MEC 450/550: Mechatronics

(Fall 2024)

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Ch1: Introduction, Analog Circuits and Basic Components

Contents:

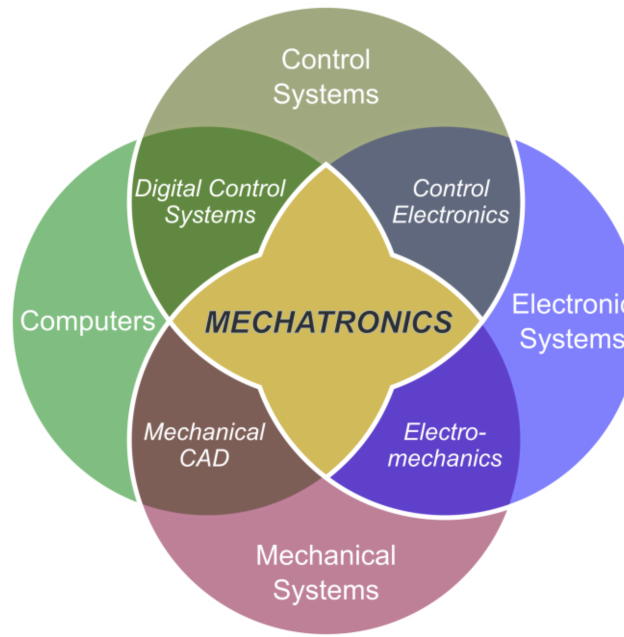
Introduction to Mechatronics

Mechatronics

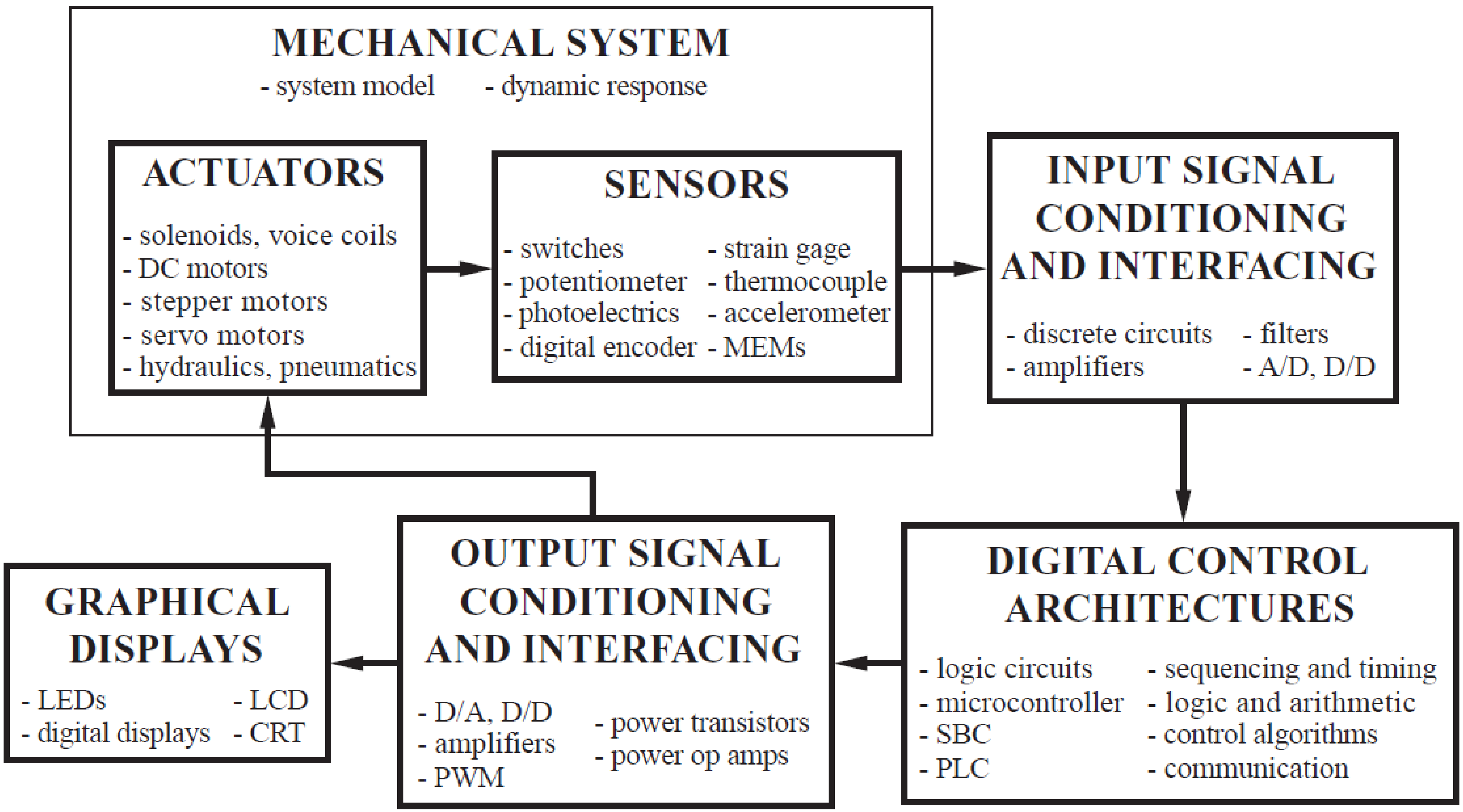
The word **Mechatronics** was invented by a Japanese engineer in 1969, as a combination of '**mecha**' from mechanics/mechanisms and '**tronics**' from electronics.

