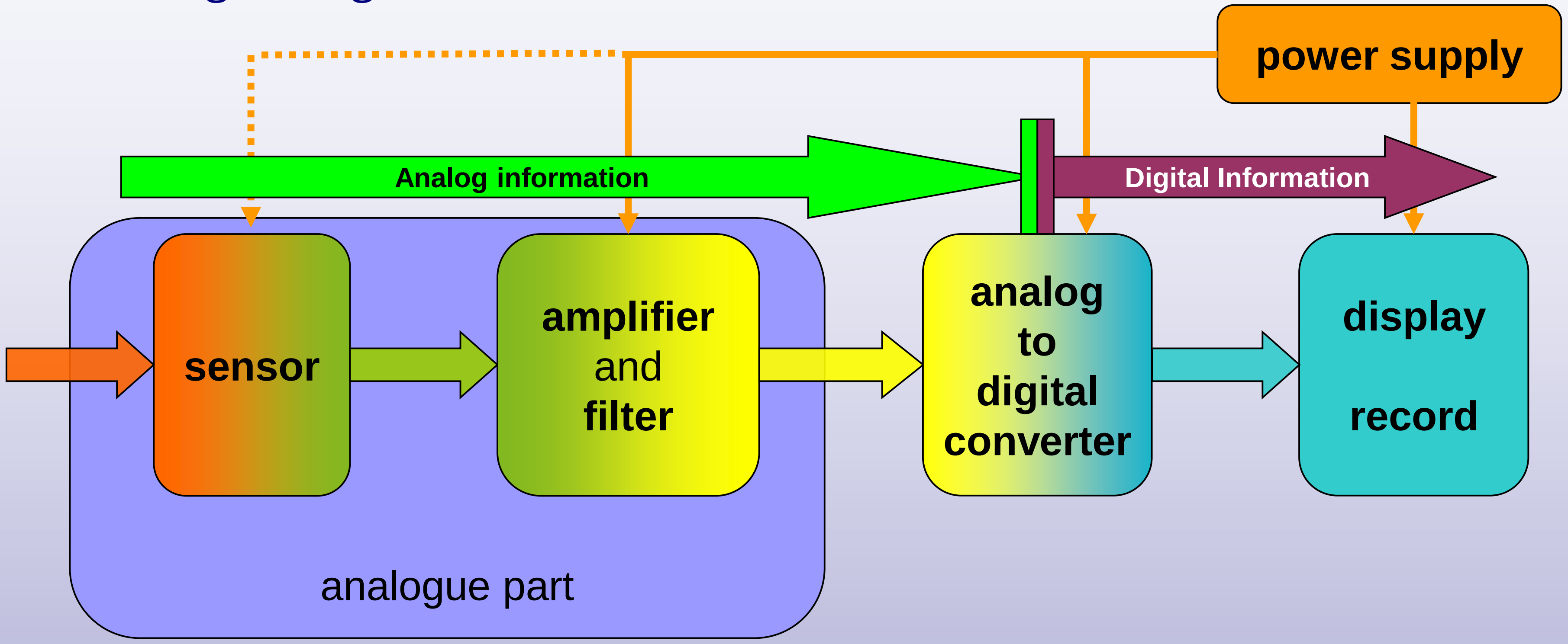
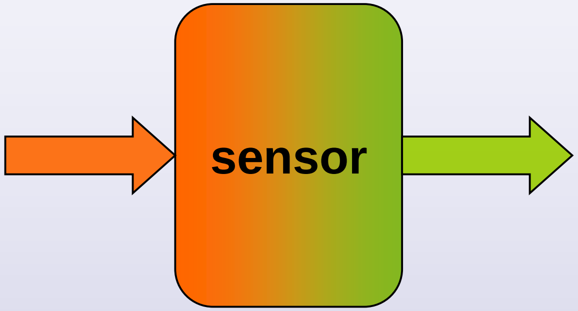
Measurement device component properties

Analogue part

Analogue - digital measurement device



1. Sensor

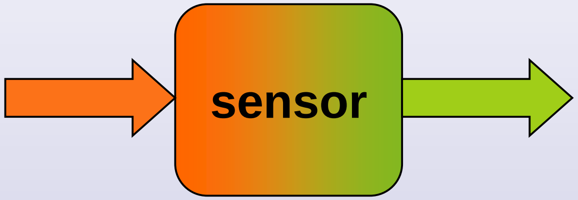


sensor converts the monitored physical quantity into electrical physical quantity (voltage, current, ….)

- **1.1. sensor static properties**
- **1.2. static transmission characteristic errors**
- **1.3. sensor dynamic properties**
- **1.4. sensor properties = summary**

1.1. Sensor static properties

- **input range**
  - **the minimum and maximum values of the input quantity that the sensor is able to process**

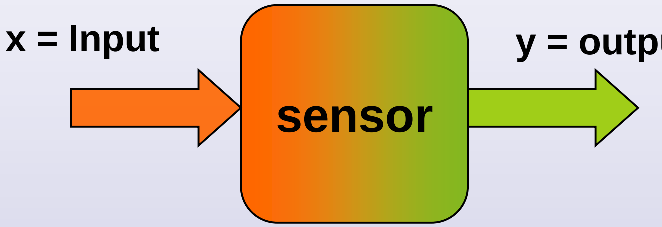


- **if the input quantity is inside the sensor range the output signal is proportional to the input quantity**

- **if the input quantity is outside the sensor range**
  - **the output signal does not match the input quantity**
  - **the sensor may be destroyed**

1.1. Sensor static properties

- **sensor static transmission characteristic (sensitivity)**
  - **the relationship between the output and input signal**



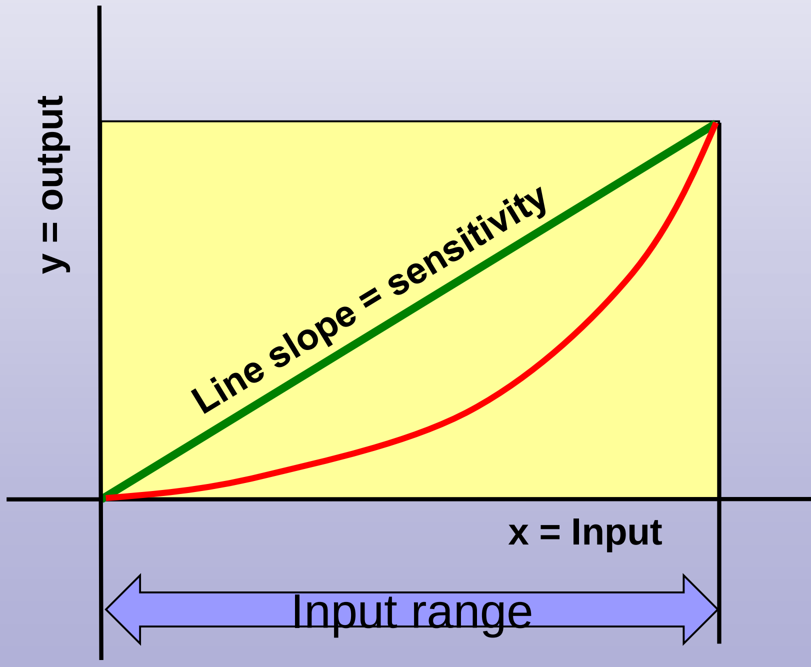
- **generally it can be a polynomial function**
- $y = a_0 + a_1x + a_2x^2 + \ldots.. + a_nx^n$

