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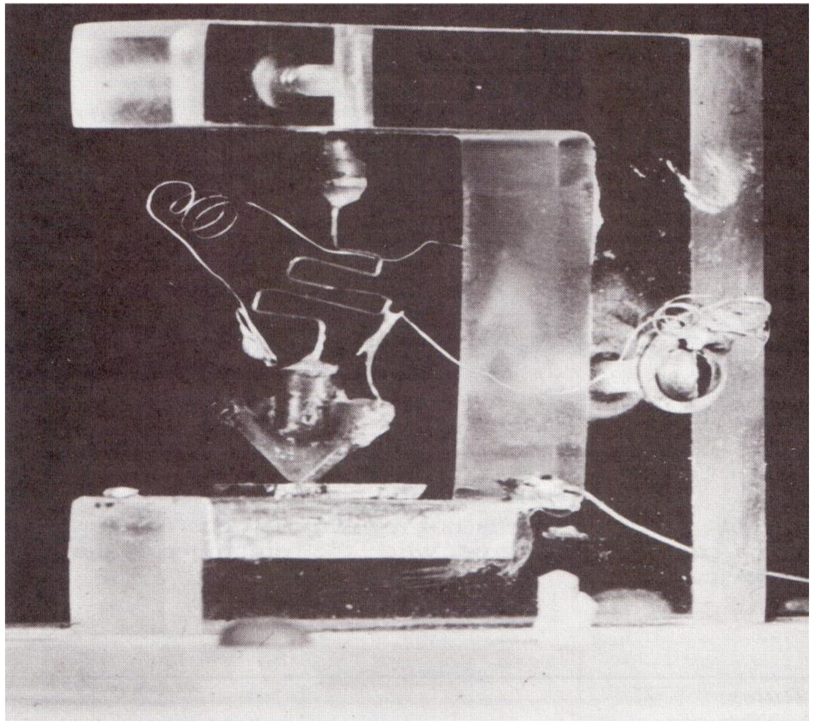
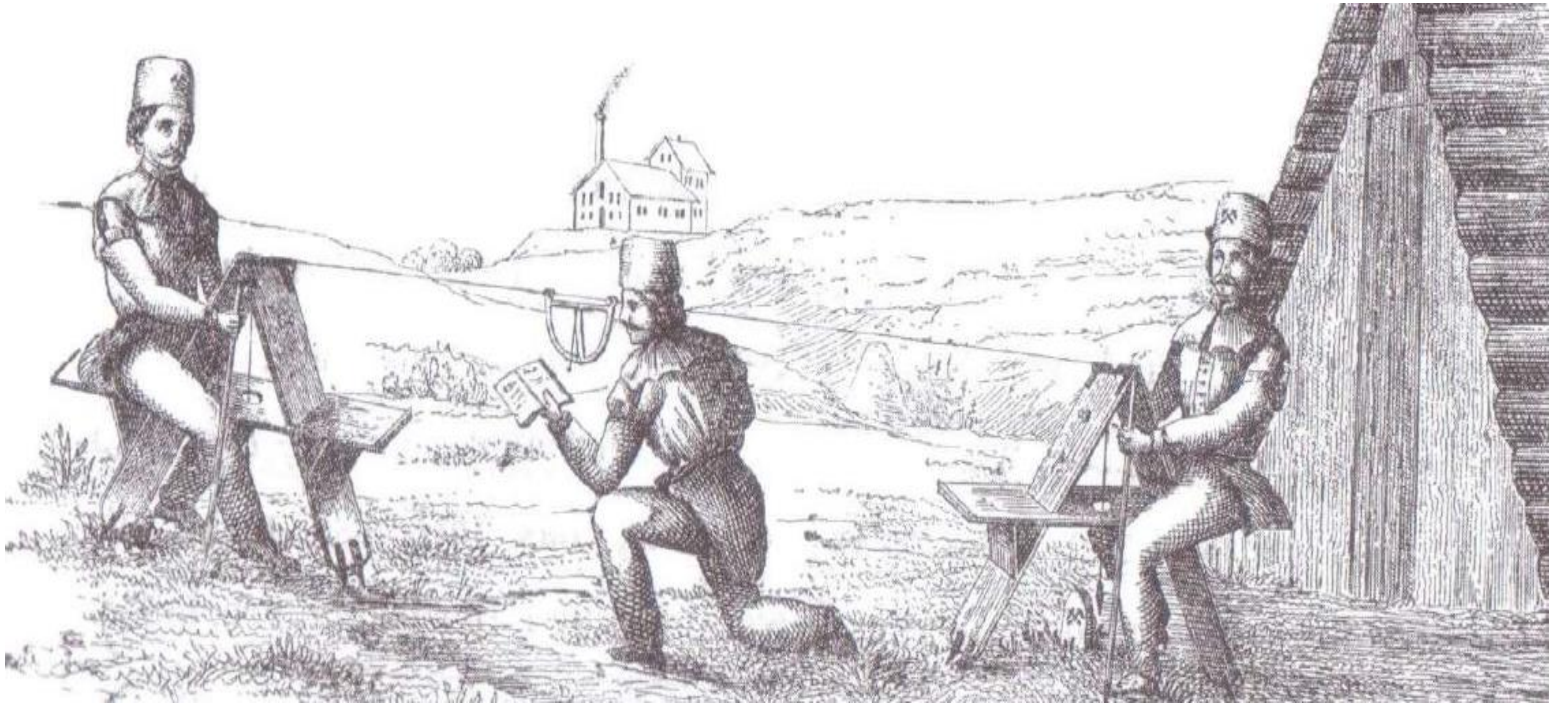
Electronic Devices and Measurements

MATERIAL 1





Coordinator: **Raul Ionel** (raul.ionel@upt.ro)

1. Basic Electrical and Electronic Engineering Principles and Terminology.

1.1 Measurement Units & Systems. Definition of Measurements (True Value, Conventional True Value, Measured Value, Absolute & Relative Errors etc.).
1.2 Defining units of Charge, Force, Energy, Power, Electrical potential, Resistance, Conductance etc.
1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

2. Introduction to Measurement and Instrumentation Principles.

2.1 Measurement methods classification (direct, indirect, deflection methods, comparison methods, Null methods or zero methods, Differential methods, Coincidence methods).
2.2 Elements of a Measurement System.
2.3 Classifications of measurement instrumentation (Primary & Secondary, Analog & Digital, Null Type or Deflection Type, Stand Alone or PC Based, Smart vs Non-Smart, Active or Passive).
2.4 Measurement instruments characteristics (Static & Dynamic characteristics).

3. Questions & exercises.

2.1 Measurement methods classification (direct, indirect, deflection methods, comparison methods, Null methods or zero methods, Differential methods, Coincidence methods).

- **Direct measurement methods** – is a technique used to obtain a quantity or property of an object or phenomenon **without the need for intermediate calculations or inferences**. This means the measurement is taken directly from the subject using an instrument that provides an immediate reading. For example, we are using a stopwatch to measure time, we are directly reading the instrument indication from a display or a deviated needle.

- **Indirect measurement methods** – is a technique used to determine/evaluate a quantity or property of an object or phenomenon **by using calculations, inferences, or relationships with other directly measured variables.** For example, we are calculating the **resistivity** (ρ) of a cable, after we have directly measured the cable Resistance (Ω), Cross-sectional area (m^2) and cable Length (m).

Present the resistivity value of a cable for which we have measured the following parameters: R = (2 ± 0.1)Ω, L = (1 ± 0.01)m, A = $(2 \cdot 10^{-6} \pm 1.5 \cdot 10^{-8})$m². Estimate the maximum tolerated error interval by means of overestimation, quadrature calculation and error propagation law.

Present the consumed power value for a circuit after we have directly measured an applied potential difference of U=(70 ± 1.5)V and a current of I =(80 ± 2.25)mA. Estimate the maximum tolerated error interval by means of overestimation, quadrature calculation and error propagation law.

- **Null method of measurement** – is a technique used in precision measurement where the goal is to achieve a **zero (null) reading** on a measuring instrument by balancing or compensating for the measured quantity. This method minimizes errors caused by instrument imperfections and external factors, leading to highly accurate results. For example, a **Wheatstone Bridge** is used for measuring an unknown electrical resistance by balancing two legs of a bridge circuit.

2.1 Measurement methods classification (direct, indirect, deflection methods, comparison methods, Null methods or zero methods, Differential methods, Coincidence methods).

Present the resistivity value of a cable for which we have measured the following parameters: R = (2 ± 0.1)Ω, L = (1 ± 0.01)m, $A = (2 \cdot 10^{-6} \pm 1.5 \cdot 10^{-8})m^2$. Estimate the maximum tolerated error interval by means of overestimation, quadrature calculation and error propagation law.

$R = (2 \pm 0.1)\Omega \Rightarrow \delta_R = \pm 5\%$
$L = (1 \pm 0.01)m \Rightarrow \delta_L = \pm 1\%$
$A = (2 \cdot 10^{-6} \pm 1.5 \cdot 10^{-8})m^2 \Rightarrow \delta_A = \pm 0.75\%$

RELATIVE TOLERATED ERRORS

$$\rho = \frac{R \cdot A}{L} = \frac{2\Omega \cdot 2 \cdot 10^{-6} m^2}{1m} \cong 4\mu\Omega m \pm ???$$

HOW CAN WE EVALUATE THE TOLERATED ERROR INTERVAL??

EASY METHOD, SUM OF INDIVIDUAL ERRORS => $\delta_\rho \cong \pm 6.75\%$ $\quad \rho = (4 \pm 0.27)\mu\Omega m$ (overestimation)

$$\rho_{max} = \frac{R_{max} \cdot A_{max}}{L_{min}} \cong 4.27\mu\Omega m \qquad \rho_{min} = \frac{R_{min} \cdot A_{min}}{L_{max}} \cong 3.73\mu\Omega m$$

QUADRATURE CALCULATION => $\delta_\rho = \pm\sqrt{5^2 + 1^2 + 0.75^2}\ [\%] \cong \pm 5.15\%$ $\quad \rho = (4 \pm 0.21)\mu\Omega m$ (better, more realistic)

ERROR PROPAGATION LAW =>
$$\delta_\rho = \pm\sqrt{\left(\underbrace{\frac{\partial\rho}{\partial L}}_{\text{PARTIAL DERIVATIVE TERM}} \cdot \underbrace{\delta_L}_{\text{INDIVIDUAL ERROR TERM}}\right)^2 + \left(\frac{\partial\rho}{\partial A} \cdot \delta_A\right)^2 + \left(\frac{\partial\rho}{\partial R} \cdot \delta_R\right)^2}$$

2.1 Measurement methods classification (direct, indirect, deflection methods, comparison methods, Null methods or zero methods, Differential methods, Coincidence methods).

Present the resistivity value of a cable for which we have measured the following parameters: $R = (2 \pm 0.1)\Omega$, $L = (1 \pm 0.01)$m, $A = (2 \cdot 10^{-6} \pm 1.5 \cdot 10^{-8})m^2$. Estimate the maximum tolerated error interval by means of overestimation, quadrature calculation and error propagation law.

$$R = (2 \pm 0.1)\Omega \Rightarrow \delta_R = \pm 5\%$$
$$L = (1 \pm 0.01)m \Rightarrow \delta_L = \pm 1\%$$
$$A = (2 \cdot 10^{-6} \pm 1.5 \cdot 10^{-8})m^2 \Rightarrow \delta_A = \pm 0.75\%$$

RELATIVE TOLERATED ERRORS

$$\rho = \frac{R \cdot A}{L} = \frac{2\Omega \cdot 2 \cdot 10^{-6} m^2}{1m} \cong 4\mu\Omega m \pm ???$$

HOW CAN WE EVALUATE THE TOLERATED ERROR INTERVAL??

ERROR PROPAGATION LAW $\Rightarrow$ $\delta_\rho = \pm\sqrt{\left(\frac{\partial\rho}{\partial L}\cdot\delta_L\right)^2 + \left(\frac{\partial\rho}{\partial A}\cdot\delta_A\right)^2 + \left(\frac{\partial\rho}{\partial R}\cdot\delta_R\right)^2}$

$$\frac{\partial\rho}{\partial L} = \frac{\partial\left(\frac{RA}{L}\right)}{\partial L} = -\frac{RA}{L^2} = -\frac{4\mu\Omega m^2}{1m^2} = -4\mu\Omega$$
$$\frac{\partial\rho}{\partial A} = \frac{\partial\left(\frac{RA}{L}\right)}{\partial A} = \frac{R}{L} = 2\frac{\Omega}{m}$$
$$\frac{\partial\rho}{\partial R} = \frac{\partial\left(\frac{RA}{L}\right)}{\partial R} = \frac{A}{L} = \frac{2\mu m^2}{1m} = 2\mu m$$

$$\delta_\rho = \pm\sqrt{(-4\mu\Omega \cdot 0.01m)^2 + \left(2\frac{\Omega}{m}\cdot 0.015\mu m^2\right)^2 + (2\mu m \cdot 0.1\Omega)^2} \cong \underbrace{\pm 0.21\mu\Omega m}_{\text{better estimation}}$$

$$\rho = (4 \pm 0.21)\,\mu\Omega m$$

2.1 Measurement methods classification (direct, indirect, deflection methods, comparison methods, Null methods or zero methods, Differential methods, Coincidence methods).

Present the consumed power value for a circuit after we have directly measured an applied potential difference of U=(70 ± 1.5)V and a current of I =(80 ± 2.25)mA. Estimate the maximum tolerated error interval by means of overestimation, quadrature calculation and error propagation law.

$P = 70V \cdot 80mA \simeq 5.6W \quad , \quad \delta_P = ??$

$\delta_I \cong \pm 2.81\% \qquad \delta_U = \pm 2.14\%$

OVERESTIMATION $\quad \delta_P \cong \pm 4.95\% \Rightarrow P \cong (5.6 \pm 0.3)\ W$

QUADRATURE $\quad \delta_P = \pm\sqrt{2.81^2 + 2.14^2}\ [\%] = \pm 3.53\% \Rightarrow P \cong (5.6 \pm 0.2)W$

PROPAGATION
$$\left.\begin{aligned} \frac{\partial P}{\partial u} &= \frac{\partial(u \cdot i)}{\partial u} = i = 80mA \\ \frac{\partial P}{\partial i} &= \frac{\partial(u \cdot i)}{\partial i} = u = 70V \end{aligned}\right\} \quad \delta_P = \pm\sqrt{(80mA \cdot 1.5V)^2 + (70V \cdot 2.25mA)^2} = \pm\sqrt{(120\ mAV)^2 + (157.5\ mAV)^2} \cong$$

$$\cong \pm 0.2W$$

$$\Rightarrow P \cong (5.6 \pm 0.2)\ W$$

2.1 Measurement methods classification (direct, indirect, deflection methods, comparison methods, Null methods or zero methods, Differential methods, Coincidence methods).

Present your results as accurately as possible, especially when dealing with indirect measurement methods.

a) Quantity to be evaluated presented as sum of identical quantities.

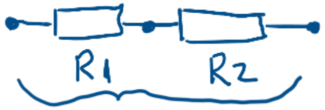
$R1 = 300\ k\Omega$

$R2 = 600\ k\Omega$

Tolerances 5%

$\delta_{R1} = \pm 15\ k\Omega$

$\delta_{R2} = \pm 30\ k\Omega$



$Rx = 900\ k\Omega \pm \boxed{\delta_{Rx}}$??

$\delta_{Rx} = \pm 45\ k\Omega \Rightarrow Rx = (900 \pm 45)\ k\Omega$ - OVERESTIMATED

$\delta_{Rx} = \pm \sqrt{(15\ k\Omega)^2 + (30\ k\Omega)^2} \cong \pm 34\ k\Omega$ - QUADRATURE

In this case, measurands are of the same type -> Ω. Measurands are independent of each other, meaning that a change in R1, does not modify the value of R2. Note that we are dealing with absolute error values.

