Instrumentation & Measurement

Signal Conditioning

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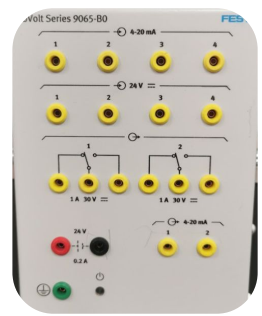
Sensor Components

Actual value to measure → Input → **Measurement Element (Sensor)** → Output → Measured Value

Sensing Element → Signal Conditioning → Digital processing → Output or Display



A sensor might or might not include signal conditioning, digital processing or display.

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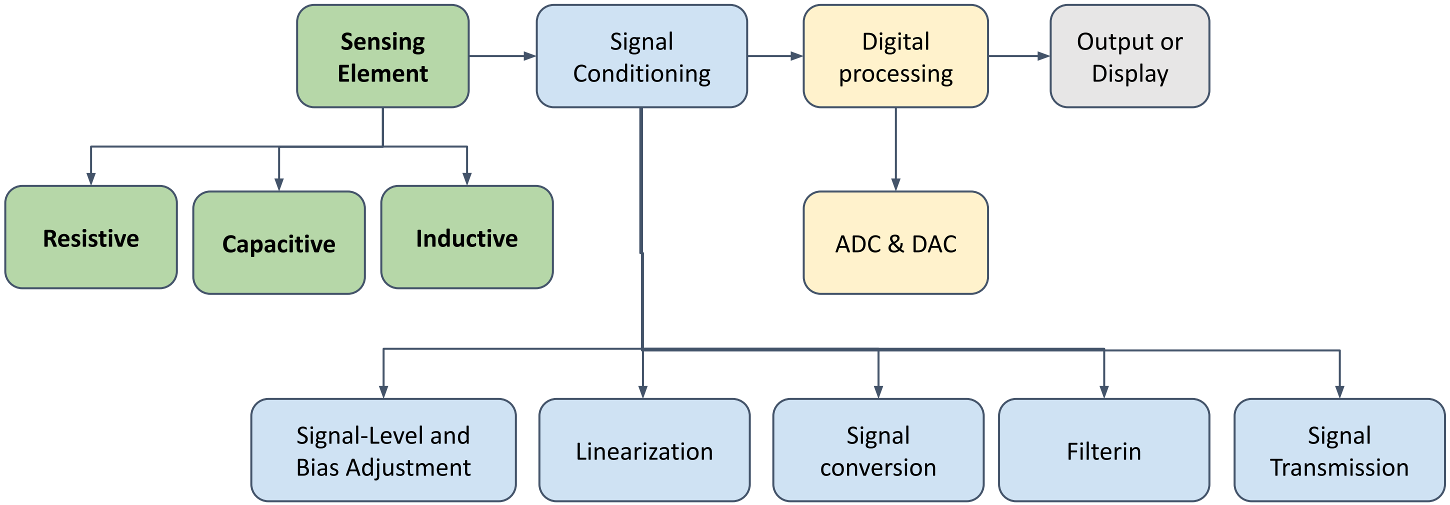
Sensor Components



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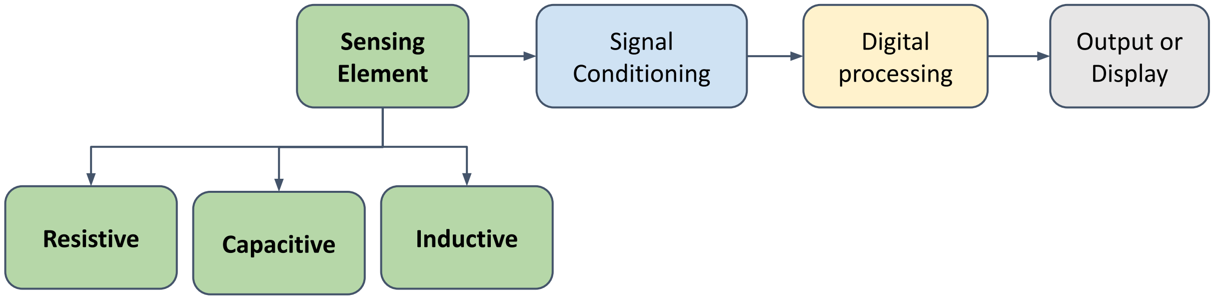
Sensor Elements



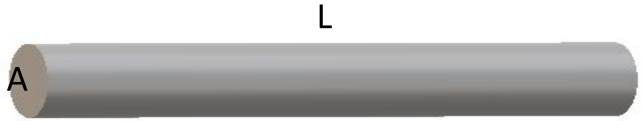
- The sensing element converts the environment energy to an electrical form of energy, directly or indirectly.
- In non-electrical sensor the environmental energy is harnessed or converted to pneumatic or hydraulic energy and this energy is directly used in control loop.
- The common property which are used for measurement are Resistance, Capacitance and Inductance

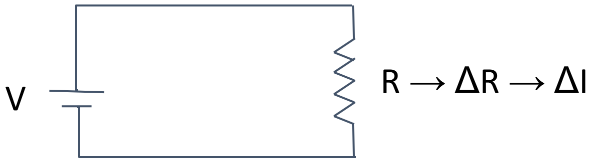
Sensing Elements: Resistance Property

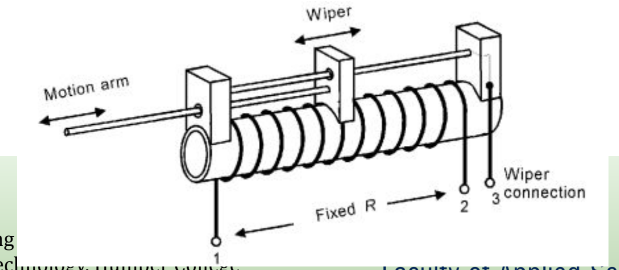
- Resistance of a conductor depends on the type, length and cross sectional area.
- This property can be used for measurement. For example if it is desired to measure force , pulling the wire will stretch the wire and therefore the length increases and the cross sectional area decreases consequently the resistance of conductor will change. Change of resistance in an electrical circuit can be converted to change of voltage or current.
- The resistance of a conductor depends on temperature also. This property is used to measure temperature.

$$R = \rho\frac{l}{A}$$

$$R(T) = R(T_0) \times (1 + \alpha \times \Delta T)$$







Sensing Elements: Capacitance Property

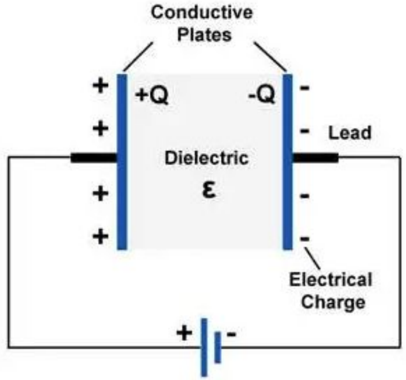
$$Q = C \times V$$

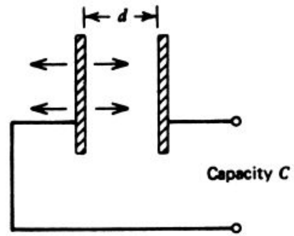
$$I = \frac{\Delta Q}{\Delta t} = C \times \frac{\Delta V}{\Delta t}$$

