COMP 3721
Introduction to Data Communications

02. Week 2

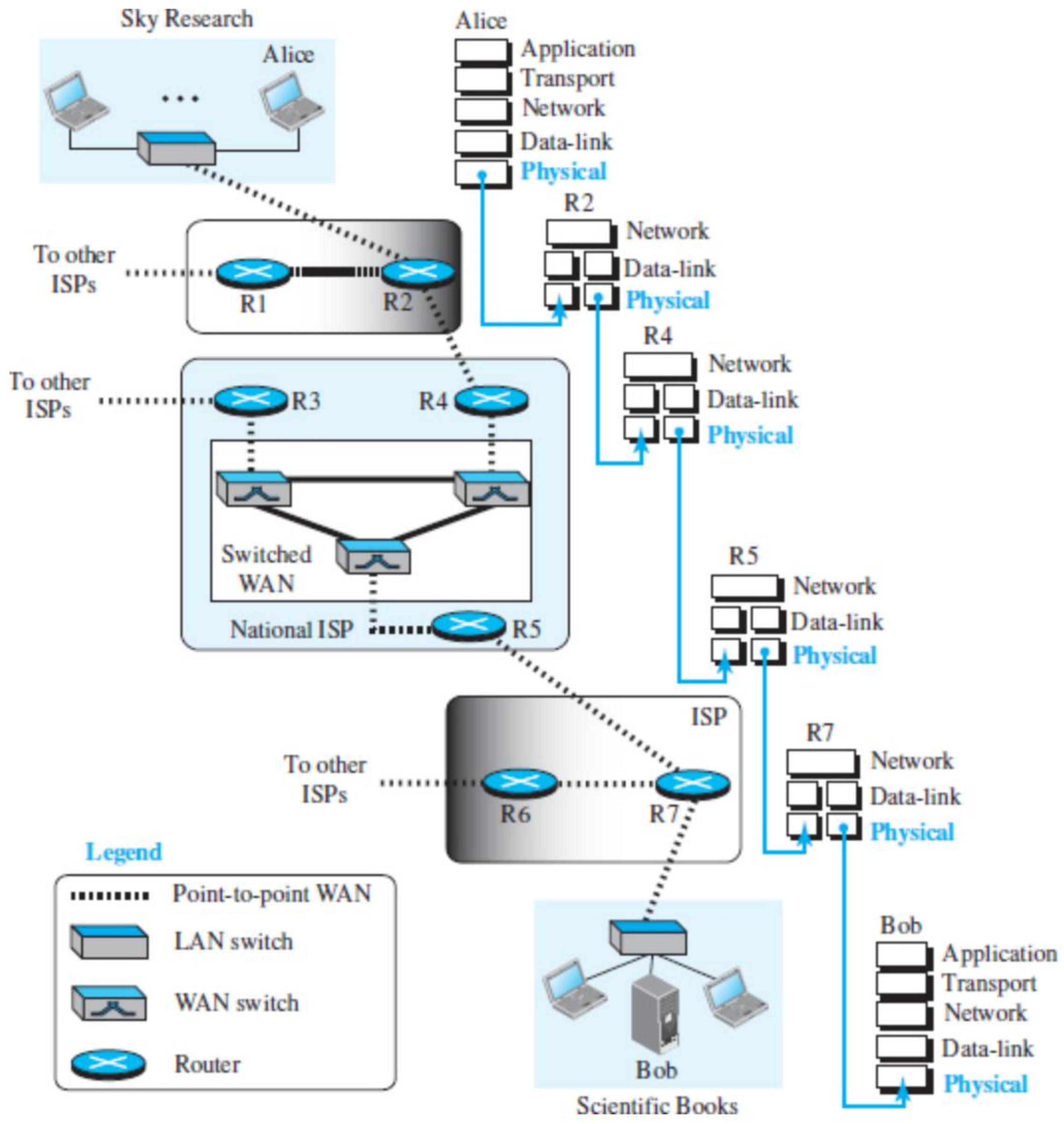
Learning Outcomes

- By the end of this lecture, you will be able to:
  - Explain what are data and signal as well as their types.
  - Explain the characteristics of periodic analog signals.
  - Explain the characteristics of digital signals.

Introduction

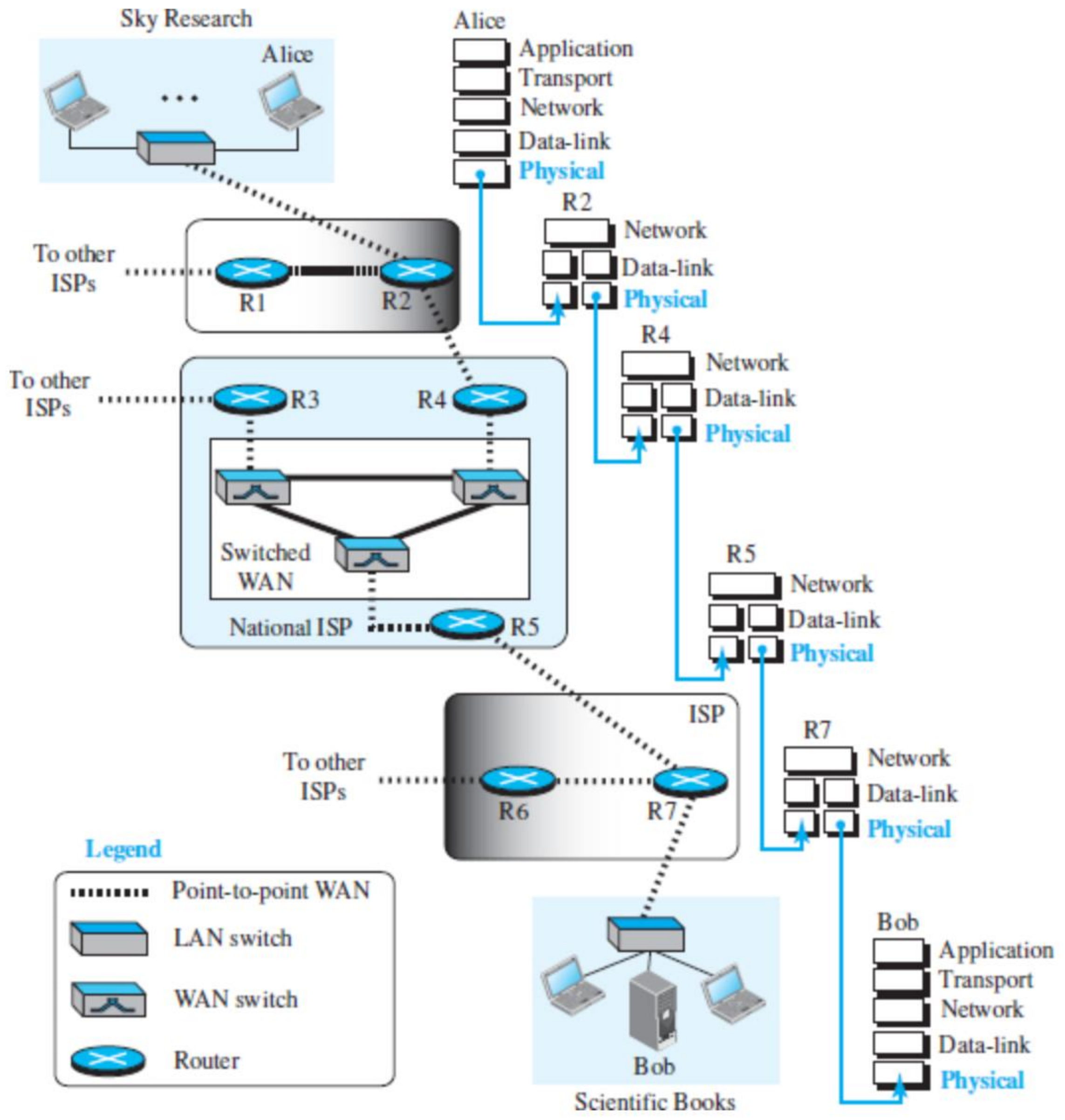
- What are really exchanged between Alice and Bob?

- What goes through the network connecting Alice to Bob at the physical layer?



Introduction

- What are really exchanged between Alice and Bob?
  - Data (information)
- What goes through the network connecting Alice to Bob at the physical layer?
  - Signals (e.g., electrical signals)



Introduction

- **Physical layer**
  - Moving data in the form of **electromagnetic signals** across a **transmission medium**.
- **Data** must be changed to **signals** for **transmission**.
- **Communication** at application, transport, network, and data-link is **logical**.
- Communication at the physical layer is **physical**.

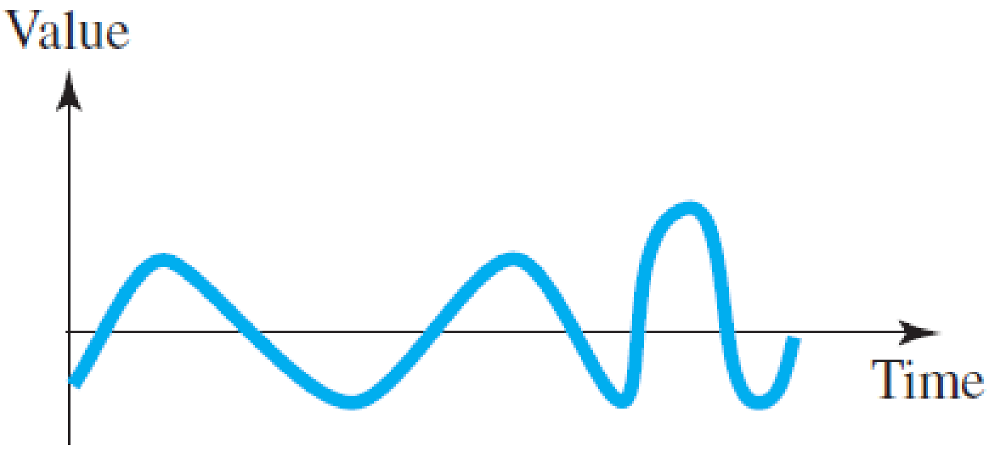
Analog and Digital Data

- **Analog data**
  - Information that is **continuous** (takes on continuous values)
  - **Real-life example**: **sound** (when someone speaks, an analog wave is created in the air)
- **Digital data**
  - Information that has **discrete** states (takes on discrete values)
  - Real-life example: **data are stored in computer memory** in the form of 1s and 0s

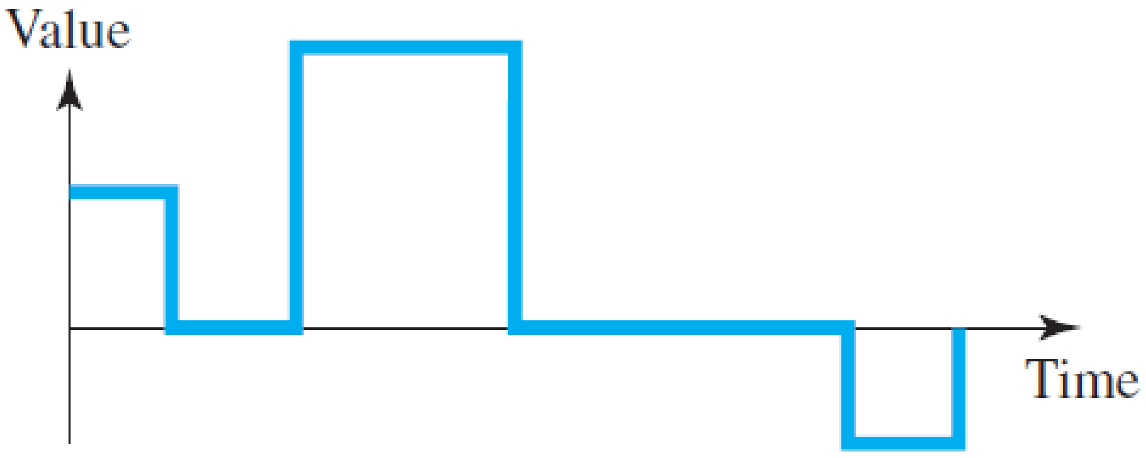
vs.

Analog and Digital Signals

- Analog signal
  - Has many levels of intensity over a period of time.
- Digital signal
  - Has a limited number of defined values (often 0 and 1).



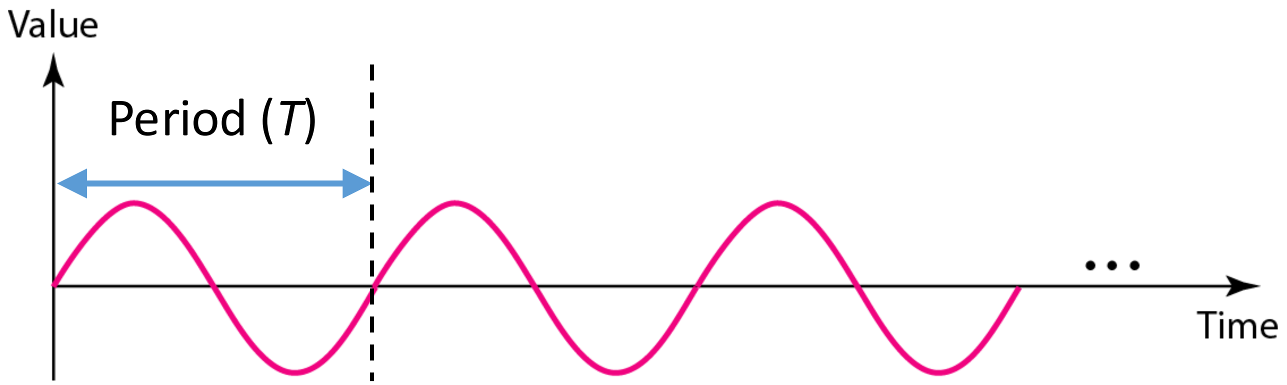
a. Analog signal



b. Digital signal

Periodic and Nonperiodic Signals

- Both analog and digital signals can take one of two forms:
  - **Periodic**
    - **Cycle**: the completion of one full pattern
    - **Period** (*T*): the amount of time, in seconds, a signal needs to complete one full pattern (i.e., one cycle)
    - A simple periodic analog signal, a **sine wave**, cannot be decomposed into simpler signals.
  - **Nonperiodic** (**Aperiodic**)



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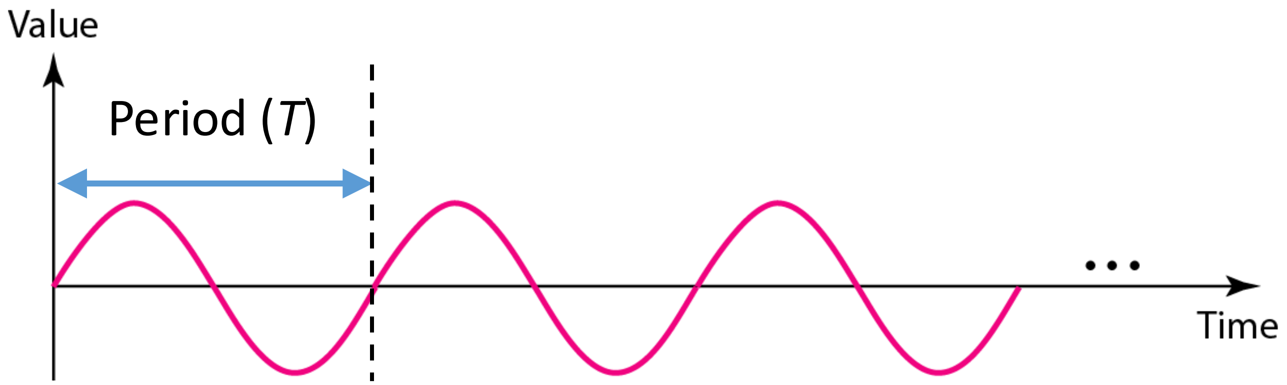


In data communications, we commonly use **periodic analog signals** and **nonperiodic digital signals**.

