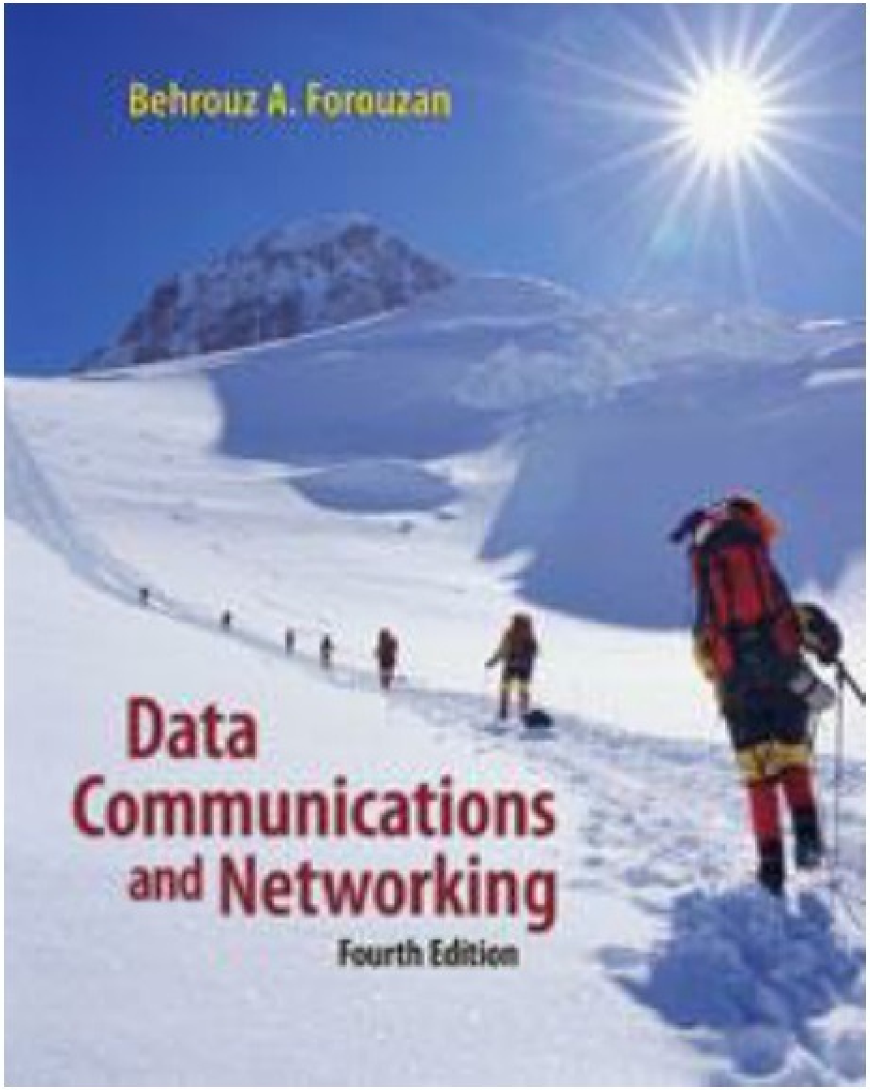


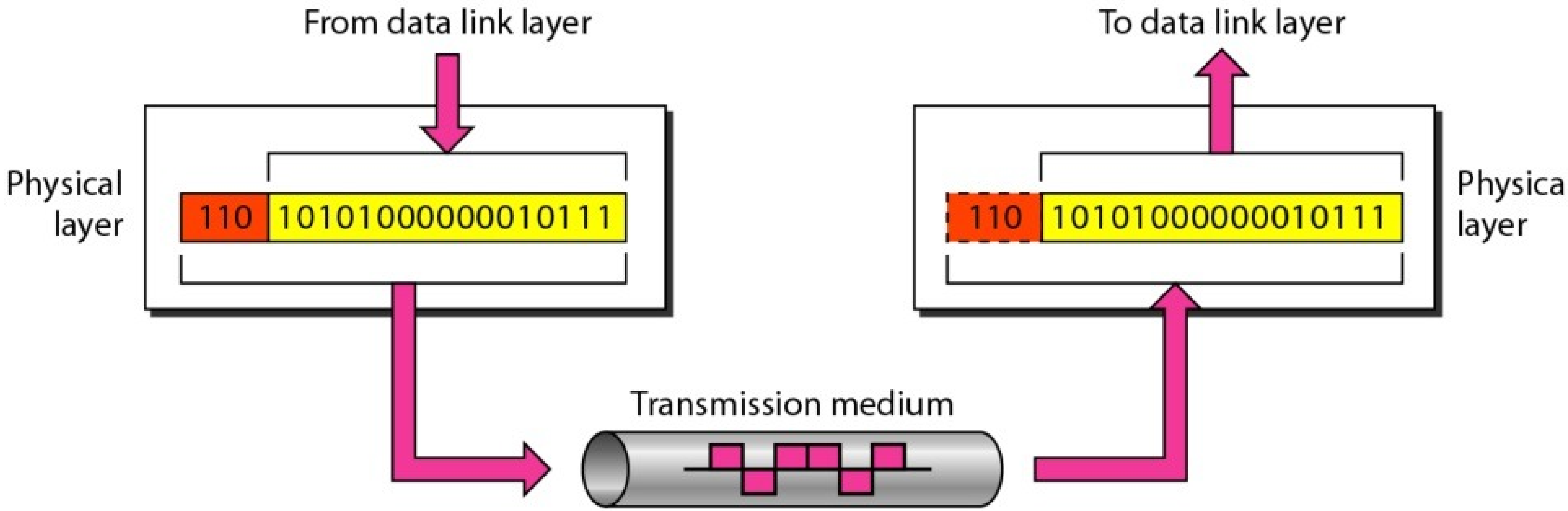
Physical Layer
(Data and Signals)

slides are modified from **Behrouz A. Forouzan**

Chapter 3: Data and Signals

- 3.1 Analog and Digital
- 3.2 Periodic Analog Signals
- 3.3 Digital Signals
- 3.4 Transmission Impairment
- 3.5 Data-rate Limits
- 3.6 Performance

Physical layer



To be transmitted,
data must be transformed to electromagnetic signals.

3-1 ANALOG AND DIGITAL

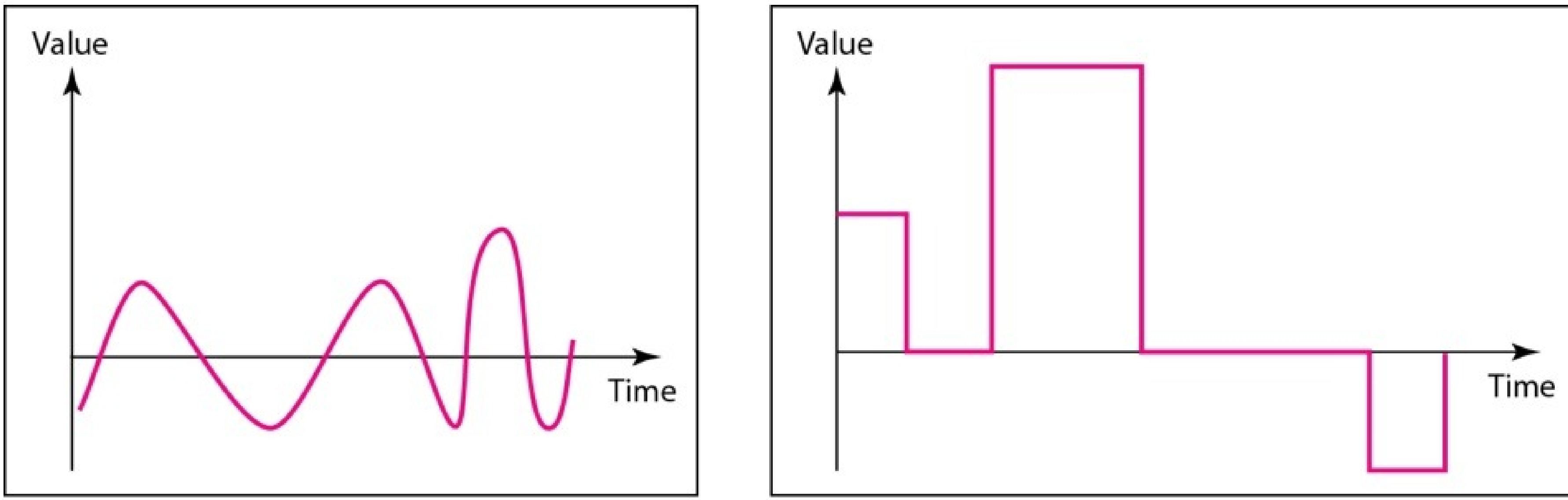
Data can be analog or digital

- Analog data refers to information that is continuous
- Analog data take on continuous values
- Analog signals can have an infinite number of values in a range

- Digital data refers to information that has discrete states
- Digital data take on discrete values
- Digital signals can have only a limited number of values

In data communications, we commonly use
periodic analog signals and nonperiodic digital signals.

