

MEC302: Embedded Computer Systems

Theme II: Design of Embedded Computer Systems

Lecture 4 – Sensors and Actuators

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Lecture outline

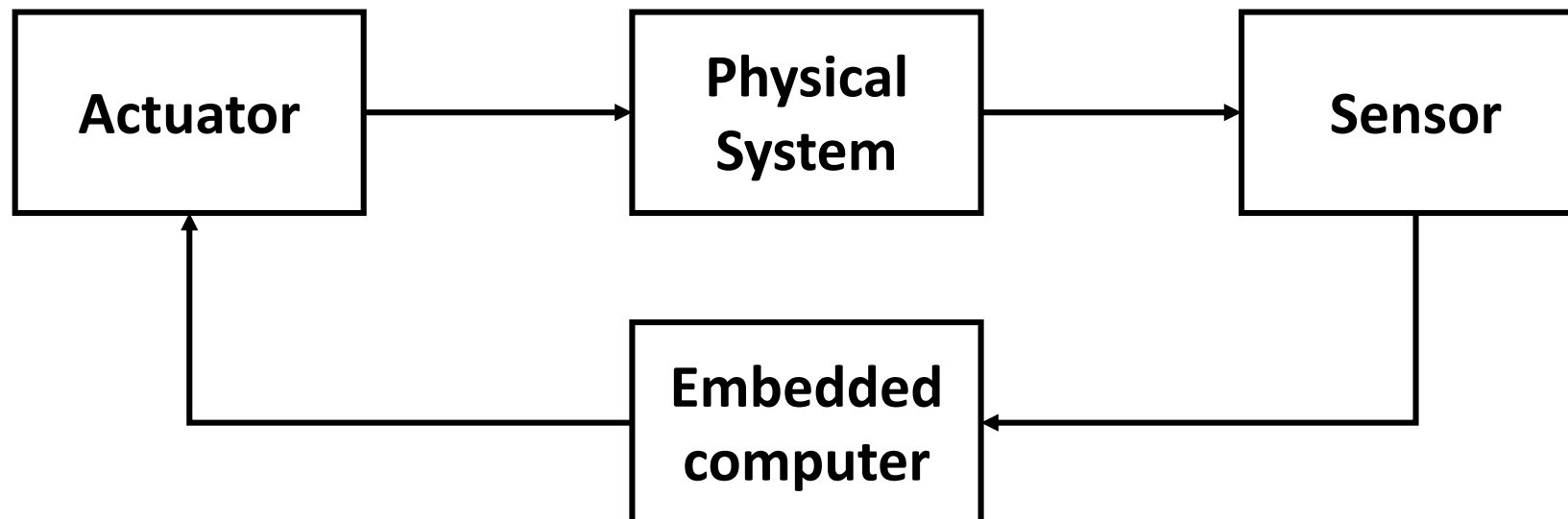
- Sensors and actuators (S&A)
- Interfacing S&A with computers/controllers
- Models of S&A
- Characteristics of S&A
- Signal conditioning (i.e., filtering)
- Common sensors and actuators

Sensors and actuators (S&A)

执行器

Let us define what do we mean by **sensors** and **actuators**:

- A **sensor** is a device that detects or measures a physical property or quantity – produces voltage or current proportional to the physical quantity being measured (e.g., microphone, accelerometer, temperature sensor).
- An **actuator** is a device that alters a physical property or quantity – driven by a voltage or current applied to it (e.g., speaker, LED, electric motor).
- They both serve as bridges between the physical and the cyber worlds.