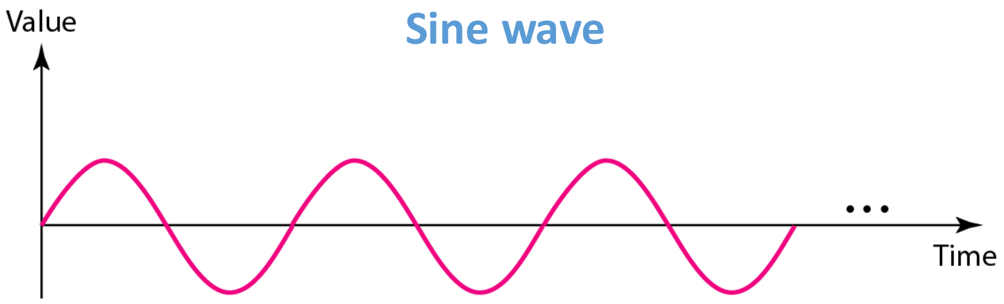
Periodic Analog Signals

Simple

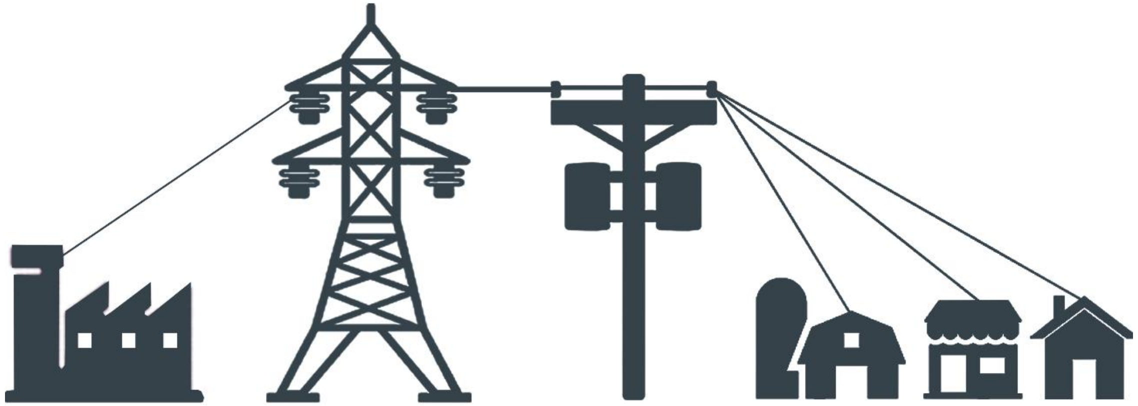
- Cannot be decomposed into simpler signals.

Composite

- Is composed of multiple sine waves.



Sine Wave – Real-life Applications



Power Distribution

The sine wave is carrying energy.

The sine wave is a signal of danger.

Burglar Alarm

Sine Wave

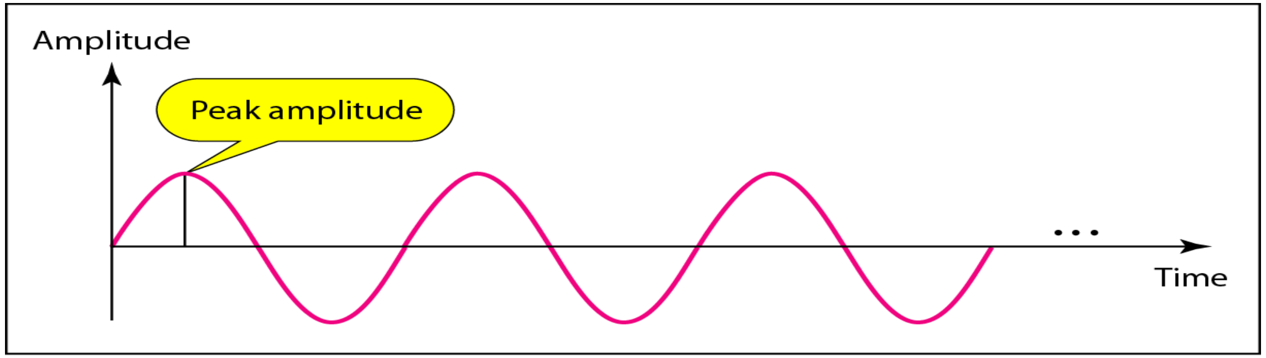
- The sine wave is the most fundamental form of a periodic analog signal.
- **Three** parameters that represent the sine wave:
  1. **Peak amplitude** (A): value of its highest intensity
  2. **Frequency** (f): # of completed cycles (periods) in 1s.
  3. **Phase** or **phase shift** (φ) : position of the waveform relative to time 0.
     - Phase is measured in degrees or radians (360° is 2π rad).

Example

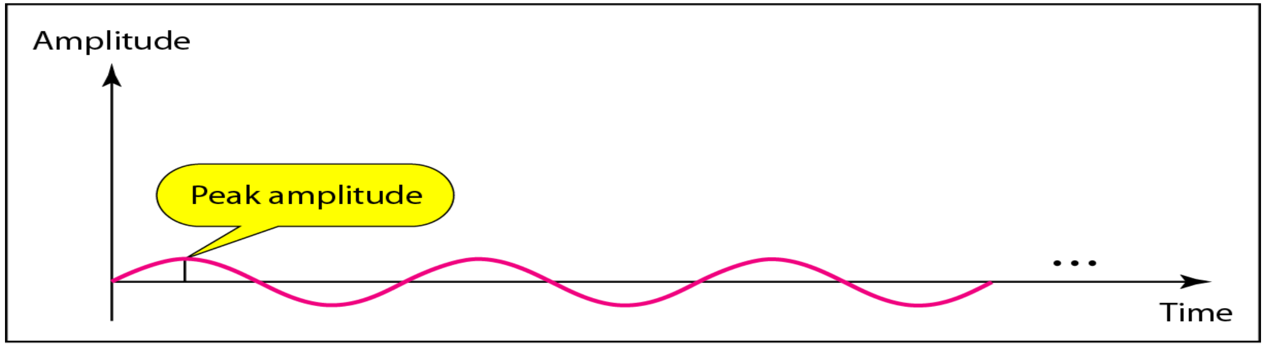
- The electrical voltage in our homes in the Canada is periodic with a peak value about $120\sqrt{2} \cong 170$ **V**. Its frequency is **60 Hz**.
- The voltage of a battery is constant (for example, **1.5 V**).
  - Periodic with a frequency of **0**.

Sine Wave – Peak Amplitude

1. **Peak amplitude**
   - The **absolute value of the signal's highest intensity**, proportional to the energy it carries.
   - Measured in **volts**.



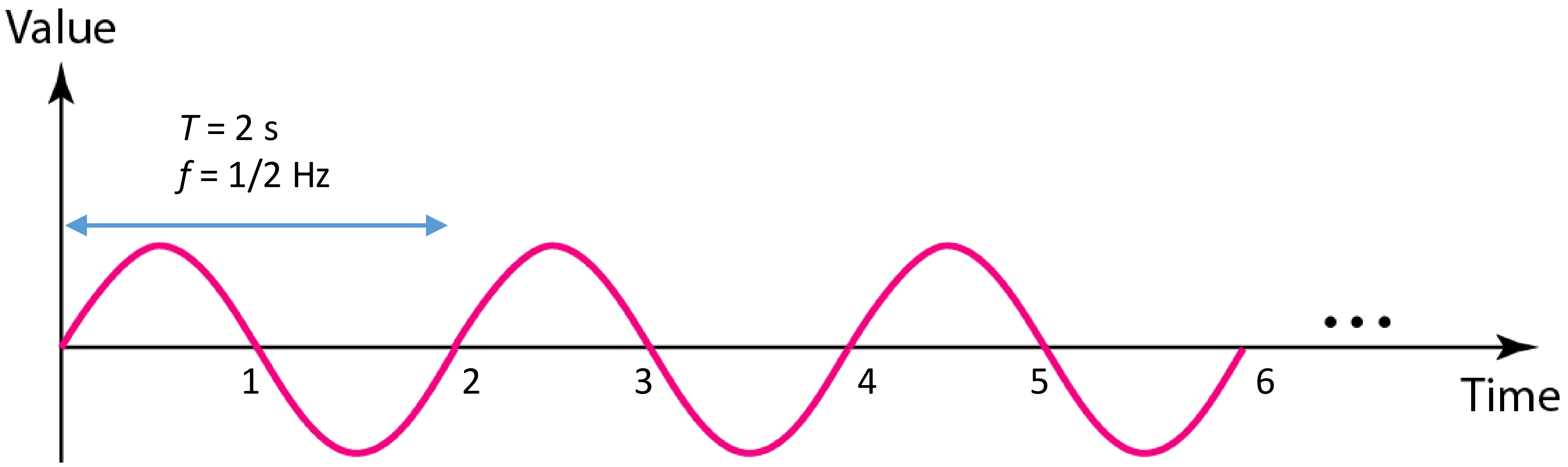
a. A signal with high peak amplitude



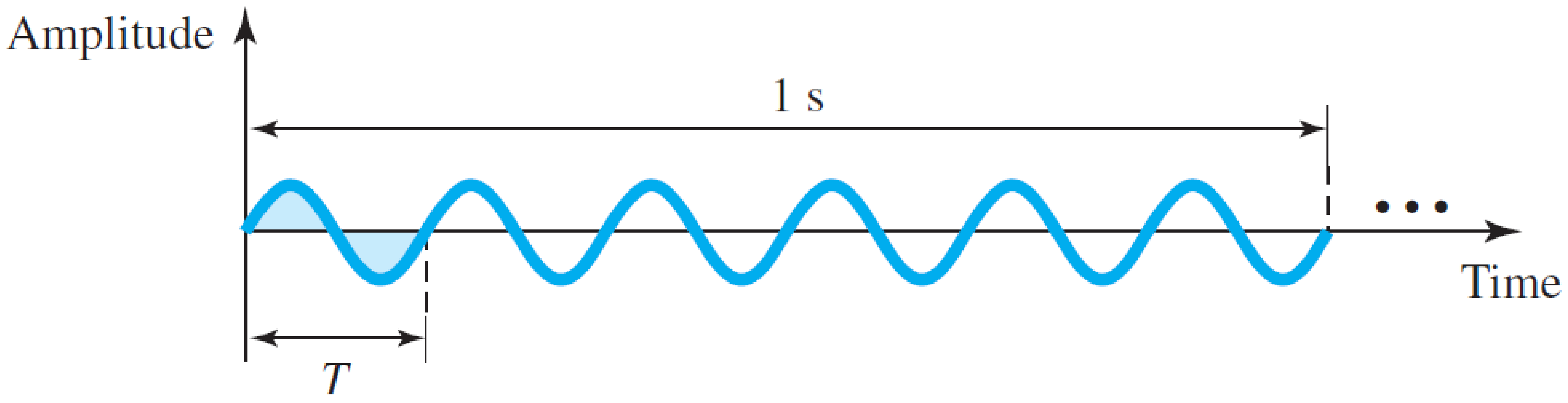
b. A signal with low peak amplitude

Sine Wave – Frequency

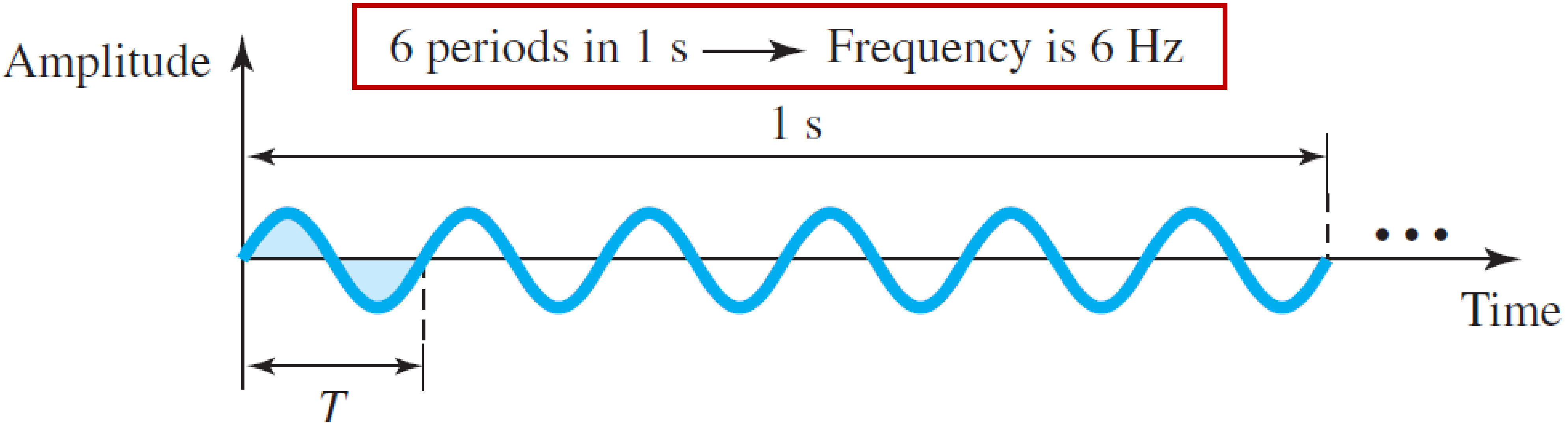
2. **Frequency** (*f*)
   - The number of cycles in 1 second (the rate at which the signal repeats).
   - Measured in **Hertz** (Hz) = **cycles per second**