Comparison of analog and digital signals



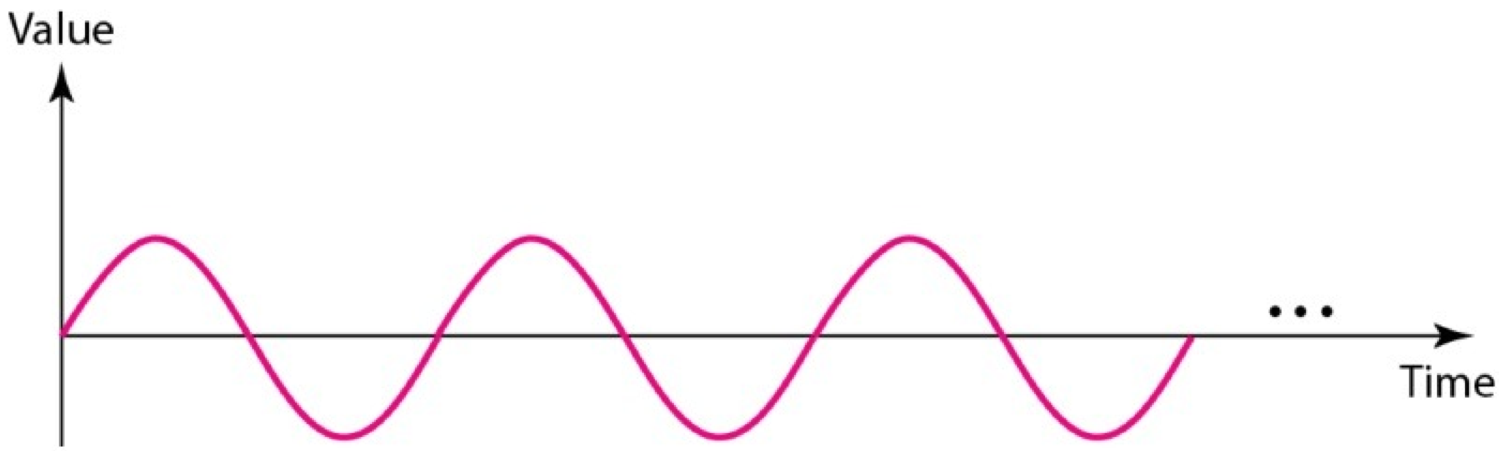
a. Analog signal

b. Digital signal

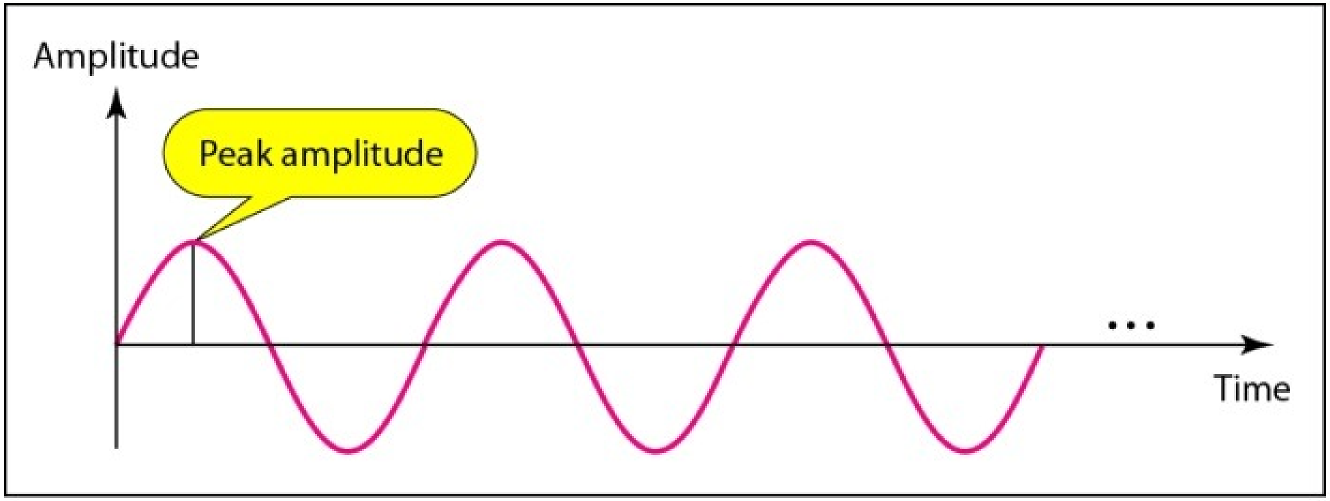
3-2 PERIODIC ANALOG SIGNALS

Periodic analog signals can be classified as simple or composite.

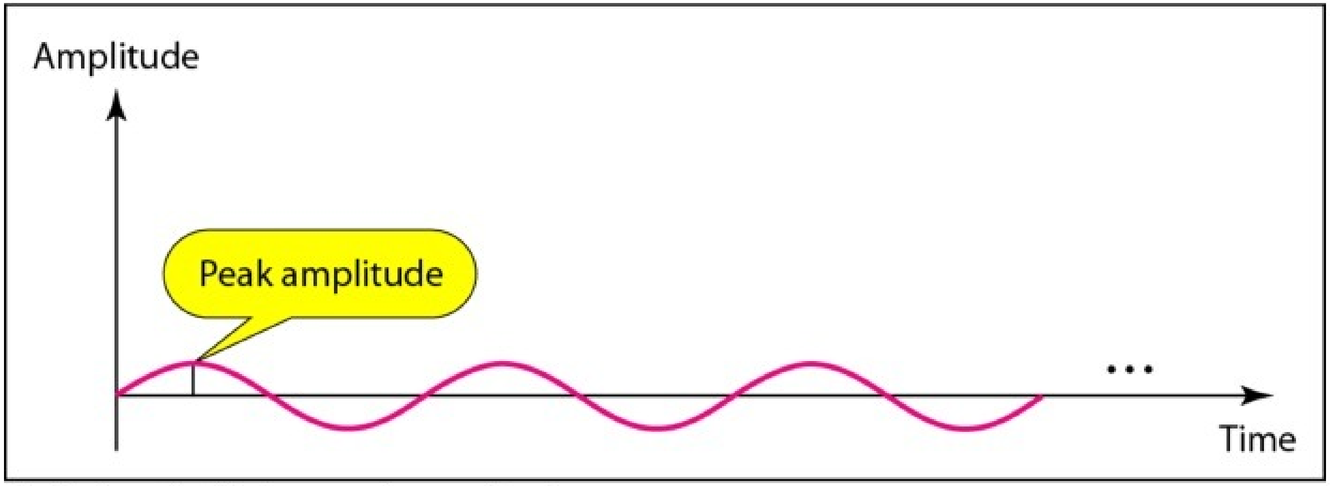
- A simple periodic analog signal, a sine wave, cannot be decomposed into simpler signals.
- A composite periodic analog signal is composed of multiple sine waves.



Signal amplitude



a. A signal with high peak amplitude



b. A signal with low peak amplitude

Frequency

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.

Frequency and Period

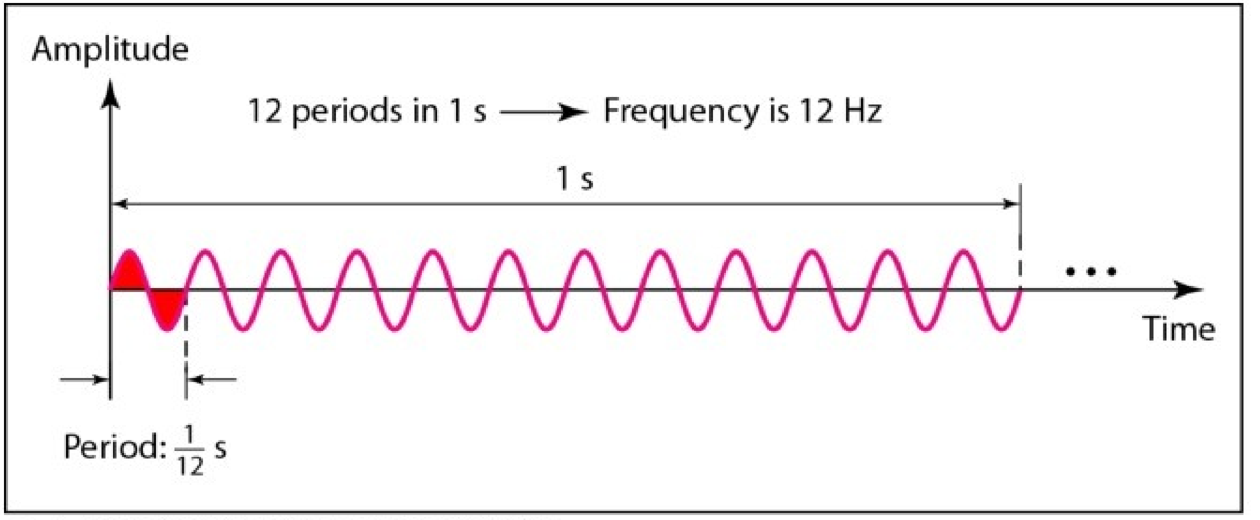
Frequency and period are the inverse of each other.

