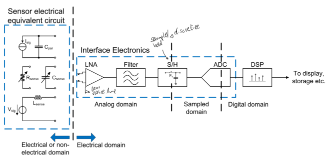
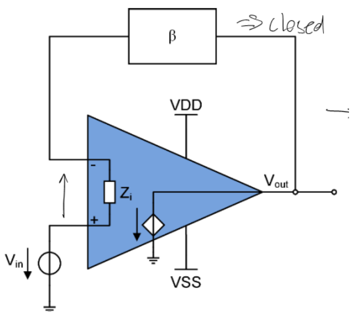
# Sensor Principles

## A generic sensor interface




## OPAMP Basics

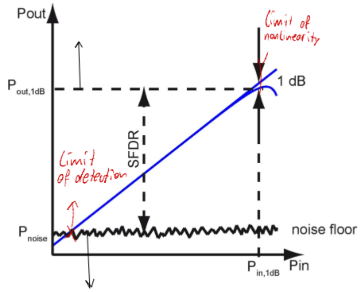
## Opamps in feedback




Gain : $T(\omega) = \beta \cdot A_0(\omega)$
Phase Margin:
$PM = 180° + \angle(T(\omega_1)|_{|T(\omega_1)|=1}$
Gain margin:$GM =$
$20 \cdot log_{10}(\frac{1}{T(\omega_2)})|_{\angle(T(\omega_2)=-180°}$
**Generic Transfer function**
$V_x = \beta \cdot V_{\text{out}} =$
$\beta \cdot A(\omega) \cdot (V_{\text{in}} - V_x) =$
$\beta \cdot A(\omega) \cdot (V_{\text{in}} - \beta \cdot V_{\text{out}})$
$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{A(\omega)}{1+\beta \cdot A(\omega)} \overset{A(\omega)]\gg 1}{\approx} \frac{1}{\beta}$
**Negative Feedback and linear operation**
$A(\omega) \gg 1 \Rightarrow$ virtual short at the input $\Delta V \approx 0$
$Z_i \to \infty \Rightarrow i_{oa} \approx 0$
Voltage Drive → negative feedback
Current drive → positive feedback

## Errors and Noise

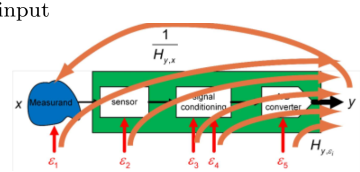
**Limit of detection(LOD):** minimum measurable input amplitude ($SNR \approx 0$)
**Dynamic range()DR:** ratio of max and min amplitude within inaccuracy levels.




**Errortypes**:
Deterministic: source loading, offset, gain error
Random: thermal noise, 1/f noise
**Quantification**:
Absolute : $\Delta x = |\hat{x} - x_0|$
Relative: $\left|\frac{\Delta x}{x_0}\right| = \left|\frac{\hat{x}-x_0}{\hat{x}}\right|$
Max inaccuracy:
$\Delta x_{max} | x \in [\hat{x} - \Delta x_{\max}, \hat{x} + \Delta x_{\max}]$
**Error Propagation**
$y = f(x_1, x_2, \ldots, x_N)$
Deterministic fluctuations of $x_i \to$ total error:
$\Delta y \approx \sum_{i=1}^{N} \frac{\partial f}{\partial x_i} \cdot \Delta x_i$
Partial derivative $\frac{\delta f}{\delta x_i}$ is called **sensitivity**
Additive errors are best specified absolute and multiplicative errors are best specified relative
**Interference:**
Unwanted coupling of external signal
Noise: random fluctuations from setup → can be modeled as error sources

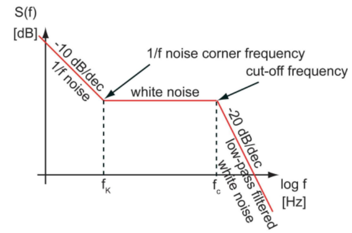
## Combining Error sources

**Output referred noise**
Effect of an error-source on the output
**Input referred noise** Equivalent effect of the error-source on the input




