Signals and sensors

Internet of Things

CS5055 – 2025I

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Outline

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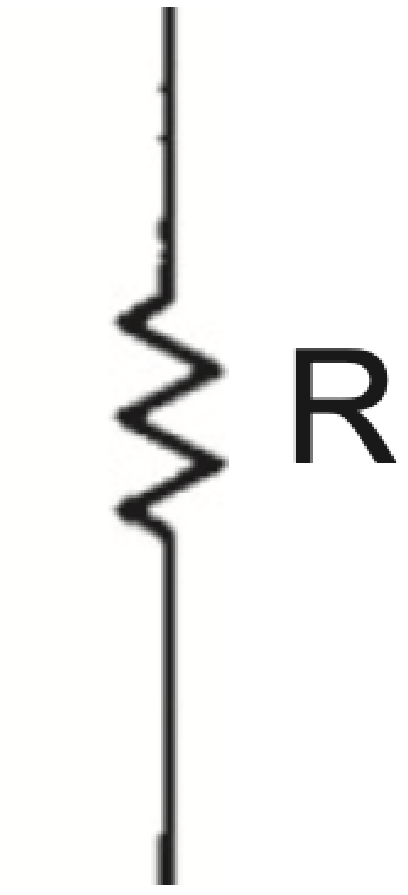
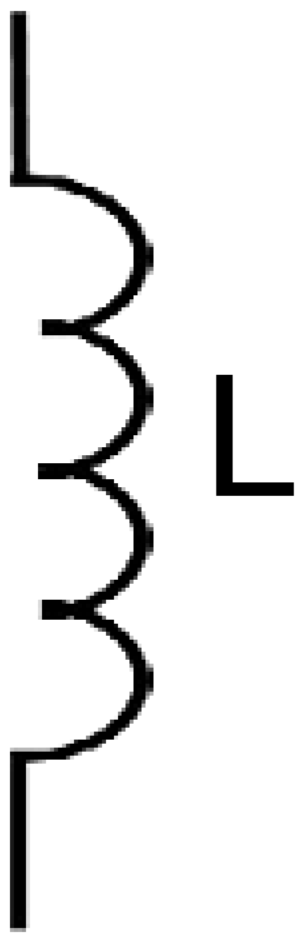
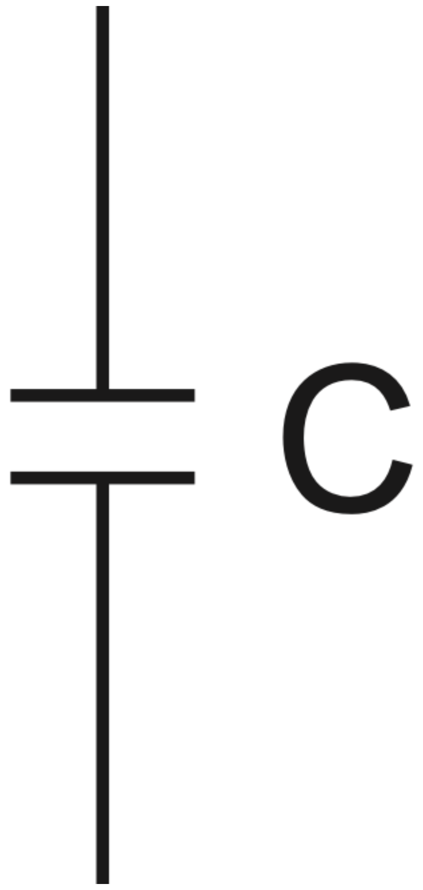
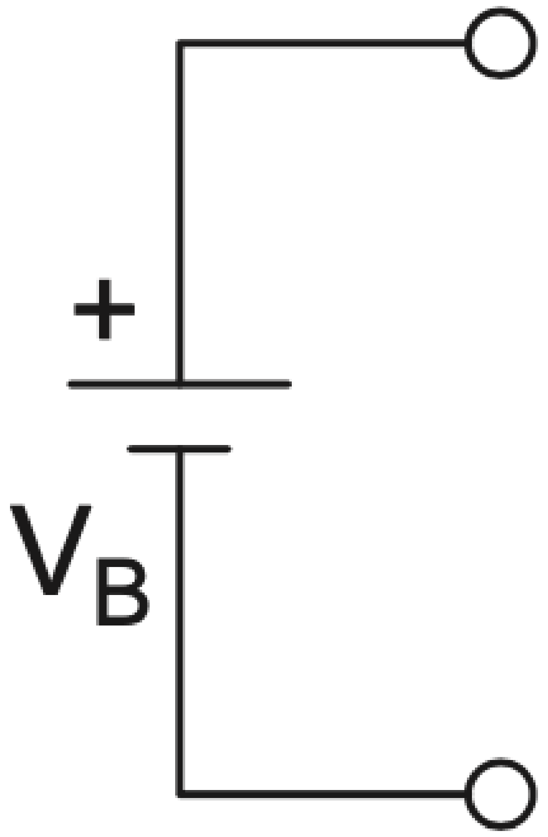
Recall: Circuit elements

- How do they work? Passive vs active elements?



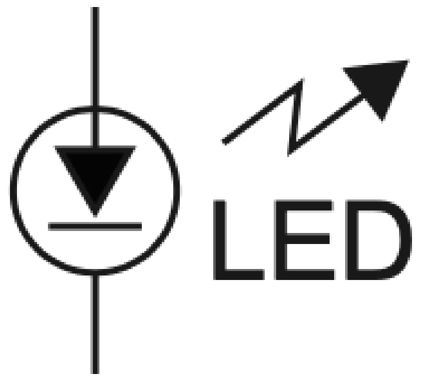




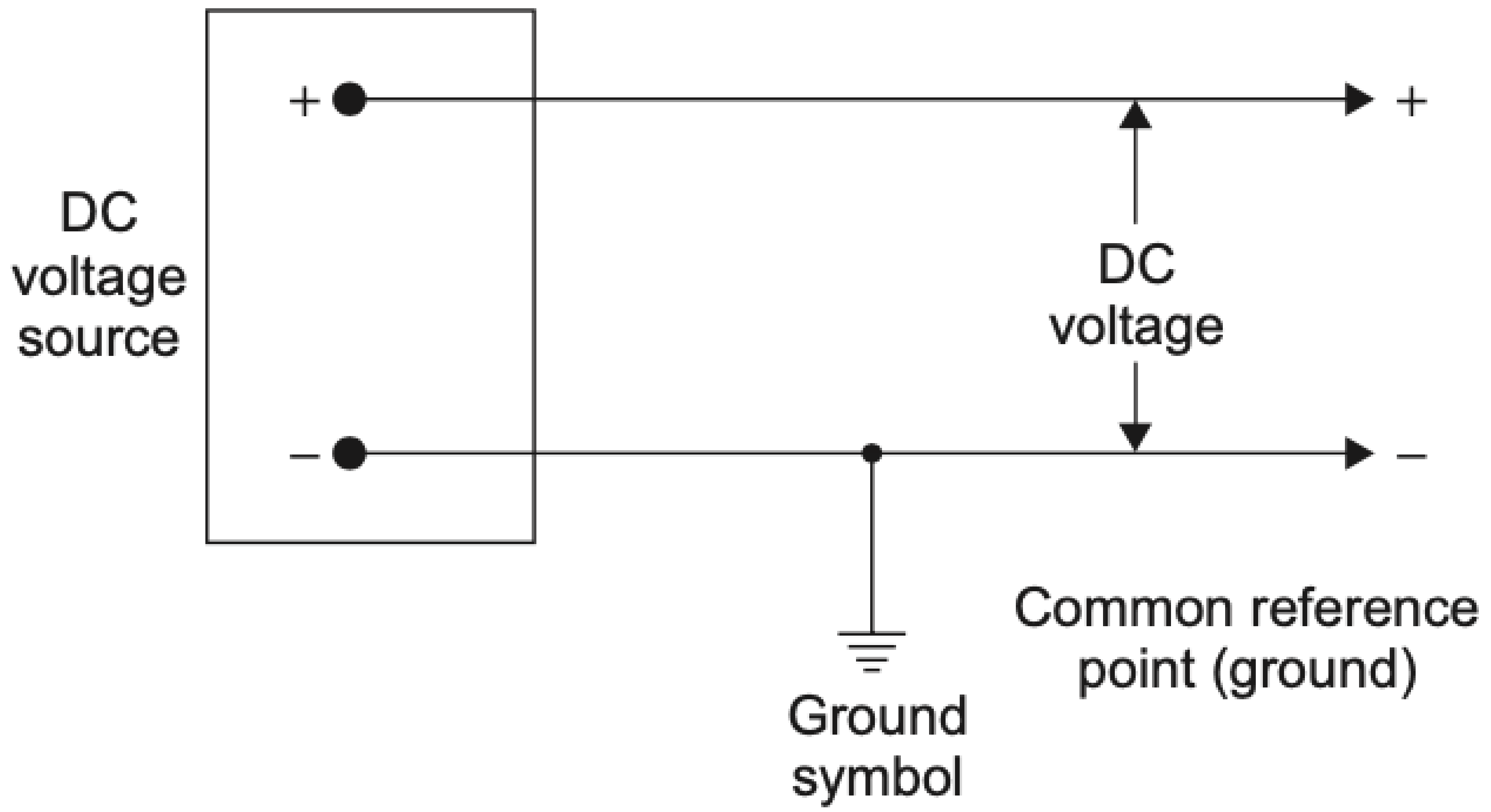


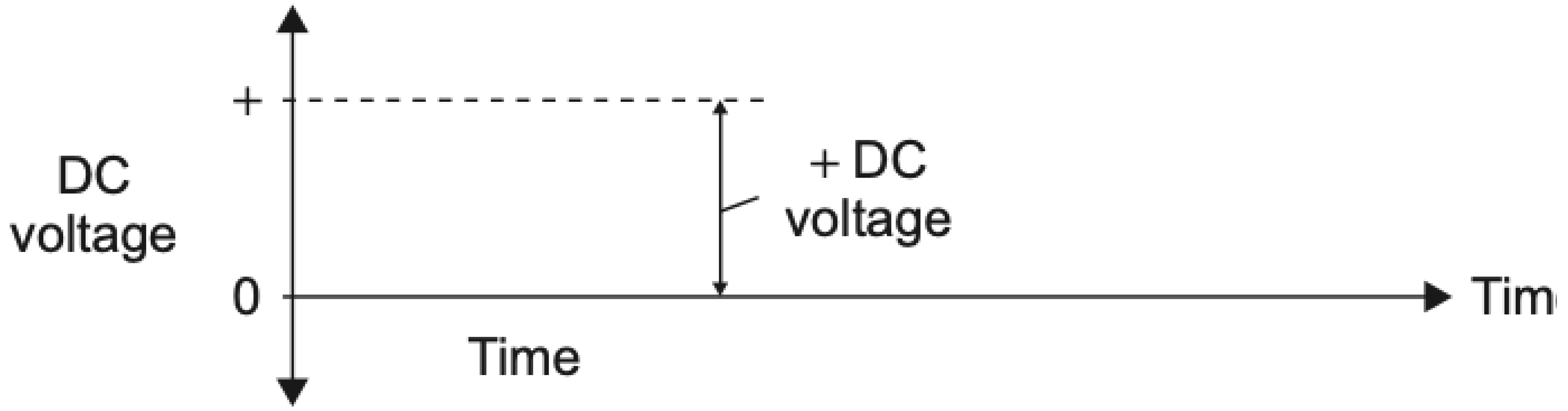
Resistor	Inductor	Capacitor	Voltage Source

- What about a LED?