$$f = \frac{1}{T} \qquad \text{and} \qquad T = \frac{1}{f}$$

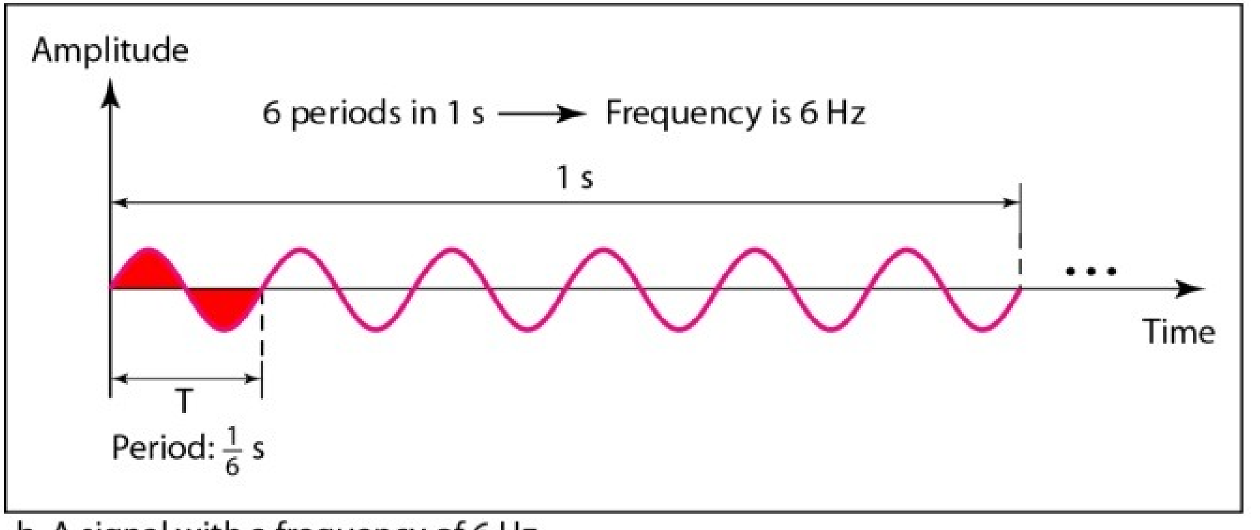
Units of period and frequency

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

Two signals with the same amplitude, but different frequencies



a. A signal with a frequency of 12 Hz



b. A signal with a frequency of 6 Hz

Examples

The power we use at home has a frequency of 60 Hz.
What is the period of this sine wave ?

$$\boxed{T = \frac{1}{f} = \frac{1}{60} = 0.0166\text{ s} = 0.0166 \times 10^{3}\text{ ms} = 16.6\text{ ms}}$$

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

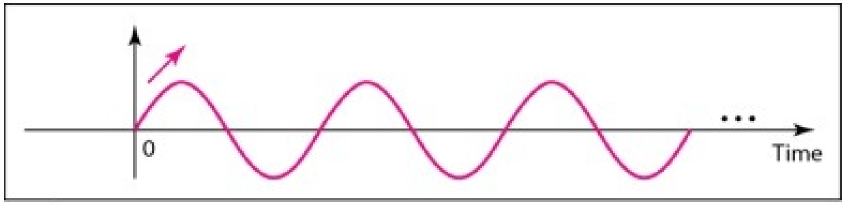
$$100\text{ ms} = 100 \times 10^{-3}\text{ s} = 10^{-1}\text{ s}$$

$$f = \frac{1}{T} = \frac{1}{10^{-1}}\text{ Hz} = 10\text{ Hz} = 10 \times 10^{-3}\text{ kHz} = 10^{-2}\text{ kHz}$$

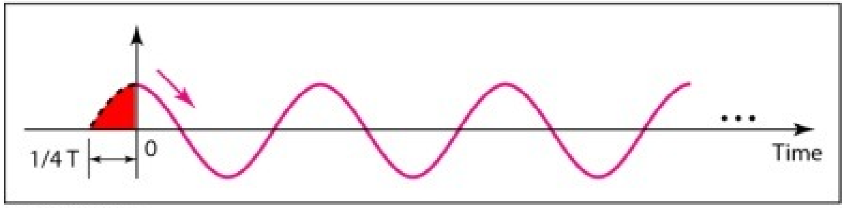
Phase

Phase describes the position of the waveform relative to time 0

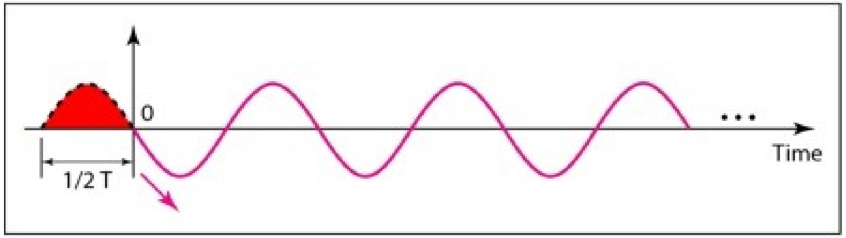
Three sine waves with the same amplitude and frequency, but different phases



a. 0 degrees



b. 90 degrees



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?

Solution

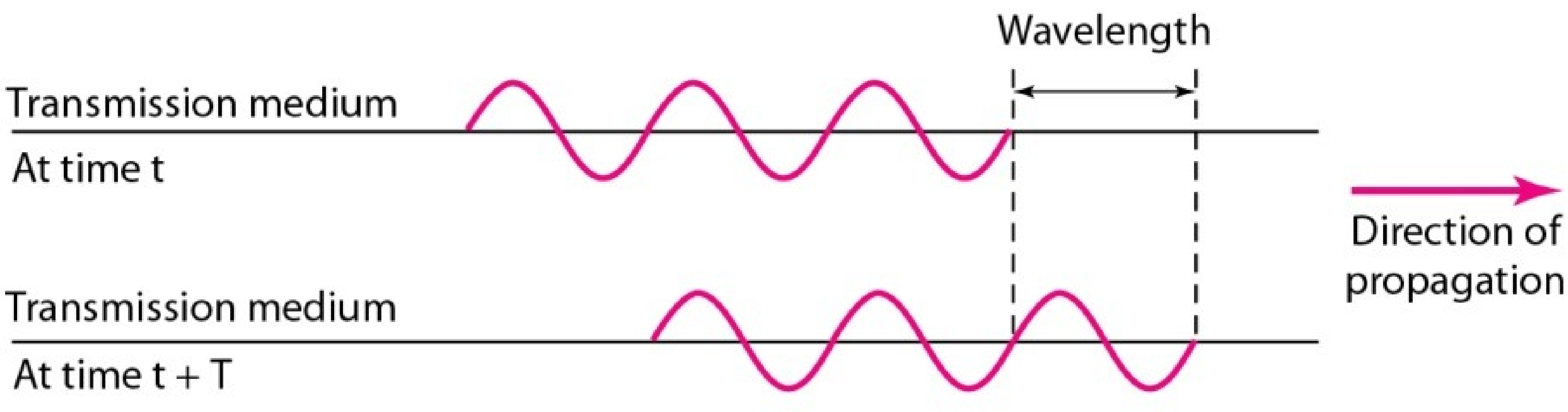
We know that 1 complete cycle is 360°.

Therefore, 1/6 cycle is

$$\boxed{\frac{1}{6} \times 360 = 60^\circ = 60 \times \frac{2\pi}{360} \text{ rad} = \frac{\pi}{3} \text{ rad} = 1.046 \text{ rad}}$$

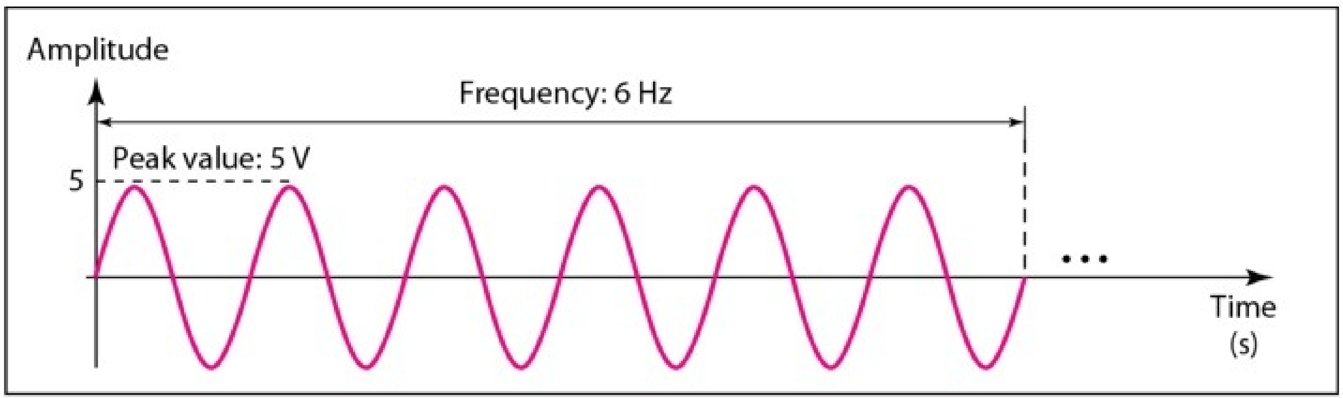
Wavelength and period

Wavelength = Propagation speed x Period
= Propagation speed / Frequency

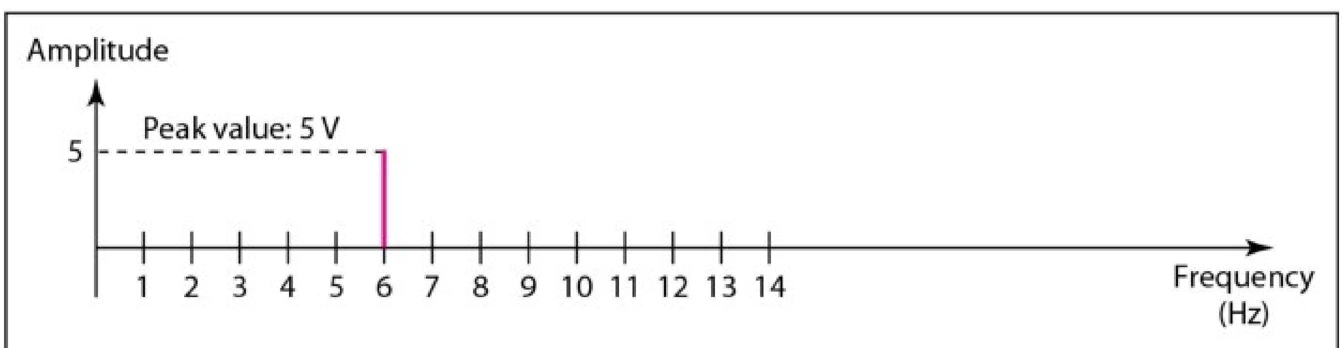


Time-domain and frequency-domain plots of a sine wave

A complete sine wave in the time domain can be represented by a single spike in the frequency domain.