Interfacing S&A with computers/controllers

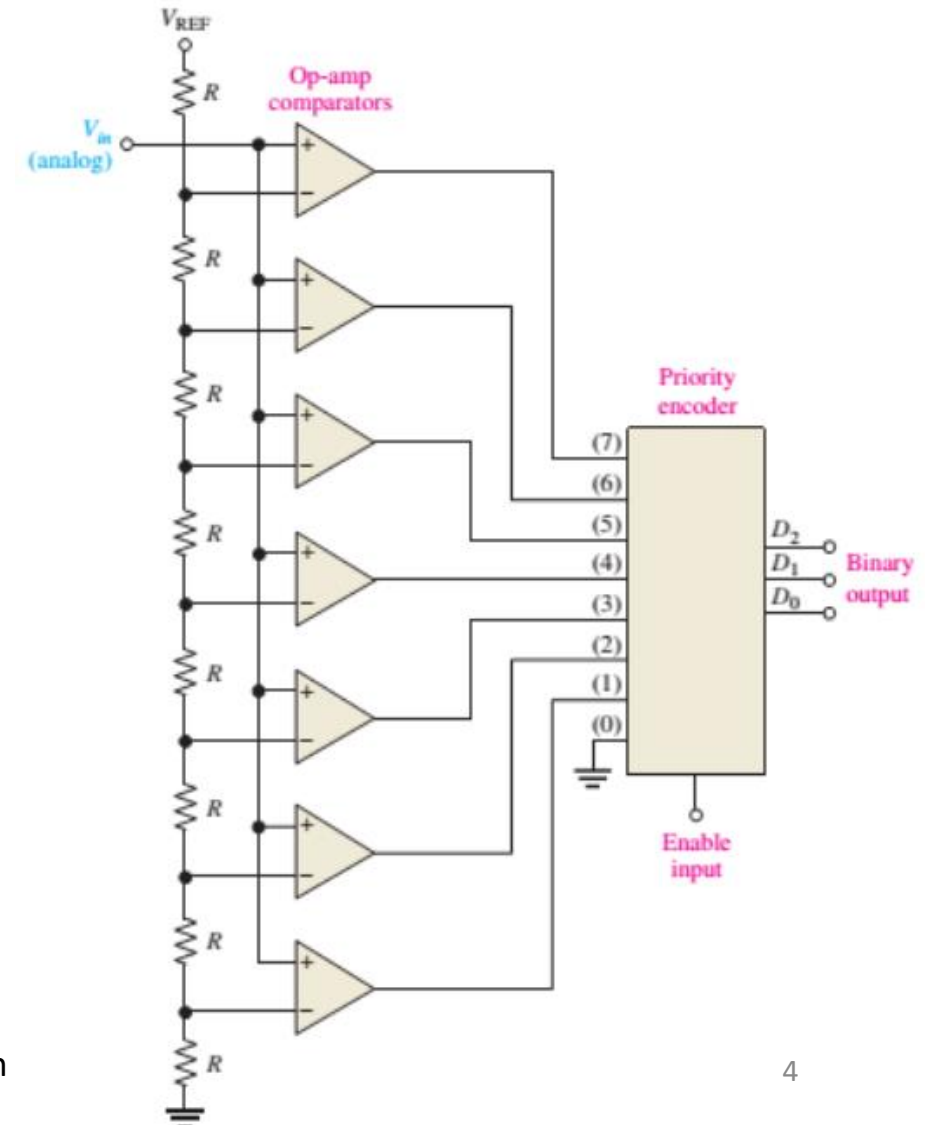
To interface with computers/controllers, **sensors** and **actuators** need to be compatible with them (i.e., voltage, current and data).

For data compatibility

- **Analog-to-Digital Converter (ADC)** converts continuous signal to binaries (for sensors).
- **Digital-to-Analog Converter (DAC)** converts binaries to a continuous signal (for actuators).

Devices packaged with ADC or DAC are called **Digital**.

Analog-to-digital converter (ADC) [2]:



Models of S&A

In **ECS**, **sensors** produce output (typically, voltage or current) to characterize measured quantity.

Most sensors are either **linear** or **affine**:

- **Linear sensor** outputs: $f(x(t)) = a x(t)$;
 - **Affine sensor** outputs: $f(x(t)) = a x(t) + b$,
- where $x(t) \in \mathbb{R}$ – measured physical quantity;
 a – proportionality constant (ie,sensitivity); b – bias.

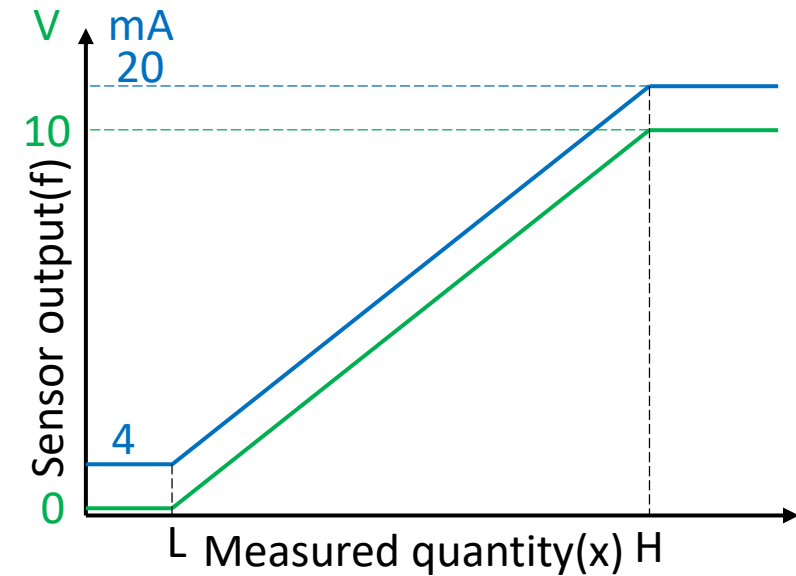
Generally, a sensor output can be modelled:

$$f(x(t)) = \begin{cases} a x(t) + b & \text{if } L \leq x(t) \leq H \\ a H + b & \text{if } x(t) > H \\ a L + b & \text{if } x(t) < L, \end{cases}$$

where $a, b, L, H \in \mathbb{R}$; $[L, H]$ – operating range.

#Typical **sensors** in industry are:

- Voltage output (e.g., 0-10V)
- Current output (e.g., 4-20mA)



L – lowest quantity distinguished by a sensor;
 H – Highest quantity distinguished by a sensor.