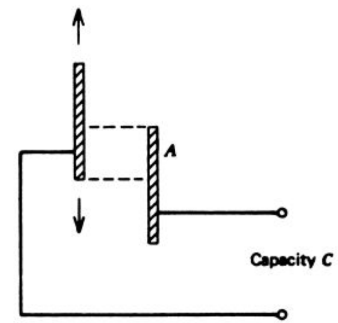
- Capacitance depends on three factors:
  - A, the area of the plates, bigger plate more charge can be stored
  - d , the distance between plates, further away plate, less charge
  - ε (Epsilon) is called dielectric constant. the insulator material between two plates called dielectric. Higher dielectric constant more capacitance , more charges
- Change of distance between two plates can be used to measure acceleration and therefore speed and displacement or it can be used to measure pressure or force
- Change of dielectric can is used in proximity sensor or level measurement.
- The change of capacity will lead to change of voltage or electric current.

$$C = \epsilon \frac{A}{d}$$

$$\Delta C \rightarrow \Delta V \; or \; \Delta I$$







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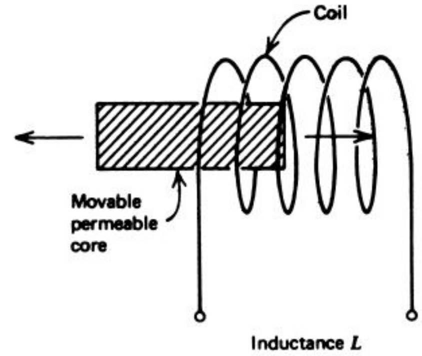
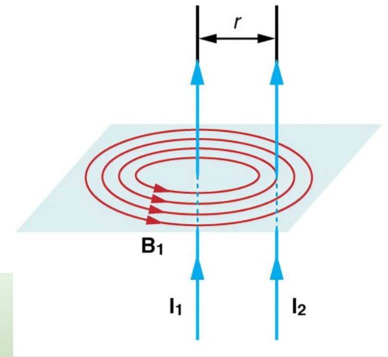
Sensing Elements: Inductance Property

$$V = L \times \frac{\Delta I}{\Delta t}$$

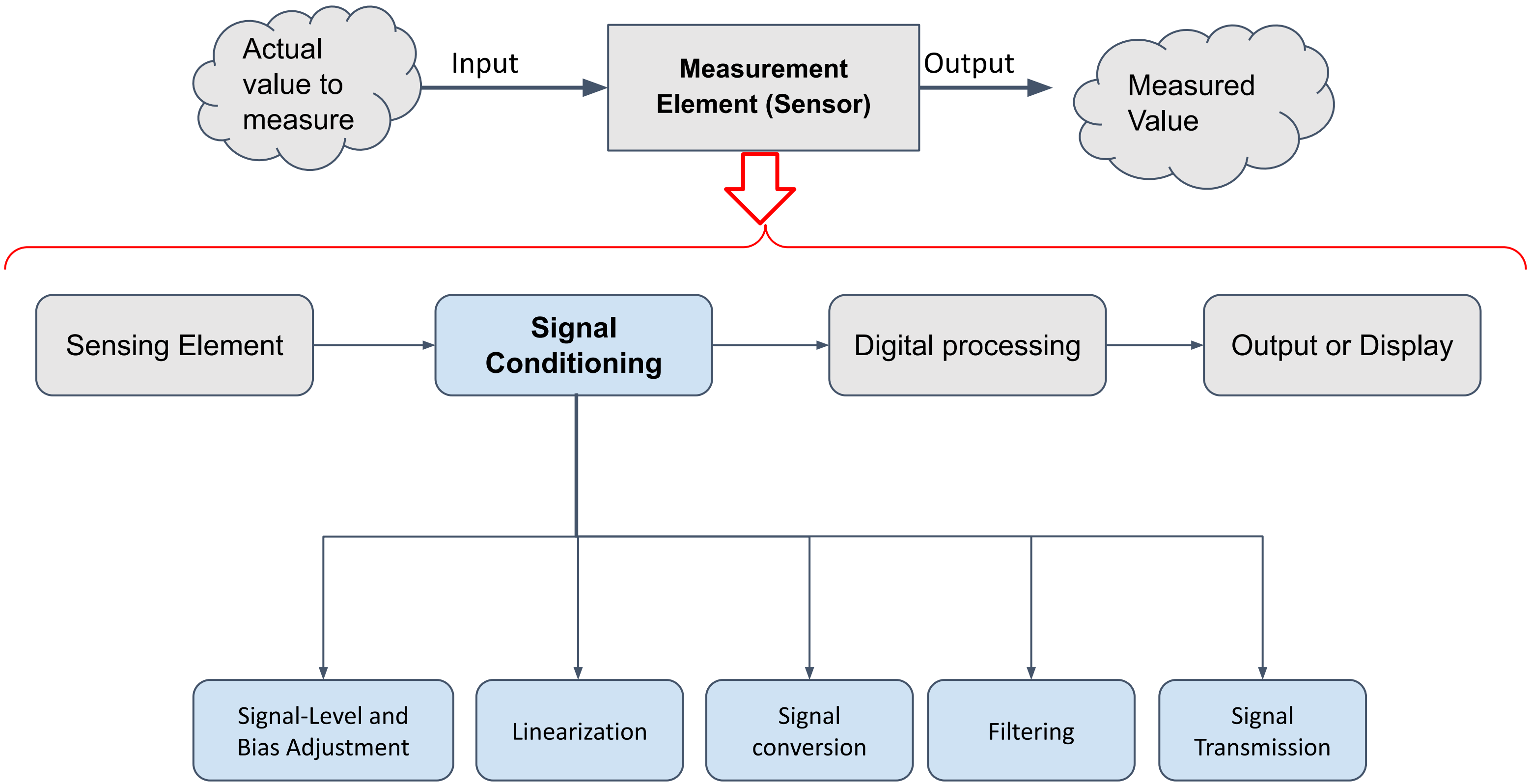
$$L = \mu_0 \frac{N^2}{l} A$$

- When an electric current passing through a conductor creates magnetic field.
- When the magnetic field around conductor changes it will induce a voltage across the conductor.
- Change of magnetic field around a conductor can happen:
    - Moving a wire in magnetic field
    - Moving the magnetic field around the wire physically, like moving a permanent magnet around the wire
    - moving a ferromagnetic metal in the magnetic field around wire
    - Changing intensity of magnetic field by changing the current in magnetic field generator





Sensor Components



Signal Conditioning- Signal-Level and Bias Adjustment

Common type of signal conditioning involves adjusting the magnitude and bias of voltage or current produced by sensing element.

Magnitude increased known as amplification and it is done by electronic analog circuit like transistor, amplifier and so on

- Amplification
- Bias Adjustment

For example a sensing element output voltage may vary from 0.2 to 0.6 volt for the measurement range and the sensor output is set to be 0-10 volt as standard output.

For converting the 0.2-0.6 volt to 0-10 volt, first the bias of 0.2 can be removed then the sensing element output will vary from 0 - 0.4 volt.