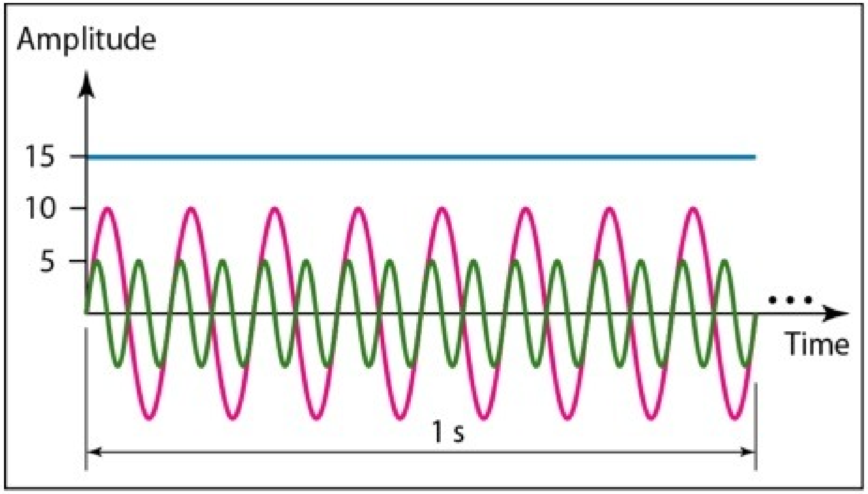


a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)

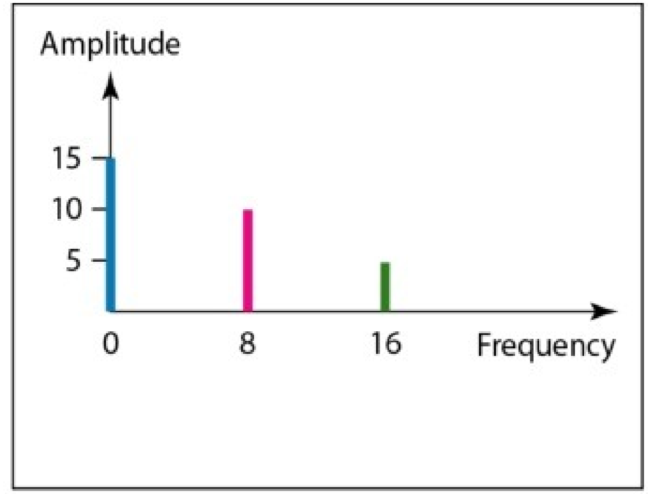


b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

Frequency Domain



a. Time-domain representation of three sine waves with frequencies 0, 8, and 16



b. Frequency-domain representation of the same three signals

- The frequency domain is more compact and useful when we are dealing with more than one sine wave.

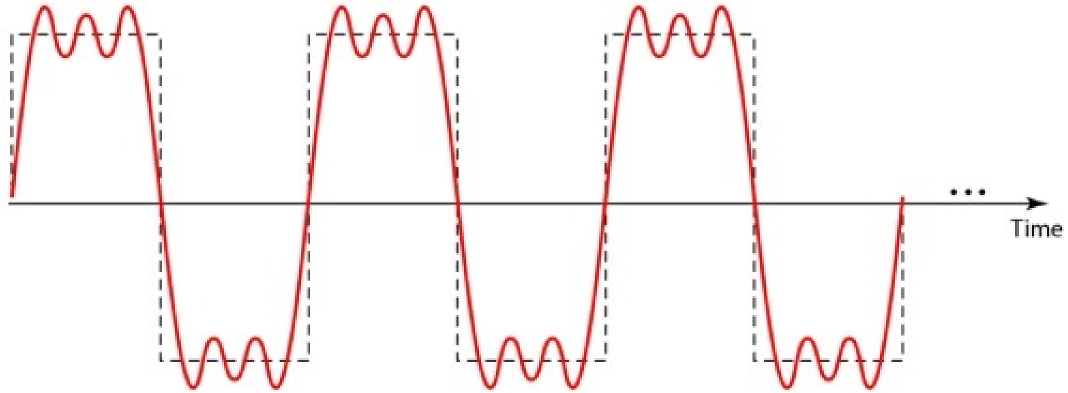
- A single-frequency sine wave is not useful in data communication
  - We need to send a composite signal, a signal made of many simple sine waves.

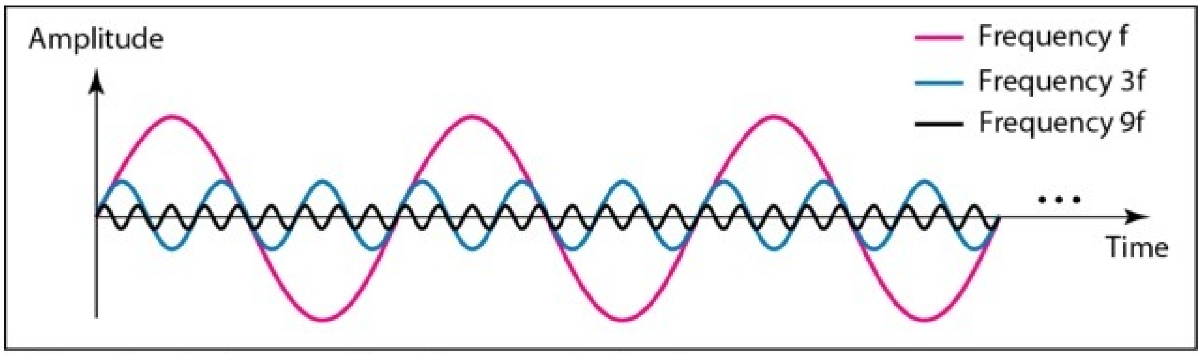
Fourier analysis

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

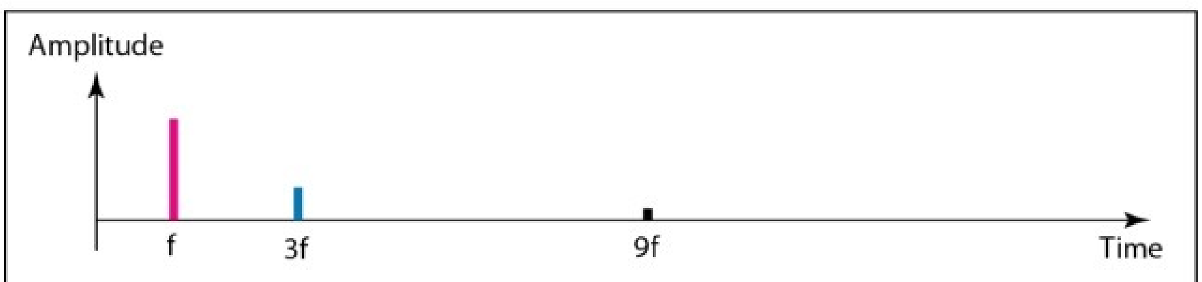
- If the composite signal is periodic, the decomposition gives a *series of signals with discrete frequencies;*
- If the composite signal is nonperiodic, the decomposition gives a *combination of sine waves with continuous frequencies.*

