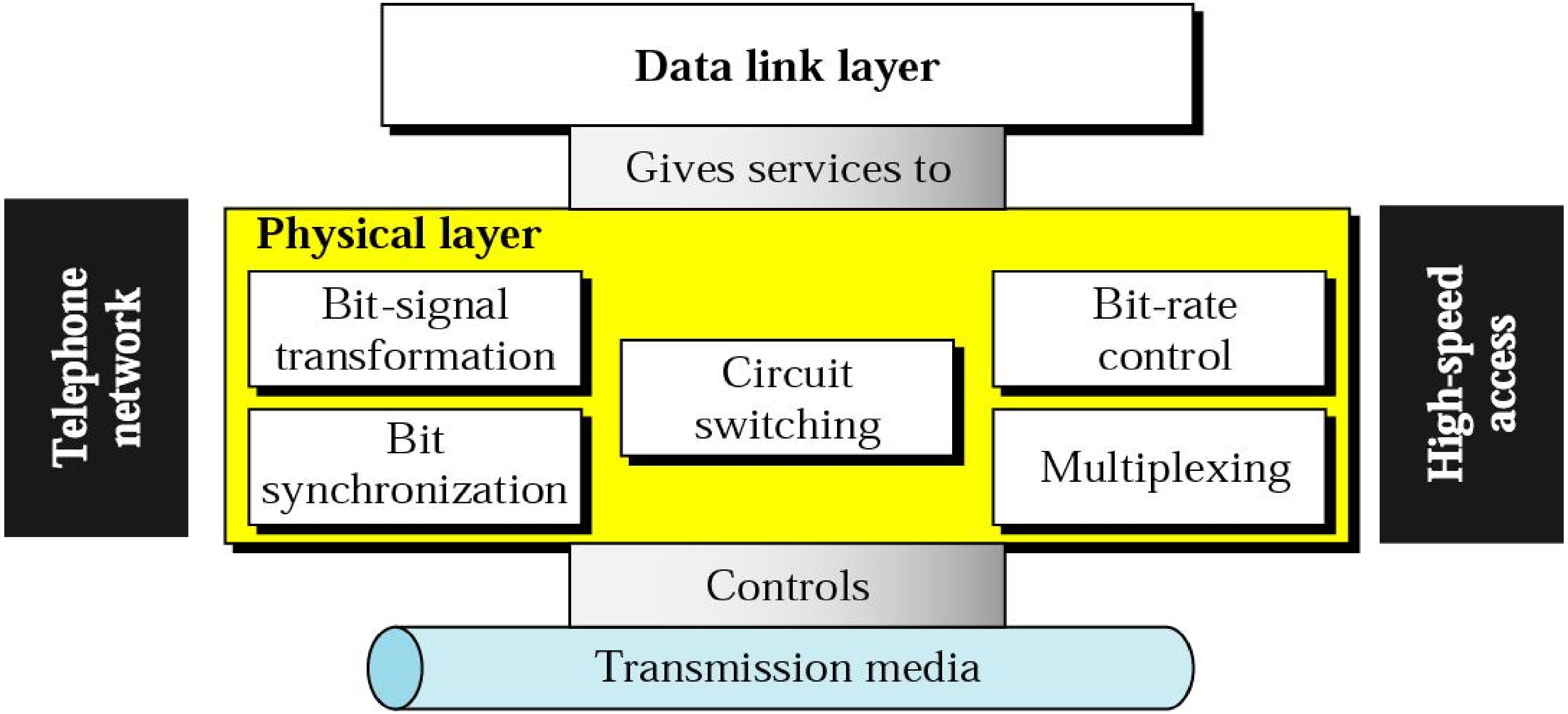
Physical Layer

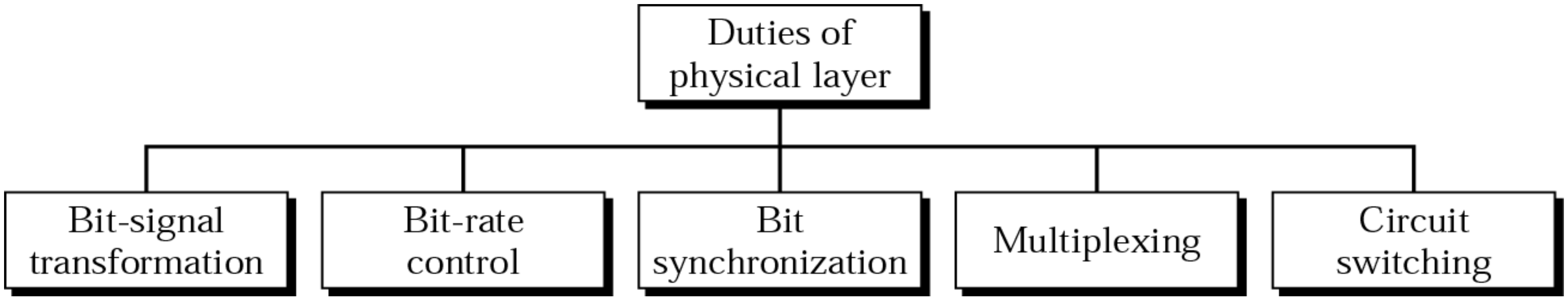
Position of the physical layer



Physical aspects of data communications

- differences between and characteristics of analog and digital signals
- encoding and modulation
- transmitting digital data using modems, digital subscriber lines, and cable modems
- the guided and radiated media used to transmit signals
- multiplexing and its use in current communications systems
- methods of detecting and correcting errors

Services


Duties of physical layer
Bit-signal transformation
Bit-rate control
Bit synchronization
Multiplexing
Circuit switching

Analog and Digital

Analog and Digital Data

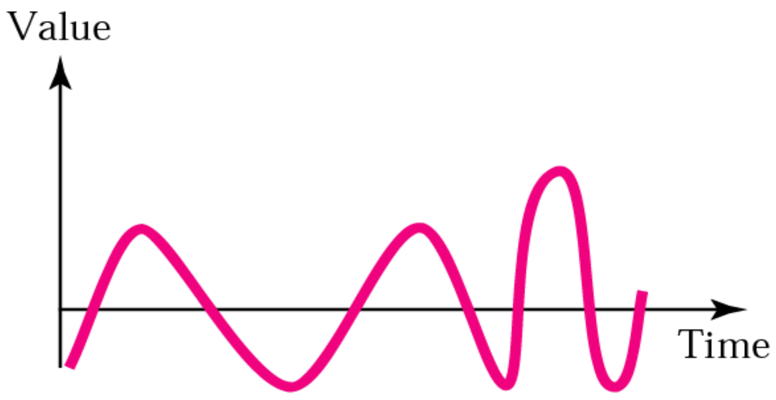
Analog and Digital Signals

Periodic and Aperiodic Signals

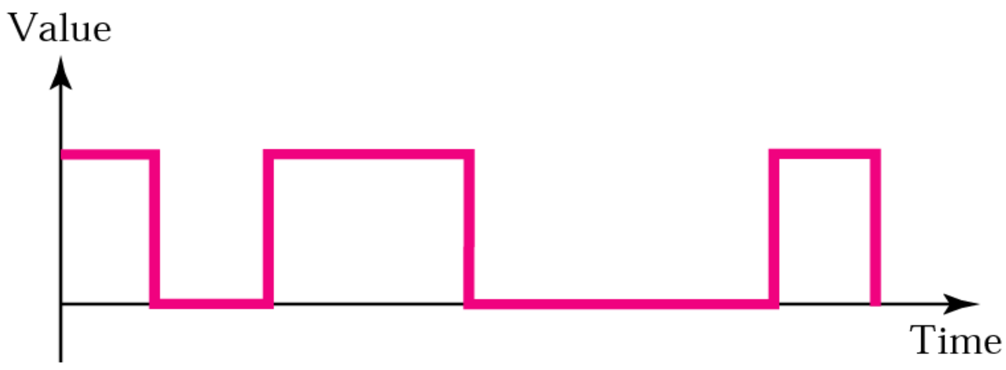
Comparison of analog and digital signals

Signals can be analog or digital

- ***Analog signals can have an infinite number of values in a range;***
  - ***Analog refers to something that is continuous, i.e., a set of specific points and all the points between them.***
- ***Digital signals can have only a limited number of values;***
  - ***Digital refers to something that is discrete, e.g., a set of specific points and no points between them.***



a. Analog signal



b. Digital signal

Analog Signals

Sine Wave

Phase

Examples of Sine Waves

Time and Frequency Domains

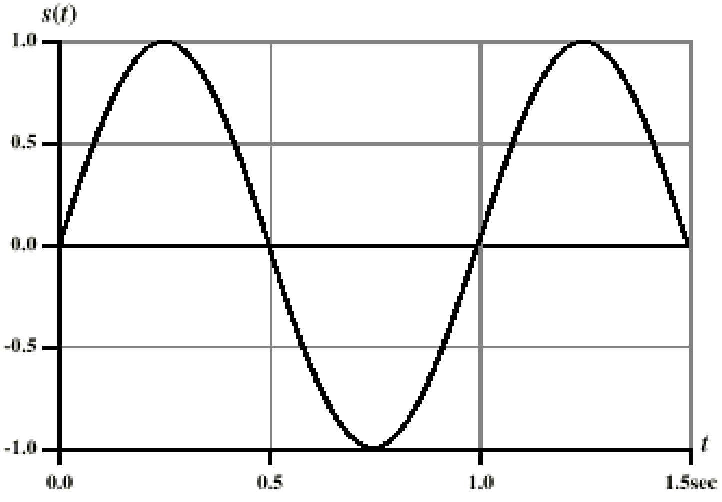
Composite Signals

Bandwidth

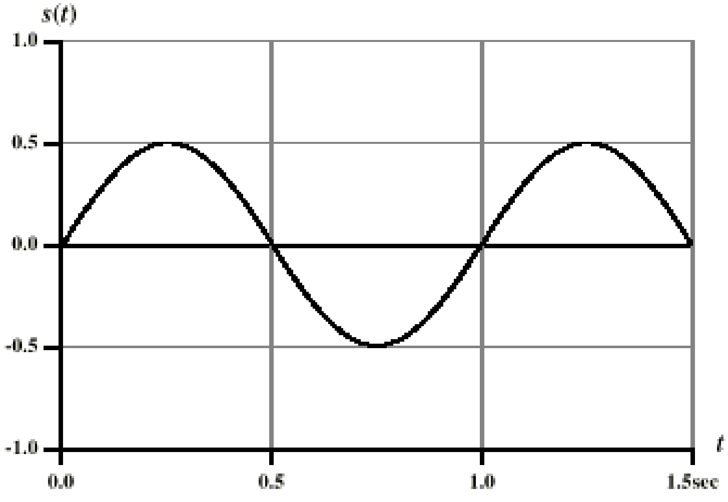
Sine Wave

- Peak Amplitude (A)
  - maximum strength of signal
  - volts
- Frequency (f)
  - Rate of change of signal
  - Hertz (Hz) or cycles per second
  - Period = time for one repetition (T)
  - $T = 1/f$
- Phase (ϕ)
  - Relative position in time