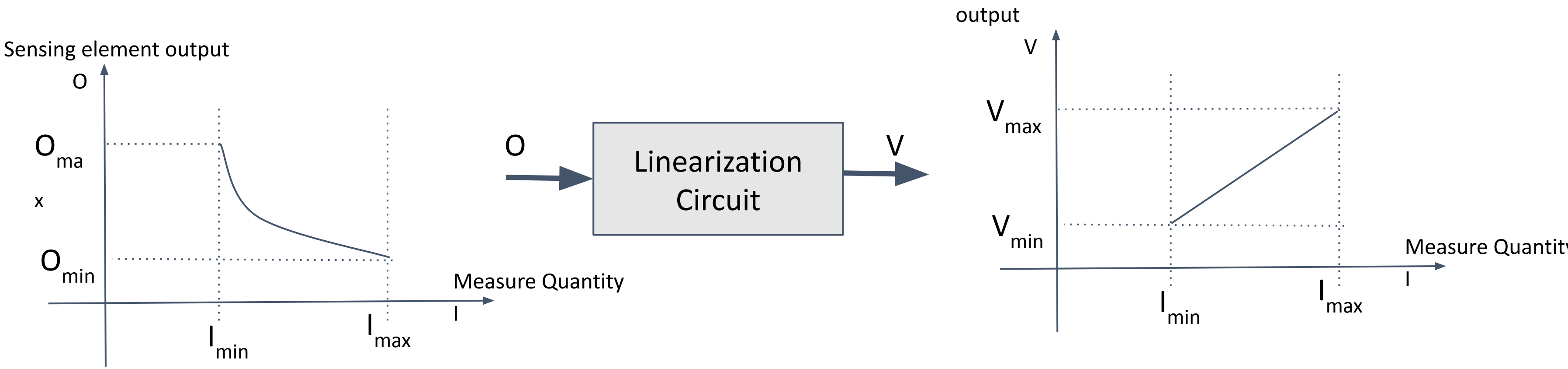
Then to convert the 0.4 to 10 volt an electronic circuit can be made to amplify the signal 25 times. (10/0.4=25)

The act of enhancing signal is called **amplification** and the electronic circuit is referred to as **amplifier** and 25 is called the **amplifier gain**.

Sometimes the signal must become smaller, this act would call **attenuation**.

Signal Conditioning - Linearization

Two convert the sensing element output to a linear output an electronic circuit is used as part of signal conditioning.

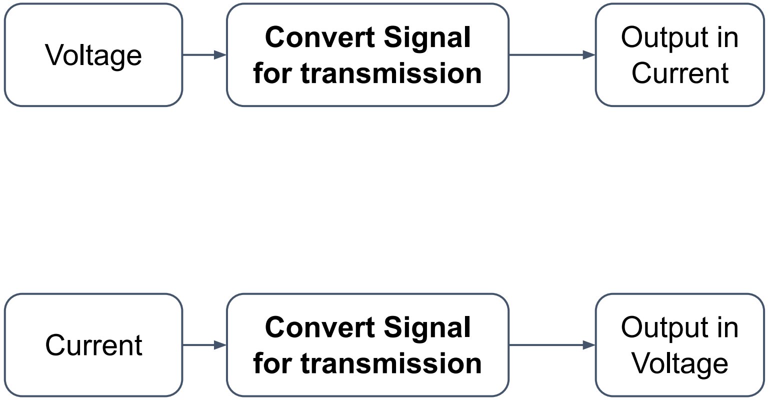


example : capacitance dependency to distance between two plate

This linear output might not be perfectly linear. Therefore the linearization error factor is introduced

Signal Conditioning - Transmission

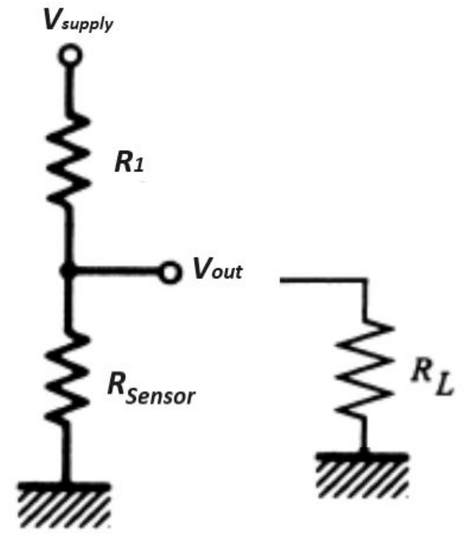
- Analog Sensors (Transducers) commonly come with standard outputs in form of voltage like 0-10 V or current 4-20 mA or both as option.
- The sensing element generates one form like current or voltage..
- Conversion from voltage to current or current to voltage needs to have an electronic circuit as part of signal conditioning



Signal Conditioning - Conversion (Resistance to Voltage)

For example to convert the resistance changes to voltage a circuit like the figure can be used. This circuit has some property which might appear as issue in applications:

- The relation between V_{out} as output and the resistance of the sensor is not linear.
- If a load with internal resistance of R_L is connected to output point, V_{out} will drop. This is known as loading effect.



$$V_{out} = \frac{V_s}{R_1 + R_{sensor}} \times R_{sensor}$$

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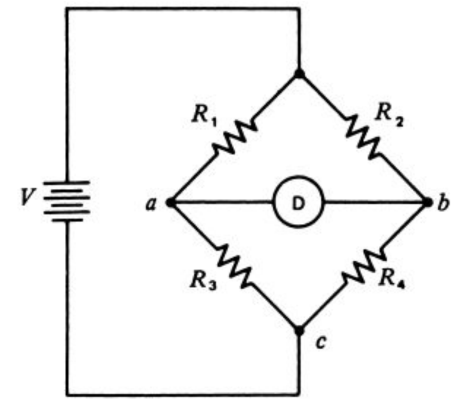
Signal Conditioning - Conversion (Resistance to Voltage)

Because of the issues mentioned in previous slide for divider circuit, instead a bridge circuit is usually used for conversion of resistance change to voltage.

The bridge circuit advantage are:

- Conversion
- Linearization
- Bias Addition/Removal
- noise and disturbance removal

Bridge Circuit



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Bridge Circuit

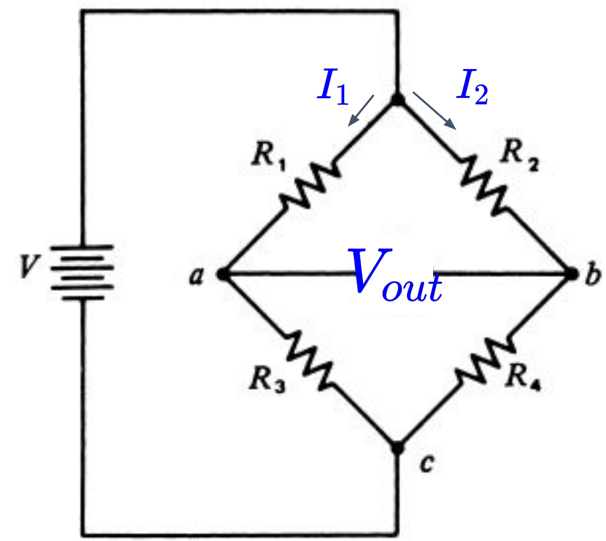
In General:

$$V_{out} = V_b - V_a$$

$$V_a = R_3 \times I_1 = R_3 \times \frac{V}{R_1 + R_3}$$

$$V_b = R_4 \times I_2 = R_4 \times \frac{V}{R_2 + R_4}$$

$$\Rightarrow \; V_{out} = V\left(\frac{R_4}{R_2 + R_4} - \frac{R_3}{R_1 + R_3}\right)$$



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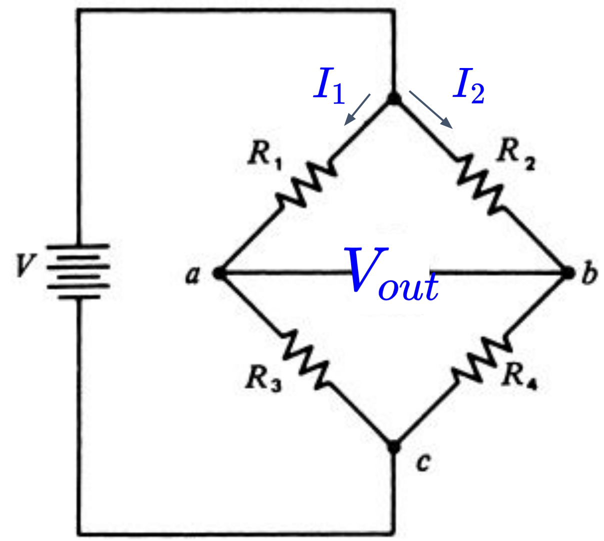
Balanced Bridge

In General:

$$V_{out} = V\left(\frac{R_4}{R_2 + R_4} - \frac{R_3}{R_1 + R_3}\right)$$

$$0 = V\left(\frac{R_4}{R_2 + R_4} - \frac{R_3}{R_1 + R_3}\right)$$

$$\Rightarrow \frac{R_4}{R_2 + R_4} = \frac{R_3}{R_1 + R_3} \Rightarrow \frac{R_1}{R_3} = \frac{R_2}{R_4}$$



In front circuit if we select the resistors so that $\frac{R_1}{R_3} = \frac{R_2}{R_4}$ then the output will be 0 volt

In this case $\frac{R_1}{R_3} = \frac{R_2}{R_4}$ the bridge is known as **balanced bridge**.