A composite periodic signal





a. Time-domain decomposition of a composite signal

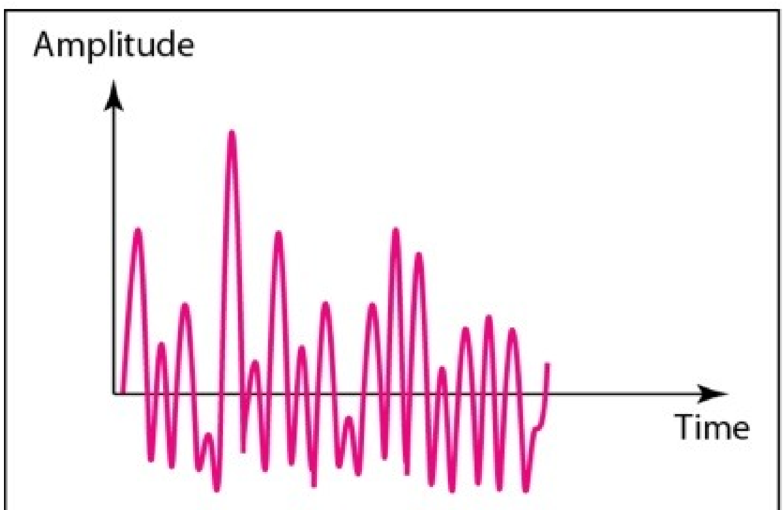


b. Frequency-domain decomposition of the composite signal

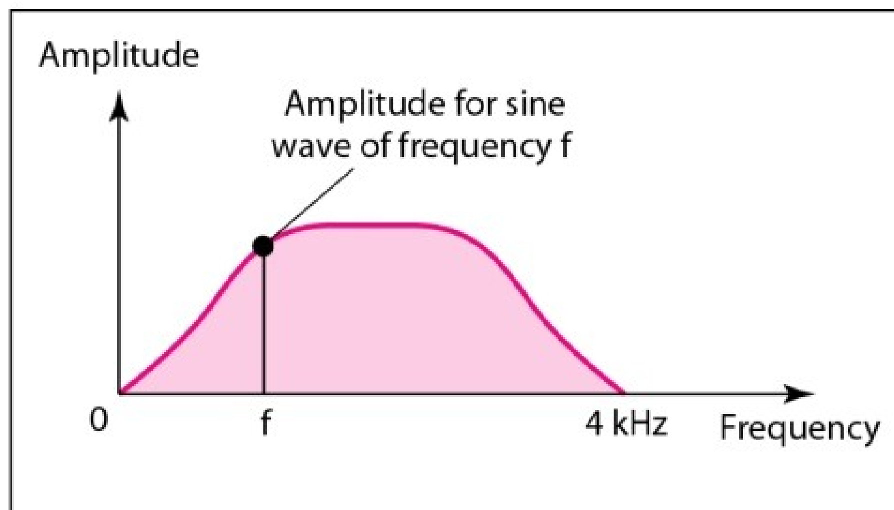
Decomposition of the composite periodic signal in the time and frequency domains

Time and frequency domains of a nonperiodic signal

- A nonperiodic composite signal
  - It can be a signal created by a microphone or a telephone set when a word or two is pronounced.
  - In this case, the composite signal cannot be periodic
    - because that implies that we are repeating the same word or words with exactly the same tone.



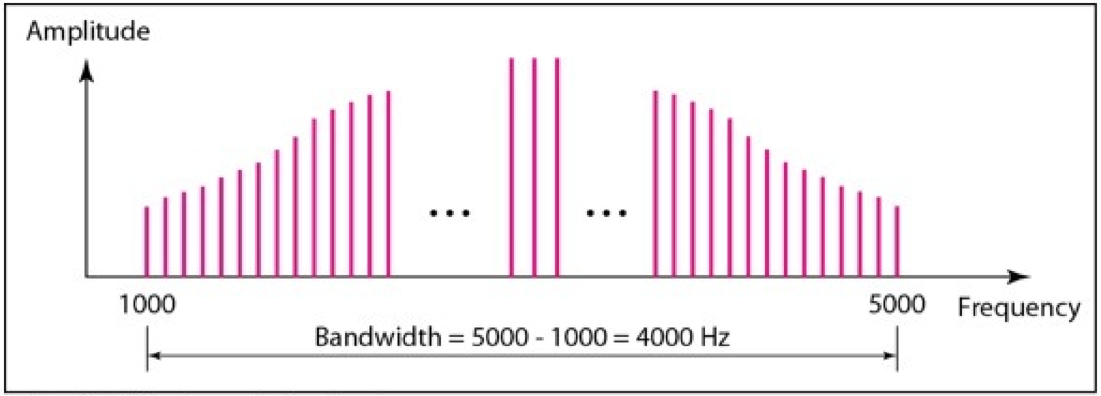
a. Time domain



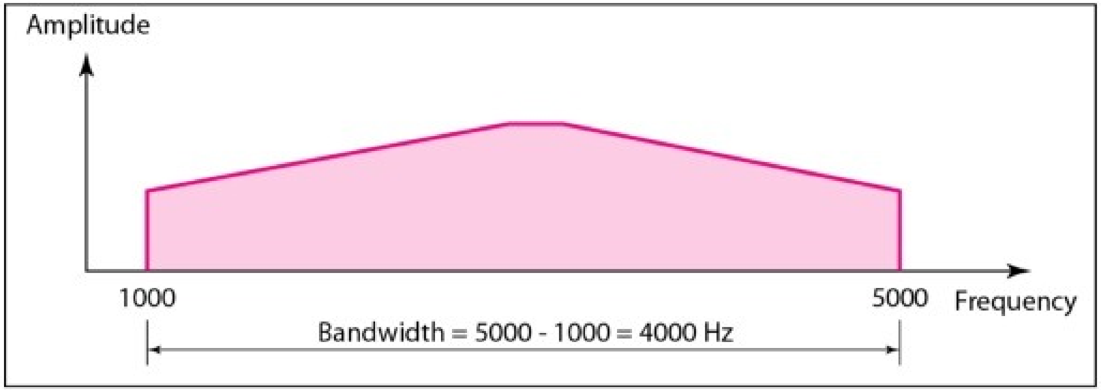
b. Frequency domain

Bandwidth

The bandwidth of a composite signal is the difference between the highest and the lowest frequencies contained in that signal.



a. Bandwidth of a periodic signal



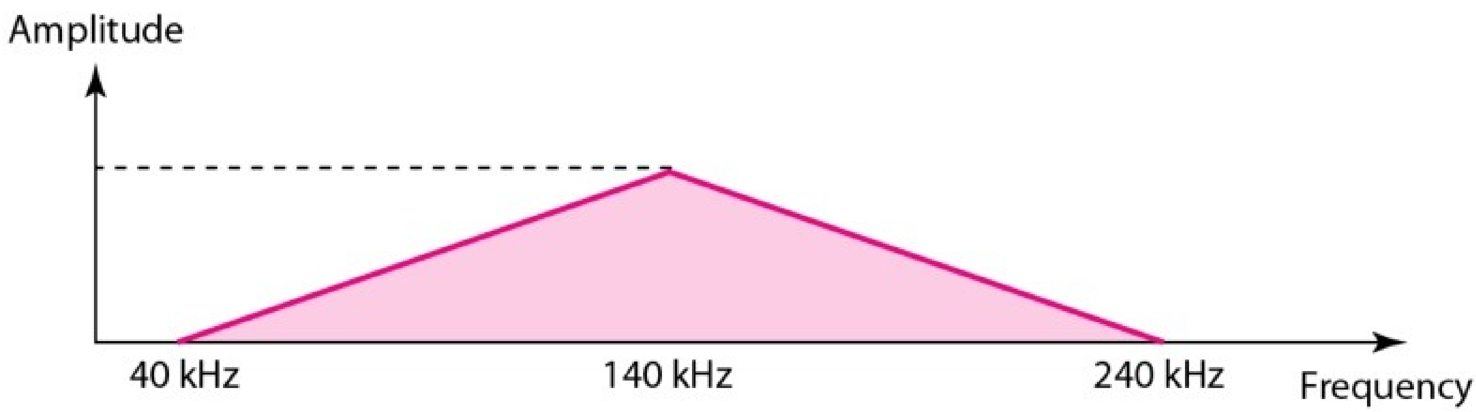
b. Bandwidth of a nonperiodic signal

Example

A nonperiodic composite signal has a bandwidth of 200 kHz, with a middle frequency of 140 kHz and peak amplitude of 20 V. The two extreme frequencies have an amplitude of 0. Approximately, draw the frequency domain of the signal.

Solution

The lowest frequency must be at 40 kHz and the highest at 240 kHz.



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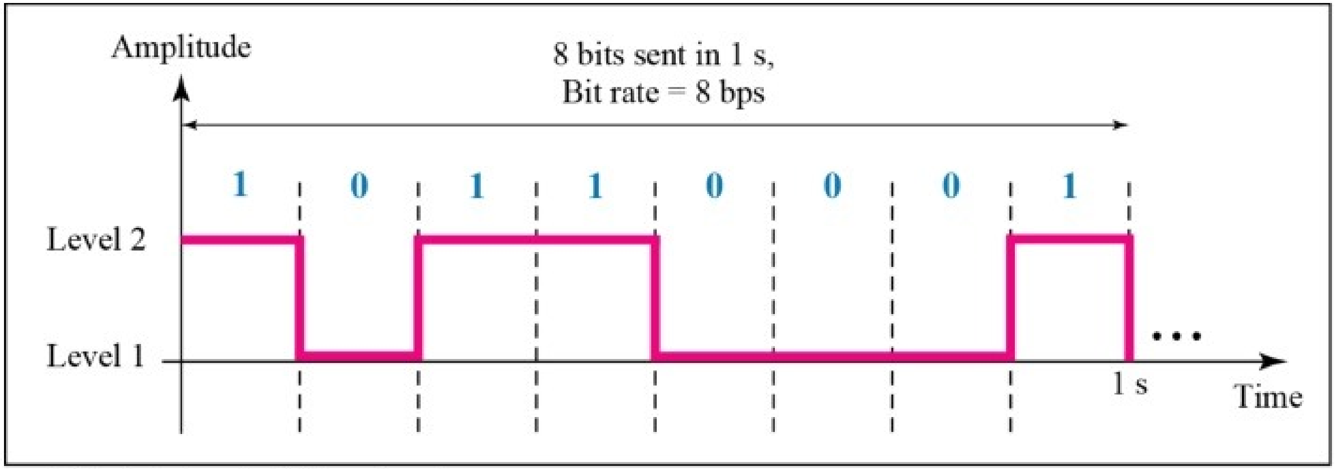
3-3 DIGITAL SIGNALS

- In addition to being represented by an analog signal, information can also be represented by a digital signal.

