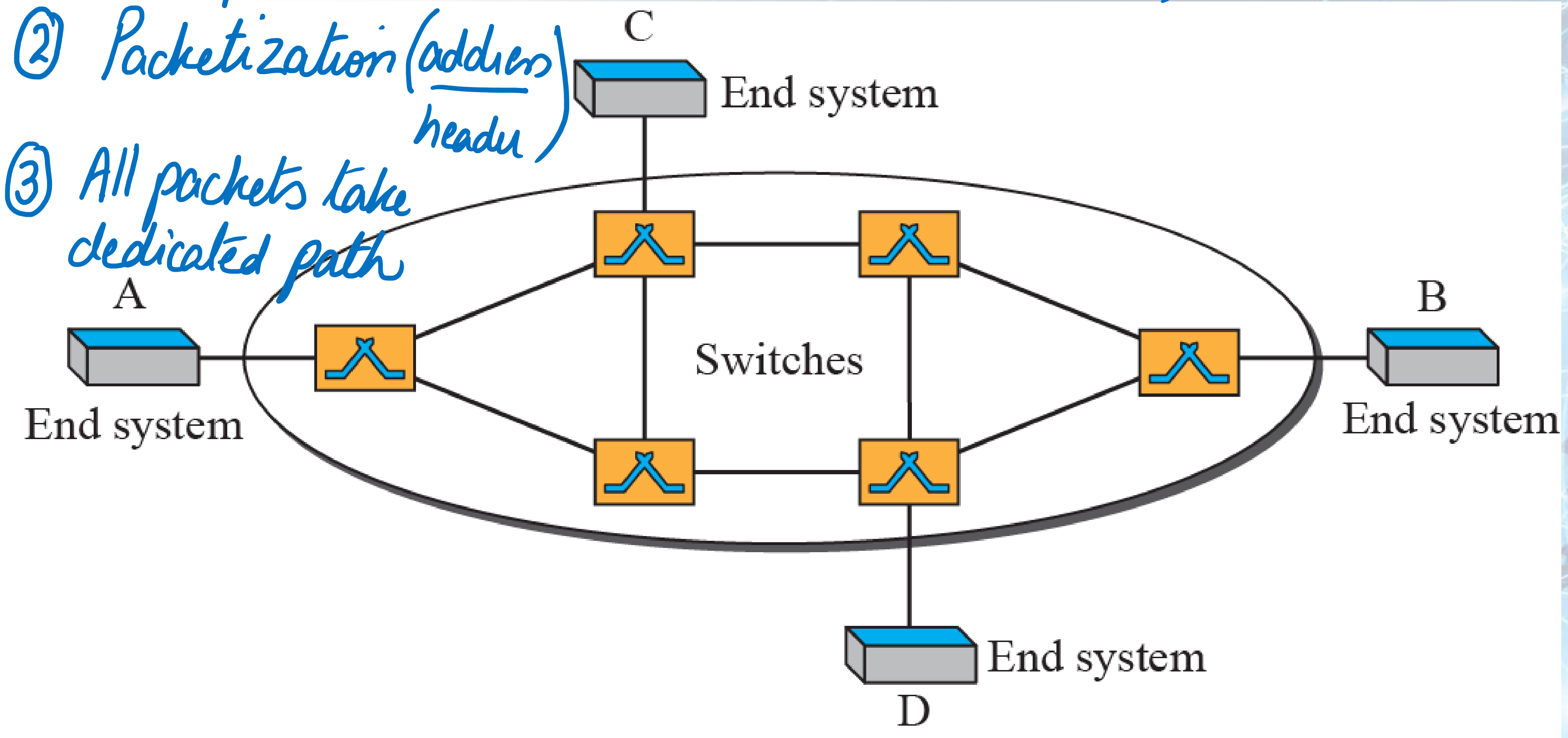
- **A virtual-circuit network is a cross between a circuit-switched network and a datagram network**

# Virtual-circuit network

① Setup & Teardown process (resources reservation)

② Packetization (address header)

③ All packets take dedicated path



# Virtual-Circuit Networks

- **A virtual-circuit network is a cross between a circuit-switched network and a datagram network**

# Virtual-Circuit Networks

Physical → Circuit Switching (Set up, Transfer & Tear down)

Data Link Layer → Virtual Circuit Approach (Set up, Transfer & Tear down)
↳ Packets (Frames)

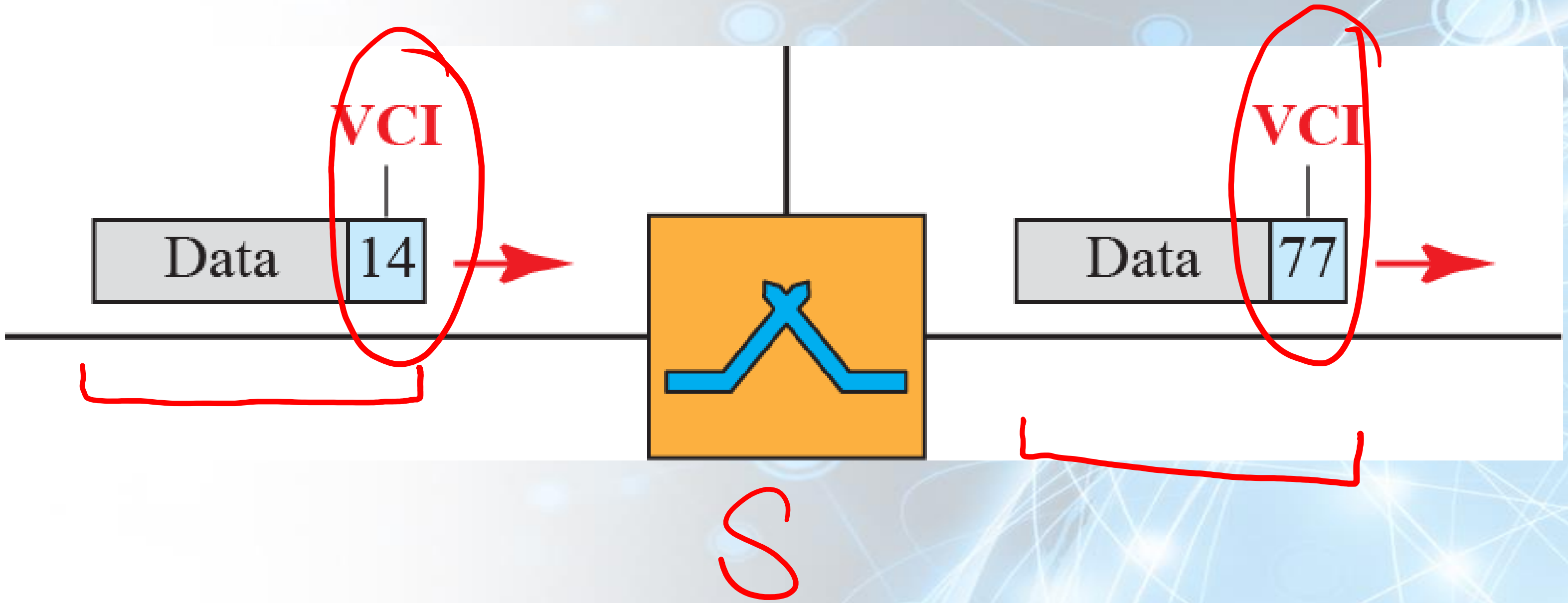
Network Layer → Datagram Switching (Independent Datagrams or Packets)

# Virtual-Circuit Networks

- **A virtual-circuit network is a cross between a circuit-switched network and a datagram network**