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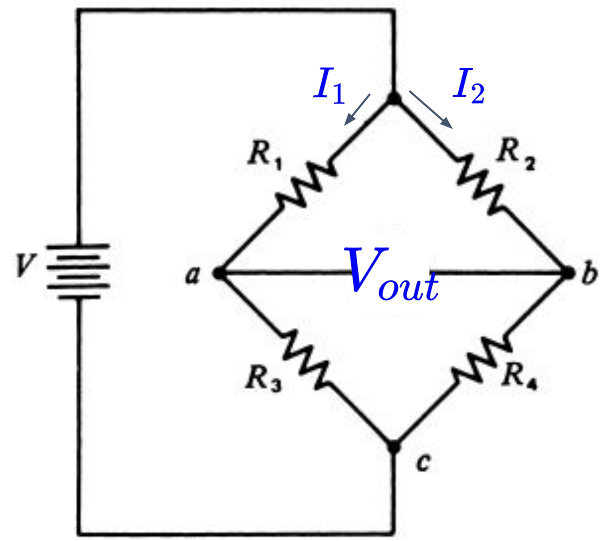
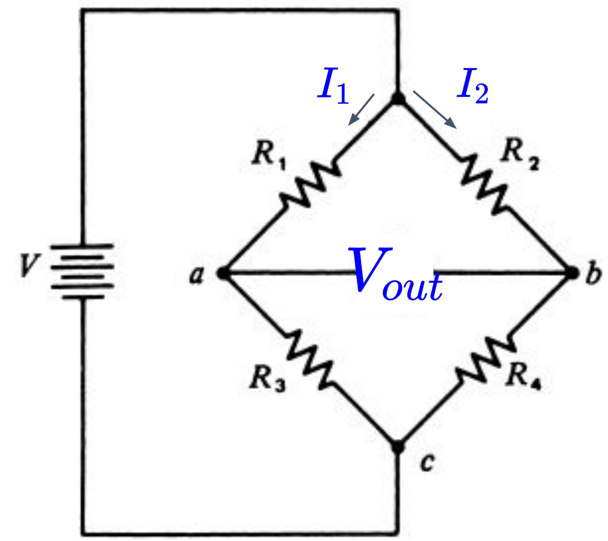
Example:

If R4=100, R2=205 and R1=395 then what should be R3 to make bridge a balanced bridge?



Example:

If R4=100, R2=205 and R1=395 then what should be R3 to make bridge a balanced bridge?



395/R3=205/100

$$\frac{R_1}{R_3} = \frac{R_2}{R_4}$$

R3= 192.7

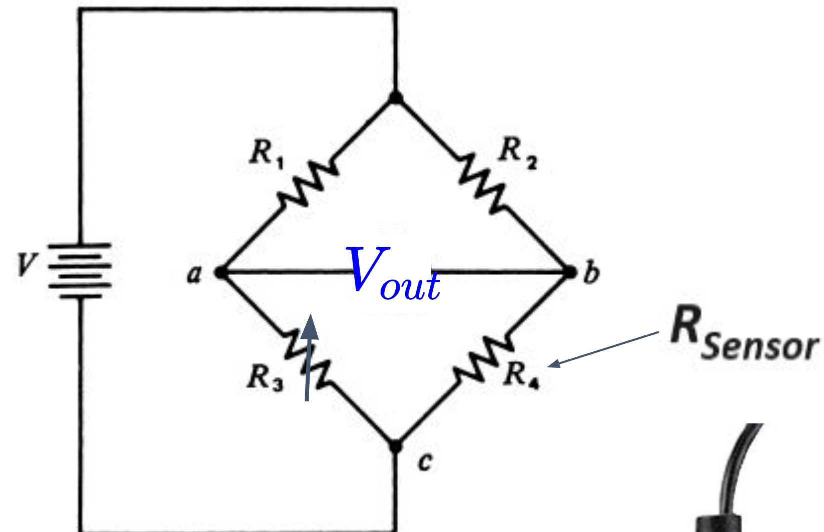
Finding exact resistor is hard then a variable resistor should be used

Balanced Bridge Application - Zero calibration

In the front figure assume the R4 is the resistance of a *temperature sensor*. This resistance will change by temperature. At 0 °C the resistance of sensor is R0 and at T °C it increases by ΔR.

The objective is to make V_{out} = 0 V at 0 °C .

To achieve this objective we need to select the other resistors so that $\frac{R_1}{R_3} = \frac{R_2}{R_4}$



We can select R1and R2 as fixed resistors with fixed value and select the R3 a variable resistor (Potentiometer).

When the sensor is sensing 0 °C then we can turn the potentiometer knob so that the reading voltage becomes 0.

In this way the sensor will be calibrated at 0 °C .

Zero knobs on sensors

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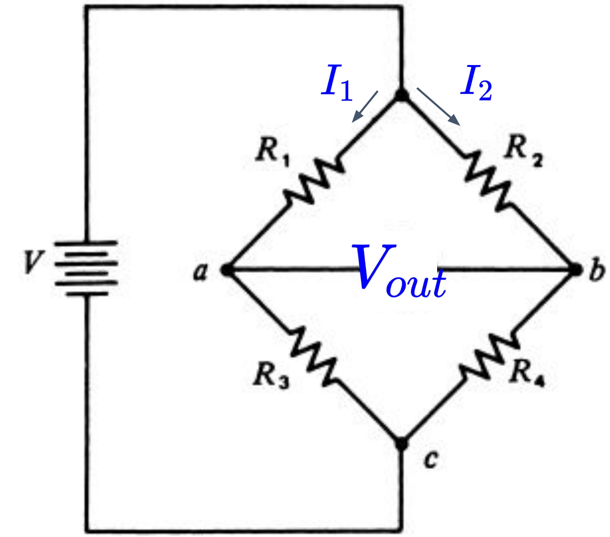
Bridge Circuit Application- Linearization



Now let's assume all the resistors are equal. It can be calculated that the output voltage is almost directly proportional to change of resistance (ΔR).