Statistically, the quadrature calculation is more realistic since it assumes that the reported tolerances are not either maximal or minimal at the same time.

b) Quantity to be evaluated presented as difference of identical quantities.

$R2 = Rx - R1 = 600\ k\Omega \pm \delta_{R2}$

$\delta_{Rx} = \pm 45\ k\Omega$, $\delta_{R1} = \pm 15\ k\Omega \Rightarrow \delta_{R2} = \pm 60\ k\Omega$ (OVERESTIMATION) OR $\delta_{R2} = \pm \sqrt{\delta_{Rx}^2 + \delta_{R1}^2} \cong \boxed{\pm 47\ k\Omega}$

MORE FEASIBLE ESTIMATION !!!

2.1 Measurement methods classification (direct, indirect, deflection methods, comparison methods, Null methods or zero methods, Differential methods, Coincidence methods).

Present your results as accurately as possible, especially when dealing with indirect measurement methods.

c) Quantity to be evaluated presented as multiplication of different quantities.

See example problem dealing with indirect calculation of Power, by means of voltage and current measurements. We are using relative errors.

d) Quantity to be evaluated presented as division of different quantities.

$U = (2.6 \pm 0.2)V$, $i = (0.65 \pm 0.02)A$, $R = \frac{U}{i}$ => $R = 4\Omega \pm \delta_R$

ABSOLUTE ERROR WILL BE CONVERTED TO A RELATIVE VALUE!

$\delta_{V\%} = \pm \frac{0.2V}{2.6V} \cdot 100 \cong \pm 7.7\%$

$\delta_{i\%} \cong \pm 3.1\%$

=> $\delta_{R\%} \cong \pm 10.8\%$ AS OVER ESTIMATION

$\delta_{R\%} \cong \pm \sqrt{7.7^2 + 3.1^2}$ [%] $\cong \pm 8\%$ AS QUADRATURE CALCULATION

$R \cong (4 \pm \begin{matrix} 0.4 \\ 0.3 \end{matrix})\Omega$

2.1 Measurement methods classification (direct, indirect, deflection methods, comparison methods, Null methods or zero methods, Differential methods, Coincidence methods).

- **Differential measurements** – is a technique used in precision measurement where the difference between two similar quantities is evaluated, as opposed to measuring an absolute value. Often used in bridge circuits, instrumentation amplifiers, for example it is used in electrical circuits to measure voltage differences between two points rather than referencing a common ground.

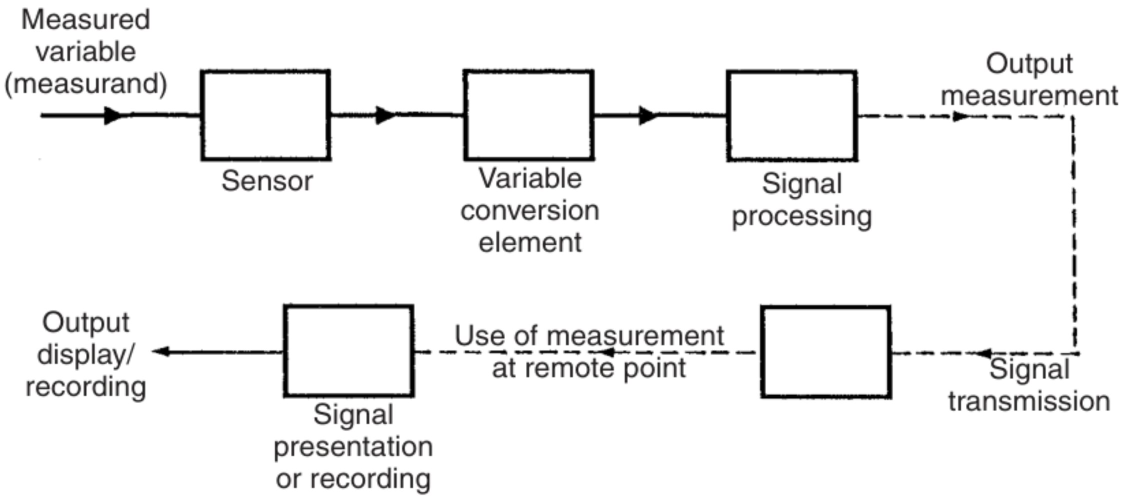
- **Substitution measurements** – is a technique used such that an unknown quantity is measured by replacing it with a known standard until equilibrium or balance is achieved. This method is commonly used to improve accuracy by minimizing systematic errors. For example, an unknown resistance is replaced with a standard resistor in a balanced bridge circuit (Wheatstone Bridge).

- **Coparison methods** – is used when an unknown quantity is compared directly with a known reference standard. The result is determined based on the difference or similarity between the two values. For example, a Wheatstone Bridge compares an unknown resistance with a known standard to determine the value.

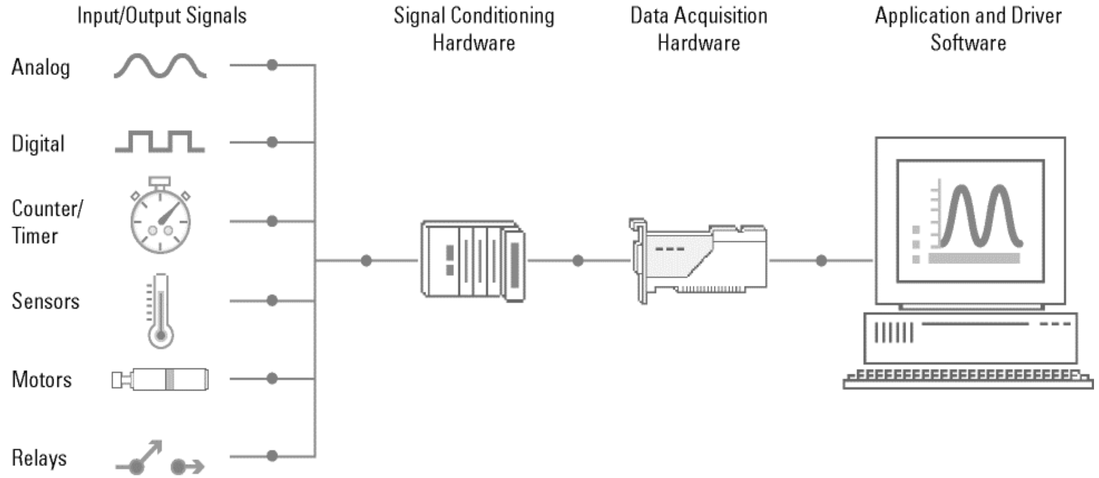
- **Coincidence methods** – used measurement technique that determines the value of an unknown quantity by aligning or matching it with a known standard. The method ensures that **two signals, scales, or reference points coincide** to achieve minimal measurement error. For example, **Lissajous Figures (Oscilloscope Method)** measure phase differences and frequency by observing when waveforms coincide with predefined images.

2.2 Elements of a Measurement System.

A measurement system is designed to provide information about the physical value of a variable being measured. In simple cases, it may consist of a single unit that produces an output reading or signal based on the magnitude of the applied variable. However, in more complex measurement scenarios, the system is composed of multiple interconnected elements.



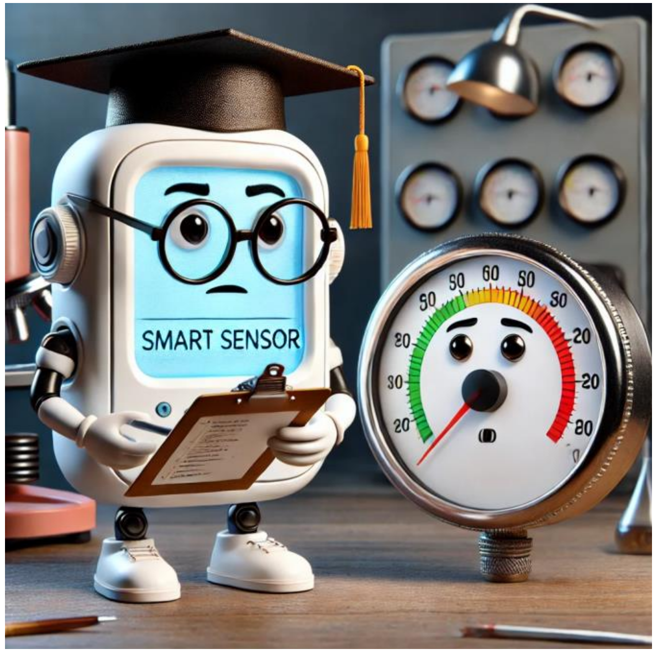
An example of measurement system architecture, as defined by Alan S. Morris, Measurement and Instrumentation Principles, 3rd Edition.



INTELLIGENT MEASUREMENT DEVICES - a unit that includes either a complete measurement system or a component within one, integrated with a digital processor. By processing measurement sensor outputs to compensate for inherent errors, these devices significantly enhance measurement accuracy. They are commonly known by various names, such as **intelligent instruments, smart sensors, and smart transmitters**.

2.2 Elements of a Measurement System.

INTELLIGENT MEASUREMENT DEVICES - a unit that includes either a complete measurement system or a component within one, integrated with a digital processor. By processing measurement sensor outputs to compensate for inherent errors, these devices significantly enhance measurement accuracy. They are commonly known by various names, such as **intelligent instruments, smart sensors, and smart transmitters**.



Some functions performed by intelligent instruments:

- Compensation **for the loading effect** of measurement on the measured system.
- Automatically **switchable ranges** (using several primary sensors within the instrument, each working on a different range).
- **Switchable output units** (display in Imperial or SI units).
- Output **linearization and self fault diagnosis**.
- **Remote adjustment and control** of instrument parameters.

A significant advancement has been the **integration of a microprocessor directly within the sensor**, creating what are commonly known as smart sensors. With ongoing miniaturization and increased device integration, these smart sensors have been combined with other sensors and signal processing circuits into a single package.

2.2 Elements of a Measurement System.

INTELLIGENT/SMART SENSORS - a unit equipped with built-in processing capabilities, allowing it to respond to local conditions independently without relying on a central controller. These sensors typically offer at least twice the accuracy of traditional sensors, require less maintenance, and minimize wiring needs at the installation site. Additionally, they provide enhanced long-term stability, reducing the frequency of required calibrations (TEMP/HUMIDITY/BAR PRESSURE SMART PROBE).

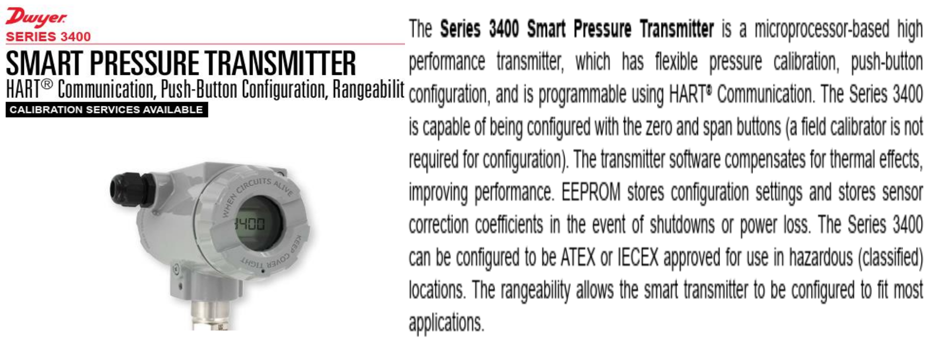
Some functions performed by intelligent sensors:

- **Remote calibration** capability - Sensors with an electrical output can use a known reference voltage level to do self-calibration.
- **Self-diagnosis** of faults - by monitoring internal signals for evidence faults. Whilst it is difficult to achieve a sensor that can carry out self-diagnosis of all possible faults that might arise, it is often possible to make simple checks that detect many of the more common faults.
- Calculation of measurement accuracy and **compensation for random errors** by averaging.
- **Adjustment for measurement of non-linearities** to produce a linear output by digital processing to convert the output to a linear form, if the non-linearity is known so that an equation describing it can be programmed into the sensor.

2.2 Elements of a Measurement System.

INTELLIGENT TRANSMITTERS – analog, programmable & smart.

Analog	Programmable	Smart
One transmitter for every sensor type and every sensor range. Additional transmitters to correct for environmental changes. Prone to frequent calibration. The analog transmitter converts the sensor's raw signal into a standardized 4-20mA current signal, which is commonly used in industrial automation and control systems.	Include a microprocessor but do not have bi-directional communication. Prone to frequent calibration. The **Pt100 RTD** (Resistance Temperature Detector) sensor measures temperature by changing resistance with temperature variations. A **universal temperature transmitter** can be programmed to output a user-defined signal, such as **4-20mA, 0-10V, or digital protocols (Modbus, Profibus, etc.)**. Or, can be programmed to Apply corrections or linearization to improve measurement accuracy.	Include a microprocessor and have bi-directional communication. Include secondary sensors that can measure, and so compensate for, environmental disturbances. Incorporate signal conditioning and ADC. Incorporate multiple sensors covering different measurement ranges and allow automatic selection of the required range. Include self-calibration capability that allows removal of zero drift and sensitivity drift errors. Can adjust for non-linearities to produce a linear output.


Dwyer
SERIES 3400
SMART PRESSURE TRANSMITTER
HART® Communication, Push-Button Configuration, Rangeabilit
CALIBRATION SERVICES AVAILABLE

The **Series 3400 Smart Pressure Transmitter** is a microprocessor-based high performance transmitter, which has flexible pressure calibration, push-button configuration, and is programmable using HART® Communication. The Series 3400 is capable of being configured with the zero and span buttons (a field calibrator is not required for configuration). The transmitter software compensates for thermal effects, improving performance. EEPROM stores configuration settings and stores sensor correction coefficients in the event of shutdowns or power loss. The Series 3400 can be configured to be ATEX or IECEX approved for use in hazardous (classified) locations. The rangeability allows the smart transmitter to be configured to fit most applications.

2.2 Elements of a Measurement System.

Communicating with smart devices.

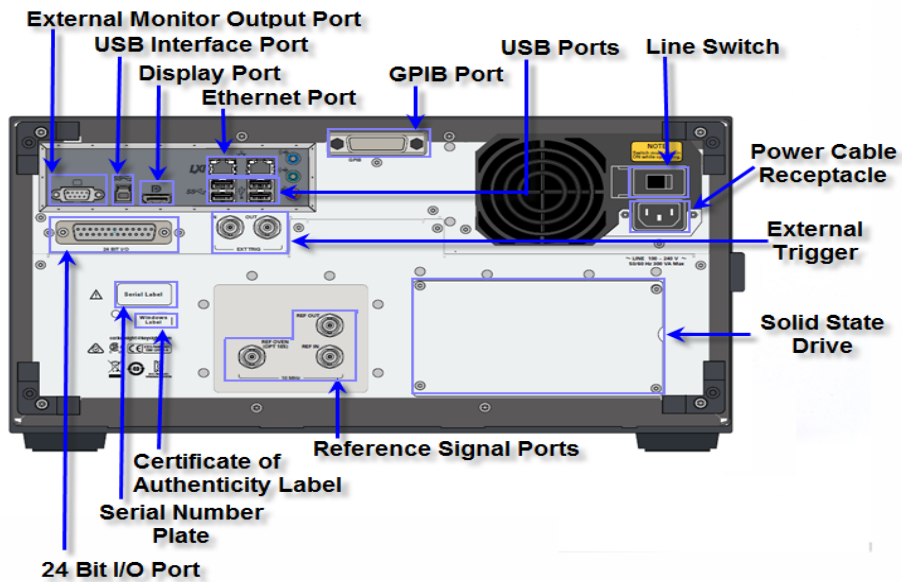
- **HART (Highway Addressable Remote Transducer) protocol** - is a cost-effective and widely used industrial communication standard that enhances traditional analog systems by adding digital intelligence, remote diagnostics, and flexible device configuration. It remains a preferred choice for smart transmitters, process sensors, and industrial automation applications.