# Virtual-Circuit Identifier

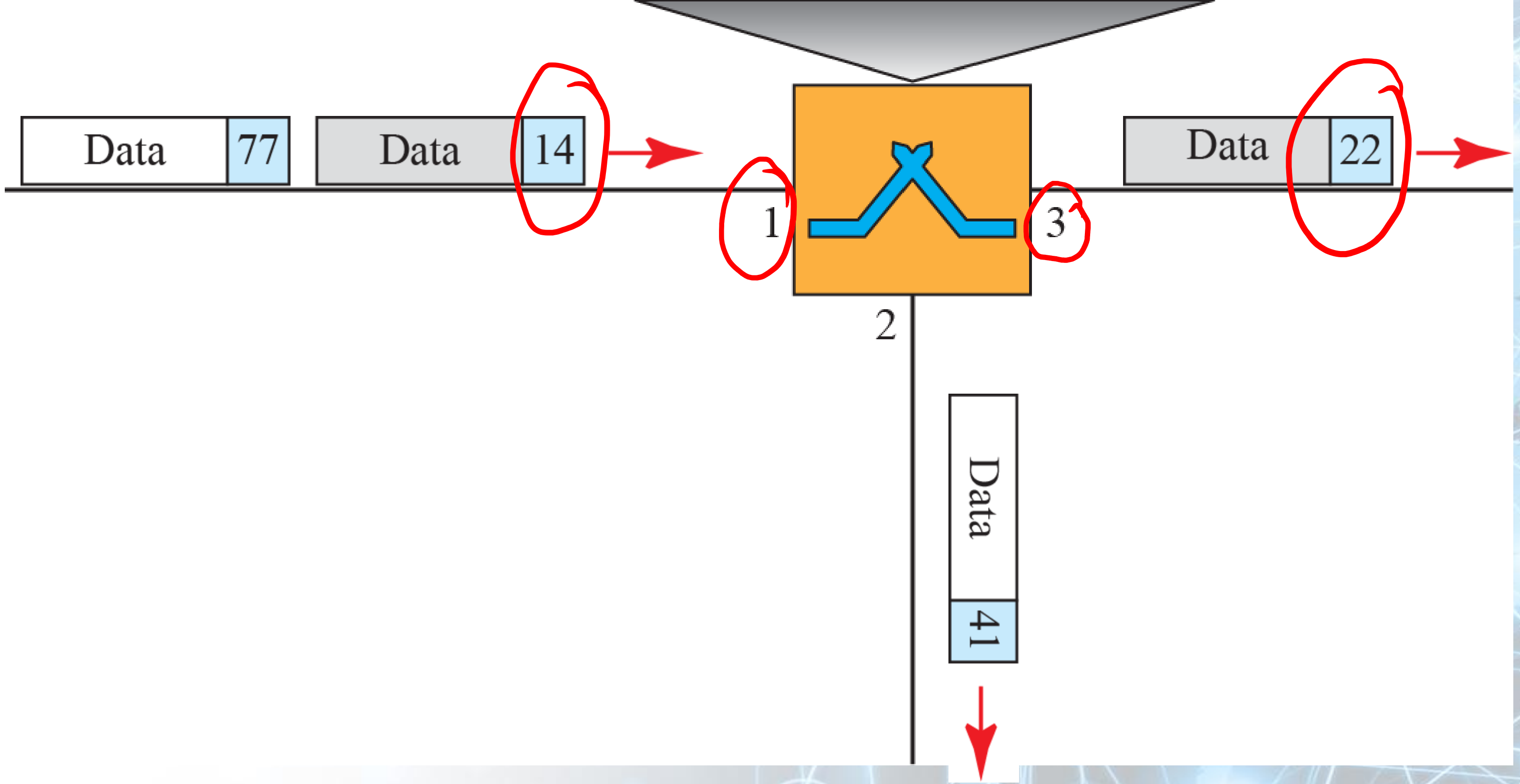
VCI (label) → local switch scope



# Switch & table for a virtual-circuit network

Data Transfer Phase

| Incoming | | Outgoing | |
|---|---|---|---|
| Port | VCI | Port | VCI |
| 1 | 14 | 3 | 22 |
| 1 | 77 | 2 | 41 |

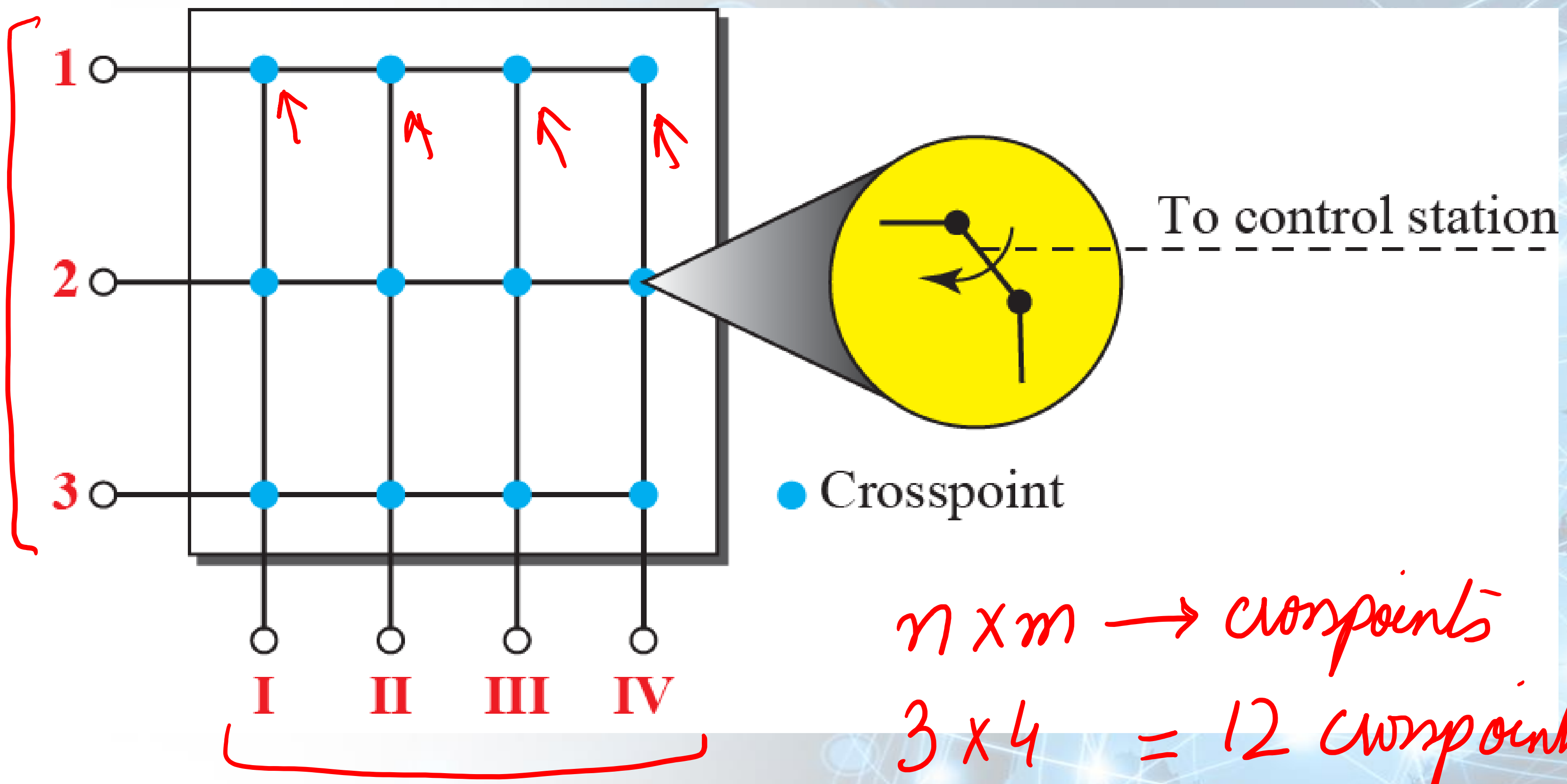


# Structure Of A Circuit Switch

- **Circuit switching today can use either of two technologies:**
  - ✓ **The Space-Division switch**
  - ✓ **The Time-Division switch**

# Crossbar switch with 3 inputs & 4 outputs

n inputs m outputs (n=3; m=4)



