Chapter 3: Introduction to Physical Layer

Outline

3.1 DATA AND SIGNALS

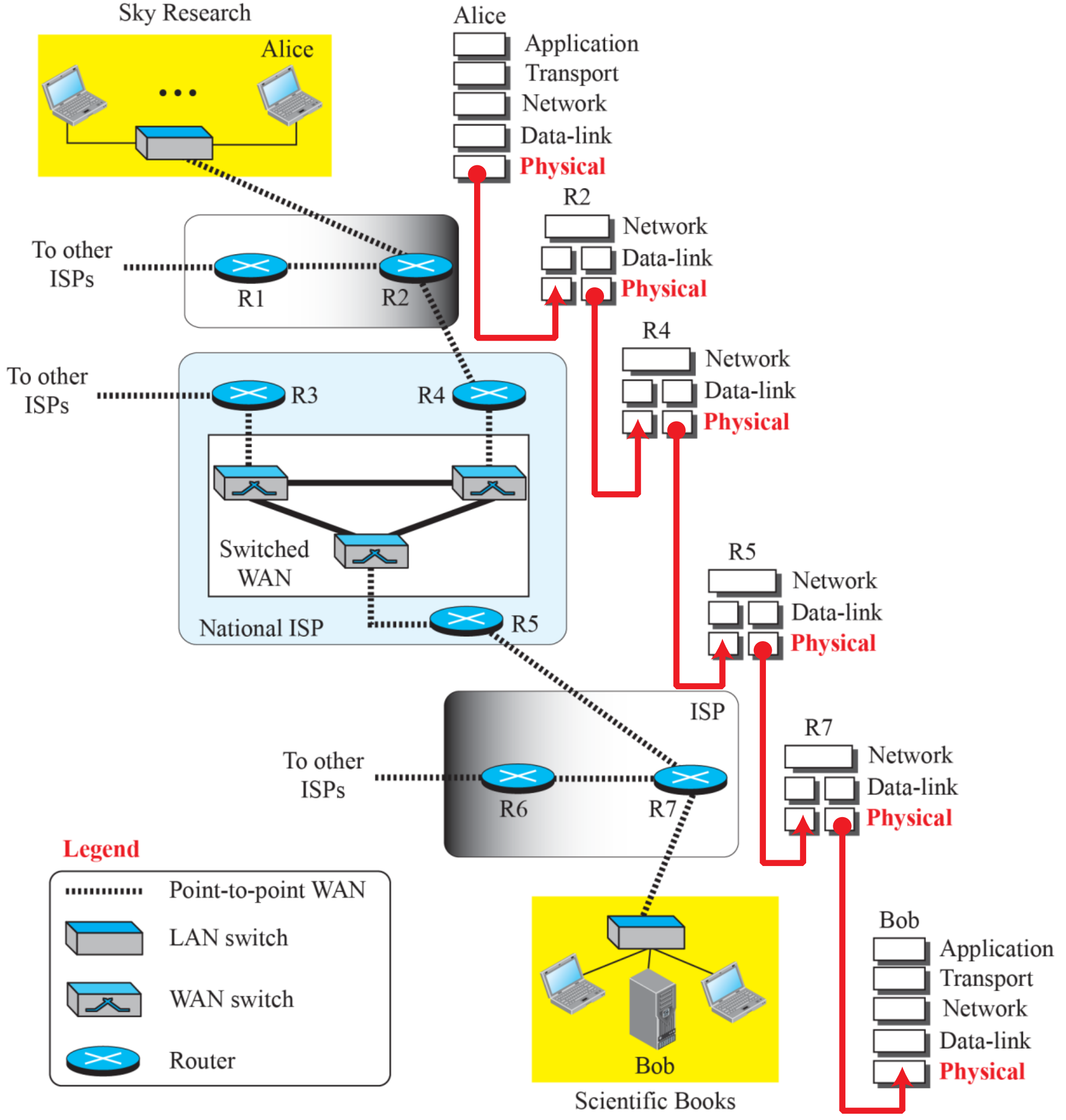
3.2 ANALOG SIGNALS

3.3 DIGITAL SIGNALS

Supplementary Material:

1. **Appendix E: "Mathematical Review" - E.1 (Trigonometric Functions), E.3 (Exponent and Logarithm)**
2. **http://www.mhhe.com/forouzan - Practice set solutions available for odd-numbered questions**
3. **"A Mathematical Theory of Communication" by Claude Shannon (1948)**

Figure 3.1: Communication at the physical layer



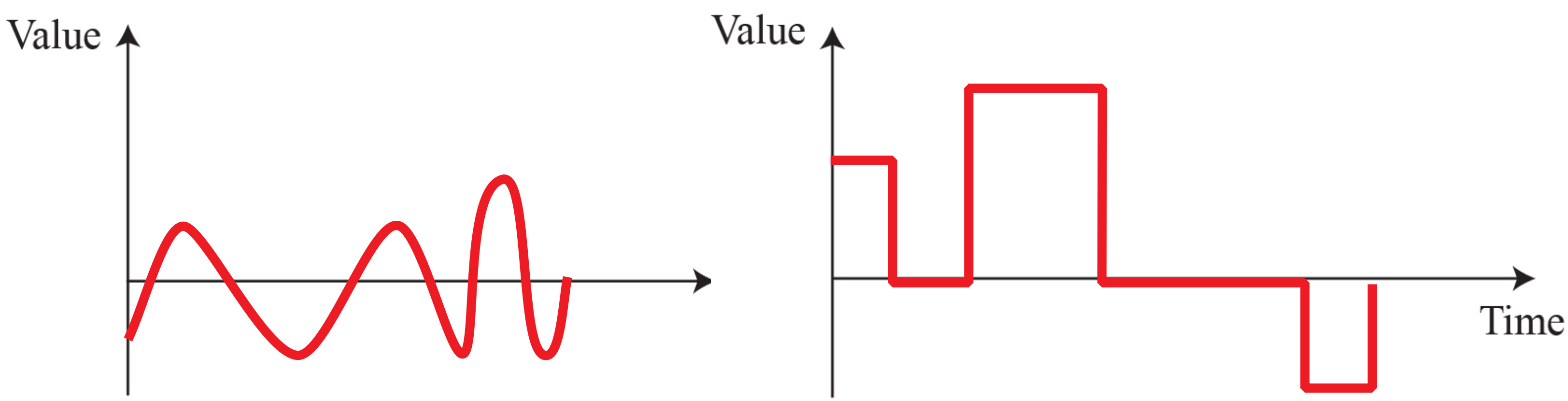
3-1 DATA AND SIGNALS

***Data** can be **analog** or **digital**. The term **analog data** refers to **information that is continuous**; **digital data** refers to **information that has discrete states**.*

For example, an analog clock that has hour, minute, and second hands gives information in a continuous form; the movements of the hands are continuous. On the other hand, a digital clock that reports the hours and the minutes will change suddenly from 10:10 to 10:11.

3.1.2 Analog and Digital Signals

Like the data they represent, <u>signals</u> can be either analog or digital. An <u>analog signal has infinitely many levels of intensity over a period of time</u>. As the wave moves from value A to value B, it passes through and includes an infinite number of values along its path. A <u>digital signal</u>, on the other hand, <u>can have only a limited number of defined values</u>. Although each value can be any number, it is often as simple as 1 and 0.



a. Analog signal b. Digital signal

3.1.3 Periodic and Nonperiodic

Signals (both analog and digital) can also be either periodic or nonperiodic:

A periodic signal completes a pattern within a measurable time frame, called a period, and repeats that pattern over subsequent identical periods. The completion of one full pattern is called a cycle.

A nonperiodic signal changes without exhibiting a pattern or cycle that repeats over time.

Period and Frequency

***Period**, **T**, in seconds, refers to the amount of time a signal needs to complete 1 cycle. **Frequency**, **f**, in Hertz (Hz), refers to the number of periods in 1 second.*

Note that period and frequency are the inverse of each other, i.e., one characteristic defined in two ways.

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

Example

The power we use at home has a frequency of 60 Hz (50 Hz in Europe). The period of this sine wave can be determined as follows:

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

This means that the period of the power for our lights at home is 0.0166 s, or 16.6 ms.