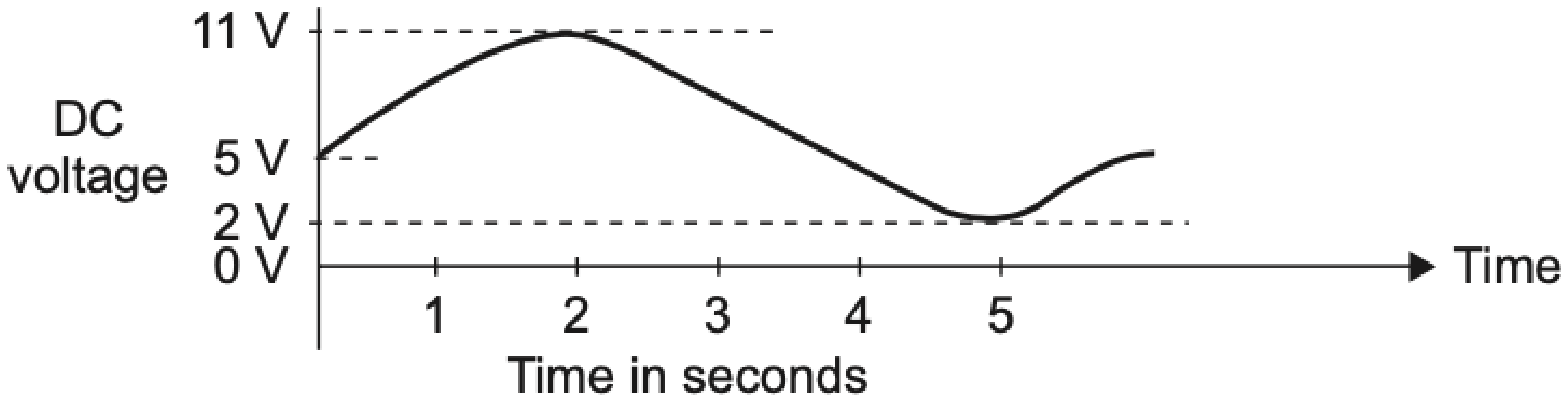


Recall: DC Voltage

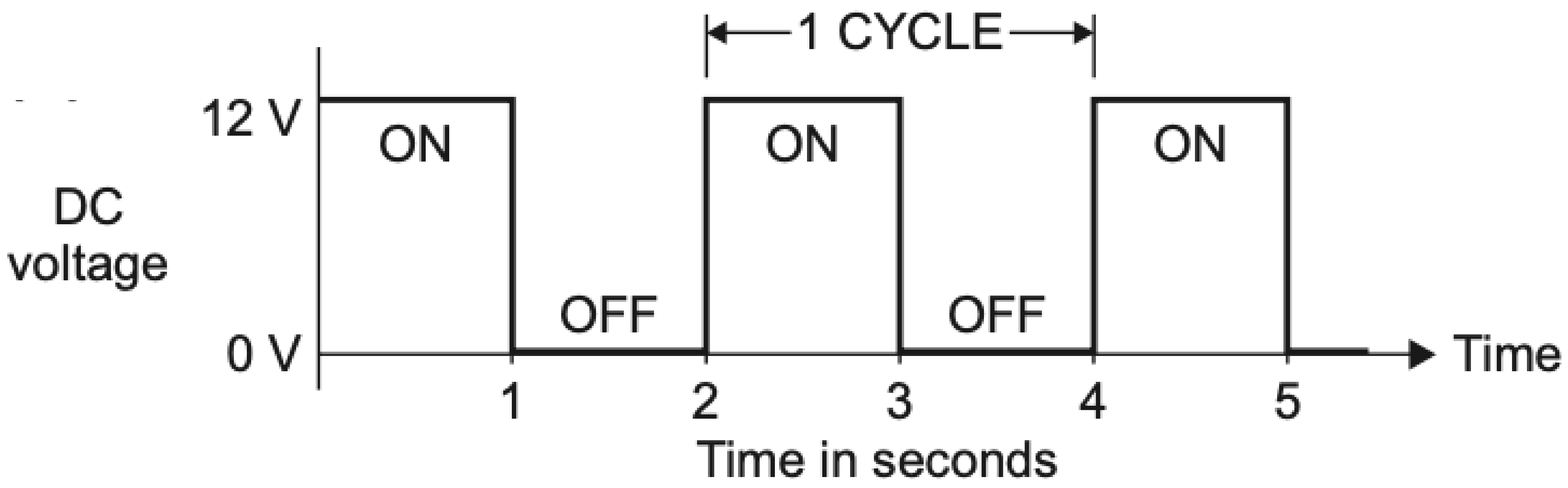




Fixed, positive DC voltage

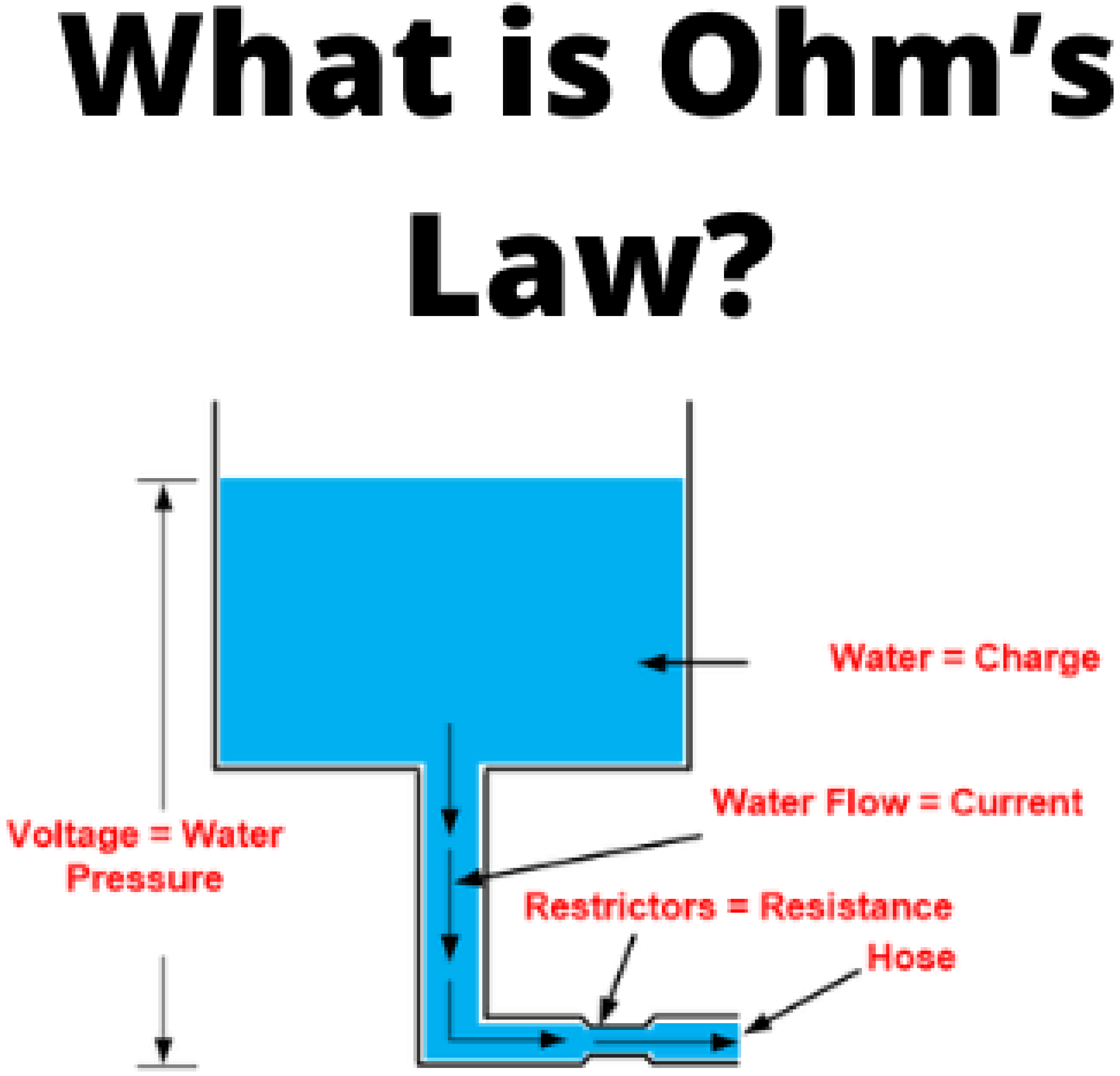


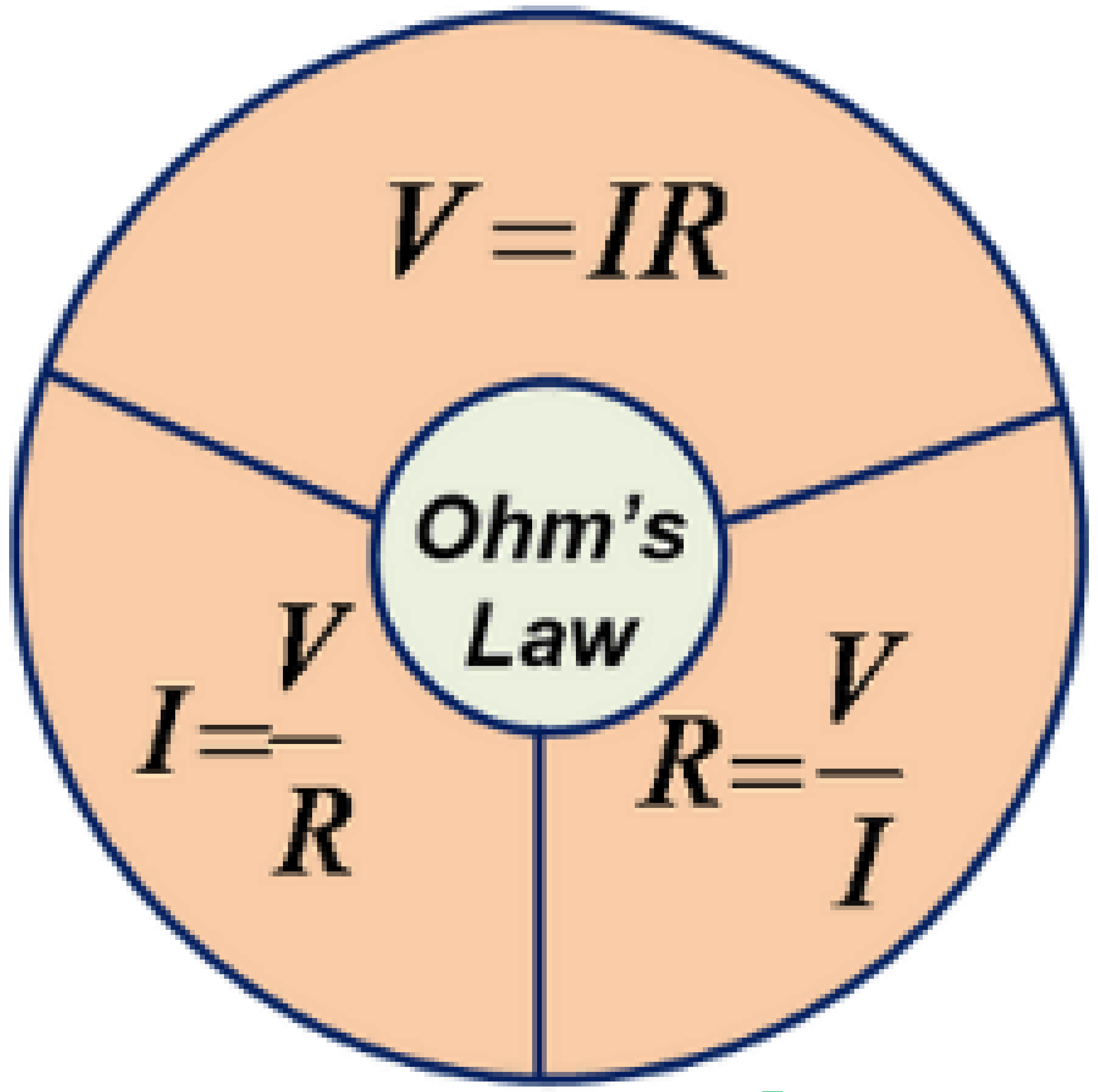
Varying, positive DC voltage



Pulsating DC voltage

Ohm’s law

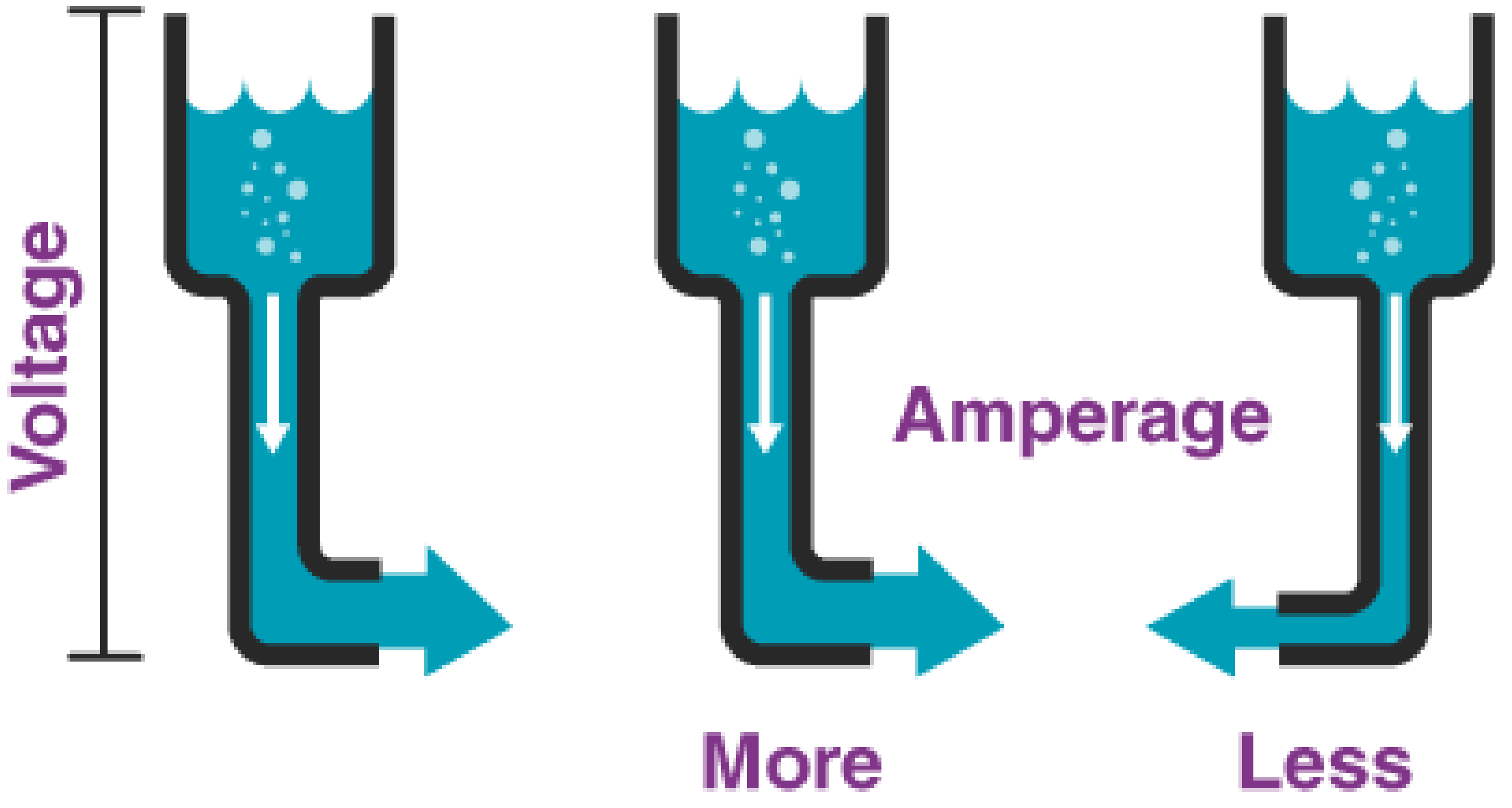


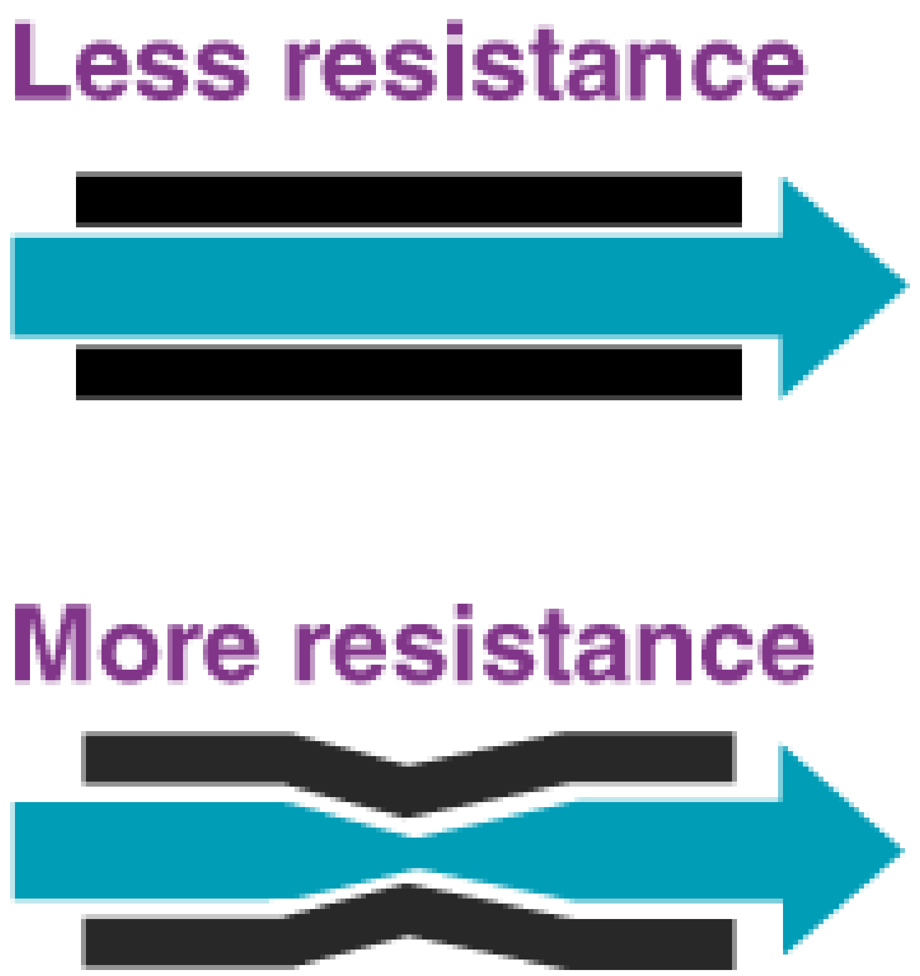


[ELECTRICAL4U.COM]

Voltage != Current

What is resistance?





Outline

Circuit Elements

Signals

Sensors

Conclusions

Signals

- Example **Biosignals:**

Energy	Variables (Specific Fluctuation)	Common Measurements
Chemical	Chemical activity and/or concentration	Blood ion, O_2, CO2, pH, hormonal concentrations and other chemistry.
Mechanical	Position Force, torque or pressure	Muscle movement, Cardiovascular pressures, muscle contractility Valve and other cardiac sounds
Electrical	Voltage (potential energy of charge carriers) Current (charge carrier flow)	EEG, ECG, EMG, EOG, ERG, EGG, GSR
Thermal	Temperature	Body temperature, thermography

Sensors

- **Example Biotransducers:**
  - **Transducer is a devices that** converts energy from one form to another. In measurement systems, all transducers are so-called *input transducers*, they convert non-electrical energy into an electronic signal.

  - In signal processing applications, **the purpose of energy conversion is to transfer information, not to transform energy.**
  - In physiological measurement systems, all transducers are input transducers: they convert non-electrical energy into an electronic signal.

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Biotransducers

The biotransducer is often the most critical element in the system: it often defines the accuracy or resolution of the measurement and acts as an interface between the life process and the rest of the system.