- **4–20 mA current interface protocol** - is the most-used analogue transmission mechanism because of the protection against noise that it offers to the measurement values transmitted. The signal ranges from **4 mA (minimum value)** to **20 mA (maximum value)**. It has been extended for communication with intelligent devices to allow for the transmission, where necessary, of command/status information and the device power supply in analogue form on the signal wires. Signals in the range 3.8 mA to 20.5 mA are regarded as measurement signals. Currents in the 3.6 mA to 3.8 mA and 20.5 mA to 21.0 mA are used for the conveyance of commands to the sensor/transmitter and the receipt of status information from it. If the signal wires are also used to carry the power supply to the sensor/transmitter, the power supply current must be limited to 3.5 mA or less to avoid the possibility of it being interpreted as a measurement signal or fault indicator.
  0 – 3.5 mA - Possible **fault condition** (e.g., broken wire, sensor failure). Some devices use this range to carry **power in loop-powered systems**.
  3.5 – 4.0 mA - **Low-end error indication** or sensor warning (some transmitters signal minor faults here).
  4 – 20 mA - **Normal operating range**, where the sensor transmits valid process measurements.
  20 – 20.5 mA - **Over-range warning**, indicating the process is exceeding the calibrated limit.
  20.5 – 21 mA - **High-end fault condition**, used by some devices to signal sensor malfunctions.

2.2 Elements of a Measurement System.

Communicating with smart devices.

Protocol	Type	Medium & Usage
PROFIBUS	Digital Fieldbus	RS-485, Fiber Optics for Factory & Process Automation
MODBUS	Digital Serial	RS-232, RS-485, TCP/IP for PLC & SCADA Systems
FOUNDATION Fieldbus	Digital Fieldbus	Twisted Pair (H1), High-Speed Ethernet (HSE) for Process Control
EtherNet/IP	Digital Ethernet	Standard Ethernet for Real-Time Industrial Control



Product	Display Count	Ranging	Correction Factor	Interface
5492CGPIB	120000	Auto	True RMS	LAN, GPIB, RS232, USB
5493C	120000	Auto	True RMS	LAN, RS232, USB
5492C	120000	Auto	True RMS	LAN, GPIB, RS232, USB
5491B	50000	Auto	True RMS	RS232, USB
2831E	50000	Auto	True RMS	RS232, USB

2.3 Classifications of measurement instrumentation (Primary & Secondary, Analog & Digital, Null Type or Deflection Type, Stand Alone or PC Based, Smart vs Non-Smart, Active or Passive).

Active vs. Passive instruments – divided into active or passive ones according to whether the instrument output is entirely produced by the quantity being measured or whether the quantity being measured simply modulates the magnitude of some external power source. PASSIVE instruments **do not require an external power source** to operate. They **respond naturally to a measured variable** and generate a signal without amplification or external energy. ACTIVE instruments **require an external power source** (battery, DC supply, etc.) to function. They can **amplify, process, or transmit** the measured signal using that power.

PASSIVE: **Thermocouple** (generates a voltage from temperature difference), **Pressure gauge** (mechanically displays pressure through needle movement), **Resistive temperature detector** (RTD - changes resistance with temperature, but requires a circuit to read it).

Spring scale example.

Liquid-in-glass thermometer example.

Pressure-measuring device with movement of a pointer against a scale example.

Thermocouple example.

2.3 Classifications of measurement instrumentation (Primary & Secondary, Analog & Digital, Null Type or Deflection Type, Stand Alone or PC Based, Smart vs Non-Smart, Active or Passive).

Active vs. Passive instruments – divided into active or passive ones according to whether the instrument output is entirely produced by the quantity being measured or whether the quantity being measured simply modulates the magnitude of some external power source. PASSIVE instruments **do not require an external power source** to operate. They **respond naturally to a measured variable** and generate a signal without amplification or external energy. ACTIVE instruments **require an external power source** (battery, DC supply, etc.) to function. They can **amplify, process, or transmit** the measured signal using that power.

ACTIVE: **Strain gauge amplifier** (requires power to convert small resistance changes to a usable voltage), **Smart transmitter** (uses power to convert and transmit sensor signals), **Ultrasonic level sensor** (uses power to emit and receive signals).

Weather station example.

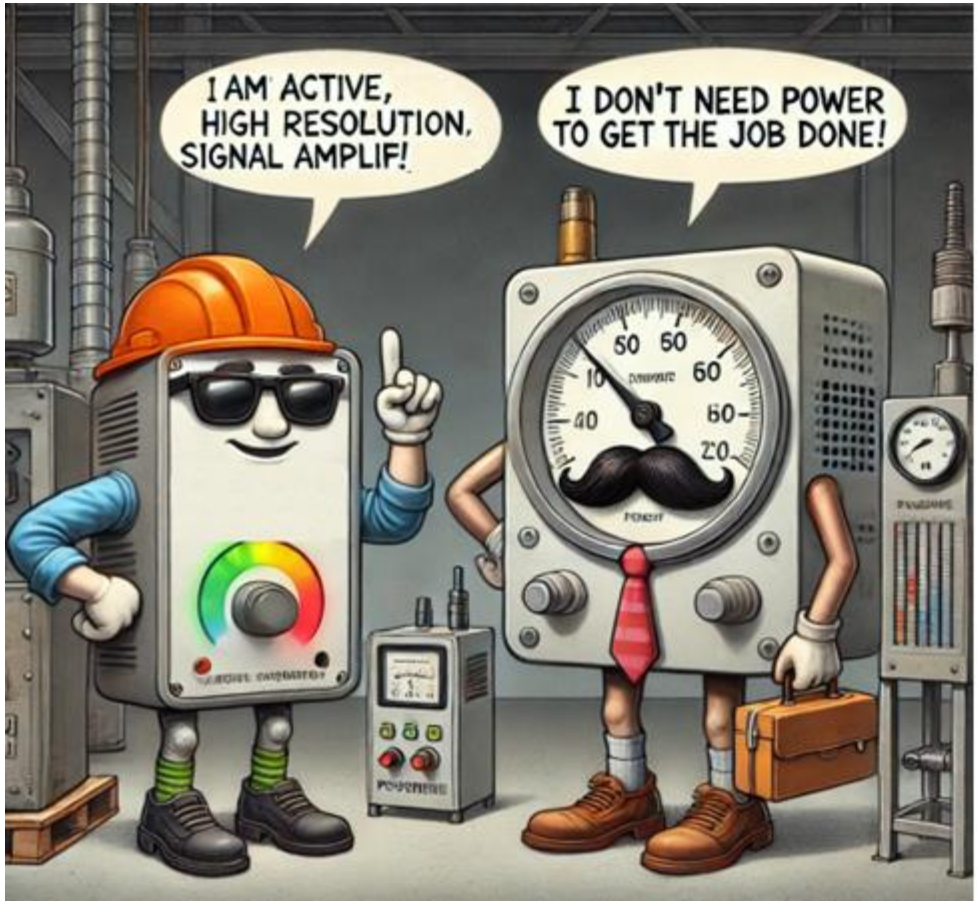
Ultrasonic level sensor example.

Smart transmitter example.

Strain Gauge Amplifier example.

2.3 Classifications of measurement instrumentation (Primary & Secondary, Analog & Digital, Null Type or Deflection Type, Stand Alone or PC Based, Smart vs Non-Smart, Active or Passive).

Active vs. Passive instruments – A key distinction between active and passive instruments lies in the **measurement resolution** they can achieve. For instance, in a simple pressure gauge, the pointer's movement in response to a pressure change is inherently limited by the instrument’s mechanical design. While increasing the pointer’s length can slightly enhance resolution—by allowing the tip to sweep a wider arc—this improvement is constrained by practical limitations on how long the pointer can realistically be. **Active instruments** offer much greater flexibility in **controlling measurement resolution**, as the level of external energy supplied can be adjusted to fine-tune performance. However, this improvement has its limits—excessive energy input can lead to **heating issues or safety concerns**, which place restrictions on how much power can be used. From a cost perspective, **passive instruments** tend to be **simpler in design** and therefore, **less expensive to produce**. As a result, selecting between active and passive instruments for a given application requires **careful consideration of the trade-off between resolution needs and overall cost**.



2.3 Classifications of measurement instrumentation (Primary & Secondary, Analog & Digital, Null Type or Deflection Type, Stand Alone or PC Based, Smart vs Non-Smart, Active or Passive).

Null-type vs. deflection-type instruments – a pressure gauge is a good example of a deflection type of instrument, where the value of the quantity being measured is displayed in terms of the amount of **movement (deflection)** it causes in a mechanical or electronic element. While a **null-type instrument** works by **balancing or nullifying the effect** of the measured quantity with a known reference. Measurement is taken when the system is at **equilibrium (zero deflection)**. In terms of usage, the deflection type instrument is clearly more convenient. It is far simpler to read the position of a pointer against a scale, rather than balancing an electronic setup (for example in a **Wheatstone bridge**).

When voltage is applied across the terminals of the analog voltmeter, **current flows through a coil**. This current creates a **magnetic field** that interacts with a permanent magnet, causing a **pointer (needle) to deflect** over a calibrated scale. The **amount of deflection is proportional to the input voltage**—hence, it's a deflection-based measurement.

Analog voltmeters are based on the **D'Arsonval galvanometer** principle.

Feature	Null-Type	Deflection-Type
Response Time	Slower	Faster
Accuracy	Very high	Moderate to good
Ease of Use	Requires setup and adjustment	Simple to read and operate
Examples	Wheatstone bridge, deadweight gauge	Analog voltmeter/ammeter

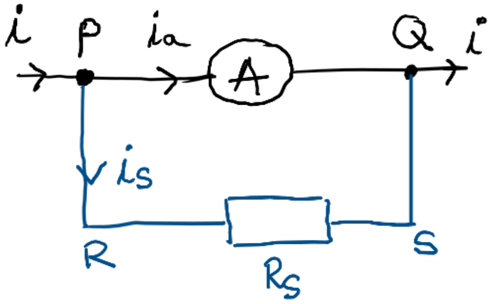
Analog voltmeter example.

2.3 Classifications of measurement instrumentation.

Shunts and multipliers

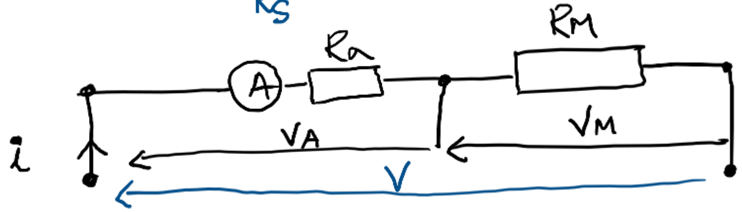
An **ammeter**, which measures current, has a low resistance (ideally zero) and must be connected in series with the circuit.
A **voltmeter** measures potential difference, has a high resistance (ideally infinite) and must be connected in parallel with the part of the circuit.

There is no difference between the basic instrument used to measure current and voltage. Both use a milliammeter as their basic part. This is a sensitive instrument which gives Full Scale Deflection for currents of only a few milliamperes.
When an ammeter is required to measure currents of larger magnitude, a proportion of the current is diverted through a low-value resistance connected in parallel with the meter. **Such a diverting resistor is called a shunt**.



$$\boxed{V_{PQ} = V_{RS} \Rightarrow i_a \cdot R_a = i_s \cdot R_s \Rightarrow R_s \cong \frac{i_a R_a}{i_s}\ \Omega}$$

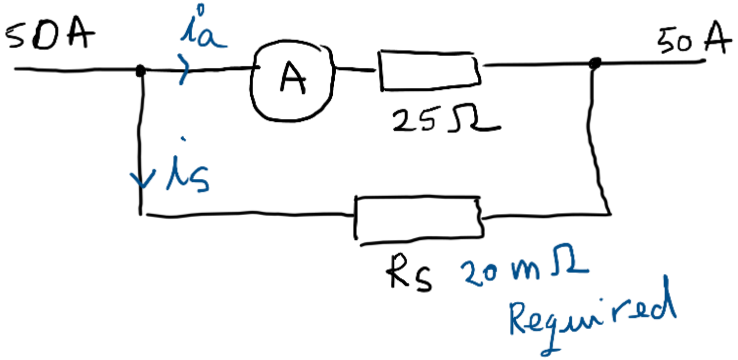
The milliammeter is converted into a voltmeter by connecting a high value resistance **RM** (called a multiplier) in series with it.



$$\boxed{V = V_A + V_M = iR_a + iR_M \Rightarrow R_M = \frac{V - iR_a}{i}\ \Omega}$$

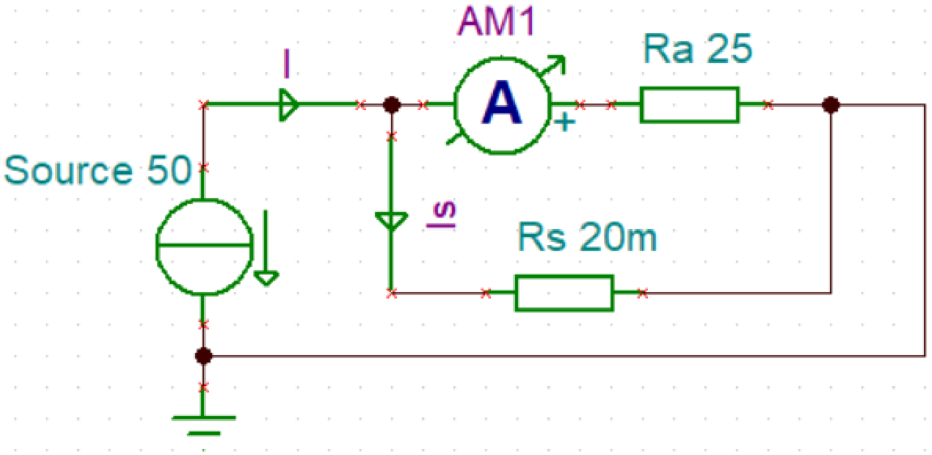
2.3 Classifications of measurement instrumentation.

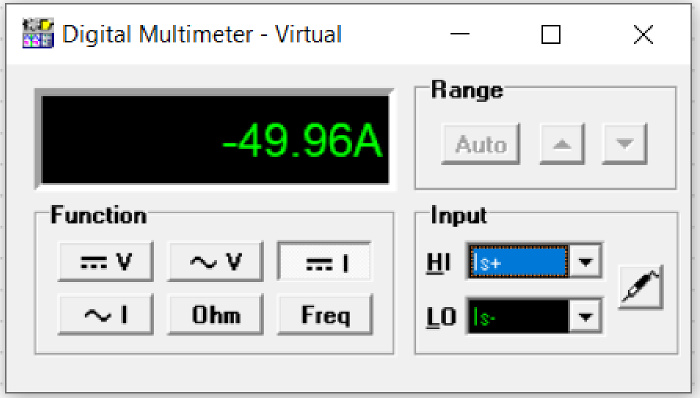
A moving – coil instrument reaches full – scale deflection (f. s. d.) with a current of 40 mA and has an internal resistance of 25Ω. Determine the value of the shunt resistor that must be connected in parallel with the meter to convert it into an ammeter capable of measuring currents up to 50 A.



i_a = f.s.d current, $i_a \cong \underbrace{40\,mA}_{0.04A} \Rightarrow 50A = i_a + i_s \Rightarrow i_s \cong 49.96\,A$

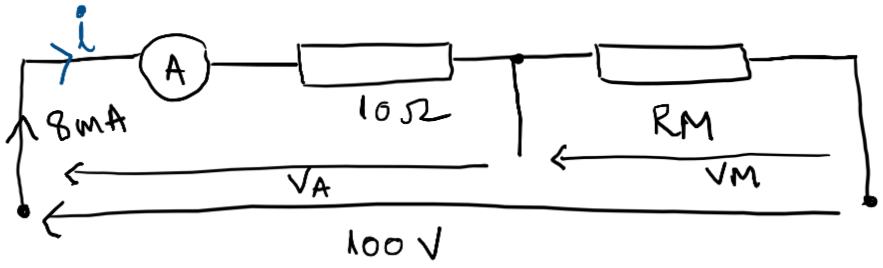
$$i_a \cdot R_a = i_s \cdot R_s \Rightarrow R_s = \frac{i_a \cdot R_a}{i_s} = \frac{0.04A \cdot 25\Omega}{49.96A} \boxed{\cong 20\,m\Omega}$$





2.3 Classifications of measurement instrumentation.

A moving – coil instrument with a resistance of 10Ω reaches full – scale deflection at a current of 8 mA. Calculate the value of the series multiplier resistor required to use the instrument as a voltmeter capable of measuring potential differences up to 100 V.