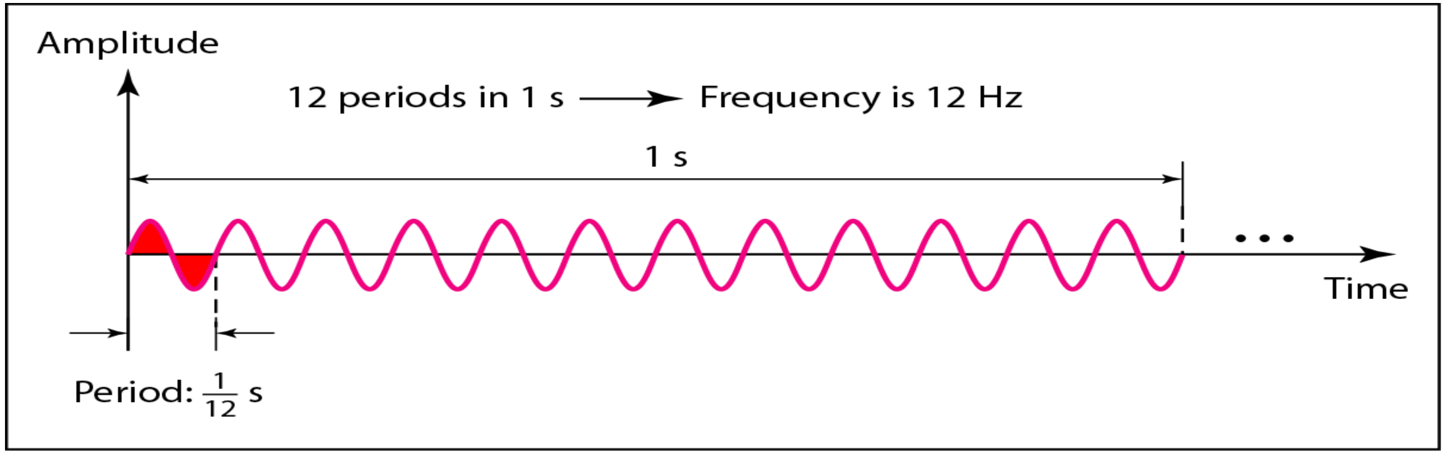
Sine Wave – Frequency (Cont.)



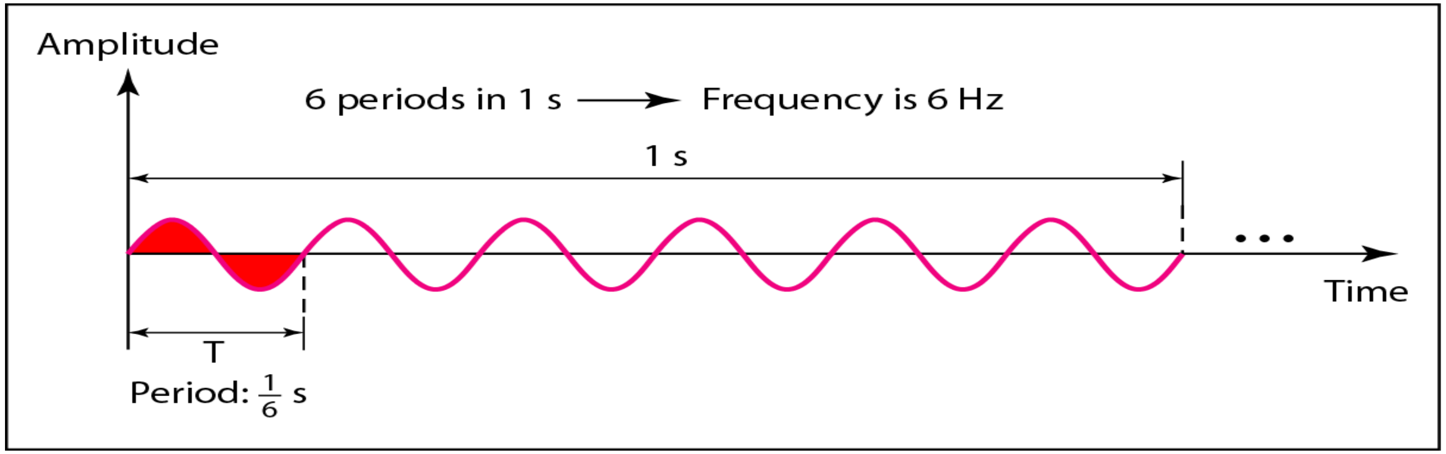
Sine Wave – Frequency (Cont.)



Two signals with the same amplitude and phase, but different frequencies



a. A signal with a frequency of 12 Hz



b. A signal with a frequency of 6 Hz

Sine Wave – Frequency vs. Period

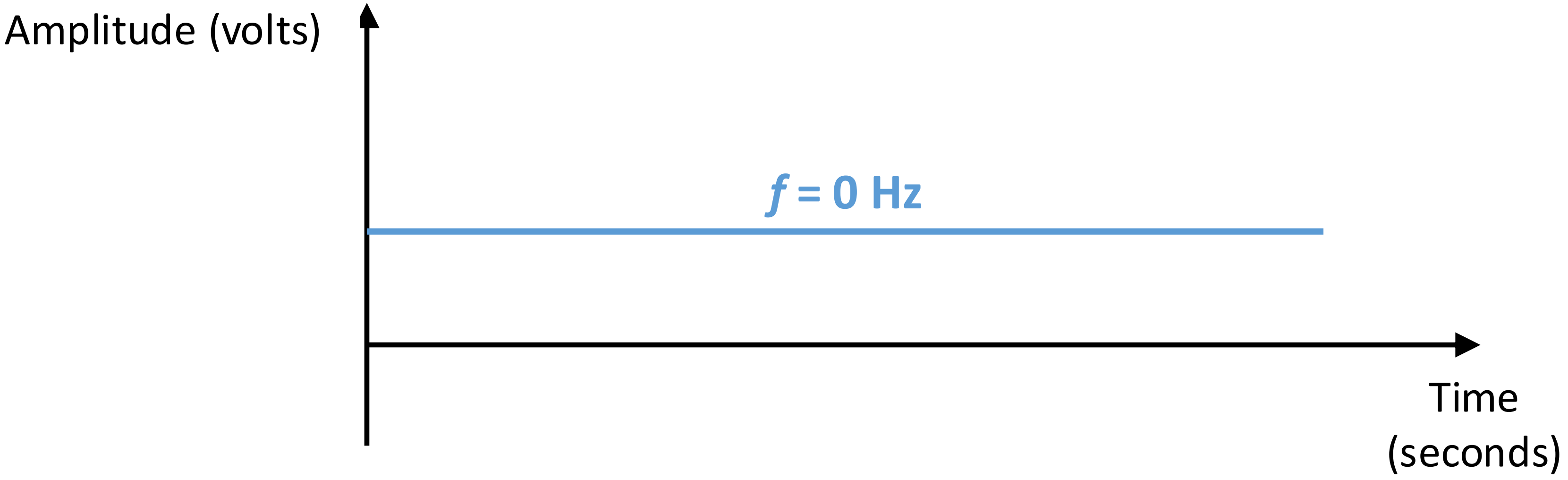
- **Period** and **Frequency** are just one characteristic described in two ways. Period is the inverse of frequency, and frequency is the inverse of period:

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

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

More about 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** (T = 0 s).



Units of Period and Frequency

Period		Frequency	
Unit	**Equivalent**	**Unit**	**Equivalent**
Second (s)	1 s	Hertz (Hz)	1 Hz
Millisecond (ms)	10^{-3} s	Kilohertz (kHz)	10^{3} Hz
Microsecond (μs)	10^{-6} s	Megahertz (MHz)	10^{6} Hz
Nanosecond (ns)	10^{-9} s	Gigahertz (GHz)	10^{9} Hz
Picosecond (ps)	10^{-12} s	Terahertz (THz)	10^{12} Hz

Sine Wave – Frequency – Example 1

- The power we use at home has a frequency of 60 Hz. Find the period of this sine wave in milliseconds (ms)?

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- **Answer**:

$$T = \frac{1}{f} = \frac{1}{60\ Hz} = 0.0167\ \text{s} = \mathbf{16.7\ ms}$$

Sine Wave – Frequency – Example 2

- What is the frequency (in kHz) of a sine wave if the period is 200 μs?

Sine Wave – Frequency – Example 2

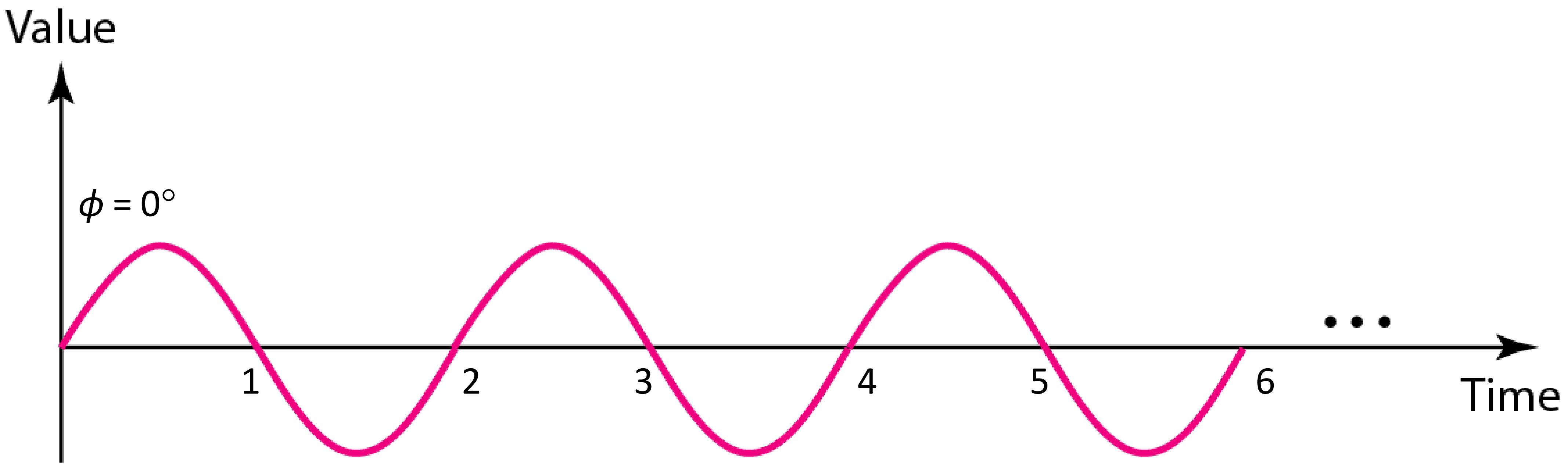
- What is the frequency (in kHz) of a sine wave if the period is 200 μs?

- **Answer**:

$$f = \frac{1}{T} = \frac{1}{200\text{x}10{-}6\text{s}} = 5000 \text{ Hz} = \mathbf{5 \text{ kHz}}$$

Sine Wave – Frequency

3. **Phase** or **Phase shift** (ϕ)
   - The position of the waveform relative to time 0 (indicates the status of the first cycle).
   - Measured in **degrees** or **radians**.



Sine Wave – Mathematical Representation

- We can mathematically describe a sine wave as follows.

$$s(t) = A\sin(2\pi f t) = A\sin\left(\frac{2\pi}{T}t\right)$$

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Instantaneous amplitude **Peak amplitude** **Frequency** **Period**

Mathematical Representation – Example

- Find the peak amplitude, frequency, and period of the following sine waves.
  a. $s(t) = 5\sin(20\pi t)$
  b. $s(t) = \sin(10t)$

Mathematical Representation – Example

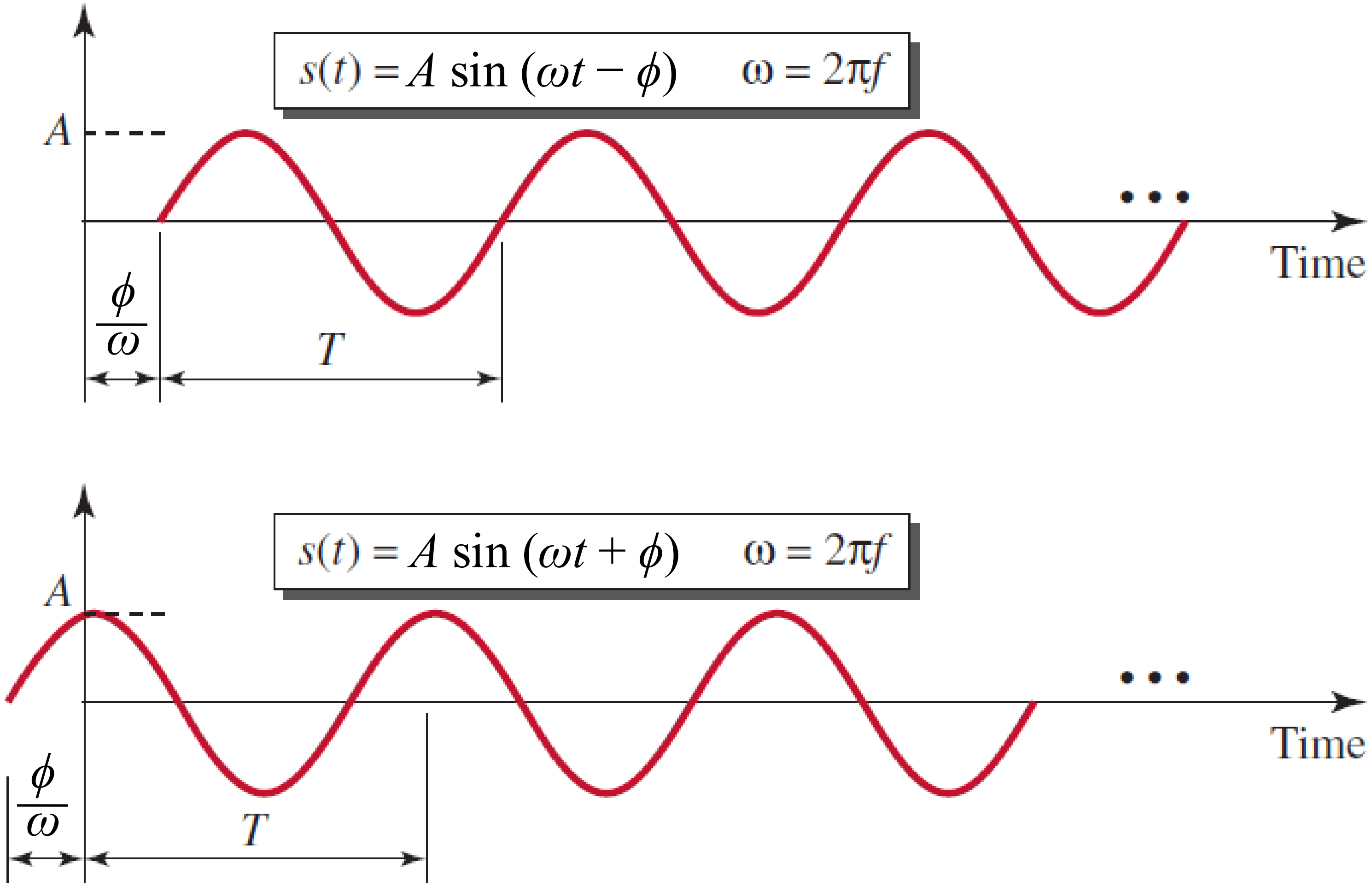
- Find the peak amplitude, frequency, and period of the following sine waves.
  a. $s(t) = 5\sin(20\pi t)$
  b. $s(t) = \sin(10t)$

