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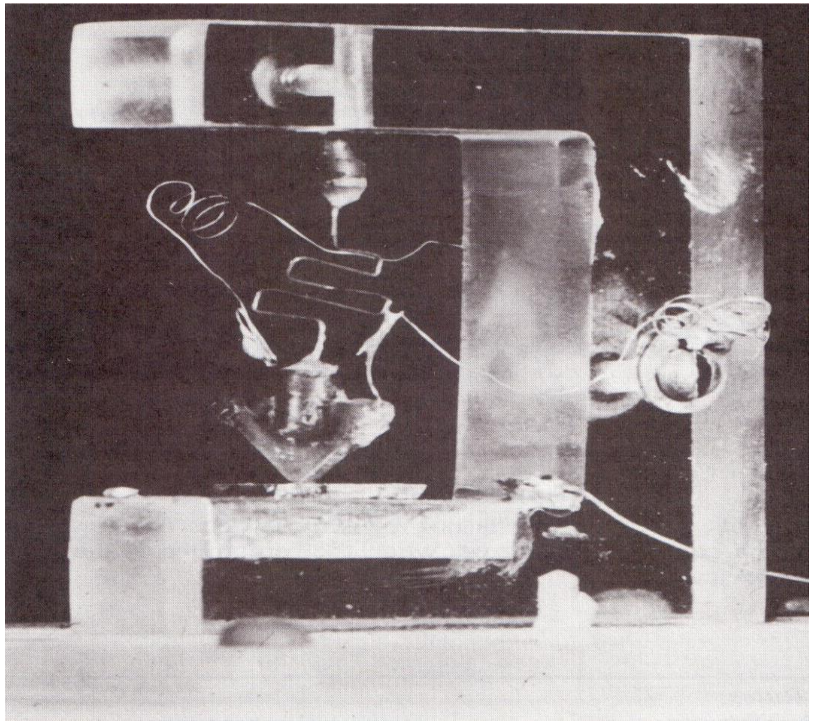
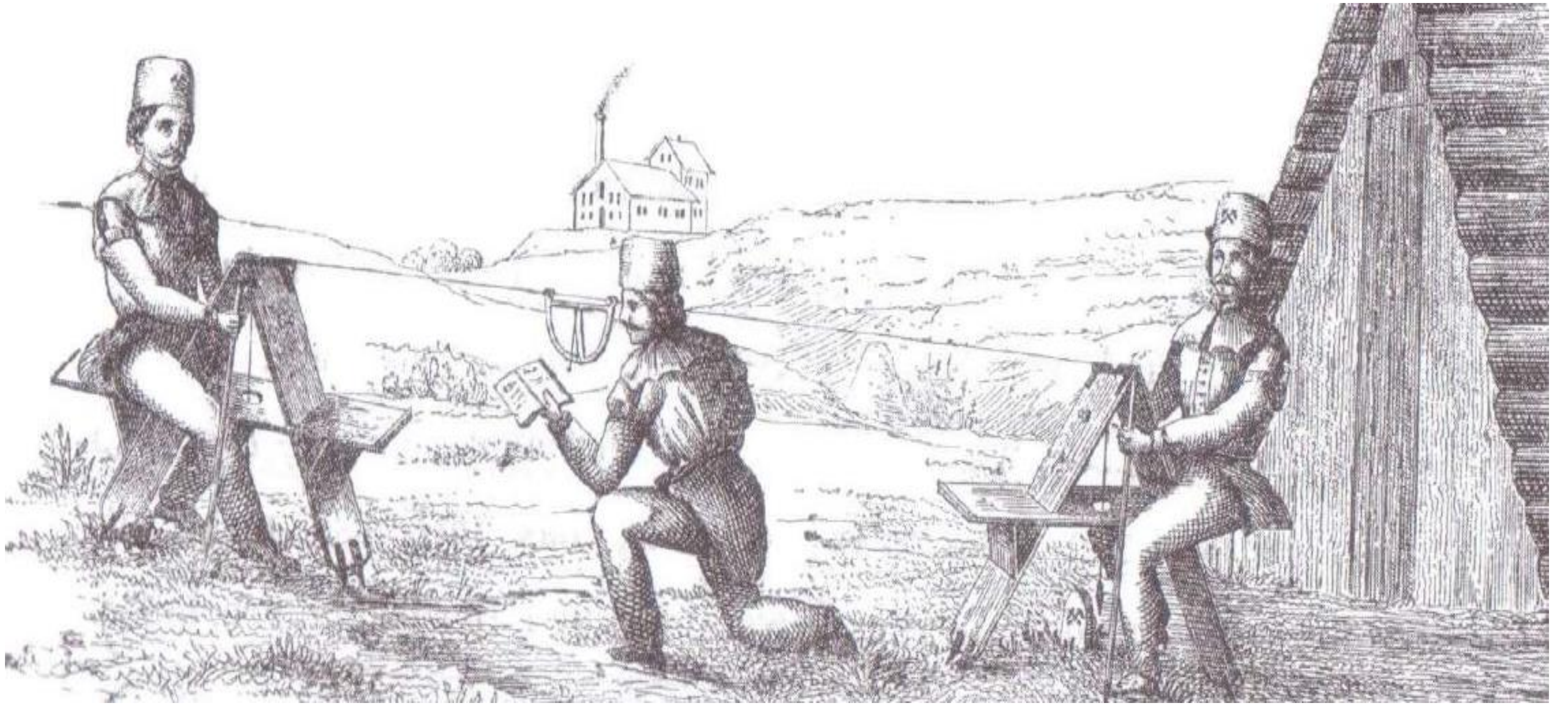
Electronic Devices and Measurements

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.

1.2 Defining units of Charge, Force, Energy, Power, Electrical potential, Resistance, Conductance etc.

The Coulomb (C) is the unit of electric charge, defined as the amount of electric charge that flows through a specific point in a circuit when a steady current of one Amp is maintained for one second. In other words, one Coulomb represents the charge transported by a one-ampere current in one second.

⇨ $\boldsymbol{Q\ (in\ Coulombs,\ C) = I \cdot t,}$ where ***I*** is the current in amperes and ***t*** is the time in seconds.

The Newton (N) is the unit of force. One newton is one kilogram meter per second squared. It is defined as the force required to accelerate a mass of one kilogram at a rate of one meter per second squared.

⇨ $\boldsymbol{F\ (in\ Newtons,\ N) = m \cdot a,}$ where ***m*** is the mass in kilograms and ***a*** is the acceleration in meters per second squared.
Gravitational force (weight) is $\boldsymbol{m \cdot g}$, where $g = 9.81\ \mathrm{m/s^2}$.

The unit of work or energy is the Joule (J). The joule is defined as the work done or energy transferred when a force of one newton is exerted on a distance of one meter in the direction of the force.