3-2 ANALOG SIGNALS

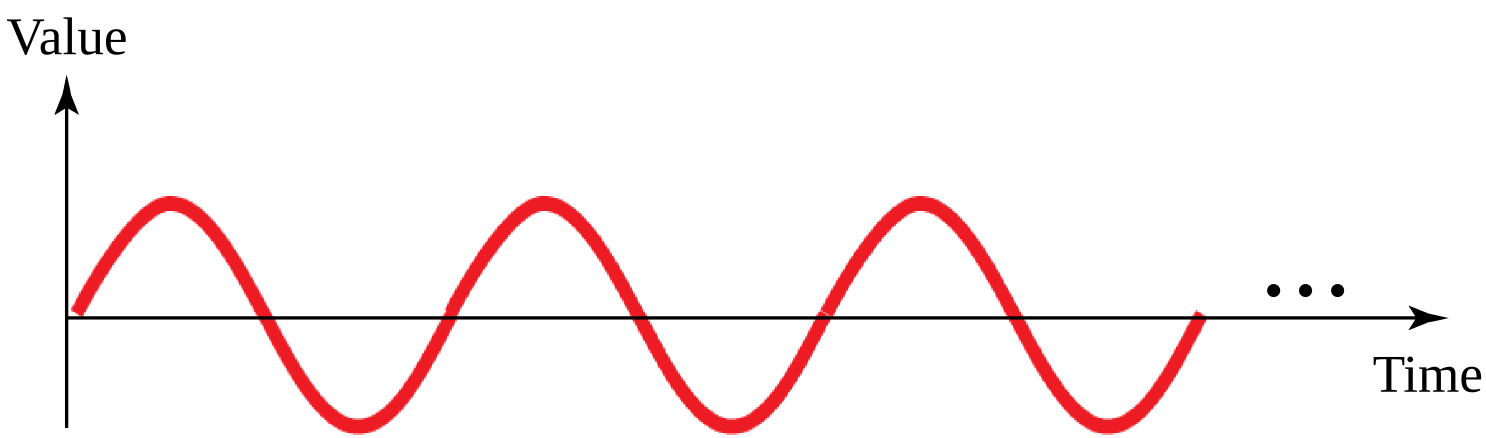
Periodic analog signals can be classified as simple or composite:

A <u>simple periodic analog signal</u>, a sine wave, <u>cannot be decomposed into simpler signals</u>.

A <u>composite periodic analog signal is composed of multiple sine waves</u>.

3.2.1 Sine Wave

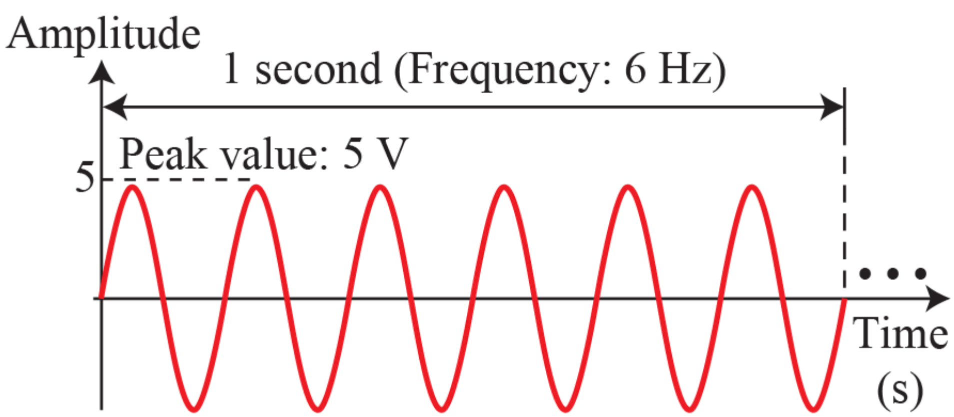
The sine wave is the most fundamental form of a periodic analog signal. It is a simple oscillating curve and its change over the course of a cycle is smooth and consistent, a continuous, rolling flow. Each cycle consists of a single arc above the time axis followed by a single arc below it.



3.2.1 Sine Wave (continued)

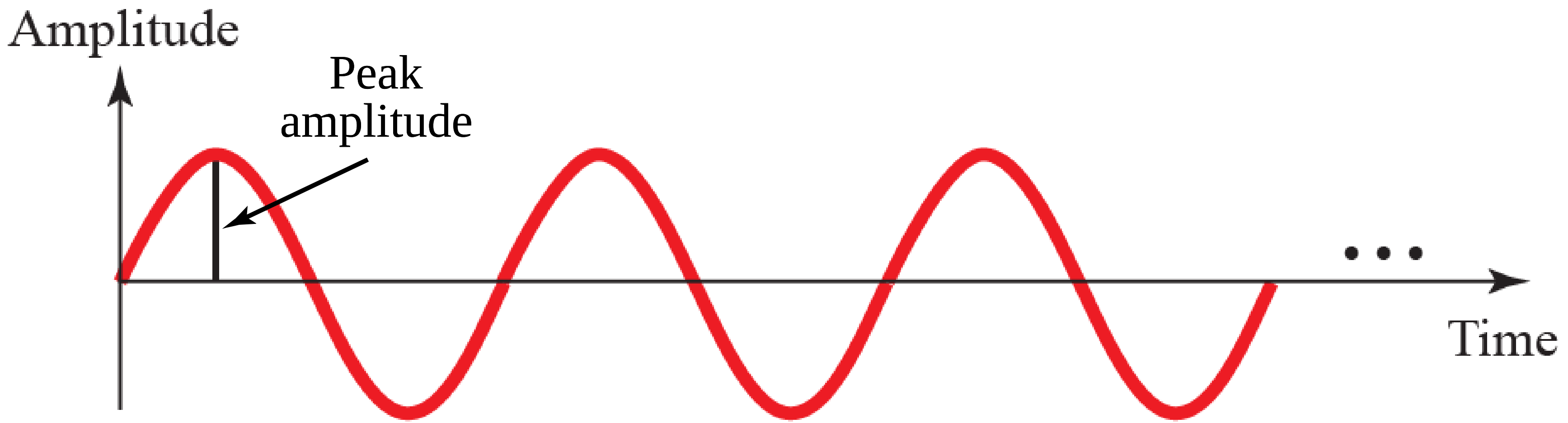
A sine wave, $y(t) = A \sin(2\pi f t + \vartheta)$, is <u>comprehensively defined</u> by its <u>peak amplitude</u>, A, <u>frequency</u>, f, and <u>phase</u>, ϑ (in radians).

The time-domain plot shows changes in signal amplitude with respect to time. Phase is not explicitly shown on a time-domain plot.