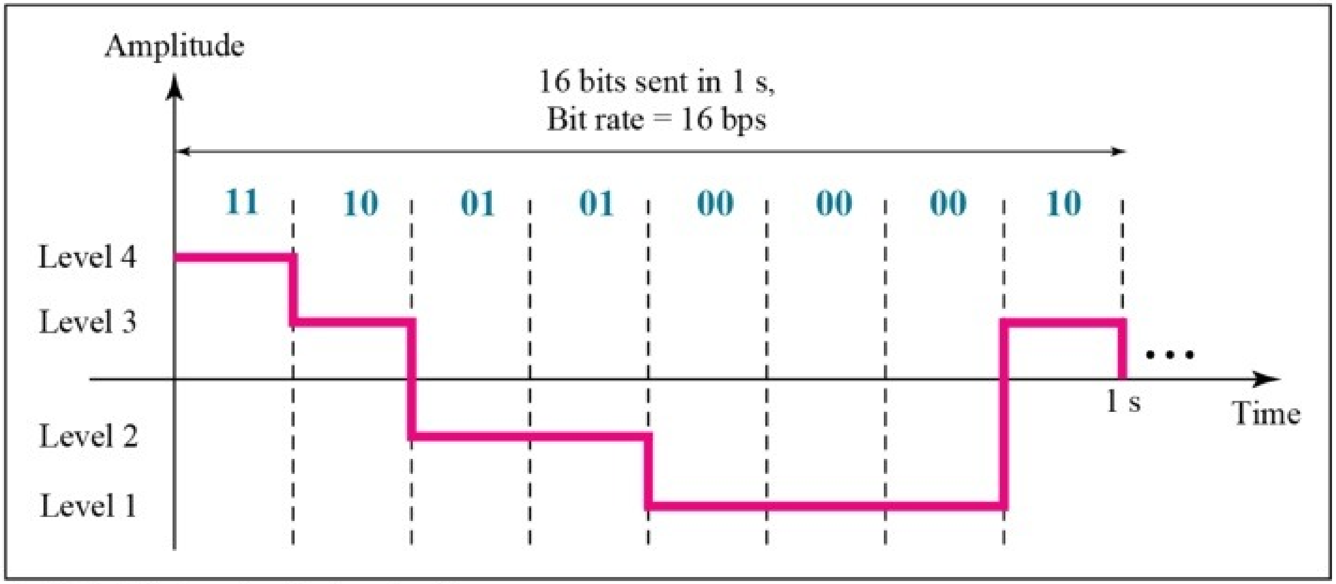
- For example, a 1 can be encoded as a positive voltage and a 0 as zero voltage.

- A digital signal can have more than two levels.
  - In this case, we can send more than 1 bit for each level.

Two digital signals: one with two signal levels and the other with four signal levels



a. A digital signal with two levels



b. A digital signal with four levels

Examples

A digital signal has 8 levels. How many bits are represented by each level?

We calculate the number of bits from the formula

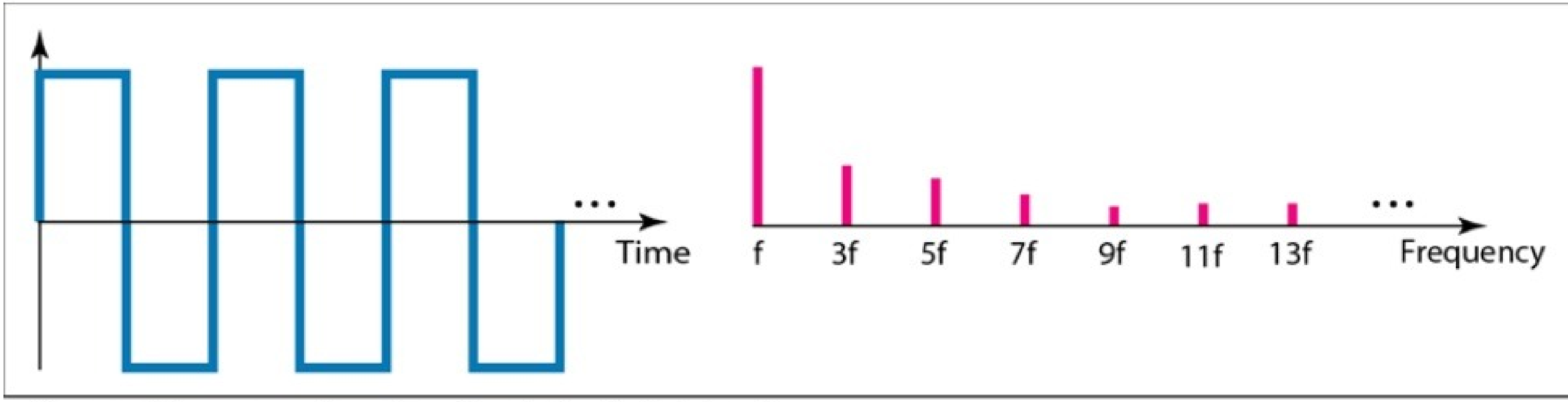
$$\text{Number of bits per level} = \log_2 8 = 3$$

Each signal level is represented by 3 bits.

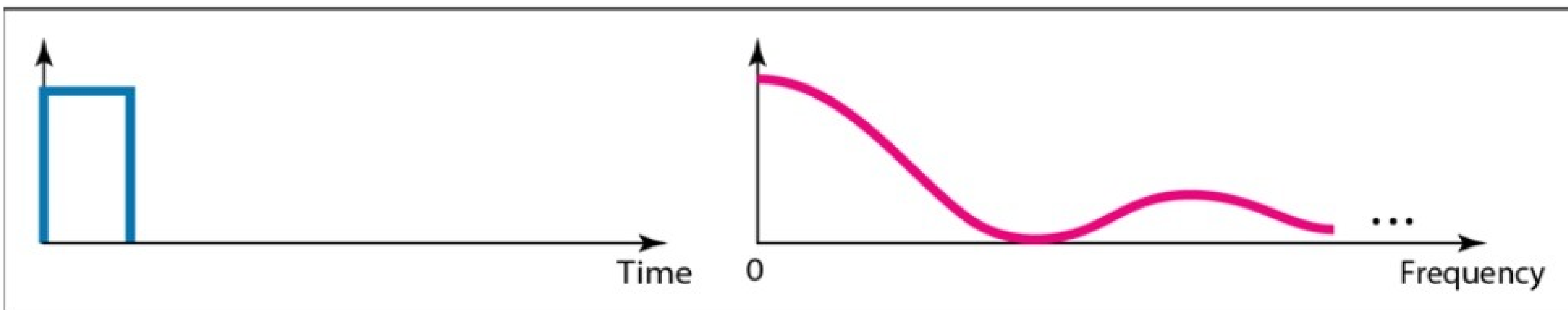
A digital signal has 9 levels. How many bits are represented by each level?

Each signal level is represented by 3.17 bits.
The number of bits sent per level needs to be an integer as well as a power of 2.
Hence, 4 bits can represent one level.