If R_0 is the resistance of the sensor at minimum of measurement range then by selecting other resistors equal to R_0 the output voltage would become linear product of change of resistance.

$$V_{out} = V\left(\frac{R_4}{R_2+R_4} - \frac{R_3}{R_1+R_3}\right)$$

$$V_{out} = V\left(\frac{R_0+\Delta R}{2R_0+\Delta R} - \frac{R_0}{R_0+R_0}\right)$$

$$x = \frac{\Delta R}{R_0}$$

$$V_{out} = V\left(\frac{1+x}{2+x} - \frac{1}{2}\right) = V\frac{x}{2(2+x)} = \frac{V}{4} \times \frac{x}{1+\frac{x}{2}}$$

$$\frac{x}{1+\frac{x}{2}} \approx x \text{ (In case ratio of change of resistance to initial resitance is verysmall)}$$

$$\Rightarrow V_{out} \approx \frac{V}{4} \times \frac{\Delta R}{R_0}$$

$$\text{Linearity} : \frac{\Delta O}{\Delta I} = \text{constant}$$

$$= \frac{V_{out}}{\Delta R} \approx \frac{V}{4R_0} = \text{constant}$$

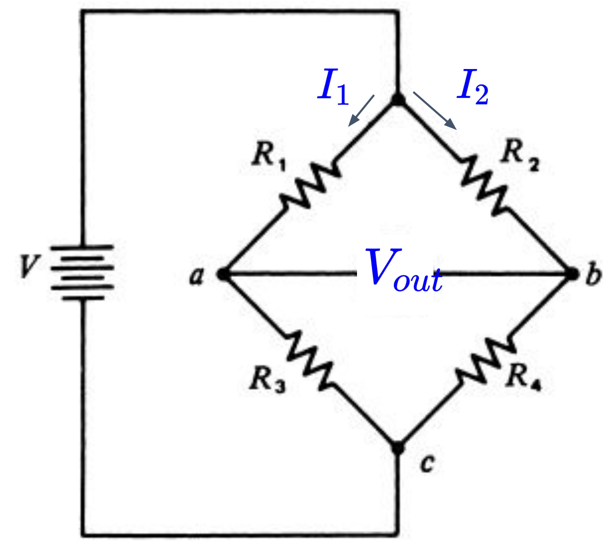
$$if\ x = \frac{\Delta R}{R_0} \ll 1$$

$$Linearity\ implies\ \frac{\Delta O}{\Delta I} = Constant$$

$$\frac{\Delta O}{\Delta I} = \frac{V_{out}}{\Delta R} \approx \frac{V}{4R_0} \leftarrow constant$$

Bridge Circuit Property- Sensitivity

$$\text{Sensitivity} = \frac{\Delta O}{\Delta I}$$
$$= \frac{V_{out} - 0}{\Delta R} = \frac{V_{out}}{\Delta R} \approx \frac{V}{4R_0}$$



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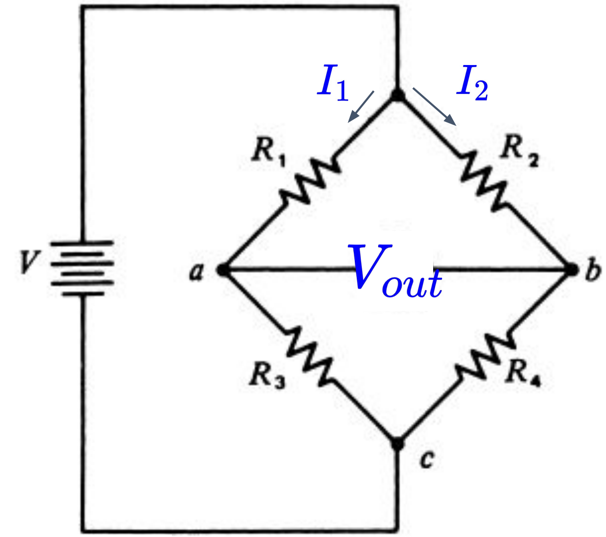
Sensitivity vs Nonlinearity Error



As below calculation shows x is the ratio of resistance change over initial resistance value.

Higher initial resistance (Higher R_0 and smaller x) will make the approximation more accurate then the it will be more linear, on the other hand the smaller x means larger R0 which makes the sensing element sensitivity $V/4R_0$ smaller.
Thwn with smaller x sensitivity is compromised with non-linearity error.
Higher sensitivity, higher nonlinearity error

$$V_{out} = V\left(\frac{R_0 + \Delta R}{2R_0 + \Delta R} - \frac{R_0}{R_0 + R_0}\right)$$

$$x = \frac{\Delta R}{R_0}$$

$$V_{out} = V\left(\frac{1+x}{2+x} - \frac{1}{2}\right) = V\frac{x}{2(2+x)} = \frac{V}{4} \times \frac{x}{1+\frac{x}{2}}$$

$$\frac{x}{1+\frac{x}{2}} \approx x \text{ (In case ratio of change of resistance to initial resitance is verysmall)}$$

$$\Rightarrow V_{out} \approx \frac{V}{4} \times \frac{\Delta R}{R_0}$$

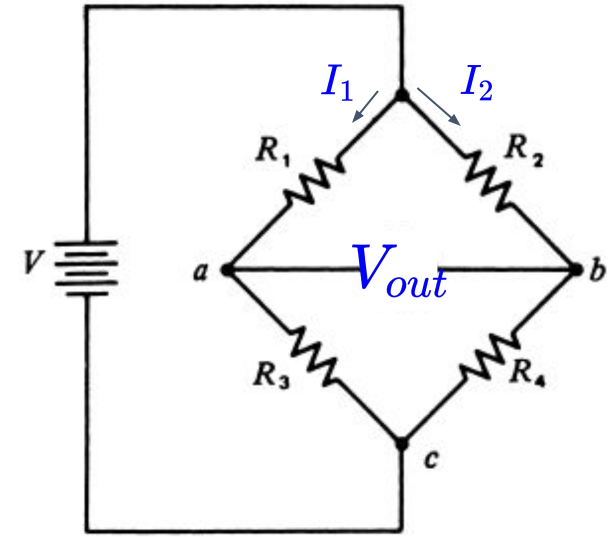
$$\text{Sensitivity} = \frac{\Delta O}{\Delta I}$$
$$= \frac{V_{out} - 0}{\Delta R} = \frac{V_{out}}{\Delta R} \approx \frac{V}{4R_0}$$

Bridge Circuit Property

Example:

For the front bridge circuit R_4 is the resistance of a sensor and the bridge output is linearly proportional to resistance change of R_4. If R_4 value is 1000 ohm at the minimum of measurement range, what would be the voltage reading when the resistance is 1010 ohm? V=10 volt

If the sensor output supposed to be 1 volt at this measurement, what should be the amplifier gain?



$$V_{out} = \frac{V}{4R_0}\Delta R$$

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Bridge Circuit Property

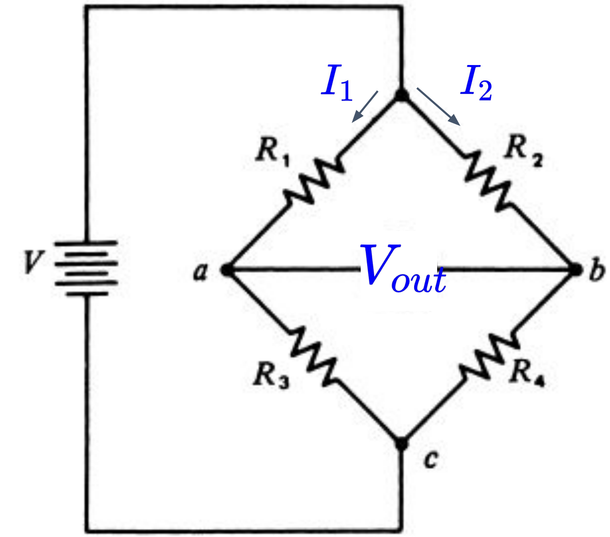
Example:

For the front bridge circuit R_4 is the resistance of a sensor and the bridge output is linearly proportional to resistance change of R_4 and V=10 V. If R_4 value is 1000 ohm at the minimum of measurement range, what would be the voltage reading when the resistance is 1010 ohm?