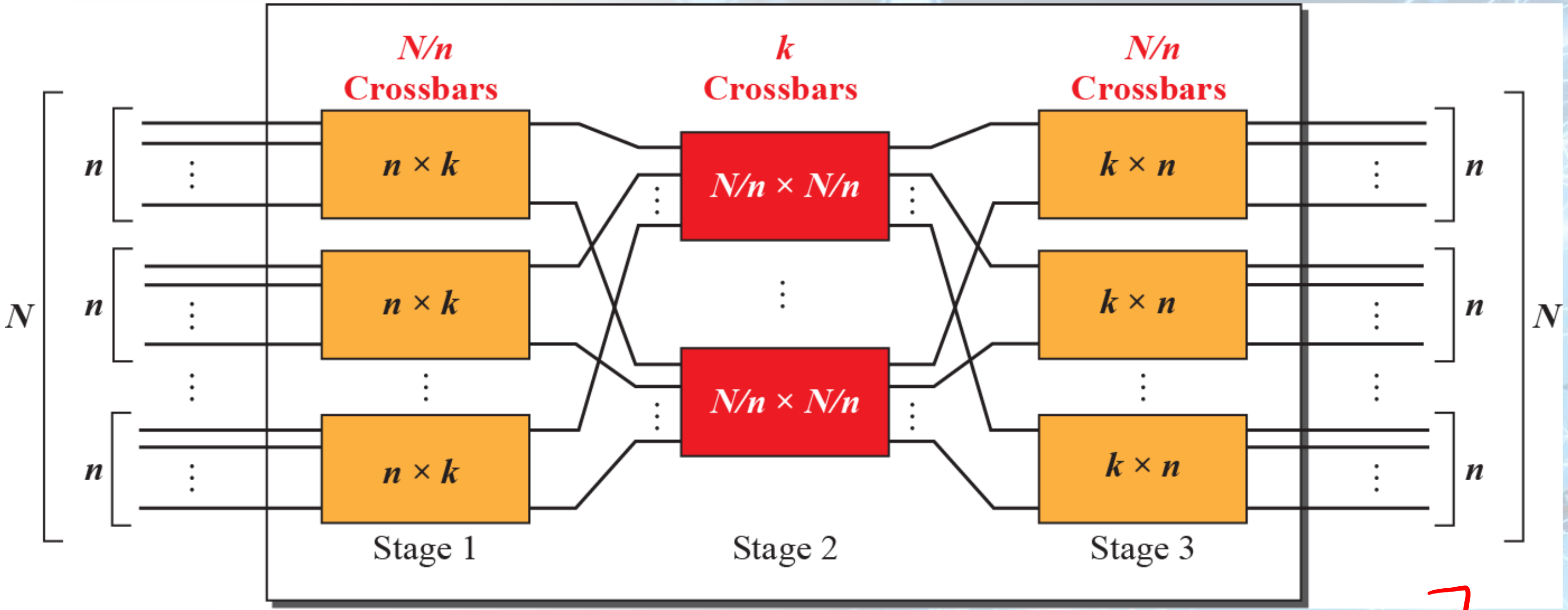

n x m → crosspoints

3 x 4 = 12 crosspoints

25% of crosspoints

# Multistage Switch

N x N crosspoints



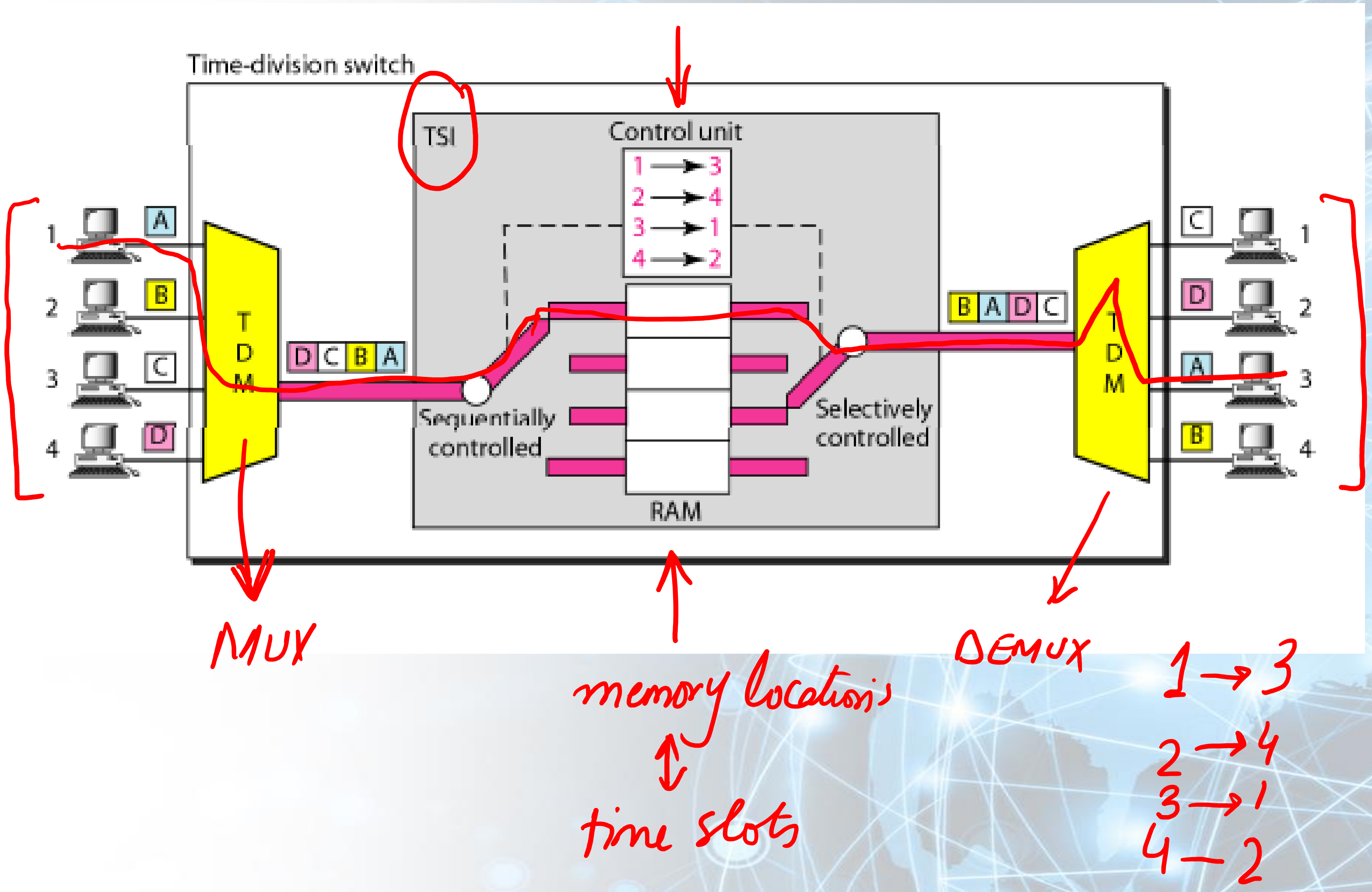

No. of crosspoints ⇒ $2kN + k\left(\frac{N}{n}\right)^2$ → lesser

" " " ⇒ $N^2$

# Time-Division Switch

- **Uses TDM inside a switch**
- **Most popular technology is Time-Slot Interchange (TSI)**

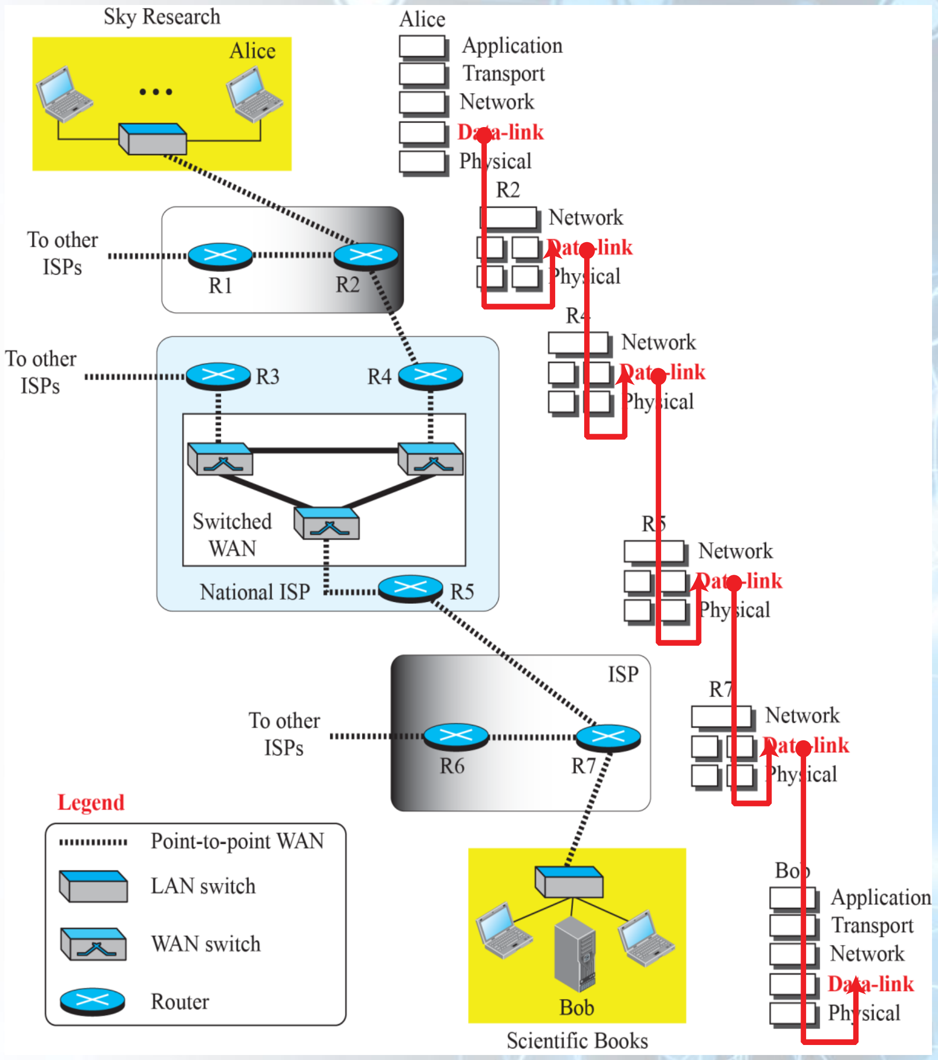
# Time-Division Switch



# Data-Link Layer

- The Internet is a combination of networks glued together by connecting devices (routers or switches)
- If a packet is to travel from a host to another host, it needs to pass through these networks
- Data Link layer controls node-to-node communication