⇨ $\boldsymbol{W\ (in\ Joules,\ J) = F \cdot s,}$ where ***F*** is the force expressed in newtons and ***s*** (sometimes ***d***) is the distance in meters moved by the body in the direction of the force. **The energy is the capacity for doing work.**

1.2 Defining units of Charge, Force, Energy, Power, Electrical potential, Resistance, Conductance etc.

The unit of power is the Watt (W). One watt is one joule per second as Power is defined as the rate of doing work or transferring energy.

⇨ $P \text{ (in Watts, W)} = W/t,$ where ***W*** is the work done or energy transferred (in Joules) and ***t*** is the time in seconds.

⇨ $W \text{ (in Joules, J)} = P{\cdot}t.$

The unit of electric potential is the Volt (V). One volt is one joule per coulomb. Or, the volt is defined as the difference in potential between two points in a conductor which, when carrying a current of one Amp, dissipates a power of one Watt. The change in electric potential between two points in an electric circuit is called **potential difference**. A power supply, voltage generator or a battery, generate an electromotive force that is measured in Volts.

⇨ $$\text{Volts (V)} = \frac{Watts}{Amps} = \frac{Joules/Seconds}{Amps} = \frac{Joules}{Seconds \cdot Amps} = \frac{Joules}{Coulombs}.$$

The unit of electric resistance is the Ohm (Ω). This parameter is defined as the resistance between two points in a conductor when a constant **electric potential** of one Volt applied at the two points generates a **current flow** of one Amp.

⇨ $$\text{Resistance (in } \Omega) = \frac{V}{I}. \ Reciprocical\ is\ the\ Conductance\ (in\ Siemens) = \frac{1}{R}.$$

1.2 Defining units of Charge, Force, Energy, Power, Electrical potential, Resistance, Conductance etc.

The electrical Power and Energy.

When a direct current of **I Amps** is flowing in an electric circuit and the voltage across the circuit is **V Volts**.

- $\boldsymbol{P \text{ (in Watts, } W) = V \cdot I},$ where ***W*** is the work done or energy transferred (in Joules) and ***t*** is the time in seconds.
- $\boldsymbol{E \text{ (in Joules, } J) = V \cdot I \cdot t}.$

The **kilowatt hour** (kWh) unit is used for defining large amounts of energy.

- $\boldsymbol{1kWh = 1000\ W \cdot h = 1000 \cdot 3600\ W \cdot s = 3600000\ \text{Joules}}.$

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

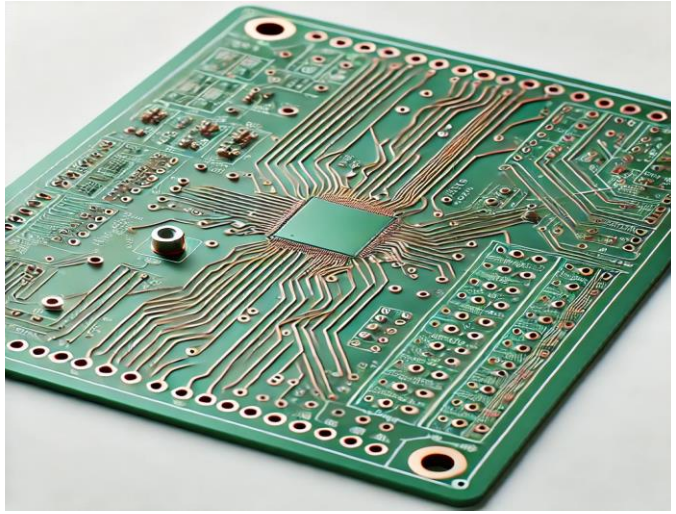
Common terminology.

An electronic system is a network of interconnected electronic components (resistors, capacitors, inductors, diodes, transistors etc.), connected using conductive wires or traces and are arranged to perform specific functions such as amplifying signals, processing data, or powering devices, controlling etc. Electronic circuits can be categorized into two main types:

- **Analog Circuits:** used for continuous signals and are used in applications like audio amplification and radio frequency systems.
- **Digital Circuits:** used for discrete signals, are the basis of computers, digital communication or logical circuitry.

What is the PCB (Printed Circuit Board) or Bare Board?

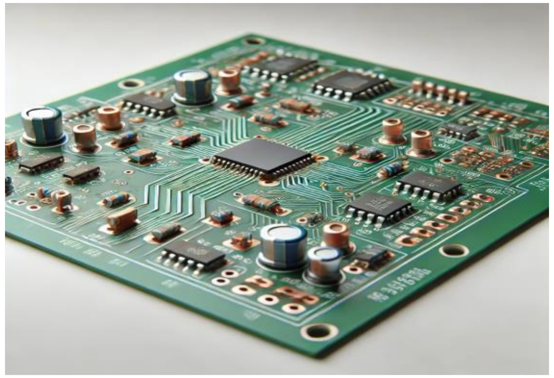
An A PCB is a flat, rigid board made from an insulating material (fiberglass) that contains thin layers of conductive pathways (usually copper) etched or printed onto its surface.
These pathways connect electronic components, enabling current to flow and creating an electronic circuit.


AI generated PCB image.

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

What is the PCBA (Printed Circuit Board Assembly)?

PCBA refers to a PCB that has been populated with electronic components, such as resistors, capacitors, integrated circuits (ICs) etc. The process of assembling components onto a bare PCB involves techniques like **soldering** (**surface-mount technology** or **through-hole mounting**). The PCBA represents a fully functional electronic assembly, prepared for testing or integration.



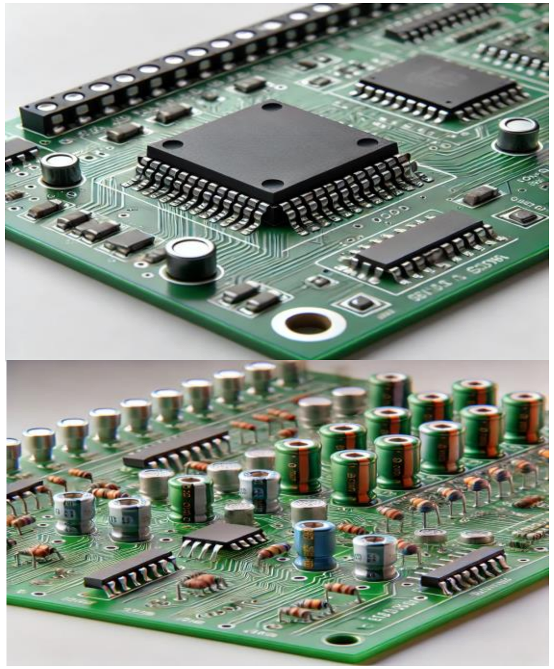
AI generated PCBA image.

What is Surface-Mount Technology (SMT)?

A method of assembling electronic components directly onto the surface of a PCB without drilling holes. SMT allows for smaller components and higher component density.

What is Through-Hole Technology (THT)?

A traditional method of PCB assembly where electronic components are inserted into pre-drilled holes and soldered onto the opposite side of the board. It is commonly used in applications requiring mechanical strength.



AI generated SMT & THT PCBA images.