If the sensor output supposed to be 1 volt at this measurement, what should be the amplifier gain?

V_{out} = 10/4000x 10 =25 mV

Amplifier Gain = 1/0.025= 40



$$V_{out} = \frac{V}{4R_0} \Delta R$$

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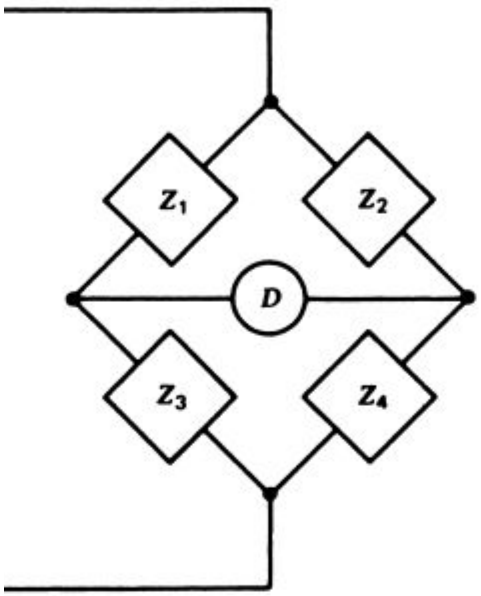
Bridge Circuit for Capacitors and Inductors

The bridge circuit configuration can be used for the sensors based on the capacitance and inductance variations.



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Signal Conditioning - Conversion Loading Effect

In front figure, the sensor internal electronic circuit is modeled with one voltage source Vx and internal resistance Rx.

When the sensor is not connected anywhere $V_y = V_x$

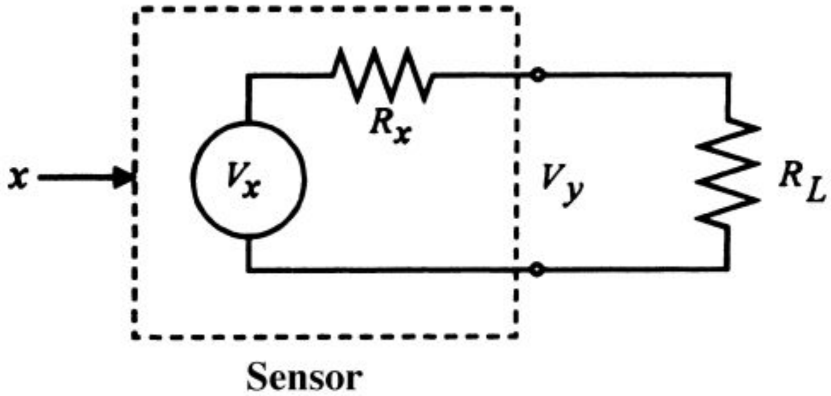
When this sensor is connected to another device known as load. The load has its own internal resistance also.

The current will start flow in circuit. Therefor the output voltage V_y will be dropped.

This drop is not desired because the data associated with it will be distorted, For example 5 v means temperature is 50 ℃ , if it drops 4.9 we will see measurement as 49 ℃.

The objective is to have voltage as V_x To do so $R_L >> R_x$

An internal resistance considered to be a positive factor.



$$
\begin{aligned}
V_y &= V_x - V_{Rx} \\
&= V_x - IR_x \\
&= V_x - \frac{V_x}{R_L + R_x} R_x \\
&= V_x \left(1 - \frac{R_x}{R_L + R_x}\right)
\end{aligned}
$$

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Measurement uncertainty- Chapter 3 Morris

Measurement uncertainty- Chapter 3 Morris

The existence of measurement uncertainty means that we would be entirely wrong to assume (though the uninitiated might assume this) that the output of a measuring instrument or larger measurement system gives the exact value of the measured quantity

Measurement errors are impossible to avoid, although we can minimize their magnitude by good measurement system design accompanied by appropriate analysis and processing of measurement data.

We can divide errors in measurement systems into:

1- those that arise during the measurement process

2- those that arise due to later corruption of the measurement signal by induced noise during transfer of the signal from the point of measurement to some other point.

The starting point in the quest to reduce the incidence of errors arising during the measurement process is to carry out a detailed analysis of all error sources in the system. Each of these error sources can then be considered in turn, looking for ways of eliminating or at least reducing the magnitude of errors.

Errors arising during the measurement process can be divided into two groups, known as:

- systematic errors
- random errors.

Systematic error

Systematic errors describe errors in the output readings of a measurement system that are consistently on one side of the correct reading, i.e., either all the errors are positive or they are all negative.

Two major sources of systematic errors are system disturbance during measurement and the effect of environmental changes

Other sources of systematic error include bent meter needles, the use of uncalibrated instruments, drift in instrument characteristics, and poor cabling practices.

Even when systematic errors due to the above factors have been reduced or eliminated, some errors remain that are inherent in the manufacture of an instrument. These are quantified by the accuracy value quoted in the published specifications contained in the instrument data sheet.

- **System disturbance due to measurement**

The measurement device might impact the process and therefore change the measured quantity value before being exposed to measuring device.

For example:

Mercury-in-glass thermometer to measure the temperature f glass of water.

Measuring voltage or current by multimeter.

Systematic Error 1: System disturbance due to measurement

- **System disturbance due to measurement**

The measurement device might impact the process and therefore change the measured quantity value before being exposed to measuring device.

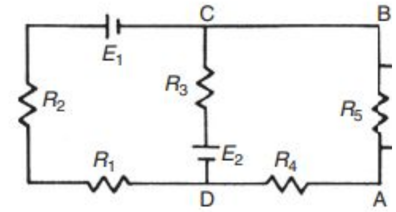
For example:

Measuring voltage or current by multimeter.

To reduce the systematic error in voltmeter the internal resistance is selected to be big and in ammeter is selected to be small.

This is why the multimeter has two different ports for voltage and current measurement.

This also explain why if a multimeter is configured for ampere measurement but is connected in parallel to the circuit will burn fuse right away.



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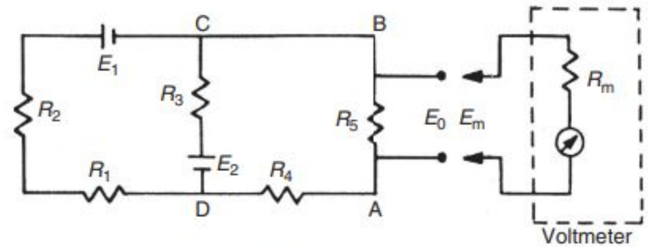

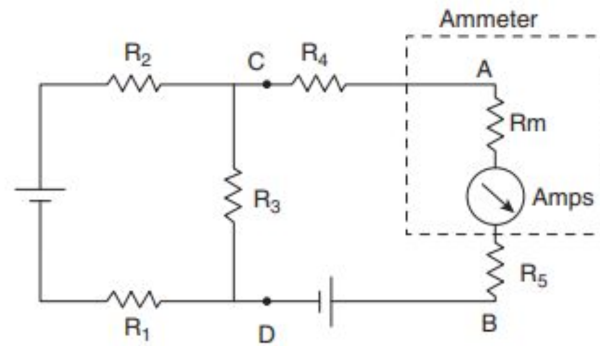

(a)

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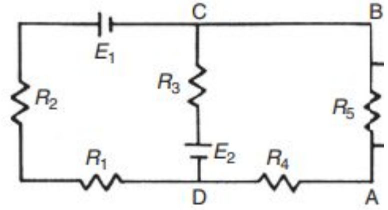
Systematic Error 1: System disturbance due to measurement