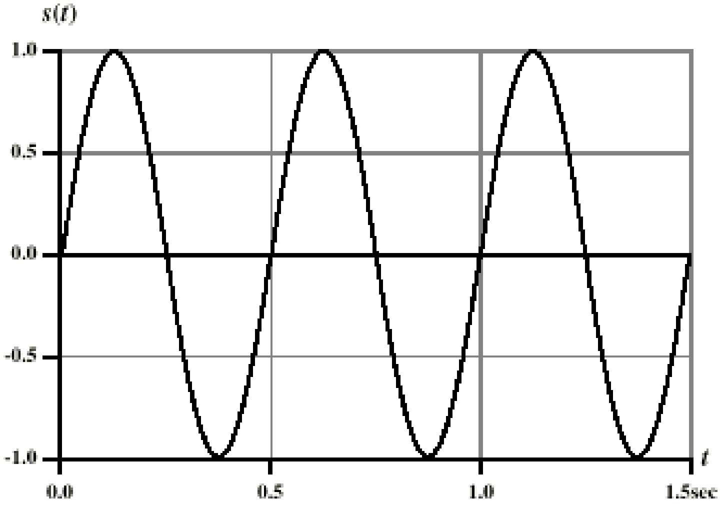
Varying Sine Waves
s(t) = A sin(2πft +Φ)



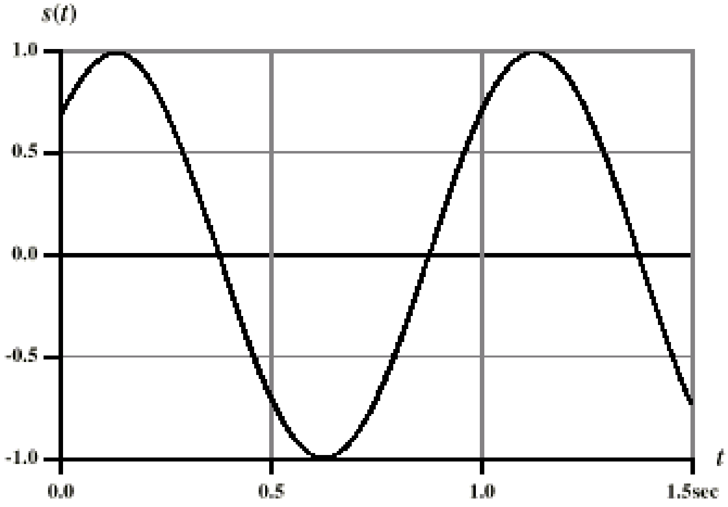
(a) A = 1, f = 1, ϕ = 0



(b) A = 0.5, f = 1, ϕ = 0



(c) A = 1, f = 2, ϕ = 0

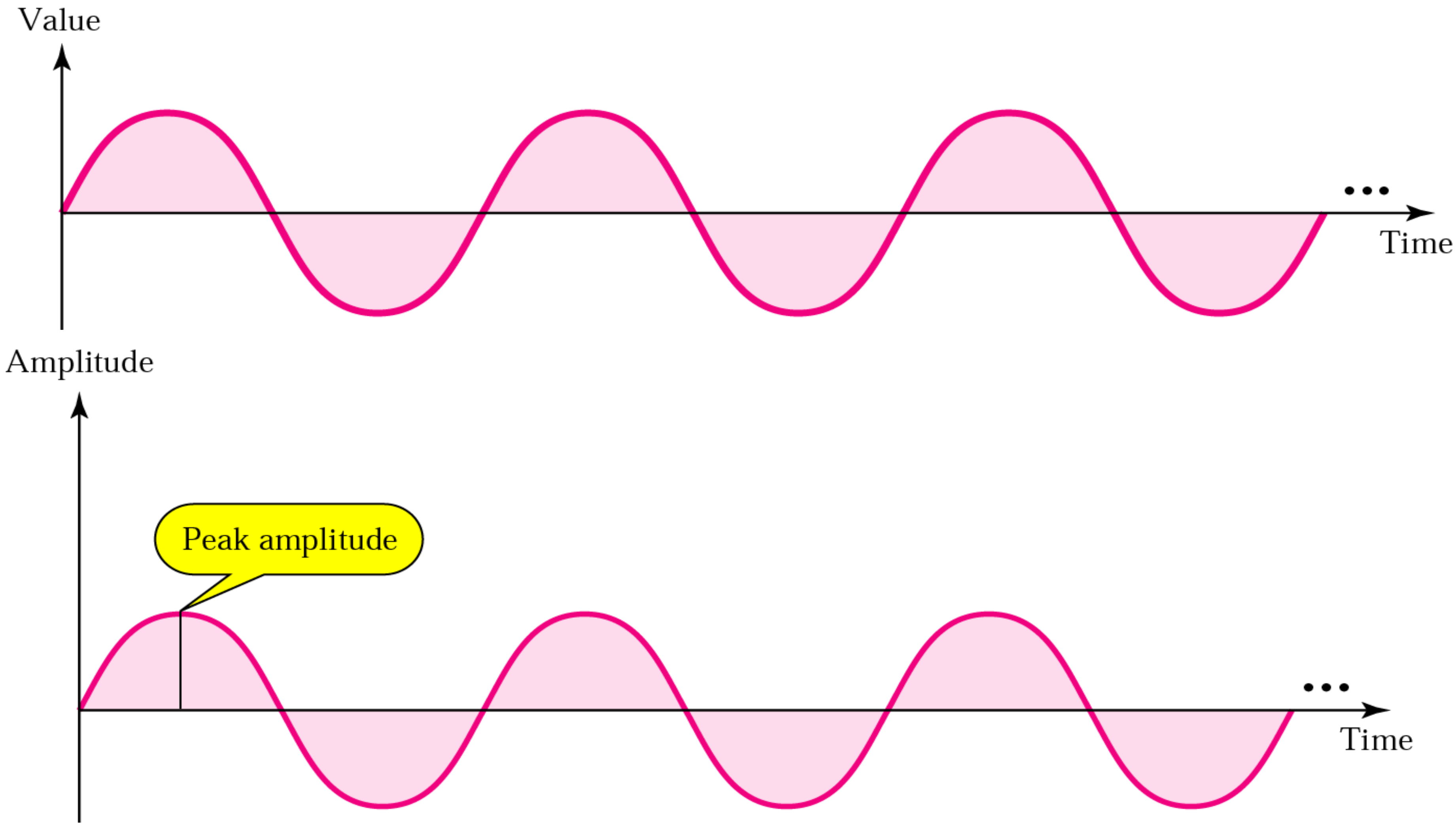


(d) A = 1, f = 1, ϕ = π/4

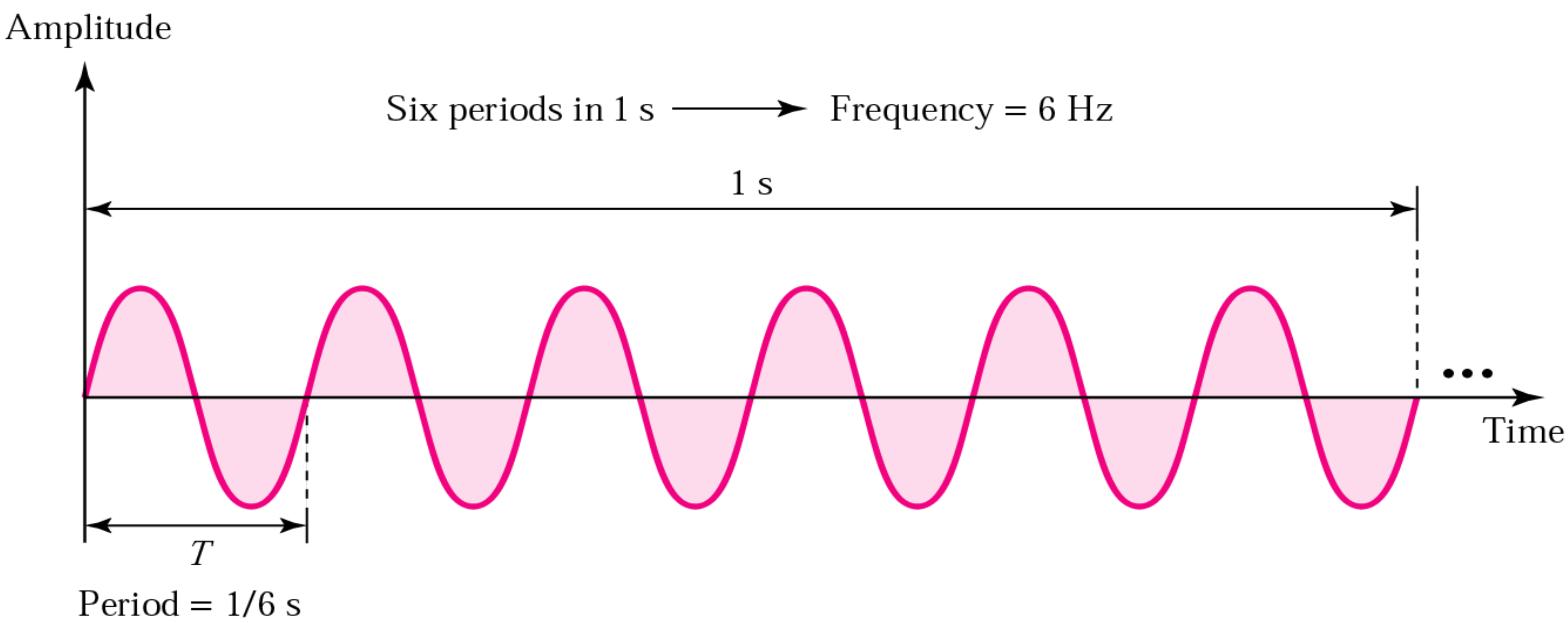
Wavelength

- Distance occupied by one cycle
- Distance between two points of corresponding phase in two consecutive cycles
- λ
- Assuming signal velocity *v*
  - $\lambda = vT$
  - $\lambda f = v$
  - c = $3*10^8$ ms^{-1} (speed of light in free space)

A sine wave



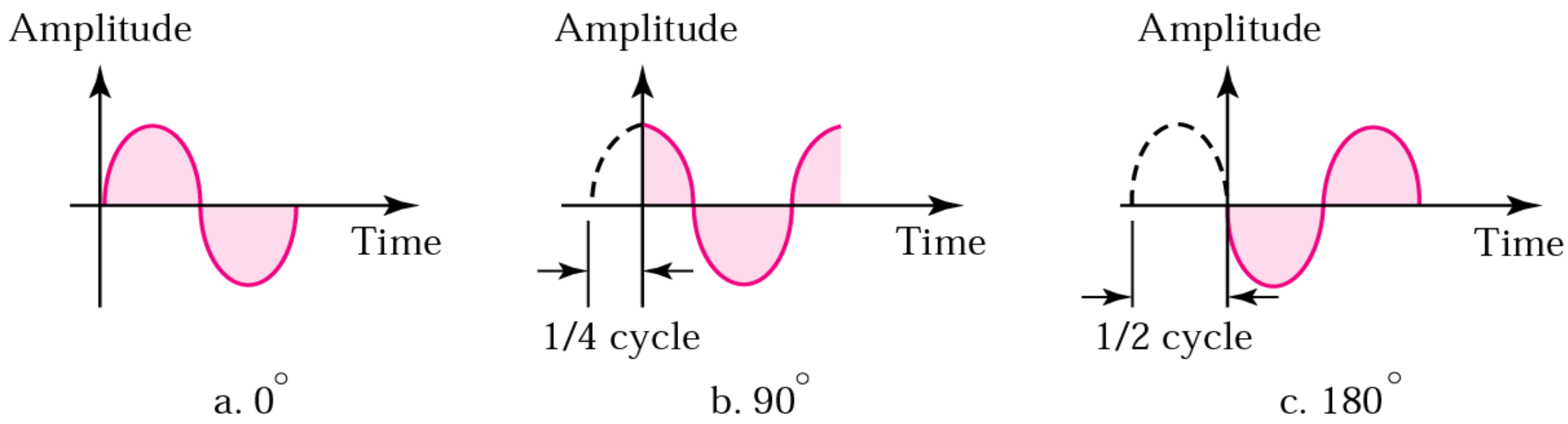
Frequency and period are inverses of each other.