- **usually the function is linear**

  $y = a_1x$
- **the symbol S is used instead of the coefficient a_1**

  $y = S * x$

  where S is the sensor sensitivity

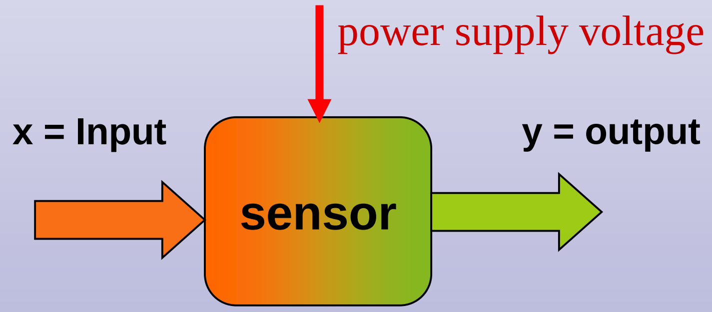


- **static conversion characteristic is valid only if the input quantity is within the range !!!!**

1.1. Sensor static properties

- **examples of the sensor description**
- input range + sensitivity — input 0 - 100°C, sensitivity 5mV/°C
- input range + output range — input 0 - 100°C, output 0 – 500mV

- **the sensitivity can be depended on power supply voltage for some types of sensors** (eg strain gauge force sensors)



y = S * V * x

where S is the sensor sensitivity
V is the power voltage

- **example of this sensor description**
  - input range **10kN**
  - output **2mV/V** this information means that for the maximum force 10 kN the output will be 2mV per each one volt of power supply

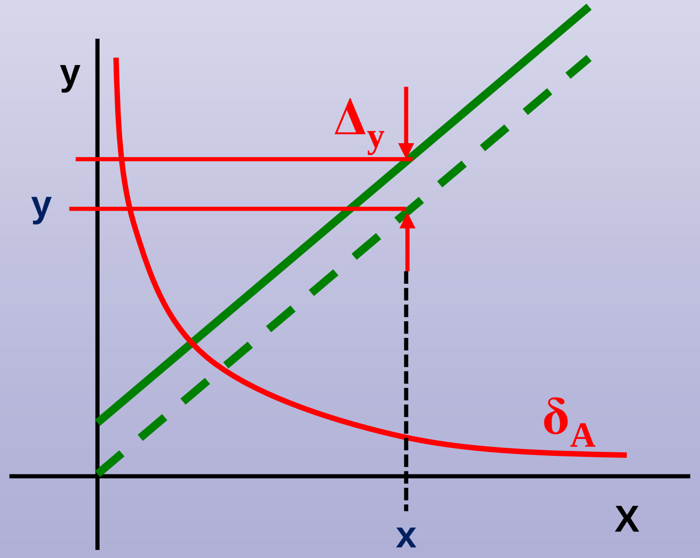
  - for example, if the power supply is 10V, the sensor output will be 20mV at full load by force of 10kN

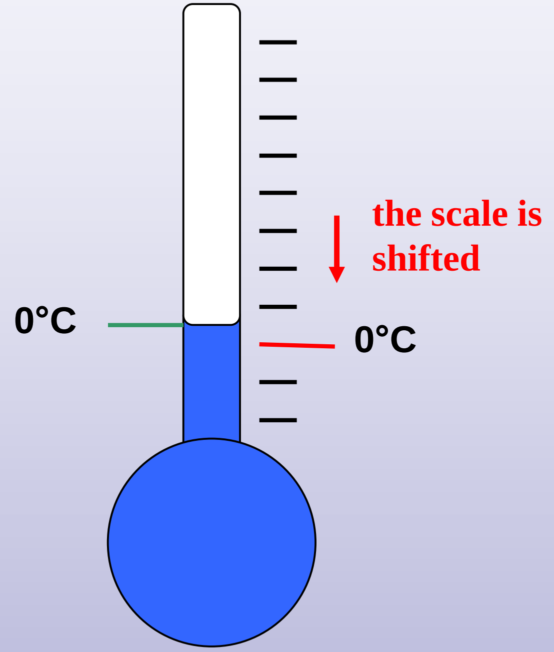
1.2. static transmission characteristic errors

- **additive error (zero shift) δ_A**

- **the zero input does not correspond to the zero output**
  $y = S * x + q$
- deviation from the correct value **$\Delta y = q$**
- the deviation is constant over the entire range

- error calculaciton: $\delta_A = \frac{\Delta y}{y}$ $(* \, 100 \ [\%])$





Example:
thermometer range: 0 - 100°C
zero shift Δy =1°C

reality	thermometr value	error δ_A
1°C	2°C	100%
100°C	101°C	1%

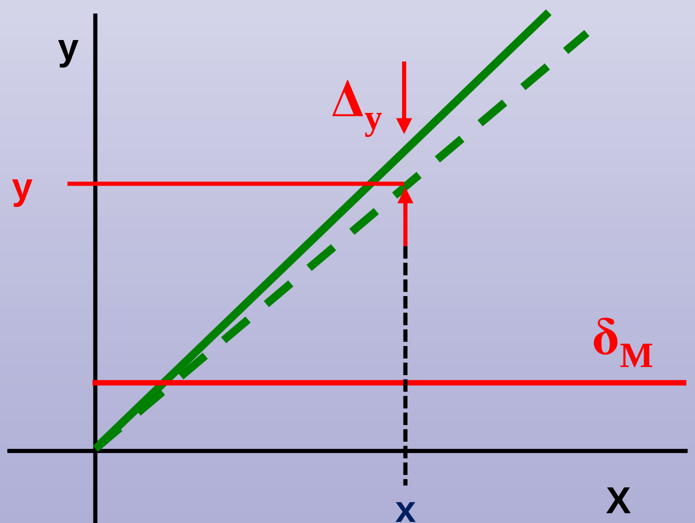
- **the additive error hyperbolically distorts the output, that is, most at the beginning of the range**

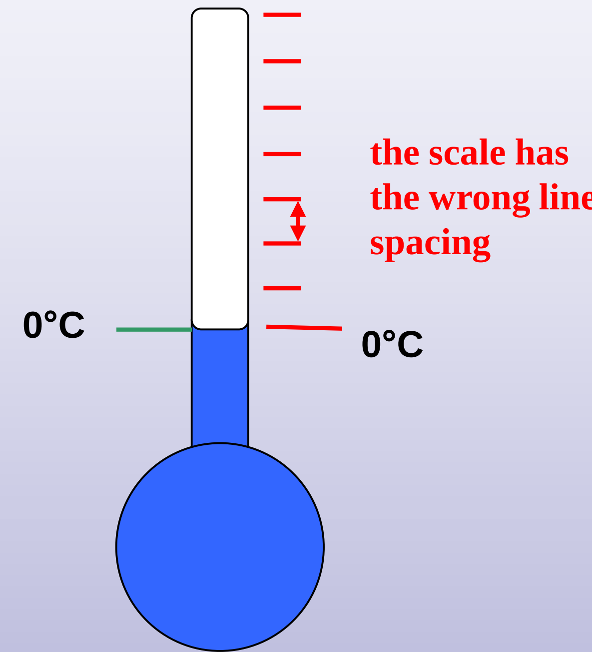
1.2. static transmission characteristic errors