Multimeter Loading effect example

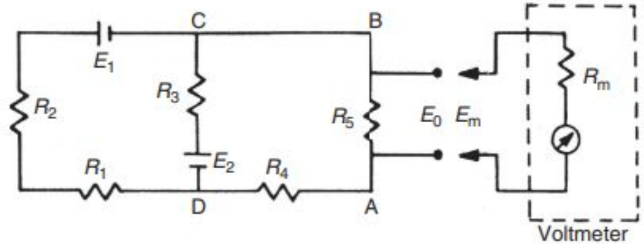
Let's assume

R_1 = 400 Ω, R_2 = 600 Ω, R_3 = 1000 Ω, R_4 = 500 Ω,

R_5 = 1000Ω, R_m = 9500 Ω



(a)



(a)

Measurement Error = E_0 - E_m = ? x E_0

Answer:

R_{AB} = 500 Ω

E_0 - E_m = 0.05 x E_0 → 5 % error

Systematic Error 1: System disturbance due to measurement

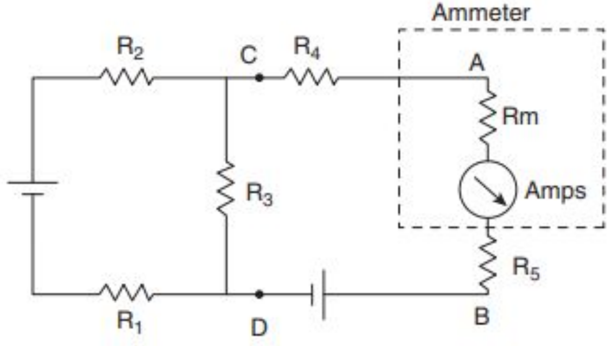
Multimeter Loading effect example

Lets assume

$R_1 = 250\ \Omega$, $R_2 = 750\ \Omega$, $R_3 = 1000\ \Omega$, $R_4 = 500\ \Omega$,

$R_5 = 500\Omega$, $R_m = 50\ \Omega$

Measurement Error = I_m/I = ?



(a)

Answer:

I_m/I = 0.968 → 3.2% error

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Systematic Error 2: Errors due to environmental inputs

The instrument measurement can be influenced by environmental conditions such as temperature or pressure .

For example an instrument which measure the force uses a wire resistor. When the wire is stretched the resistance changes. But in this sensor resistance changes also by temperature the resistance increase due to temperature is environmental effect on measurement.

The electronic elements such as resistors capacitors or inductors characteristic are used in signal conditioning circuit. these elements characteristic also depends on environmental temperature.

In any general measurement situation, it is very difficult to avoid environmental inputs, because it is either impractical or impossible to control the environmental conditions surrounding the measurement system. System designers are therefore charged with the task of either reducing the susceptibility of measuring instruments to environmental inputs or, alternatively, quantifying the effect of environmental inputs and correcting for them in the instrument output reading.

Wear in instrument components

Systematic errors can frequently develop over a period of time because of wear in instrument components.

Recalibration often provides a full solution to this problem

Connecting leads

In connecting instruments to the control loop, a common source of error is the failure to take proper account of the resistance of connecting leads.

For instance, in typical applications of a resistance thermometer, it is common to find that the thermometer is separated from other parts of the measurement system by perhaps 100 m. The resistance of such a length of 20-gauge copper wire is 7 Ω, and there is a further complication that such wire has a temperature coefficient of 1 mΩ/ °C .

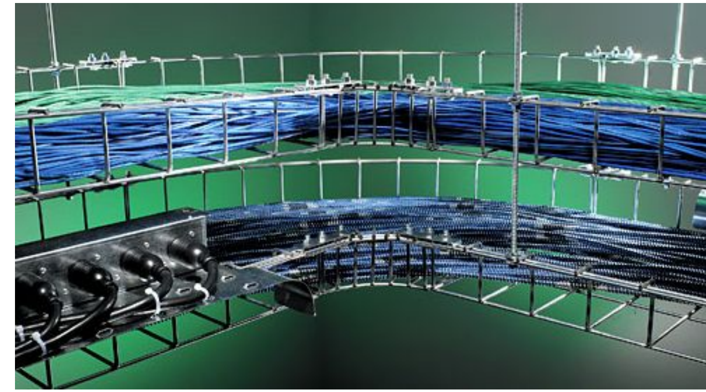
Noise in the form of voltage transients

When motors and other electrical equipment (both a.c. and d.c.) are switched on and off, large changes of power consumption suddenly occur in the electricity supply system.

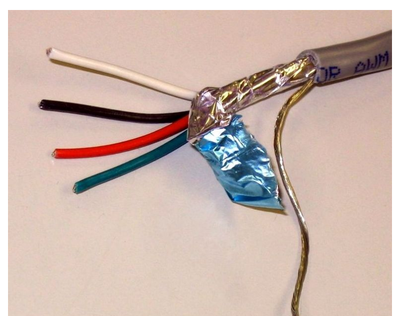
This can cause voltage transients ("spikes") in measurement circuits connected to the same power supply. Such noise voltages are of large magnitude but short time duration.

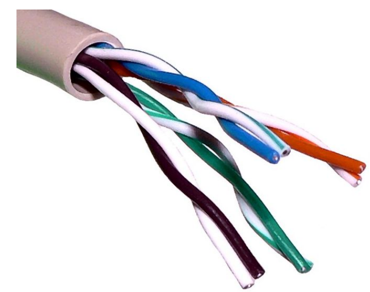
Corona discharge can also cause voltage transients on the mains power supply. This occurs when the air in the vicinity of high-voltage d.c. circuits becomes ionized and discharges to earth at random times.

Techniques for reducing induced measurement noise



- Seperation of power cable and instrument cable, 0.3 meter essential, 1m prefered
- Using Twisted pair
- Shielded cable for instruments
- Earthing





Reduction of systematic errors

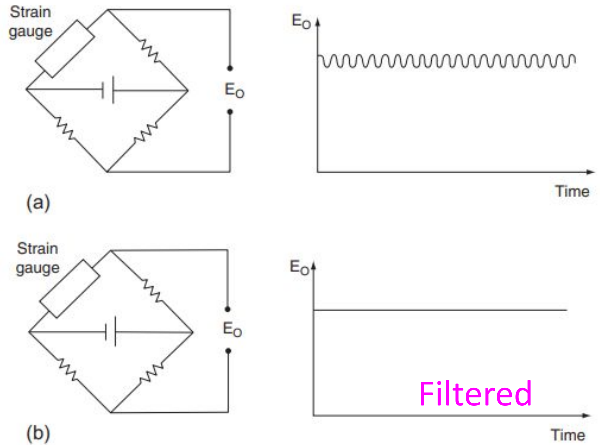
- **Careful instrument design** or selecting an instrument which has provision to cancel environment effect.
- **Calibration:** Instrument calibration is a very important consideration in measurement systems.
- **Method of opposing inputs:** The method of opposing inputs compensates for the effect of an environmental input in a measurement system by introducing an equal and opposite environmental input that cancels it out.
- **Manual correction of output reading:** In the case of errors that are due either to system disturbance during the act of measurement or due to environmental changes, a good measurement technician can substantially reduce errors at the output of a measurement system by calculating the effect of such systematic errors and making appropriate correction to the instrument readings.

Intelligent instruments: Intelligent instruments contain extra sensors that measure the value of environmental inputs and automatically compensate the value of the output reading. They have the ability to deal very effectively with systematic errors in measurement systems, and errors can be attenuated to very low levels in many cases.

