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

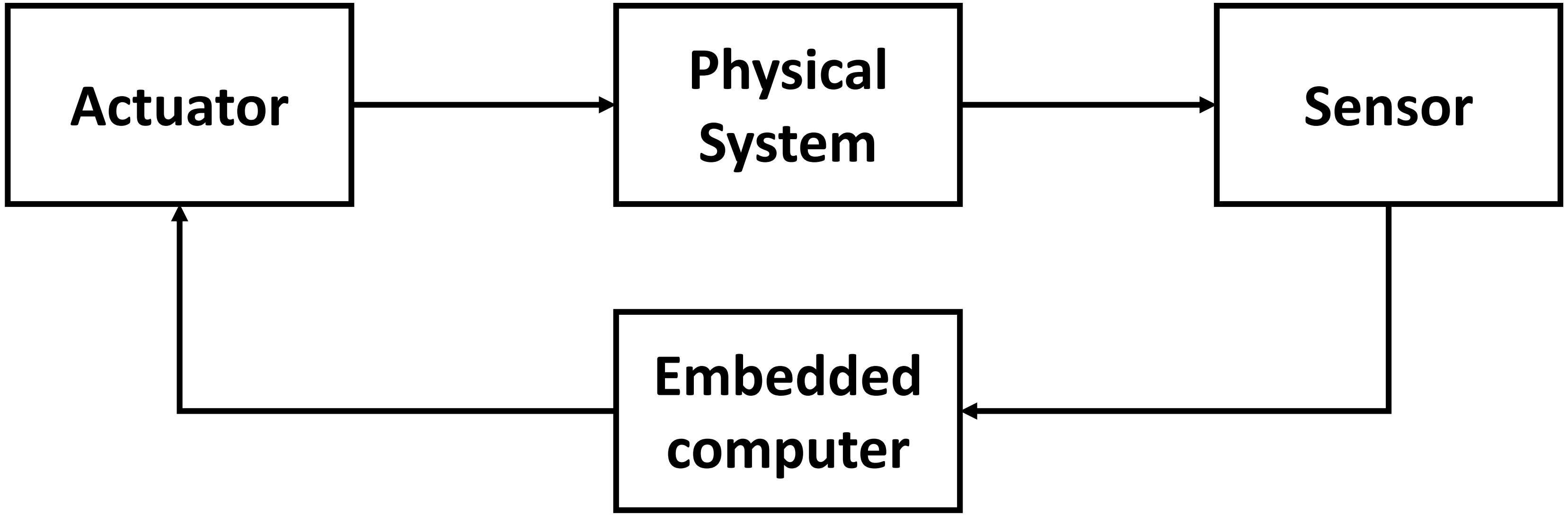
Sensors and actuators (S&A)

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).

actuator 和sensor 作为物理和网络的通道

- They both serve as bridges between the physical and the cyber worlds.