- **Answers**:
  a. Peak amplitude: A = **5 V**
     Frequency: $2\pi f = 20\pi \rightarrow f$ = **10 Hz**
     Period: $T = 1/f = 1/10$ = **0.1 s**
  b. Peak amplitude: A = **1 V**
     Frequency: $2\pi f = 10 \rightarrow f = 10/(2\pi)$ = **1.59 Hz**
     Period: $T = 1/f = 1/1.59$ = **0.628 s**

Shifting

- By replacing $\boldsymbol{2\pi f}$ with $\boldsymbol{\omega}$ in the sine wave mathematical representation, we have $s(t) = A\sin(\omega t)$. In this equation, the phase (i.e., phase shift) is zero. If we add or subtract a non-zero number ϕ to/from ωt, then our phase will be non-zero.

Horizontal Shifting (Phase Shift)

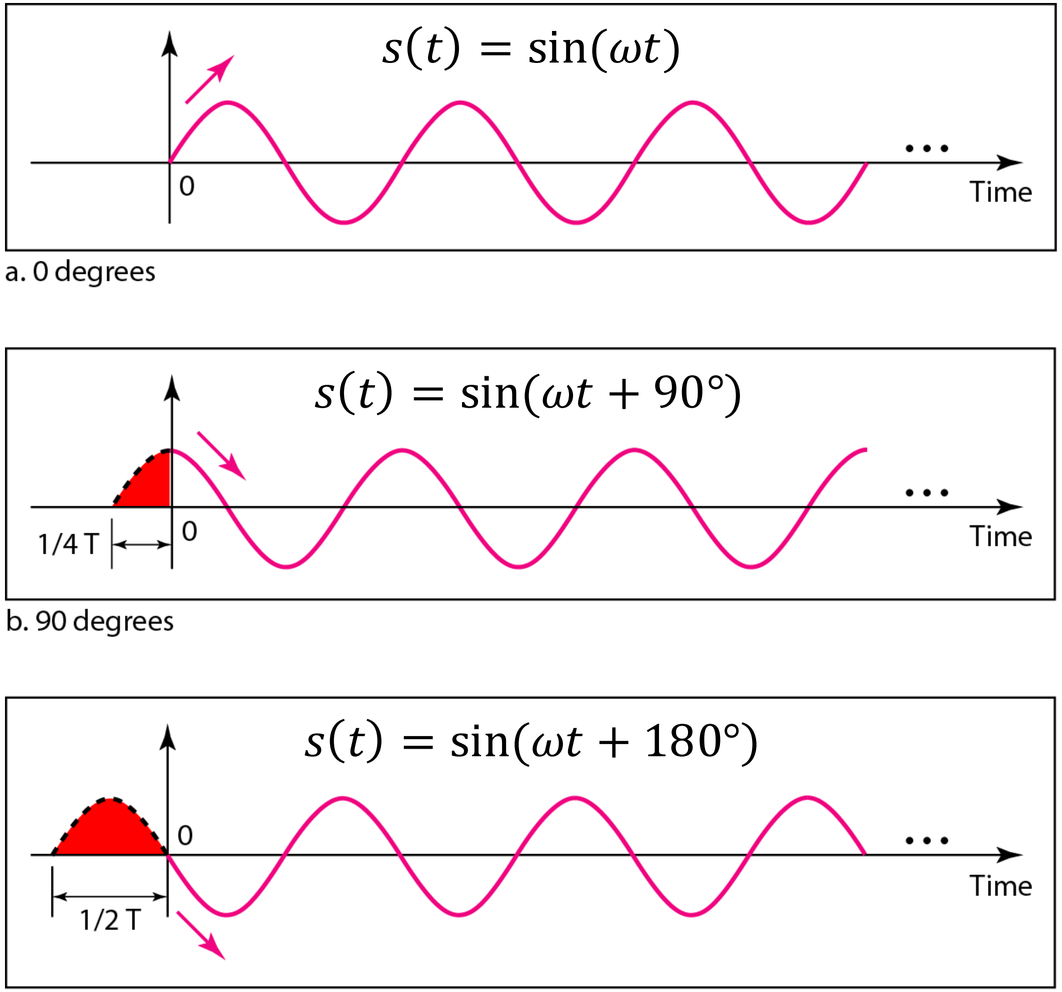


More about Phase

- 360° = 2π rad
- 1° = $(2\pi/360)$ rad
- 1 rad = $(360/(2\pi))$°
- A shift of a complete cycle is a phase shift of 360°.

Example 1

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



a. 0 degrees

b. 90 degrees

c. 180 degrees

Example 2

- A sine wave is offset 1/9 cycle with respect to time 0. What is its phase in degrees and radians?

Example 2

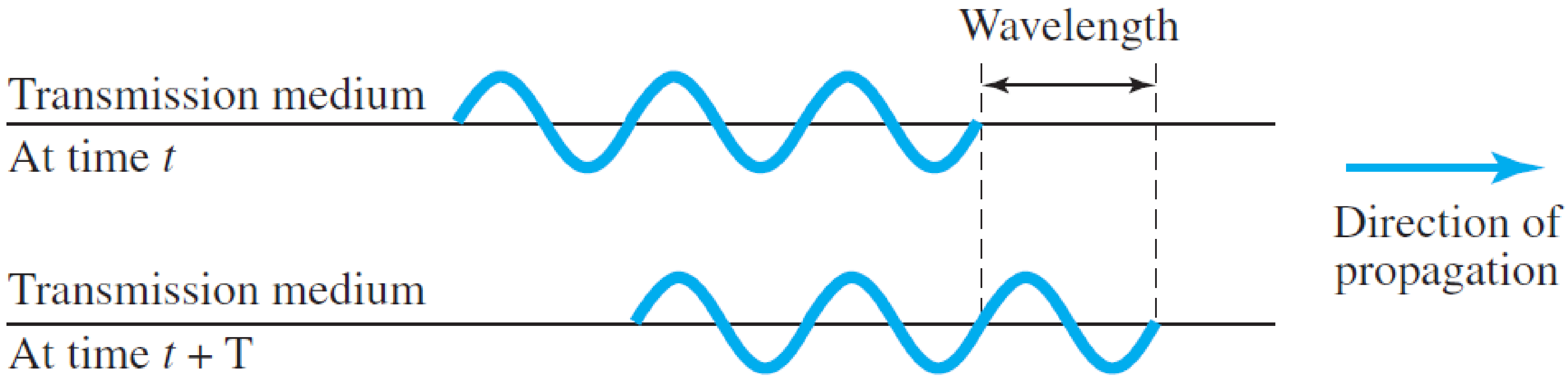
- A sine wave is offset 1/9 cycle with respect to time 0. What is its phase in degrees and radians?

- **Answer**:

$$\phi = \frac{1}{9} \times 360° = \mathbf{40°}$$
$$= 40° \times \frac{2\pi}{360°}\,\mathrm{rad} = \frac{2\pi}{9}\,\mathrm{rad} = \mathbf{0.698\ rad}$$

Wavelength

- Wavelength (λ)
  - The distance a simple signal can travel in one period.
    - (Distance that is travelled by a signal in 1 cycle.)
  - Usually used to describe the transmission of light in an optical fiber.
  - Usually measured in micrometres (µm).



Propagation Speed of a Signal

- Wavelength binds the period or the frequency of a simple sine wave to the **propagation speed** of the medium.
  - The propagation speed of electromagnetic signals depends on the medium and on the frequency of the signal.
  - For example, in a vacuum, light is propagated with a speed of $\mathbf{3 \times 10^8}$ **m/s**. That speed is lower in air and even lower in cable.

Wavelength (Cont.)

- **Frequency** vs **wavelength**
  - Frequency of a signal is **independent** of the **transmission medium**.
    - (so, what it really depends on?)
  - Wavelength relies on both **frequency** and **transmission medium**.

$$\boxed{\lambda = \frac{c}{f} = c \times T}$$

***c* is propagation speed.**

$c = 3 \times 10^8$ m/s (light)

Wavelength – Example

- What is the wavelength of red light if its frequency is 4×10^{14} Hz? Assume the propagation speed is 3×10^{8} m/s.

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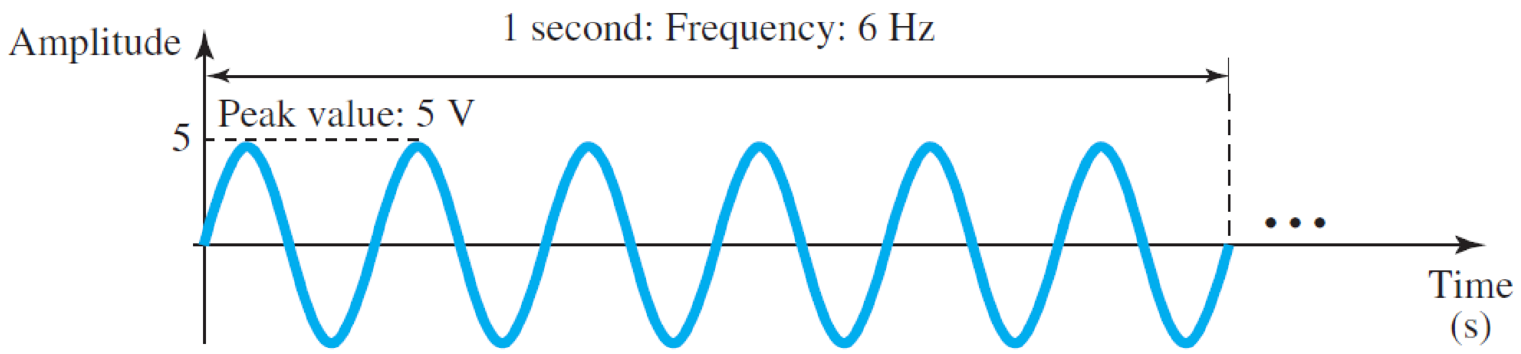
- **Answer**:

$$\lambda = \frac{c}{f} = \frac{3 \times 10^{8}}{4 \times 10^{14}} = 0.75 \times 10^{-6} = \mathbf{0.75\ \mu m}$$

Time and Frequency Domains

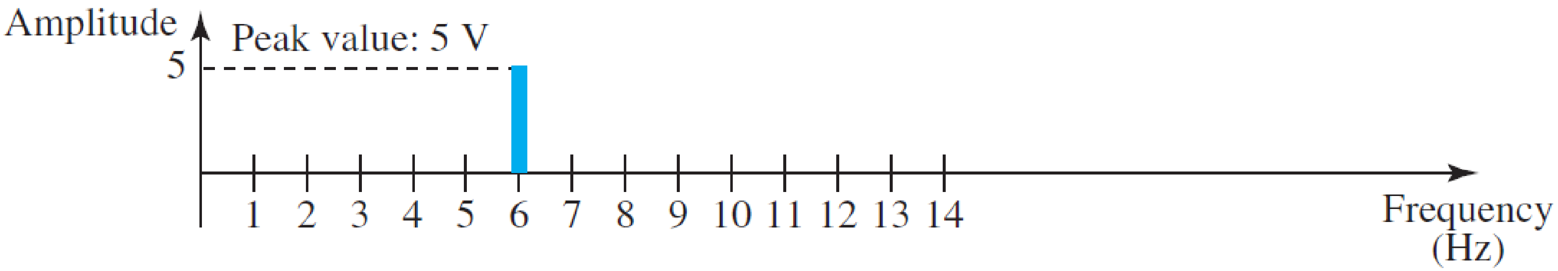
- **Time-domain** plot
  - Changes in **signal amplitude** with respect to (w.r.t.) **time**.
  - Phase is not explicitly shown.



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

Time and Frequency Domains (Cont.)

- **Frequency-domain** plot
  - Relationship between **amplitude** (**peak value**) and **frequency**.
  - **Advantage**: one can immediately see the values of the frequency and peak amplitude (a sine wave is represented by one spike).
  - More compact and helpful when dealing with **more than one sine wave**.



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

Time and Frequency Domains (Cont.)