Find TF from ES to output
$y : H_{y,ES} \Rightarrow y_{\text{out}}\ ,_{\epsilon_2} = H_{y,\epsilon_2} \cdot \epsilon_2$
Refer result back to input wit
$H_{y,x} : x_{\epsilon_2} = \frac{y_{\text{out}}\ ,_{\epsilon_2}}{H_{y,x}} = H_{y,\epsilon_2} \cdot \frac{\epsilon_2}{H_{y,x}}$

**Lin. System noise:**
$PSD = S_y(f) = |H(f)|^2 \cdot S_x(f)$




## Noise Types

**Thermal noise:** excitation of charge carriers(white)
**Shot noise:** carriers randomly crossing the barrier, dependent on DC bias and white
**Flicker Noise:**, due to traps in semiconduct. 1/f spectral density. MOS trans at low freq.
**Thermalnoise Theorem:** Every closed system at temp. T has average. Energy of $kT/2 \to$
$S_u(f) = 2kTR($ double-sided $)$ math
$S_u(f) = 4kTR($ single-sided $)$ physics

## Langevin Approach kt/C noise

PSD noise voltage of $V_n$
$= S_{v_n}(f) = 4kT \cdot \Re\{Z(j2\pi f)$
$\to \overline{V_n^2} = kT\left[\frac{1}{C_\infty} - \frac{1}{C_0}\right] = \frac{kT}{C}$
**MOS IRN**
$S_{\Delta V^2_{\text{nG-tot}}} = 4kT \cdot$
$R_{\text{nG-tot}}\ , \quad R_{\text{nG-tot}} = \frac{\rho}{W \cdot L \cdot f} + \frac{\gamma_{nD}}{G_m}$
with GateExcess Noise factor
$:\gamma_{nD} = (n = 1.3) \cdot [0.5WI; 2/3SI]$
**Bipolar Trans IRN:**
$S_{\Delta V^2_{nR}} = 4kT \cdot R_B$

## Noise Aanalysis

small-signal-equivalent is valid.
Total ORN:
$S_{n,\text{ out}}(f) = \sum_{k=1}^{N} |H_k(f)|^2 \cdot S_{nk}(f)$
N uncorrelated NS.
$H_k(f)$ TF from NS ton output.
IRN: $S_{V_{\text{neq,IRN}}}(f) = \frac{S_{V_{\text{nout}}}(f)}{|A(f)|^2}$
with $A(f)$ is TF

## Sensor types

Information domain → Electrical domain

Transduction: Converting a signal from the energy domain into another.
Sensors and actuators are transducers

## Sources of eerror

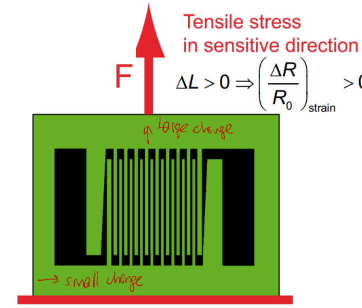
Noise, sensitivity to unintended quantities, Noise, EMI