Interfacing S&A with computers/controllers

sensor和actuator需要
对电脑和控制器兼容

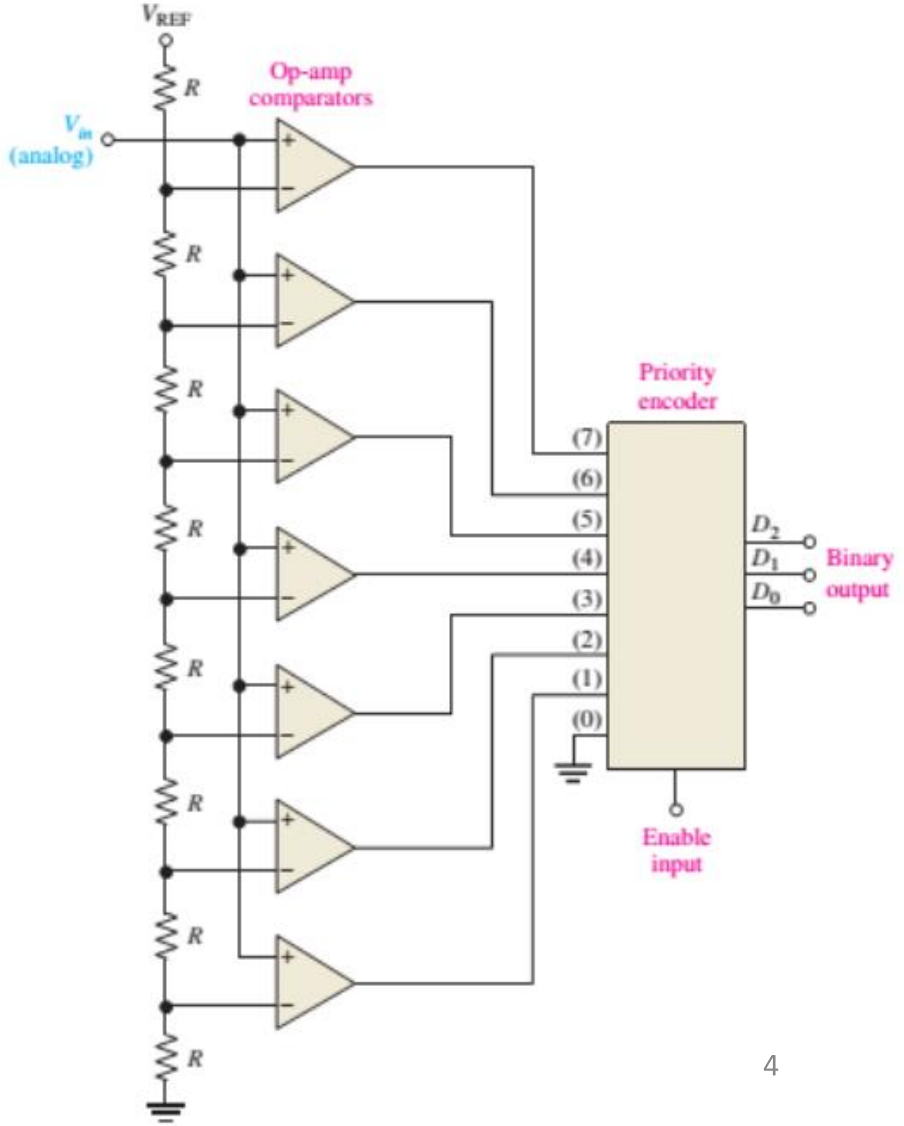
To interface with computers/controllers, **sensors** and **actuators** need to be compatible with them (i.e., voltage, current and data).

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]:



[2] Al-Yoonus, Marwan. (2019). Understanding analog to digital conversion and pulse width modulation using Arduino.. 10.13140/RG.2.2.10299.57120.

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: $f\big(x(t)\big) = a\,x(t)$;
- **Affine sensor** outputs: $f\big(x(t)\big) = a\,x(t) + b$,

where $x(t) \in \mathbb{R}$ – measured physical quantity;

a – proportionality constant (ie,sensitivity); b – bias.

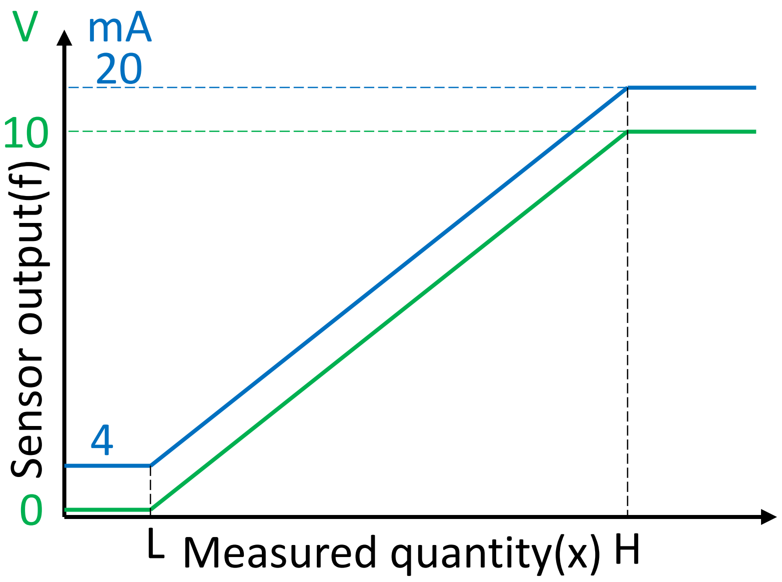
Generally, a sensor output can be modelled:

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

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)



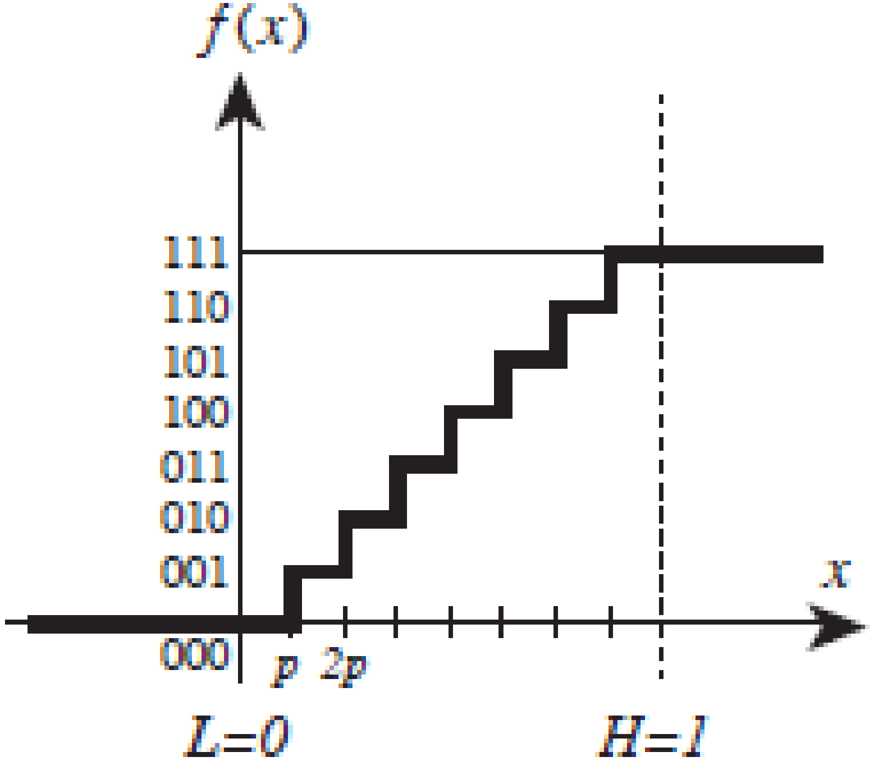
L – lowest quantity distinguished by a sensor;
H – Highest quantity distinguished by a sensor.

Characteristics of S&A

Quantization:

- A **digital sensor (actuator)** represents (can read) a physical quantity using an *n*-bit number, e.g.:
$$f: \mathbb{R} \to \{0,1,\ldots,7\}.$$
- 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.

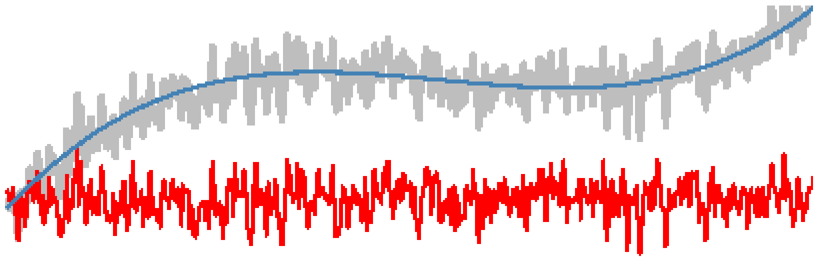
When accounting for noise, **SDF** can be modelled as additive to noise:

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

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

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

#**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:

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

[3] https://www.realclimate.org/index.php/archives/2012/12/what-is-signal-and-what-is-noise/

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 $s: \mathbb{Z} \rightarrow \mathbb{R}$):