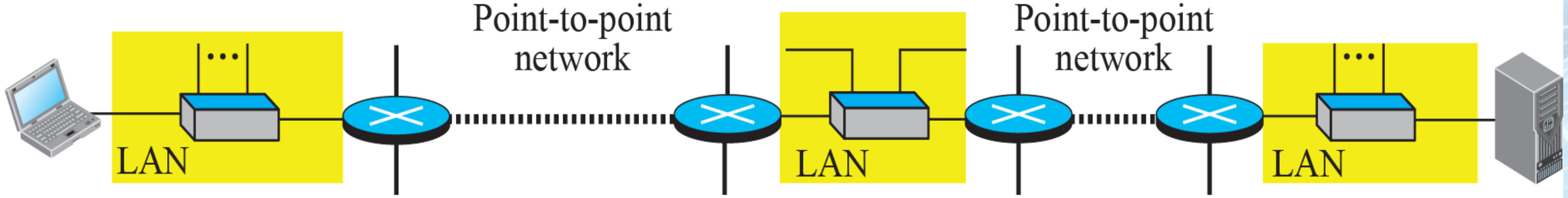
# Communication at the Data-Link Layer



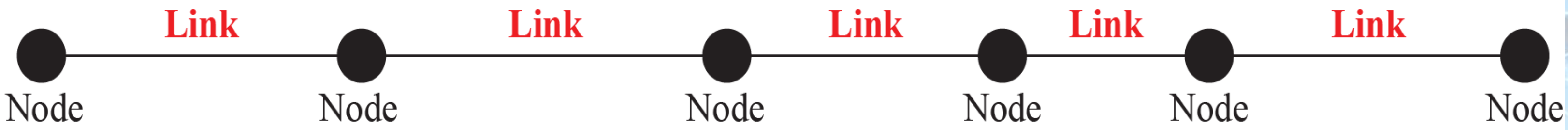
# Nodes and Links

- Communication at the data-link layer is node-to-node
- A data unit from one point in the Internet needs to pass through many networks (LANs and WANs) to reach another point
- We refer to the two end hosts and the routers as nodes and the networks in between as links

# Nodes and Links




a. A small part of the Internet

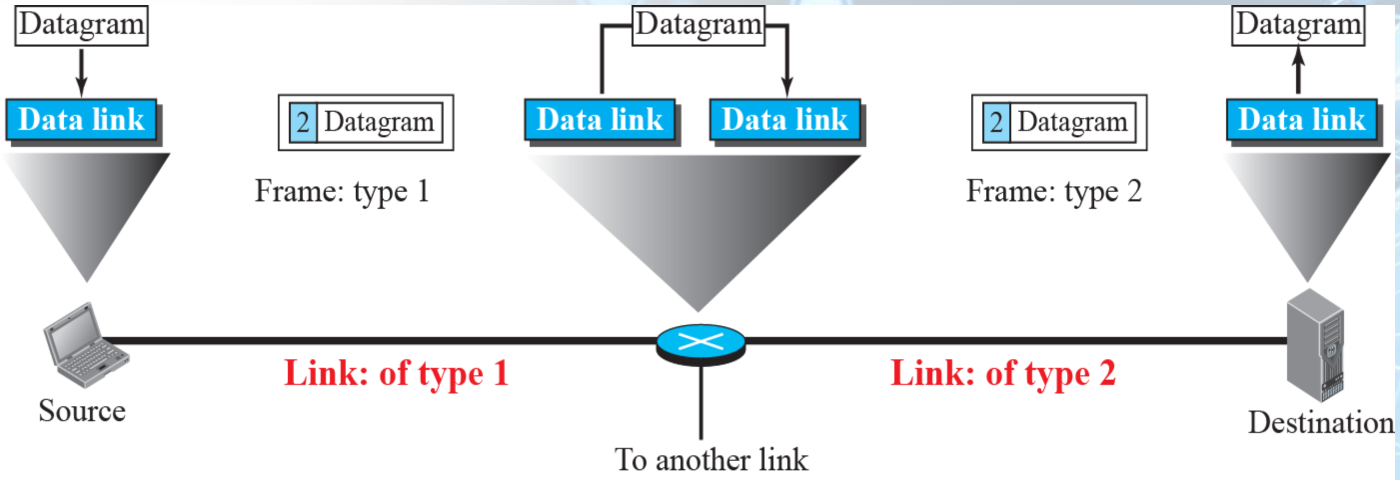



b. Nodes and links

# Services provided by Data-Link Layer

- **Located between the physical and the network layers**
- **Provides services to Network Layer and receives services from Physical layer**
- **Framing**
- **Flow Control**
- **Error Control**
- **Congestion Control**

# A Communication with only Three Nodes



# Services provided by Data-Link Layer

- **Data-Link layer provides services to Network Layer and receives services from Physical layer**

  - ✓ **Framing**
  - ✓ **Flow Control**
  - ✓ **Error Control**
  - ✓ **Congestion Control**

# Two Categories of Links

- Two nodes are physically connected by a transmission medium such as cable or air
- Data-link layer controls how the medium is used
  - ✓ Data-link layer can use whole capacity
  - ✓ Data-link layer can use only part of the capacity

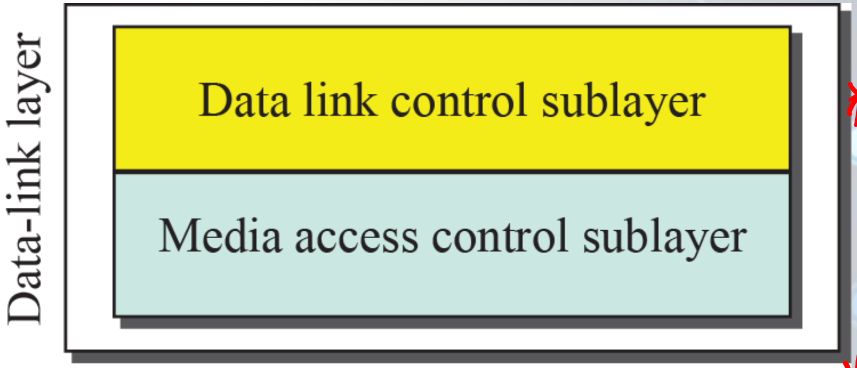
# Two Categories of Links

- **We can have the following two types of links:**
  - ✓ **Point-to-point link or a**
  - ✓ **Broadcast link**

# Two Sublayers of Data-Link Layer

- **We can divide the data-link layer into two sublayers:**
  - **Data Link Control (DLC)**
  - **Media Access Control (MAC)**

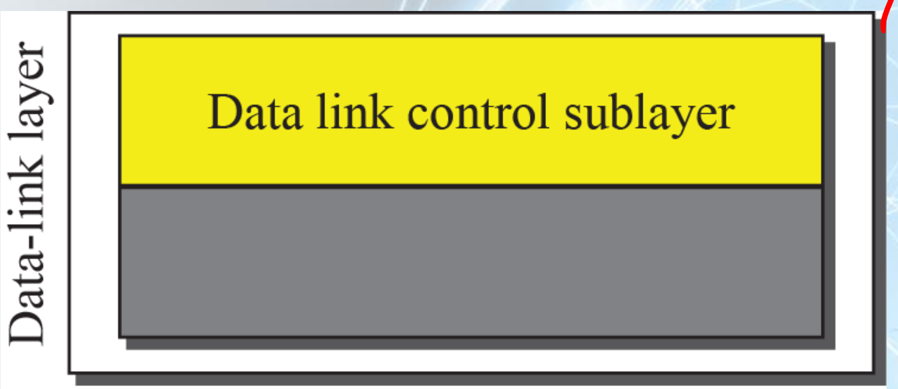
# Dividing the data-link layer into two sublayers