Units of periods and frequencies

Unit	Equivalent	Unit	Equivalent
Seconds (s)	1 s	hertz (Hz)	1 Hz
Milliseconds (ms)	10^{-3} s	kilohertz (KHz)	10^{3} Hz
Microseconds (ms)	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

Phase describes the position of the waveform relative to time zero.

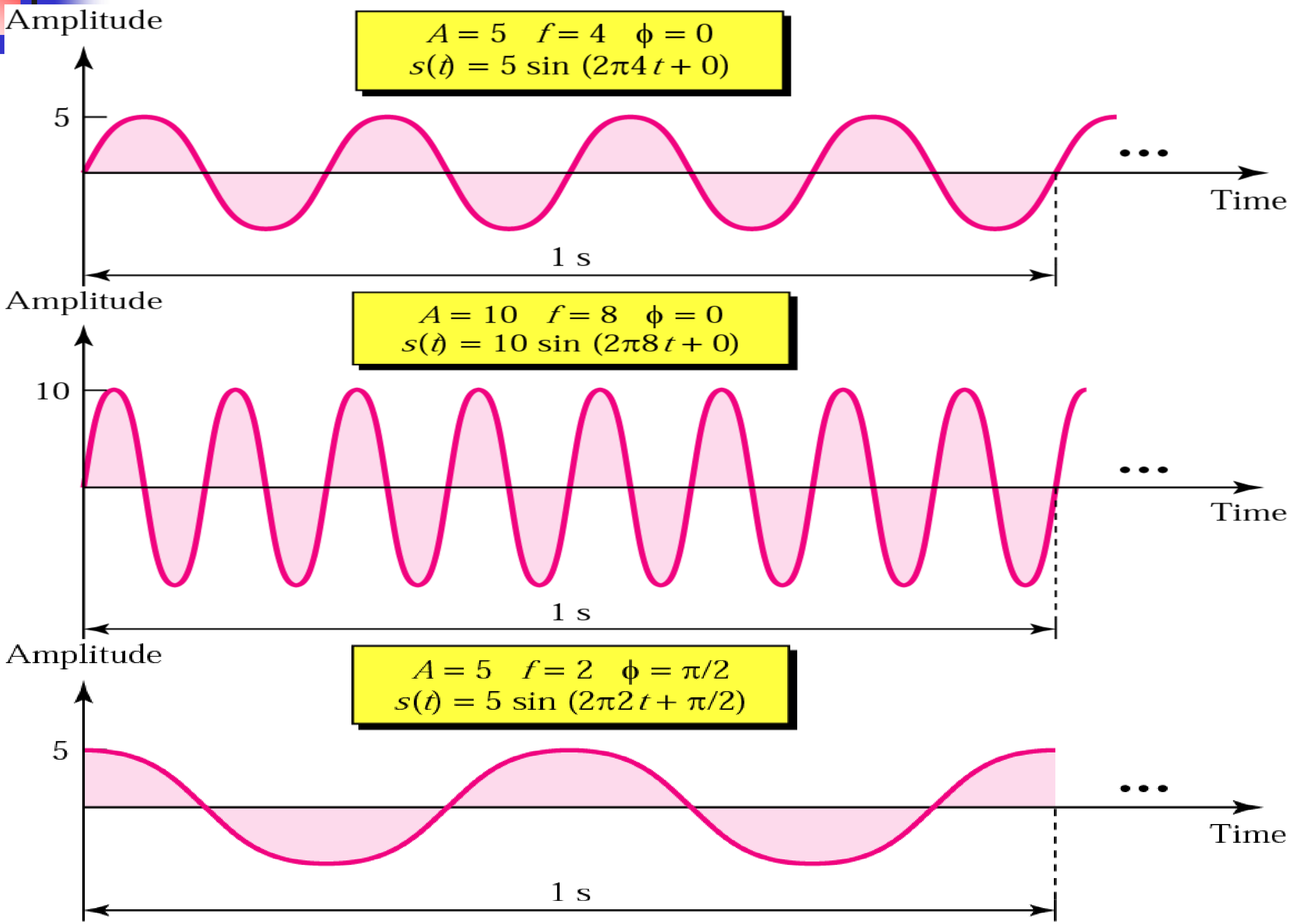


Frequency is the rate of change with respect to time.

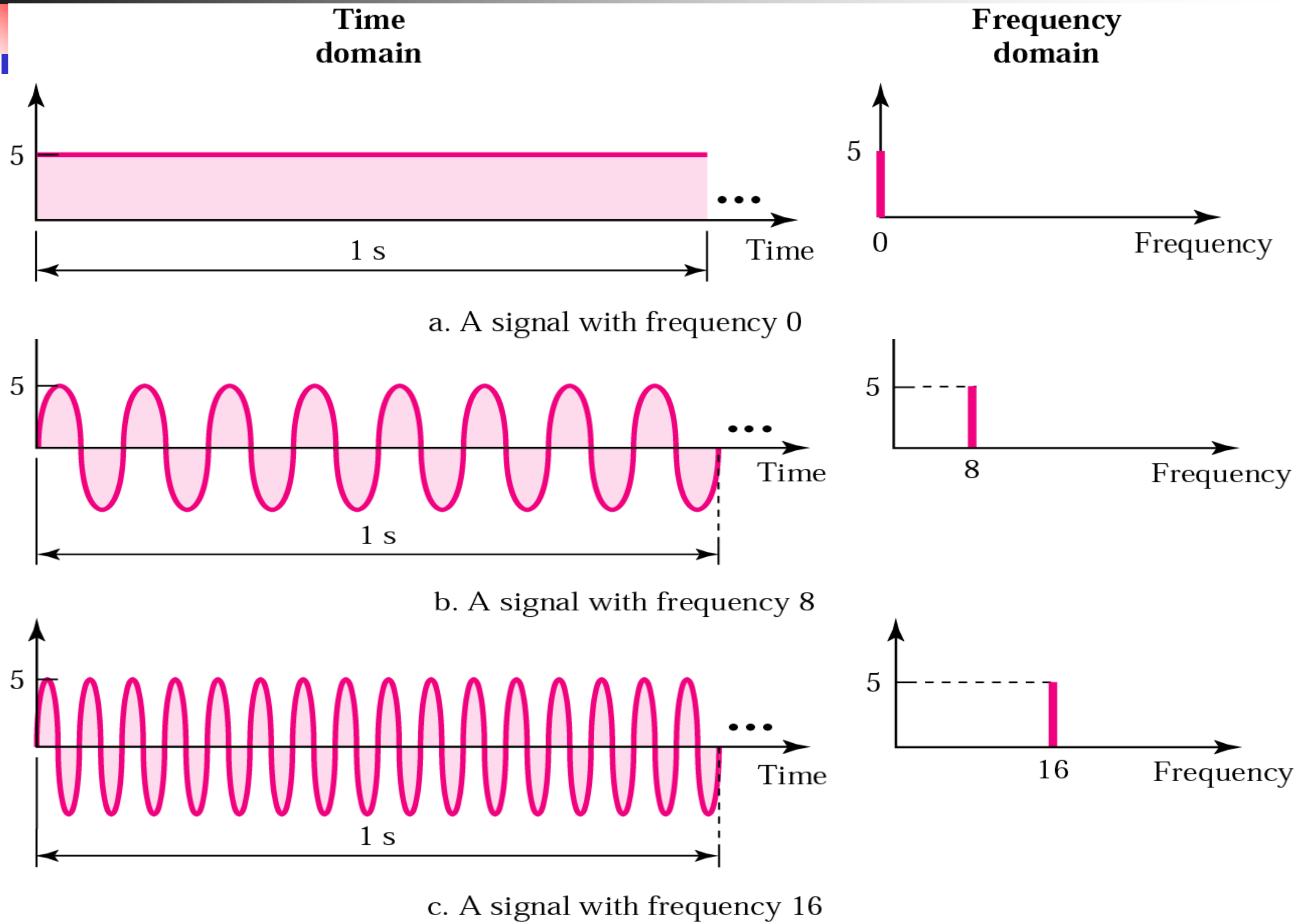
- ***Change in a short span of time means high frequency.***
- ***Change over a long span of time means low frequency.***

- ***If a signal does not change at all, its frequency is zero.***
- ***If a signal changes instantaneously, its frequency is infinite.***