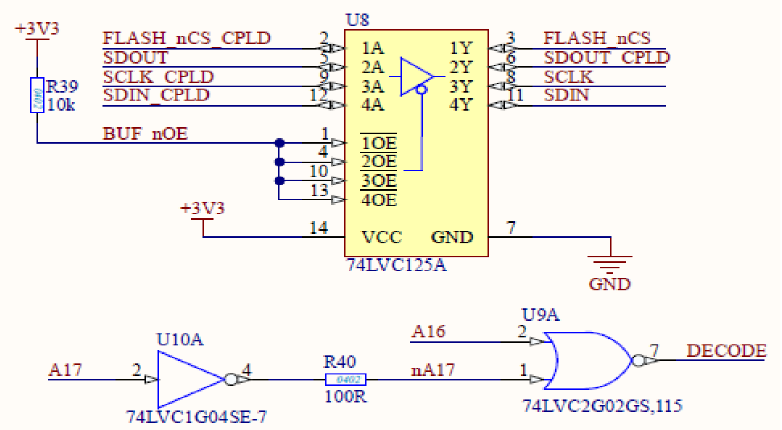
Other terms to be documented:

Solder Mask, Silkscreen, Single-Layer PCB, Multi-Layer PCB, Gerber File, Vias, PCB Panelization, Stencil.

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

From the engineer working with the PCBA - What is the Schematics?

A **PCBA schematics file** is a digital representation of an electronic circuit that visually illustrates how various components (e.g., resistors, capacitors, ICs) are interconnected on a printed circuit board assembly (PCBA). The schematics file serves as the blueprint or logical design of the circuit, which is later translated into the physical PCB layout. It is used for Debugging and Troubleshooting, Documentation, Circuit Design Representation etc. Generated from programs such as **Altium Designer, Eagle, KiCad, OrCAD** etc.



Excerpt from the schematics file of a PCBA.

From the engineer working with the PCBA - What is the Netlist?

A **Netlist file** is generated from the schematics to map all component pins and connections. They contain a detailed list of electrical connections between components. Common file extensions for netlists are *.NET, *.ASC, *.XML etc. Circuit design tools may have proprietary netlist file extensions (Eagle, Mentor Graphics, Zuken) or they can be generated to accommodate simple editing by means of common text editors.

```
<Net Name="PWR_8V">
  <Pin Component="C463" Number="1" />
  <Pin Component="C630" Number="1" />
  <Pin Component="CN2" Number="19" />
  <Pin Component="P992" Number="1" />
  <Pin Component="R752" Number="2" />
  <Pin Component="U54" Number="4" />
</Net>
<Net Name="PWR12V_FB">
  <Pin Component="C682" Number="1" />
  <Pin Component="P993" Number="1" />
  <Pin Component="R914" Number="1" />
  <Pin Component="R915" Number="1" />
  <Pin Component="U61" Number="12" />
</Net>
```

Excerpt from the netlist file of a PCBA.

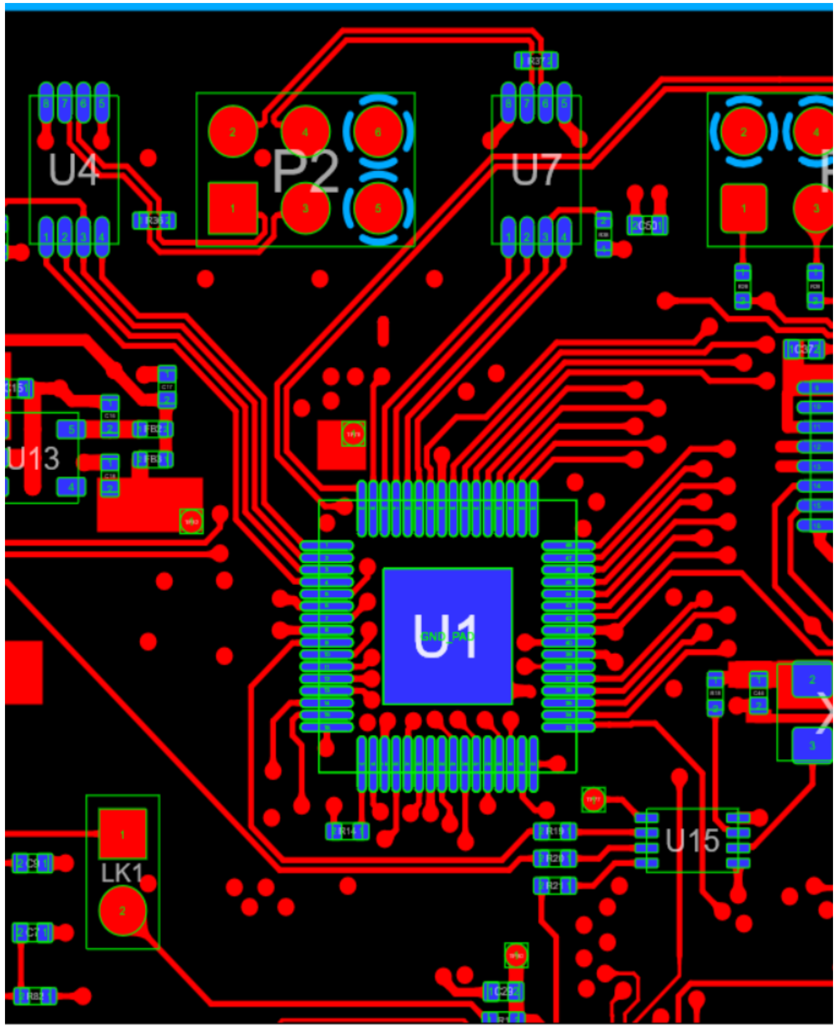
1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

From the engineer working with the PCBA - What is the CAD data package?

A **CAD data package** is a comprehensive collection of files and information generated during the PCB design process. It is delivered to manufacturers to enable the accurate fabrication, assembly, and testing of a PCB. The package typically includes all the necessary data for manufacturing the bare PCB, assembling components (PCBA), and ensuring the final product meets the design specifications.

Important components of a CAD data package (estimated, some optional)

- **Gerber Files** – used for the defining PCB layers, including copper layers, solder mask, silkscreen, drill files, and paste layers.
- **Drill Files** – used to define locations, sizes, and types of all holes (vias, through-holes, blind vias) in the PCB.
- **Netlist File** – already discussed.
- **Bill of Materials (BOM)** – contains a detailed list of all components required for assembly (part numbers, descriptions, quantities, and additional attributes like tolerance and voltage ratings etc.).