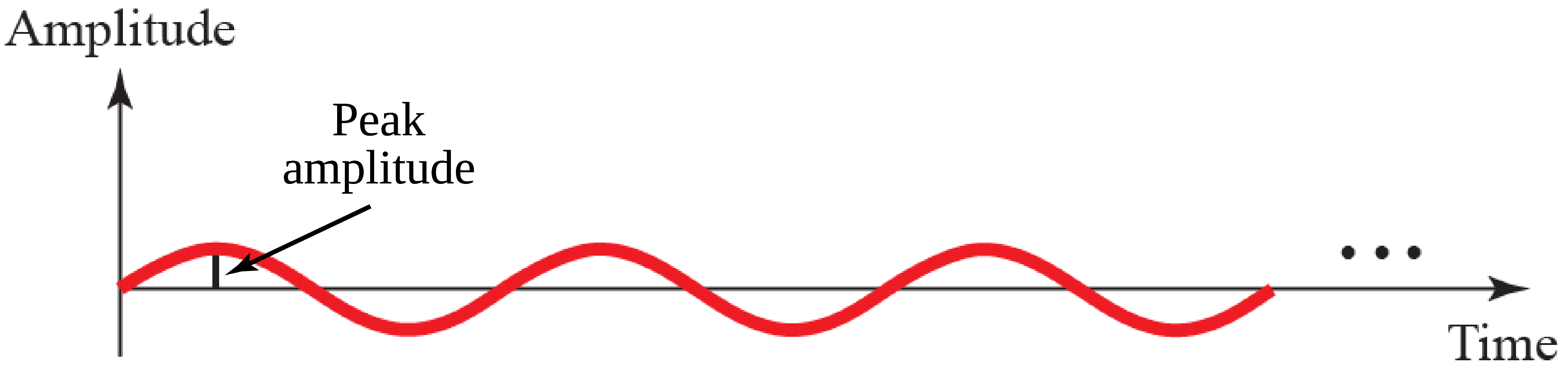


a. A sine wave in the time domain

Figure 3.4: Two signals with different amplitudes

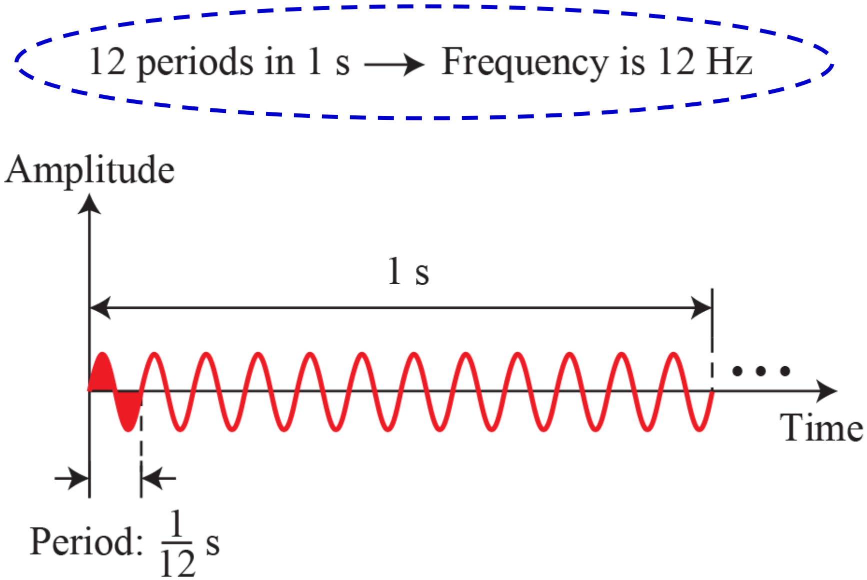


a. A signal with high peak amplitude

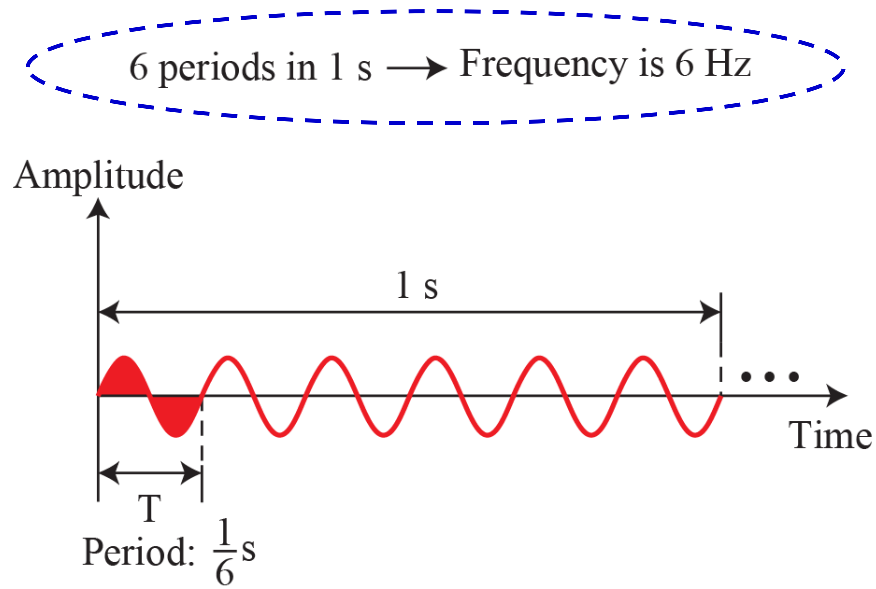


b. A signal with low peak amplitude

Figure 3.5: *Two signals with <u>different frequencies</u>*



a. A signal with a frequency of 12 Hz



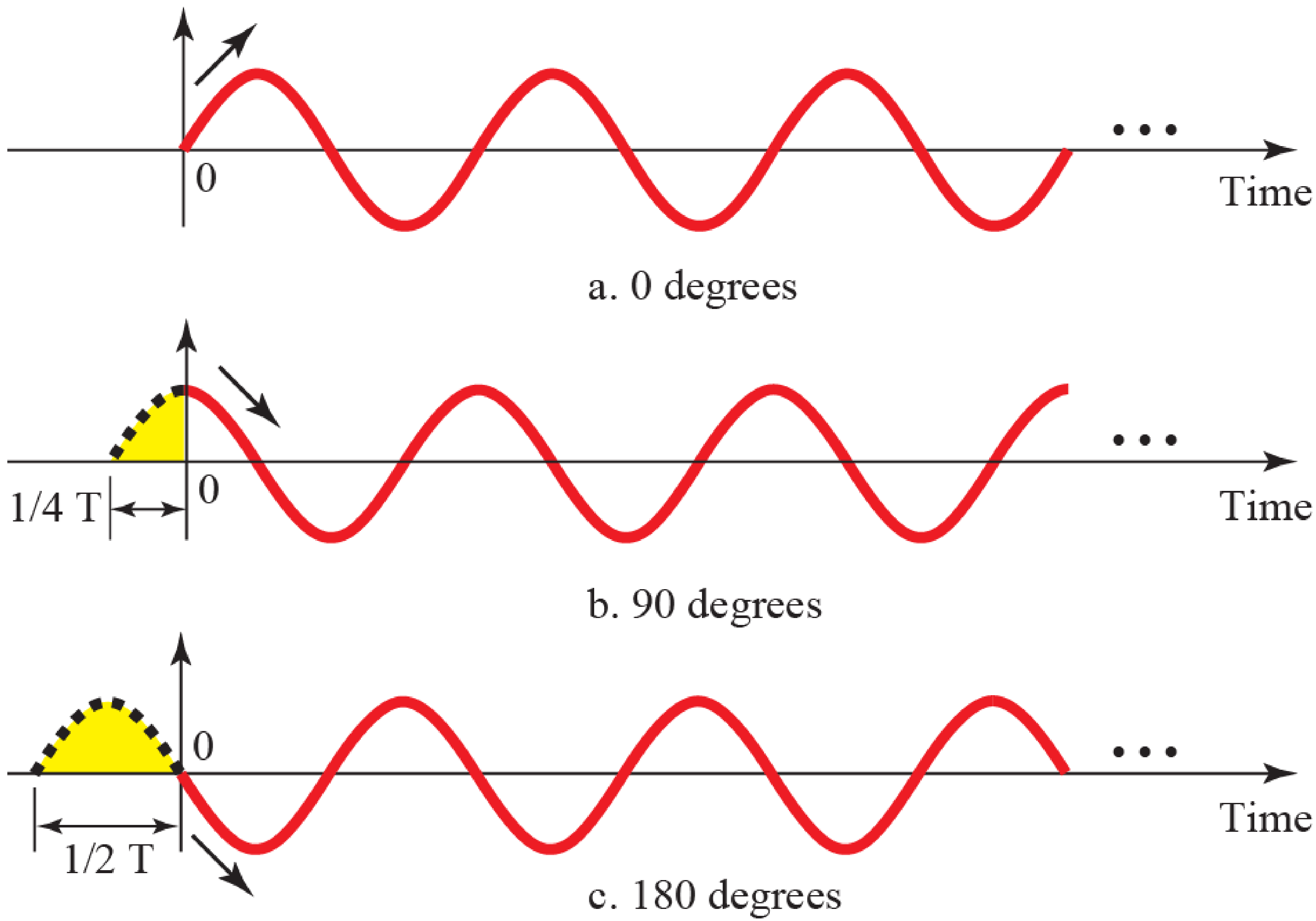
b. A signal with a frequency of 6 Hz

3.2.2 Phase

The term <u>phase</u>, or phase shift, <u>describes the position of the waveform relative to time 0</u>.

If we think of the wave as something that can be shifted backward or forward along the <u>time axis</u>, <u>phase describes the amount of that shift</u>.