Sine wave examples



Time and frequency domains



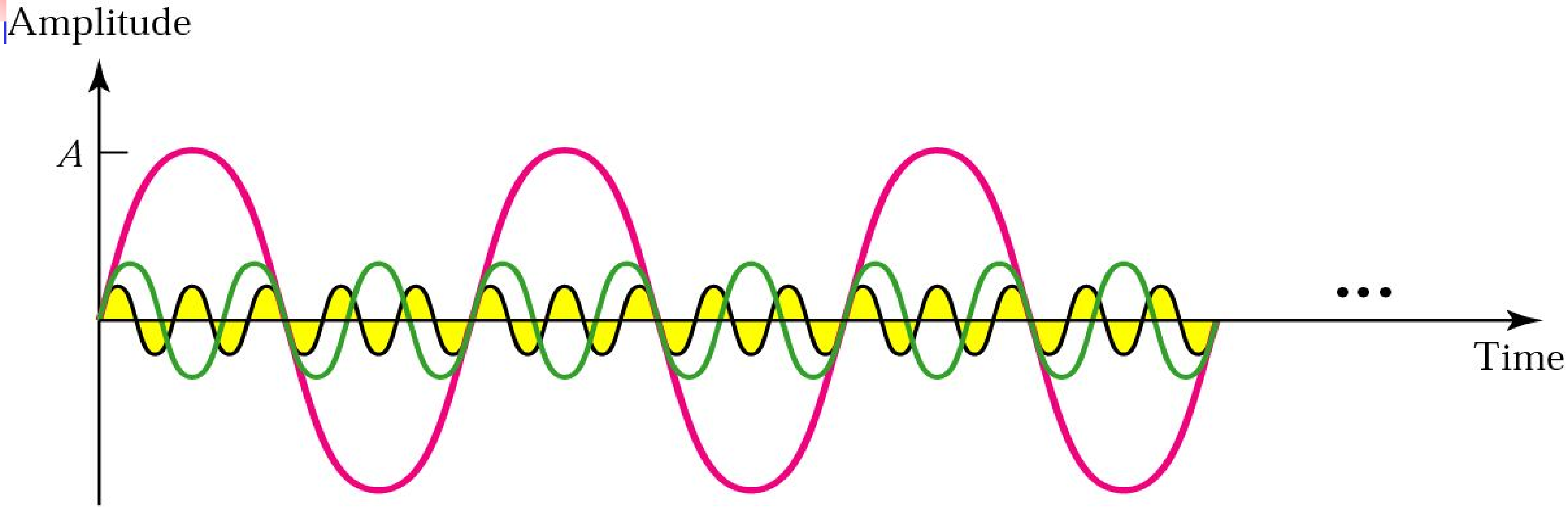
An analog signal is best represented in the frequency domain.

A single-frequency sine wave is not useful in data communications;
We need to change one or more of its characteristics to make it useful.

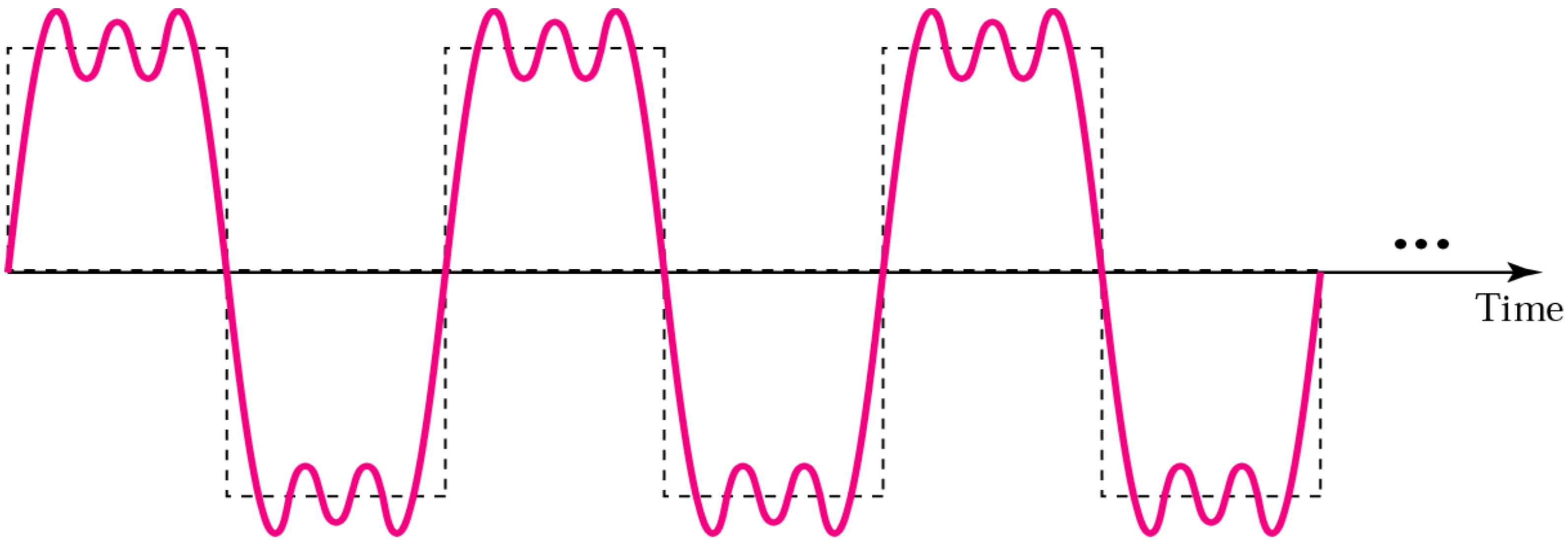
When we change one or more characteristics of a single-frequency signal,
it becomes a composite signal made of many frequencies.

According to Fourier analysis, any composite signal can be represented as a combination of simple sine waves with different frequencies, phases, and amplitudes.

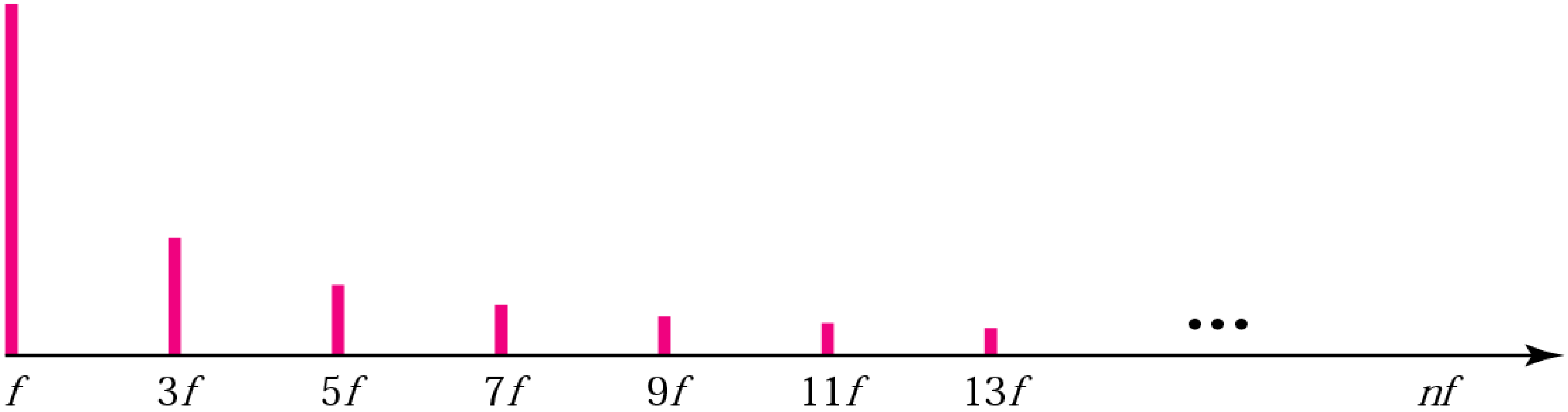
Three harmonics



Adding first three harmonics



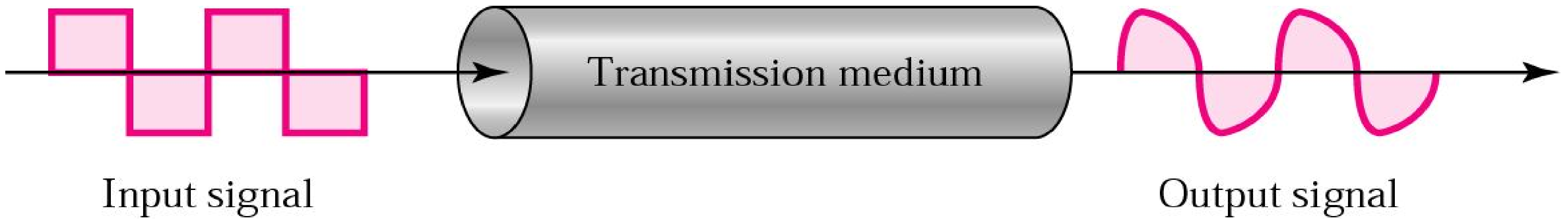
Frequency spectrum comparison



a. Frequency spectrum of a square wave

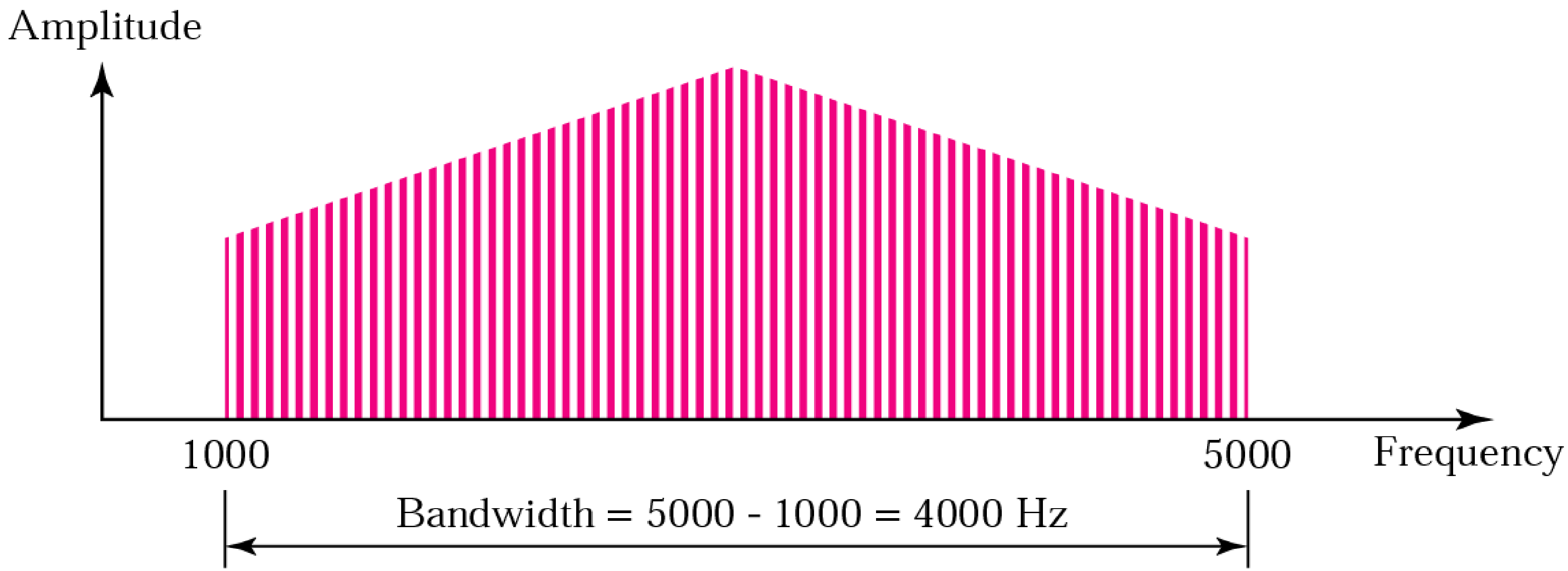
b. Frequency spectrum of an approximation with only three harmonics

Signal corruption



The bandwidth is a property of a medium:

It is the difference between the highest and the lowest frequencies that the medium can satisfactorily pass.