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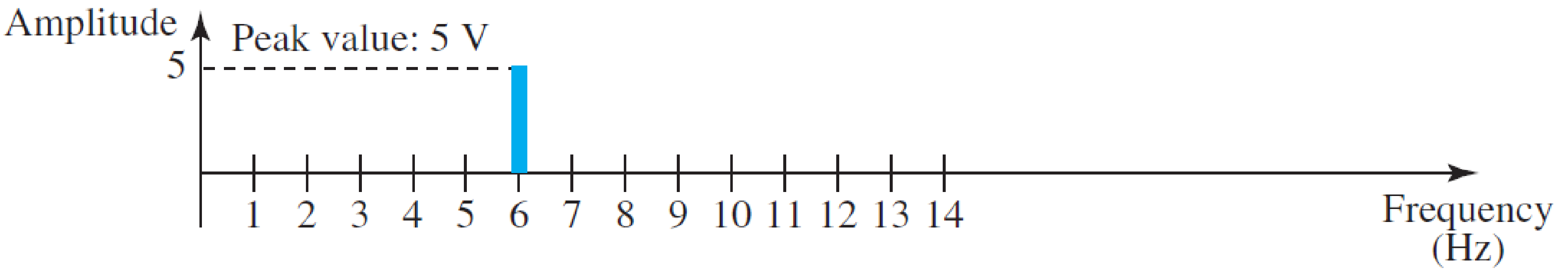
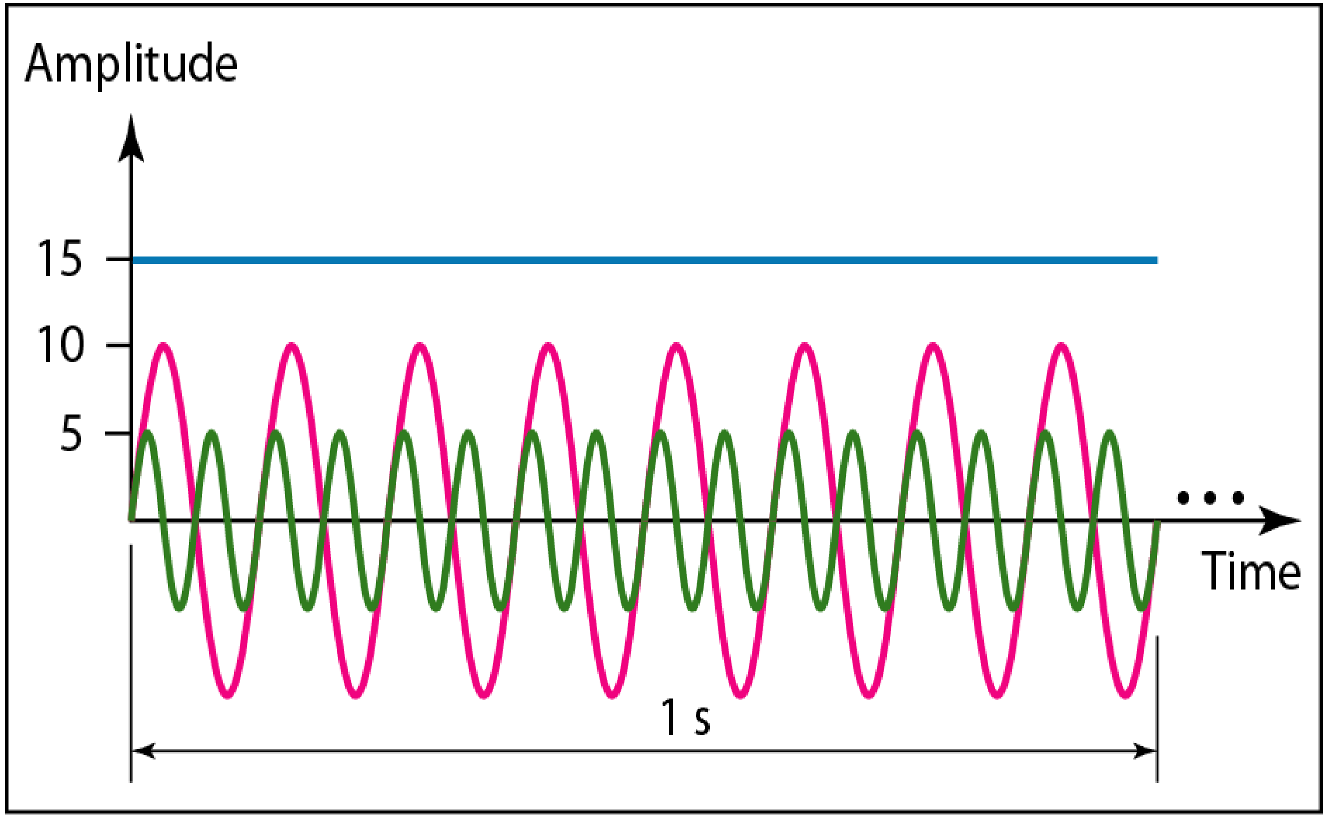


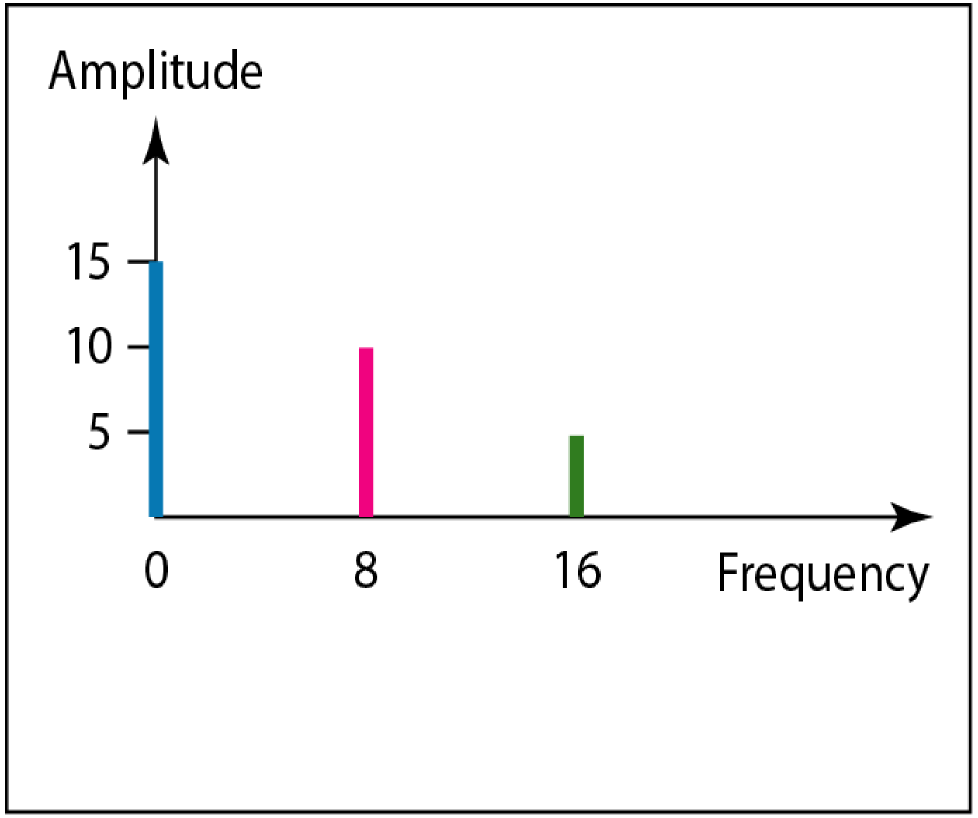
b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

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

The time domain and frequency domain of three sine waves



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



b. Frequency-domain representation of the same three signals

Composite Signals

- Simple sine waves have many applications in daily life, such as **sending energy** from one place to another (**power distribution**).
- However, if we had only one single sine wave to convey a conversation over the phone, it would make no sense and carry no information. We would just hear a **buzz.** (Why?):
  - Imagine a **pure sine wave** at a single frequency — for example, a 1 kHz tone. If you hear that on a speaker, it's just a **steady beep**!
  - It carries **no variation**, no pattern that represents actual speech or data.
- Thus:
  - We need to send a **composite signal** to communicate data.

Composite Signals

- **Composite signal**
  - A single-frequency sine wave is not useful in data communications!
  - A signal made of **many simple sine waves**.
- **Fourier analysis**
  - Any composite signal is a combination of simple sine waves with **different frequencies**, **peak amplitudes**, and **phases**.
  - Fourier analysis is a tool that changes a **time domain** signal to a **frequency domain** signal and vice versa.

Jean-Baptiste Fourier

Fourier Series

- Every composite periodic signal can be represented with a series of **sine** and **cosine** functions.
- The functions are **integral harmonics** of the fundamental frequency "f" of the composite signal.
- Using the series we can **decompose** any periodic signal into its **harmonics**.

Fourier series

$$s(t) = A_0 + \sum_{n=1}^{\infty} A_n \sin(2\pi nft) + \sum_{n=1}^{\infty} B_n \cos(2\pi nft)$$

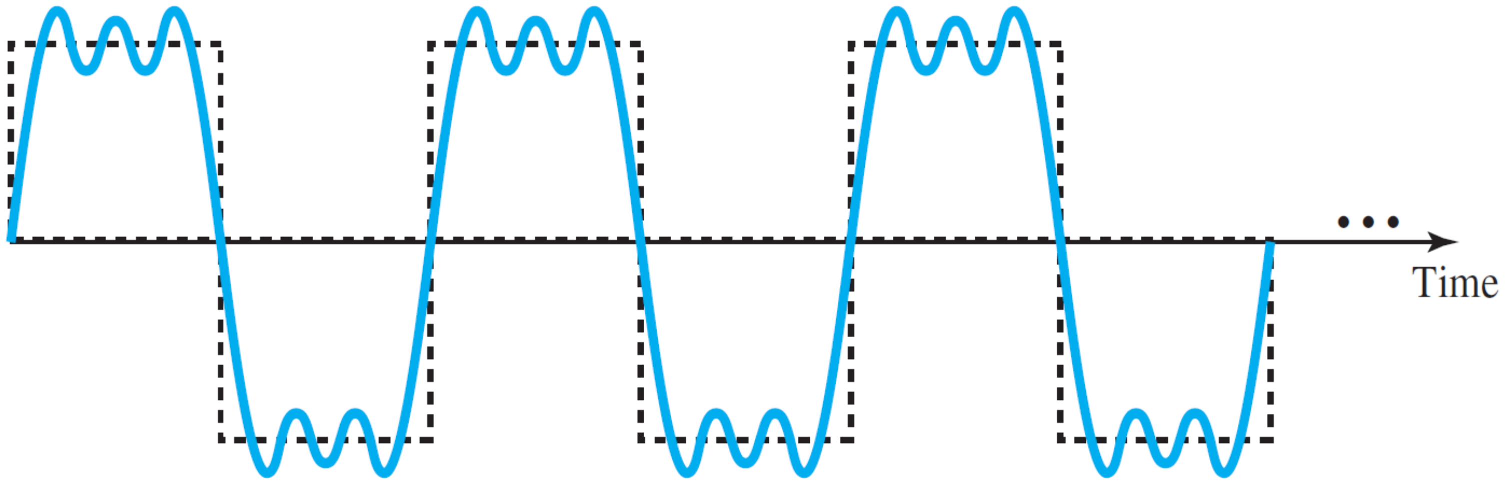
$$A_0 = \frac{1}{T}\int_0^T s(t)\,dt \qquad A_n = \frac{2}{T}\int_0^T s(t)\cos(2\pi nft)\,dt$$

$$B_n = \frac{2}{T}\int_0^T s(t)\sin(2\pi nft)\,dt$$

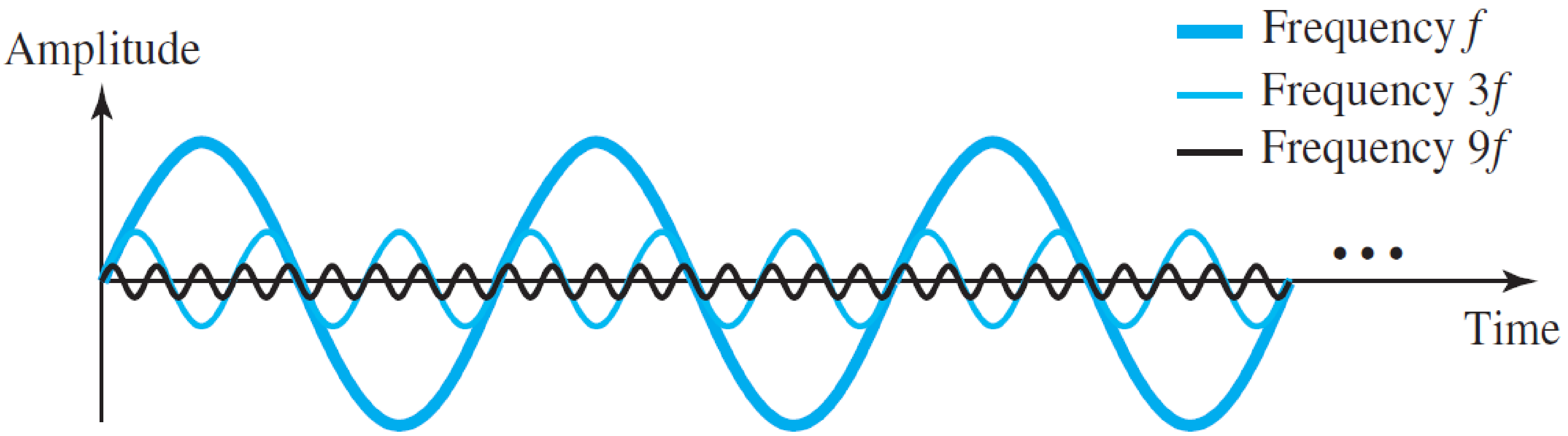
Coefficients

A Composite Periodic Signal

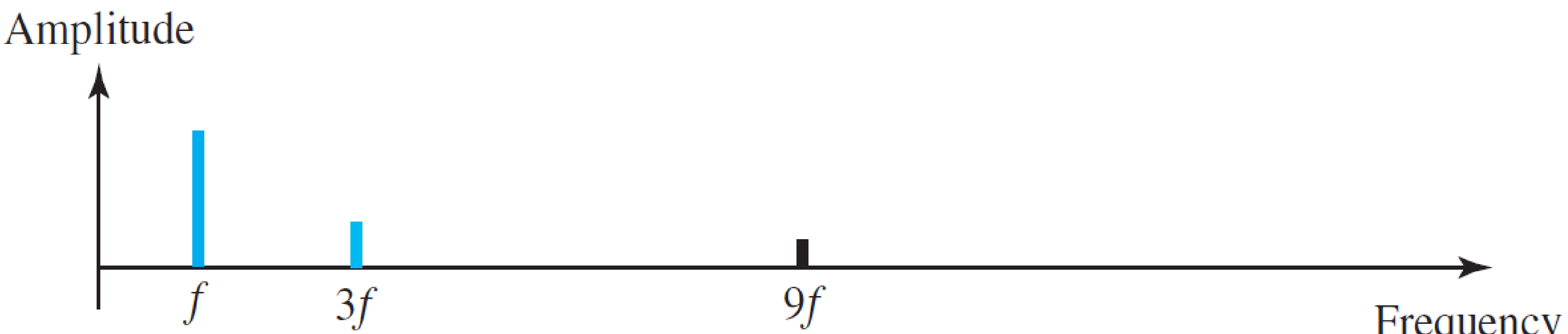
- **Composite periodic signal**
  - The decomposition gives a series of simple sine waves with **discrete frequencies** (frequencies with integer values). See next slide.