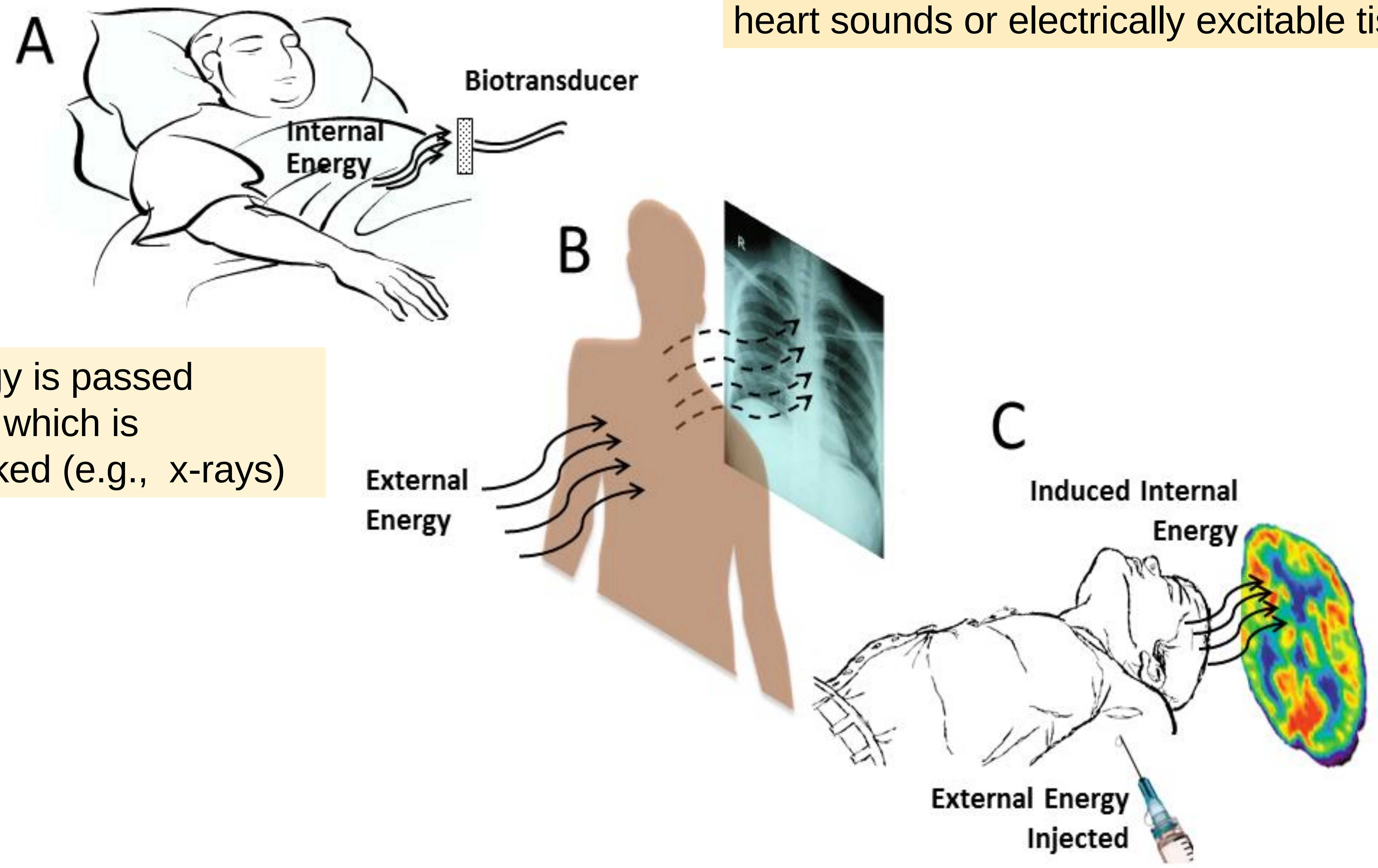
- This is not an stethoscope:

A cardiac microphone is a biotransducer that converts the mechanical sound energy produced by the heart into an electrical signal is shown. The device uses a piezoelectric disk that produces a voltage when it is deformed by movement of the patient’s chest.

The white foam pad covers the piezoelectric disk and is specially designed to improve the coupling of energy between the chest and the piezoelectric disk.

Three strategies for obtaining measurements from the body (or other physiological systems).

A) The body generates the energy such as in heart sounds or electrically excitable tissue.



B) External energy is passed through the body which is differentially blocked (e.g., x-rays)

C) The body is converted to a signal source by an external substance or energy source (e.g. positron emission tomography..

Example: Bio-electric transducers

- **Physiological electrical activity is monitored with a transducer that converts electrical energy from ionic to electronic current termed and electrode.**

- These sources are usually given the term ExG, where the “x” represents the physiological process that produces the electrical energy:

  ECG—electrocardiogram (heart)
  EEG—electroencephalogram (brain)
  EMG—electromyogram (muscle)
  EOG—electrooculogram (eye)
  ERG—electroretinogram (retina)
  EGG—electrogastrogram. (stomach)

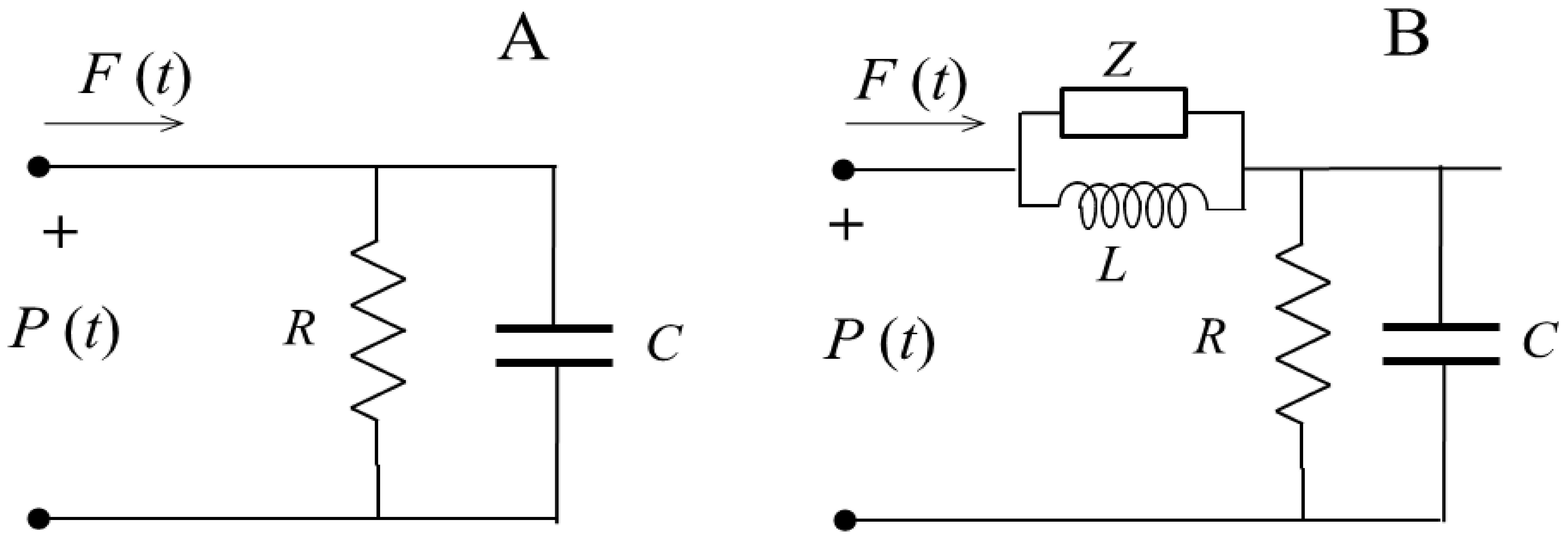
Example: Cardiac Analog Model

The original model, A, represented the load on the heart as two passive elements: a parallel resistor and a capacitor driven by pressure *P*(*t*), the pressure generated by the heart.

The resistor, *R*, represents the combined resistance of all the blood vessels (in units of mmHg sec/cm^3) although the primary contribution comes from the smaller peripheral vessels.

The capacitor, *C*, represents the net compliance of the blood vessels (in units of cm^3/mmHg) which is mainly due to the aorta.

This is why understanding Ohm's law is important



The two-element Windkessel model was successful at modeling flow during diastole, but not systole, motivating the addition of other elements, B.

Signal Encoding ~ Signal Representation

- Irrespective of the energy form or specific variable used to carry information, **some type of encoding scheme is necessary.**

- **Signals fall into two broad categories:** 1) one-dimensional signals where the dimension is usually time, and 2) two-dimensional signals where the dimensions are usually spatial.

- **Signals are represented in either of two domains:** 1) *continuous* and 2) *discrete*. These two domains are also termed *analog* and *digital*.

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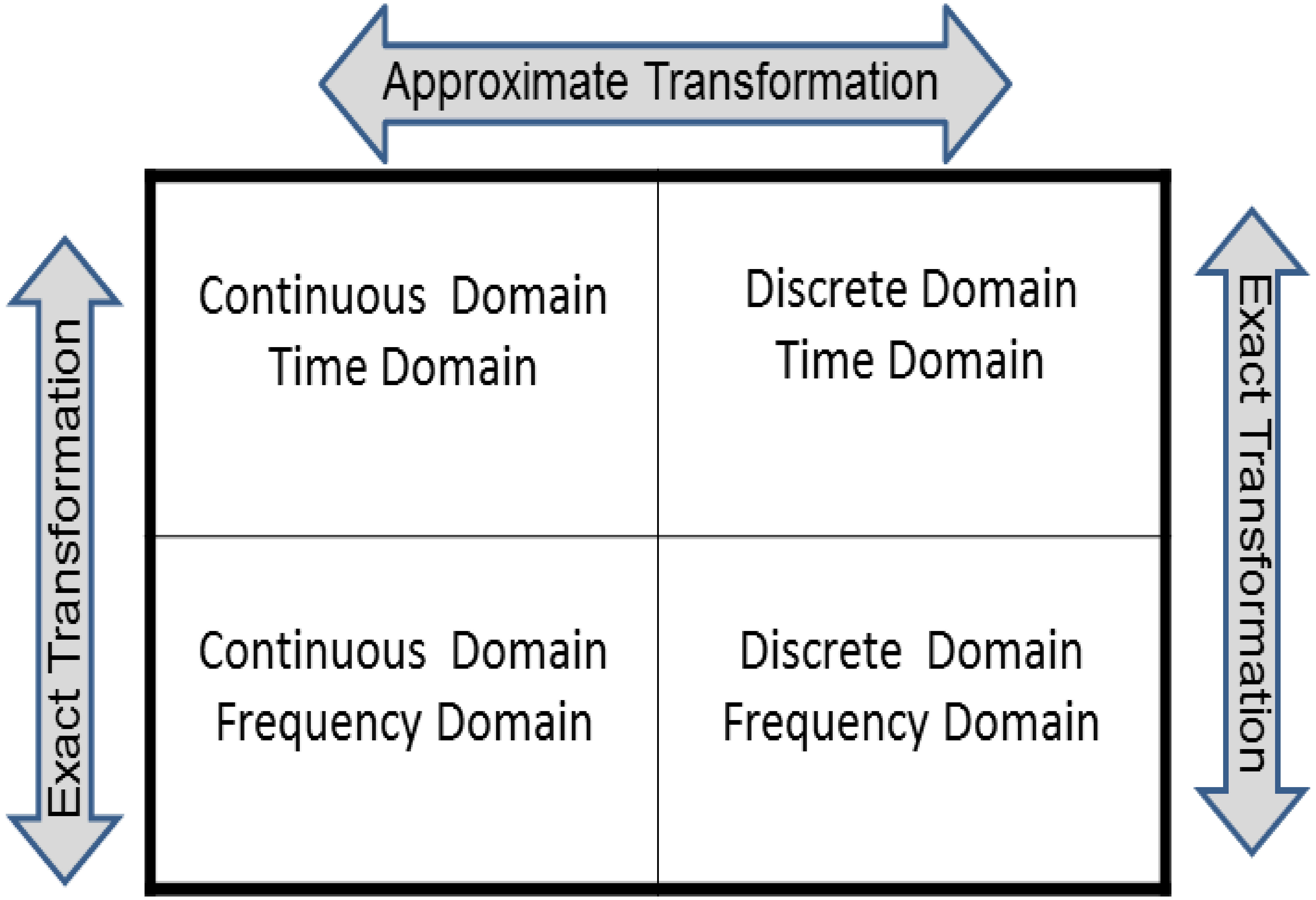
Signal Encoding

A signal is represented in either the continuous or discrete domain, and in either the time or frequency domain.