- **multiplicative error (sensitivity error) δ_M**

- **the sensitivity is not S, but S + ΔS**
- **y= (S + ΔS) * x**
- deviation from the correct value **Δy = ΔK * x**
- the deviation increases with value

- error calculaciton: $\delta_M = \frac{\Delta Y}{Y} = \frac{\Delta K * x}{K * x}$ $(* \ 100 \ [\%])$





Example:
thermometer range: 0 - 100°C
scale division **S + ΔS** =1.01°C

reality	thermometr value	error δ_M
1°C	1.01°C	1%
100°C	101°C	1%

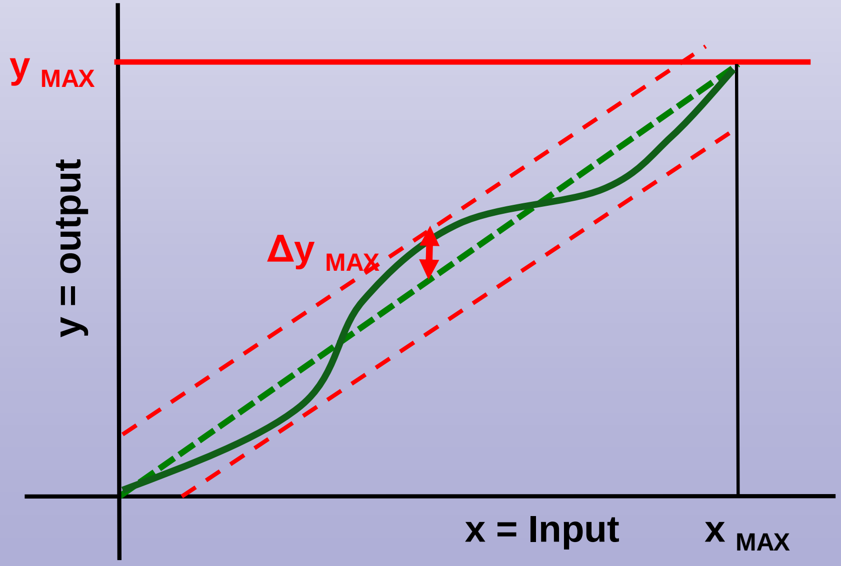
- **the multipicative error is constant over the entire range**

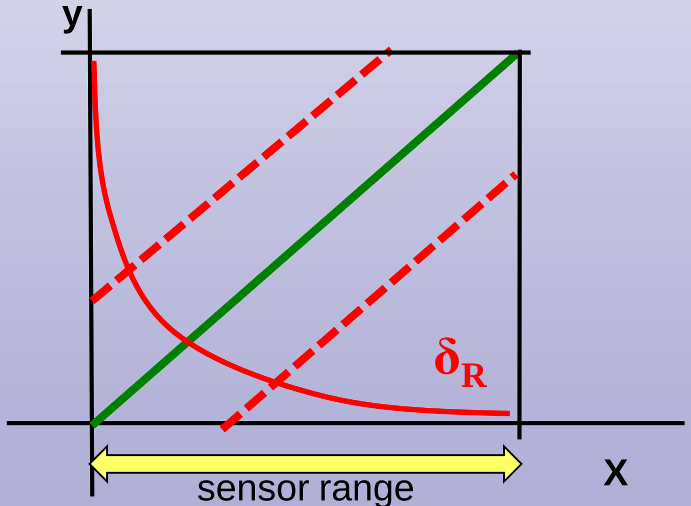
1.2. static transmission characteristic errors

- **the sensor relative error (the sensor accuracy) δ_r**

- multiplicative and additive error can occur simultaneously
- static characteristic can have other errors - nonlinearity, hysteresis, etc.
- **determining the resulting error would be very difficult**
- therefore the sensor producer publishes the maximum output deviation Δy_{MAX} and guarantees that deviations in the whole range are always smaller than this maximum

- **sensor relative error** $\delta_r = \dfrac{\Delta y_{MAX}}{y_{MAX} - y_{MIN}} = \dfrac{\Delta y_{MAX}}{\text{sensor range}}$





- **the relative error hyperbolically distorts the output**

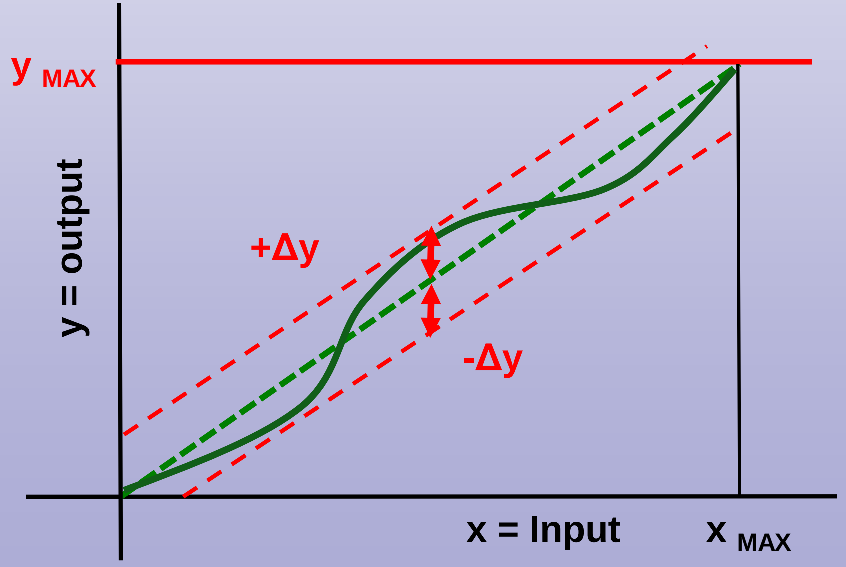
1.2. static transmission characteristic errors

- **the sensor resolution**

- the deviation **Δy** caused by the relative error can be **positive or negative**
- **the sensor resolution is the smallest change in a sensed quantity that can be unambiguously determined**

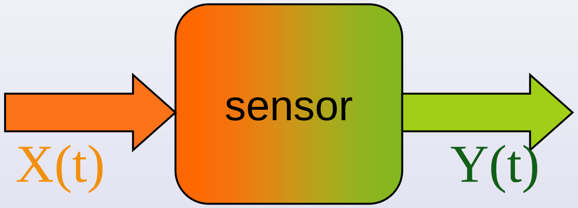
- the resolution $r = \frac{1}{\frac{y_{MAX}-y_{MIN}}{2*\Delta y_{MAX}}+1} \cong \frac{2*\Delta y_{MAX}}{y_{MAX}-y_{MIN}} = 2*\delta_R$