Figure 3.6: Three sine waves with __different phases__



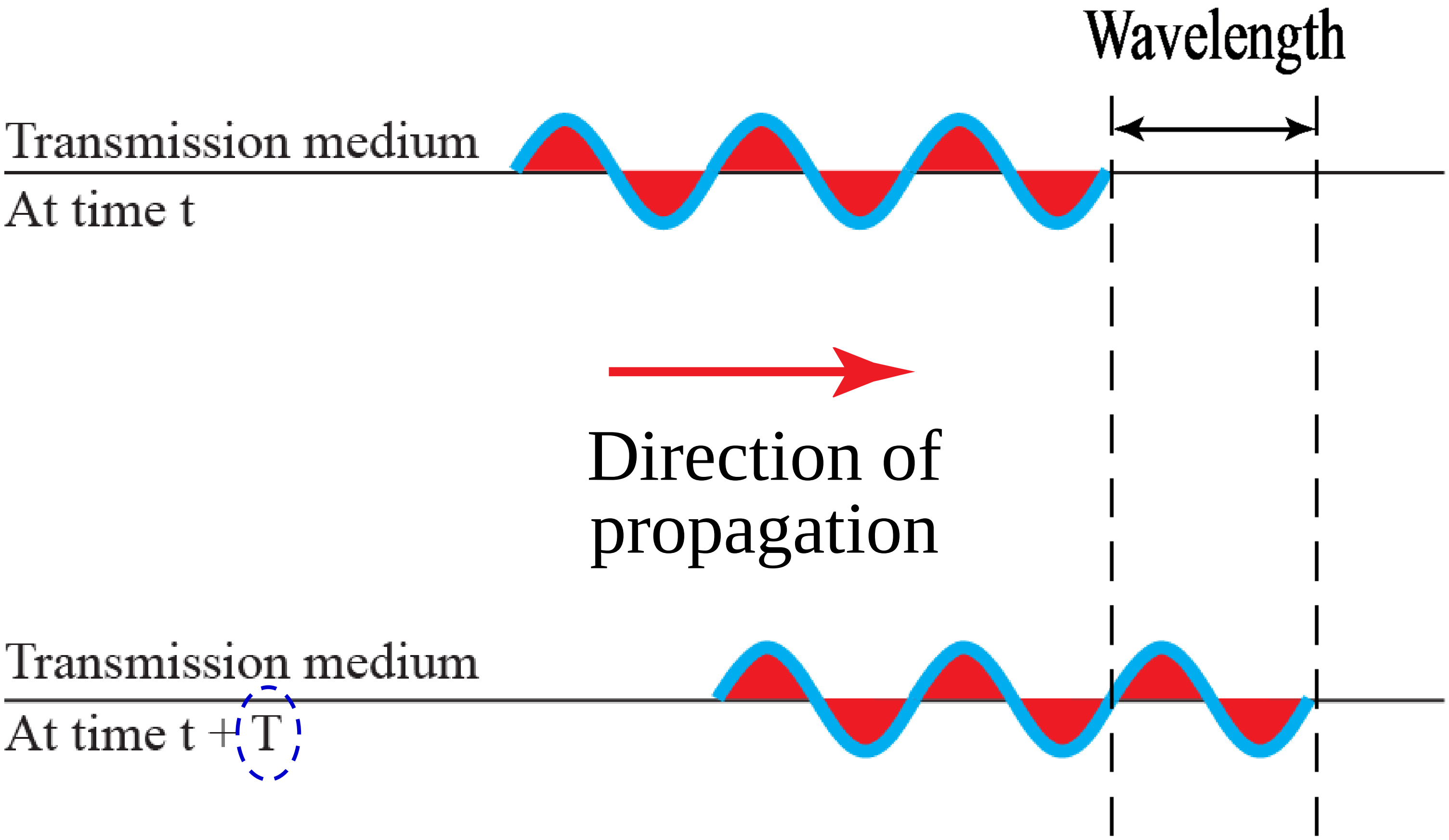
360 degrees = 2π radians

Problem

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

3.2.3 Wavelength

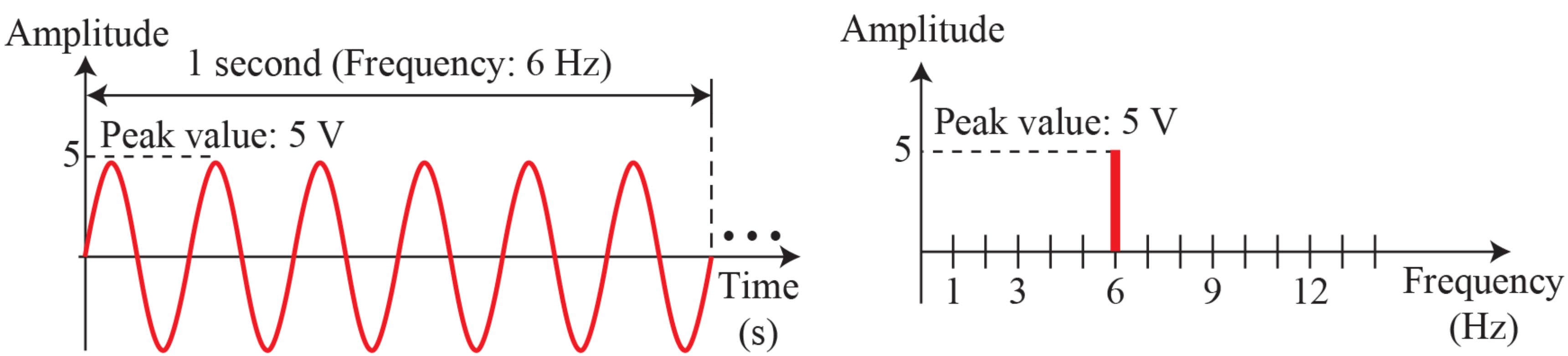
Wavelength is another characteristic of a signal traveling through a transmission medium.



Wavelength, $\lambda = cT$, is the <u>distance</u> a signal travels in one period, T. The term, c, is the propagation speed (speed of light).

3.2.4 Time and Frequency Domains

Previously, time-domain plot shows changes in signal amplitude with respect to time. To show the relationship between amplitude and frequency, we can use a frequency-domain plot.



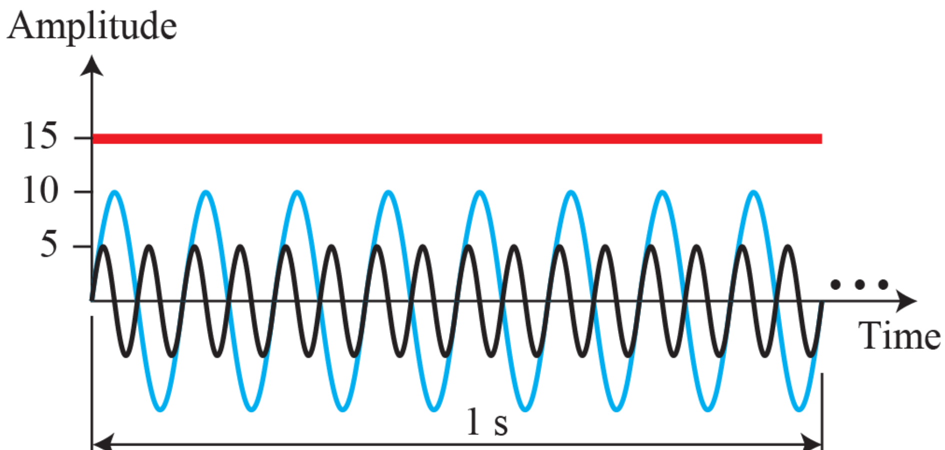
a. A sine wave in the time domain

b. The same sine wave in the frequency domain

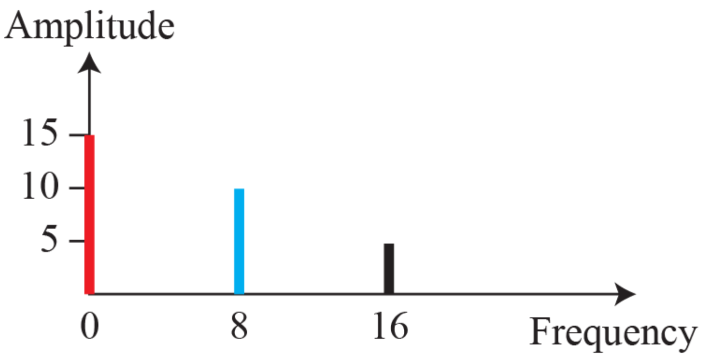
A frequency-domain plot is concerned with the peak value and the frequency.