a. Data-link layer of a broadcast link

*DLC → - Broadcast links
- Point-to-point Links

*MAC → - Broadcast Link only



b. Data-link layer of a point-to-point link

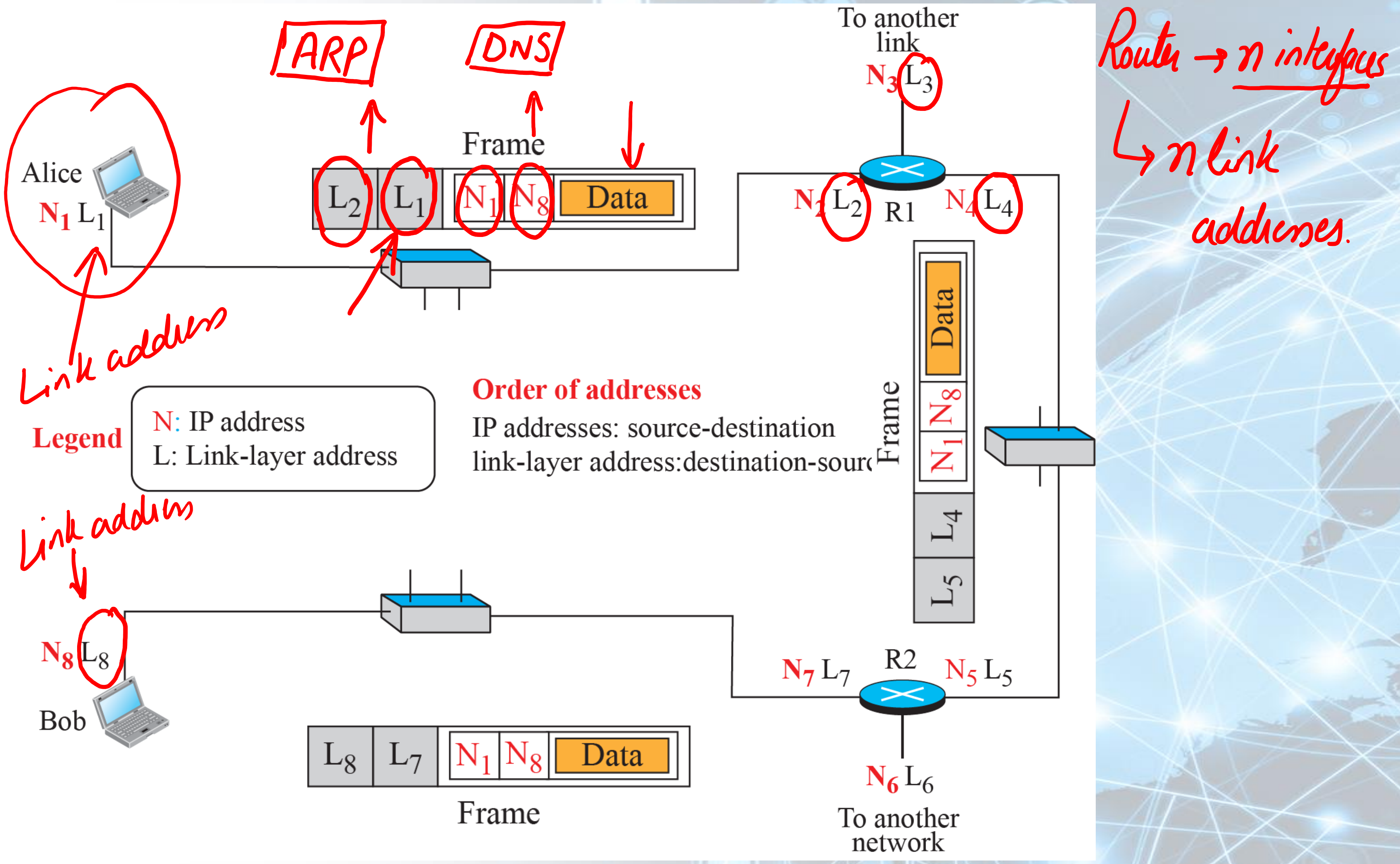
# Why LINK-LAYER ADDRESSING?

- **IP addresses are the identifiers at the network layer**

- **In Internet we cannot make a packet reach its destination using only IP addresses**

- **Source and destination IP addresses define the two ends but cannot define which links the packet  will take**

# IP addresses & Link-Layer Addresses



# Three Types of addresses

- Some link-layer protocols define three types of addresses:
- Unicast
- Multicast
- Broadcast

# Example

The unicast link-layer addresses in the most common LAN, Ethernet, are 48 bits (six bytes) that are presented as 12 hexadecimal digits separated by colons; for example, the following is a link-layer address of a computer. The second digit needs to be an odd number.

A3:34:45:11:92:F1

48 bits

↳ 6 Bytes

12 Hex digits separated by colons

# Example

The multicast link-layer addresses in the most common LAN, Ethernet, are 48 bits (six bytes) that are presented as 12 hexadecimal digits separated by colons. The second digit, however, needs to be an even number in hexadecimal. The following shows a multicast address:

even → multicast address

A2:34:45:11:92:F1

# Example

The broadcast link-layer addresses in the most common LAN, Ethernet, are 48 bits, all 1s, that are presented as 12 hexadecimal digits separated by colons. The following shows a broadcast address:

FF:FF:FF:FF:FF:FF

# Address Resolution Protocol (ARP)

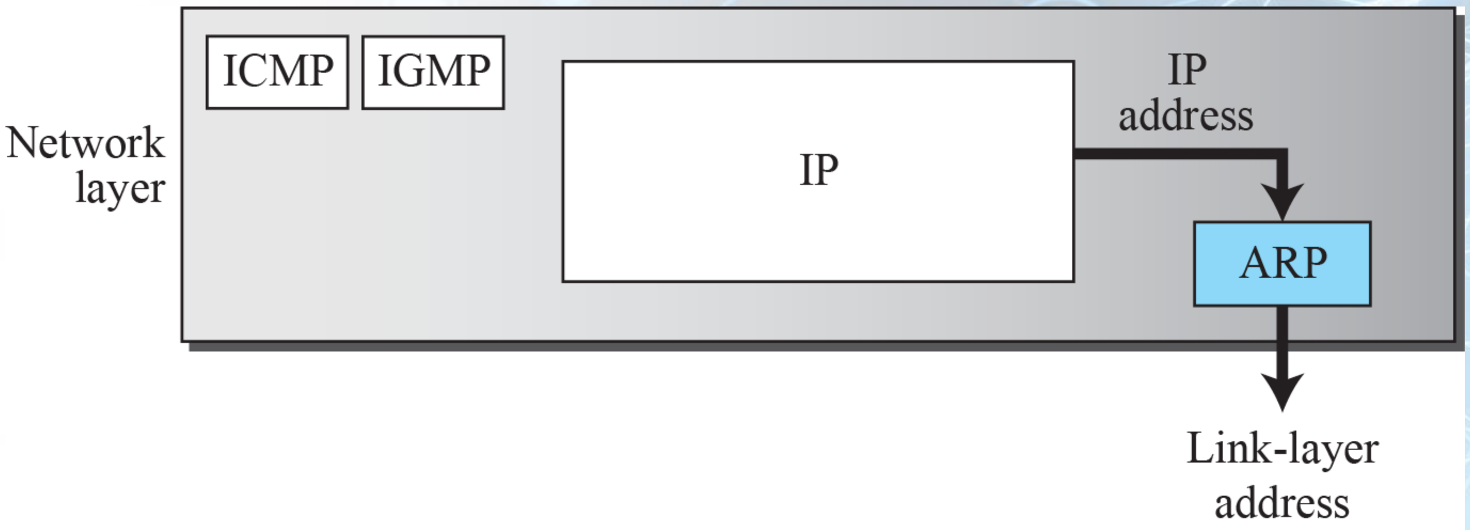
- **Anytime a node has an IP packet to send to another node in a link, it has the IP address of the receiving node**

- **IP address of the next node is not helpful in moving a frame through a link; we need the link-layer address of the next node**

# Address Resolution Protocol (ARP)

- **We need Address Resolution Protocol (ARP)**

# Position of ARP in TCP/IP protocol suite



# Address Resolution Protocol (ARP)

- **Anytime a node has an IP packet to send to another node in a link, it has the IP address of the receiving node**

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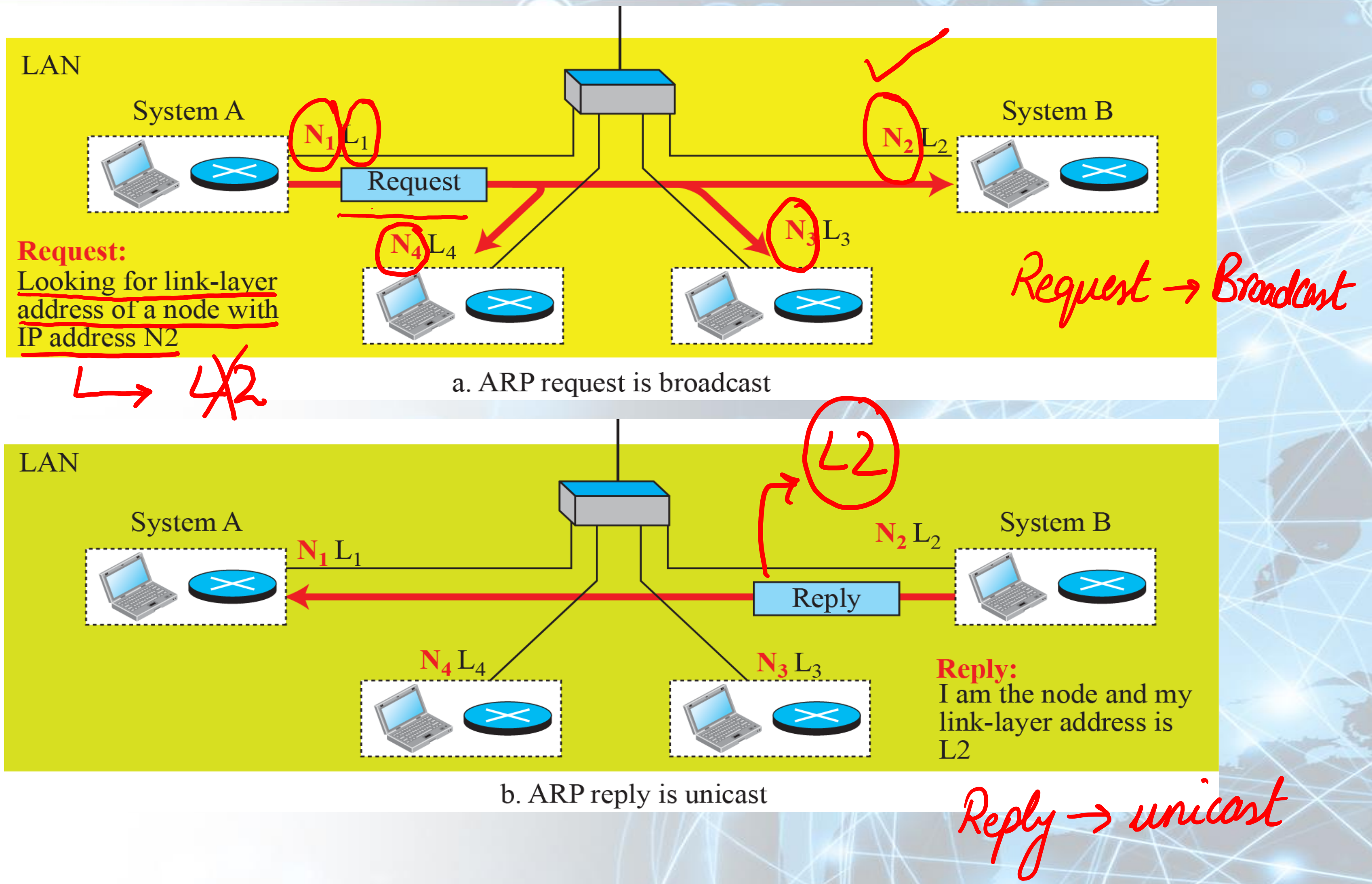
# ARP Operation