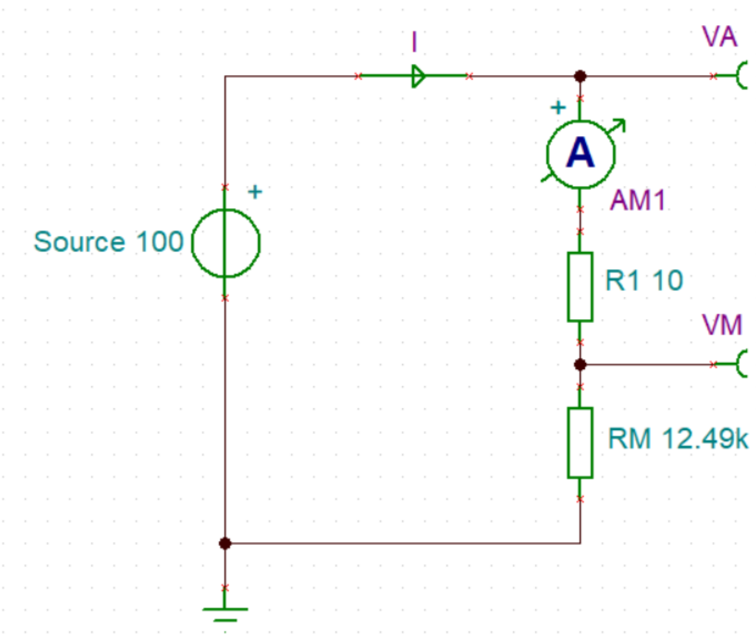
$V_A + V_M = V = 100\,V$

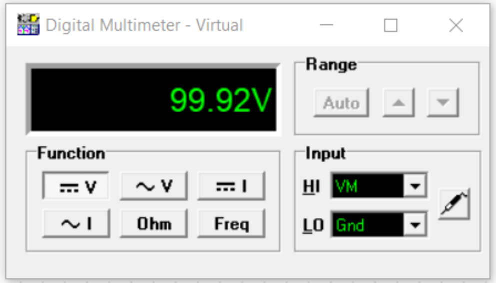
8 mA – total allowed current

$V_A = i R_a$, $V_M = i R_M$

$100V = i R_a + i R_M \Rightarrow$

$\Rightarrow R_M \cong \dfrac{100V - 0.008A \cdot 10\Omega}{0.008\,A} \cong 12.49\,k\Omega$





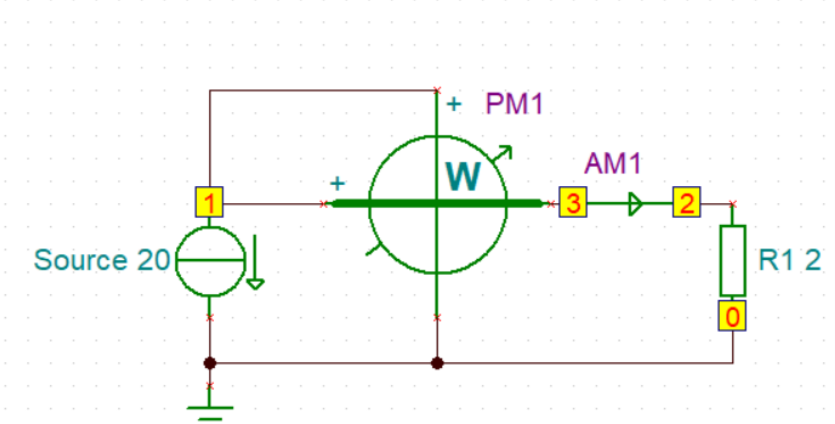
$V_A \cong 0.08\,V$

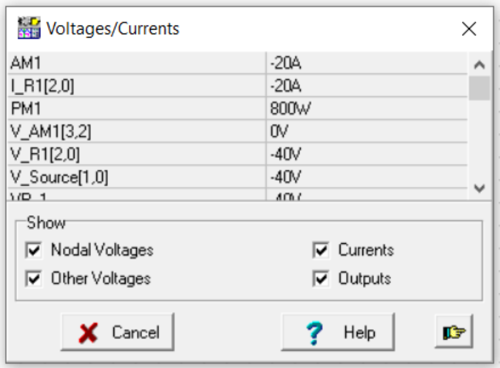
$V_M \cong 99.92\,V$

2.3 Classifications of measurement instrumentation.

A **wattmeter** is an instrument for measuring electrical power in a circuit. It is composed of a current coil, connected in series with the load, like an ammeter. And a voltage coil, connected in parallel with the load, like a voltmeter.

A current of 20A flows through a load having a resistance of 2Ω. Determine the power dissipated in the load. A wattmeter, whose current coil has a resistance of 0.01Ω is connected as shown. Determine the wattmeter reading.

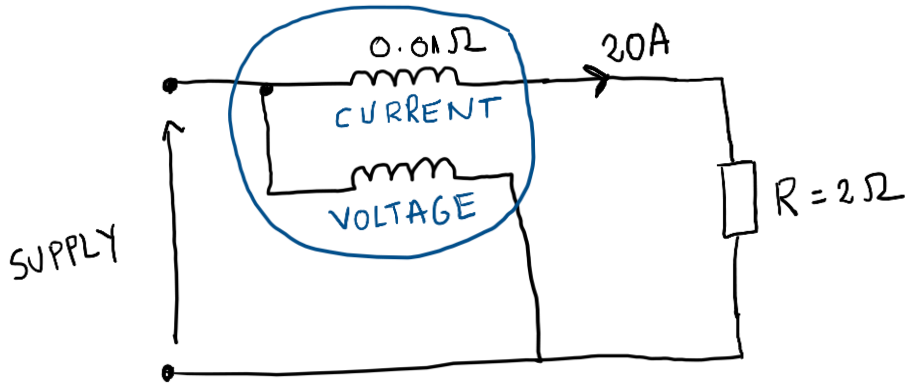




$$P = i^2 \cdot R = (20\,A)^2 \cdot 2\,\Omega \cong 800\,W$$

Total resistance $0.01\,\Omega + 2\,\Omega = 2.01\,\Omega$

Wattmeter reading $(20A)^2 \cdot 2.01\,\Omega \cong 804\,W$



2.3 Classifications of measurement instrumentation.

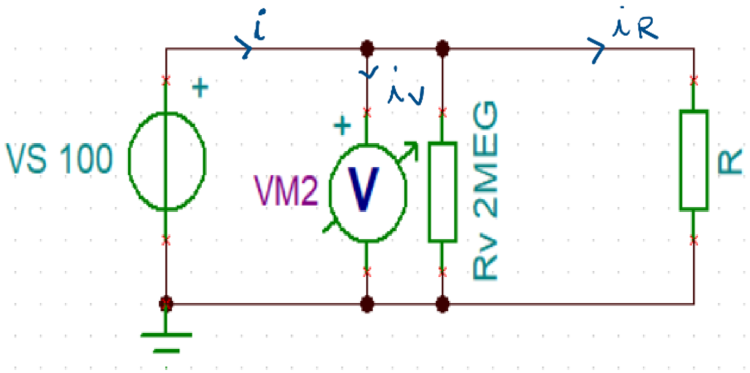
The **loading effect** occurs when a measuring instrument (like a voltmeter or ammeter)draws significant current from the circuit being measured, thereby altering the voltage or current in the circuit and affecting the accuracy of the measurement.
Every measuring device has its own internal resistance.

A **voltmeter** ideally should have **very high resistance**, so it **draws little to no current**.
An **ammeter** ideally should have **very low resistance**, so it doesn't **drop voltage** across it.

But in real life, these resistances are not perfect.

If the voltmeter has **low internal resistance**, it **draws current**, causing a **voltage drop** in the circuit.
If the ammeter has **high internal resistance**, it **reduces current flow**, changing the circuit behavior.

A voltmeter has a full – scale deflection of 200V. It has an internal resistance, from specifications, at 10kΩ/V. Calculate the power dissipated by the voltmeter and the resistor, if R = 250Ω and if R = 2MΩ.



$R_V = 10k\Omega/V \cdot 200V \cong 2M\Omega$ – internal voltmeter resistance.

$i_V = \dfrac{100V}{2M\Omega} \cong 50 \cdot 10^{-6}A \cong 50\mu A \Rightarrow P_V \cong 100V \cdot 50\mu A \cong 5mW$

$i_R = \dfrac{100V}{250\Omega} \cong 400mA \Rightarrow P_R \cong 100V \cdot 400mA \cong 40W$ (if $R = 250\Omega$)

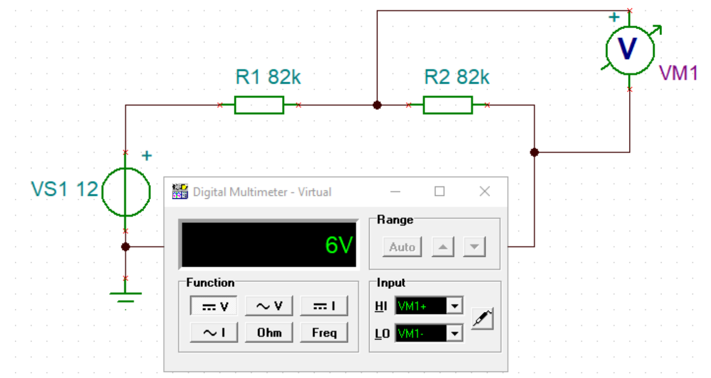
$i_R = \dfrac{100V}{2M\Omega} \Rightarrow P_R \cong 5mW$ (if $R = 2M\Omega$, power dissipation reduced)

$R = 250\Omega$
$i \cong 400.050\ mA$

$R = 2M\Omega$
$i \cong 100\mu A$

2.3 Classifications of measurement instrumentation.

The **loading effect** occurs when a measuring instrument (like a voltmeter or ammeter)draws significant current from the circuit being measured, thereby altering the voltage or current in the circuit and affecting the accuracy of the measurement.

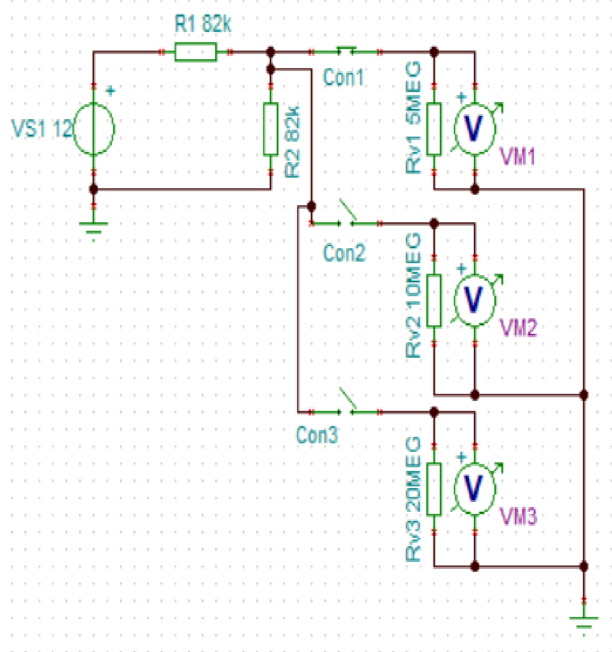


$$U_{R_2} = 12V \cdot \frac{R_{eq}}{R_1 + R_{eq}}$$

$R_V = 10M\Omega \Rightarrow R_{eq} \cong 81.33 k\Omega$

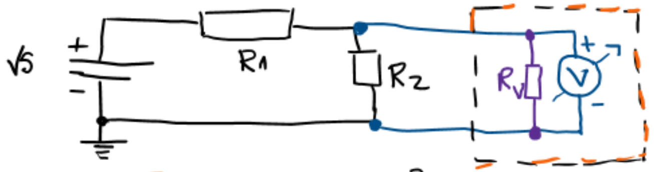
$R_V = 20M\Omega \Rightarrow R_{eq} \cong 81.67 k\Omega$

$R_V = 5M\Omega \Rightarrow R_{eq} \cong 80.68 k\Omega$



WHEN MEASURING VOLTAGE WE ALWAYS HAVE TO CONSIDER THE INTERNAL RESISTANCE OF THE VOLTMETER. THIS HAS (THEORY) INFINITE VALUE. IN PRACTICE IT HAS LIMITED VALUE FOR EXAMPLE THE MS8250 HAS ≈ 10 MΩ.

$$\boxed{U_{R_2} = 12V \cdot \frac{R_2}{R_1+R_2} = 12V \cdot \frac{82k}{82k+82k} = \boxed{6V} \ (R_1 = R_2, \text{simple case})}$$



$\boxed{R_V}$ - INTERNAL VOLTMETER RESISTANCE, THIS COMES IN PARALLEL WITH R2.

$$\boxed{R_{eq}} = R_2 \| R_V = \frac{R_2 \cdot R_V}{R_2 + R_V}, \text{ if } R_V \gg R_2$$ (WE SHOULD HAVE REDUCED ERROR)

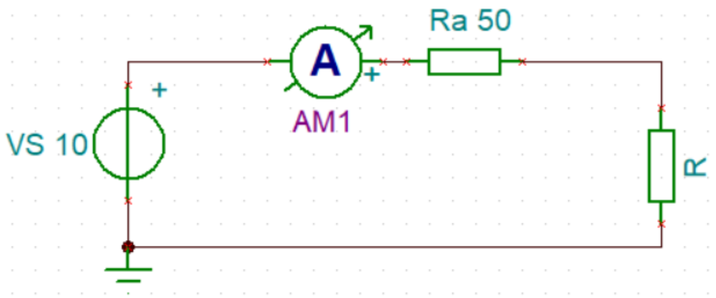
Theoretically, if we apply the voltage division rule, we get the 6V drop over R2. In reality, the voltmeter internal resistance Rv will be connected in parallel with R2. And it will affect the accuracy of our measurements. If Rv is 5MΩ, the equivalent resistance Req is about 81kΩ. The voltage reading is 5.95V instead of 6V. If Rv is 10MΩ, the equivalent resistance Req is about 81.3kΩ. The voltage reading is 5.98V instead of 6V. If Rv is 20 MΩ, the equivalent resistance Req is about 82 kΩ. The voltage reading is 5.99V instead of 6V.

Conclusion - try to select a voltmeter with higher internal resistance Rv. Always pay attention if you have voltage measurements over resistors with high values.

2.3 Classifications of measurement instrumentation.

The **loading effect** occurs when a measuring instrument (like a voltmeter or ammeter) draws significant current from the circuit being measured, thereby altering the voltage or current in the circuit and affecting the accuracy of the measurement.