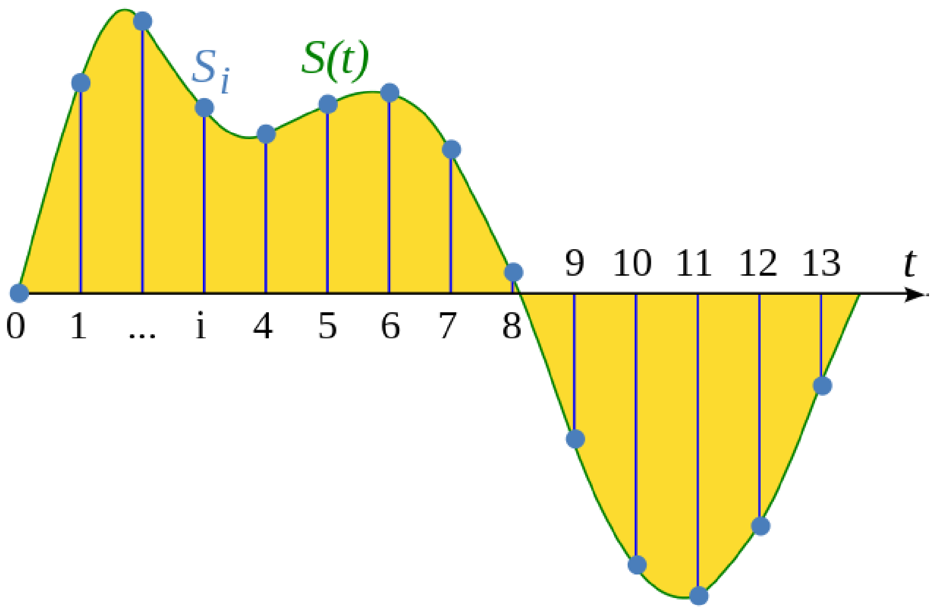
$$s(n) = f\big(x(nT)\big)\ \forall\, n \in \mathbb{Z},$$

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]:



[4] https://en.wikipedia.org/wiki/Sampling_%28signal_processing%29

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):

$$C \propto R\, b$$

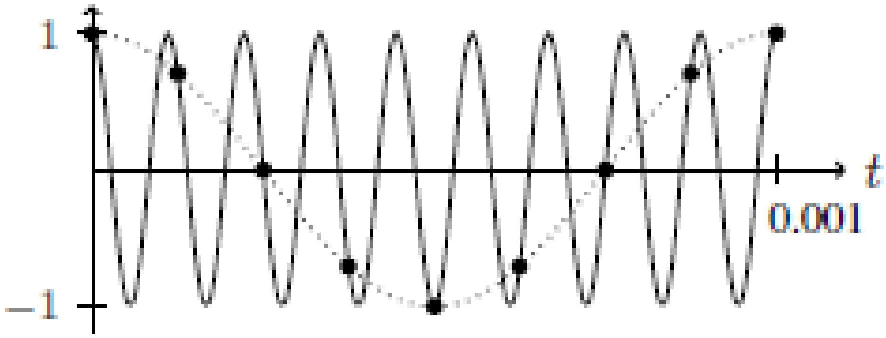
where C is the cost* and b is number of bits.

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

#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.*

* – **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

Characteristics of S&A

Harmonic distortion

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

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

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):

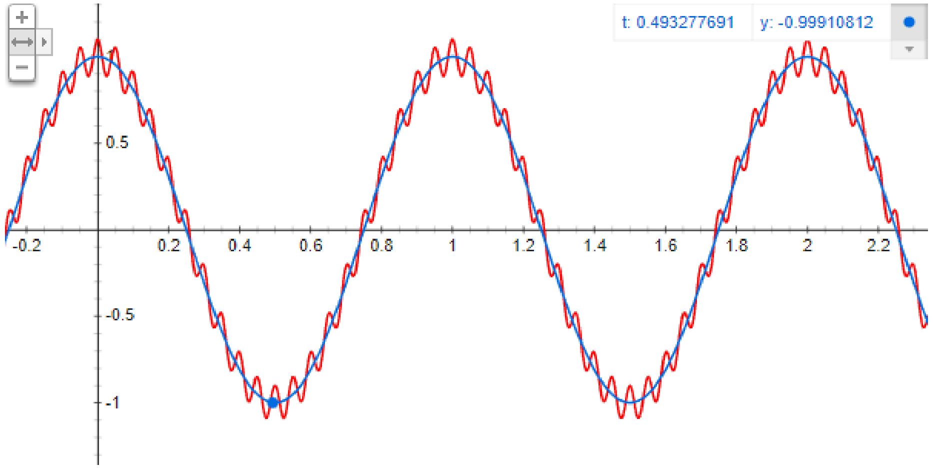
$$x(t) = \cos(\omega_0 t)$$

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

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

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

Графики функций cos(2*π*t), cos(2*π*t)+0.1*cos(2*π*20*t)