a. ARP request is broadcast

b. ARP reply is unicast

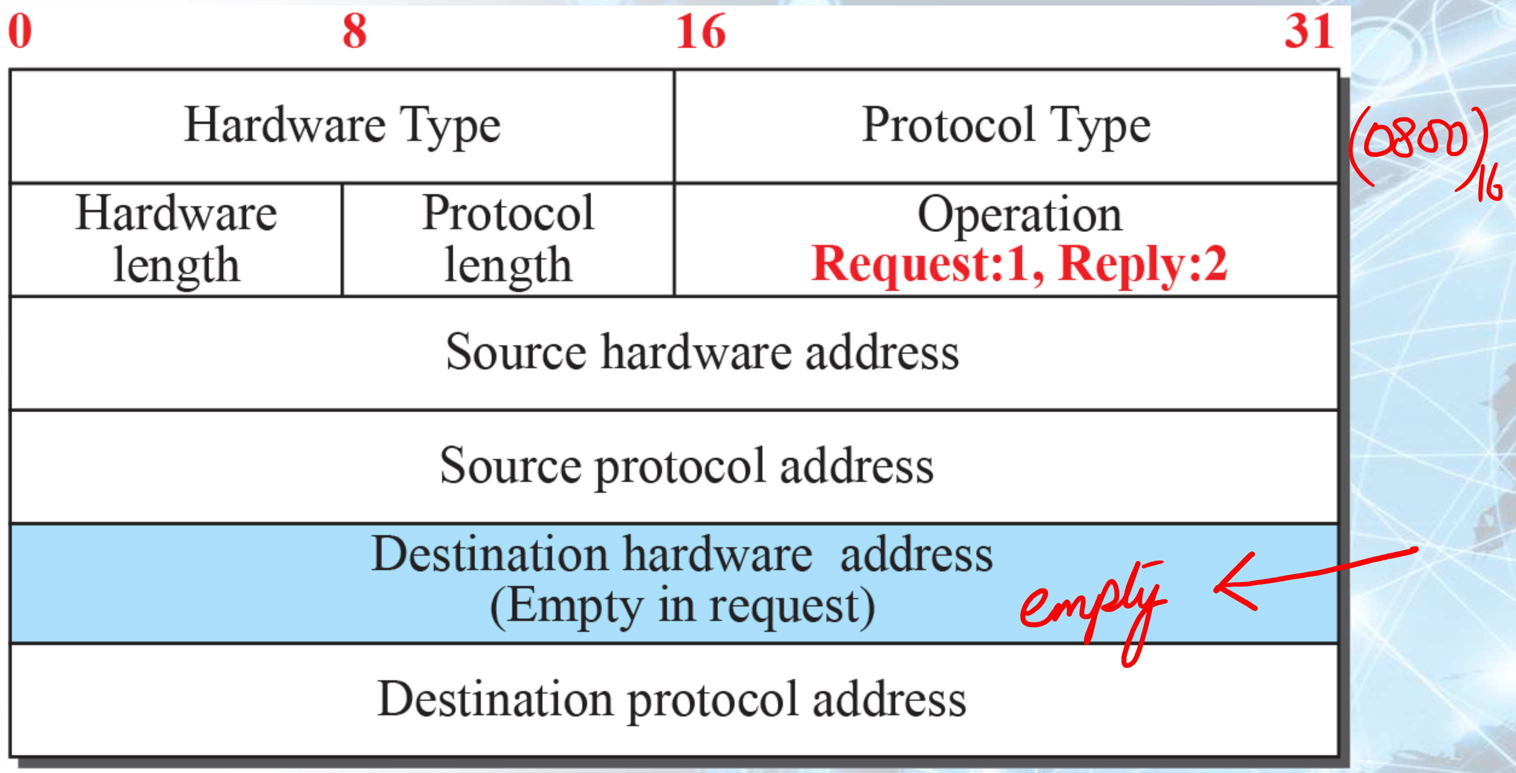
# Address Resolution Protocol (ARP)

- **Anytime a node has an IP packet to send to another node in a link, it has the IP address of the receiving node**

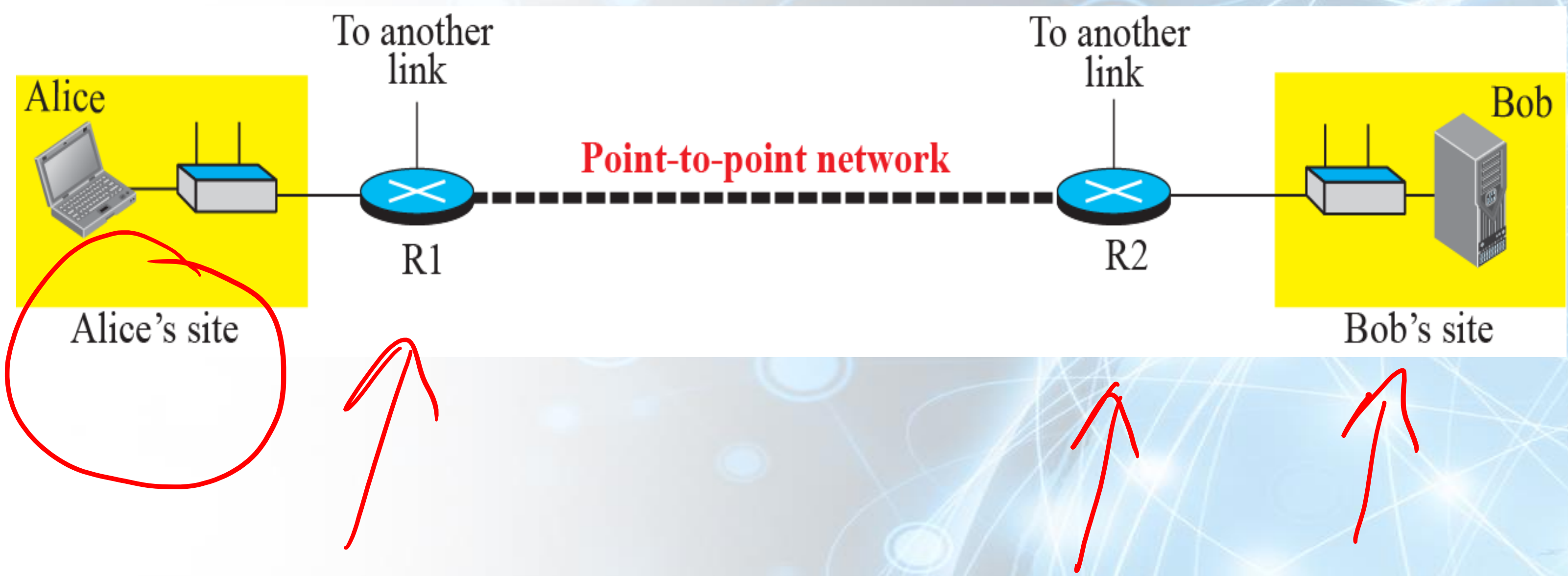
- **IP address of the next node is not helpful in moving a frame through a link; we need the link-layer address of the next node**