Example

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



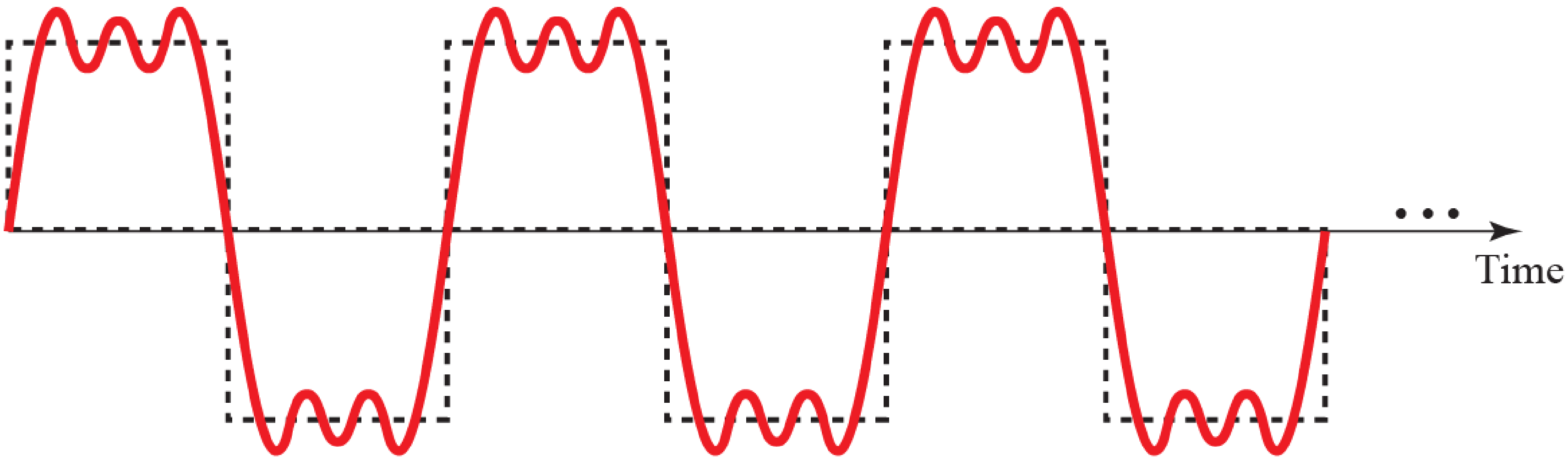
a. Time-domain representation



b. Frequency-domain representation

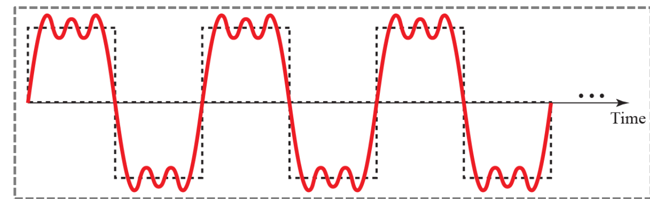
3.2.5 Composite Signals

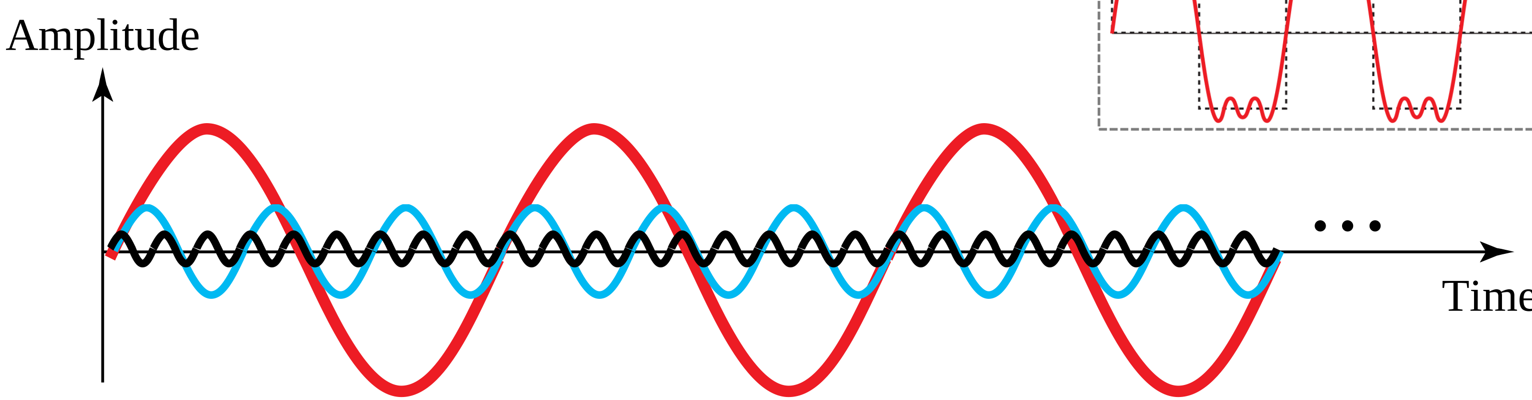
So far, we have focused on simple sine waves. The figure below shows a periodic composite signal with frequency f.



Example

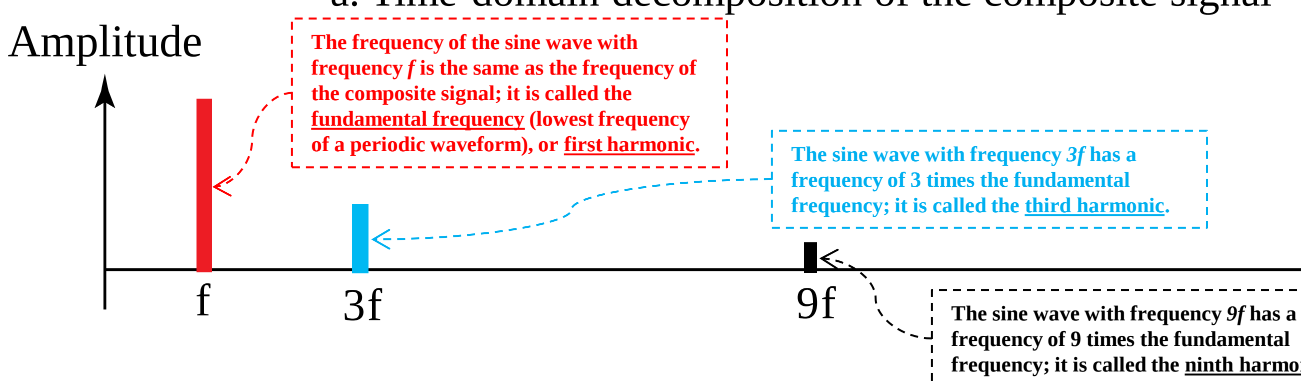
The plots below show the decomposition of the previous periodic composite signal in both the time and frequency domains.





a. Time-domain decomposition of the composite signal

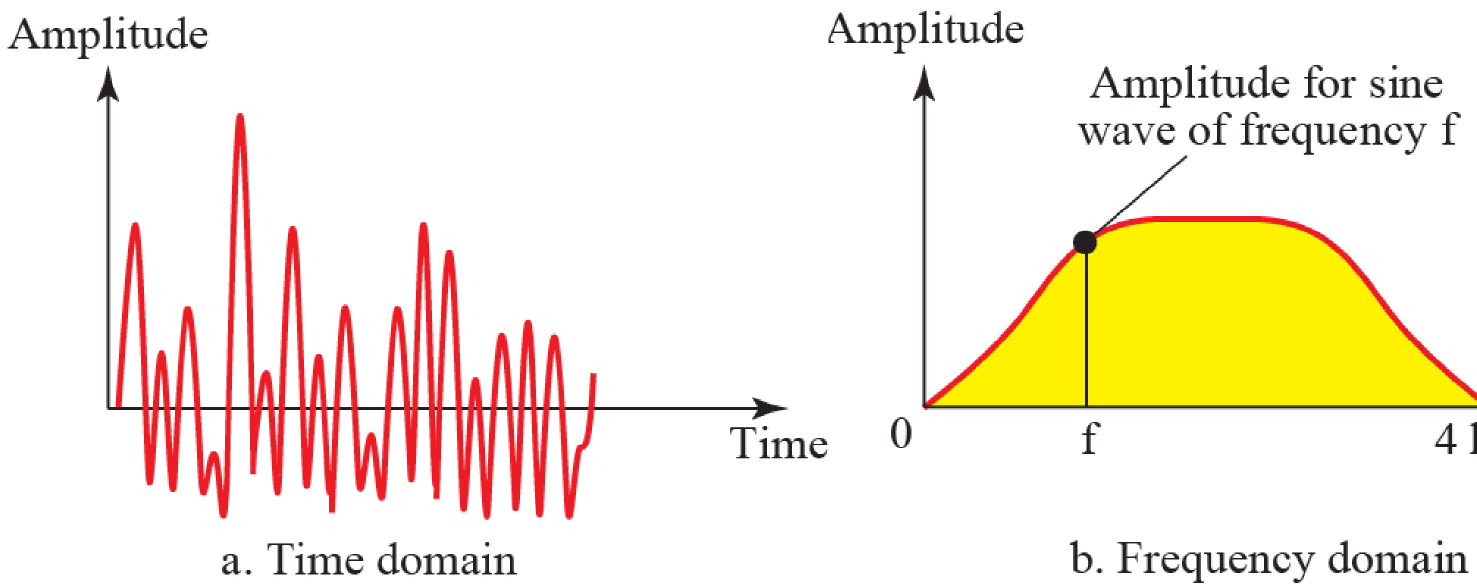
Note that the frequency decomposition of the periodic signal is represented by spikes in the frequency-domain.