Mechatronics is an interdisciplinary, integrated, and concurrent approach to engineering design which integrates the traditional boundaries of mechanical engineering, electrical engineering, computer engineering/science, and control engineering in the design and manufacture of products and processes.

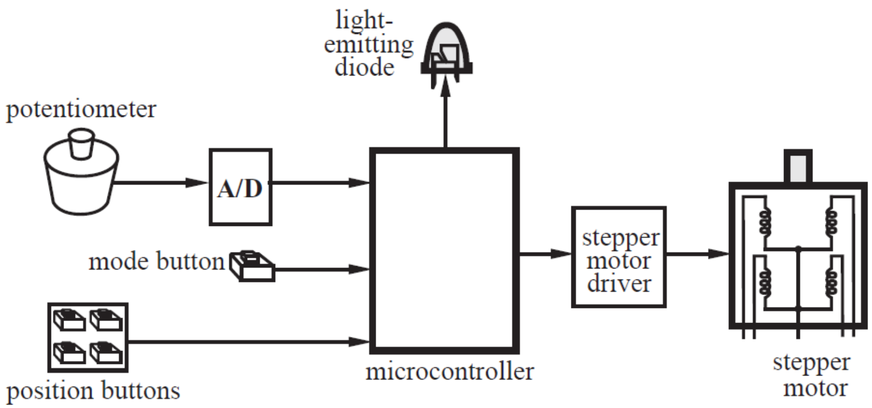


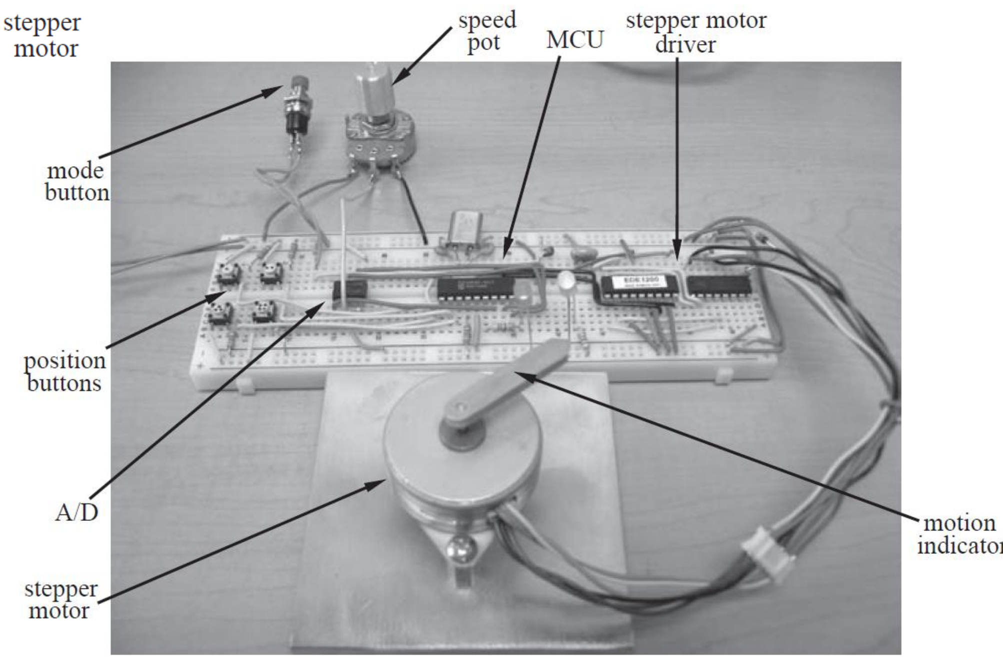