# ARP Packet

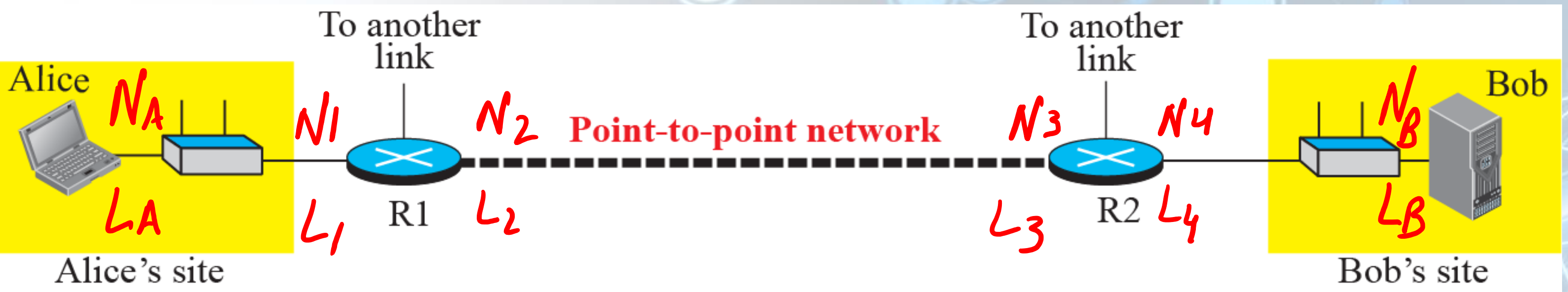
**Hardware:** LAN or WAN protocol
**Protocol:** Network-layer protocol