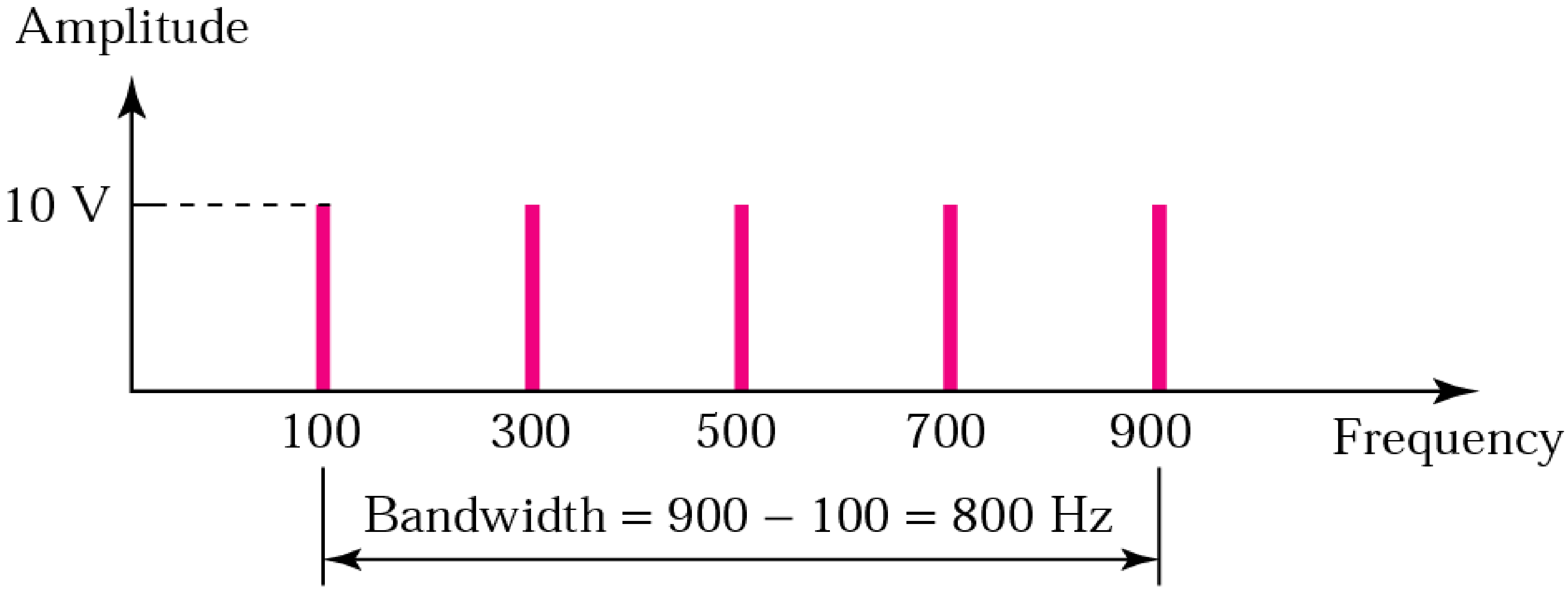


Example

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

$B = f_h - f_l = 900 - 100 = 800$ Hz

The spectrum has only five spikes, at 100, 300, 500, 700, and 900



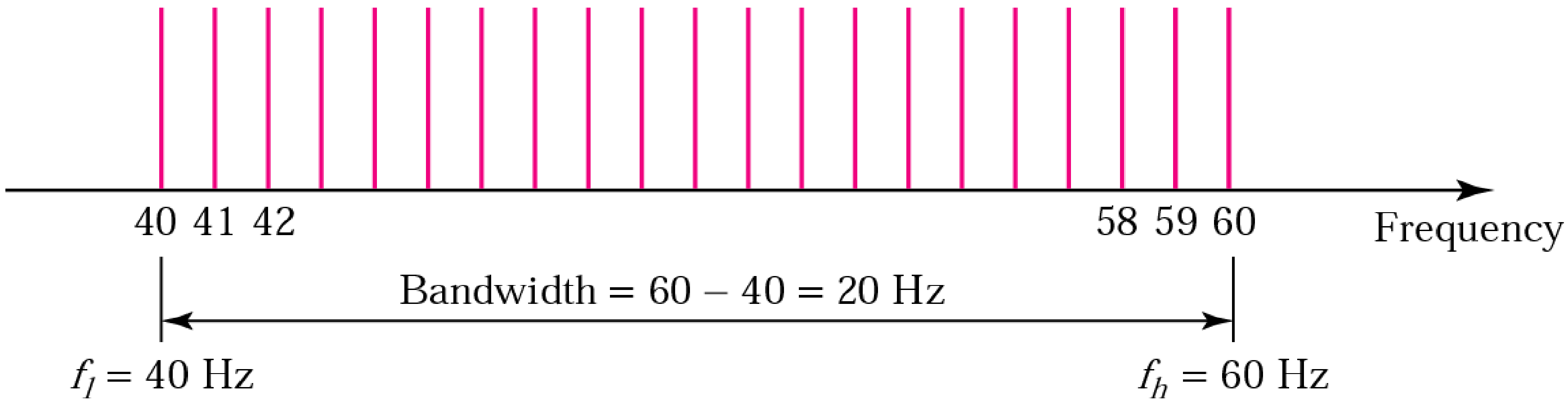
Example

A signal has a bandwidth of 20 Hz. The highest frequency is 60 Hz. What is the lowest frequency? Draw the spectrum if the signal contains all integral frequencies of the same amplitude.

$B = f_h - f_l$

$20 = 60 - f_l$

$f_l = 60 - 20 = 40$ Hz



Example

A signal has a spectrum with frequencies between 1000 and 2000 Hz (bandwidth of 1000 Hz). A medium can pass frequencies from 3000 to 4000 Hz (a bandwidth of 1000 Hz). Can this signal faithfully pass through this medium?

The answer is definitely no.

Although the signal can have the same bandwidth (1000 Hz), the range does not overlap. The medium can only pass the frequencies between 3000 and 4000 Hz;

the signal is totally lost.