- **Transformations between the time and frequency domain are exact:** there is no loss of signal information during the transfer.
- **Transformations between continuous and discrete domains are approximate** and only done in the time domain..



Continuous or Analog Domain Signals

An analog signal mathematically encodes information as fluctuations in time. Such time-varying signals can be described by the equation:

$$x(t) = f(t)$$

where $f(t)$ is some function of time and can be quite complex. For an electronic signal, this could be the value of the voltage or current at a given time.

Often an analog signal encodes the information it carries as a linear change in signal amplitude.

Signal Encoding Example

A temperature transducer encodes room temperature into voltage as shown in the table.

Temperature (^{O}C)	Voltage (volts)
-10	0.0
0.0	5.0
+10	10.0
+20	15.0

Then the encoding equation for temperature would be:

$$temperature = voltage * amplitude - 10$$

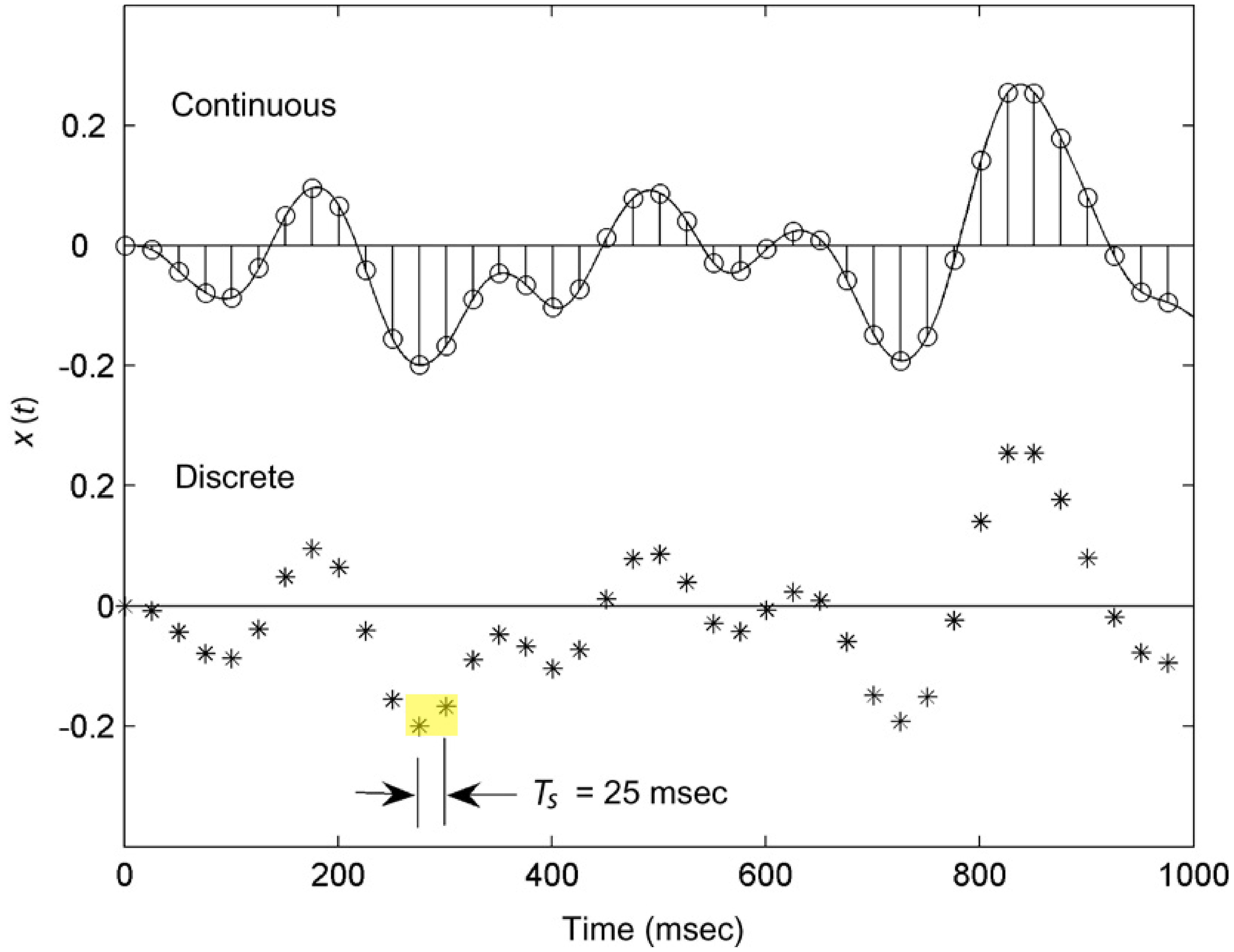
As defined later this is a linear encoding scheme.

Discrete-Time or Digital Signals

To be stored or processed in a digital computer, a continuous analog signal be converted to a series of numbers through a process **known as *sampling***.

A continuous analog signal, $x(t)$, is sliced up into a sequence of digital numbers usually at equal time intervals, T_s.

T_s is known as the *sampling interval*.



Digital Signals

- **These sequential numbers** represent the value of the analog signal at a discrete points in time determined by the sample interval, T_s:

$$t = nT_s = n/f_s$$

Where f_s is the *sampling frequency*, $f_s = 1/T_s$ and where n is the position of the number in the sequence.

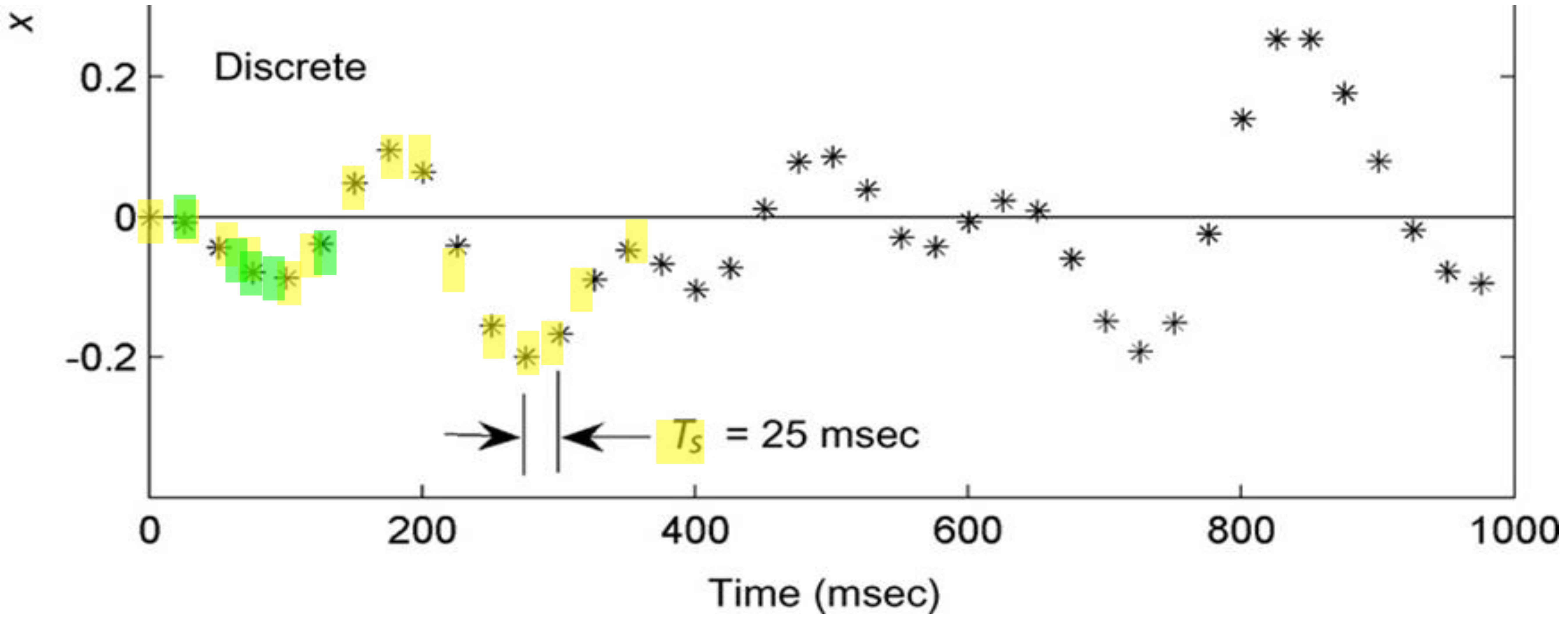
- **Usually this series of numbers would be stored in sequential memory locations (called and array or vector)** with x[1] followed by x[2], then x[3], and so on.

Sampled or Digitized Signals

- **A sampled time signal,** also referred to as a digitized signal or simply digital signal, can be easily stored in a digital computer.