Characteristics of S&A

Quantization:

- A **digital sensor (actuator)** represents (can read) a physical quantity using an n -bit number, e.g.:

$$f: \mathbb{R} \rightarrow \{0, 1, \dots, 7\}.$$

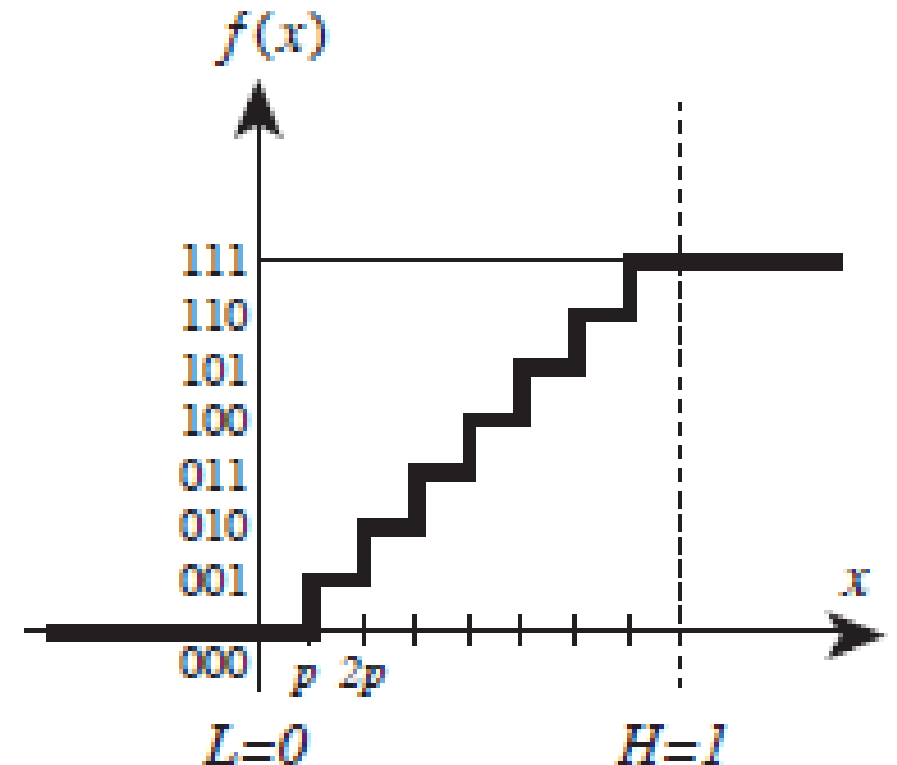
- The **precision** of such sensors/actuators is the smallest absolute difference between two values of a physical quantity whose readings are distinguishable:

$$p = \frac{H - L}{2^n}.$$

- **Dynamic range** is the ratio between the largest and the smallest values that a digital sensor can distinguish:

$$D = \frac{H-L}{p} \text{ or } D_{dB} = 20 \log_{10} \left(\frac{H-L}{p} \right)$$

Sensor Distortion Function (SDF)
(e.g., 3-bit digital sensor output):



Characteristics of S&A

Noise

In practice, the **measurement** we obtain from a sensor is a composition of **signal** and **noise**:

- The **signal** is the meaningful information that we're actually trying to detect from a sensor;
- The **noise** is the random, unwanted variation or fluctuation that interferes with the signal.

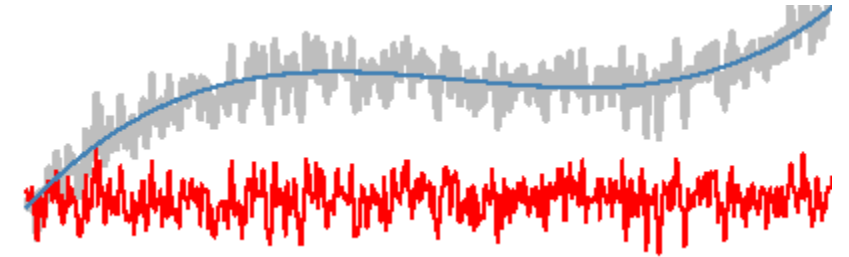
When accounting for noise, **SDF** can be modelled as additive to noise:

$$f(x(t)) = x(t) + n(t).$$

Hence, by definition, **noise** is:

$$n(t) = f(x(t)) - x(t)$$

#**Measurement, signal, and noise** illustration [3]:



The **measurement** quality is characterized with **signal to noise ratio (SNR)**:

$$SNR_{dB} = 20 \log_{10}(X/N),$$

where X is the input signal RMS;

N is the noise Root Mean Square (RMS).