- **the sensor resolution is thus essentially twice the relative error (accuracy) of the sensor**



1.3. sensor dynamic properties

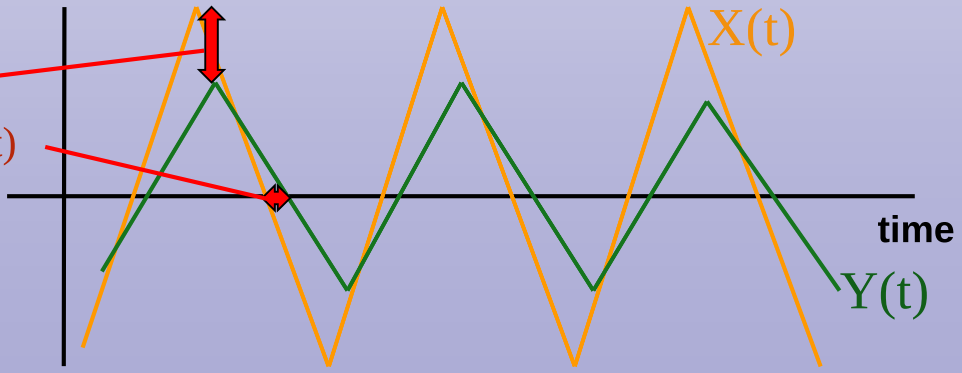
the sensor transfer characteristic G(t) is defined as ratio of the outup function to the input function



$$G(t) = \frac{Y(t)}{X(t)}$$

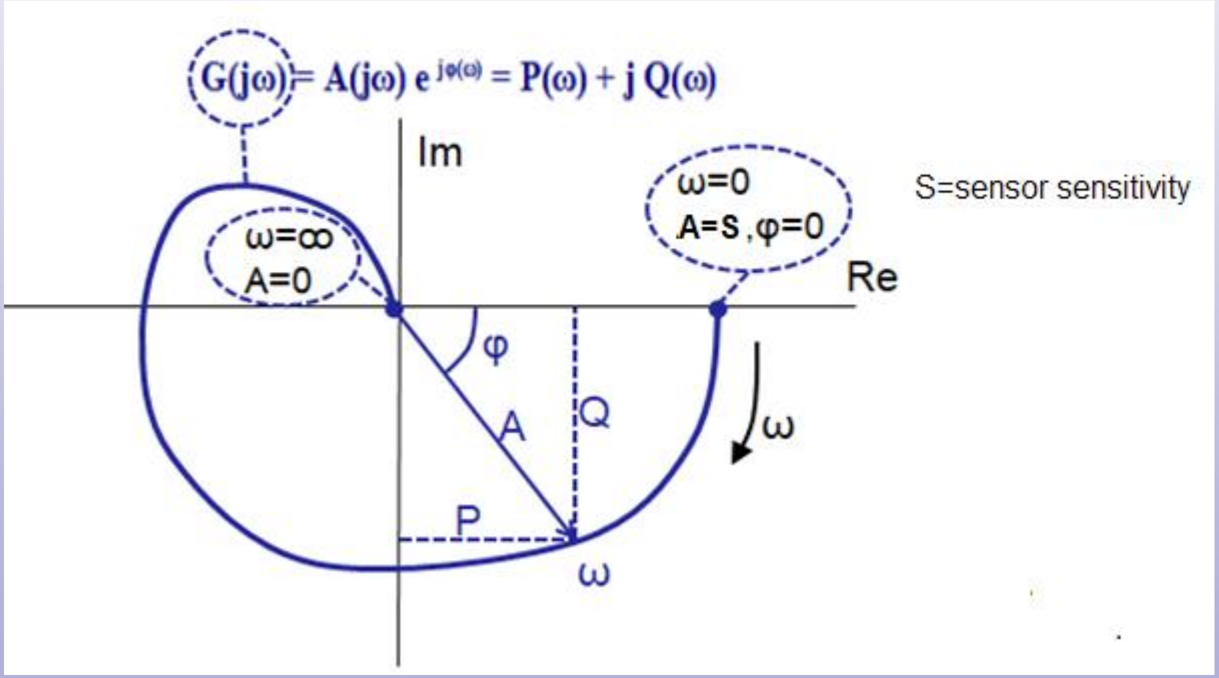
- the ideal state is when the output function exactly follows the input function, thus G(t) is constant and it is G(t) = S, where S is the sensor sensitivity
- the input function is variable over time
- the internal circuits of the sensor work at some maximum speed
- **if the rate of change of the input function exceeds the capabilities of the sensor, G(t) ceases to be constant and the output signal is distorted**

- less amplitude
- time delay (phase shift)



1.3. sensor dynamic properties

- **the sensor frequency characteristic**
- this time function $G(t) = \frac{Y(t)}{X(t)}$ is converted by the Fourier Transform into the frequency domain
  - $\boldsymbol{G(j\omega) = \frac{Y(j\omega)}{X(j\omega)} = A(j\omega) * e^{j\varphi(\omega)} = P(\omega) + j * Q(\omega)}$ *where* ω= 2πf
  - the frequency characteristic can be drawn in a complex plane:

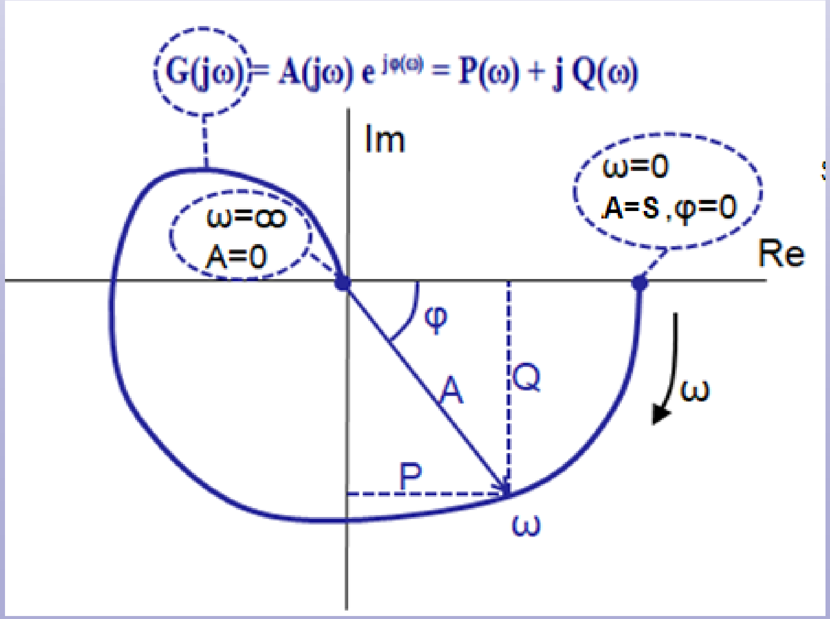


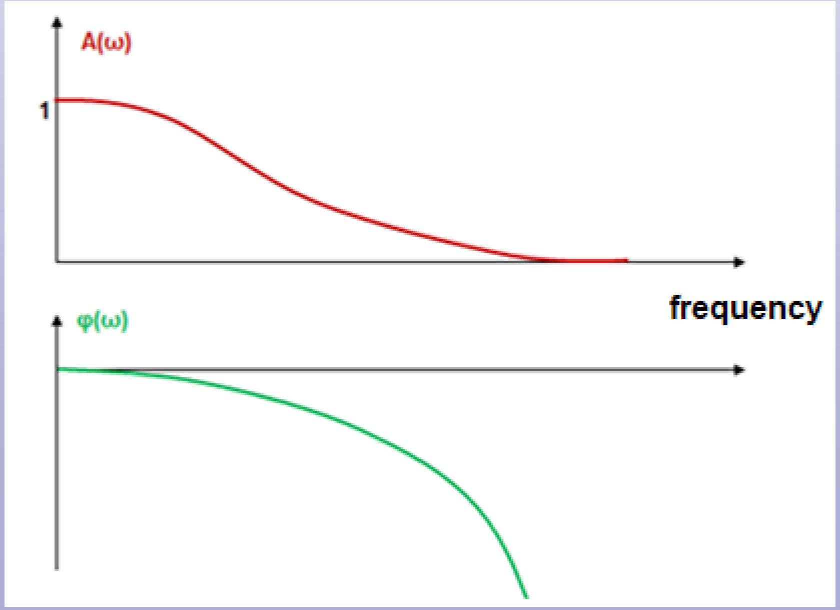
1.3. sensor dynamic properties

- **the sensor amplitude and phase characteristic**
- the representation of the frequency response in the complex plane may be incomprehensible therefore, the amplitude and phase characteristics are displayed more often as a dependence of amplitude and phase on frequency

- $G(j\omega) = P(\omega) + j * Q(\omega)$ ⇒ $A(\omega) = \sqrt{P^2(\omega) + Q^2(\omega)}$

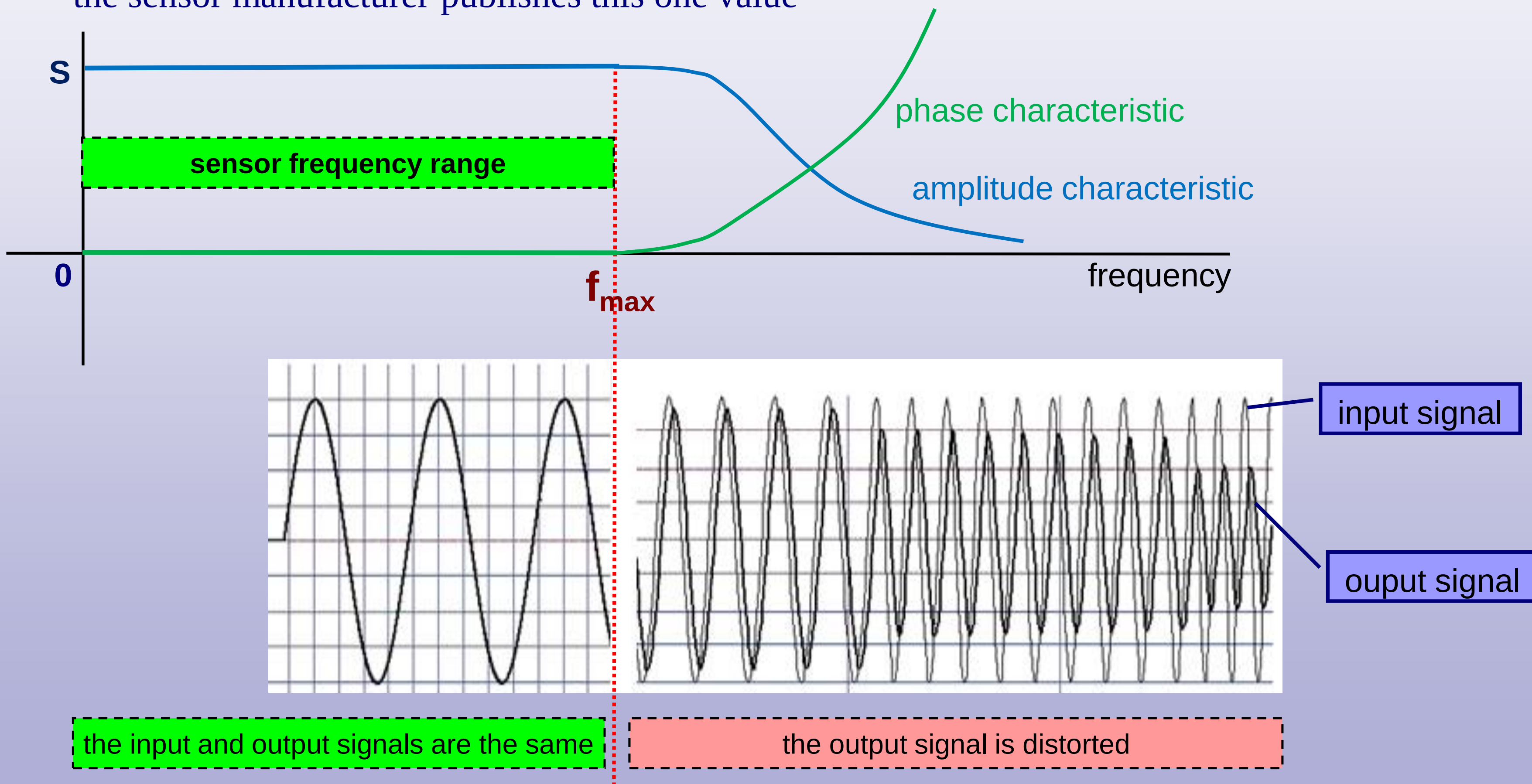
$$\varphi(\omega) = arctan\,\frac{Q(\omega)}{P(\omega)}$$



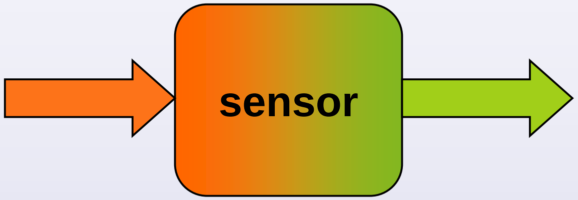


1.3. sensor dynamic properties

- **the sensor frequency range**
- it is the maximum frequency of the input signal where no output distortion
- the sensor manufacturer publishes this one value



1.4. sensor properties = summary

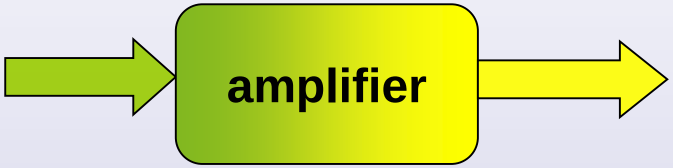


the manufacturer writes the following basic sensor properties in it data sheet:

- **sensor input range**
  - the minimum and maximum values of the input quantity that the sensor is able to process
- **sensor sensitivity**
  - the relationship between the output and input signal
- **sensor accuracy and resolution**
  - the maximum output deviation in the whole range are always smaller than sensor accuracy
  - the sensor resolution as twice the sensor accuracy
- **sensor frequency range**
  - the maximum frequency of the input signal where no output signal distortion

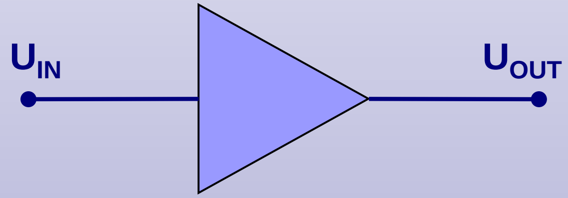
2. Amplifier

- **amplifier regulates (increases) the size of the output sensor signal to the level required for its processing in the A/D converter**



amplifier gain G

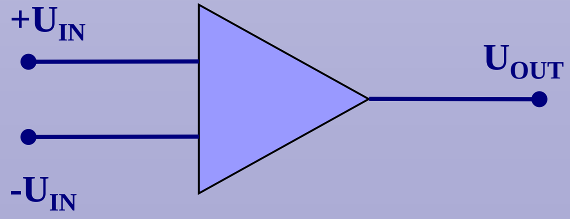
- one value gain for single-purpose input
- adjustable gain for universal input (set by the user program today)



$U_{OUT} = G * U_{IN}$ where G is gain

differential amplifier

- used for sensors with differential output (eg strain gauges force sensors)
- it has two inputs + IN and -IN and amplifies the signal difference between these inputs



$U_{OUT} = G * (+U_{IN} - -U_{IN})$

2. Amplifier

- **the amplifier properties are practically identical to the properties of the sensor so the amplifier also has 4 basic parameters**
    - input range
    - gain (usually can be set to several values)
    - relative error (accuracy)
    - frequency range (maximum rate of input change)

- **since the parameter definitions are identical to the sensor, they will not be explained again here (**only instead of sensitivity is here gain)

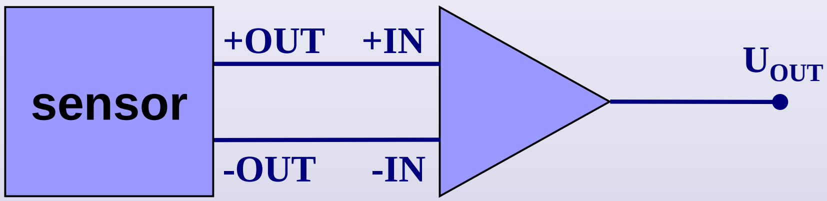
- amplifier
    - is an electronic circuit
    - relative error and frequency range are usually much better than the sensor properties

- **measurement accuracy depends predominantly on the sensor**

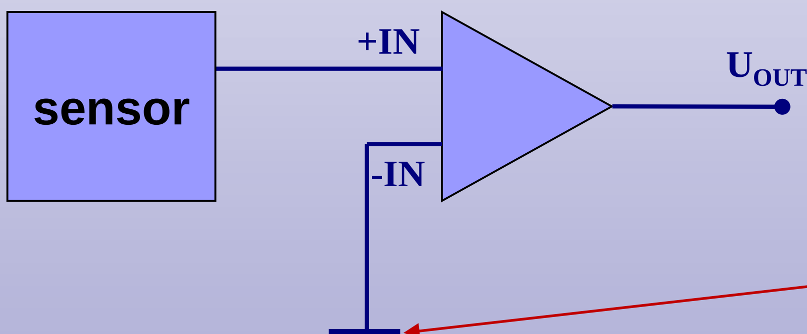
2. Amplifier

differential amplifier connection

- if a sensor with a differential output is used, the sensor outputs + OUT and -OUT are connected to the + IN and -IN amplifier inputs:



- if a sensor with a unipolar output is used, its output is connected to the amplifier + IN input:



$$U_{OUT} = G *(+U_{IN} - -U_{IN})$$

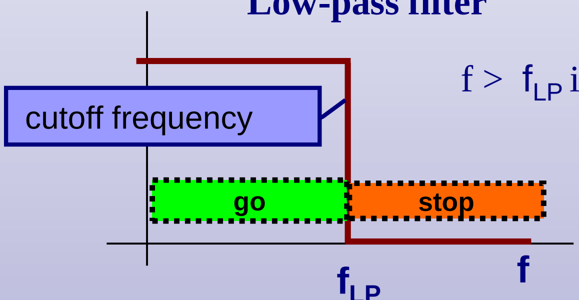
$$U_{OUT} = G *(+U_{IN} - 0) = G * +U_{IN}$$

- **the amplifier input - IN must be connected to ground so that it has a zero signal**
- **not connected amplifier input - IN is an antenna for noise reception**

3. Filter

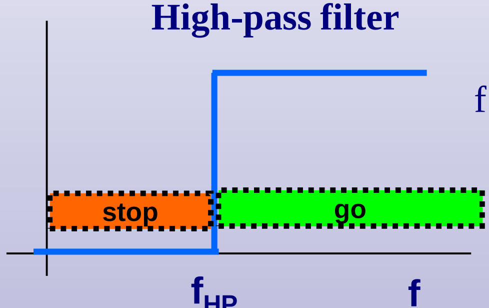
- **removes unwanted components (noise) from the signal**
  - it is part of the amplifier
  - the filter principle is not to transfer certain frequencies in the signal, so it can prevent the transfer of noise
  - there exist 4 types of filters according to the band of non transferred frequencies
- **filters classification according to the non transferred band:**
  - two basic filters

Low-pass filter



$f > f_{LP}$ is stopped

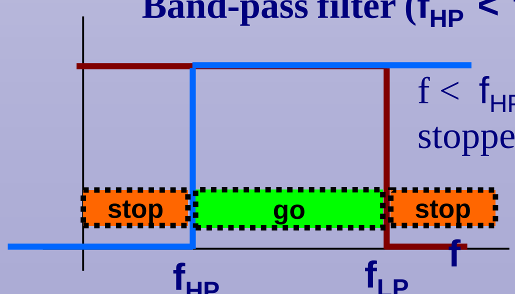
High-pass filter



$f < f_{HP}$ is stopped

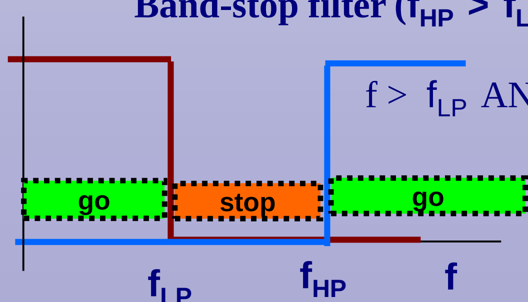
- two compoud filters - consist of a pair of basic filters

Band-pass filter ($f_{HP} < f_{LP}$)