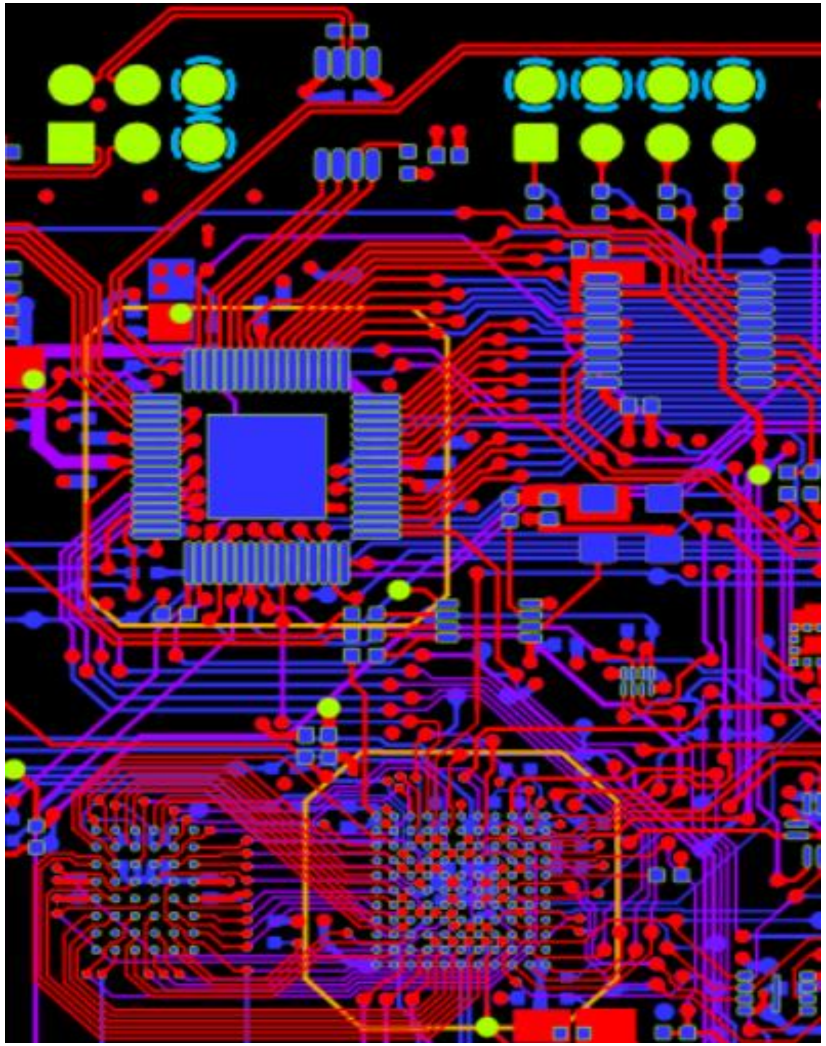
Excerpt from the CAD Viewer software tool.

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

From the engineer working with the PCBA - What is the CAD data package?

Important components of a CAD data package (estimated, some optional)

- **Assembly Drawings** – used for a visual representation of component placements. Includes reference designators, polarity markers, and other assembly instructions.
- **Pick-and-Place Files** – used by automated assembly machines for component placement. Specifies the X, Y coordinates, rotation, and side of the board (Top/Bottom) for each component.
- **Schematics File** – already discussed.
- **3D Model Files** – provided in STEP (.stp) or IGES (.igs) formats for visualization of the PCB's mechanical fit within the enclosure, if any. Important for ensuring proper integration with mechanical designs.
- **ODB++ or IPC-2581 Files** – provided as all-in-one formats that encapsulate all fabrication, assembly, and testing data. Preferred by many manufacturers for their comprehensive nature.



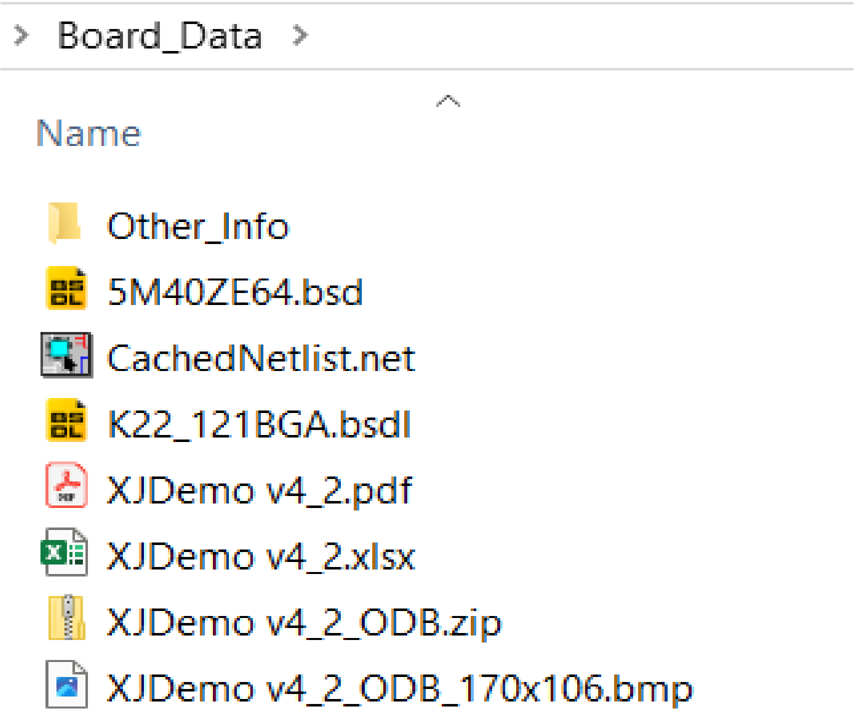
Excerpt from the CAD Viewer software tool.

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

From the engineer working with the PCBA - What is the CAD data package?

Important components of a CAD data package (File Formats)

Category	File Types/Formats
Design Layers	Gerber (.gbr), ODB++ (.tgz), IPC-2581
Drill Data	Excellon (.drl), NC Drill
Assembly Data	Pick-and-Place (.txt, .csv), Assembly Drawings
3D Models	STEP (.stp), IGES (.igs)
Netlist	.net, .asc, .xml
BOM	.xls, .csv, .txt
Schematics	.schdoc, .dsn, .pdf



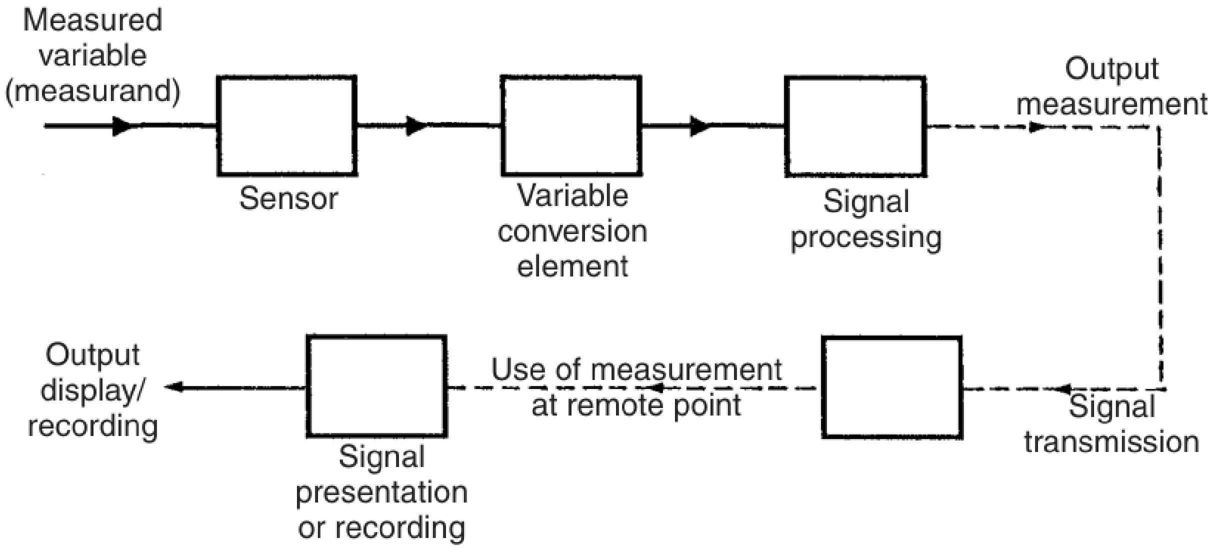
Excerpt from the CAD Viewer software tool.