Mechatronic System Components



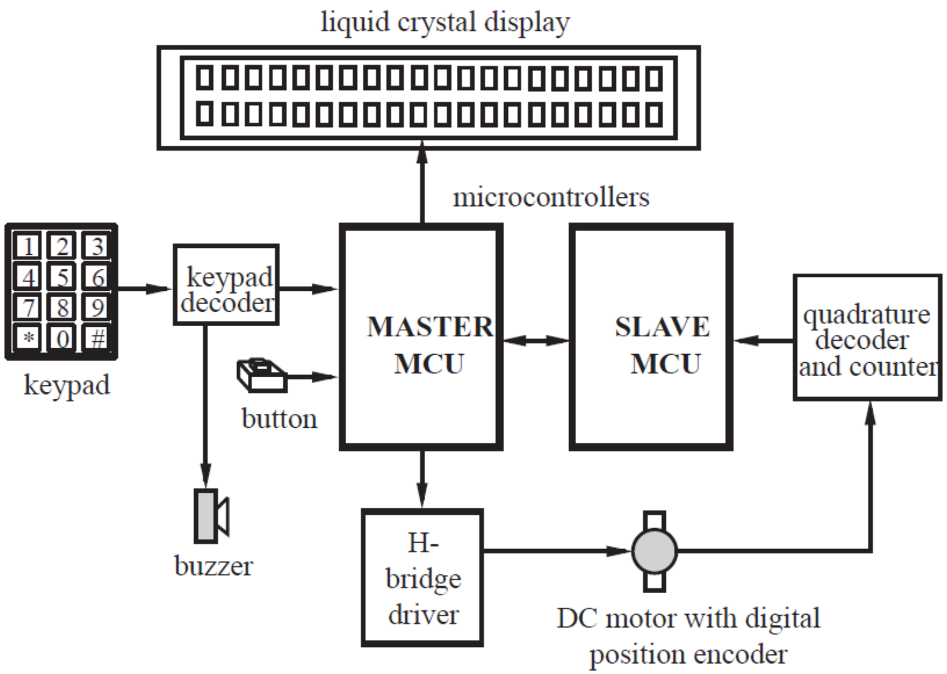
Example: Stepper Motor Position & Speed Controller

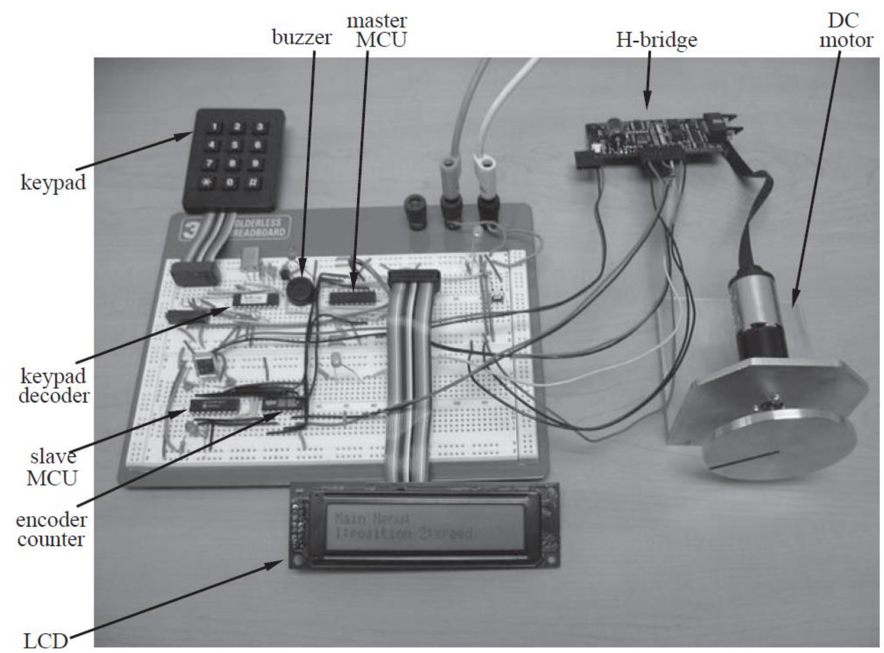


A pot to control the speed manually, four buttons to select predefined positions, a mode button to toggle between speed and position control, and an LED provides a visual cue to the user to indicate that the MCU is cycling properly.