$f < f_{HP}$ OR $f > f_{LP}$ are stopped

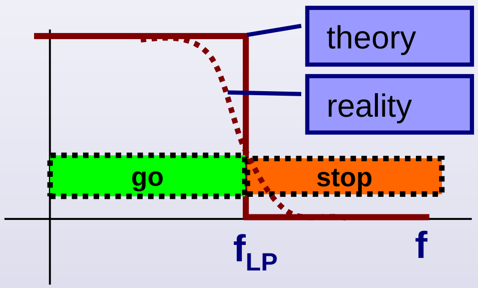
Band-stop filter ($f_{HP} > f_{LP}$)



$f > f_{LP}$ AND $f < f_{HP}$ is stopped

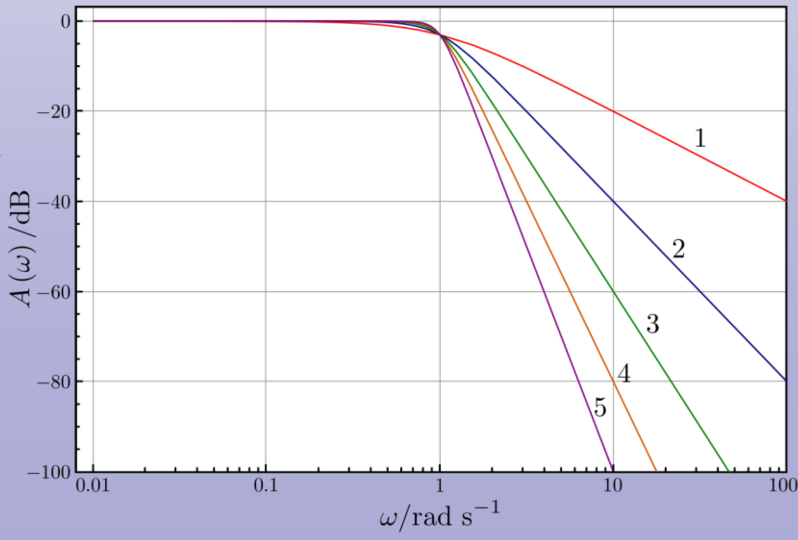
3. Filter

- **it is not possible to realize a rectangular filter frequency characteristic in practice**



- **the course of the characteristic (slope) is given by:**
  - **filter type**
    type of electrical circuit
    the filter type is named after the its author – Bessel, Butterworth
  - **filter order**
    can be simply explained as the number of filters included in the series - the first order filter is one filter, the second order filter is two identical filters in a serie, etc.
    higher filter order = steeper characteristic slope

- **the slope of the filter amplitude characteristic is given in dB/decade or dB/octave for sound**



3. Filter

- **decibel (dB) definition**
  - base unit **bel** (B) is named after A. G. Bell (he used it for attenuation in the telephone line)
  - **1B** = **ratio of 10 : 1** between **power** of sound at the beginning and end of the telephone line
  - **1dB** (decibel) is **the tenth** of the base unit **bel**
  - ie power ratio 10 : 1 = 1B (10dB), 100 : 1 = 2B (20dB), 1000 : 1 = 3B (30dB)

- **1B** $= \log(\frac{P_2}{P_1})$ $[-, W, W]$
- **1dB** $= 10 * \log\left(\frac{P_2}{P_1}\right)$ $[-, W, W]$
- if we need to express the ratio of the signal amplitudes instead of signal powers, we can define:

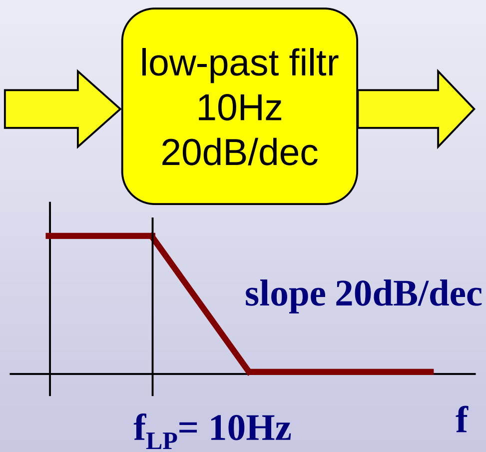
  $P = \frac{U^2}{R}$ and $\log(x^2) = 2 * \log(x)$

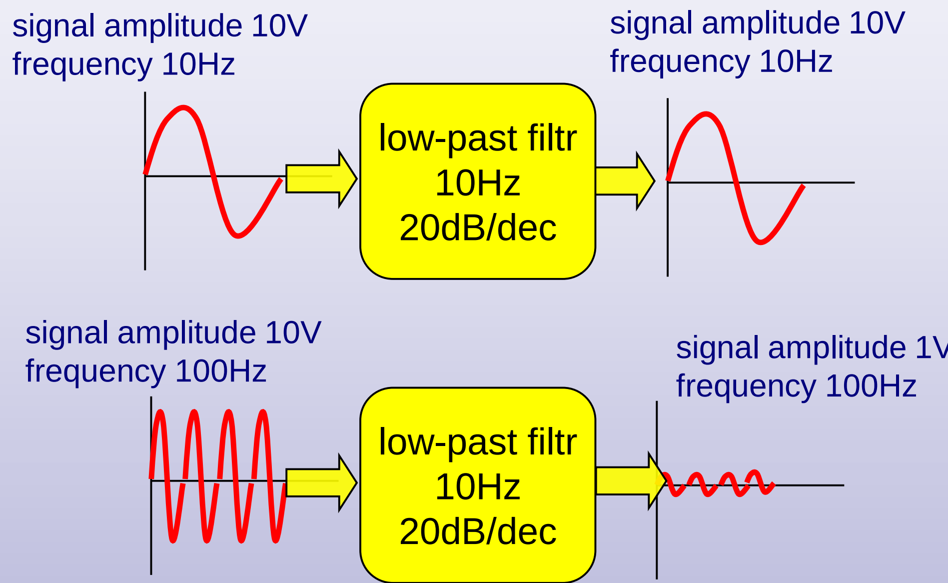
- **1dB**$= \mathbf{20 * \log(\frac{U_2}{U_1})}$ $[-, V, V]$

U [V]		P [W]
reduction	dB	reduction
1	0	1
0,89	1	0,79
0,79	2	0,63
0,707	3	0,5
0,5	6	0,25
0,35	9	0,125
0,316	10	0,1
0,22	13	0,05
0,1	20	0,01
0,01	40	0,0001

3. Filter

- **example of the low-past filter**
  - cutoff frequency 10Hz
  - slope 20dB/dec