b. Frequency-domain decomposition of the composite signal

Example

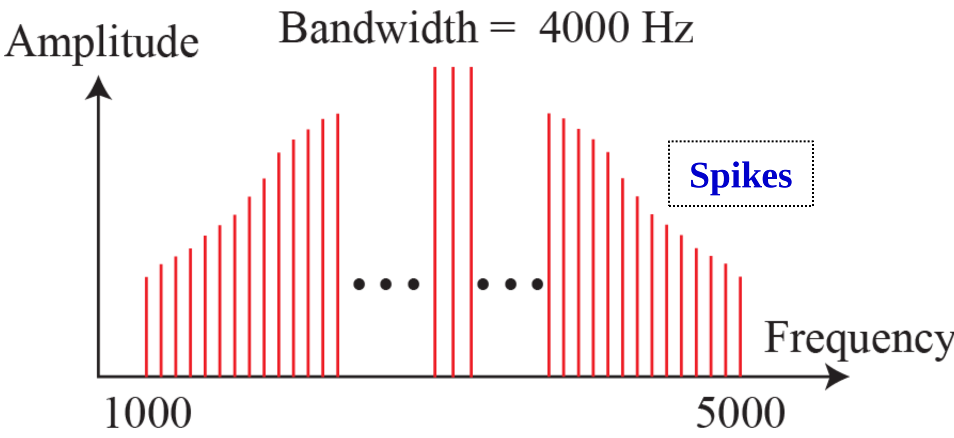
Figure (a) below shows a nonperiodic composite signal. It can be a signal created by a microphone or a telephone set when a word or two is pronounced. In this case, the composite signal cannot be periodic, because that implies that we are either repeating the same word or words with exactly the same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



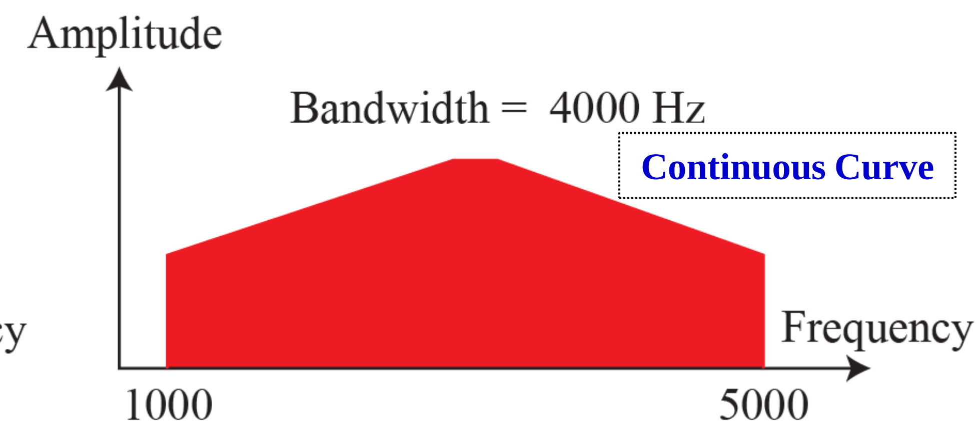
Note that the frequency decomposition of the nonperiodic signal yields a continuous curve in the frequency-domain.

3.2.6 Bandwidth

The <u>range of frequencies contained in a composite signal is its bandwidth</u>. The bandwidth is normally a difference between two numbers. For example, if a composite signal contains frequencies between 1000 Hz and 5000 Hz, its bandwidth, $B = f_h - f_l$, where f_l, f_h, respectively, are the lowest and highest frequencies contained in that signal, is 5000 − 1000 = 4000 Hz.



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

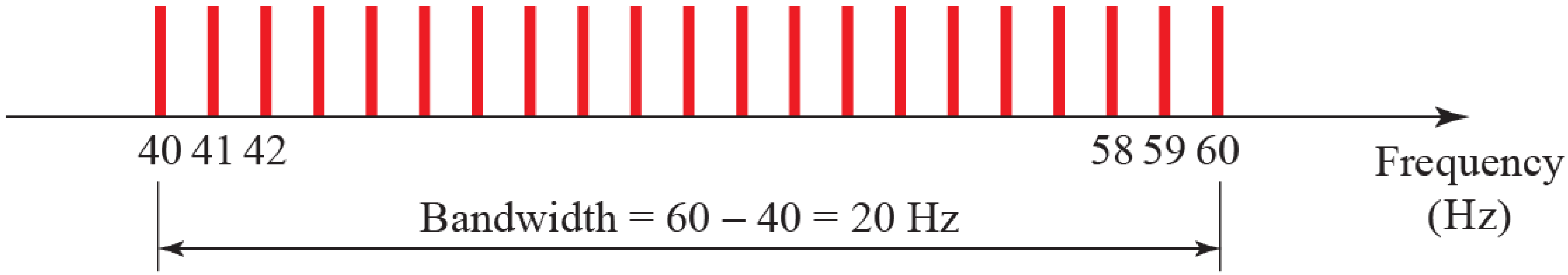
Example

A periodic 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 frequencies, each with the same amplitude.

Solution

Let f_h be the highest frequency, f_l the lowest frequency, and B the bandwidth. The lowest frequency, f_l, is

$$B = f_h - f_l \longrightarrow 20 = 60 - f_l \longrightarrow f_l = 60 - 20 = 40 \text{ Hz}$$



Problem

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.

Problem

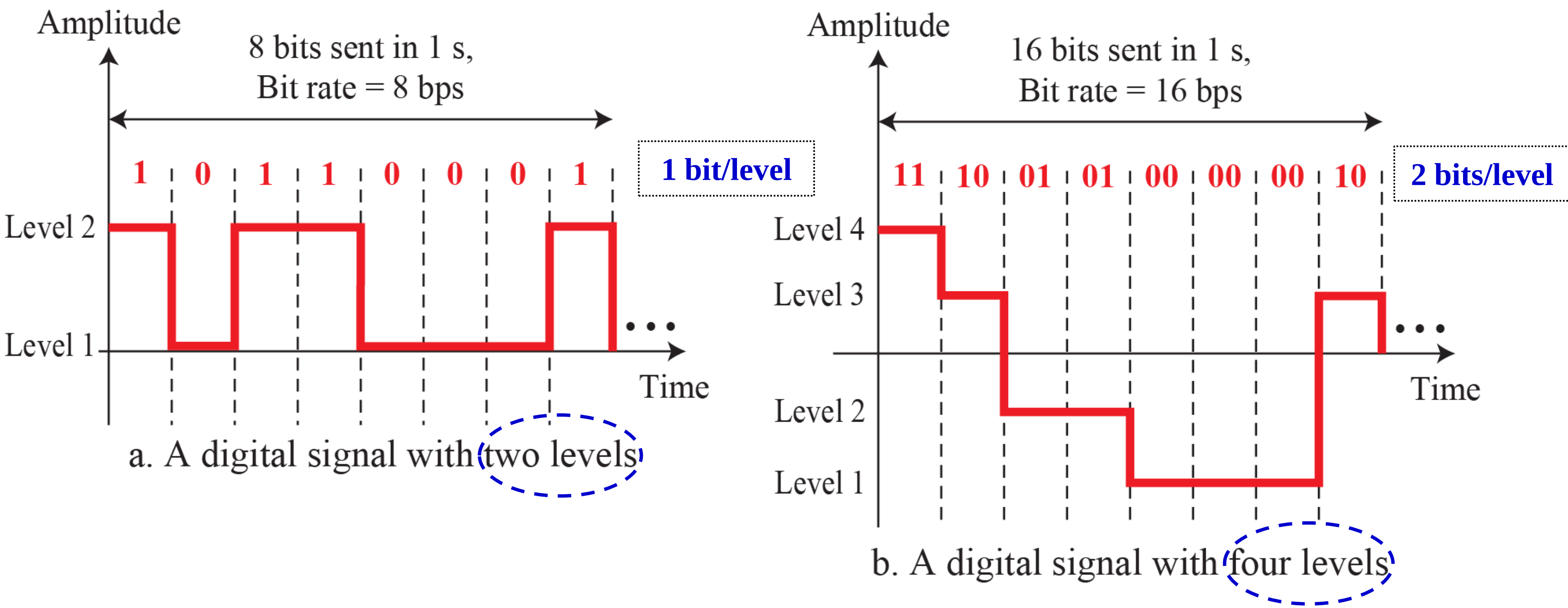
A nonperiodic composite signal has a bandwidth of 200 kHz, with a middle frequency of 140 kHz and peak amplitude of 20 V. The two extreme frequencies have an amplitude of 0 V. Draw the frequency domain of the signal.