Decomposition of a Composite Periodic Signal

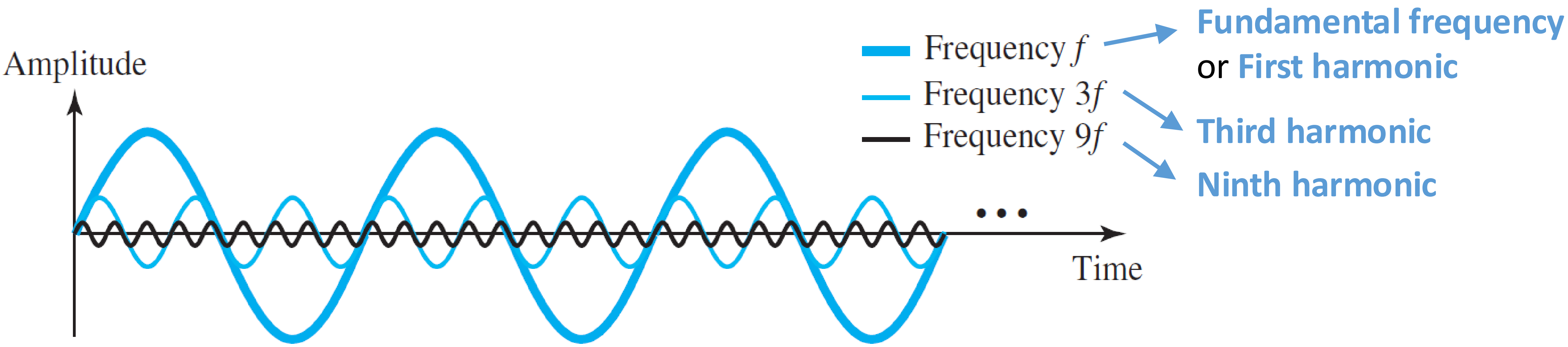


a. Time-domain decomposition of a composite signal

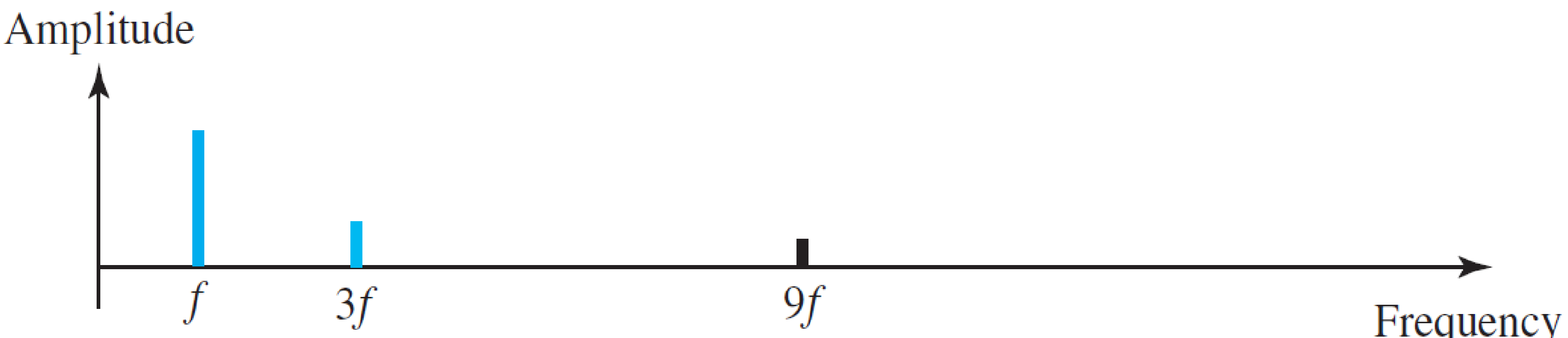


b. Frequency-domain decomposition of the composite signal

Decomposition of a Composite Periodic Signal



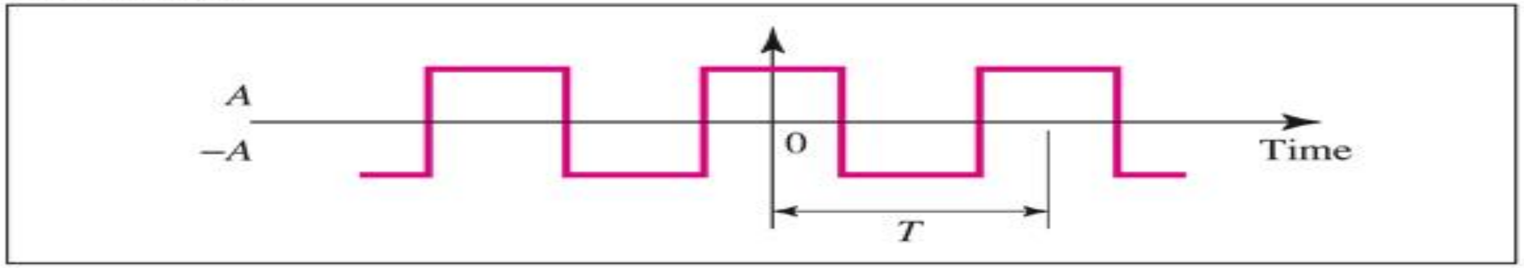
a. Time-domain decomposition of a composite signal



b. Frequency-domain decomposition of the composite signal

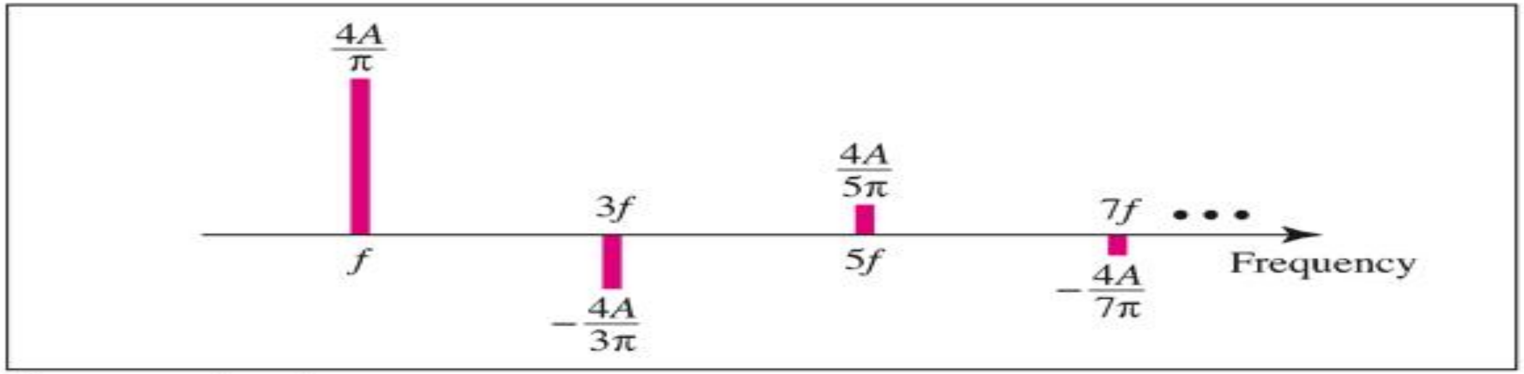
Examples of Signals and the Fourier Series Representation

Time domain



$$A_0 = 0 \qquad A_n = \begin{cases} \frac{4A}{n\pi} & \text{for } n = 1, 5, 9, \ldots \\ -\frac{4A}{n\pi} & \text{for } n = 3, 7, 11, \ldots \end{cases} \qquad B_n = 0$$

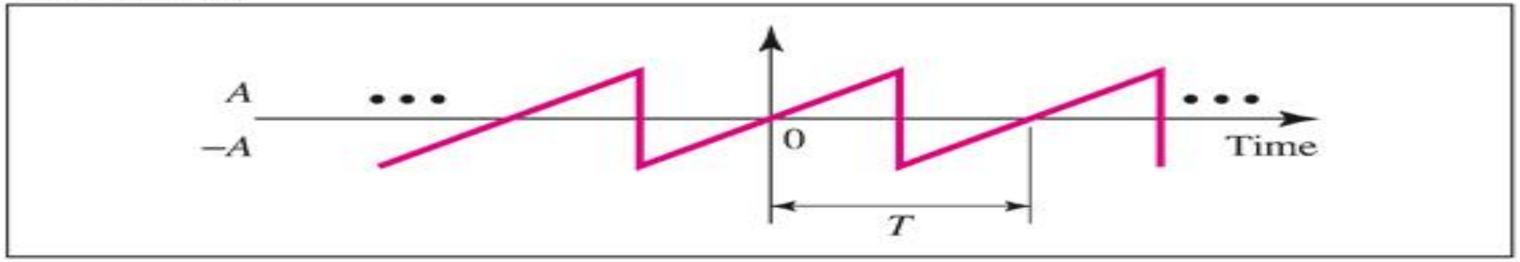
$$s(t) = \frac{4A}{\pi}\cos(2\pi ft) - \frac{4A}{3\pi}\cos(2\pi 3ft) + \frac{4A}{5\pi}\cos(2\pi 5ft) - \frac{4A}{7\pi}\cos(2\pi 7ft) + \cdots$$



Frequency domain

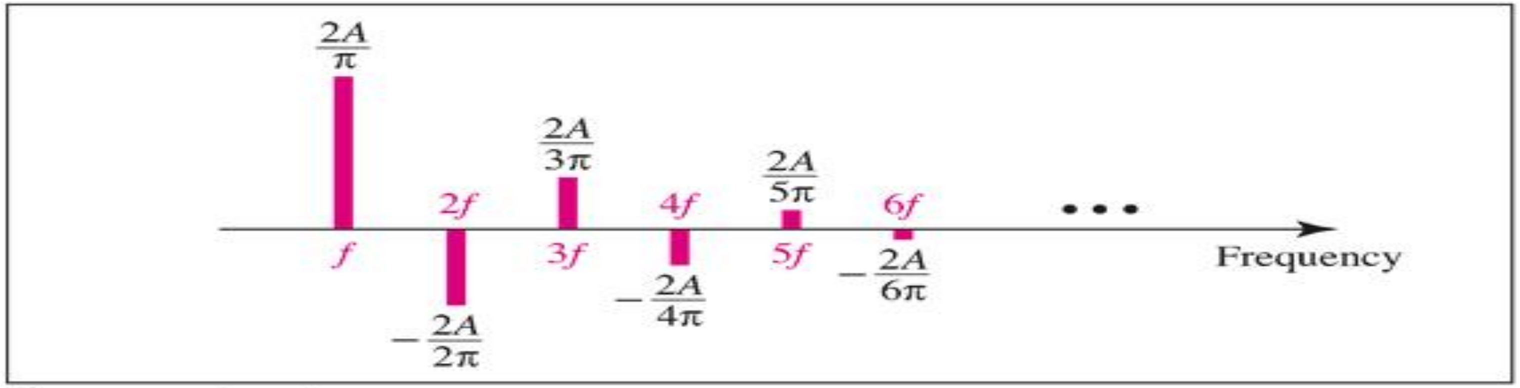
Sawtooth Signal

Time domain



$A_0 = 0 \qquad A_n = 0 \qquad B_n = \begin{cases} \dfrac{2A}{n\pi} & \text{for } n \text{ odd} \\ -\dfrac{2A}{n\pi} & \text{for } n \text{ even} \end{cases}$

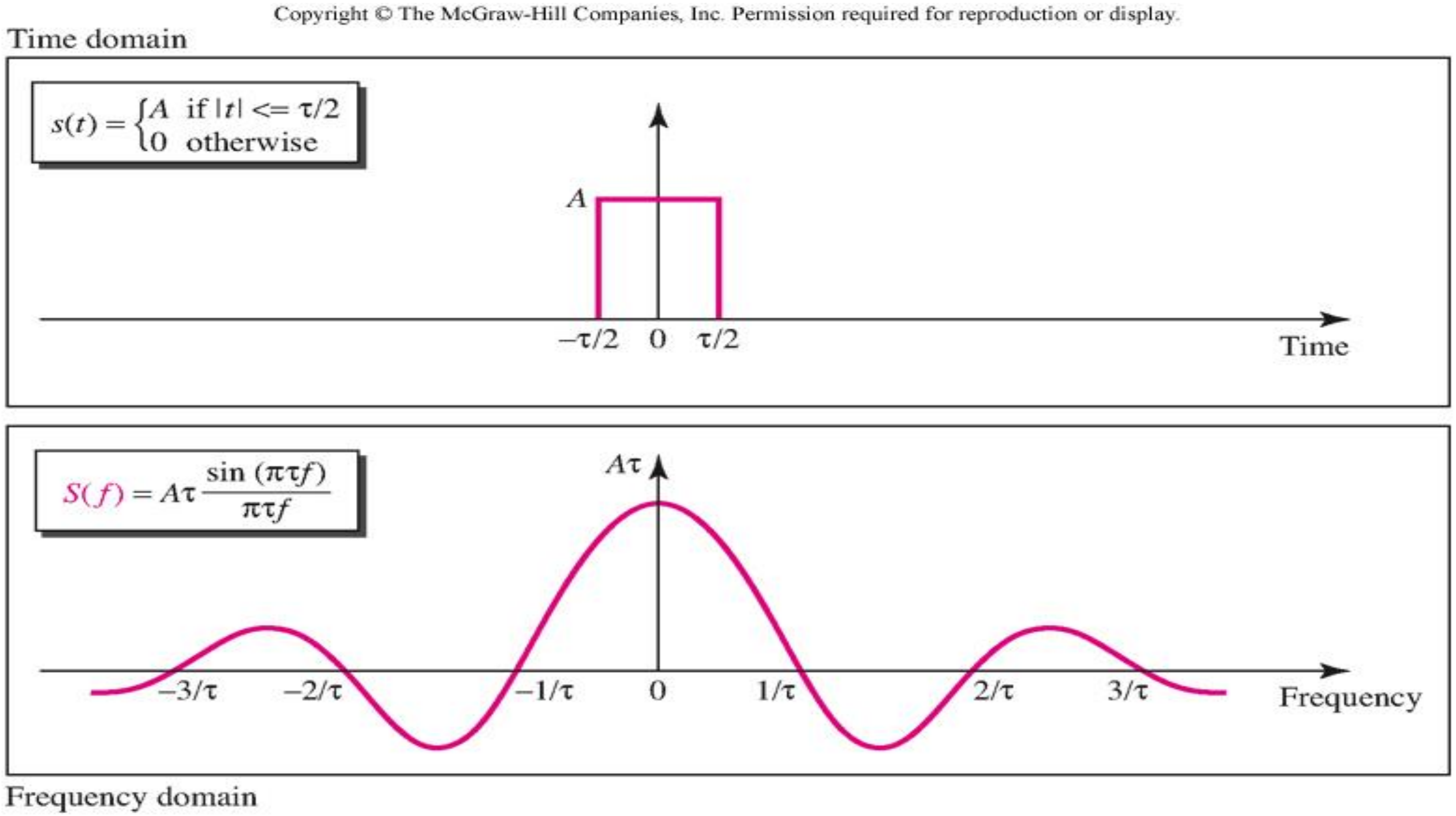
$$s(t) = \frac{2A}{\pi}\sin(2\pi ft) - \frac{2A}{2\pi}\sin(2\pi 2ft) + \frac{2A}{3\pi}\sin(2\pi 3ft) - \frac{2A}{4\pi}\sin(2\pi 4ft) + \cdots$$



Frequency domain

Fourier Transform

- Fourier Transform gives the frequency domain of a **nonperiodic** time domain signal.