The **noise** RMS (i.e., **noise power**) is found:

$$N = \lim_{T \rightarrow \infty} \sqrt{\frac{1}{2T} \int_{-T}^T (n(\tau))^2 d\tau}.$$

Characteristics of S&A

Sampling rate

A digital sensor samples the physical quantity $x(t)$ at particular points in time to create a discrete signal (modelled as a function $s: \mathbb{Z} \rightarrow \mathbb{R}$):

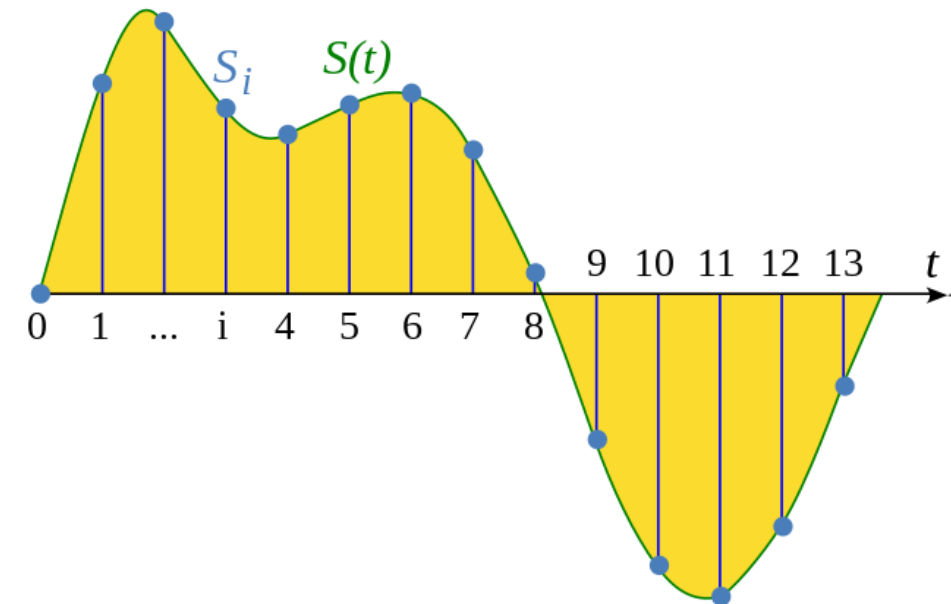
$$s(n) = f(x(nT)) \quad \forall n \in \mathbb{Z},$$

where T is the **sampling interval** (fixed for **uniform sampling**).

The **sampling rate** is $R = 1/T$, measured in Hertz (samples per second).

Obviously, the higher R , the more accurately a signal can be represented in a discrete form.

Signal sampling illustration [4]:



Characteristics of S&A

Together with **precision** (range and number of bits), **sample rate** determines a quality of the measurement.

The higher the **sampling rate** R , the more costly it becomes to provide more bits in an ADCs (the same for DACs):

$$C \propto R b$$

where C is the cost* and b is number of bits.

To accurately capture the signal, it is better to know its characteristics beforehand (e.g., how rapidly it changes, by what amount, etc.).

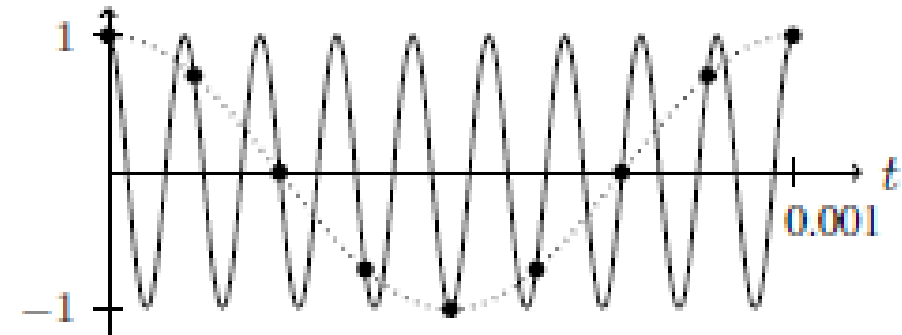
* – **Computational cost** is a measure of the number and the complexity of tasks that a processor performs per time step. By the end of the day, it leads to monetary costs of computational hardware.

[5] Nyquist–Shannon sampling theorem, en.wikipedia.org/wiki/Nyquist%E2%80%93Shannon_sampling_theorem

#Consider two signals:

- $x(t) = \cos(2,000 \pi t)$
- $y(t) = \cos(18,000 \pi t)$

And sampling rate at 8 kHz.



– Effect of aliasing.

Rule of thumb [5], *choose the sampling rate at least 2 times higher than the most rapid change of the measured signal.*

Characteristics of S&A

Harmonic distortion

In practice, S&A are **nonlinear** even within an **operating range**, which is usually described with **harmonic distortion**:

$$f(x(t)) = a x(t) + b + \sum_{n=2}^N d_n (x(t))^n,$$

where $n \in \mathbb{N}$ is the harmonic distortion order, $d_n \in \mathbb{R}$ is its magnitude.