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, i.e., we can send more than 1 bit for each level.

Figure 3.17: ***Two digital signals: one with two signal levels; the other with four signal levels***



Problem

A digital signal has eight levels. How many bits are needed per level?

3.3.1 Bit Rate

Most digital signals are <u>nonperiodic</u>, and thus period and frequency are not appropriate characteristics. Instead, <u>bit rate</u> is used to describe digital signals. The bit rate is the <u>number of bits sent in 1 second</u>, expressed in bits per second (bps).

Example: Assume we need to download text documents (24 lines, 80 characters/line) at the rate of 100 pages per second. What is the required bit rate of the channel?

Solution

A page has an average of 24 lines with 80 characters in each line. If we assume that one character (a byte) requires 8 bits, the bit rate is

$$100 \times 24 \times 80 \times 8 = 1{,}536{,}000 \text{ bps} = 1.536 \text{ Mbps}$$

Problem

What is the bit rate for high-definition TV (HDTV)? 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. 24 bits are used to represent each colored pixel.

3.3.2 Bit Length

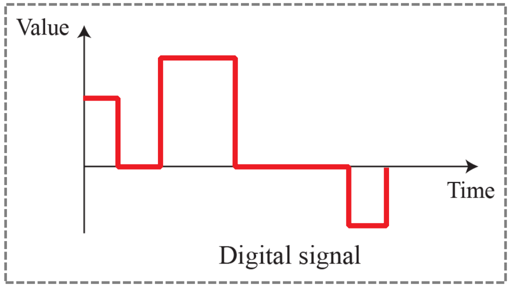
Previously, we discussed the concept of the wavelength for an analog signal: the distance one cycle occupies on the transmission medium. We can define something similar for a digital signal: the bit length. The bit length is the distance one bit occupies on the transmission medium.

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

Recall (from Physics 11): Distance = Speed x Time

3.3.3 Digital As Composite Analog

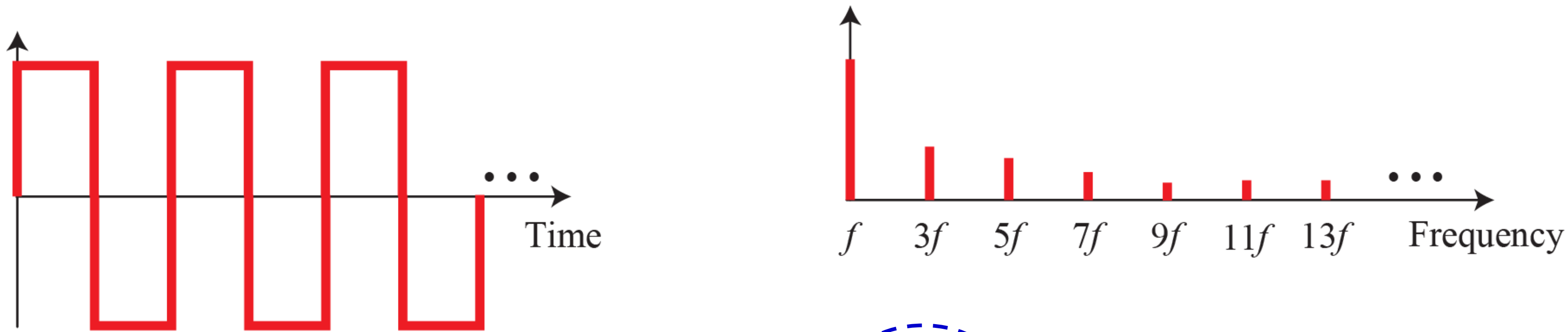
Based on Fourier analysis (Appendix E), a <u>digital signal</u> is a <u>composite analog signal</u> and the <u>bandwidth is infinite</u>.



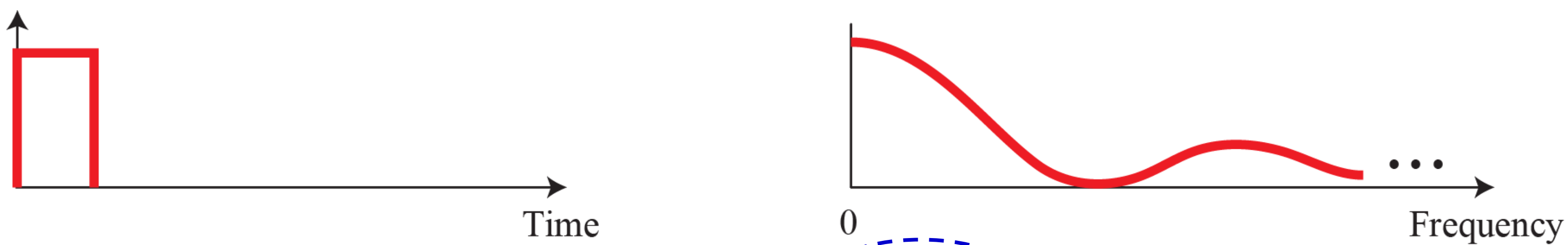
Infinite bandwidth intuition:

A digital signal, in the <u>time domain</u>, comprises of connected vertical and horizontal line segments. A <u>vertical line in the time domain means a frequency of infinity</u> and a <u>horizontal line in the time domain means a frequency of zero</u>. Hence, going from a frequency of zero to a frequency of infinity implies all frequencies in between are part of the frequency domain.

Figure 3.18: 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

Note: Both bandwidths are infinite, but the periodic signal has discrete frequencies while the nonperiodic signal has continuous frequencies.

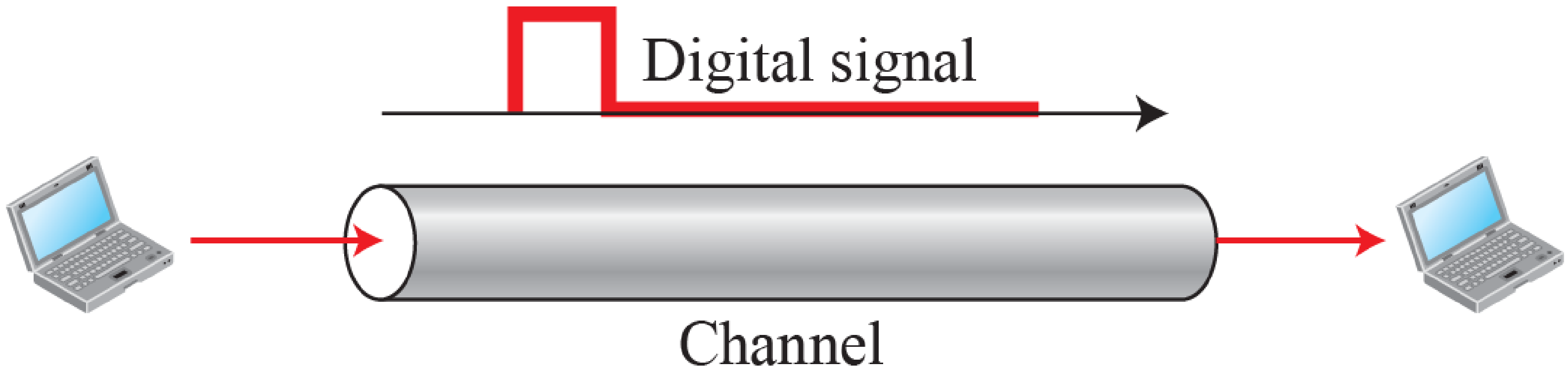
3.3.4 Transmission of Digital Signals

We can send a digital signal from point A to point B by using one of two approaches: baseband transmission or broadband transmission (using modulation).