Inverse Fourier Transform

$$S(f) = \int_{-\infty}^{\infty} s(t) e^{-j2\pi ft}\, dt$$

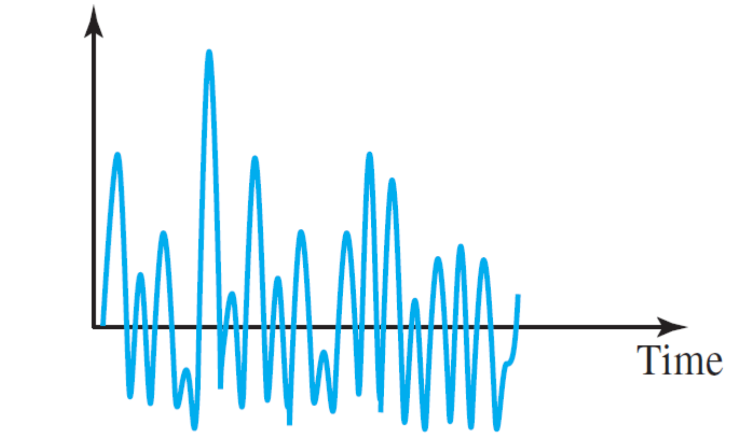
Fourier transform

$$s(t) = \int_{-\infty}^{\infty} S(f) e^{j2\pi ft}\, dt$$

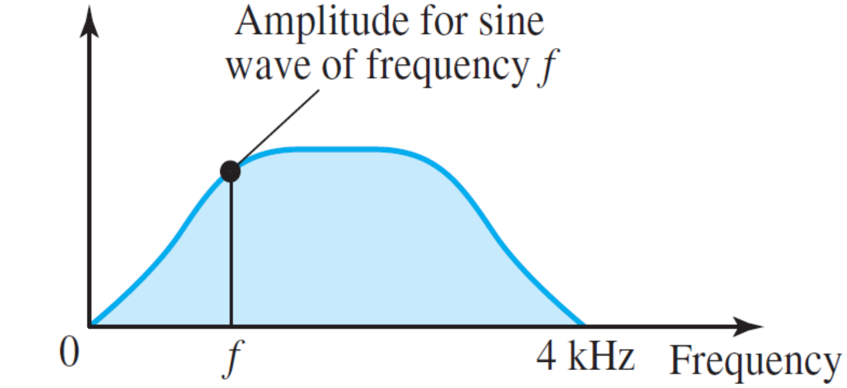
Inverse Fourier transform

A Composite Nonperiodic Signal

- **Composite nonperiodic signal**
  - The decomposition gives a combination of an **infinite number** of simple sine waves with continuous frequencies (frequencies with real values).
  - Real-life examples:
    - Human voice (continuous range of frequencies between 0 and 4 kHz).
    - The signal propagated by an AM or FM radio station.



a. Time domain



b. Frequency domain

Bandwidth of a Composite Signal

- Bandwidth (B): the **difference** between the **highest** and the **lowest frequencies** contained in a composite signal.

$$\boxed{B = f_h - f_l}$$

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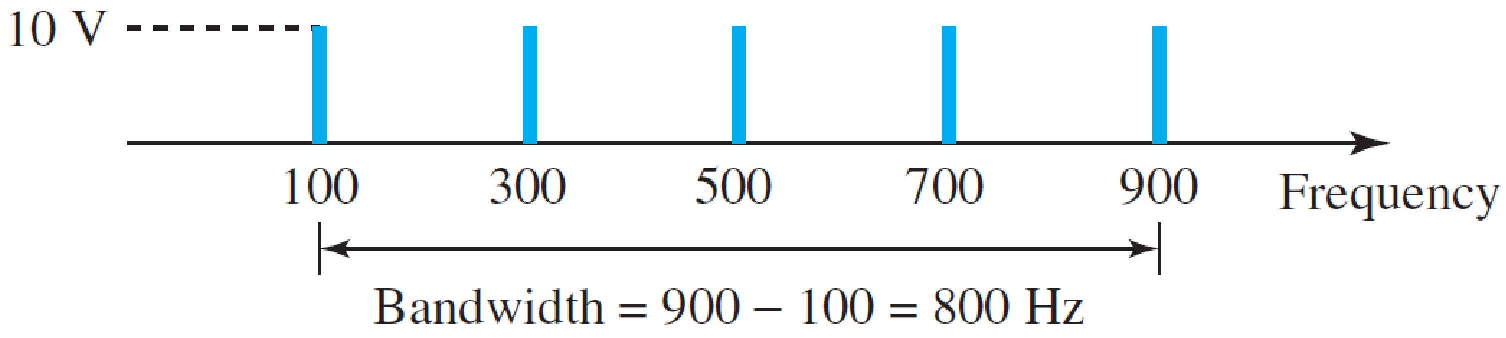
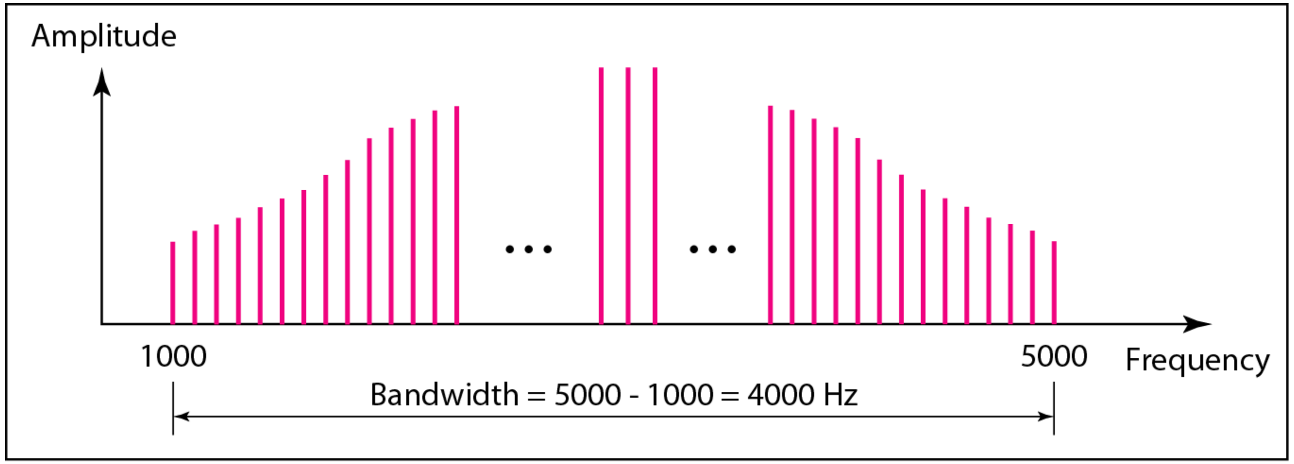
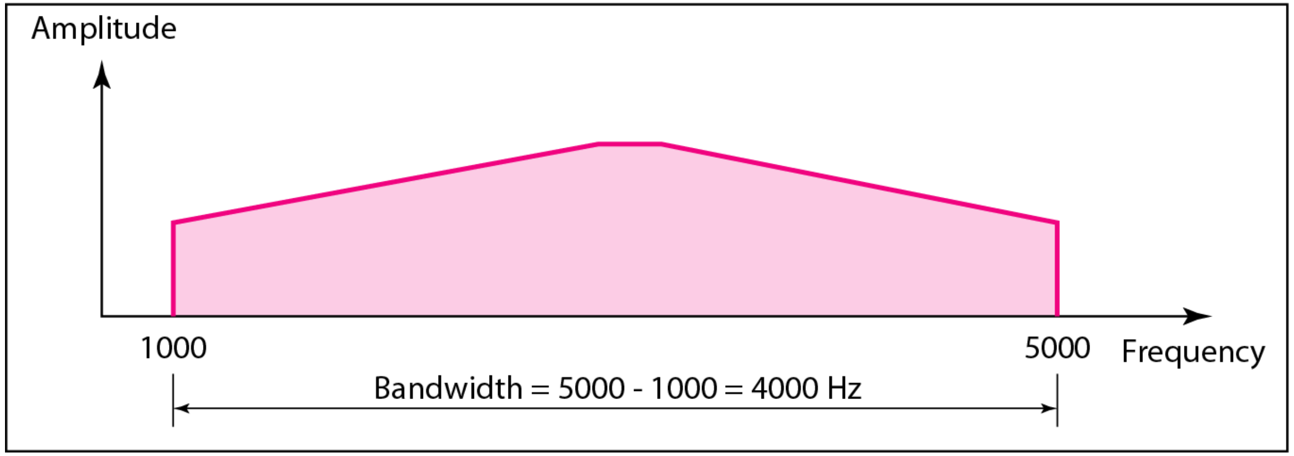


The bandwidth of periodic and nonperiodic composite signals



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

Digital Signals

- Most digital signals are **nonperiodic**.
  - **Frequency** and **period** are not suitable characteristics.
- **Bit rate** is used to describe digital signals.
  - Defined as **the number of bits sent per second**, expressed in **bits per second** (**bps**).
- **Bit length** (a similar concept to wavelength)
  - Defined as the **distance one bit occupies** on the transmission medium.
- **Bit duration**: 1/(bit rate)
  - E.g., 1/1 Mbps = 1 µs

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

Example

- What is the bit length of a signal that has a bit rate of 1 Mbps and is travelling at 2×10^8 m/s on a transmission medium.

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

Example

- What is the bit length of a signal that has a bit rate of 1 Mbps and is travelling at 2×10^8 m/s on a transmission medium.

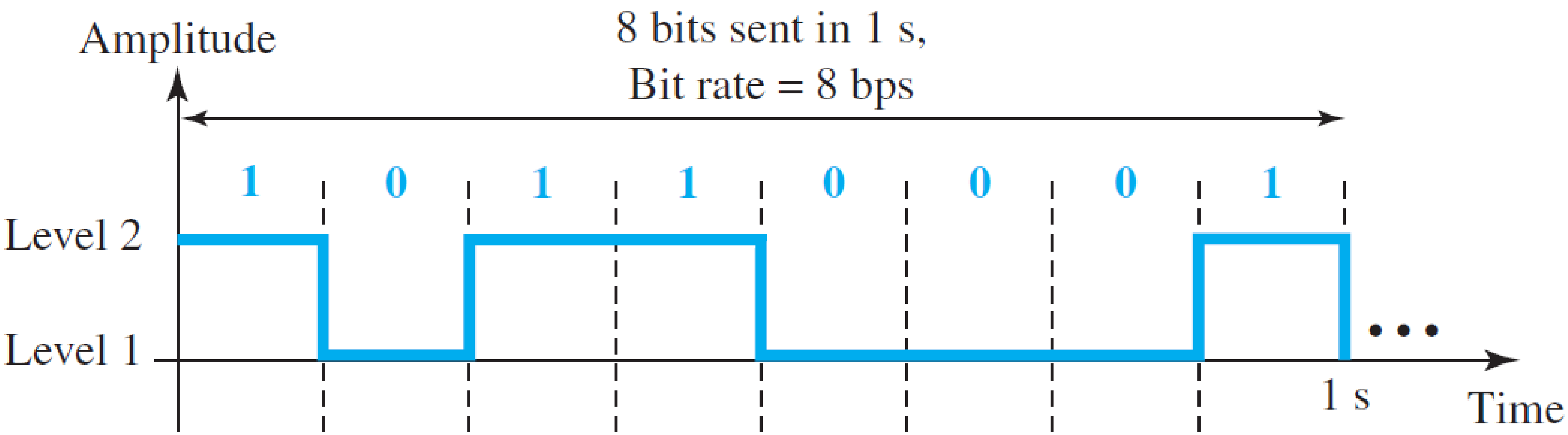
- **Answer**:
  - Bit duration = 1/(1 Mbps) = 1 μs
  - Bit length = (2×10^8 m/s) × 1 μs = **200 m**
  - This means a bit occupies 200 meters on this transmission medium.