Example: DC Motor Position & Speed Controller





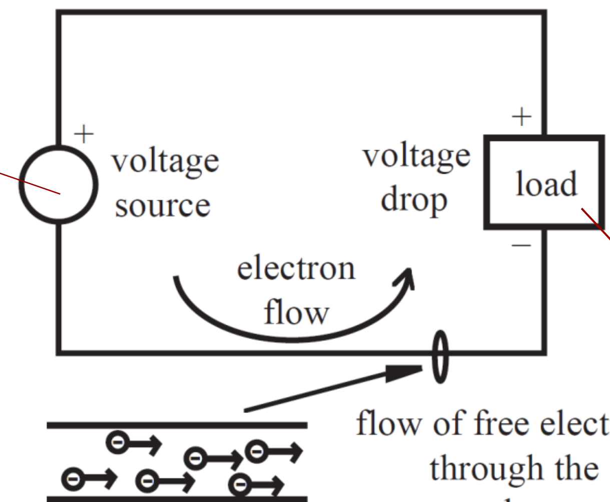
Electrical Circuits

Electrical Circuits

An **Electrical Circuit** is a **closed loop** consisting of several conductors connecting electrical components.

- The **voltage source** adds electrical energy to electrons (negative charge), which **flow from the negative terminal to the positive terminal**, through the circuit.

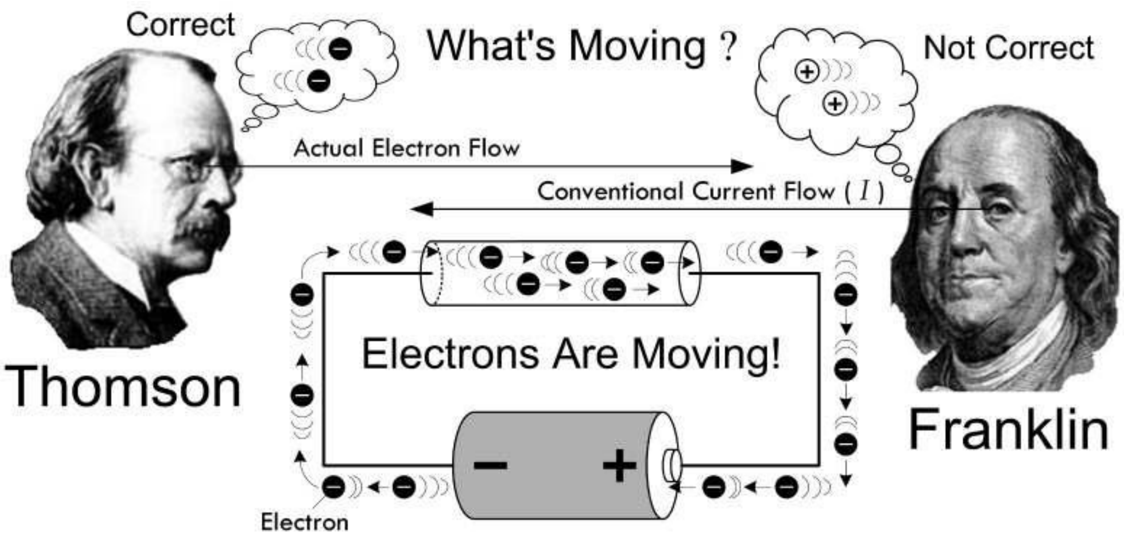
- The positive side of the source attracts electrons, and the negative side releases electrons.

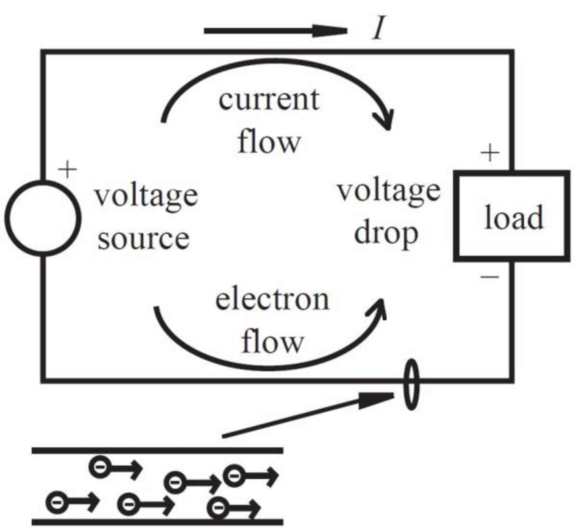


A **load** consists of a network of circuit elements that may dissipate or store electrical energy.

Electrical Circuits

By convention, **current** (positive charge) in a circuit is considered to flow from a more positive point (higher potential energy) to a more negative point (lower potential energy), **even though** the **actual** electron flow is in the opposite direction.