Filtered

Reduction of systematic errors

- **Signal filtering:** One frequent problem in measurement systems is corruption of the output reading by periodic noise, often at a frequency of 60 Hz caused by pickup through the close proximity of the measurement system to apparatus or current-carrying cables operating on a mains supply. . Periodic noise corruption at higher frequencies is also often introduced by mechanical oscillation or vibration within some component of a measurement system. The amplitude of all such noise components can be substantially attenuated by the inclusion of filtering.



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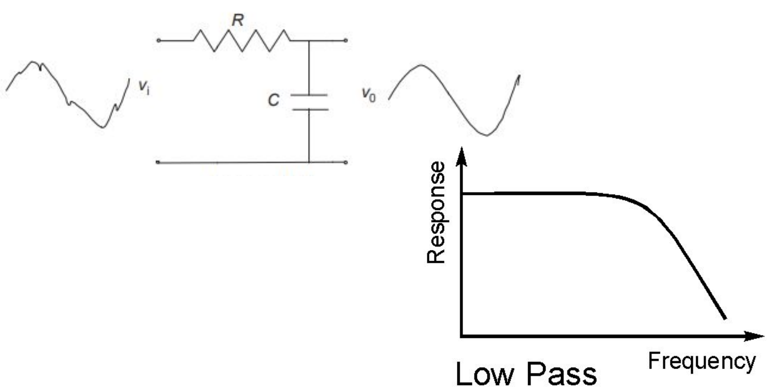
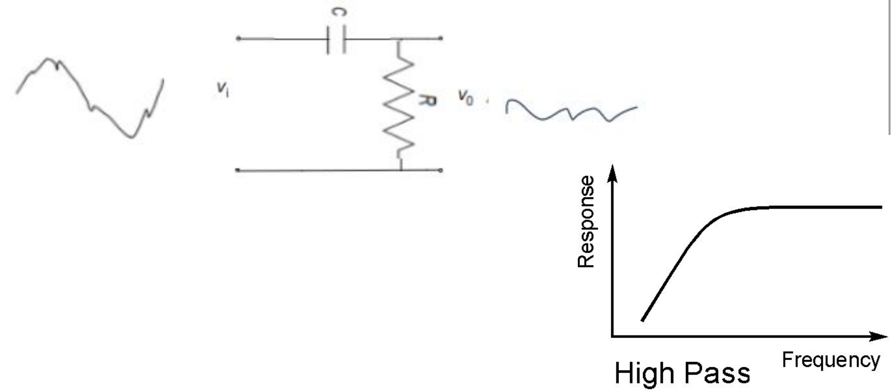
Filters

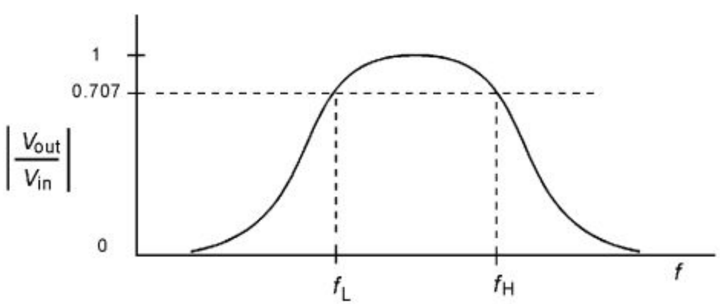
Low Pass Filter



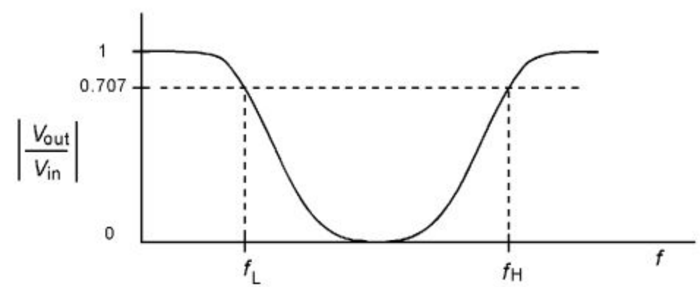
High pass Filter



Band Pass Filter



Notch filter

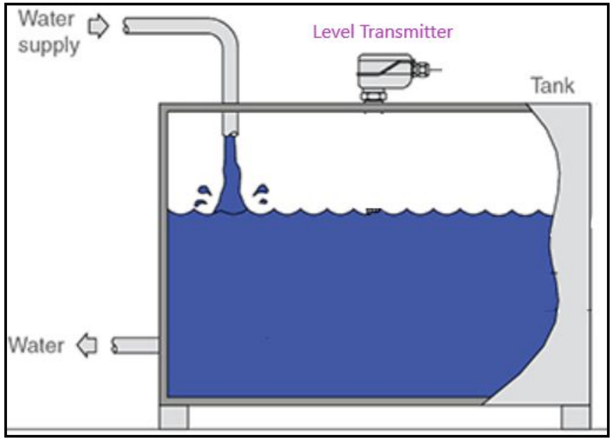


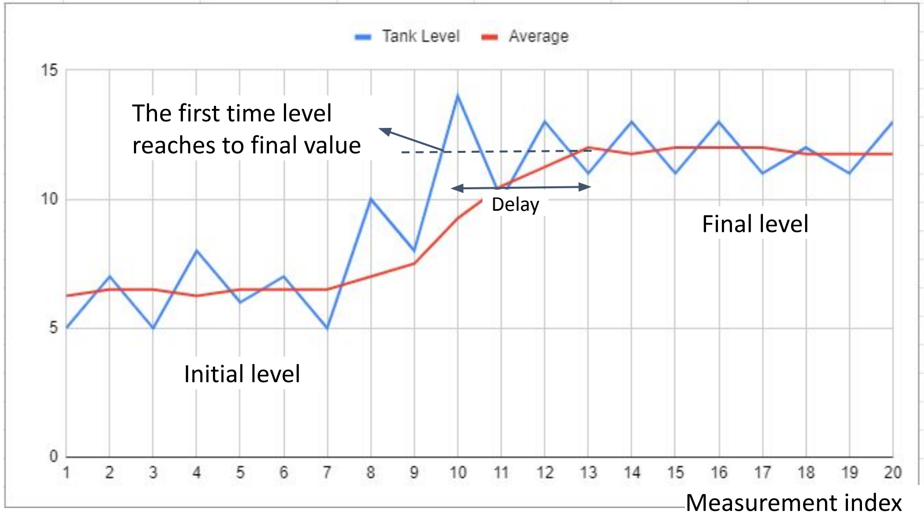
Averaging as low pass filter

- The blue shows the measured value for the tank level.
- The red shows the average of current measurement plus last three measurement.

Property:

- As figure shows the average values present more stable measurement and the wavy on the surface of fluid is ignored. The red graph is more smooth.
- The average creates delay. As graph shows the average reaches to final value after the first time level hit the final value.
- The delay depends on how many of previous measurements are used to take average.





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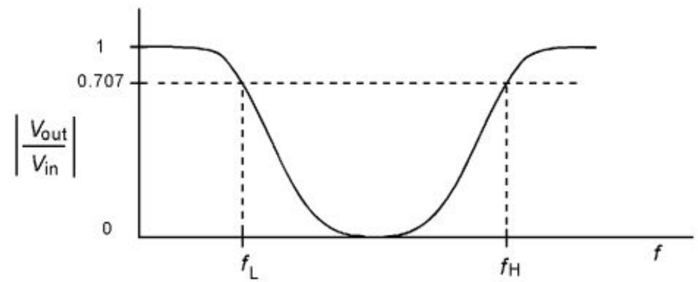
Notch Filter

- Notch filter remove specific frequencies.
- Since the noises induced by power cable will have similar frequencies 60 Hz , Notch filter can be used to remove signals with same frequency
- Using filter will increase delay in measurement or another word increase the response time



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