Digital Signals

Bit Interval and Bit Rate

As a Composite Analog Signal

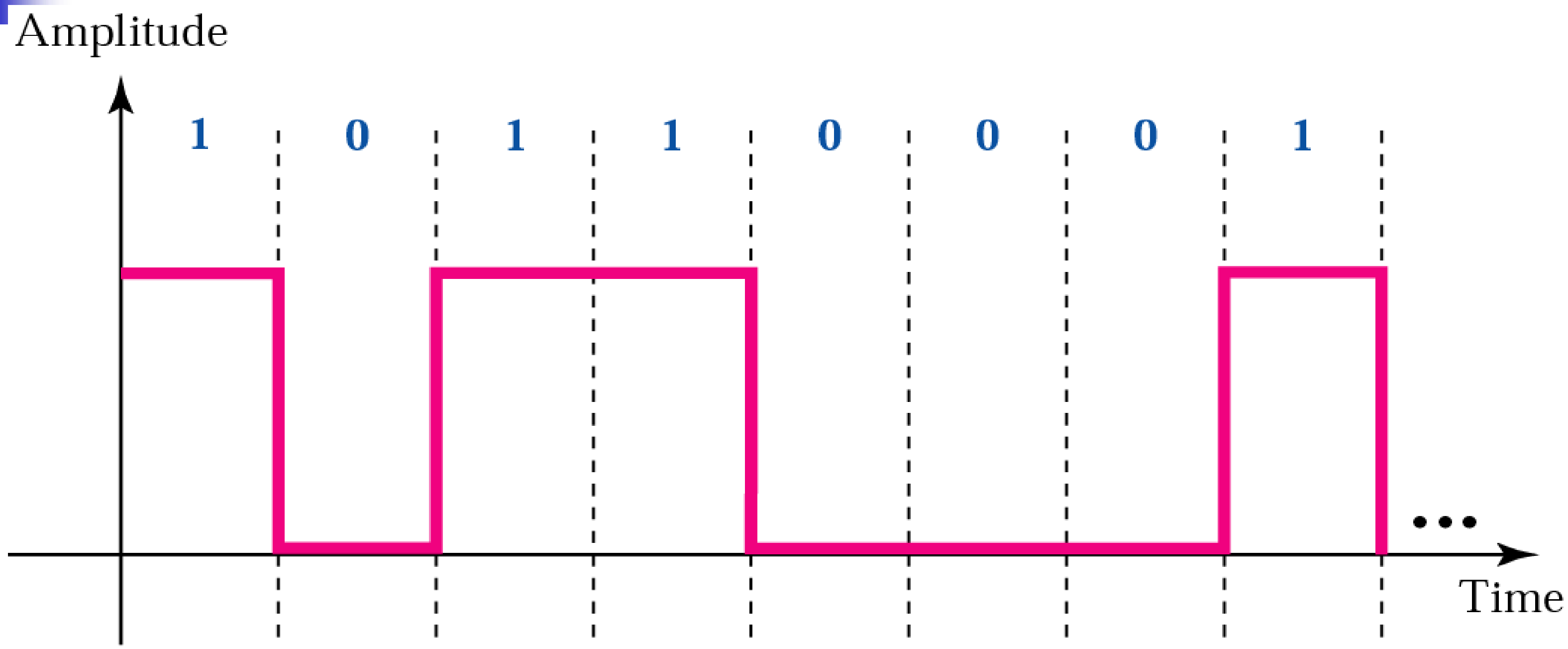
Through Wide-Bandwidth Medium

Through Band-Limited Medium

Versus Analog Bandwidth

Higher Bit Rate

A digital signal

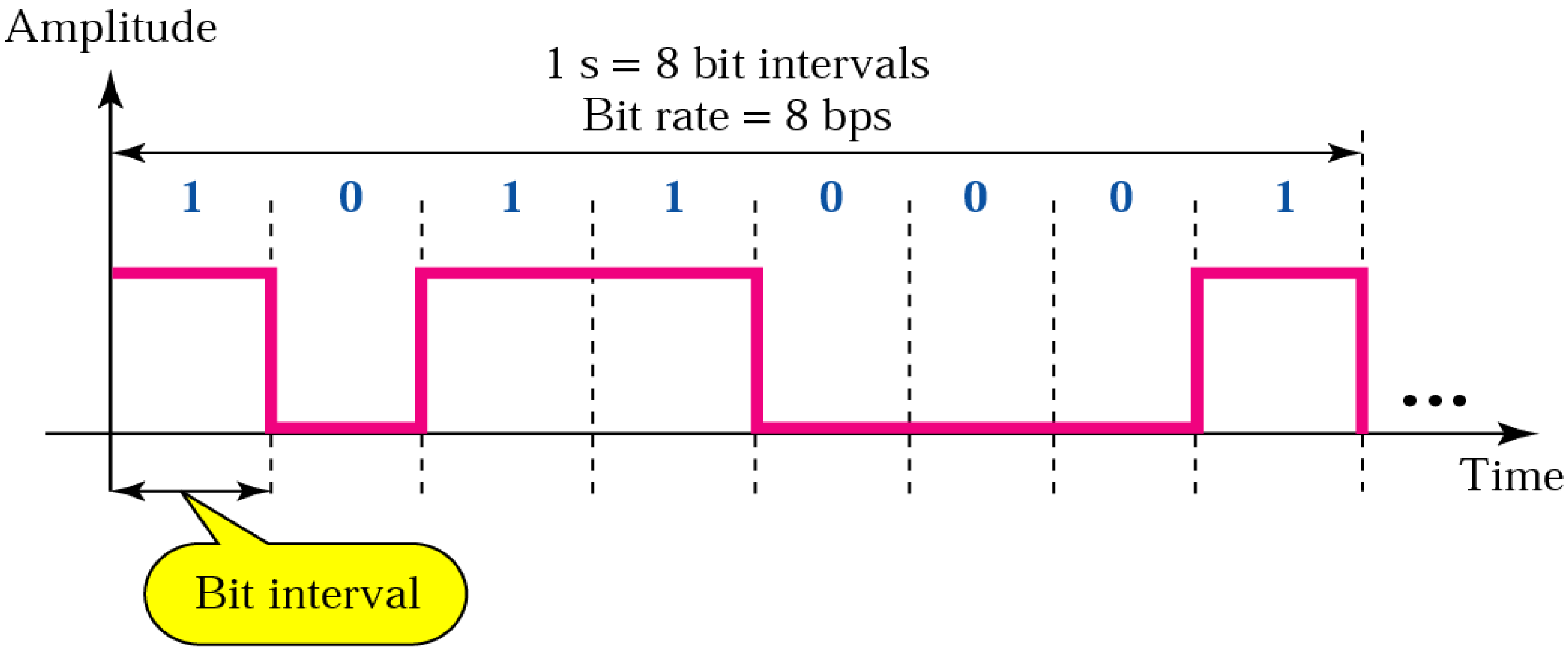


A digital signal has a bit rate of 2000 bps.
What is the duration of each bit (bit interval)?

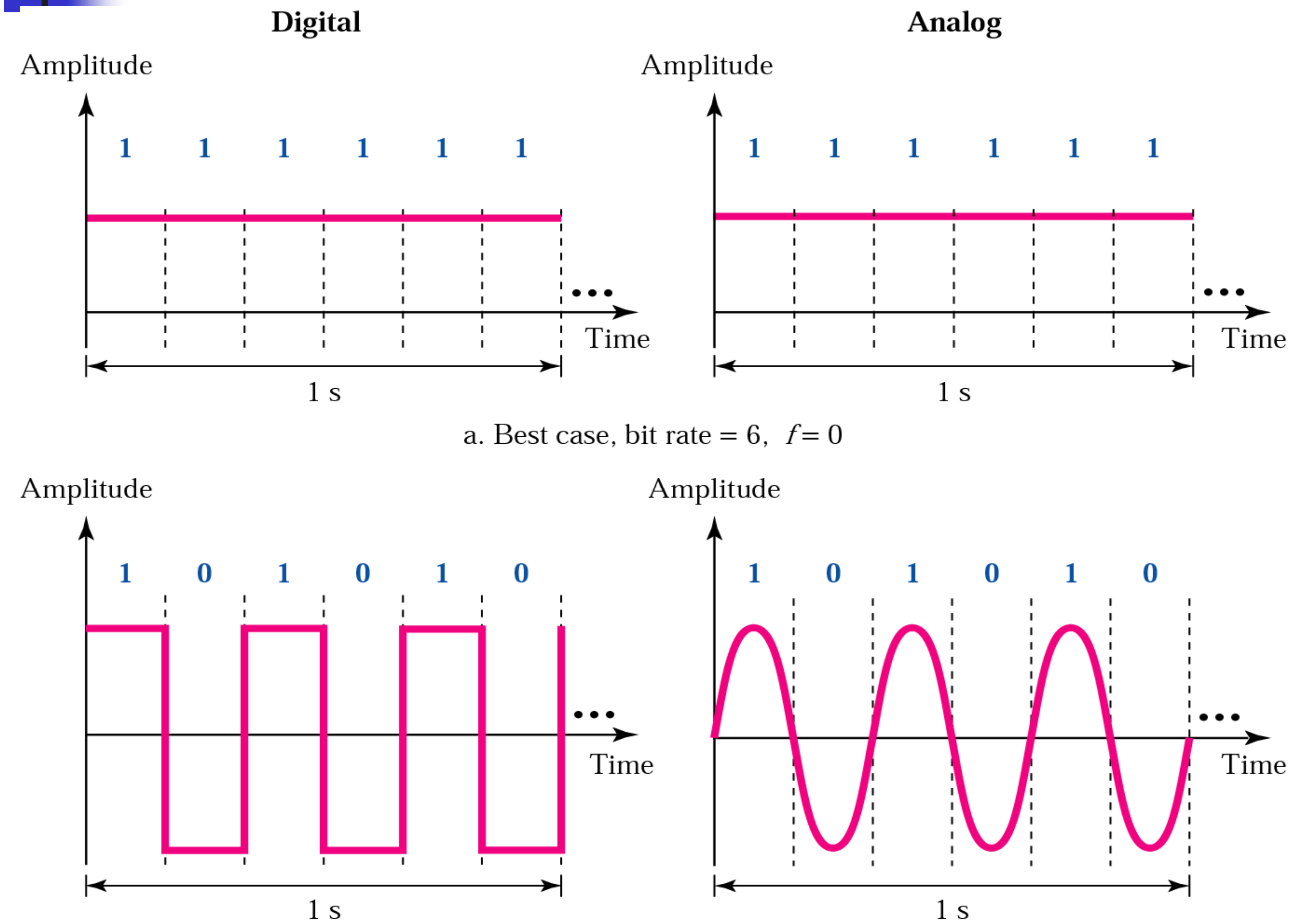
The bit interval is the inverse of the bit rate.

Bit interval = 1/ 2000 s = 0.000500 s = 0.000500 x 10^6 μs = **500 μs**

Bit rate and bit interval



Digital versus analog



a. Best case, bit rate = 6, $f = 0$

b. Worst case, bit rate = 6, $f = 3$

A digital signal is a composite signal with an infinite bandwidth.

To improve the shape of the signal for better communication, particularly for high data rates, we need to add some harmonics.

B=n/2+3n/2+5n/2 .... (n=bps)

Final B>=n/2 or n<= 2B

Bandwidth Requirement

Bit Rate	Harmonic 1 B=n/2	Harmonics 1, 3 B=4n/2	Harmonics 1, 3, 5 B=9n/2	Harmonics 1, 3, 5, 7 B=16n/2
1 Kbps	500 Hz	2 KHz	4.5 KHz	8 KHz
10 Kbps	5 KHz	20 KHz	45 KHz	80 KHz
100 Kbps	50 KHz	200 KHz	450 KHz	800 KHz

The bit rate and the bandwidth are proportional to each other.

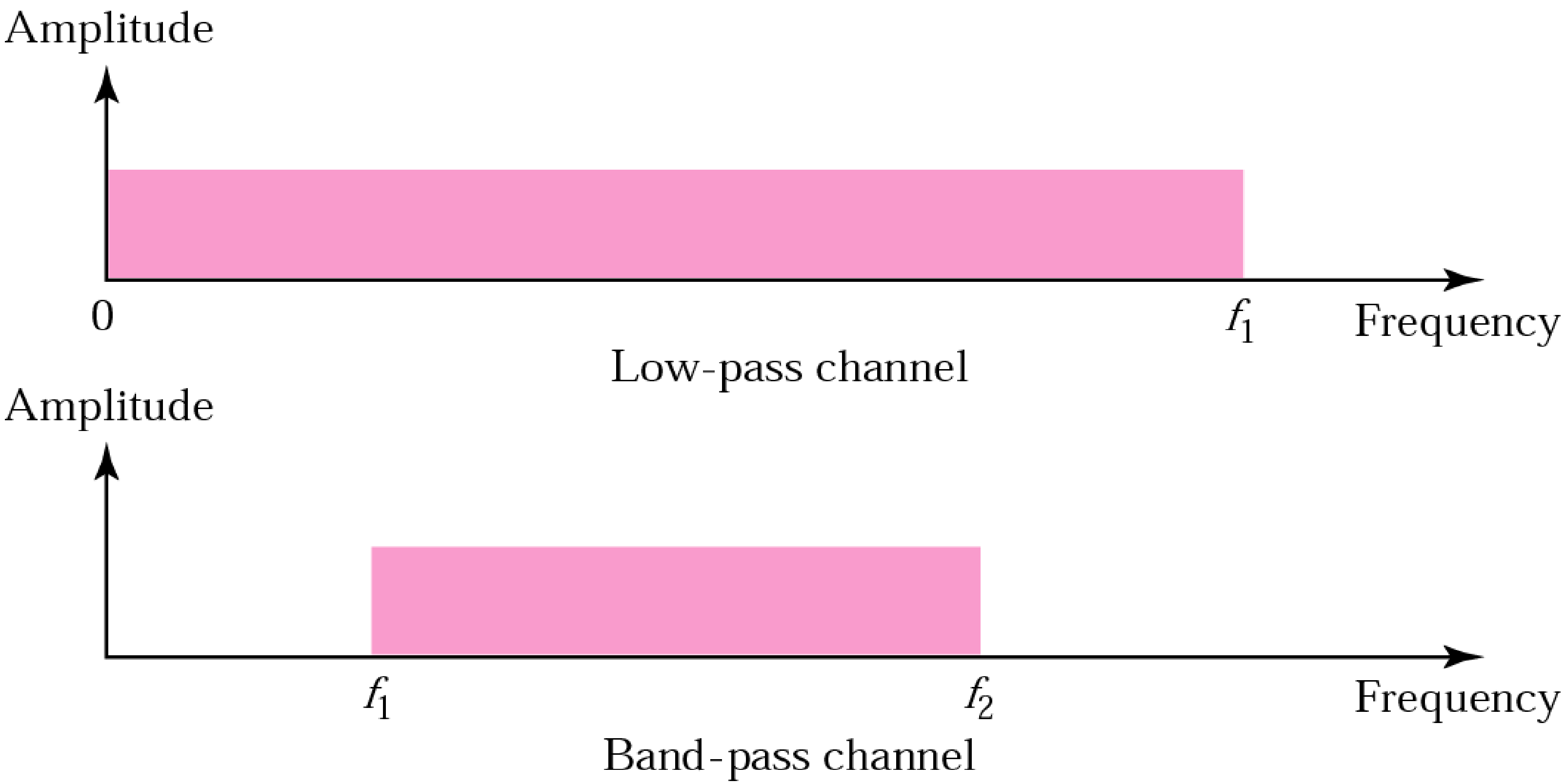
Analog versus Digital

Low-pass versus Band-pass

Digital Transmission

Analog Transmission

Digital transmission needs a low-pass channel.