U [V]		P [W]
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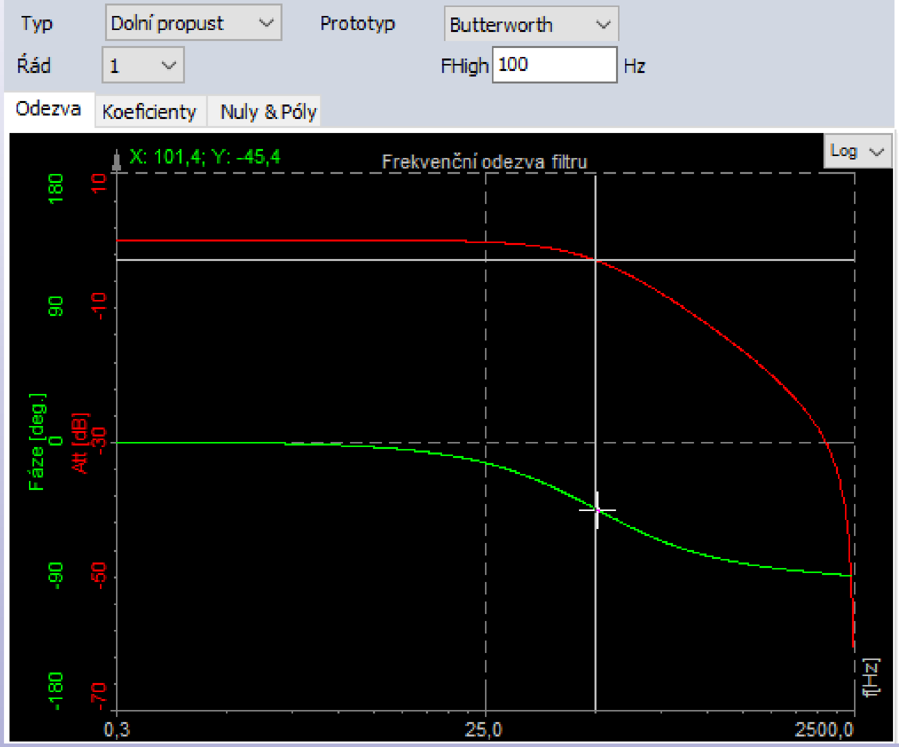
0,707	3	0,5
0,5	6	0,25
0,35	9	0,125
0,316	10	0,1
0,22	13	0,05
0,1	20	0,01
0,01	40	0,0001

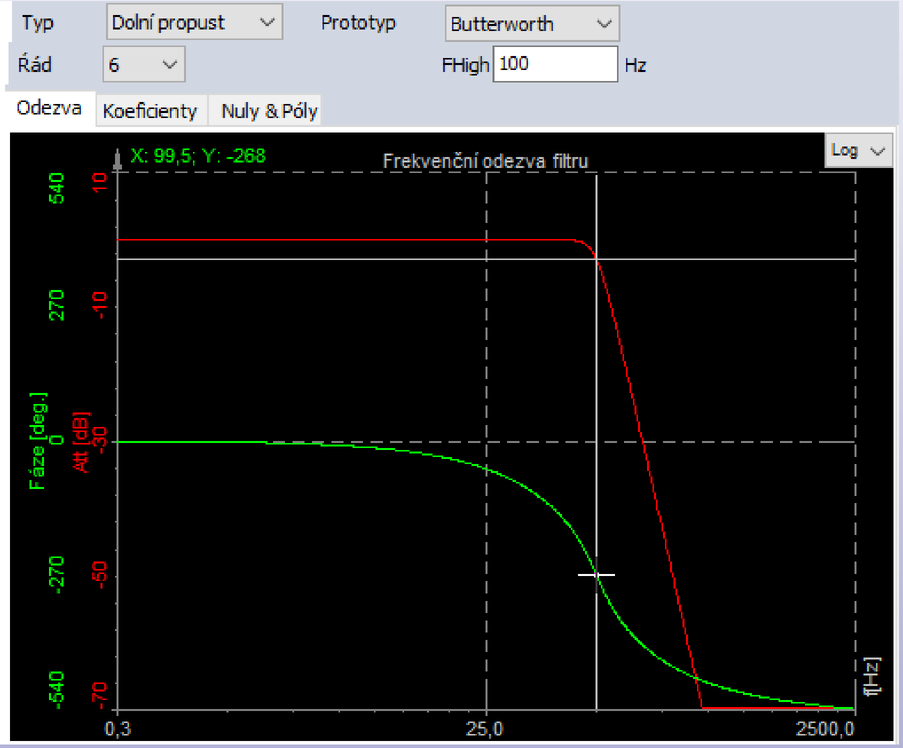
- the amplitude of the signal with a frequency lower than the cutoff frequency did not change
- 20dB/dec means that on the range of one order (for example from 10 to 100Hz) the signal amplitude is reduced 10x
- the amplitude of the signal with a frequency of 100Hz is reduced to one tenth, ie 1V

3. Filter

- **example of the real low-past filter**
  - low-pass filter, type Butterworth, cutoff frequency 100Hz
  - left first order, right sixth order

amplitude characteristic is red
phase shift is green

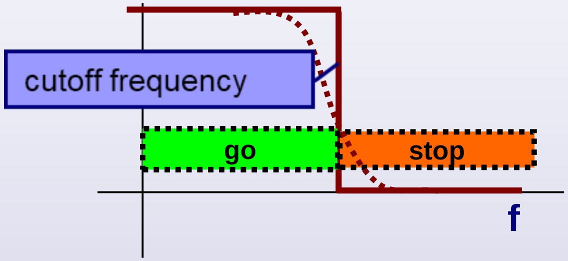




- the decrease in the real filter characteristic may not be linear
- **each filter also causes a phase shift of the signal !!!!**
- **the higher order has a steeper slope of the amplitude characteristic, but also a larger phase shift**

3. Filter

- **Summary of the filter properties**



• filter type according to the non transferred band
• cutoff frequency [Hz]
• the slope of the filter amplitude characteristic [dB/dec]
  - type of electrical circuit (Bessel, Butterworth)
  - filter order

3. Filter

- **final controversy whether to use the filter or not**
  - **it will never be in the measured data what the filter stops!!!**
  - an incorrectly set filter can invalidate the measured data
    - the data will not contain some signal component
    - there will be a phase shift on the signals
  - **the filter can also be applied mathematically to the measured data**

  - **for short-term non-repetitive measurements**
    - it is better not to use any HW filter, to record all even with noise and then do the filtering mathematically on data files
    - it can be judged (compared) how the filter will affect the signal, but it is added work

  - **for long-term repetitive measurements**
    - to measure for the first time without a filter
    - using mathematical filtering on the measured data for "tune" the filter parameters to remove noise and not affect the signals
    - to set the real filter parameters by obtained parameters and use it for further repeated measurements
    - no further mathematical filtering of the data is then required

Exam questions

- sensor static and dynamic properties
  - input range (p. 3)
  - sensor static transmission characteristic (sensitivity) (p. 4)
  - additive error and multiplicative error (p. 7, 8)
  - the sensor relative error (accuracy) and the sensor resolution (p.9, 10)
  - the sensor frequency characteristic, amplitude and phase characteristic (p. 12, 13)
  - the sensor frequency range (p. 14)
  - sensor properties summary (p. 15)
- amplifier
  - unipolar and differential amplifier, principal, gain (p. 16)
  - amplifier properties summary (p. 17)
- filter
  - filters classification according to the non transferred band (p. 19)
  - the slope of the filter amplitude characteristic, unit (p. 20, 21)
  - filter type and filter order and their influence on the characteristic slope (p. 20, 23)
  - filter properties summary (p. 24)