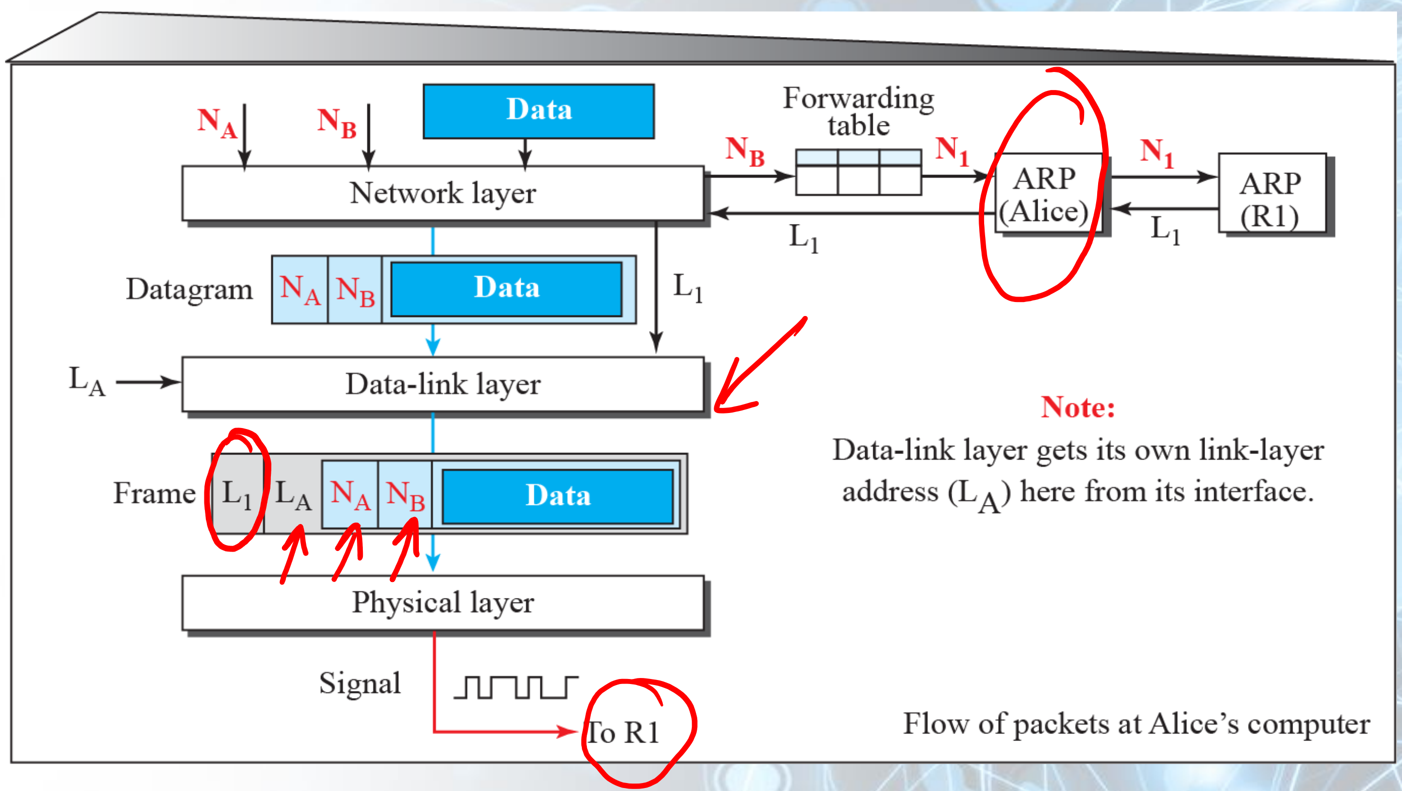


# The internet for our example



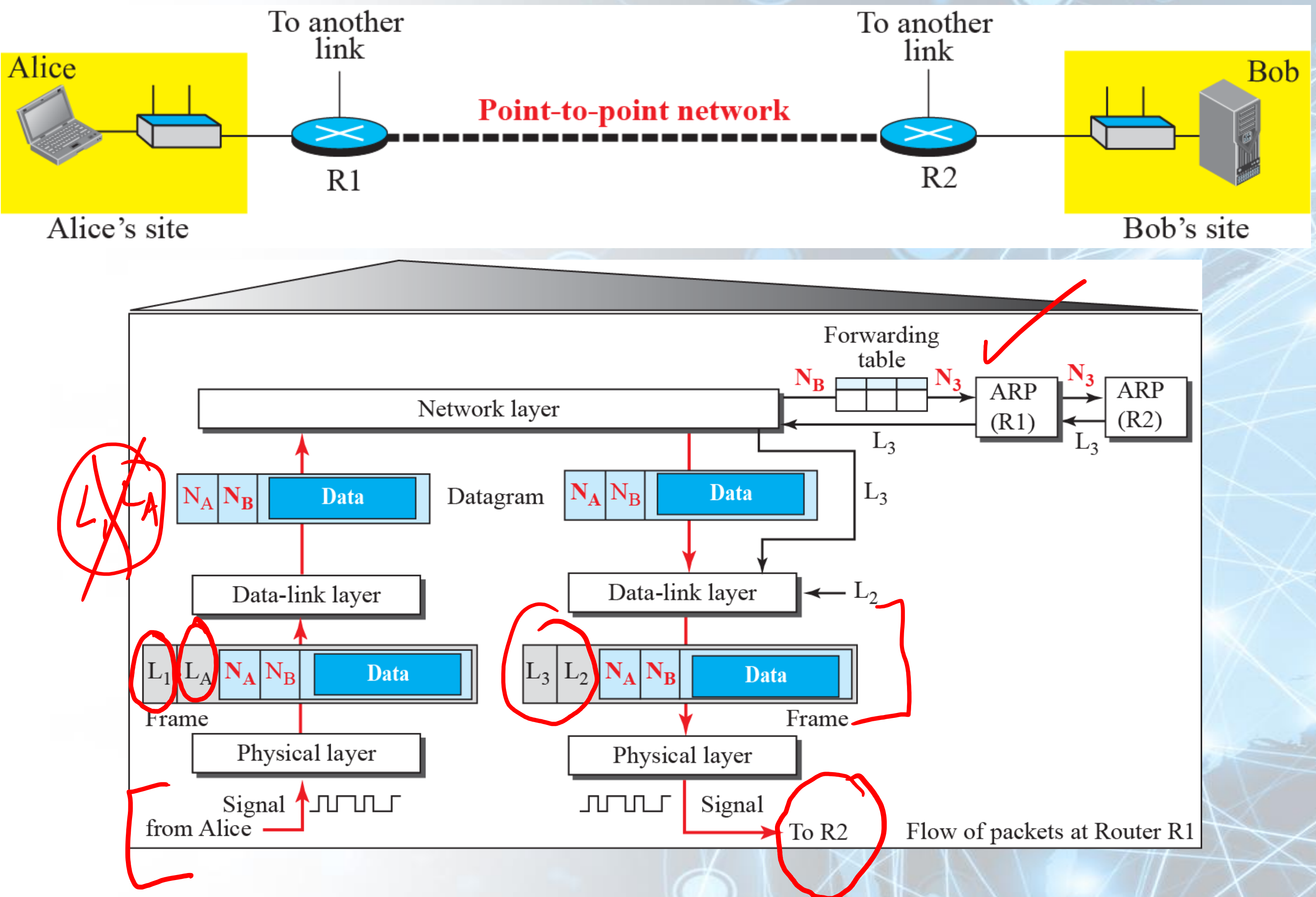
# Flow of packets at Alice site



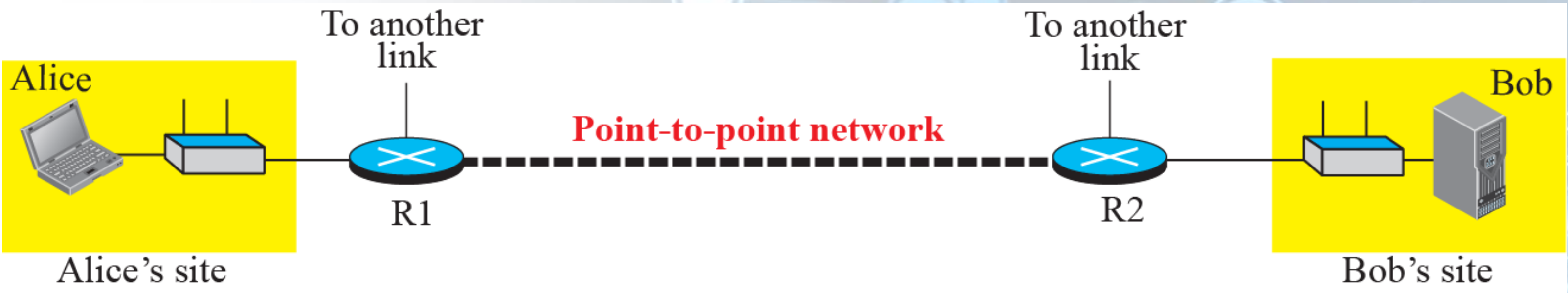



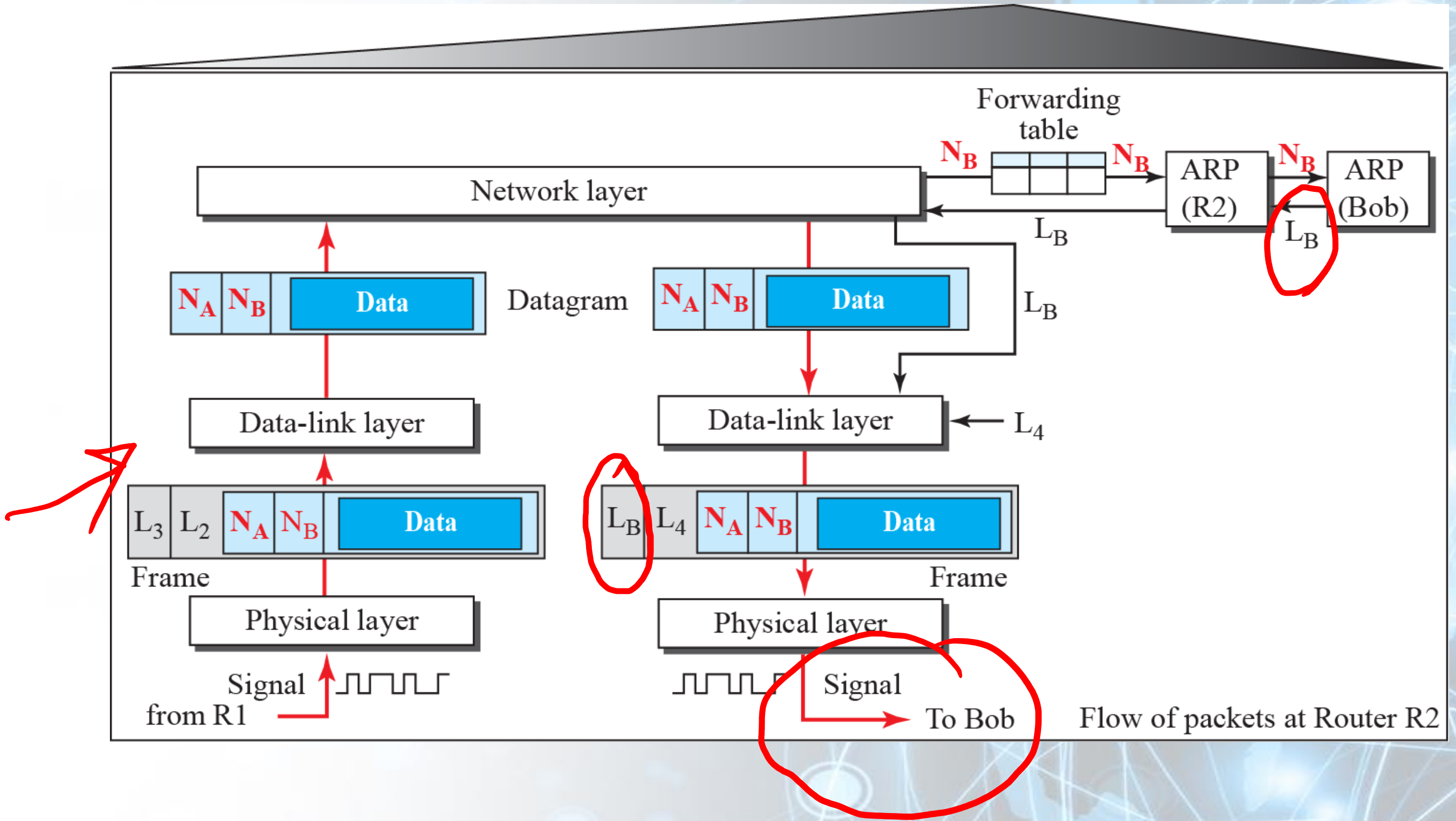

Flow of packets at Alice's computer

# Flow of activities at router R1

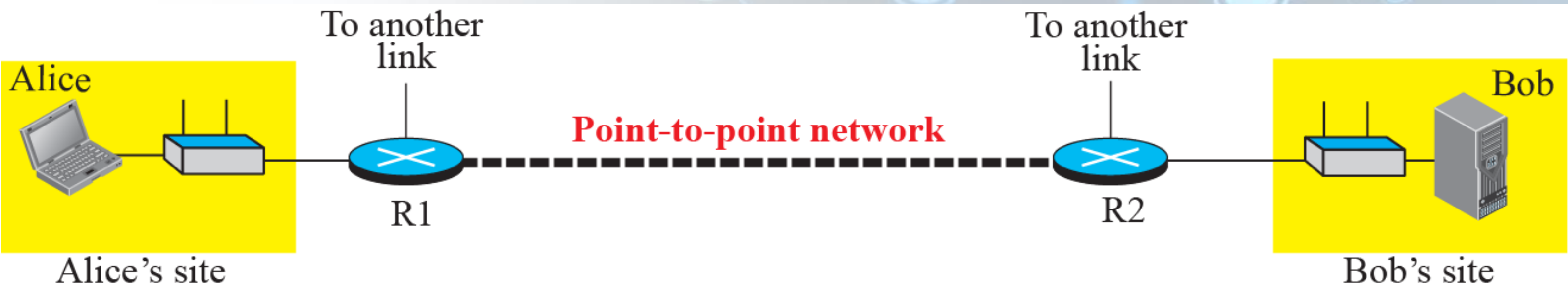


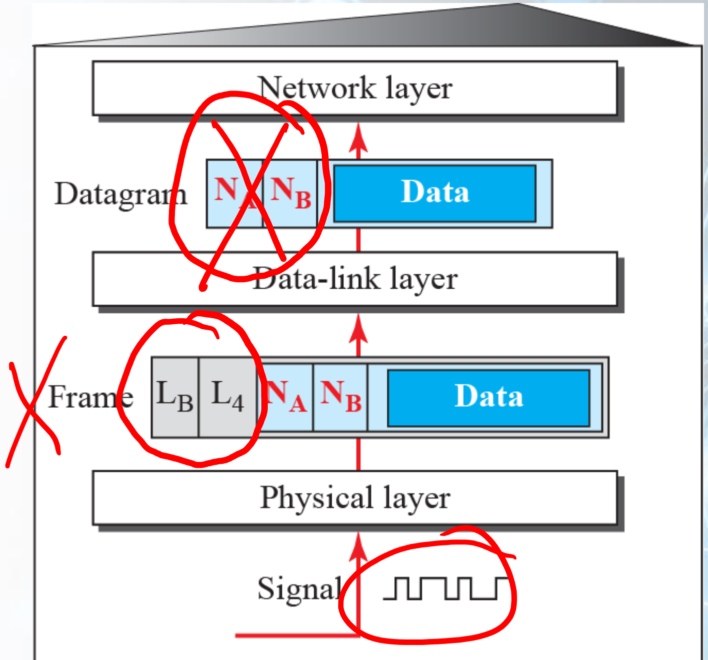
# Flow of activities at router R2



# Activities at Bob's site




Flow of packets at Bob's computer