- A digital signal, $x[k]$, is just a series of numbers:

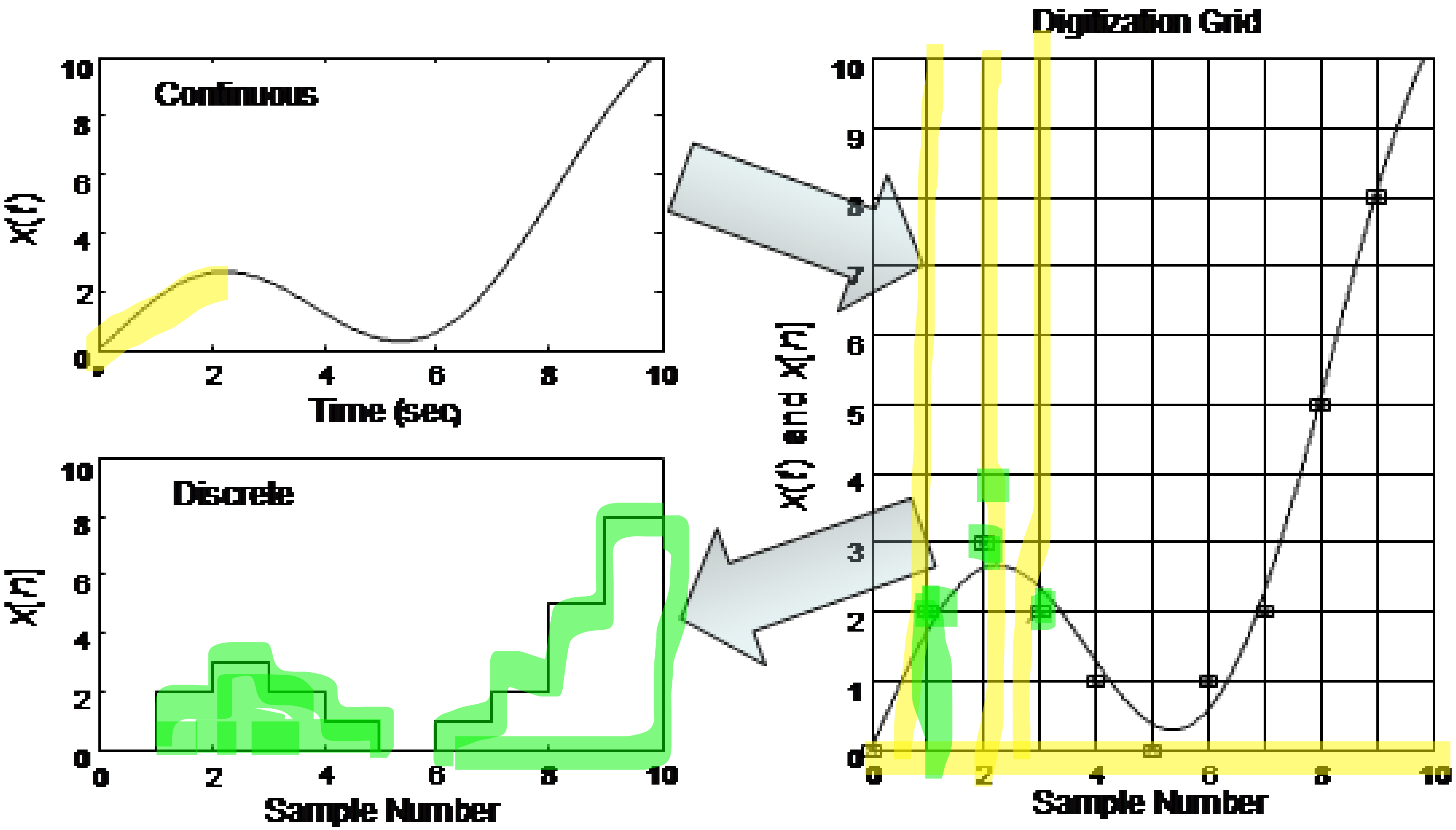
$$x[k] = x_1, x_2, x_3, \ldots x_N.$$



In this signal:
$x[n]$ = 50.0, 0.81, 0.96, 0.41, 20.3, 20.6, 20.3, 0.18, 0.34, 20.0, 20.5, 20.6, 20.0, 0.71, 0.99, 0.52).

Amplitude Slicing: Quantization

- Since digital numbers can only represent discrete or specific amplitudes, the analog signal must also be sliced up in amplitude.



To *digitize* or *sample* an analog signal requires slicing the signal in two ways: **in time and in amplitude.**

Analog-to-digital Conversion

Example 1 A 12-bit analog-to-digital converter (ADC) advertises an accuracy of ± the least significant bit (lsb). If the input range of the ADC is 0 to 10 volts, what is the accuracy of the ADC in analog volts?

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Analog-to-digital Conversion

Example 1 A 12-bit analog-to-digital converter (ADC) advertises an accuracy of ± the least significant bit (lsb). If the input range of the ADC is 0 to 10 volts, what is the accuracy of the ADC in analog volts?

<u>Solution:</u> If the input range is 10 volts, then the analog voltage represented by the lsb would be:

$$V_{LSB} = \frac{V_{\max}}{2^{\text{Nu bits}}} = \frac{10}{2^{12}} = \frac{10}{4096} = .0024 \text{ volts}$$

Hence the accuracy would be ± .0024 volts.

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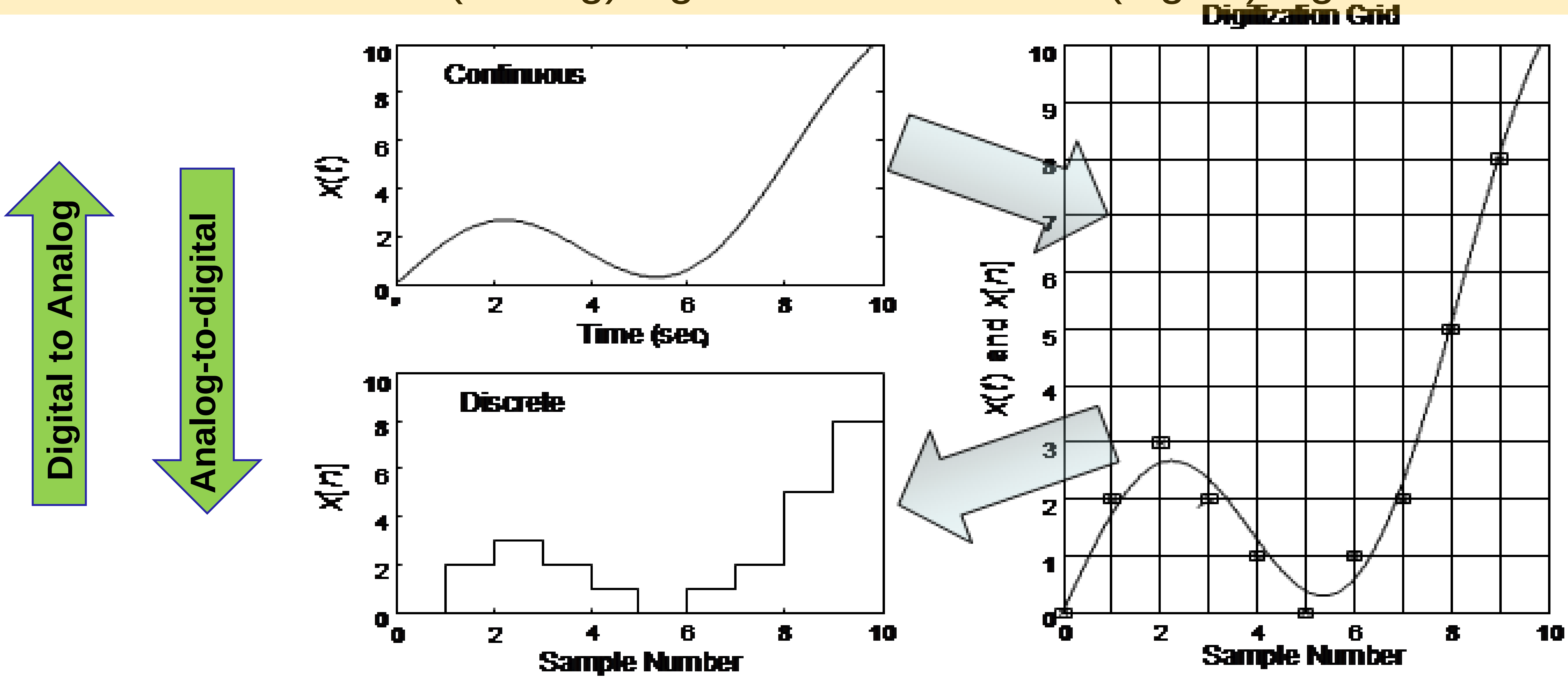
Example 2:

- Given an analog output signal whose voltage should range from 0 to 10 V, and an 8-bit digital encoding, provide the encodings for the following desired voltages: (a) 0 V, (b) 1 V, (c) 5.33 V, (d) 10 V, (e) What is the resolution of our conversion?

Analog-to Digital Conversion

Conversion between the analog and digital domain is done with special hardware devices know as analog-to-digital or digital-to-analog converters (ADC/DAC).

Continuous (analog) signal ⟷ Discrete (digital) signal



Is a signal that has been transformed from the continuous to the discrete domain the same?

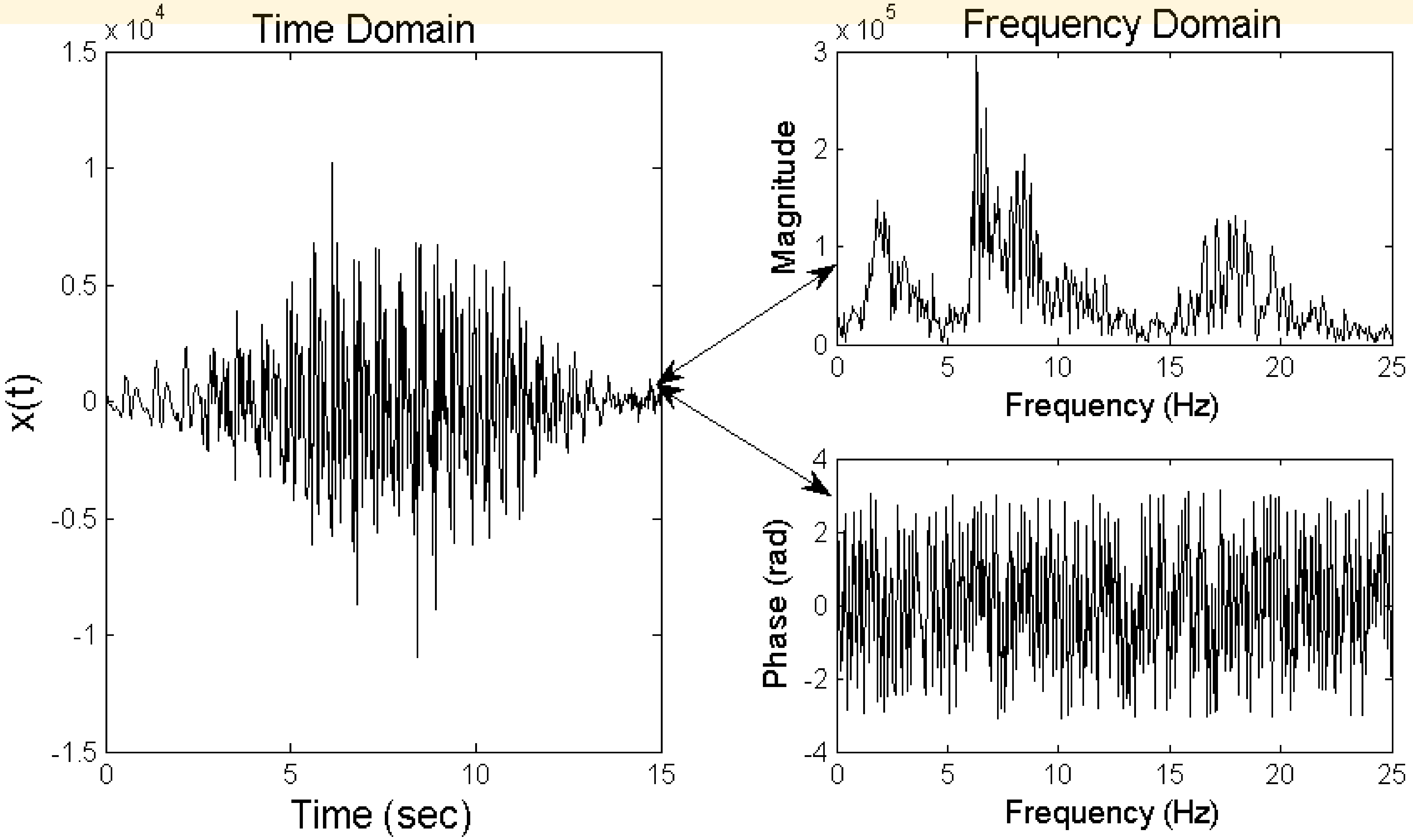
- Clearly not; as seen in the difference in the two different signals in the previous slide. Yet in signal analysis we often operate on discrete signals converted from an analog signal with the expectation (or assumption) that the discrete version is essentially the same as the original continuous signal.