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

Defining the electronic system and the components of the measurement system.

As presented, **an electronic system** is a network of interconnected electronic components (resistors, capacitors, inductors, diodes, transistors etc.), connected using conductive wires or traces and are arranged to perform specific functions such as amplifying signals, processing data, or powering devices, controlling etc.

A **sub-system** is a part of a system, and performs a specific function within the whole system. A component or element is usually the simplest part of a system which has a specific and well-defined function.

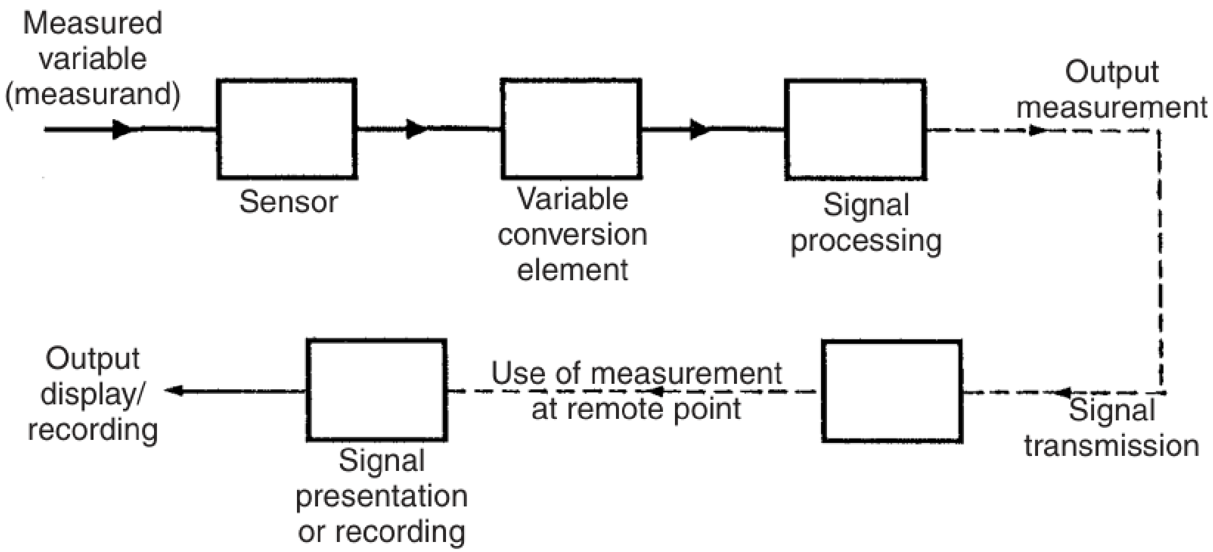


An example of measurement system architecture, as defined by Alan S. Morris, Measurement and Instrumentation Principles, 3rd Edition.

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.

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

Defining the electronic system and the components of the measurement system.



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

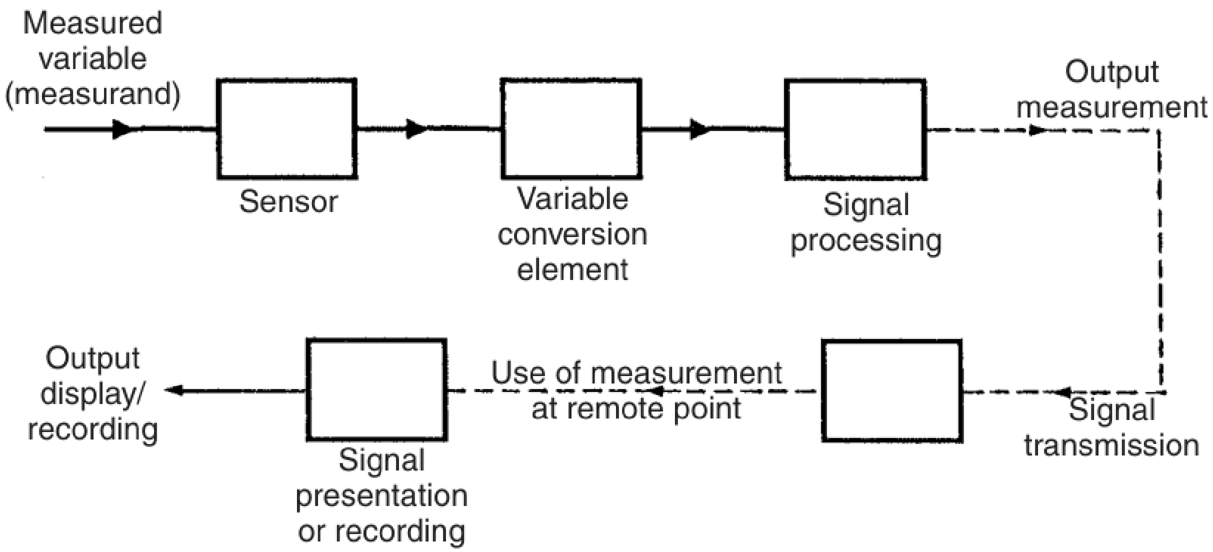
- **Signal proc.** – or signal conditioning, improves the quality of the output of a measurement system by procedures such as **amplification/filtering**. Sometimes, signal conditioning is included in the transducer.

- **The sensor** – element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured (float of a level-measuring instrument, thermocouple, strain gauge, photocell etc.).

- **The var. conversion element** – are needed if the output variable of a primary sensor is in an inconvenient format and must be converted to a more convenient one. Example, the displacement-measuring strain gauge has an output in the form of a varying resistance. Which is difficult to evaluate. For this reason, by means of a **bridge type circuit** it is converted to voltage output, which is easy to evaluate. If the **primary sensor** and **variable conversion element** are combined into a single module/device, the combination is known as a **transducer** (to be discussed later).

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

Defining the electronic system and the components of the measurement system.



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

Signal transmission, optional – It is required when the point of observation or application of a measurement system's output is located at a distance from the primary transducer. Traditionally, the signal transmission element has been composed of single or multi-core cables. Often shielded to reduce signal interference from induced electrical noise. However, modern installations are increasingly utilizing fiber-optic cables due to their low transmission loss and resistance to electrical and magnetic field disturbances.