Analog transmission can use a band-pass channel.

The analog bandwidth of a medium is expressed in hertz;

The digital bandwidth, in bits per second.

Data Rate Limit

Noiseless Channel: Nyquist Bit Rate

Bit Rate = 2 × Bandwidth × $\log_2$ Signal_levels

Noisy Channel: Shannon Capacity

Capacity = Bandwidth* $\log_2$ (1 + SNR) ;

where SNR=signal-to-noise ratio

Using Both Limits

In practice we need to use both methods

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

$$\text{Bit Rate} = 2 \times 3000 \times \log_2 2 = 6000 \text{ bps}$$

Consider the same noiseless channel, transmitting a signal with four signal levels (for each level, we send two bits). The maximum bit rate can be calculated as:

$$\text{Bit Rate} = 2 \text{ x } 3000 \text{ x } \log_2 4 = 12{,}000 \text{ bps}$$

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 is calculated as

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

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

Example

We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000 Hz (300 Hz to 3300 Hz). The signal-to-noise ratio is usually 3162.

For this channel the capacity is calculated as:

$$C = B \log_2 (1 + SNR) =$$
$$3000 \log_2 (1 + 3162)$$
$$= 3000 \log_2 (3163)$$
$$C = 3000 \times 11.62 = 34{,}860 \text{ bps}$$

Example

We have a channel with a 1 MHz bandwidth. The SNR for this channel is 31;

What is the appropriate bit rate and signal level?

Solution

First, we use the Shannon formula to find our upper limit.

$$C = B \log_2 (1 + SNR) = 10^6 \log_2 (1 + 31) = 10^6 \log_2 (32) = 5 \text{ Mbps}$$

Then we use the Nyquist formula to find the number of signal levels.

$$5\text{Mbps} = 2 \times 1 \text{ MHz} \times \log2 L \rightarrow L = 5.6$$

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

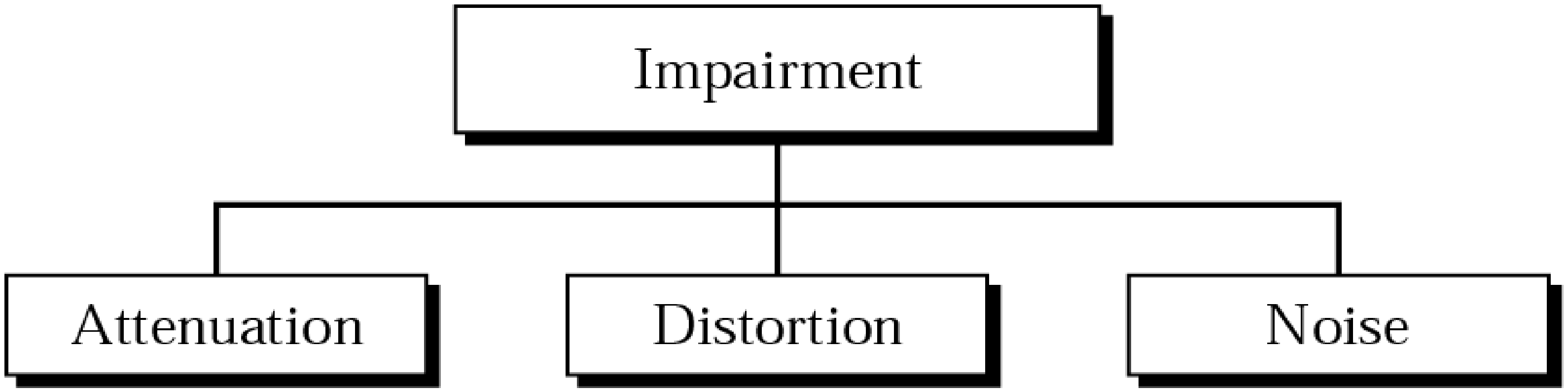
Transmission Impairment

Attenuation

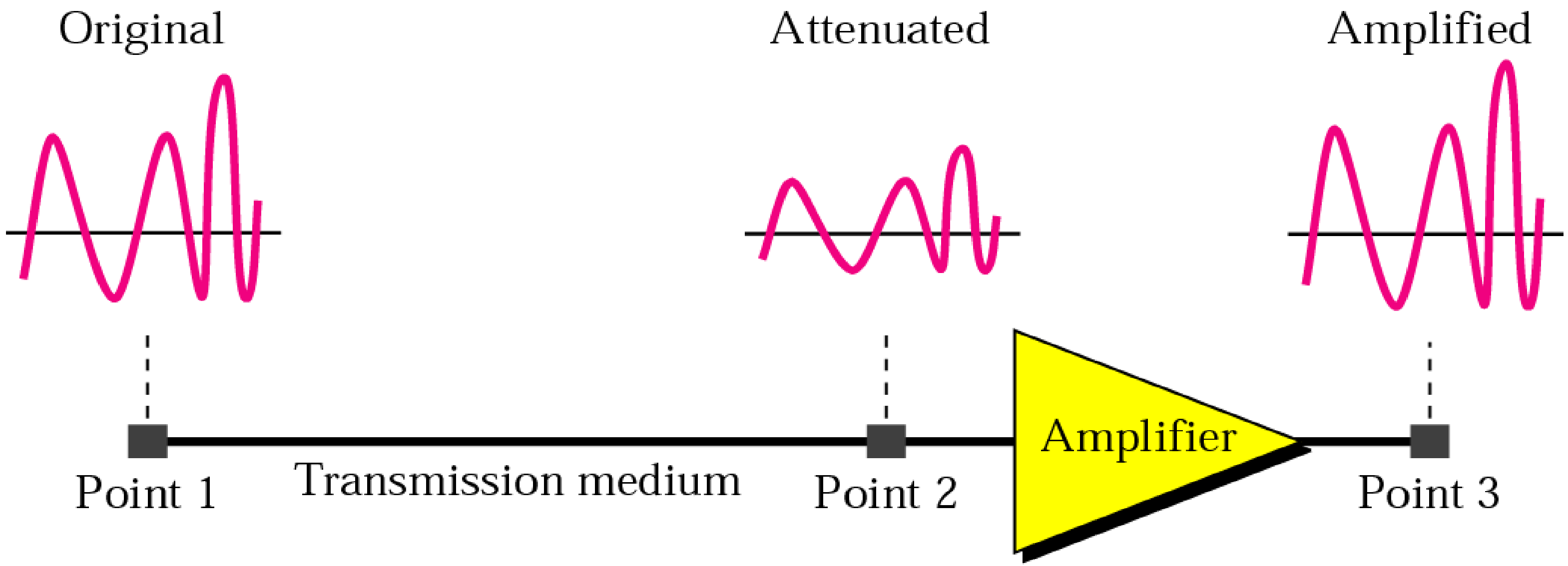
Distortion

Noise

Impairment types



Attenuation means loss of energy.
To compensate for this lost amplifiers are used to amplify the signal



Decibel (dB) measures the relative strengths of two signals or a signal at two different points.

$$dB = 10 \log_{10} (P2/P1)$$

where P1 and P2 is the power of the signal at point 1 and Point 2, respectively

Note:

The decibel is negative if the signal is attenuated
The decibel is positive if the signal is amplified

Example

Imagine a signal travels through a transmission medium and its power is reduced to half.

This means that P2 = 1/2 P1.

In this case, the attenuation (loss of power) can be calculated as

$$10 \log_{10} (P2/P1) = 10 \log_{10} (0.5P1/P1) = 10 \log_{10} (0.5)$$
$$= 10(-0.3) = -3 \text{ dB}$$

Example

Imagine a signal travels through an amplifier and its power is increased ten times.

This means that P2 = 10 * P1.

In this case, the amplification (gain of power) can be calculated as

$$10 \log_{10} (P2/P1) = 10 \log_{10} (10P1/P1)$$

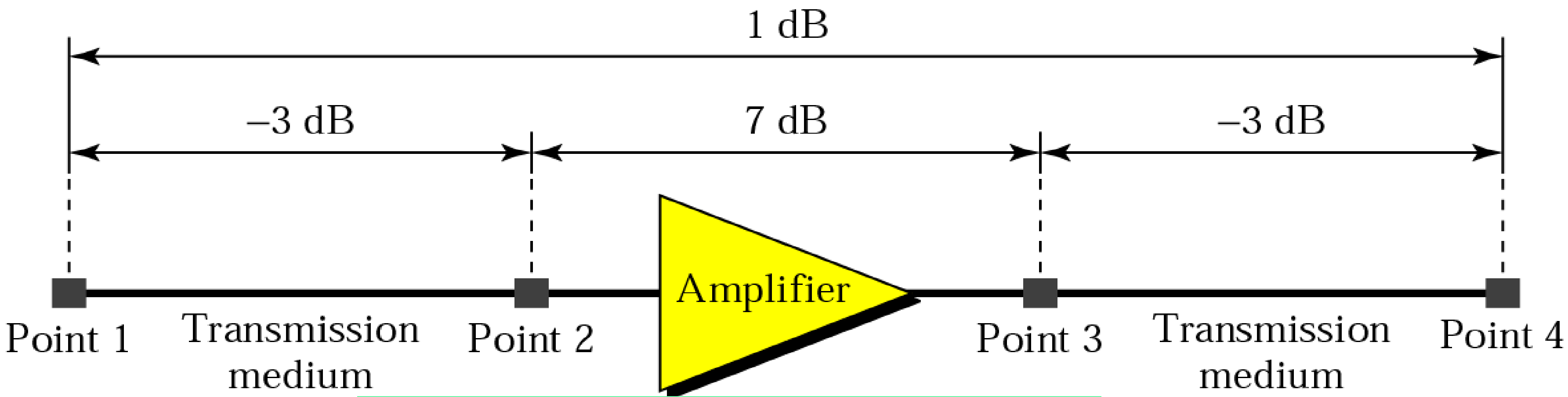
$$= 10 \log_{10} (10) = 10 (1) = 10 \text{ dB}$$

Example

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 talking about several points instead of just two (cascading).

- A signal travels a long distance from point 1 to point 4.
    - The signal is attenuated by the time it reaches point 2.
    - Between points 2 and 3, the signal is amplified.
    - Again, between points 3 and 4, the signal is attenuated.