#Consider a purely sinusoidal signal (e.g., sound):

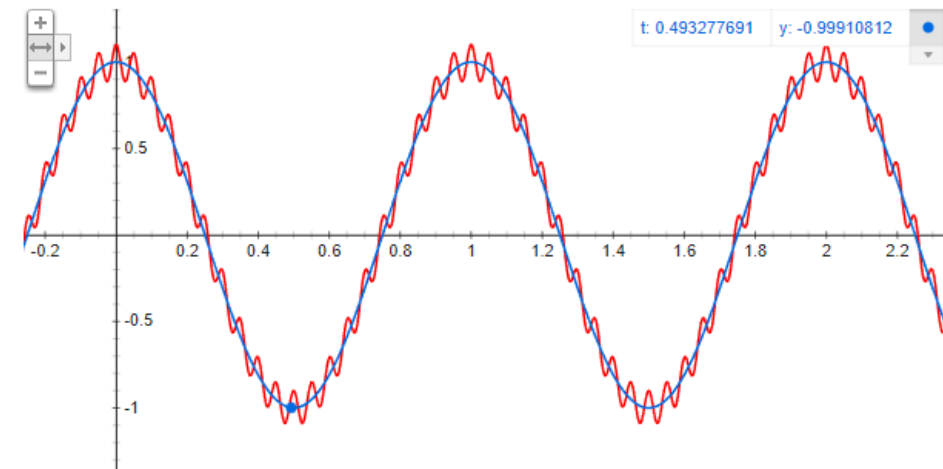
$$x(t) = \cos(\omega_0 t)$$

For $d_2 \neq 0$, the sensor will capture:

$$f(x(t)) = a \cos(\omega_0 t) + b + \frac{d_2}{2} + \frac{d_2}{2} \cos(2\omega_0 t)$$

For example, 20th harmonic distortion of 10% (relative to the base signal):

Графики функций $\cos(2\pi t)$, $\cos(2\pi t) + 0.1 \cos(2\pi \cdot 20t)$

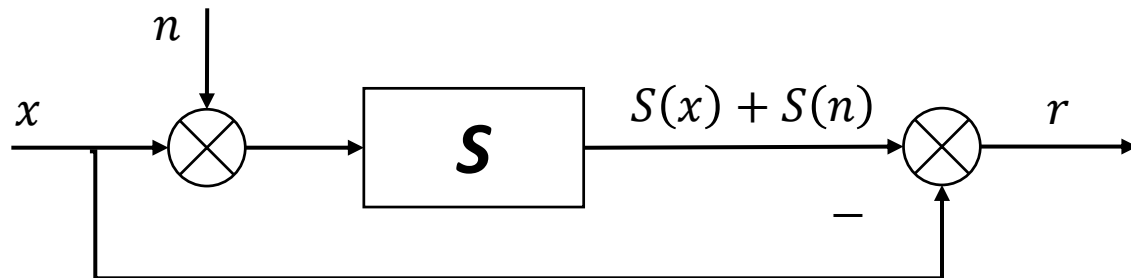


Signal conditioning

Frequency selective filtering can be applied to reduce or eliminate the noise and distortions from nonlinearities (i.e., **signal conditioning**).

Fourier theory states that a signal is an additive composition of sinusoidal signals of different frequencies (i.e., Fourier series).

#Consider the measurement $x(t) + n(t)$ going through an LTI system S (i.e., **conditioning filter**)



The goal is to find such S to maximize **SNR**:

$$SNR_{dB} = 20 \log_{10} \left(\frac{X}{R} \right)$$

Signal conditioning

Low-pass filter principle

#Let us consider a **low-pass filter** and its **frequency response characteristic** [6] →

Its ODE:

$$V_{out}(t) = V_{in}(t) - RC \frac{dV_{out}(t)}{dt},$$

where **cut-off frequency** $f_c = 1/(2\pi RC)$.

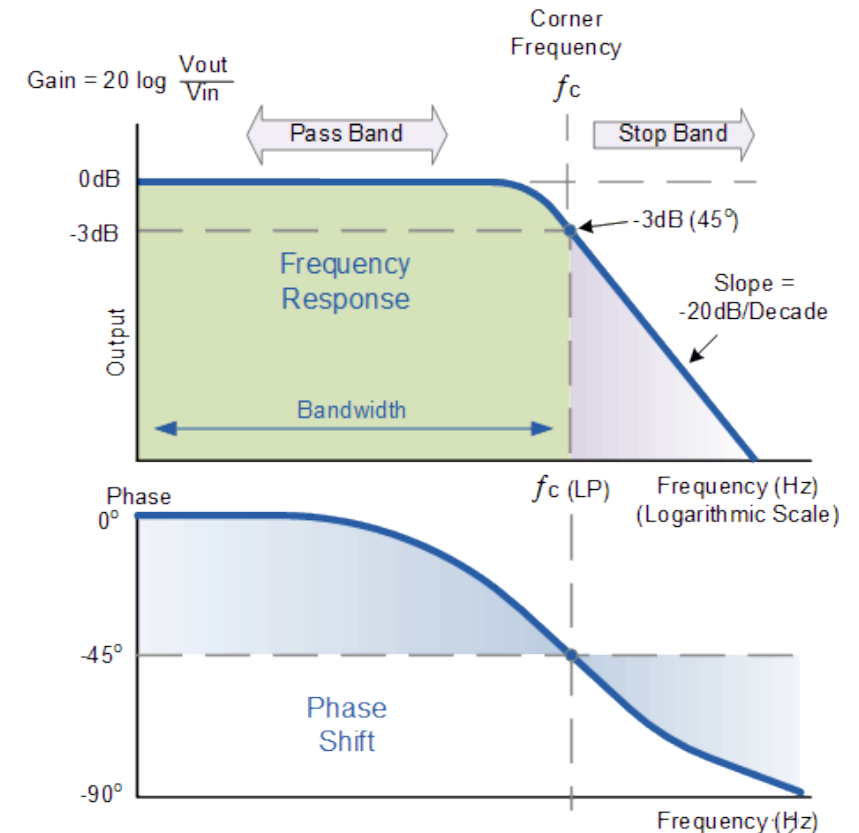
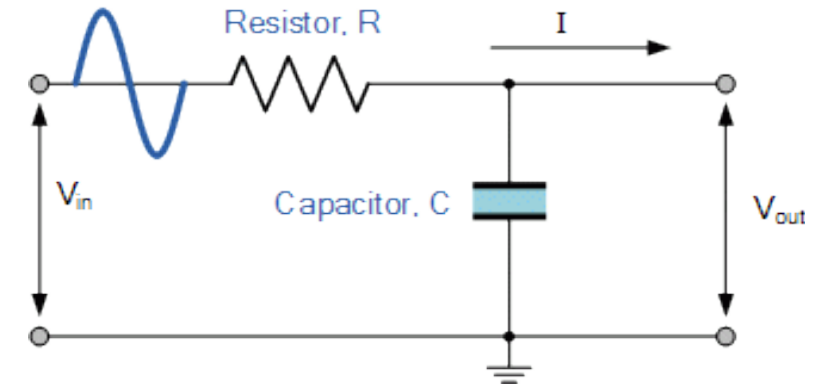
Its difference equation (for $\Delta t \rightarrow 0$):