The time and frequency domains of periodic and nonperiodic digital signals

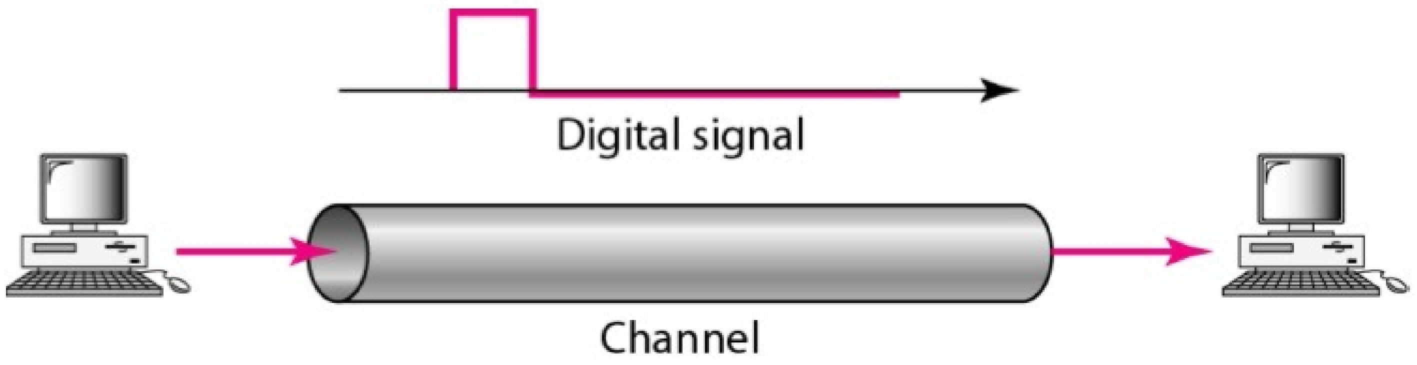


a. Time and frequency domains of periodic digital signal



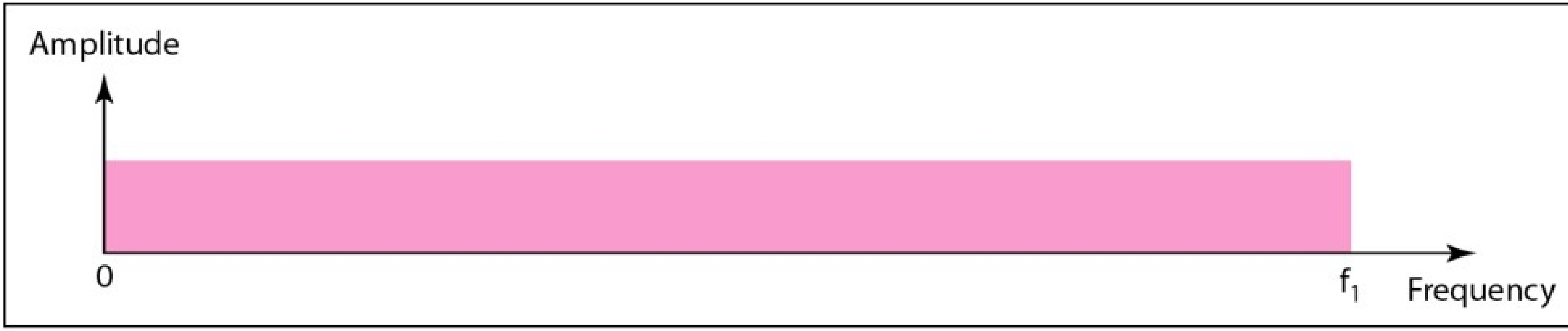
b. Time and frequency domains of nonperiodic digital signal

Baseband transmission



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

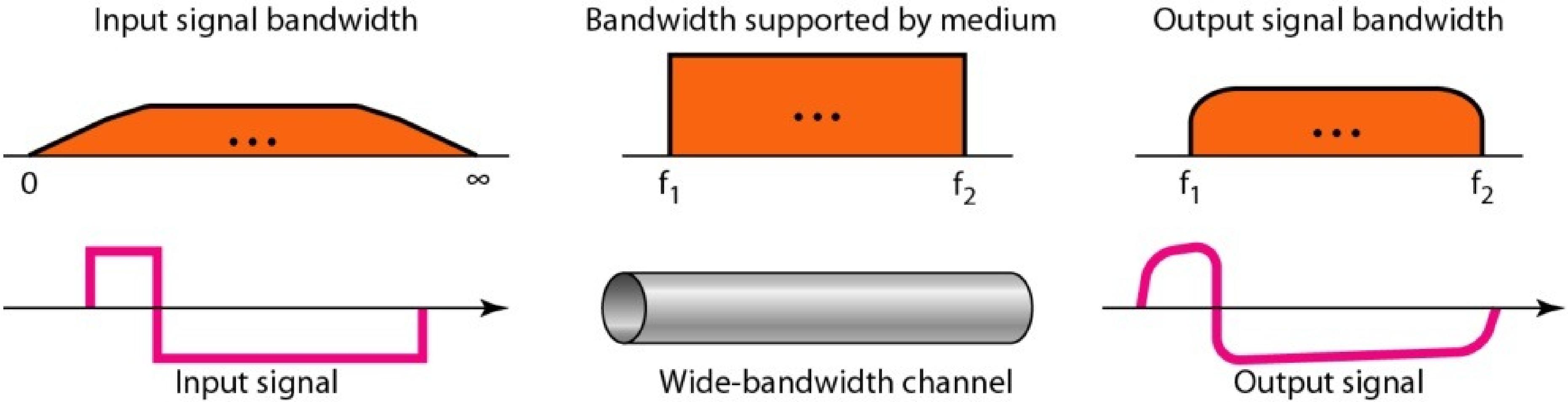
Bandwidths of two low-pass channels



a. Low-pass channel, wide bandwidth

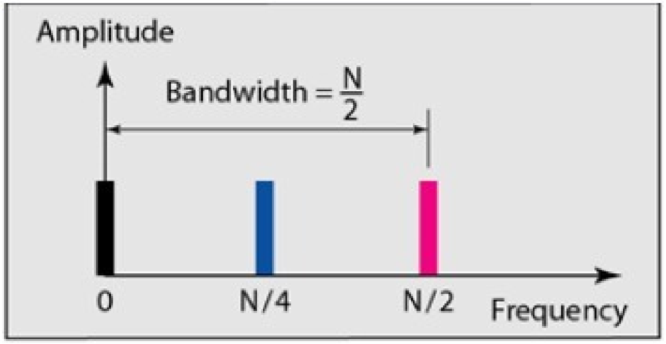
b. Low-pass channel, narrow bandwidth

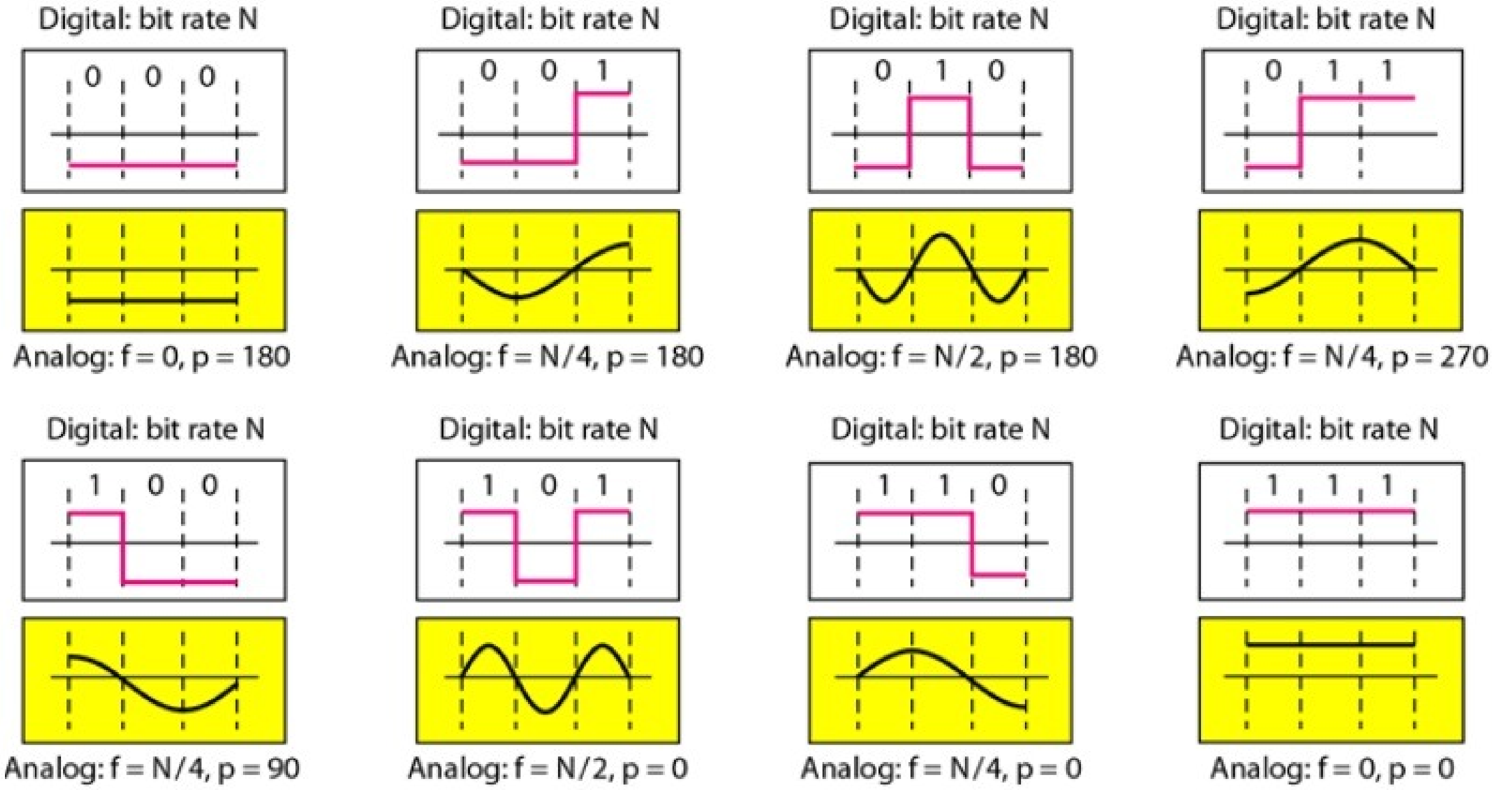
Baseband transmission using a dedicated medium