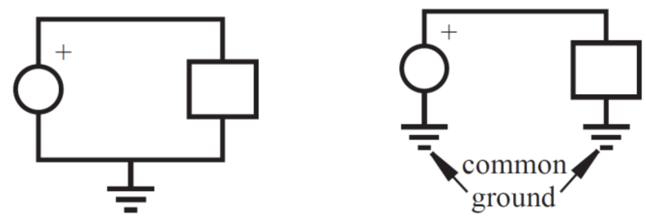




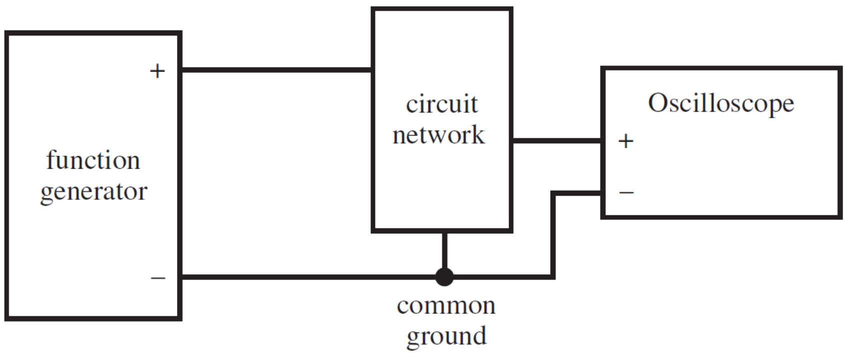
Note: We will use conventional flow notation on all schematics.

Ground in Electrical Circuits

Two alternative ways to draw a circuit schematic.



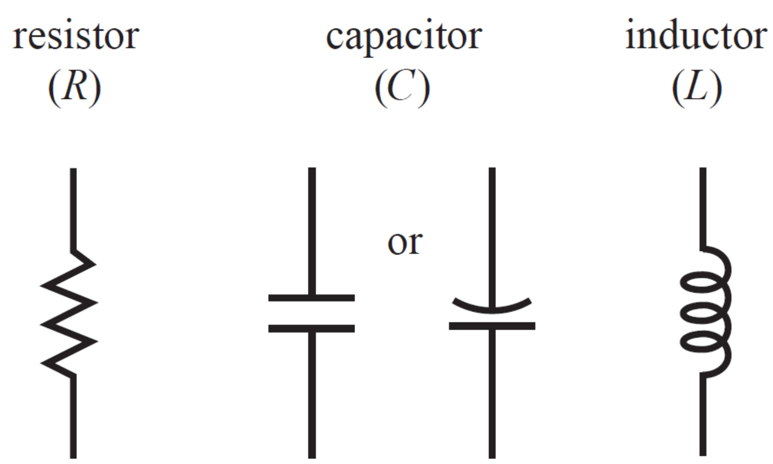
- The **ground** indicates a reference point in the circuit where the voltage is assumed to be **zero**. Even though we do not show a connection between the ground symbols, it is implied that both ground symbols represent a single **reference voltage** (i.e., there is a "common ground"). This technique can be applied when drawing complicated circuits to reduce the number of lines.
- It is important to provide a **common ground** defining a **common voltage reference** among all instruments and power sources used in a circuit or system.

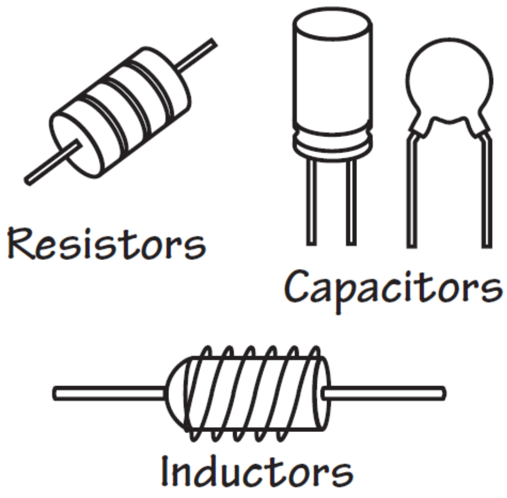


Basic Electrical Elements

Basic Passive Electrical Elements

- There are three basic **passive** electrical elements: **Resistor** (R), **Capacitor** (C), and **Inductor** (L).
- Passive elements require no additional power supply, unlike active devices such as integrated circuits.
- The passive elements are defined by their voltage-current relationships.