$$V_{out}(t) = V_{in}(t) - RC \frac{V_{out}(t) - V_{out}(t - \Delta t)}{\Delta t}$$

With discrete time sampling:

$$V_{out}(n) = V_{out}(n - 1) + \alpha(V_{in}(n) - V_{out}(n - 1))$$

where $\alpha = \Delta t / (\Delta t + RC)$.



Common sensors

Common sensors include:

- Position and velocity sensors
 - Accelerometers;
 - Global Positioning System (GPS);
- Rotation
 - Accelerometers;
 - Gyroscopes;
- Sound
 - Microphone
- Distance
 - Echo sounder (ultrasonic rangefinder);
 - Capacitive proximity sensor.

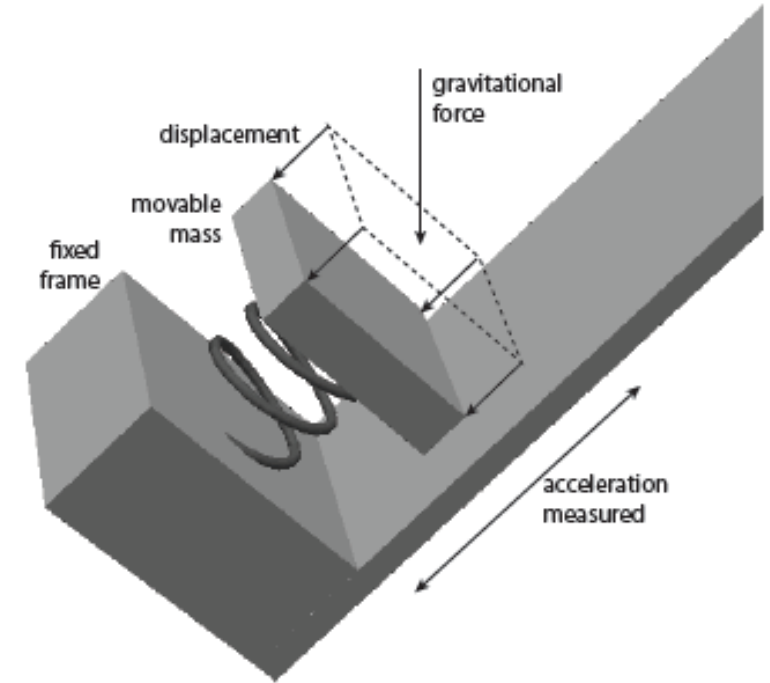
Common sensors

Accelerometer principle

- An **accelerometer** is a sensor that measures **proper acceleration***.
- If the frame is stationary (fixed), **accelerometer** can measure **tilt**:

$$\theta = \arcsin\left(\frac{k}{g} \Delta x\right).$$

- Three orthogonal **accelerometers** can give both **acceleration** and **orientation** in 3-D space.



Spring equation:

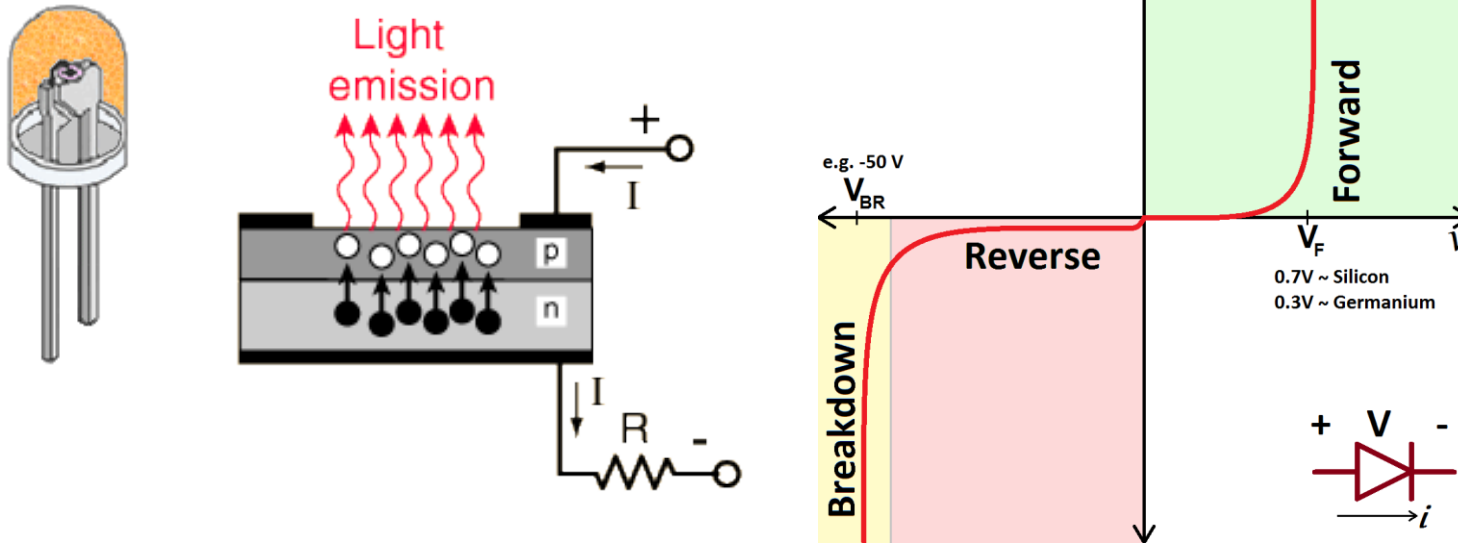
$$F = -k x$$

* – Acceleration of an object as observed by an observer in free fall

Common Actuators

Light-Emitting Diodes (LEDs) principle

LED illustrations [7]:

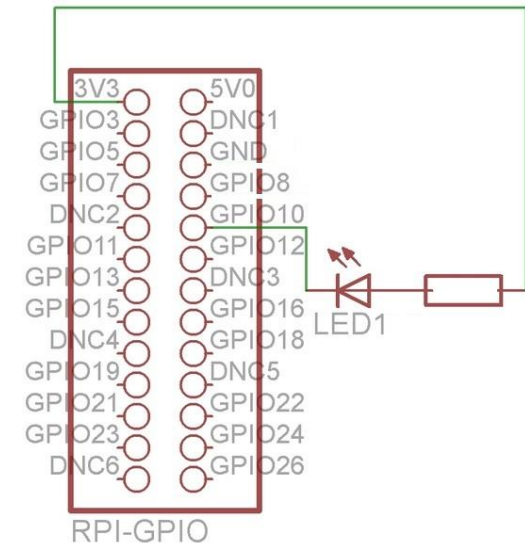


#Consider a μC powered by 3V coin bat. and 18mA is the max current can go through a DIO:

- How to connect a red diode (2V drop Forward) to DIO?
- What is the minimum resistor value required?

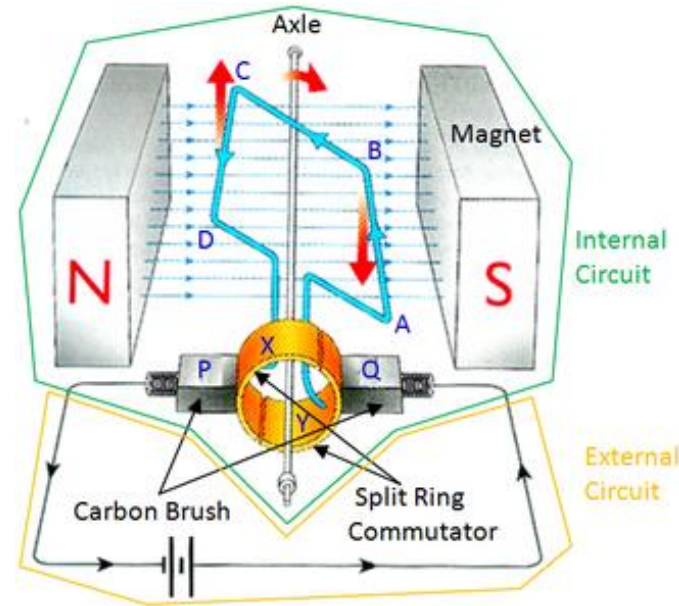
Connection to a chip GPIO:

- Limited current and voltage need to be respected



Common Actuators

Electric motors
(illustration [8]):