$$\begin{pmatrix} E_{mag} \\ E_{mech} \\ E_{therm} \\ E_{opt} \\ E_{chem} \\ E_{elec} \end{pmatrix} = \begin{pmatrix} \alpha_{mag,mag} & \alpha_{mag,mech} & \alpha_{mag,therm} & \alpha_{mag,opt} & \alpha_{mag,chem} & \alpha_{mag,elec} \\ \alpha_{mech,mag} & \alpha_{mech,mech} & \alpha_{mech,therm} & \alpha_{mech,opt} & \alpha_{mech,chem} & \alpha_{mech,elec} \\ \alpha_{therm,mag} & \alpha_{therm,mech} & \alpha_{therm,therm} & \alpha_{therm,opt} & \alpha_{therm,chem} & \alpha_{therm,elec} \\ \alpha_{opt,mag} & \alpha_{opt,mech} & \alpha_{opt,therm} & \alpha_{opt,opt} & \alpha_{opt,chem} & \alpha_{opt,elec} \\ \alpha_{chem,mag} & \alpha_{chem,mech} & \alpha_{chem,therm} & \alpha_{chem,opt} & \alpha_{chem,chem} & \alpha_{chem,elec} \\ \alpha_{elec,mag} & \alpha_{elec,mech} & \alpha_{elec,therm} & \alpha_{elec,opt} & \alpha_{elec,chem} & \alpha_{elec,elec} \end{pmatrix} \cdot \begin{pmatrix} E_{mag} \\ E_{mech} \\ E_{therm} \\ E_{opt} \\ E_{chem} \\ E_{elec} \end{pmatrix} + \begin{pmatrix} E_{mag,os} \\ E_{mech,os} \\ E_{therm,os} \\ E_{opt,os} \\ E_{chem,os} \\ E_{elec,os} \end{pmatrix}$$

Tandem transducers: Multiple steps to target domain.
cross-sensitivity, sensitivity to undesired quantity

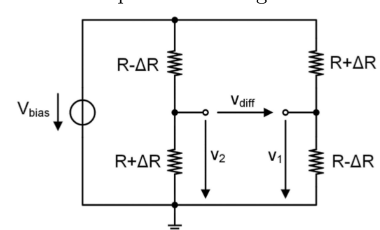
## Sensor classification:

**Active Sensors:**
Require external source of excitation
**Passive / self-generating sensors:**
Generate their own electrical output signal
Draws all required energy from the measurand(source loading) E: Potentiometer for angle measurements. **Modulating sensors:**
Measure desired quantity by modulating
Additional source with modulated energy. Also adds error. E: Non0contact displacement measrement (rotating disk) **Analog vs. Digital:**
Analog: time and value continuous
Digital: Discrete outputs
**Deflection mode sensors:**
Response to an output is a deviation from the equilibrium position
**Null mode sensors:**
Sensor or instruments exert an influence the measured system opposing the effect of the measurand. Ideally the result is a 0 measurement, typically achieved by feedback. The opposing influence is then the sensor output. Slower than deflection, but more accurate.
**Resistive sensors - strain gauges**
Change in geometry under mechanical stress produces associated resistance change
Volum. == const. →
$\frac{\partial V}{V_0} = \frac{L_0}{V_0} \cdot \partial A + \frac{A_0}{V_0} \cdot \partial L \wedge \frac{\partial V}{V_0} =$
$0 \Rightarrow \frac{\partial A}{A_0} = -\frac{\partial L}{L_0} \to \frac{\partial R}{R_0} = \frac{\partial \rho}{\rho_0} + 2\frac{\partial L}{L_0}$
$\to \frac{\partial R}{R_0} = \alpha \cdot \frac{\partial L}{L_0} + 2\frac{\partial L}{L_0} = \underbrace{(\alpha + 2)}_{\triangleq k} \cdot \frac{\partial L}{L_0}$
k: gauge factor
$\alpha$ proportionality factor $\frac{\partial \rho}{\rho_0} \propto \frac{\partial L}{L_0}$




## Readout resistive sensors

Use a half bridge resistive divider top element sensing resistor
$\frac{v_{\text{out}}}{V_{\text{bias}}} = \frac{R}{2R+\Delta R} \Leftrightarrow \frac{\Delta R}{R} = \frac{V_{\text{bias}}}{v_{\text{out}}} - 2$
Full bridge to remove offset, 2 sensing elements more sensitive, remove nonlinearity by implementing differential measurements
Best use 4point full bridge




$V_{\text{diff}} = v_2 - v_1 = \frac{\Delta R}{R} \cdot V_{\text{bias}}$