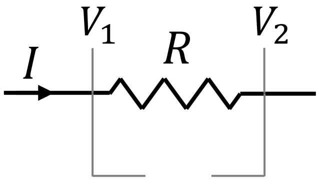
Resistor

A **Resistor** (R) is a dissipative element that converts electrical energy into **heat**. Ohm's law defines the **voltage-current characteristic** of an ideal resistor:

$$V = RI$$


Georg Ohm (1789-1854)

Unit: ohm ($\Omega = V/A$)

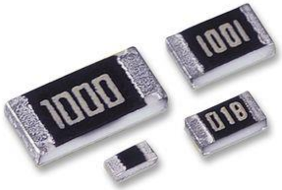


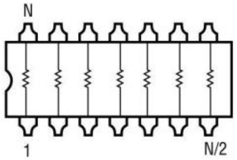
$$V = V_1 - V_2$$

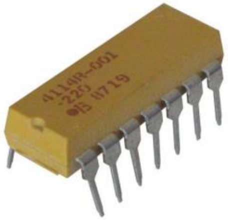
Water Flow Analogy

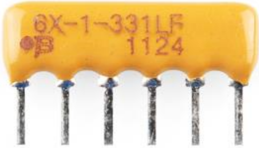
- **Resistor Packages**:

Axial-lead, Surface Mount, Dual In-line Package (DIP), Single In-line Package (SIP)









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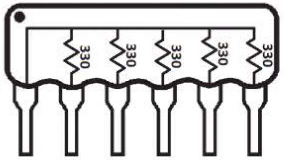


(multiple resistors in a package)

Resistance

Resistance is a **material property** whose value is the slope of the resistor's voltage-current curve.

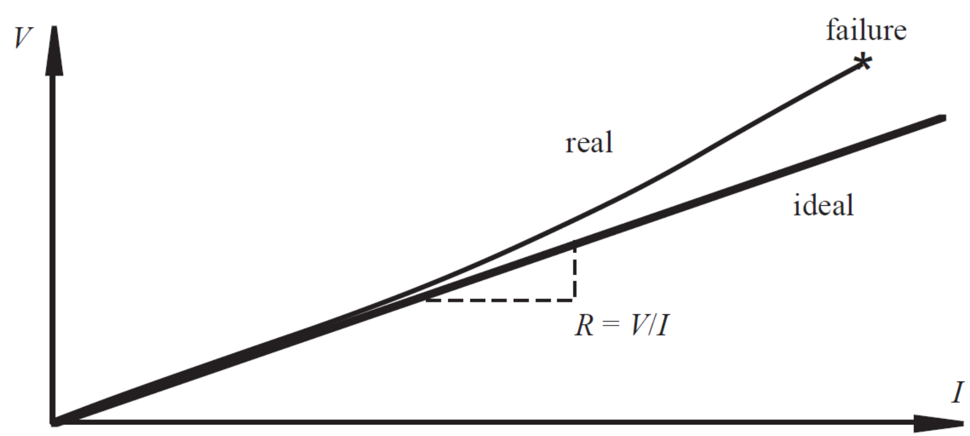
Ideal Resistors:

- $V - I$ relationship is linear (resistance is constant).

Real Resistors:

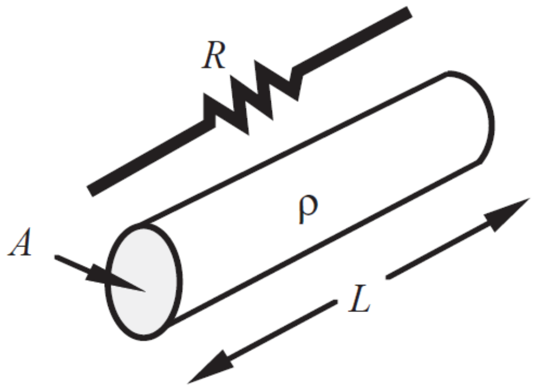
- $V - I$ relationship is typically nonlinear due to temperature effects ($I\uparrow \Rightarrow T\uparrow \Rightarrow R\uparrow$).
- They have a limited power dissipation capability designated in watts.

- The resistor's resistance limits the **flow of electrons** through a circuit.
- Voltage **drops** when current flows through a resistor.
- Resistors are used to **limit current**, **divide voltages**, and **pull-up/down I/O lines**.