An ammeter has a full – scale deflection of 100mA. It has an internal resistance, from specifications, at 50Ω. The ammeter is used to measure the current in a load of resistance 500Ω. The supply voltage is 10V. Calculate the ammeter theoretical reading (ideal case), real circuit current and the power dissipated in the ammeter & load.



$$i_{theoretical} = \frac{10V}{500\,\Omega} = 20mA$$

$$i_{Real} = \frac{10V}{(500\Omega + 50\Omega)} \cong 18mA$$

$$P_A = i^2 \cdot R_a \cong (18mA)^2 \cdot 50\Omega \cong 16.2\,mW$$

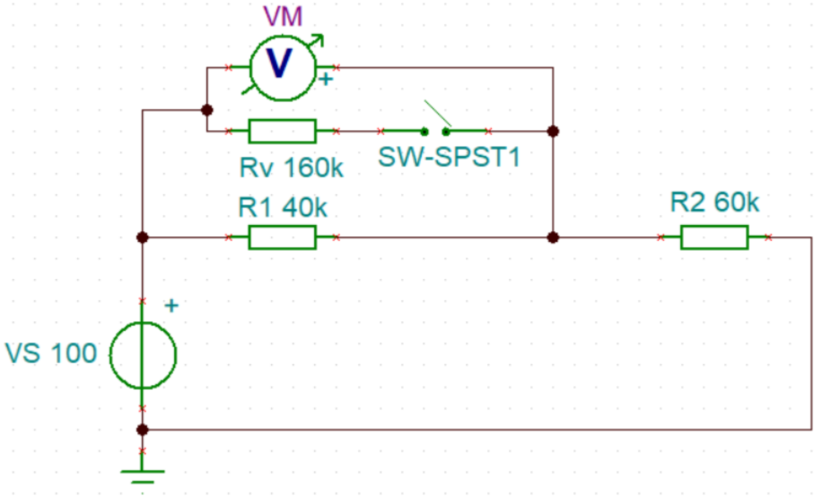
$$P_R = i^2 \cdot R \cong (18mA)^2 \cdot 500\Omega \cong 162\,mW$$

$$\left.\begin{array}{l}\text{Voltage drop over AM1} \cong 0.9V \\ \text{Voltage drop over R} \cong 9.1V\end{array}\right\}$$ Ammeter imperfection causes a voltage drop.

2.3 Classifications of measurement instrumentation.

The **loading effect** occurs when a measuring instrument (like a voltmeter or ammeter)draws significant current from the circuit being measured, thereby altering the voltage or current in the circuit and affecting the accuracy of the measurement.

A voltmeter has a full – scale deflection of 100V. It has an internal resistance, from specifications, at 1.6kΩ/V. It is used to measure the voltage drop over R1. Determine the voltmeter reading and the relative error in this measurement.



$V_s = 100V$, $V_{R_2} \cong 100V \cdot \frac{R_2}{R_1+R_2} \cong 60V \Rightarrow V_{R_1} \cong 40V$ theoretical

$R_V \cong 100V \cdot 1.6k\Omega/V \cong 160k\Omega$, or about 4 times > R_1.

With Rv connected $\Rightarrow R_{eq} = \frac{160k \cdot 40k}{160k + 40k} \cong 32k\Omega \Rightarrow$ From the perspective of Vs, the circuit has 2 resistors, one of $32k\Omega$, one of $60k\Omega$.

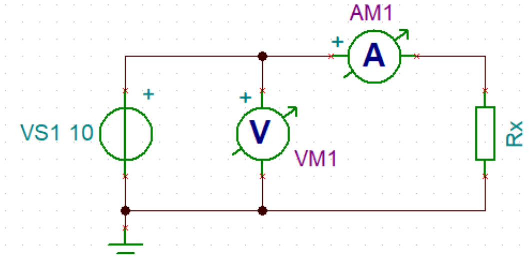
$V_{R_2} \cong 100V \cdot \frac{60k}{92k} \cong 65.2V \Rightarrow$ Voltmeter indication $\cong 34.8V$

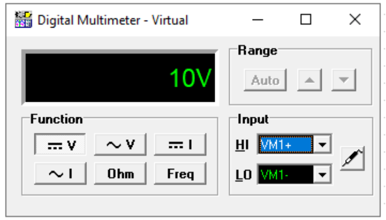
$\Delta = 34.8V - 40V = -5.2V$

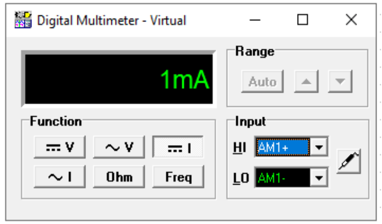
$\delta\% \cong \frac{|\Delta|}{40V} \cdot 100 \cong 13\%$ Due to voltmeter loading effect.

2.3 Classifications of measurement instrumentation.

In this example we demonstrate the **systematic error of method**. This appears when we try to do indirect measurements. For example, in a circuit we ca measure the Voltage and Current, but we want to calculate the Resistance. An unknown quantity can be calculated based on measurement of known quantities. Assume we do not know the value of Rx, but we measured the values of Voltage and Current.

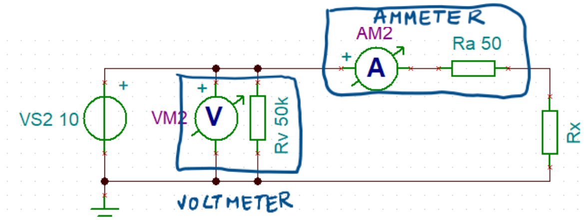




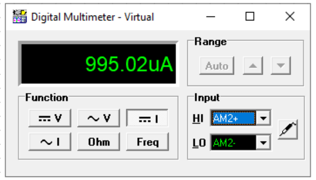


$R_x = \frac{10V}{1mA} = 10k\Omega$ (X - conventional true value)

In real measurements, there is always the issue of the internal resistances of the measurement devices.



995.02 μA ≅ 0.995mA



$R_x = \frac{10V}{0.995mA} \cong \boxed{10.05k\Omega}$

SYSTEMATICALLY LARGER THAN Rx BECAUSE Ra > 0Ω.

$\Delta i = 0.995\,mA - 1mA = -0.005\,mA$

$\delta i\% = \frac{|-0.005\,mA|}{1mA} \cdot 100 \cong 0.5\%$

RELATIVE ERROR IN CURRENT READING BECAUSE OF Ra > 0Ω.

$R_a \cong 50\Omega$, $R_v \cong 50k\Omega$ (VALUES USED FOR SIMULATION PURPOSES).

$R_x \cong \frac{U_m}{i_m} - R_a$

AFFECTS OUR MEASUREMENT PROCESS

ASSUME − $\boxed{R_x = 100k\Omega}$ => $i_m = 0.1\,mA$ (THEORETICAL)

IN OUR SIMULATION => $i_m \cong 0.099\,mA$

$R_x \cong \frac{10V}{0.099mA} \cong \boxed{101\,K\Omega}$

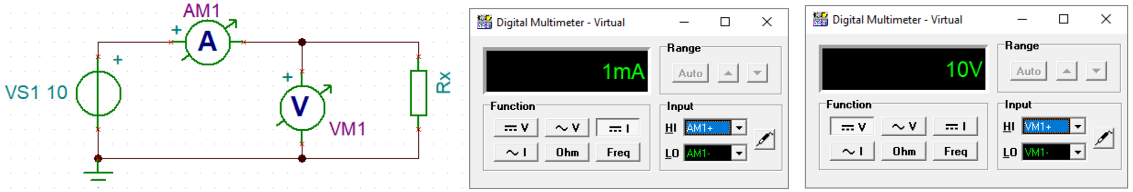
$\Delta i = 0.099mA - 0.1mA = -0.001\,mA$

$\boxed{\delta i\% \approx 0.1\%}$

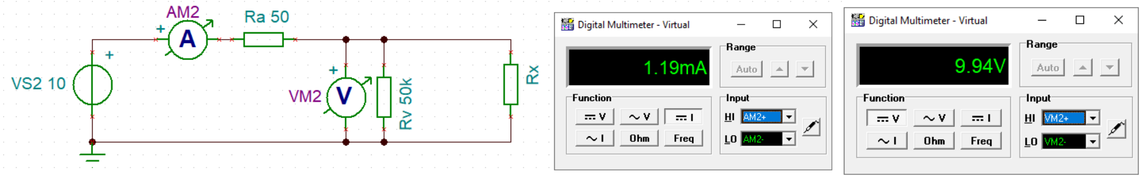
This method of indirect measurement where the <u>Ammeter is in series with Rx</u> is recommended for evaluation of **very large resistances**. If Rx is much larger than Ra, the error is smaller. As the value of Rx increases, the relative error in current measurement is lower. This means we can more accurately estimate the value of Rx.

2.3 Classifications of measurement instrumentation.

What happens if we change our setup? Assume that the Voltmeter is in parallel with the unknown resistor Rx. And that we get the following measurements.



$$R_x = \frac{10V}{1mA} = 10k\Omega$$



$$R_x = \frac{9.94V}{1.19mA} \cong \boxed{8.35k\Omega} \qquad R_V \parallel R_x = \frac{R_V \cdot R_x}{R_V + R_x}$$

TOTAL CIRCUIT RESISTANCE

$$R_a + R_{eq} \cong \boxed{8.35K}$$

BY ESTIMATION BASED ON VOLTAGE AND CURRENT READINGS

$$R_a + R_{eq} \cong 8.35K \Rightarrow R_{eq} \cong 8.3k\Omega \Rightarrow \frac{R_V \cdot R_x}{R_V + R_x} \cong 8.3k\Omega \Rightarrow R_x \cong \boxed{9.95k\Omega}$$

Our circuit includes Ra and the Req. Req is the equivalent resistance from Rx and Rv. From our readings, we get that this circuit resistance is 8.35k. This is wrong because it should be around 10kΩ. And we assumed that 8.35kΩ includes the Ammeter and Voltmeter resistances, we were able to get a better estimation of Rx as 9.95kΩ.

$$\boxed{R_x = \frac{U_m}{i_m}},\ \boxed{R_{eq} = \frac{R_V \cdot R_x}{R_V + R_x}} \Rightarrow (R_V + R_x)U_m = i_m \cdot R_V \cdot R_x \Rightarrow R_V \cdot U_m + R_x U_m = i_m \cdot R_V \cdot R_x \Rightarrow R_x(U_m - i_m R_V) = -R_V \cdot U_m \Rightarrow \boxed{R_x = \frac{R_V \cdot U_m}{i_m R_V - U_m}} = \frac{50K \cdot 9.94V}{1.19mA \cdot 50K - 9.94V} \cong \boxed{10.03k\Omega}$$

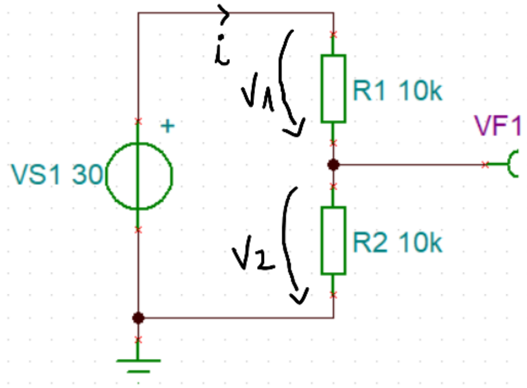
In this case, for a better estimation of Rx please remember this relation. This method of measurement is recommended for the estimation of **very small resistors**. IF WE IGNORE THE Voltmeter and Ammeter influence, how do the errors in Voltage and Current measurements propagate in the calculation of the resistance value?

$$\Delta V = 9.94V - 10V = -0.06V \Rightarrow |\delta_{v\%}| \cong \boxed{0.6\%}$$

$$\Delta i = 1.19mA - 1mA = 19mA \Rightarrow |\delta_{i\%}| \cong \boxed{19.3\%}$$

2.3 Classifications of measurement instrumentation.

Voltage divider – a discussion.



Calculate VF1

(1) $$i = \frac{VS1}{(R_1+R_2)} = \frac{30\,V}{20\,k\Omega} \cong 1.5\,mA$$

$$VF1 = 1.5\,mA \cdot 10\,k\Omega = 15\,V$$

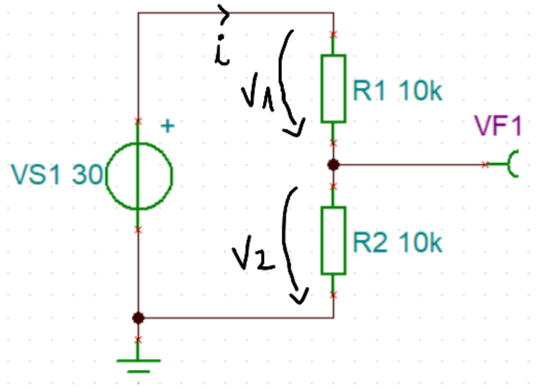
(2) By voltage division relation

$$\frac{\overset{VF1}{\widetilde{V_2}}}{\underbrace{V_1+V_2}_{VS1}} = \frac{i \cdot R_2}{i\,(R_1+R_2)} = \frac{R_2}{R_1+R_2} \quad \text{OR} \quad V_2 = \boxed{VF_1 = VS1 \cdot \frac{R_2}{R_1+R_2}} = \frac{VS1}{2} = 15\,V$$

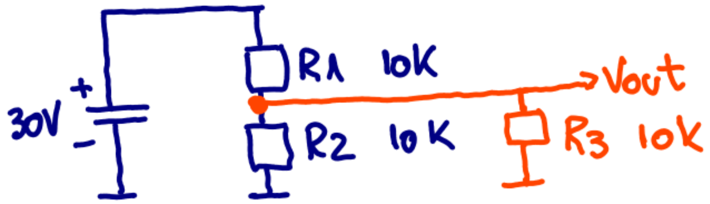
(3) In our circuit, the top and bottom current are equal, since it is a series circuit. The voltage drops are proportional to the resistors (or IMPEDANCES, a more general term which covers other types of components). If R2 makes up for half of the resistance, it sure makes up for half of the voltage. If we lower R1 such that R2 = 10 x R1, it will show 90% of the input voltage. And so on.

2.3 Classifications of measurement instrumentation.

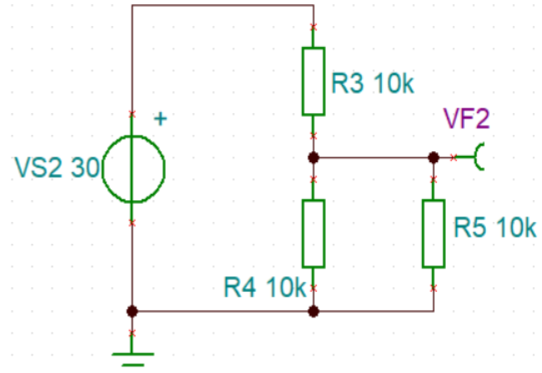
Voltage divider – loading and output impedance.

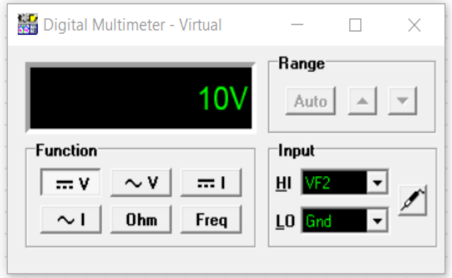


In our circuit, the top and bottom current are equal, since it is a series circuit. The voltage drops are proportional to the resistors (or IMPEDANCES, a more general term which covers other types of components). If R2 makes up for half of the resistance, it sure makes up for half of the voltage. If we lower R1 such that R2 = 10 x R1, it will show 90% of the input voltage. And so on.

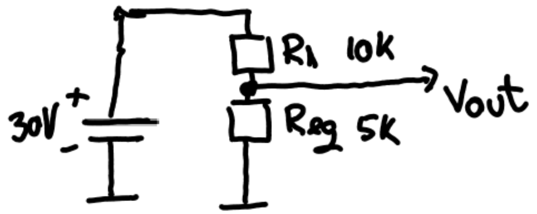


R3 is the "Load" and we need to calculate the new voltage output of this setup.