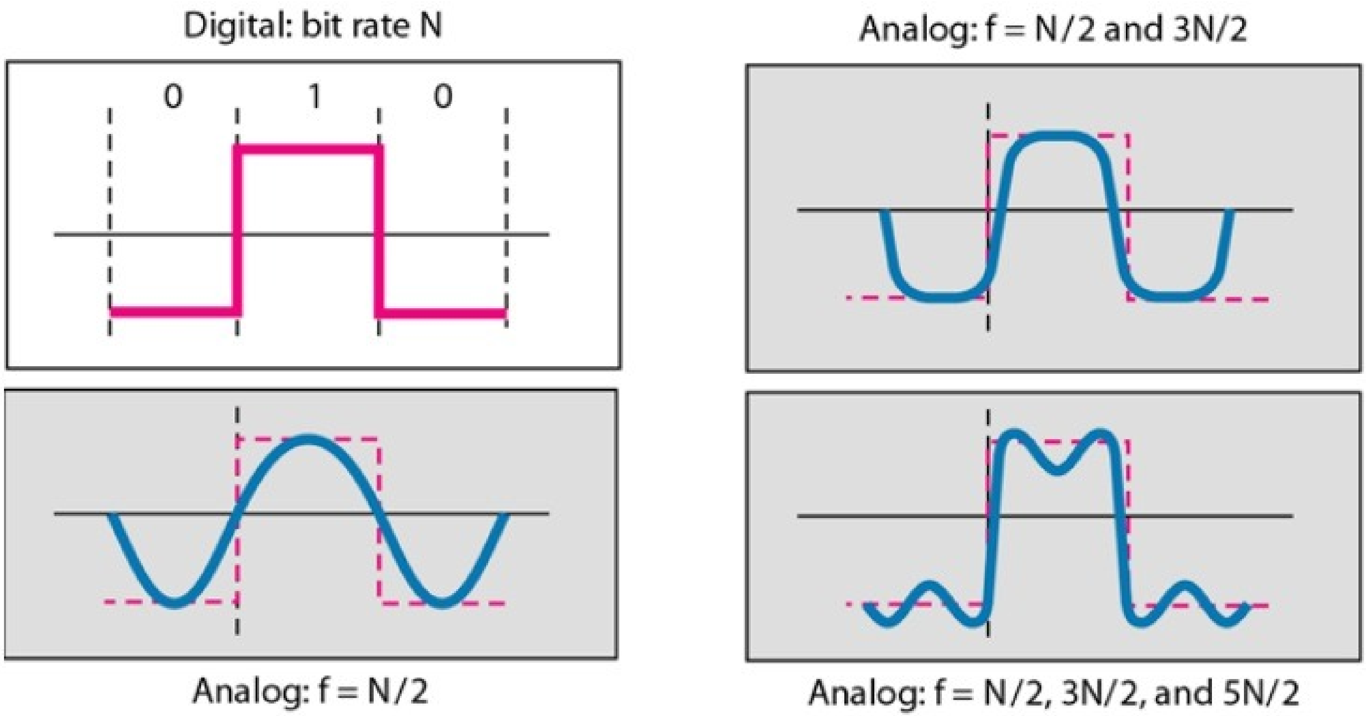
Baseband transmission of a digital signal that preserves the shape of the digital signal is possible only if we have a low-pass channel with an infinite or very wide bandwidth.

Rough approximation of a digital signal using the first harmonic for worst case





Simulating a digital signal with first three harmonics



In baseband transmission,
the required bandwidth is proportional to the bit rate;

if we need to send bits faster, we need more bandwidth.

Bandwidth requirements

Bit Rate	*Harmonic 1*	*Harmonics 1, 3*	*Harmonics 1, 3, 5*
$n = 1$ kbps	$B = 500$ Hz	$B = 1.5$ kHz	$B = 2.5$ kHz
$n = 10$ kbps	$B = 5$ kHz	$B = 15$ kHz	$B = 25$ kHz
$n = 100$ kbps	$B = 50$ kHz	$B = 150$ kHz	$B = 250$ kHz

Example

What is the required bandwidth of a low-pass channel if we need to send 1 Mbps by using baseband transmission?

Solution

The answer depends on the accuracy desired.

a. The minimum bandwidth is B = bit rate /2, or 500 kHz.

b. A better solution is to use the first and the third harmonics with B = 3 × 500 kHz = 1.5 MHz.

c. Still a better solution is to use the first, third, and fifth harmonics with B = 5 × 500 kHz = 2.5 MHz.

Example

We have a low-pass channel with bandwidth 100 kHz. What is the <u>maximum</u> bit rate of this channel?

Solution

The maximum bit rate can be achieved if we use the first harmonic.

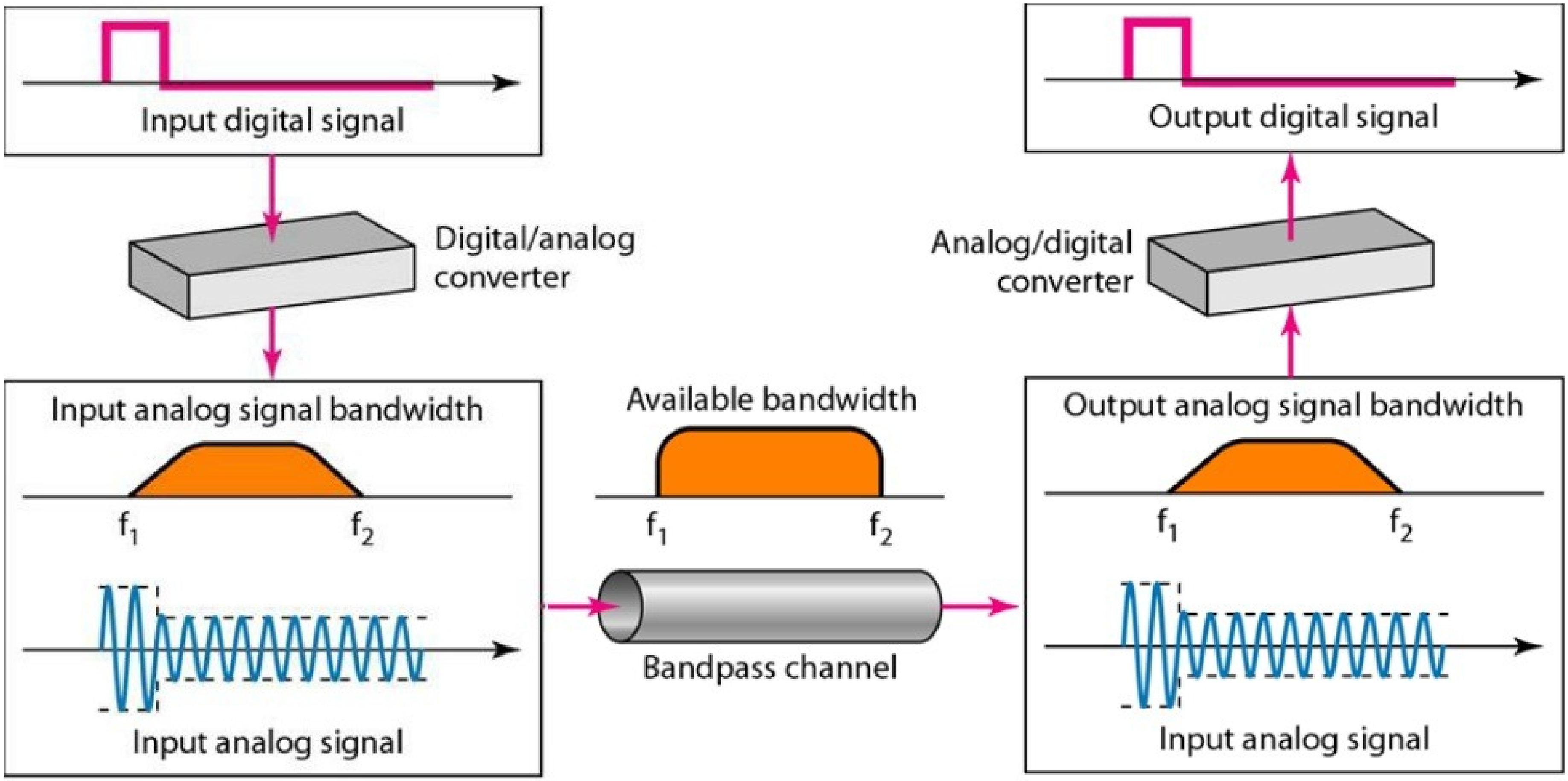
The bit rate is 2 times the available bandwidth, or 200 Kbps.

Bandwidth of a bandpass channel

If the available channel is a bandpass channel,
we cannot send the digital signal directly to the channel;

we need to convert the digital signal to
an analog signal before transmission.

Modulation of a digital signal for transmission on a bandpass channel



Example

An example of broadband transmission using modulation is the sending of computer data through a telephone subscriber line, the line connecting a resident to the central telephone office.

These lines are designed to carry voice with a limited bandwidth.

The channel is considered a bandpass channel.

We convert the digital signal from the computer to an analog signal, and send the analog signal.

We can install two converters to change the digital signal to analog and vice versa at the receiving end.

The converter, in this case, is called a modem.

Example

A second example is the digital cellular telephone.

For better reception, digital cellular phones convert the analog voice signal to a digital signal.

Although the bandwidth allocated to a company providing digital cellular phone service is very wide, we still cannot send the digital signal without conversion.

The reason is that we only have a bandpass channel available between caller and callee.

We need to convert the digitized voice to a composite analog signal before sending.

Examples

Assume we need to download files at a rate of 100 pages per second. A page is an average of 24 lines with 80 characters in each line where one character requires 8 bits. What is the required bit rate of the channel?

$$\boxed{100 \times 24 \times 80 \times 8 = 1{,}636{,}000 \text{ bps} = 1.636 \text{ Mbps}}$$

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). Assume that each sample requires 8 bits. What is the required bit rate?

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

Example

HDTV uses digital signals to broadcast high quality video signals. There are 1920 by 1080 pixels per screen, and the screen is renewed 30 times per second. Also, 24 bits represents one color pixel.

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

$$1920 \times 1080 \times 30 \times 24 = 1{,}492{,}992{,}000 \text{ or } 1.5 \text{ Gbps}$$

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