Signal presentation/recording – It the final step, usually hosted by a PC, using a dedicated interface etc. Sometimes, this element is omitted altogether because the measurement is used as part of an automatic control scheme, and the transmitted signal is fed directly into the control system.

Of course, other instruments may be involved (power supplies, multimeters, frequency meters etc.).

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

Common terminology, review, in relation with the measurement system.

- **Metrology** – The science of weights and measures, including electrical standards and electronic instruments and measurements.
- **Measurement** – The process by which the magnitude, extent, or duration of a parameter is found.
- **Measuring instrument** – A device for measuring electrical quantities or the performance of electronic equipment. A meter provides a direct indication; other devices, such as a bridge, must be adjusted, the measured quantities being determined from one or more adjustments (sometimes augmented with calculations).
- **Measurand** – Any quantity that is measured/evaluated with an instrument.
- **Sensor vs Transducer** – The sensor element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured. The transducer device, used in measurement, that provides an output quantity having a specified relation to the input quantity. The sensor specifically detects and measures a physical parameter, while transducer performs a broader function by converting energy between different forms, including but not limited to measurement applications.
  As presented, the transducer is any device that converts one form of energy into another. This conversion can happen between mechanical, electrical, optical, thermal, or acoustic forms of energy. Transducers are used in a wide range of applications, including measurement and actuation processes.

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

Common terminology, review, in relation with the measurement system.

Sensor vs Transducer – As presented, the transducer is any device that converts one form of energy into another. This conversion can happen between mechanical, electrical, optical, thermal, or acoustic forms of energy. Transducers are used in a wide range of applications, including measurement and actuation processes.
The sensor is a specific type of transducer designed to detect and measure a physical quantity (such as temperature, pressure, or light) and convert it into an electrical, mechanical, or optical signal that can be processed or interpreted.

Why Sensors can be considered Transducers?

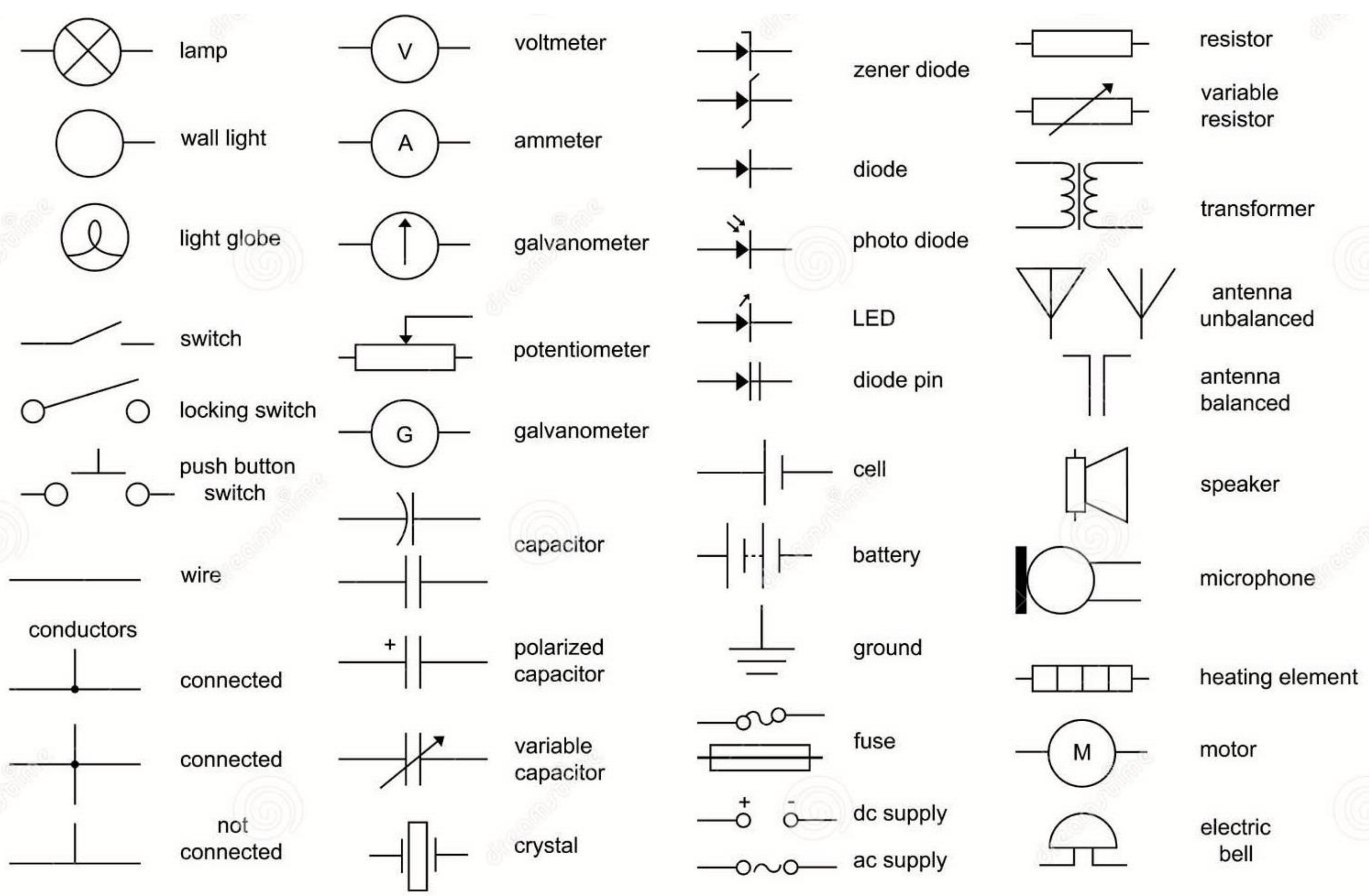
They evaluate a physical quantity and convert it into a measurable signal (usually electrical). Since they perform this conversion process (temperature to electrical signals, strain gauge detects mechanical strain and converts it into an electrical resistance change), they fit the definition of a transducer.

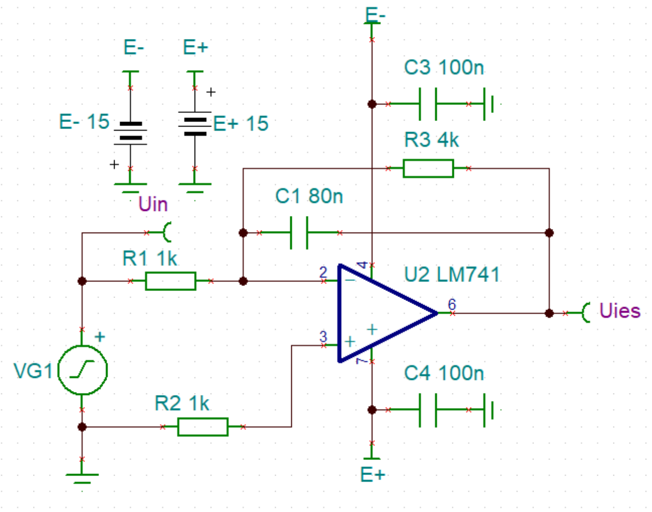
Why not all Transducers can be considered Sensors?