① if R3 || R2 => $R_{eq} = 5k\Omega$.



$$R_{eq} = \frac{10K \cdot 10K}{10K + 10K} = 5K$$

$$V_{out} = 30V \cdot \frac{5K}{15K} = 10V$$

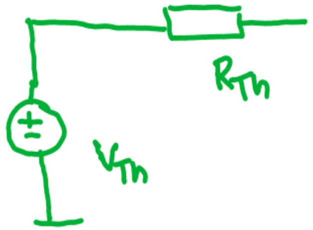
Method works fine, for each change in the Load we have to draw another circuit model.

2.3 Classifications of measurement instrumentation.

Voltage divider – loading and output impedance.

(2) By using Thevenin's model.

The Thevenin model is an idealized voltage source in series with a resistor.



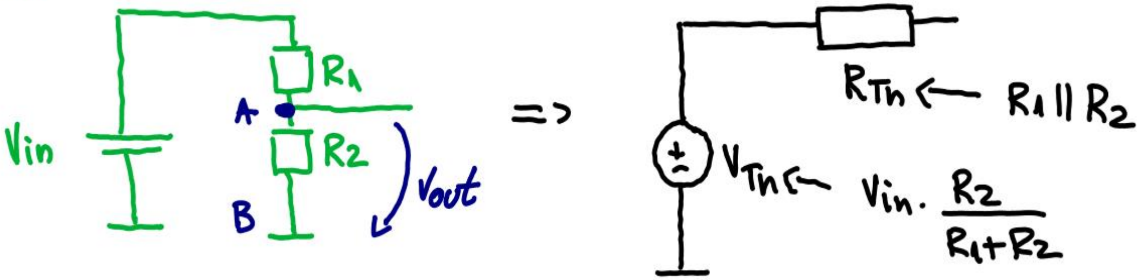
V_{Th} – the output voltage with no load attached.

$R_{Th} - \frac{V_{Th}}{I_{short}}$, where I_{short} is the current flowing from the circuit output to ground, if the output is shorted to ground.

A circuit area that includes voltage sources, current sources and resistors can be replaced with a single equivalent voltage source V_{Th} in series with the equivalent R_{Th}.

We will consider these sources as ideal, such that the voltage sources have no internal resistance, while current sources have infinite internal resistance.

For our initial circuit



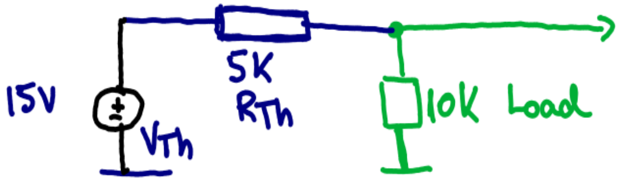
To obtain the equivalent Th circuit, voltage sources are considered short circuits (current sources are open circuits). If $V_{in} = 0V \Rightarrow$ the two resistors are in $\|$.

Such that $R_{Th} = R_1 \| R_2 = \frac{R_1 \cdot R_2}{R_1+R_2} = 5k\Omega$.

The $V_{Th} = V_{in} \cdot \frac{R_2}{R_1+R_2} = 15V$

2.3 Classifications of measurement instrumentation.

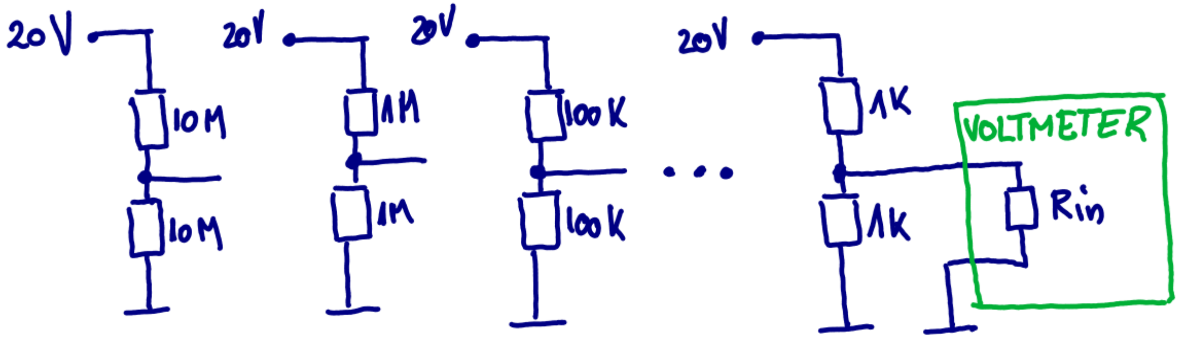
Voltage divider – loading and output impedance.



Vout = 10V, it drops exactly as we calculated in method 1.

What this Th model provides is the value of RTh. if you change the load, the Th model shows exactly what drop to expect. if we use the first method we always need to calculate the parallel resistance of the 2 bottom resistors. This takes longer. If we use the Th method it is easy to estimate the voltage drop over the attached load. we just need to see the proportion to the RTh.

Assume we have a set of voltage dividers, powered by 20 V sources, using 1% tolerance resistors. Consider we need to measure Vout at the output of each divider by means of a laboratory voltmeter.

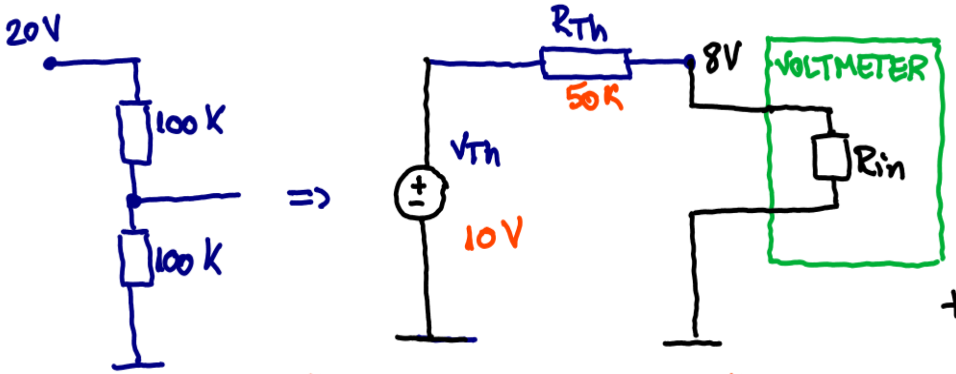


RTh calculated in the same way. And output voltage measured with an ideal voltmeter => Vout = 10V.
if we used an imperfect voltmeter, with Rin as internal resistance, we get the following results:

2.3 Classifications of measurement instrumentation.

Voltage divider – loading and output impedance.

DIVIDER R VALUES	Vout INDICATION	COMMENT
1k	9.95 V	ACCEPTABLE
10 K	9.76 V	LOADING APPARENT
100 K	8.05 V	LOADING OBVIOUS



which is the Rin Value ??

$$R_{Th} = \frac{100K \cdot 100K}{200K} = 50K \qquad V_{Th} = 20V \cdot \frac{100K}{200K} = 10V$$

$V_{Th} = 10V$, $R_{Th} = 50K$, Voltmeter reading $\cong 8V$.

So Rin drops about 8 parts in 10. R_{Th} drops about 2 parts. The relative values of these resistors are proportional to these voltage drops. This means $R_{in} \cong 4 \cdot R_{Th}$ or about 200k.

Thus, assume we have used our voltmeter set on the 10V RANGE and it presents a 200k input resistance.

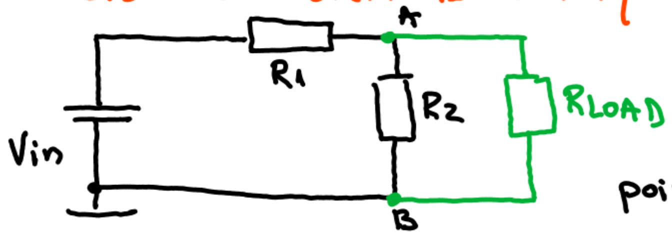
IF WE CONSIDER THE VOLTMETER DOCUMENTATION we may find the indication that the input resistance is 20 000 Ω/Volt. This holds true. By setting our voltmeter on the 10 V range we have increased the input resistance as $20000\ \Omega/V \cdot 10V \cong 200\,000\ \Omega$ or $200\ k\Omega$.

2.3 Classifications of measurement instrumentation.

Voltage divider – loading and output impedance.

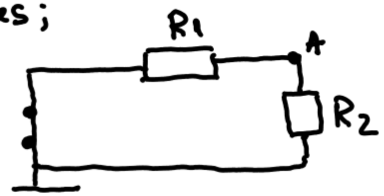
SOME CONCLUSIONS

- INPUT RESISTANCE of the Load (or measurement device) should be >> compared to the OUTPUT RESISTANCE of the circuit under loading;
- Thevenin's theorem is a very useful tool.



(1) FIND R_{Th}.

- remove R_{LOAD} from points A and B;
- short-circuit voltage sources or open-circuit current sources;

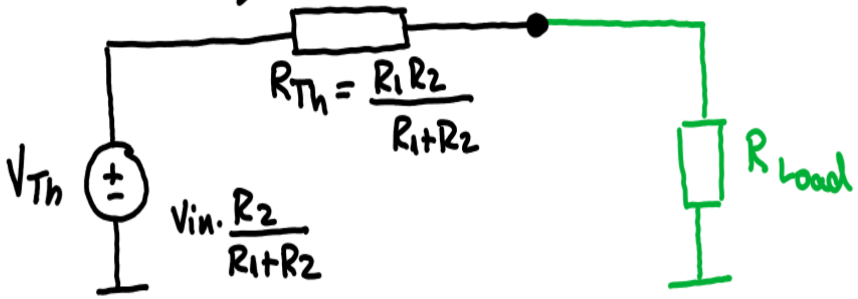


$$\boxed{R_{Th}} = R_1 \parallel R_2 = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

(2) Find Thevenin open circuit voltage.

- in this case it is the voltage over R_2 or $V_{in} \cdot \frac{R_2}{R_1+R_2}$;

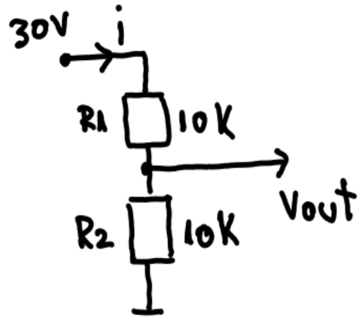
(3) Draw equivalent circuit.



2.3 Classifications of measurement instrumentation.

Voltage divider – loading and output impedance.

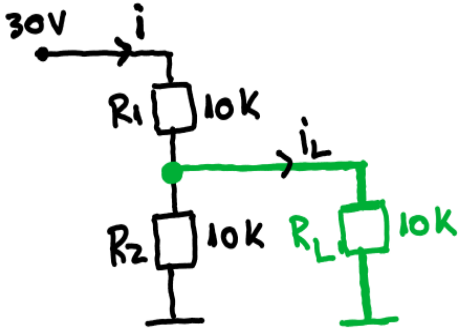
EXAMPLE PROBLEM:



$$V_{out} = 30V \cdot \frac{R_2}{R_1+R_2} \cong 15V$$

$$i = \frac{30V}{20K} = 1.5\,mA$$

LET US ATTACH THE LOAD OF 10K



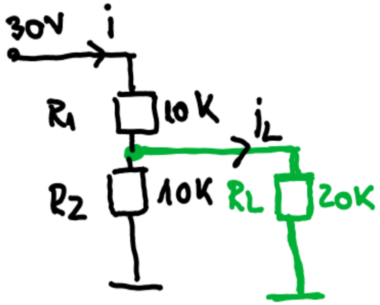
$$R_{eq} = R_2 \| R_L = \frac{10K \cdot 10K}{20K} = 5K$$

$$V_{out} = 30V \cdot \frac{5K}{5K+10K} \cong 10V$$

$$i = \frac{30V}{15K} = 2mA$$

$$i_L = i \cdot \frac{R_2}{R_L+R_2} = 1mA$$ by current division formula.

LET US ATTACH THE LOAD OF 20K

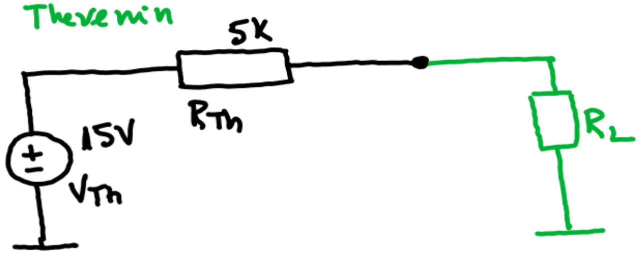


$$R_{eq} \cong 6.7\,K\Omega, \quad V_{out} = 30V \cdot \frac{6.7k}{16.7k} \cong 12V$$

$$i = \frac{30V}{16.7K} \cong 1.8\,mA$$

$$i_L = 1.8mA \cdot \frac{R_2}{R_2+R_L} \cong 0.6\,mA \quad \text{OR} \quad \frac{12V}{20K} \cong 0.6mA$$

By Thevenin



$$R_{Th} = \frac{R_1 \cdot R_2}{R_1+R_2} = 5\,k\Omega$$

$$V_{Th} = 30V \cdot \frac{R_2}{R_1+R_2} = 15V$$

$R_L = 10\,K\Omega \Rightarrow$ drops $2 \cdot R_{Th}$, 2 parts of 15V OR 10V.

$R_L = 20\,K\Omega \Rightarrow$ drops $4 \cdot R_{Th}$, 4 parts of 15V OR 12V

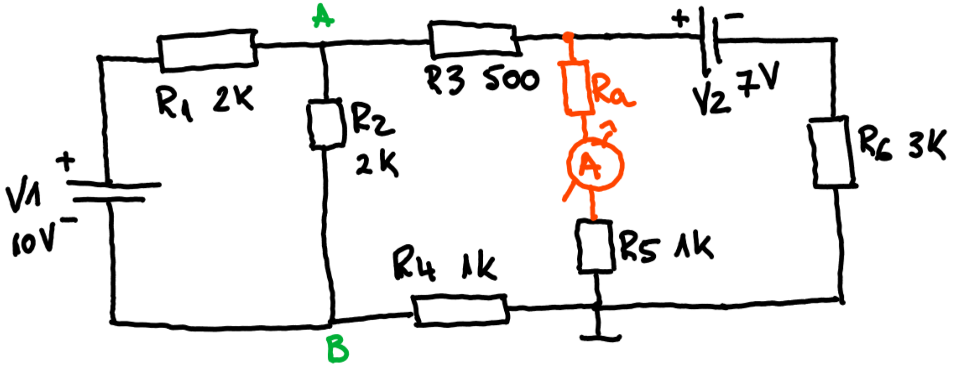
calculation becomes easier as we just need to look at the proportion of R_{Th} vs. R_L.

2.3 Classifications of measurement instrumentation.

Voltage divider – loading and output impedance.

ANOTHER EXAMPLE USING THEVENIN'S THEOREM.

Consider the circuit presented below. The Ammeter has an internal resistance $R_a = 50\,\Omega$. How does the presence of R_a influence the measurement of current through R_5?

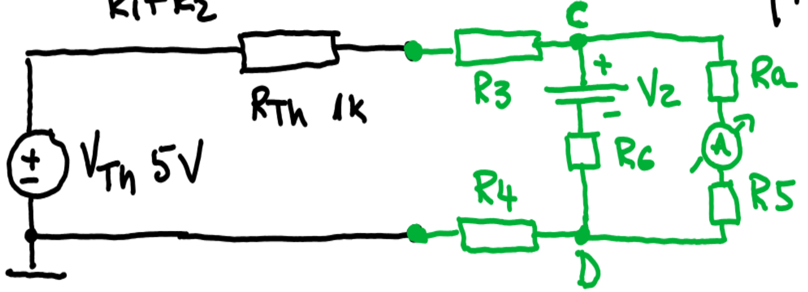


① Replace circuit composed of V_1, R_1, R_2 by the Th equivalent.

short $V_1 \Rightarrow R_1 \parallel R_2 \Rightarrow R_{Th} = 1K$

$V_{Th} = V_1 \cdot \dfrac{R_2}{R_1 + R_2} = 5V$

} For circuit connected to the left of A and B.