Resistivity

If a resistor's material is homogeneous and has a constant cross-sectional area, such as the cylindrical wire, its resistance is



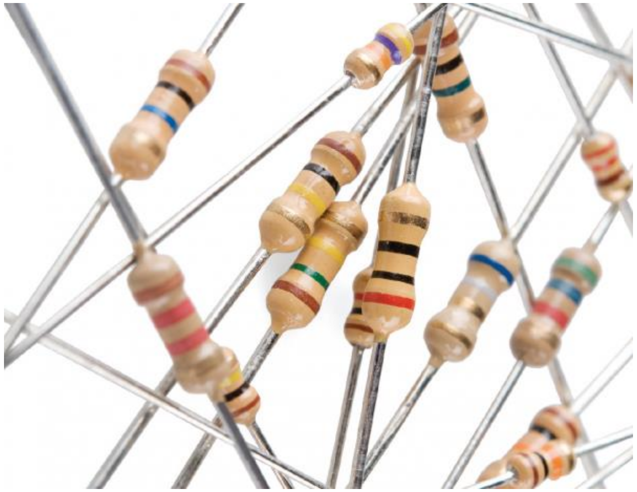
$$R = \rho \frac{L}{A}$$

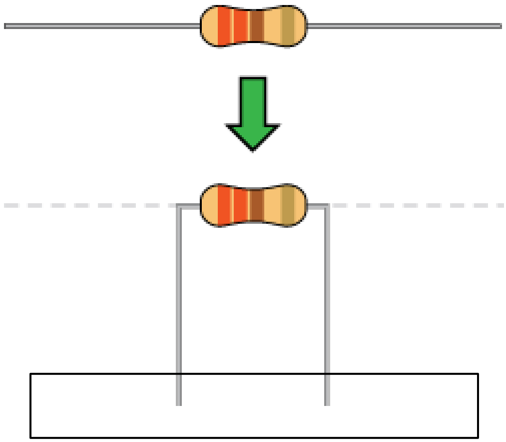
ρ: **resistivity**, L: wire length, A: cross-sectional area

Material	Resistivity ($10^{-8}\Omega$m)
Aluminum	2.8
Carbon	4000
Constantan	44
Copper	1.7
Gold	2.4
Iron	10
Silver	1.6
Tungsten	5.5

Axial-Lead Resistor

Axial-Lead Resistors come with long pliable leads which can be stuck into a breadboard. These resistors usually use the color-band system to display their value.





The power rating of these resistors are usually somewhere between 1/8W (0.125W) and 1W. The most common resistors you will use in ordinary electronic circuitry are 1/4 watt, 5% tolerance carbon or metal-film resistors.

Axial-Lead Resistor

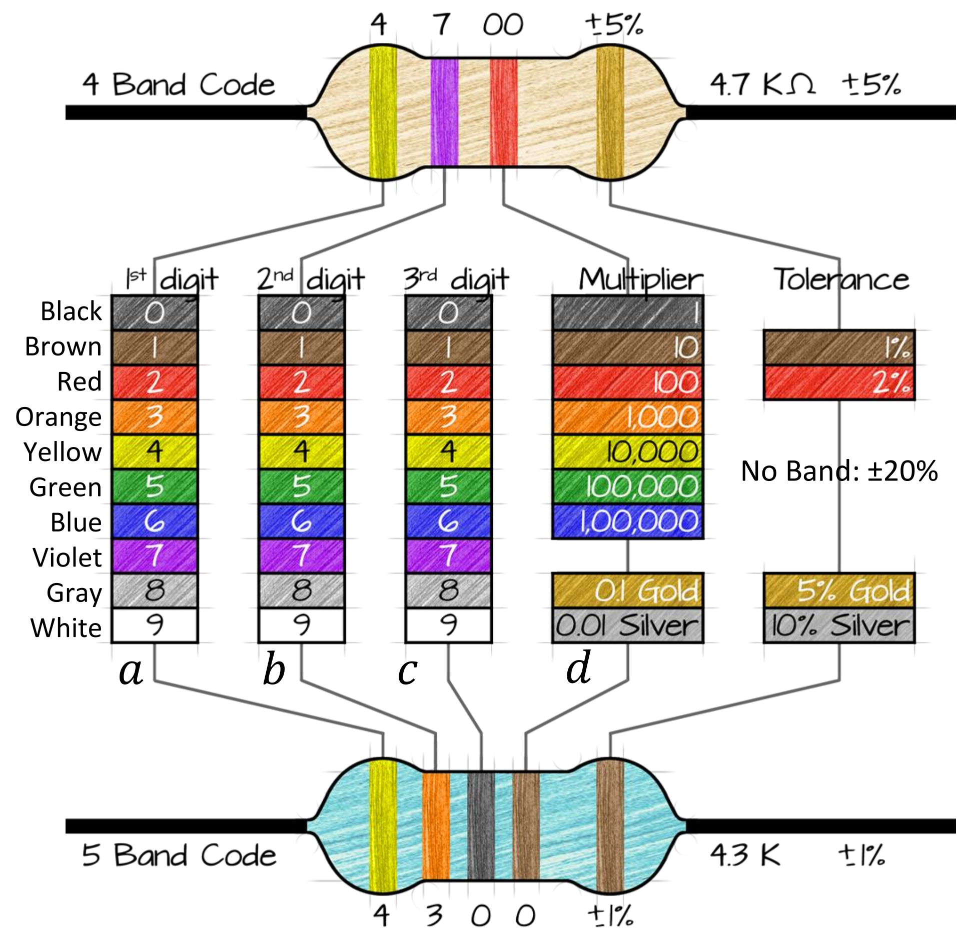
4-Band Code:
The **first two** bands indicate the two most-significant digits of the resistor's value. The **third** band is a weight value, which multiplies the two significant digits by a power of ten.