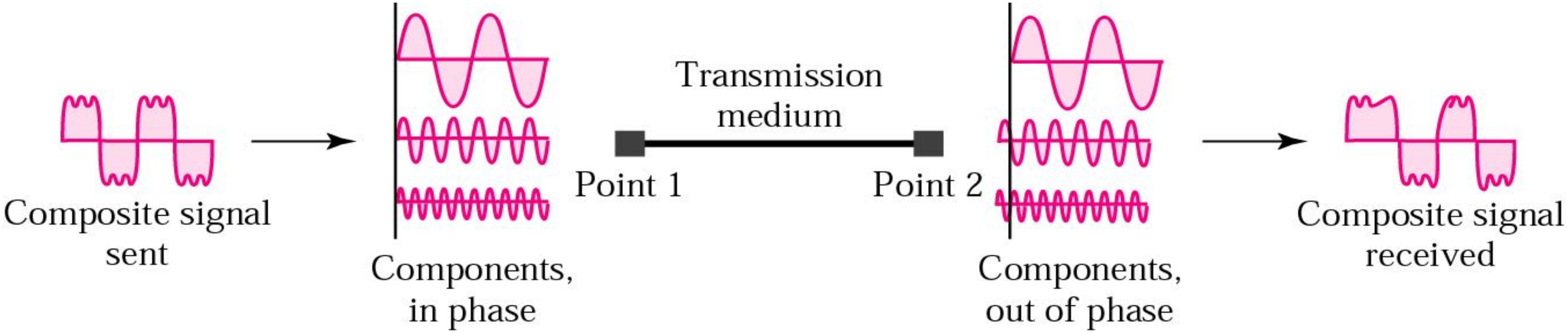
We can find the resultant decibel for the signal just by adding the decibel measurements between each set of points.



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

Distortion

Distortion means that the signal changes its form or shape. Distortion occurs in a composite signals, made of different frequencies. Each component has its own propagation speed



Noise

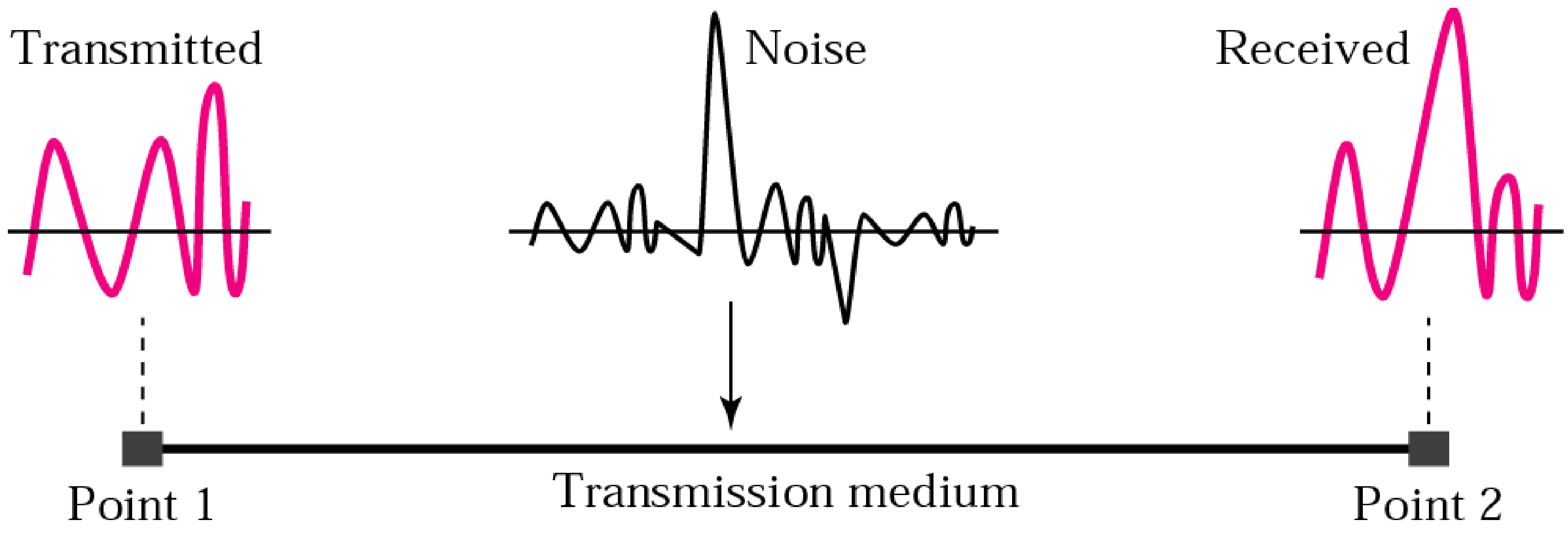
There are several type of noises:

Thermal noise – **is the random motion of the electrons in a wire which create an extra signal;**

Induced noise – **comes from sources as motors and appliances;**

Crosstalk noise- **is the effect of one wire on the other;**

Impulse noise – **is a spike**



More About Signals

Throughput

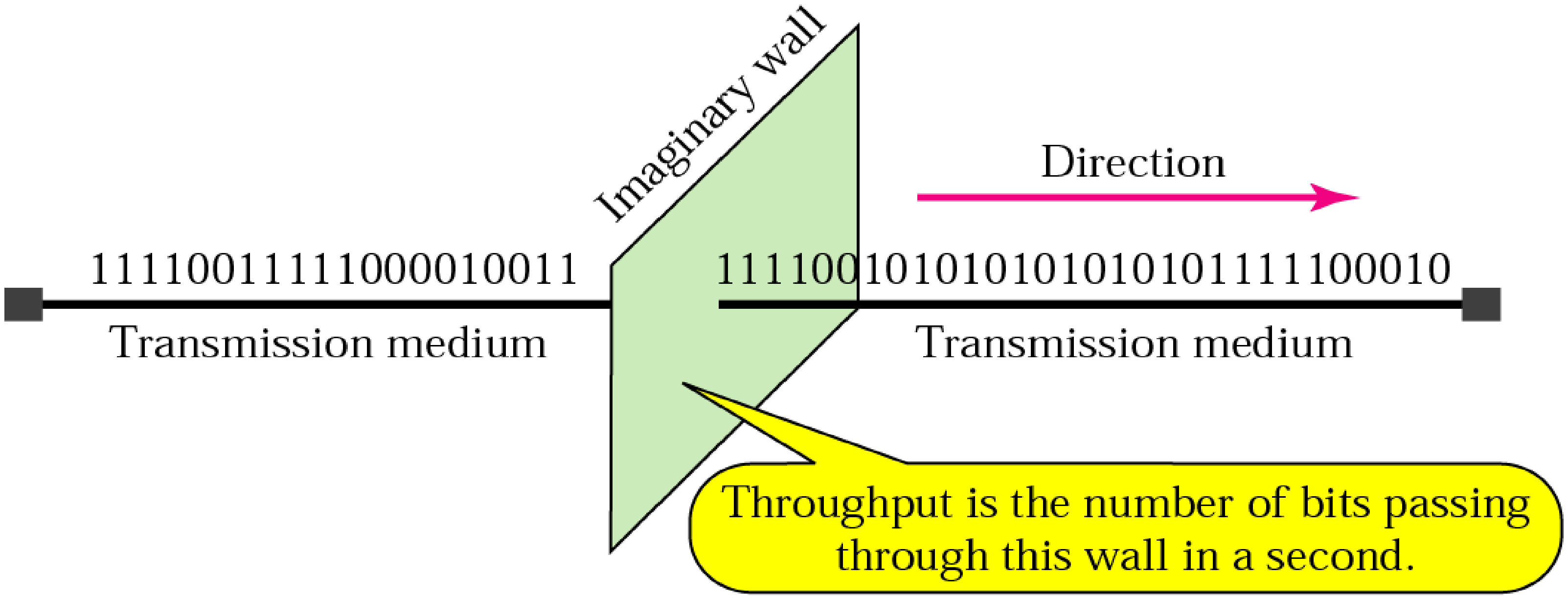
Propagation Speed

Propagation Time

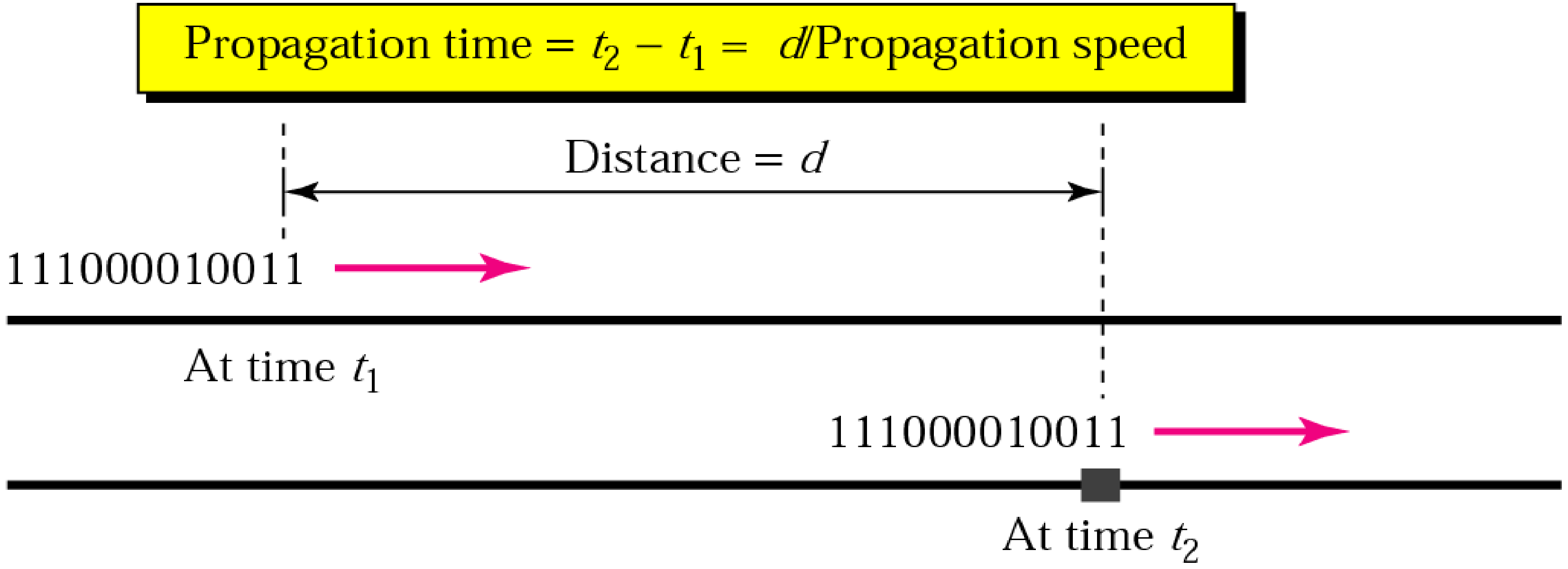
Wavelength

Throughput

Throughput is measurement of how data can pass through an entity



Propagation time measures the time required for a signal (or a bit) to travel from one point of the transmission to another.



Wavelength (λ) is the distance a single signal can travel in one period

Wavelength = Propagation speed x Period

Wavelength = Propagation speed / Frequency

$$\lambda = c / f$$