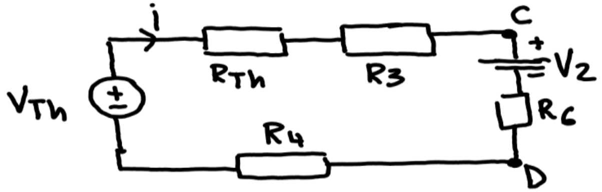


② Replace circuit to the left of points C and D with the Th.

We short V_{Th} and $V_2 \Rightarrow (\underbrace{R_{Th} + R_3 + R_4}_{\text{series}}) \parallel R_6 \cong 1.36\,K\Omega.$

The new $R_{Th} = \boxed{1.36\,K\Omega.}$

Note V_{Th} and V_2 are opposed as connectivity.



Circuit current is actually

$i = \dfrac{U}{R} = \dfrac{V_{Th} - V_2}{R_{Th} + R_3 + R_6 + R_4} = \dfrac{-2V}{5.5k}$

$\cong -0.364\ mA$

$\Rightarrow U_{R_6} = R_6 \cdot i \cong -1.09\,V.$

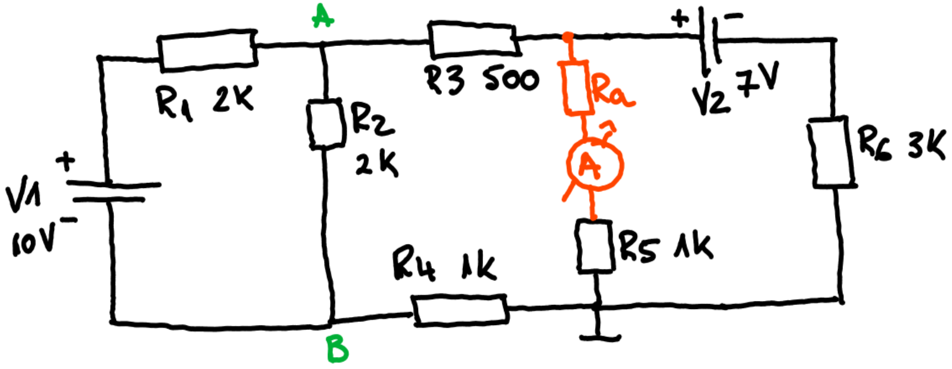
The new $V_{Th} = V_2 + U_{R_6} = 7V - 1.09\,V \cong \boxed{5.91\,V}$

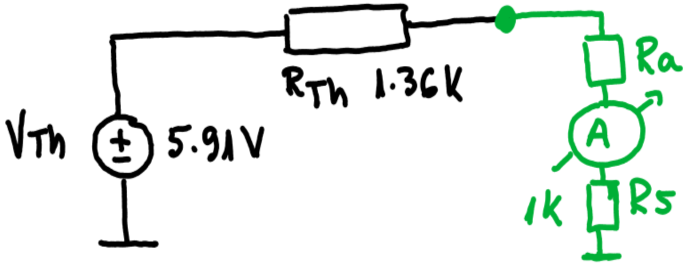
2.3 Classifications of measurement instrumentation.

Voltage divider – loading and output impedance.

ANOTHER EXAMPLE USING THEVENIN'S THEOREM.

Consider the circuit presented below. The Ammeter has an internal resistance $R_a = 50\,\Omega$. How does the presence of R_a influence the measurement of current through R_5?





IF $R_a = 0\,\Omega$ (ideal case)

$$i = \frac{U}{R} = \frac{5.91\,V}{2.36\,K} \cong 2.5\,mA$$

BUT $R_a = 50\,\Omega$

$$i = \frac{5.91\,V}{2.41\,K} \cong 2.45\,mA$$

$$\Delta = 2.45\,mA - 2.5\,mA = -0.05\,mA$$

$$\delta_{iR5}\% = \left|\frac{\Delta}{2.5\,mA}\right| \cdot 100 \cong 2\%$$ ERROR DUE TO AMMETER IMPERFECTIONS.

2.3 Classifications of measurement instrumentation (Primary & Secondary, Analog & Digital, Null Type or Deflection Type, Stand Alone or PC Based, Smart vs Non-Smart, Active or Passive).

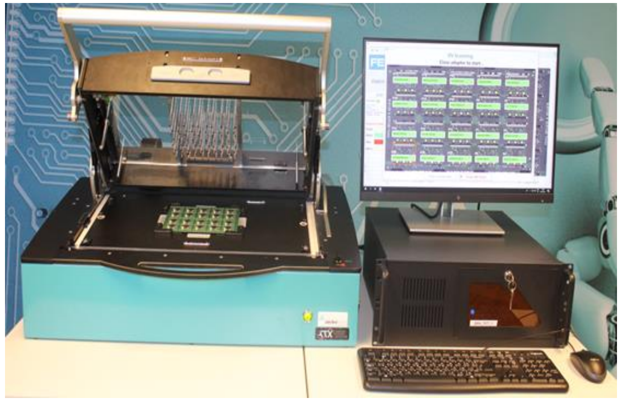
Analogue vs. digital instruments – The output of an analog instrument continuously changes as the quantity being measured changes. We can say (theoretically) that the output can have an infinite number of values within the range that the instrument is designed to measure. The deflection-type instrument is a good example. As the input value changes, the pointer moves with a smooth continuous motion along the indicator scale. We can assume that the pointer can be in an infinite number of positions within its range of movement. The number of different positions that the human eye can read is limited by how large and how accurately is the definition of the instrument scale.

A digital instrument has an output that varies in discrete steps and so can only have a finite number of values. Most modern instrument types present a digital construction. Note that they include micro-processors (or FPGAs) which perform different operations.

Feature	Analogue-Type	Digital-Type
Display	Continuous movement of pointer on a scale	Numerical readout on LCD/LED display
Accuracy	Generally lower due to parallax error, limited resolution	Higher, with precise numeric values
Resolution	Limited by scale gradation	Very high, depending on bit depth (12-bit, 16-bit)
Noise effect	More sensitive to signal interference	Better immunity through filtering & logic processing
Readability	Requires interpretation by the user	Easy to read, exact numbers shown
Maintenance	Simple mechanical parts	More complex, may need calibration, battery changes

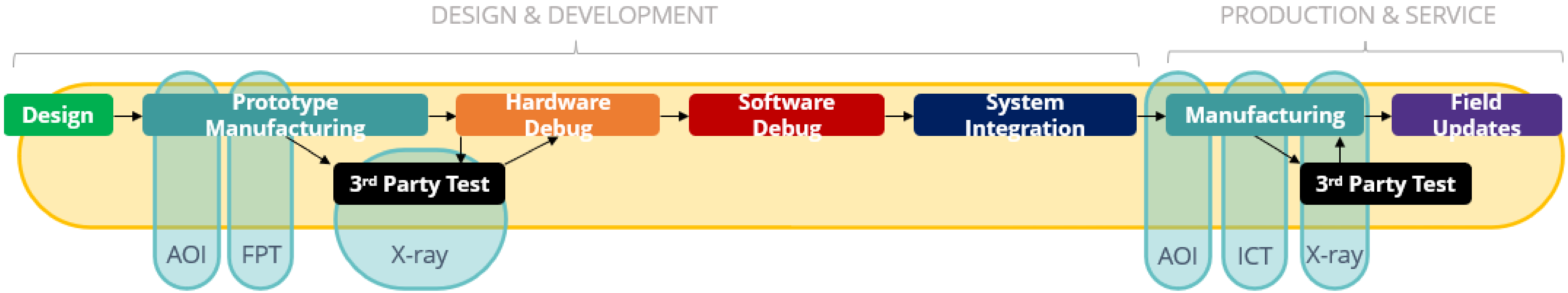
2.3 Classifications of measurement instrumentation (Primary & Secondary, Analog & Digital, Null Type or Deflection Type, Stand Alone or PC Based, Smart vs Non-Smart, Active or Passive).

Stand alone vs. PC based instruments – **Stand-alone instruments** are extremely important in any laboratory. These are fixed devices having a dedicated purpose of measurement. For example, oscilloscopes, signal generators, power supplies, DMMs, counters etc. **PC based instruments** are becoming more and more popular when dealing with sensor-based data acquisition and analysis. They rely on computer performances they have become the means to rapidly develop a competitive tool which meets the technical performances of traditional devices. Using customizable software and modular hardware, one can implement applications which are extremely powerful and complex, at the same time having lower costs. The spread of PC based instruments has impacted domains like health and medicine, environmental monitoring, structural monitoring, clean energy production, data transmission, industrial control, education, robotics and/or automation. Basically, these instruments can be defined as a software and hardware ensemble which has the purpose of replacing a stand-alone, dedicated device. The main advantage is represented by the possibility to exploit the calculus power and performances of the PC on which the software component runs.



All important computation software packages (LabVIEW, MATLAB, Python) can be interfaced with stand –alone instruments from important manufacturers like **Agilent (Keysight Technologies), Tektronix, Rohde & Schwarz, Meilhaus Electronic, Pico Technology** etc.

2.3 Classifications of measurement instrumentation (Primary & Secondary, Analog & Digital, Null Type or Deflection Type, Stand Alone or PC Based, Smart vs Non-Smart, Active or Passive).



2.3 Classifications of measurement instrumentation (Primary & Secondary, Analog & Digital, Null Type or Deflection Type, Stand Alone or PC Based, Smart vs Non-Smart, Active or Passive).

Primary vs. Secondary instruments – **Primary instruments** are the original sources of data in a measurement system, directly detecting and converting physical quantities—like temperature, pressure, or flow—into readable signals. Examples include thermocouples, pressure gauges, and flow meters. **Secondary instruments**, on the other hand, do not measure the physical quantity themselves but receive the signal from primary instruments and interpret, display, or control the data. These can include recorders, indicators, and controllers. In essence, primary instruments gather the raw data, while secondary instruments process and utilize that data for monitoring or automation purposes.

Consider a **primary sensor**, this gives an output that is a function of the measurand (the input applied to it). For most but not all sensors, this function is at least approximately linear. Some examples of primary sensors are a liquid-in-glass thermometer, a thermocouple and a strain gauge. In the case of the mercury-in-glass thermometer, the output reading is given in terms of the level of the mercury, and so this primary sensor is also a complete measurement system, itself. However, in general, the primary sensor is only part of a measurement system.

Variable conversion elements are used when the output from a primary transducer is not in a practical form for measurement or processing and needs to be transformed into a more usable format. For example, a strain gauge that measures displacement produces a change in resistance, which is difficult to measure directly. To address this, a bridge circuit is used to convert the resistance variation into a voltage change—a common method of variable conversion. Sometimes, the primary sensor and the conversion element are integrated into a single unit, which is then referred to as a transducer.

2.4 Measurement instruments characteristics (Static & Dynamic characteristics).

- **Accuracy (inaccuracy, sometimes called measurement uncertainty)** – **Static characteristic,** previously discussed, is a measure of how close the output reading of the instrument is to the correct value. In practice, it is more usual to quote the inaccuracy figure rather than the accuracy figure for an instrument. Inaccuracy is the extent to which a reading might be wrong, it is often quoted as a percentage of the full-scale reading/deflection of an instrument.

  Tolerance is a term that is closely related to accuracy and defines the maximum error that is to be expected in some quantity. The accuracy of some instruments is sometimes quoted as a tolerance figure. <u>When used correctly, tolerance describes the maximum deviation of a manufactured component from some specified value</u>. One resistor from a batch having a nominal value 1000Ω and tolerance 5% might have an actual value anywhere between 950Ω and 1050Ω.

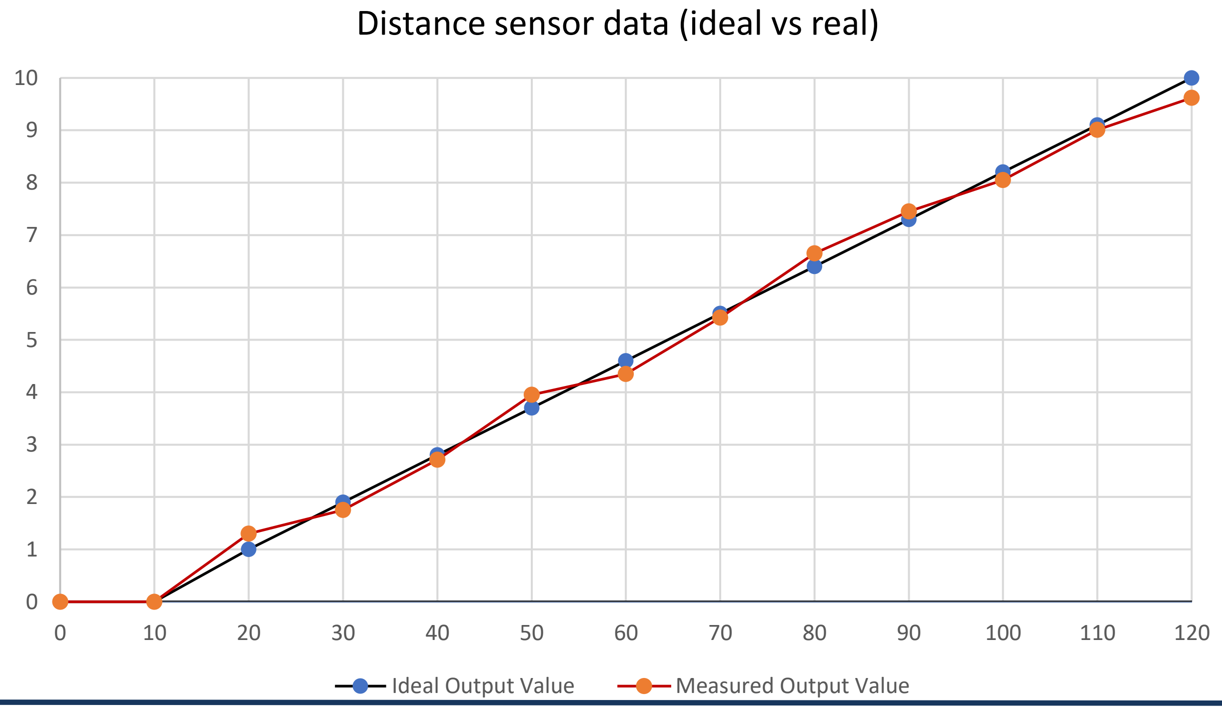
- **Precision/repeatability/reproducibility** – **Precision** is a term that describes an instrument's degree of freedom from random errors. If a sufficiently large number of readings are taken of the same quantity by a high precision instrument, then the spread of readings will be very small. Precision is often, though incorrectly, confused with accuracy. The terms **repeatability** and **reproducibility** mean approximately the same but are applied in different contexts. **Repeatability** describes the closeness of output readings when the same input is applied repetitively over a short period of time, with the same measurement conditions, same instrument and observer, same location etc. **Reproducibility** describes the closeness of output readings for the same input when there are changes in the method of measurement, observer, measuring instrument, location, conditions of use etc. Both terms describe the spread of output readings for the same input. <u>This spread is referred to as repeatability if the measurement conditions are constant and as reproducibility if the measurement conditions vary.</u>

2.4 Measurement instruments characteristics (Static & Dynamic characteristics).

- **Range/span** – defines the minimum and maximum values of a quantity that the instrument is designed to measure.
- **Linearity** – It is normally desirable that the output reading of an instrument is linearly proportional to the quantity being measured. The non-linearity is then defined as the maximum deviation of any of the output readings marked X from this straight line. Non-linearity is usually expressed as a percentage of full-scale reading.