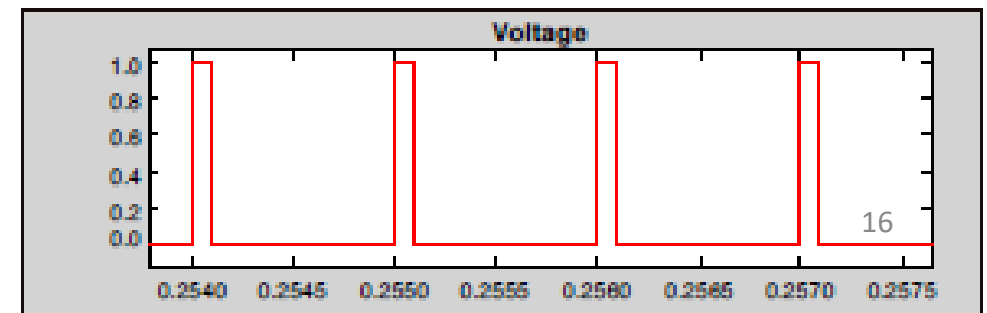
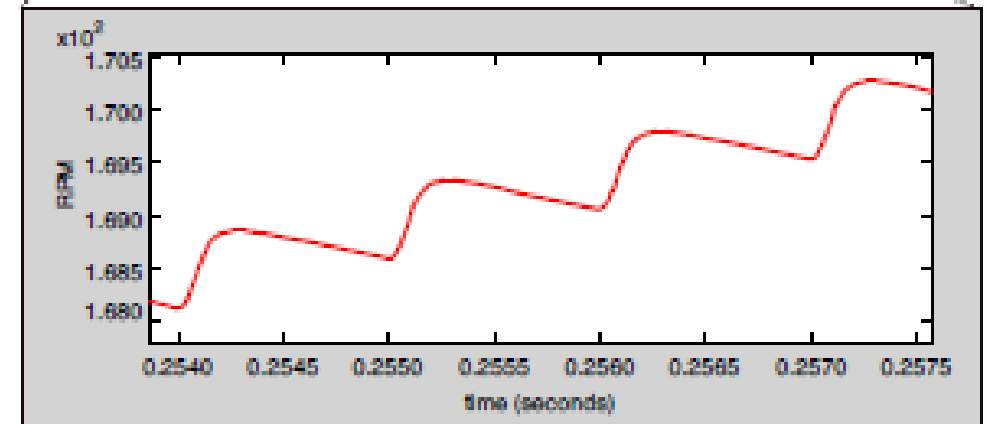
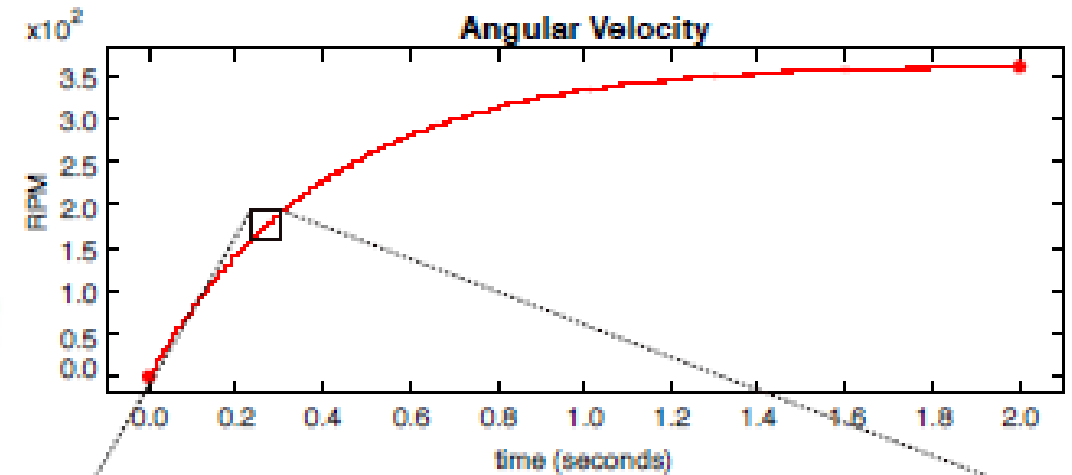


It is an electro-mechanic system:

$$\begin{cases} V(t) = R i(t) + L \frac{di(t)}{dt} + k_b \omega(t) \\ T(t) = I \frac{d\omega(t)}{dt} = k_T i(t) - \eta \omega(t) - \tau(t) \end{cases}$$

where k_b back EMF constant, $T(t)$ is torque, I moment of inertia, k_T torque constant, η friction coef., $\tau(t)$ load (torque).

PWM control of a DC motor



To sum up

- **Sensors** and **actuators** connect the cyber world with the physical world:
 - While **Sensors** measure physical quantities, **Actuators** alter them;
- **Analog-to-Digital** and **Digital-to-Analog Converters (ADC and DAC)** interface continuous systems (S&C) with digital ones (computation);
- **Sensors** and **Actuators** share certain (similar) characteristics:
 - **Linearity** and **affinity** (i.e., models);
 - **Nonlinearity** in both output quantity (i.e., quantization and saturation) and sampling (sampling rate – \exists rule of thumb to choose it);
 - **Noise** and **harmonic distortion** (can be effectively reduced/eliminated with Band-pass filters.
- Common **Sensors** and **Actuators**: accelerometer, LED and electric motor.

The End

See you next time (March 20)