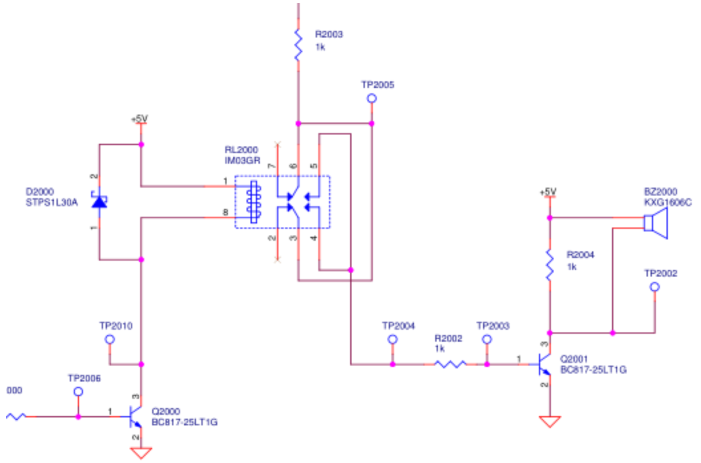
Some transducers do not provide any information regarding a measurement. They just perform the operation of conversion from one energy form to another. Their output is not meaningful for monitoring or measurement, so they are not considered sensors. A loudspeaker converts electrical signals into sound waves, but it does not detect or measure anything. An electric motor converts electrical energy into mechanical motion (actuation, not measurement).

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

Important symbols for electrical components (selection).







1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

Important electrical measuring instruments.

- **Ammeter** – a device designed to measure electrical current and must be connected in series with the circuit. Because the entire circuit current passes through the ammeter, it must have an extremely low internal resistance to minimize any impact on the circuit.
- **Voltmeter** – a device used to measure potential difference and must be connected in parallel with the circuit component whose p.d. is to be measured. To minimize current flow through the voltmeter and prevent circuit interference, it must have a very high internal resistance.
- **Ohmmeter** – a device used to measure resistance values.
- **Multimeter** – universal instrument, may be used to measure voltage, current, resistance, frequency, continuity etc.
- **Oscilloscope** – an electronic instrument used to visualize and analyze the waveform of electrical signals (AC and DC signals) in real-time. It graphically displays voltage as a function of time on a screen, allowing users to observe signal characteristics such as amplitude, frequency, phase, distortion elements etc. It can be used for troubleshooting circuits in electronics, telecommunications, and engineering applications. It can also be used to evaluate signal parameters such as peak voltage, period, frequency, and rise time.

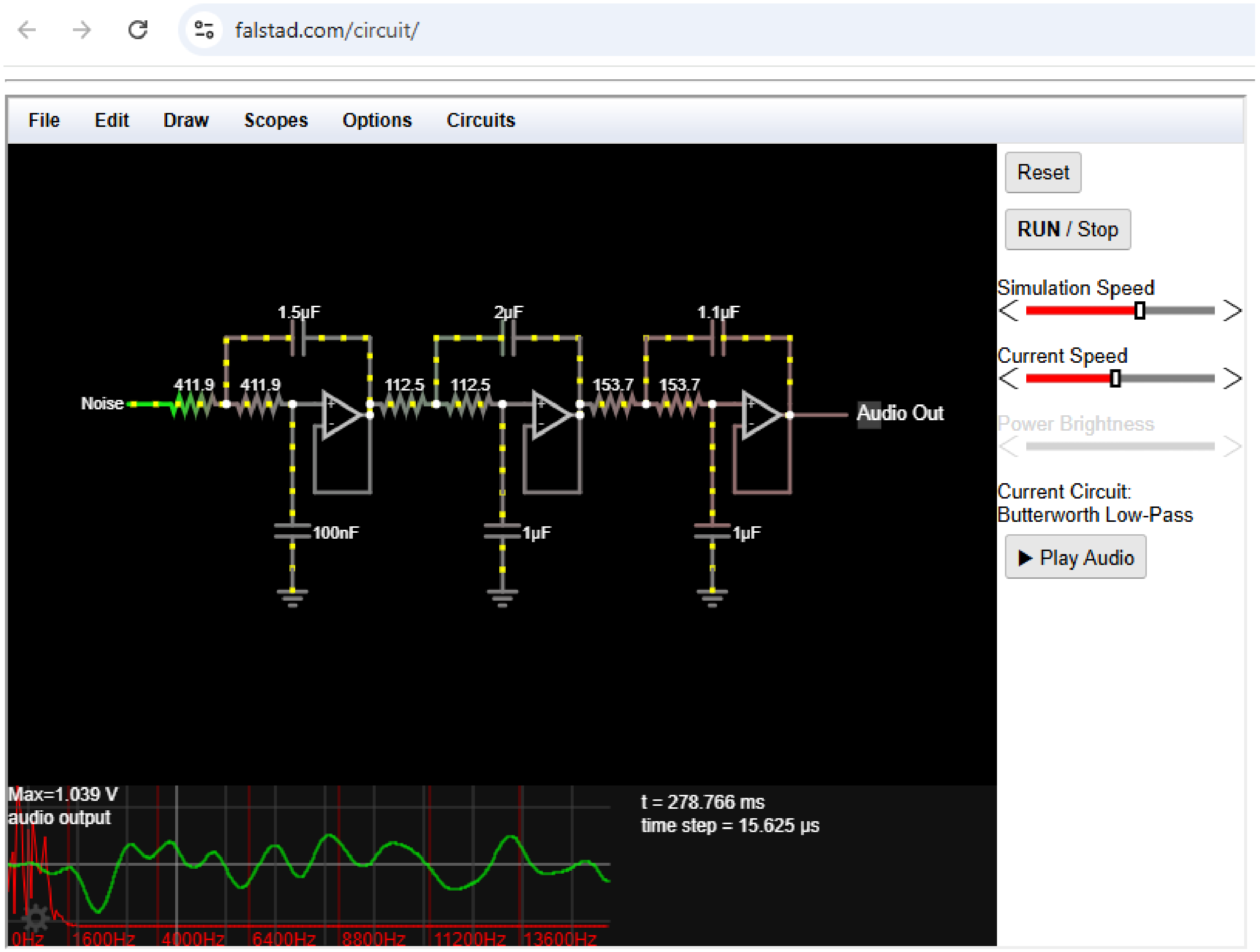
1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

Important electrical measuring instruments (preliminary discussion).

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

Some useful resources.

[EEVblog]
[INDUSTRY Videos Channel]
[Element14]
[ALL ABOUT ELECTRONICS]
[Fluke Corporation]
[MIT OpenCourseWare]
[Falstad]
[Electronzapdotcom]
[PLS]
[Applied Science]



1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

Common terminology, review, in relation with the measurement system.