- If they are not the same is there at least some meaningful relationship between the two? For now we will assume that all computer-based signals used in examples and problems are accurate representations of their associated continuous signals.

Time and frequency domain

Signals are represented in the frequency domain as two functions of frequency: a magnitude and a phase.

Example: A section of EEG (electrogastrogram) signal in the time domain (left) and frequency domain (right).



- The time domain representation is not easy to interpret, nor is the frequency phase domain.
- The magnitude does show some interesting features: peaks around 1-3 Hz and 16-18 Hz, and a large peak around 7-8 Hz. These peaks in frequency are well known to neurologists.

- Because the frequency domain signals are functions of frequency, there are called *spectra*, the magnitude spectrum and phase spectrum.
- Although the time and frequency domain representation hold the same information they do not store it in the same way so that one or the other may be more diagnostically useful in a given situation.
- It is fairly easy to transform from one domain to the other using techniques such as FFT.

Transformada Discreta de Fourier

$$X[k] = \sum_{n=0}^{N-1} x[n] \cdot e^{-j2\pi\frac{kn}{N}}$$

What does the DFT do?

•It **projects** the signal onto **complex waves** (complex exponentials) of different frequencies.

•It tells you **how much of each frequency** is present in the signal.

•The result X[k] is a **complex number**, which you can interpret as:

$$X[k] = A_k \cdot e^{j\phi_k}$$

Example 3: Transformada Discreta de Fourier

Dato del ejercicio:

- Señal: x[n]=[1,2,3,4]
- Número de muestras: N=4
- Período de muestreo: Ts=1s

- $X[0]$

$$X[0] = 1 + 2 + 3 + 4 = 10$$

- $X[1]$

$$X[1] = 1 \cdot e^{-j2\pi(1)(0)/4} + 2 \cdot e^{-j2\pi(1)(1)/4} + 3 \cdot e^{-j2\pi(1)(2)/4} + 4 \cdot e^{-j2\pi(1)(3)/4}$$

We evaluate the exponentials:

- $e^{-j2\pi(1)(0)/4} = 1$
- $e^{-j2\pi(1)(1)/4} = e^{-j\pi/2} = -j$
- $e^{-j2\pi(1)(2)/4} = e^{-j\pi} = -1$
- $e^{-j2\pi(1)(3)/4} = e^{-j3\pi/2} = j$

$$X[1] = 1 + 2(-j) + 3(-1) + 4(j) = 1 - 2j - 3 + 4j = -2 + 2j$$

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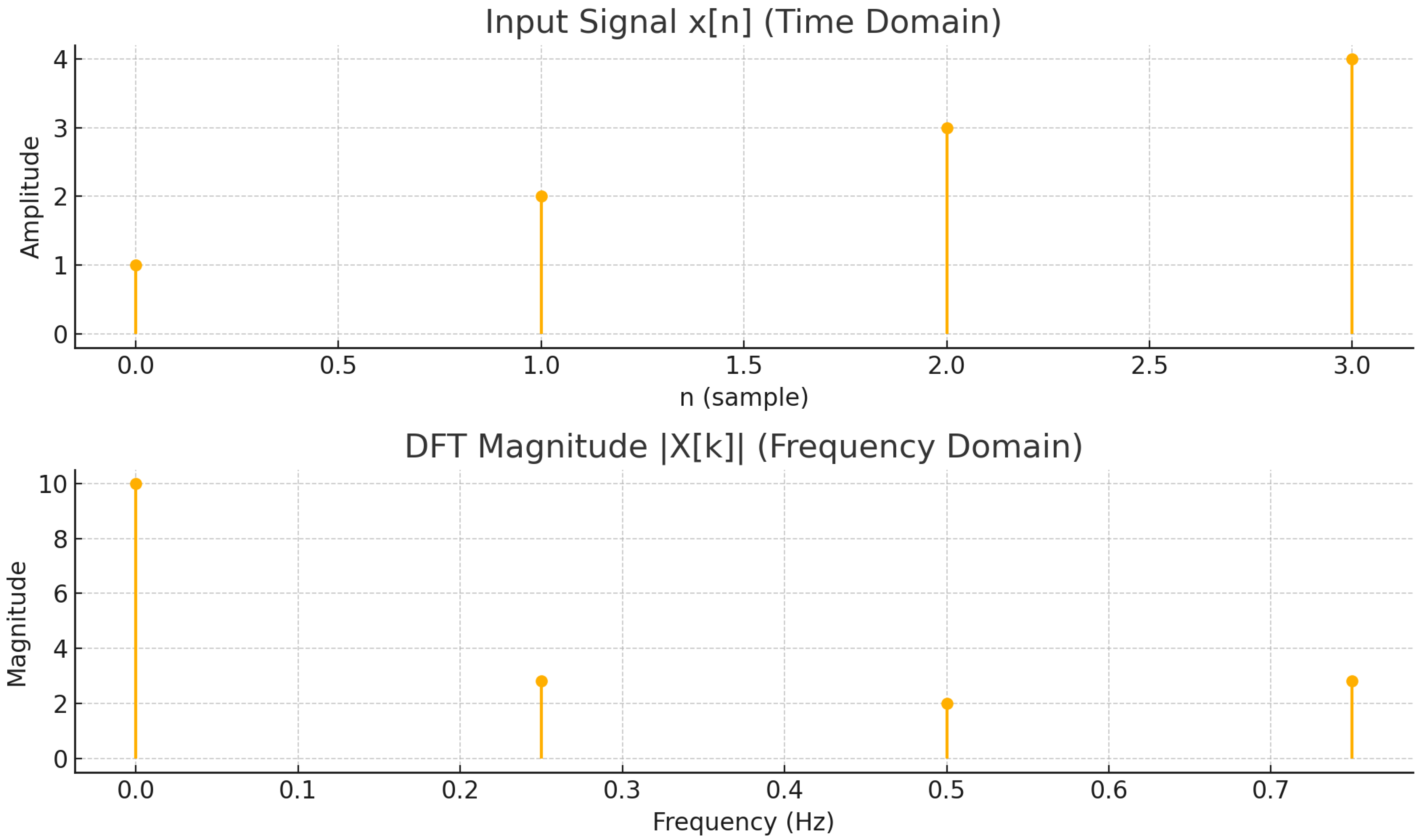
- $X[2]$

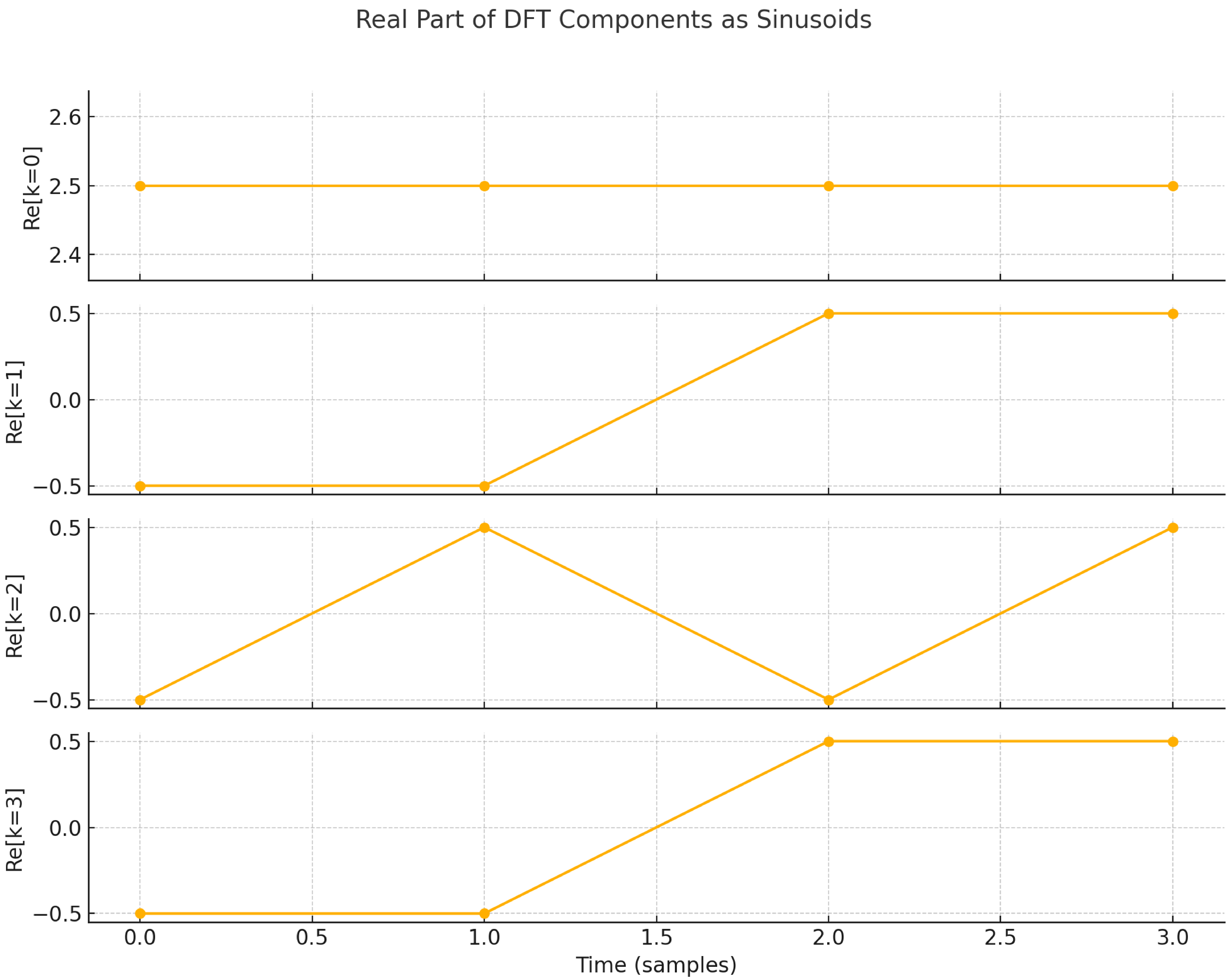
$$X[2] = 1 + 2(-1) + 3(1) + 4(-1) = 1 - 2 + 3 - 4 = -2$$