A distance sensor generates voltage values corresponding to the measured distance. The generated values versus the ideal sensor response are presented in the image. A laboratory DMM was used to measure the output value. Comment on the representation of the measurement data.

Distance from object	Ideal Output Value	Measured Output Value
0	0	0
10	0	0
20	1	1.3
30	1.9	1.75
40	2.8	2.71
50	3.7	3.95
60	4.6	4.35
70	5.5	5.42
80	6.4	6.65
90	7.3	7.45
100	8.2	8.05
110	9.1	9.01
120	10	9.62



2.4 Measurement instruments characteristics (Static & Dynamic characteristics).

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Distance from object	Ideal Output Value	Measured Output Value
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20	1	1.3
30	1.9	1.75
40	2.8	2.71
50	3.7	3.95
60	4.6	4.35
70	5.5	5.42
80	6.4	6.65
90	7.3	7.45
100	8.2	8.05
110	9.1	9.01
120	10	9.62

$$Y = 0.09X - 0.8$$

OUTPUT VOLTAGE

DISTANCE FROM OBJECT

MAXIMUM NON-LINEARITY

$\Delta = 9.62V - 10V \cong -0.38V$

OR $\cong 3.8\%$ IF REPORTED TO THE FSR = 10V.

2.4 Measurement instruments characteristics (Static & Dynamic characteristics).

- **Sensitivity** – is a measure of the change in instrument output that occurs when the quantity being measured changes by a given amount. Thus, sensitivity is the ratio scale deflection/value of measurand producing deflection. If, for example, a pressure of 2Bar produces a deflection of 10° in a pressure transducer indication, the sensitivity of the instrument is 5°/bar (assuming that the deflection is zero with zero pressure applied).

The following resistance values of a platinum resistance thermometer were recorded at a range of temperatures. Determine the measurement sensitivity of the instrument in Ω/°C.

Resistance (Ω)	*Temperature* (°C)
307	200
314	230
321	260
328	290

NOTICE, each change in temperature by 30 °C ⇒ change in the resistance by 7Ω.

$$\text{Sensitivity} = \frac{7\,\Omega}{30\,^\circ C} \cong 233\ m\Omega/^\circ C.$$

2.4 Measurement instruments characteristics (Static & Dynamic characteristics).

- **Threshold** – if the input to an instrument is gradually increased from zero, the input will have to reach a certain minimum level before the change in the instrument output reading is of a large enough magnitude to be detectable. This minimum level of input is known as the threshold of the instrument. If a car speedometer has a threshold of 10km/h, it means that, if the vehicle starts from rest and accelerates, no output reading is observed on the speedometer until the speed reaches 10km/h.
- **Resolution** – is the smallest change in a quantity being measured that causes a perceptible change in the corresponding indication. As for the **resolution of a displaying device,** we can define it as the smallest difference between displayed indications that can be meaningfully distinguished.
- **Threshold vs. Resolution** – **As presented, threshold** is the **smallest input signal change** that causes a detectable output change from the instrument. Or, the value of the measured quantity for which the instrument starts to notice something is happening. If a pressure sensor has a threshold of 0.5 psi, it won't register or respond to pressure changes smaller than that — anything below 0.5 psi is essentially ignored. **Resolution** is the **smallest measurable increment or change** in the input that the instrument can display or record. Or, how finely the instrument can distinguish between two values.

  A thermometer doesn't change the indication until the temperature changes by at least 1°C, that's **threshold**. If it can show temperatures with one decimal place (for example 23.4°C), that's **resolution**.

2.4 Measurement instruments characteristics (Static & Dynamic characteristics).

Zero drift (or Bias) and Sensitivity drift – *Zero drift* or *bias* describes the effect where the zero reading of an instrument is modified by a change in ambient conditions. This causes a constant error that exists over the full range of measurement of the instrument. *Sensitivity drift* (also known as *scale factor drift*) defines the amount by which an instrument's sensitivity of measurement varies as ambient conditions change. It is quantified by sensitivity drift coefficients that define how much drift there is for a unit change in each environmental parameter that the instrument characteristics are sensitive to.

A spring balance is calibrated in an environment at a temperature of 20°C and has the following deflection/load characteristic.

Load (kg)	0	1	2	3
Deflection (mm)	0	20	40	60

It is then used in an environment at a temperature of 30°C and the following deflection/load characteristic is measured.

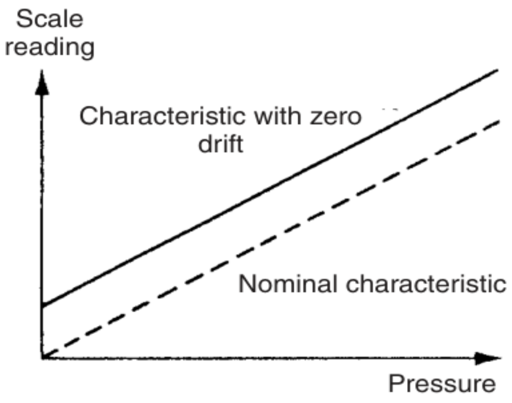
Load (kg):	0	1	2	3
Deflection (mm)	5	27	49	71

Calculate the zero drift and sensitivity drift per °C change in ambient temperature.

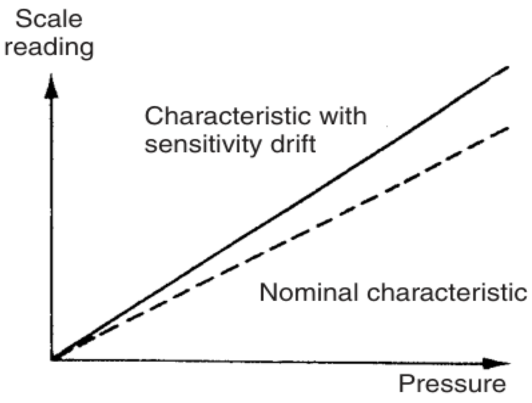
20°C : Sensitivity is 20 mm / Kg. Slope is 20 mm. Intercept is 0. BIAS - 5 mm, with no load.
30°C : Sensitivity is 22 mm / Kg. Slope is 22 mm. Intercept is 5. Sensitivity drift – 2 mm / Kg.
Zero drift/°C = 5/10 = 0.5 mm/°C. Sensitivity drift / °C = 2/10 = 0.2 mm/(Kg.°C).

2.4 Measurement instruments characteristics (Static & Dynamic characteristics).

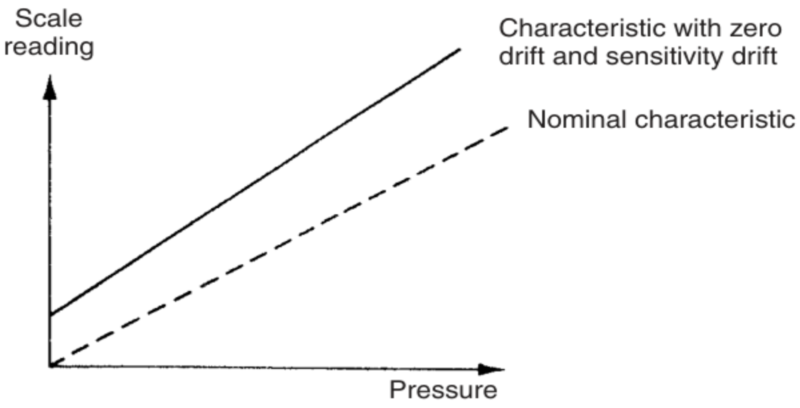
Zero drift (or Bias) and Sensitivity drift



(a)



(b)

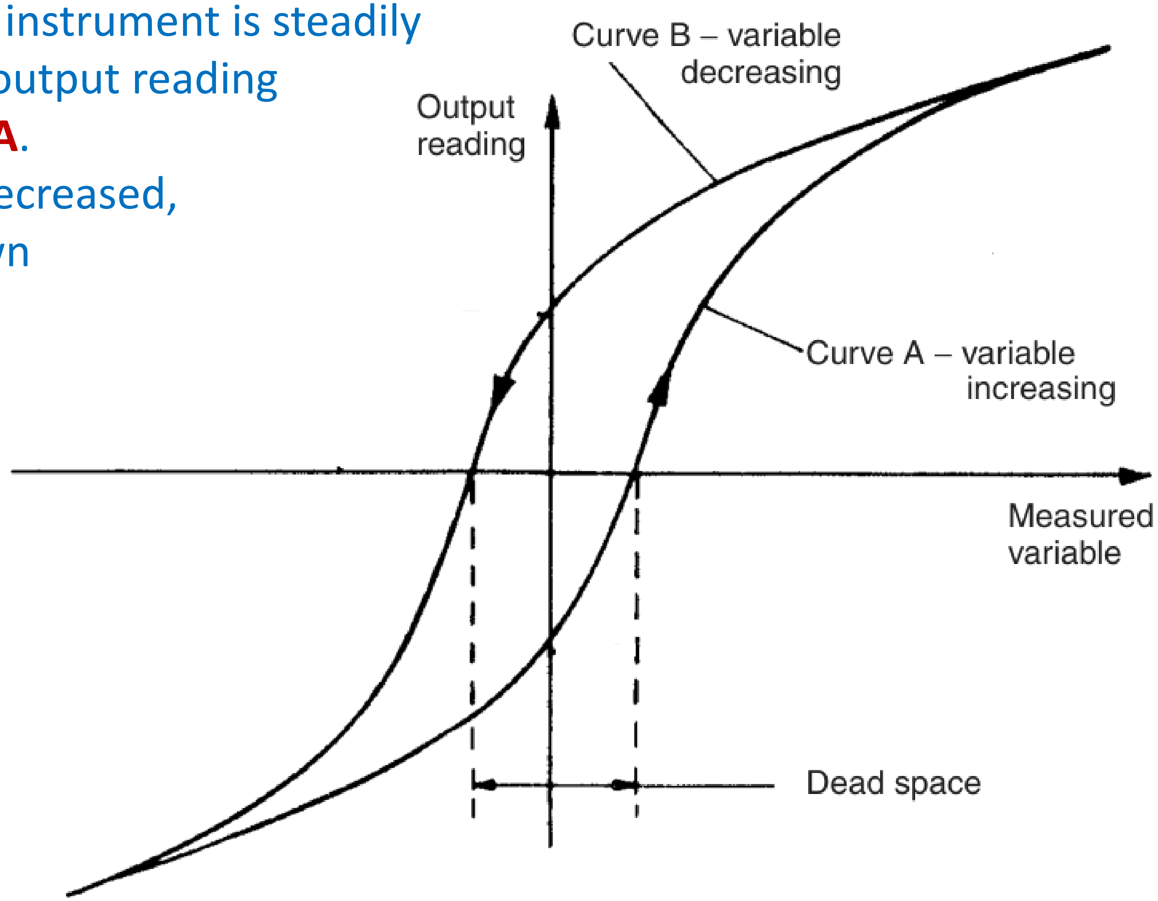


(c)

2.4 Measurement instruments characteristics (Static & Dynamic characteristics).

Hysteresis and Dead space

If the input measured quantity to the instrument is steadily increased from a negative value, the output reading varies in the manner shown in **curve A**.
If the input variable is then steadily decreased, the output varies in the manner shown in **curve B**.
The non-coincidence between these loading and unloading curves is known as hysteresis.
Hysteresis is commonly found in instruments that contain springs or electrical windings formed round an iron core.



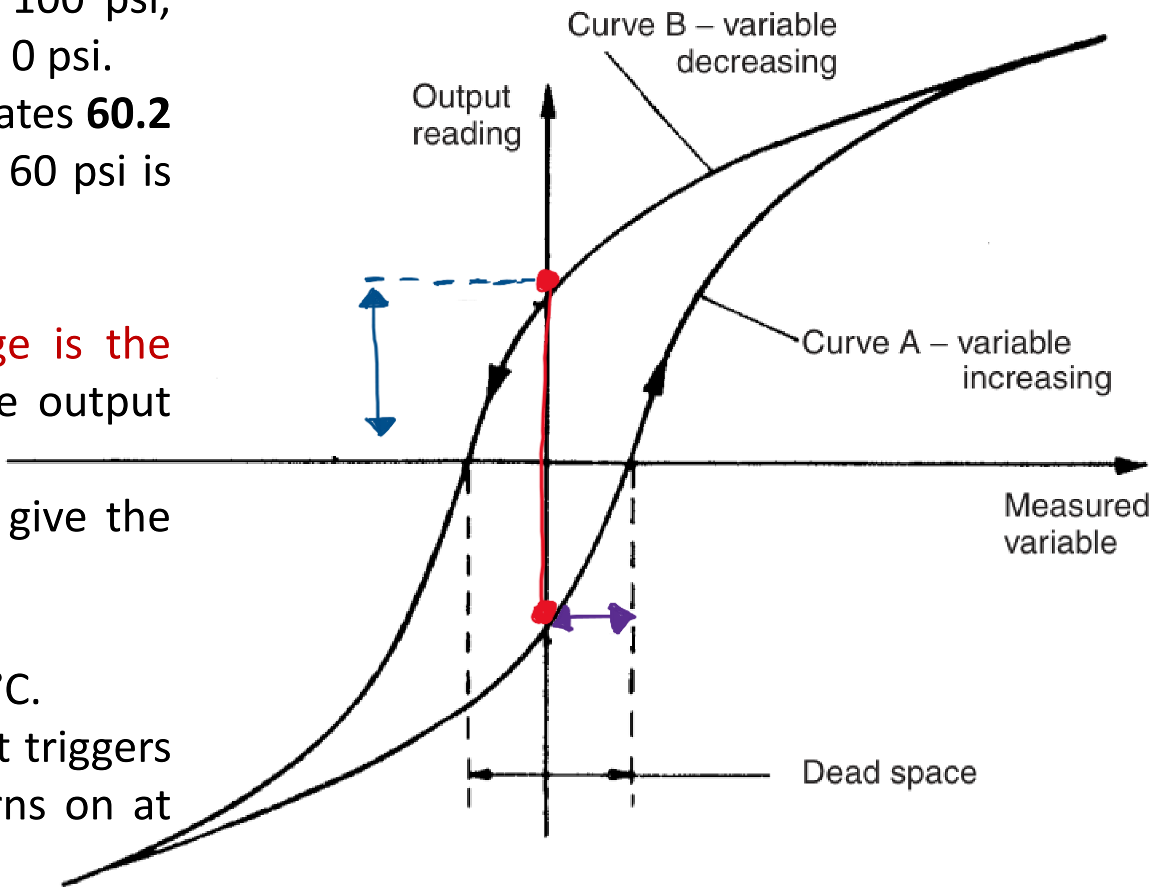
Dead space is defined as the range of different input values over which there is no change in output value. Any instrument that exhibits hysteresis also displays dead space.

2.4 Measurement instruments characteristics (Static & Dynamic characteristics).

Hysteresis and Dead space

Using a pressure sensor, we slowly increase pressure from 0 to 100 psi, recording the output. Then, we slowly decrease it back from 100 to 0 psi.
At **60 psi**, for example, we notice, when increasing the sensor indicates **60.2 psi,** while when decreasing it indicates **59.6 psi**. The hysteresis at 60 psi is 0.6 psi.

The **largest difference** observed at any point in the input range is the Maximum Hysteresis. **Output hysteresis** measures how much the output *changes* at the same input (typical in most discussions).
Input hysteresis measures how much the **input must change** to give the same output depending on the direction.



Imagine a temperature switch that turns **ON** at 75°C and **OFF** at 70°C.
The **output** (ON/OFF) is the same in both cases. But the **input** that triggers that output depends on the direction. If you're heating up it turns on at 75°C, if you're cooling down it doesn't turn off until 70°C. This **5°C** difference is the **maximum input hysteresis** for this system.