- **Conductor** – is a material with low resistance that enables the flow of electric current. All metals act as conductors, with common examples including copper, aluminum, brass, platinum, silver, gold etc.
- **Insulator** – is a material with high resistance that prevents the flow of electric current. Common examples of insulators include plastic, rubber, glass, porcelain, air, paper etc.
- **Effects of electric current** – Magnetic -> relays, motors, generators, transformers.
  – Chemical -> primary and secondary cells, electroplating.
  – Heating -> cookers, heaters, electric irons, soldering irons etc.
- **Fuses** – a protective electrical device designed to **prevent excessive current flow** in a circuit, thereby protecting electrical components and wiring from damage caused by overcurrent or short circuits. If the fuse melts (blows) then there is an open circuit, and no current can then flow – thus protecting the equipment by isolating it from the power supply. The fuse should be capable of handling slightly more than the normal operating current of the equipment to account for tolerances and minor current surges. Some devices experience a significant surge of current for a brief moment when switched on. If a fuse were chosen to withstand this high initial current, it would fail to protect against faults that cause a slight but sustained increase in current. To address this, special **anti-surge fuses** are used. These fuses can tolerate up to ten times their rated current for 10 milliseconds, but if the surge lasts beyond this period, the fuse will blow, ensuring protection.

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

Common terminology, review, in relation with the measurement system.

- **Linear devices** – are components or circuits that exhibit a direct, proportional relationship between their input and output signals. This means that when an input signal is applied, the output signal changes in a predictable and proportional manner, maintaining a constant gain or transfer function over a range of operating conditions (resistors, operational amplifiers when working in their linear region etc.).

- **Non linear devices** – are components or circuits for which the output is not directly proportional to their input. This means that their voltage-current (V-I) characteristics do not follow a straight line, and they **do not obey the principle of superposition**. Superposition means that in a linear circuit with multiple independent sources (voltage or current), the total response (voltage or current at any point) is equal to the sum of the individual responses caused by each source acting alone, while all other independent sources are turned off (replaced by their internal impedance).

Category	Linear Devices	Non Linear Devices
Output vs Input	Proportional	Non-proportional
Examples	Resistors, capacitors, inductors, transformers, op-amps	Diodes, transistors, LEDs
Application	Amplification, filtering, energy storage	Rectification, switching, signal processing
Superposition	True	False

1.3 Introduction to electronic circuits (block diagrams, schematics, symbols of circuit components etc.).

Common terminology, review, in relation with the measurement system.

- **Rate** (Sampling Rate or Measurement Rate) – the speed at which a measurement device captures data per unit time. It determines how frequently the device updates or records values. A higher rate allows for better tracking of rapidly changing signals. An oscilloscope may have a sampling rate of **1 GSa/s (1 billion samples per second)**, meaning it can capture extremely fast signal variations. Here we will have a discussion on sampling rate, sampling frequency, sampling period etc.

- **Resolution** – the smallest measurable increment a device can detect or smallest change in a quantity being measured that causes a perceptible change in the corresponding indication. It defines how precisely a device can differentiate between two close measurement values. A higher resolution means more accurate readings.

- **Range or Span** – the distance between the minimum and maximum values a device can measure. It defines the operational limits of the instrument. Exceeding the range can result in inaccurate readings or damage.

A measurement device has an input range of 5V. It uses 3 types of ADC circuits to sample de input data: 3-bit, 10-bit and 16-bit ADCs. Present in each case the provided resolution.

$\Delta_1 = \frac{5V}{2^3} = 0.625V \text{ or } 625mV$ $\quad \Delta_2 = \frac{5V}{2^{10}} = 0.0048V \text{ or } 4.8mV$ $\quad \Delta_3 = \frac{5V}{2^{16}} = 0.00007629V \text{ or } 76.3\mu V$

- Problems using different measurement units (Coulomb, Newton, Watt, Joules);
- Problems on resistance, conductance, power, energy;
- Problems on electric current and quantity of electricity;
- Problems on Ohm's law, Potential difference and resistance;
- Problems on electrical power and energy.

The current flowing in a circuit has a magnitude of 5A. It flows for 1 minute. Which quantity of electricity was transferred during this time?
We are setting a current with a constant value of 0.5A, to transfer a charge of 30C. How long does this operation take?
An object of 4000g is accelerated to $2m/s^2$. What is the required force?
An object of 200g is accelerated vertically by a force. What is the value of that force?
A force of 4N moves an object in the direction of the force, over a distance of 400cm. What amount of work was performed?
An industrial equipment is moved by a 150N force, over a distance of 10m. This action takes 5 minutes. What is the average consumed power?
An object of 400kg is raised vertically at a height of 3m. The action takes 20s. What is the average needed power?
A Power Supply device outputs 5VDC@3A for 6 minutes. What is the consumed energy during this time?
An electric heater consumes 1.5MJ of energy, for 20 minutes, when connected to a 250VDC power supply. How much current does this heater consume and what is the power rating of this equipment?
A current of 8A flows through a conductor and 10W of power is dissipated. What is the potential difference at the conductor end points?
A current of 200mA, flows in a 200Ω resistor, for 2h. What is the energy consumed by the resistor?
A 12VDC@5mA power supply is connected across a resistor. What is the value of the resistor and what happens with the current if we decrease the voltage at 3.3VDC?
What amount of power dissipates in a 2kΩ resistor, if a 40mA current flows through it?
A 12VDC battery is connected to a 60Ω resistor/load. Which is the amount of dissipated energy over a 1-minute interval?

The current flowing in an electric motor has a value of 4A. The winding of the motor has a resistance of 100Ω. Calculate the potential difference across the winding and the power dissipated by the coil.

The resistance of the filament of a lamp is 800Ω and it is supplied by a 240VDC source. Which current is drawn from the supply and what is the power rating of the lamp?

A 12VDC is connected over a 100Ω load. The connection is active for 5 minutes. Which is the value of the drawn current, which is the consumed power, and which energy is dissipated?

A d.c. motor consumed 70MJ of energy. It was connected to a 400VDC power supply for 2h. What is the value of the current generated by the supply and which is the power rating of the motor?

We have a set of fuses with the current values of 1A, 2A, 5A, 13A and 15A. A 240VDC power supply is connected to some machines. The first machine has a power rating of 1kW, while the other has a power rating of 3kW. Select the most suitable fuses to ensure protection on these machines.

Determine the maximum number of light bulbs, each of 100W power rating, which can be safely operated from the same 240VDC power supply setup with a 13A fuse.

A 3A current flows through a 10Ω resistor for a period of 20h. Determine the energy consumed by the resistor.

Fill in the missing terms in the following statements:

a) An ammeter has a _______________ internal resistance and must be connected ___________________ with the load;

b) A voltmeter has a ________________ resistance and must be connected ____________________ with the load.

The AI generated graph of Current vs. Voltage, for 2 resistors is presented in the following image.

Determine the value of these resistors.

The range of a measurement device is denoted as r[a; b], where a = -2 and b = 4. How wide is this measurement interval?