Baseband transmission: means sending a digital signal over a channel without changing the digital signal to an analog signal. It requires a low-pass channel, i.e., a channel with a bandwidth that starts from zero.

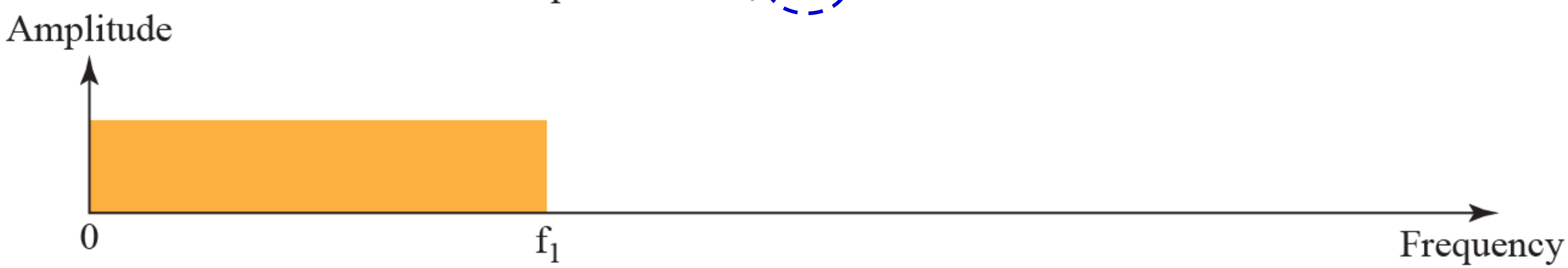
Broadband transmission: means changing the digital signal to an analog signal for transmission. It requires a band-pass channel, i.e., a channel with a bandwidth that does not start from zero.

Figure 3.19: Baseband transmission



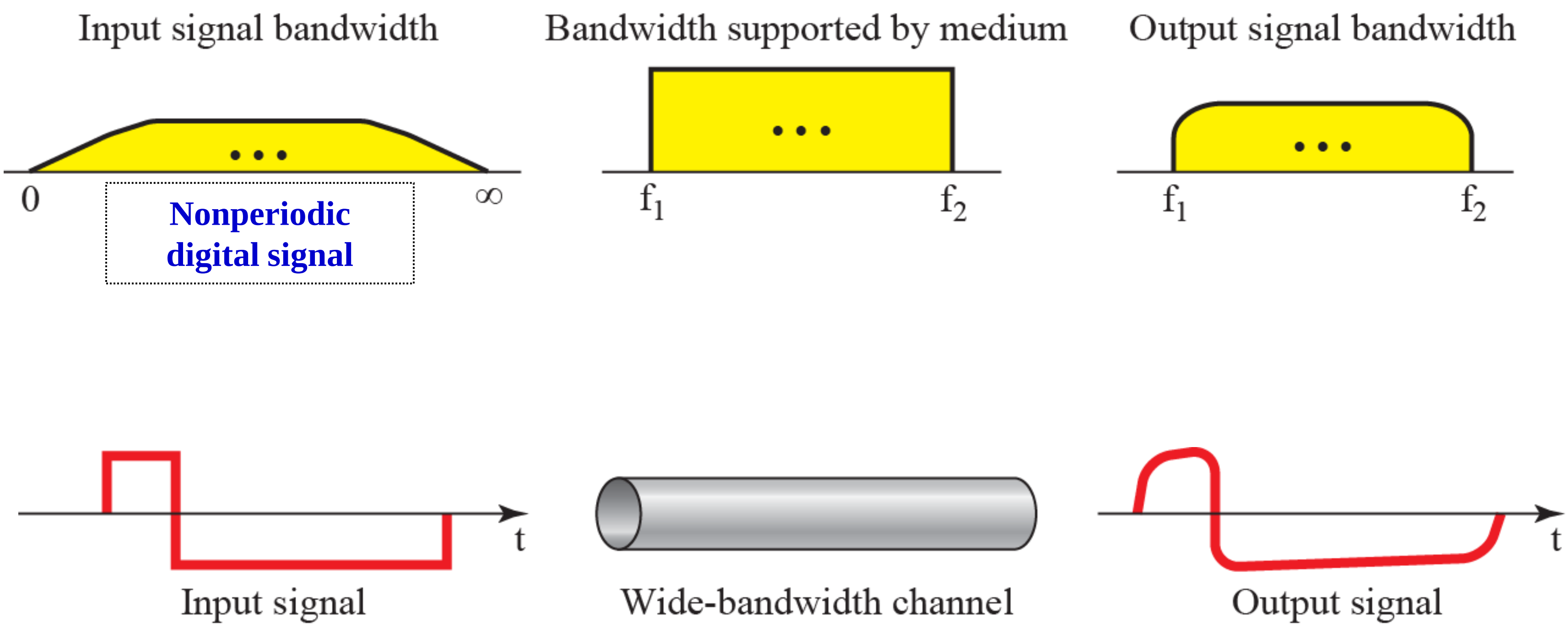
A low-pass channel with infinite bandwidth is ideal,
but we cannot have such a channel in real life.

a. Low-pass channel, wide bandwidth



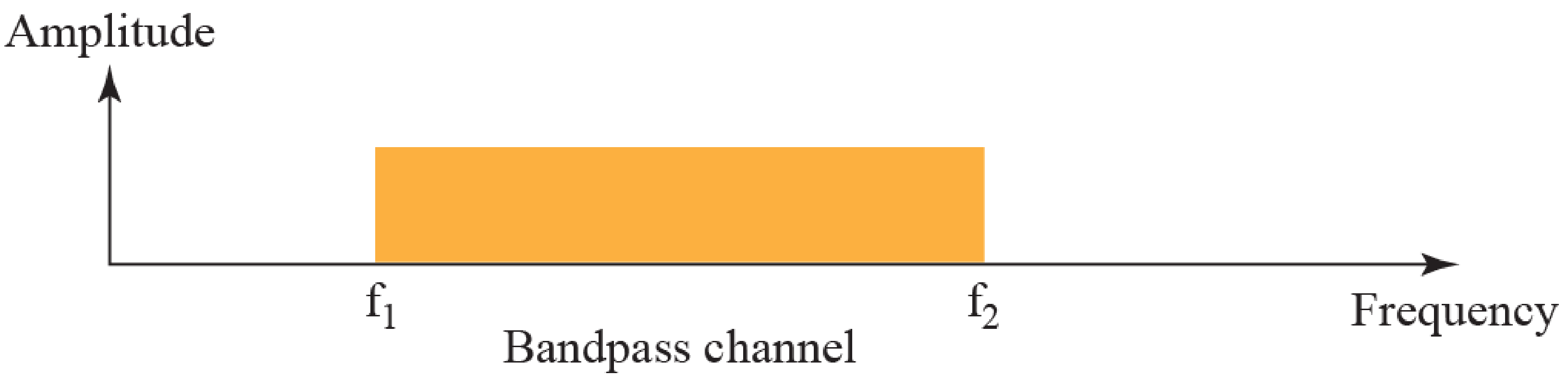
b. Low-pass channel, narrow bandwidth

Figure 3.21: Low-pass channel with wide bandwidth



Note: Although the output signal is not an exact replica of the original signal (some of the frequencies are blocked by the medium), the data can still be deduced from the received signal.

Figure 3.24: ***Bandwidth of a band-pass channel***



Notes:

1) Band-pass channel is more available than a low-pass channel.
2) If available channel is a band-pass channel, we need to modulate the signal (convert the digital signal to an analog signal) before transmission.
3) A low-pass channel can be considered a band-pass channel with the lower frequency starting at zero.