- $X[3]$

$$X[3] = 1 + 2(j) + 3(-1) + 4(-j) = 1 + 2j - 3 - 4j = -2 - 2j$$

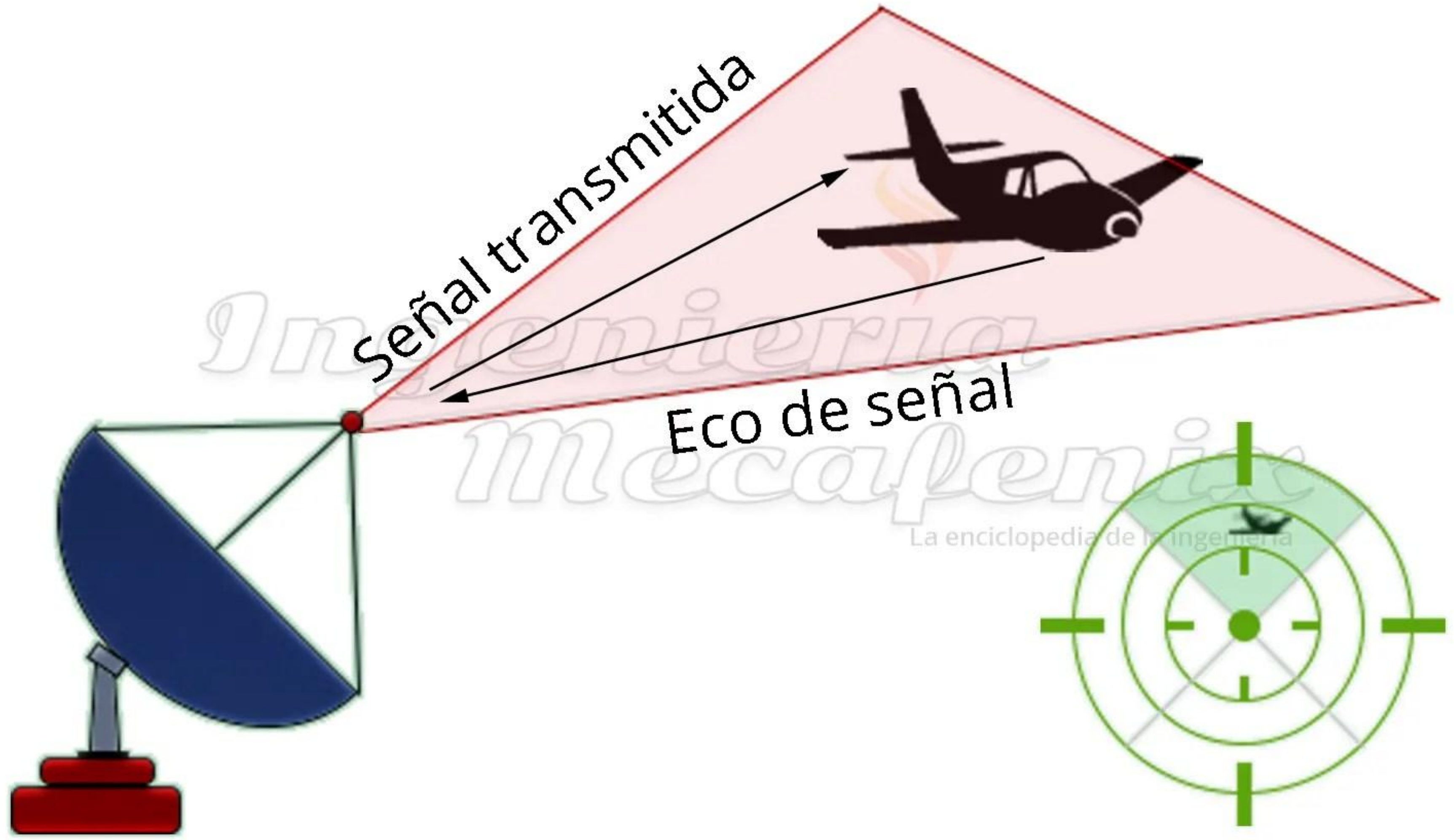
$$\boxed{\begin{gathered} X[0] = 10 \qquad \text{(DC component)} \\ X[1] = -2 + 2j \\ X[2] = -2 \\ X[3] = -2 - 2j \end{gathered}}$$


Input Signal x[n] (Time Domain)
Amplitude
0
1
2
3
4
0.0
0.5
1.0
1.5
2.0
2.5
3.0
n (sample)
DFT Magnitude |X[k]| (Frequency Domain)
Magnitude
0
2
4
6
8
10
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Frequency (Hz)


Real Part of DFT Components as Sinusoids
Re[k=0]
2.6
2.5
2.4
Re[k=1]
0.5
0.0
−0.5
Re[k=2]
0.5
0.0
−0.5
Re[k=3]
0.5
0.0
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (samples)

Inverse DFT (frequency to time)

In the same way we can apply the inverse transform, going from the frequency domain to the time domain.



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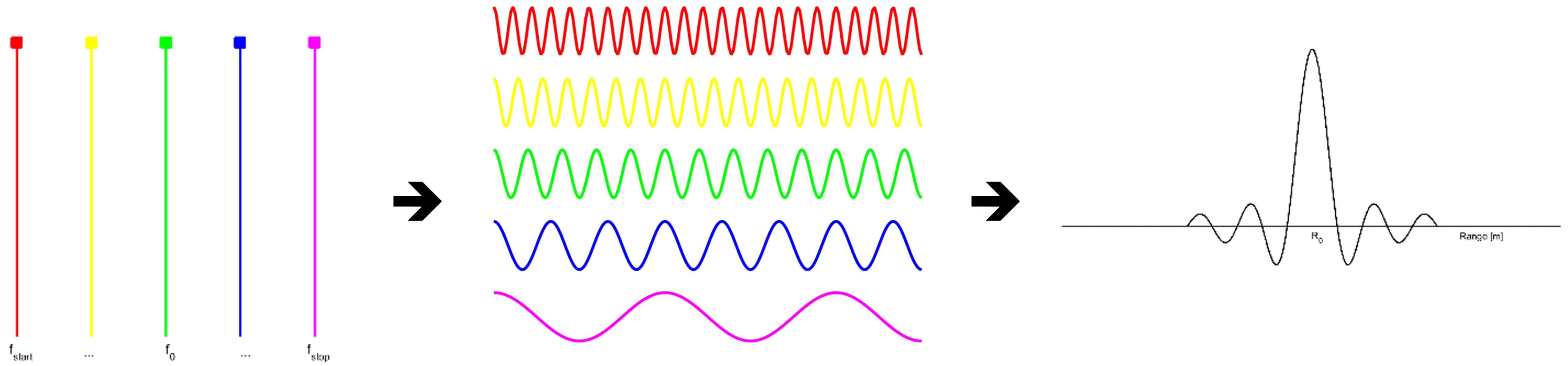
Application: SFCW radar



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Signals

Sensors

Conclusions

Sensors

- **Definition:** Measures some physical quantity and converts that measurement reading into a digital representation.

- **That digital representation is typically passed to another device for transformation into useful data that can be consumed by intelligent devices or humans.**
  - **Recall:** last lab session digitization and sampling.

Sensor Classification

Active or passive	based on whether they produce an energy output and typically require an external power supply (active) or whether they simply receive energy and typically require no external power supply (passive).
Invasive or non-invasive	based on whether a sensor is part of the environment it is measuring (invasive) or external to it (non-invasive).
Contact or no-contact	based on whether they require physical contact with what they are measuring (contact) or not (no-contact).
Absolute or relative	based on whether they measure on an absolute scale (absolute) or based on a difference with a fixed or variable refer- ence value (relative).
Area of application	based on the specific industry or vertical where they are being used.
How sensors measure	based on the physical mechanism used to measure sensory input (for example, thermoelectric, electrochemical, piezo- resistive, optic, electric, fluid mechanic, photoelastic).
What sensors measure	based on their applications or what physical variables they measure.

Sensor Types

Sensor Types	Description	Examples
Position	A position sensor measures the position of an object; the position measurement can be either in absolute terms (absolute position sensor) or in relative terms (displacement sensor). Position sensors can be linear, angular, or multi-axis.	Potentiometer, inclinometer, proximity sensor
Occupancy and motion	Occupancy sensors detect the presence of people and animals in a surveillance area, while motion sensors detect movement of people and objects. The difference between the two is that occupancy sensors generate a signal even when a person is stationary, whereas motion sensors do not.	Electric eye, radar
Velocity and acceleration	Velocity (speed of motion) sensors may be linear or angular, indicating how fast an object moves along a straight line or how fast it rotates. Acceleration sensors measure changes in velocity.	Accelerometer, gyroscope
Force	Force sensors detect whether a physical force is applied and whether the magnitude of force is beyond a threshold.	Force gauge, viscometer, tactile sensor (touch sensor)
Pressure	Pressure sensors are related to force sensors, measuring force applied by liquids or gases. Pressure is measured in terms of force per unit area.	Barometer, Bourdon gauge, piezometer
Flow	Flow sensors detect the rate of fluid flow. They measure the volume (mass flow) or rate (flow velocity) of fluid that has passed through a system in a given period of time.	Anemometer, mass flow sensor, water meter

Sensor Types	Description	Examples
Acoustic	Acoustic sensors measure sound levels and convert that information into digital or analog data signals.	Microphone, geophone, hydrophone
Humidity	Humidity sensors detect humidity (amount of water vapor) in the air or a mass. Humidity levels can be measured in various ways: absolute humidity, relative humidity, mass ratio, and so on.	Hygrometer, humistor, soil moisture sensor
Light	Light sensors detect the presence of light (visible or invisible).	Infrared sensor, photodetector, flame detector
Radiation	Radiation sensors detect radiation in the environment. Radiation can be sensed by scintillating or ionization detection.	Geiger-Müller counter, scintillator, neutron detector
Temperature	Temperature sensors measure the amount of heat or cold that is present in a system. They can be broadly of two types: contact and non-contact. Contact temperature sensors need to be in physical contact with the object being sensed. Non-contact sensors do not need physical contact, as they measure temperature through convection and radiation.	Thermometer, calorimeter, temperature gauge
Chemical	Chemical sensors measure the concentration of chemicals in a system. When subjected to a mix of chemicals, chemical sensors are typically selective for a target type of chemical (for example, a CO_2 sensor senses only carbon dioxide).	Breathalyzer, olfactometer, smoke detector
Biosensors	Biosensors detect various biological elements, such as organisms, tissues, cells, enzymes, antibodies, and nucleic acid.	Blood glucose biosensor, pulse oximetry, electrocardiograph

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Summary

- **We introduced the design perspective: defines things and computing stack requirements.**
- **We reviewed sensors and actuators:**
  - Fundamentals and types.
  - Definition of smart ”thing”.
- We highlighted the **relevance of the hardware platform for deployment of the IoT system as a sensor layer.**