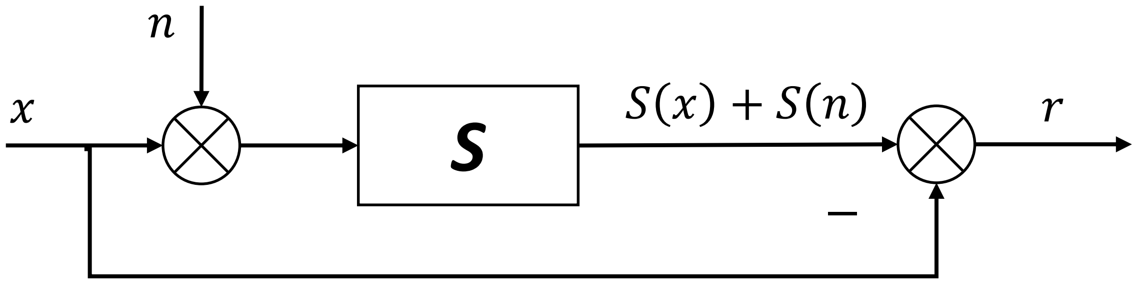
Signal conditioning

频率选择性滤波 可以应用于减少或消除 由非线性产生的噪声和畸变。

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**)



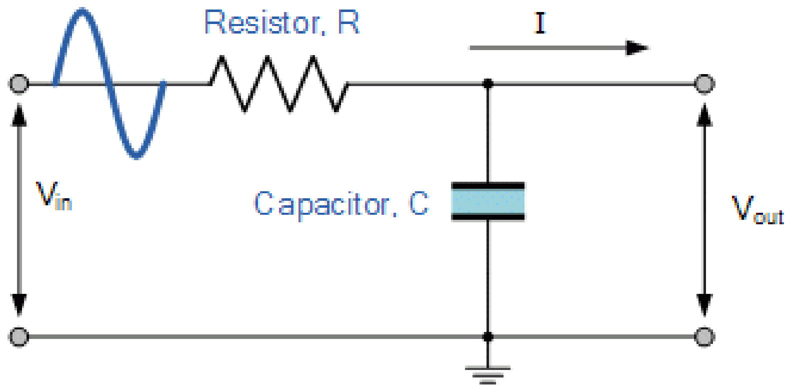
The goal is to find such $\boldsymbol{S}$ to maximize **SNR**:

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

Signal conditioning

Low-pass filter principle

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



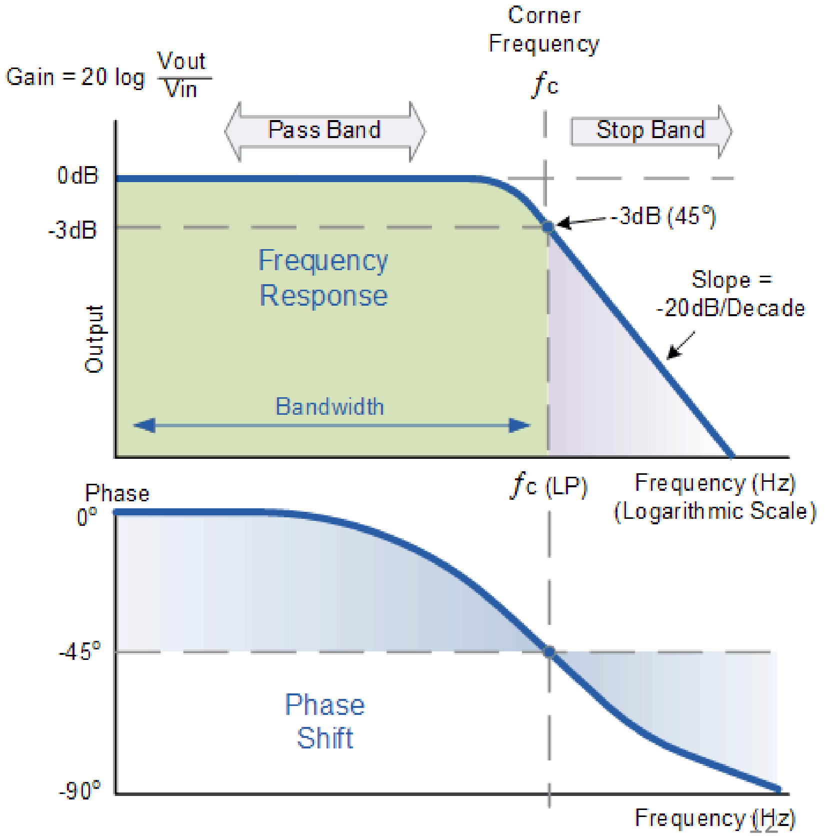
Its ODE:

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

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:

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

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

[6] Electronics tutorials, Passive Low Pass Filter, https://www.electronics-tutorials.ws/filter/filter_2.html

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.

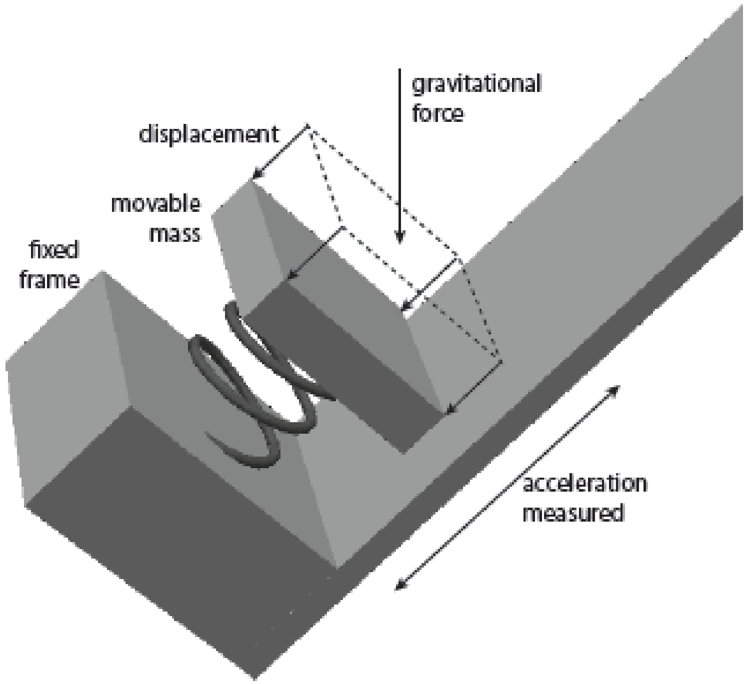
Common sensors

Accelerometer principle

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

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

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



Spring equation:

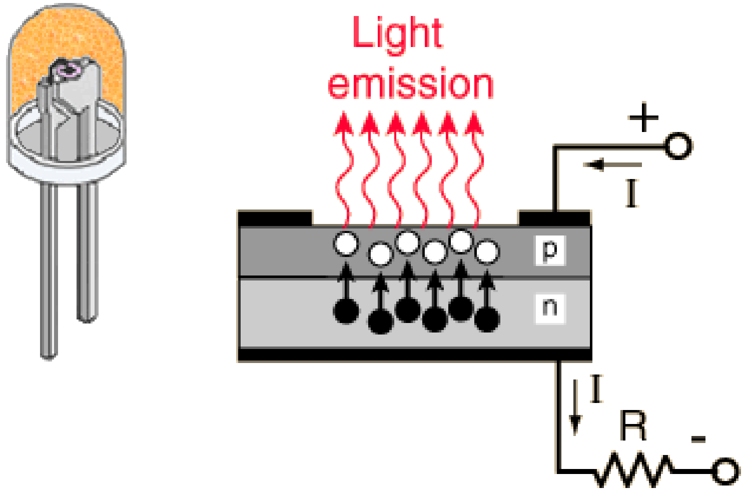
$$F = -k\,x$$

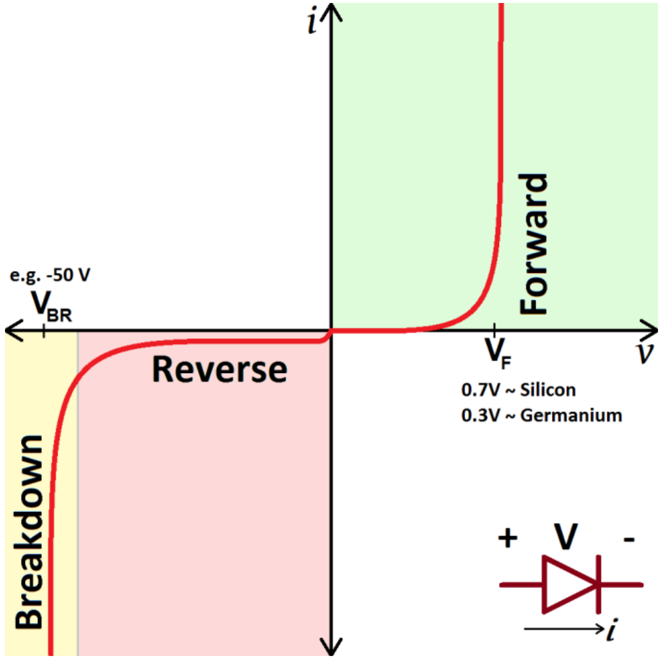
* – Acceleration of an object as observed by an observer in free fall

Common Actuators

Light-Emitting Diodes (LEDs) principle

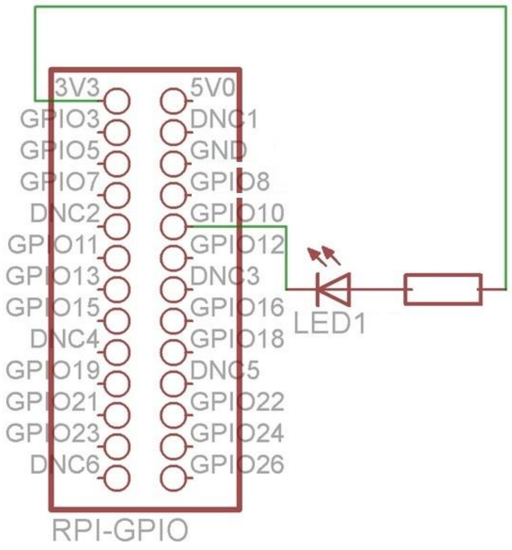
LED illustrations [7]:





Connection to a chip GPIO:

- Limited current and voltage need to be respected



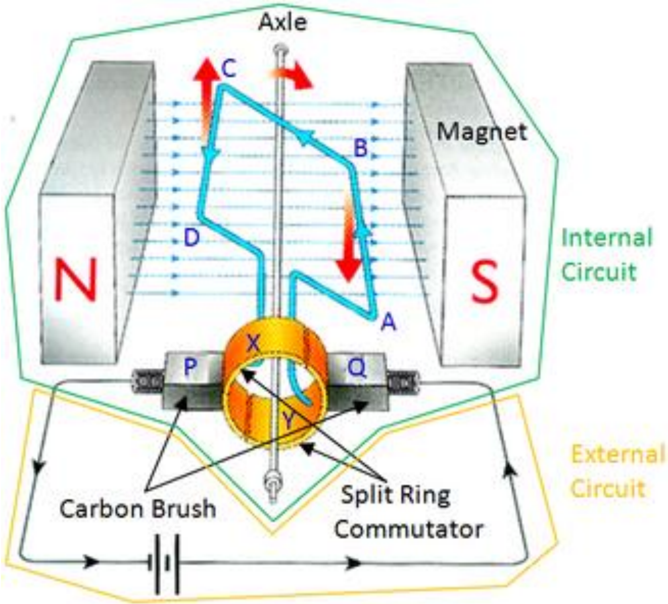
#Consider a µC powered by 3V coin bat. and 18mA is the max current can go through a DIO:

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

[7] Light Emitting Diode Structure, http://hyperphysics.phy-astr.gsu.edu/hbase/Electronic/led.html

Common Actuators

Electric motors (illustration [8]):

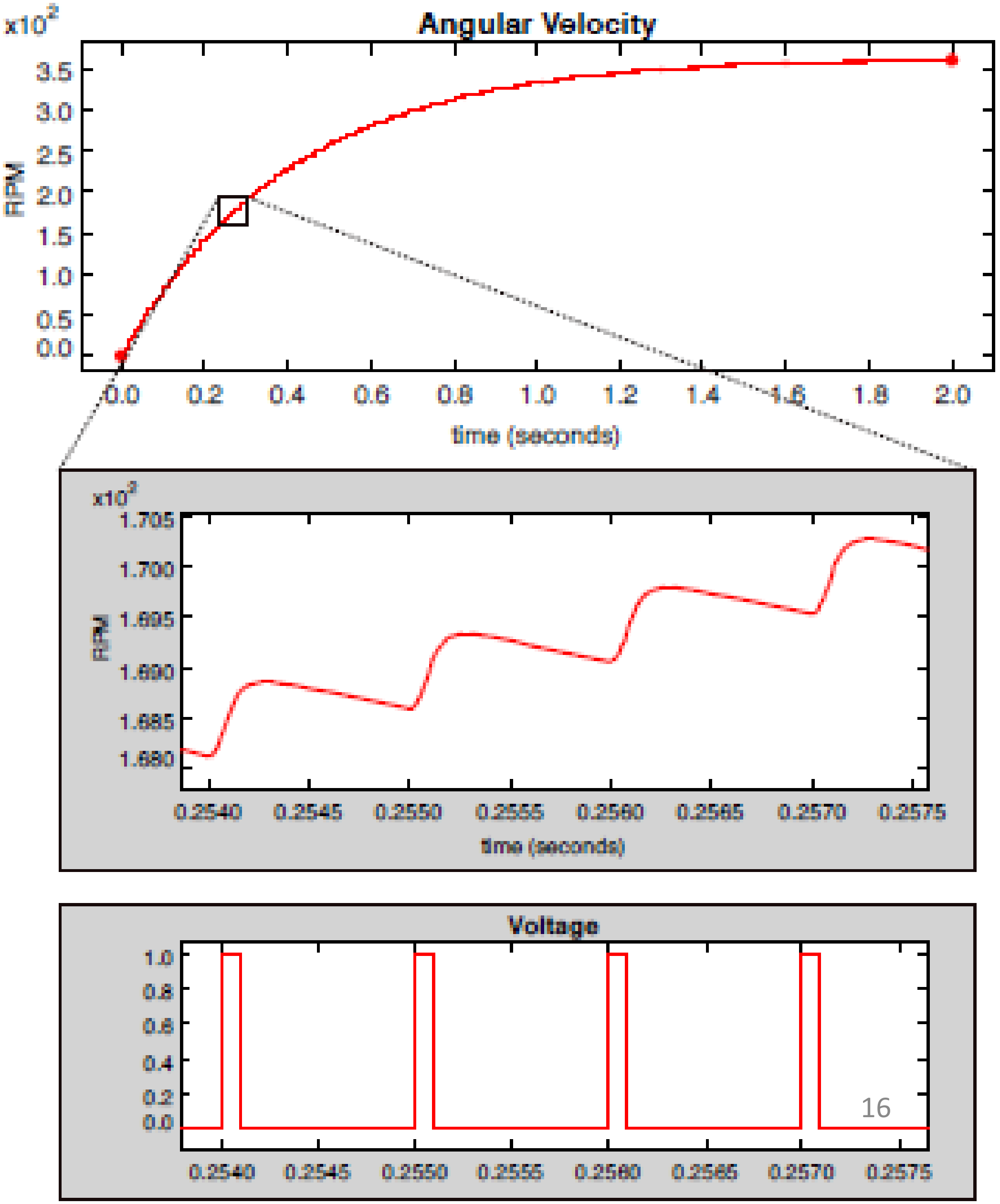


It is an electro-mechanic system:

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

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



[8] http://www.excelatphysics.com/dc-motor.html

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)