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

Digital Signals – Level

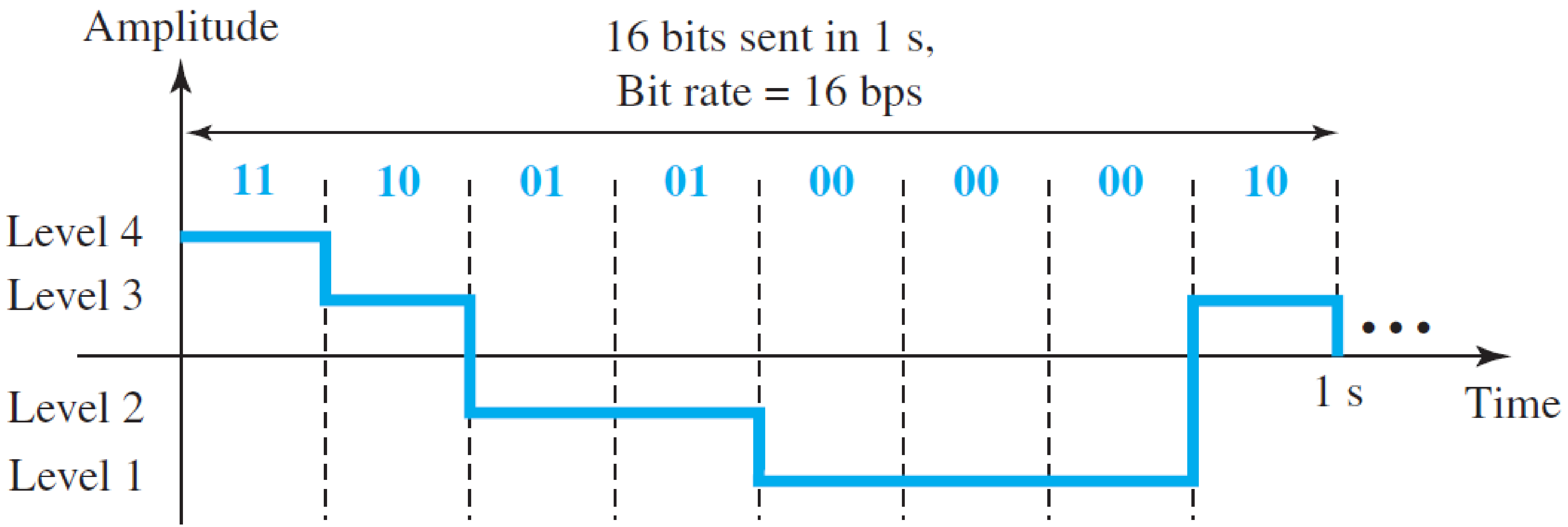
- "**Level**" refers to a specific **state** or **value** that a digital signal can have at a given point in time.
- Digital signals are characterized by having **discrete** levels or states, each of which represents a distinct value or symbol. These levels are typically associated with **voltage** or **current** levels in electronic circuits.
  - In **binary** digital systems, there are usually two signal levels: a "**low**" level (often represented as 0) and a "**high**" level (often represented as 1).
  - In more advanced digital systems, you can have even more signal levels, such as octal (eight levels) or hexadecimal (sixteen levels).

A Digital Signal with Two Levels



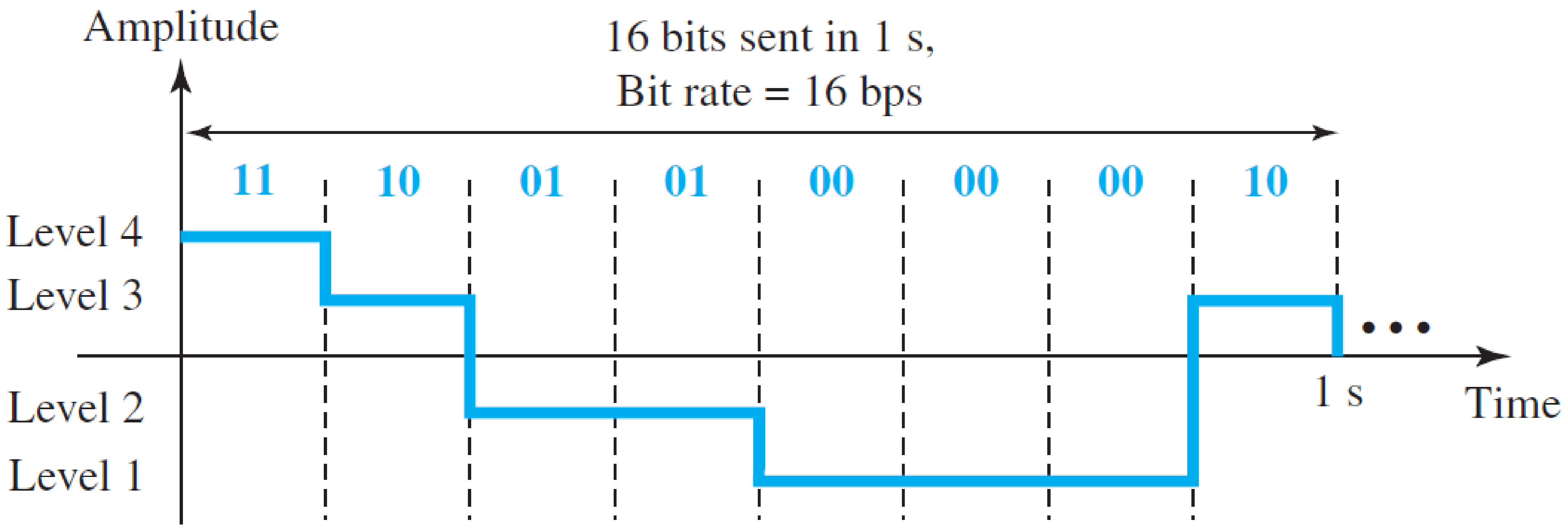
a. A digital signal with two levels

A Digital Signal with Four Levels



b. A digital signal with four levels

A Digital Signal with Four Levels



b. A digital signal with four levels

To encode 4 levels, $\log_2 4 = 2$ bits are required.

Digital Signals – Example (Signal Levels)

- A digital signal has 11 levels. How many bits are needed?

Digital Signals – Example (Signal Levels)

- A digital signal has 11 levels. How many bits are needed?

- **Answer**:
  - $\log_2 11$ = **3.46 bits**
  - However, this answer is not realistic.
  - The number of bits needed has to be an integer and usually as a power of 2. For this example, **4 bits** should be used in this case.

Digital Signals

- For a signal with L levels, **number of bits needed** = $\lceil \boldsymbol{log_2 L} \rceil$
- **Ceiling** function ($\lceil x \rceil$): rounds the number up to the nearest integer greater than or equal to the original value.
  - E.g., ceiling of π: $\lceil \pi \rceil = \lceil 3.1416 \rceil = 4$
- **Floor** function ($\lfloor x \rfloor$): rounds the number down to the nearest integer less than or equal to the original value.
  - E.g., floor of π: $\lfloor \pi \rfloor = \lfloor 3.1416 \rfloor = 3$

Digital Signals – Example (Bit Rate)

- Assume we need to download text documents at the rate of 100 pages per second. What is the required bit rate of the channel? A page is an average of 24 lines with 80 characters in each line. If we assume that one character requires 8 bits, the bit rate is:

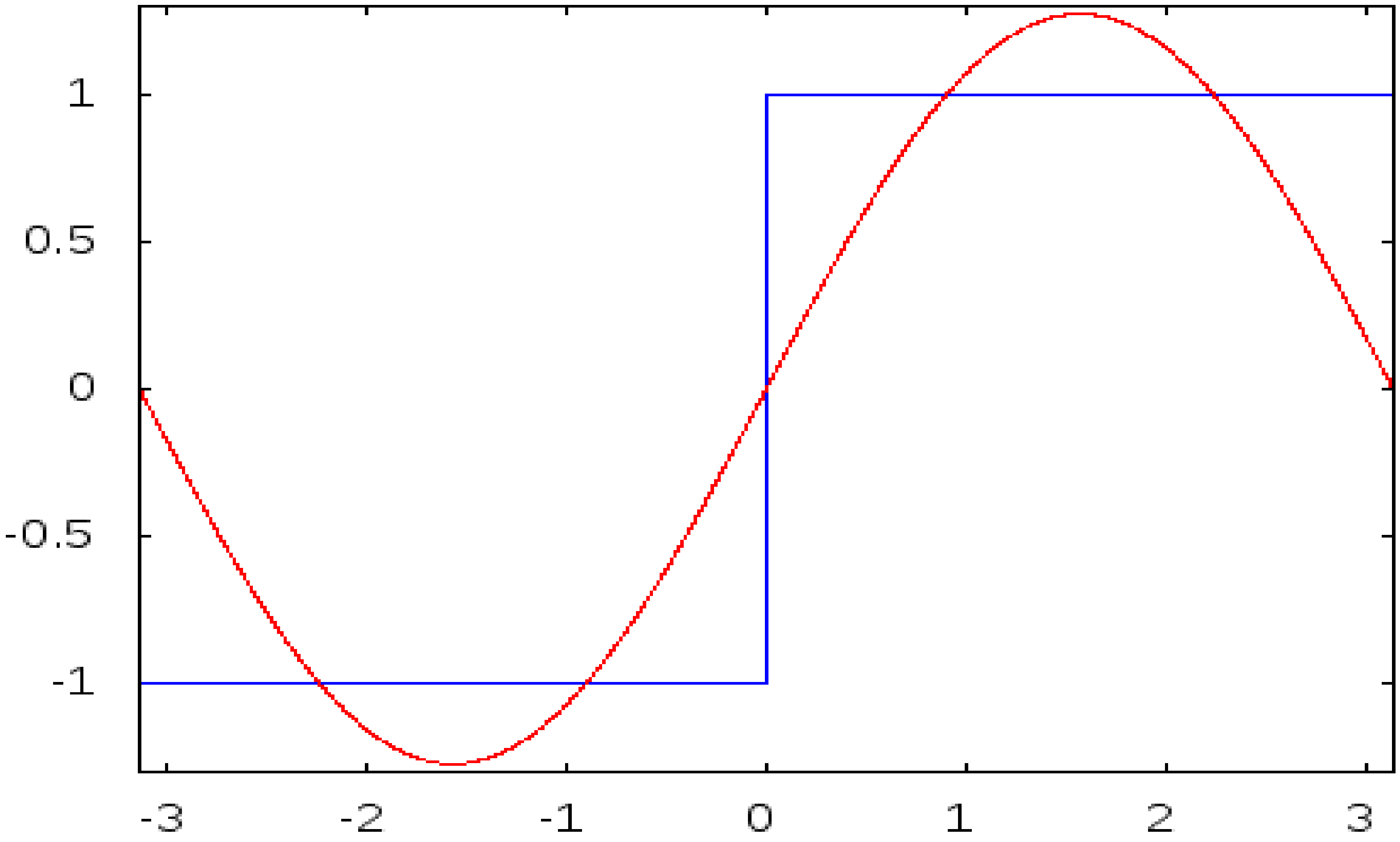
- **Answer**:

$$100 \times 24 \times 80 \times 8 = 1536000 \text{ bps} = \mathbf{1.536\ Mbps}$$

Digital Signal as a Composite Analog Signal

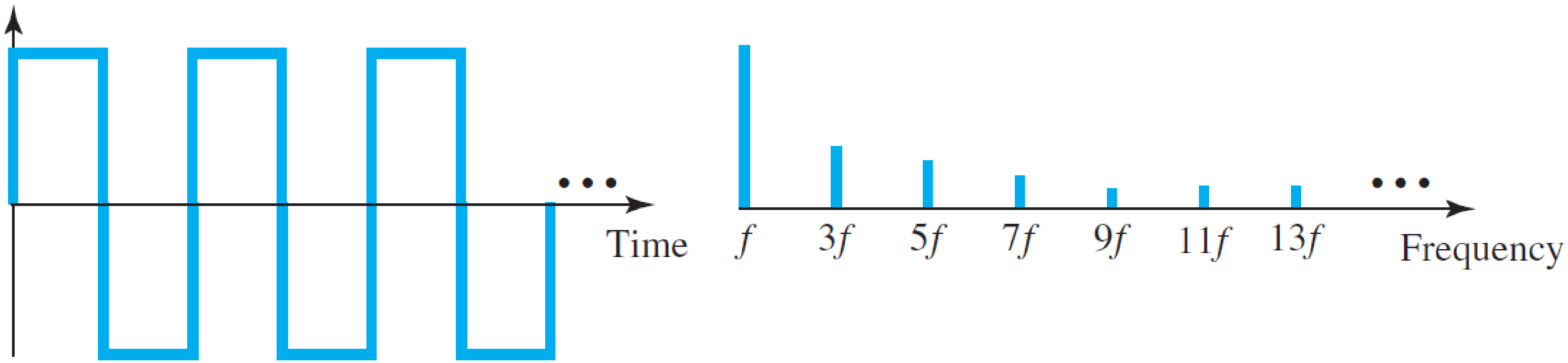
- A **periodic** or **nonperiodic** digital signal is a **composite analog signal** with frequencies between zero and infinity (**infinite bandwidth**).
- **Fourier analysis** can be used to decompose a digital signal.

Example



Periodic Digital Signal as a Composite Analog Signal

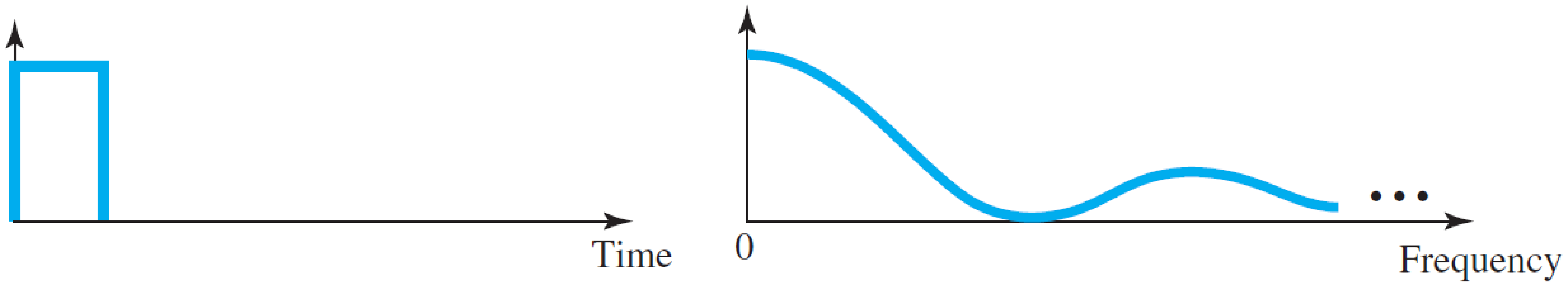
- **Periodic** digital signal (rare in data communications)
  - In **frequency** domain representation of this signal:
  - **Infinite bandwidth** and **discrete** frequencies



a. Time and frequency domains of periodic digital signal

Nonperiodic Digital Signal as a Composite Analog Signal

- **Nonperiodic** digital signal
  - In **frequency** domain representation of this signal:
  - **Infinite bandwidth** and **continuous** frequencies



b. Time and frequency domains of nonperiodic digital signal

Summary

- Transformation of data to electric signals for transmission.
- Types of data and signals as well as their characteristics.
- Analog signals and their characteristics.
- Digital signals and their characteristics.

References

[1] Behrouz A.Forouzan, Data Communications & Networking with TCP/IP Protocol Suite, 6th Ed, 2022, McGraw-Hill companies.

Reading

- Chapter 2 of the textbook, section 2.1
- Chapter 2 of the textbook, section 2.8 (Practice Test)