The **last**, tolerance band is often clearly **separated** from the value bands.

$$R = ab \times d \pm \text{tolerance (\%)}$$

5-Band Code:
It is similar to explanation of 4-Band Code.

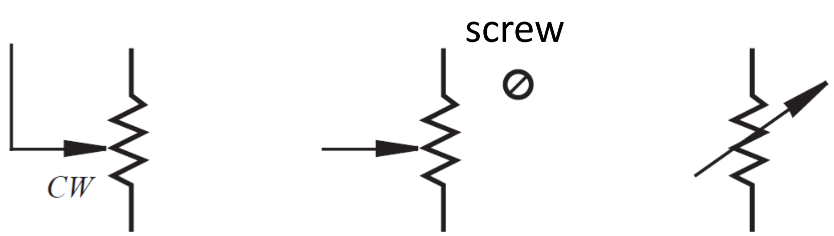
$$R = abc \times d \pm \text{tolerance (\%)}$$

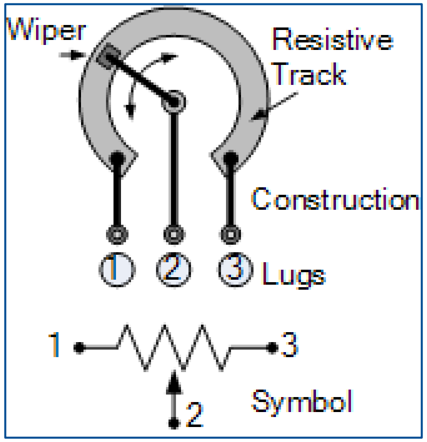


Variable Resistors

Variable Resistors are available that provide **a range of resistance values** controlled by a mechanical screw, knob, or linear slide. The most common type is called a **potentiometer**, or **pot**.

Potentiometer can be
- used to create an adjustable **voltage divider**.
- used as a simple **analog sensor** that you can find them in stereos, speakers, thermostats, ...





Conductance

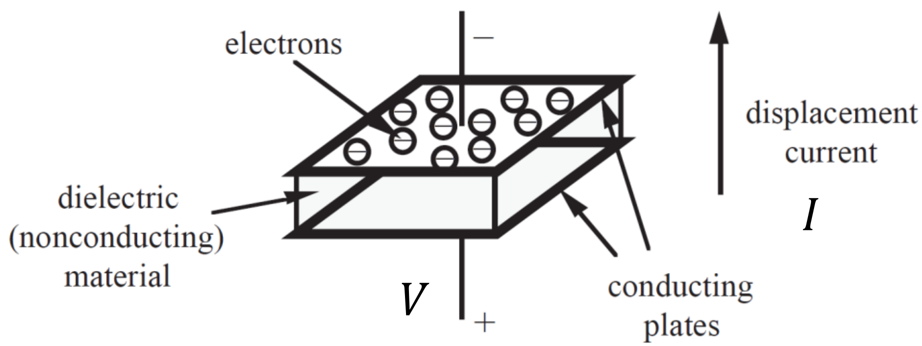
Conductance is defined as the **reciprocal of resistance**. It is a measure of how easily an element conducts current as opposed to how much it resists it. The unit of conductance is the **Siemens** ($S = 1/\Omega = \mho = \mathrm{mho}$).

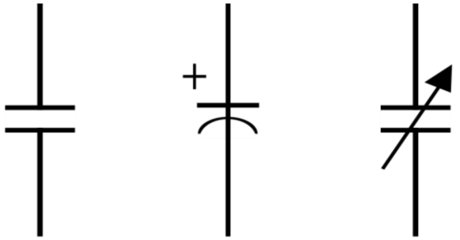
$$R = \frac{V}{I} \qquad\qquad G = \frac{I}{V} = \frac{1}{R}$$

Capacitor

A **Capacitor** (or **cap**) **stores energy** in the form of an electric field which is the result of a **separation of electric charge**.

The simplest capacitor consists of a pair of parallel conducting plates separated by a **dielectric material** which is an insulator that increases the capacitance as a result of permanent or induced electric dipoles in the material.





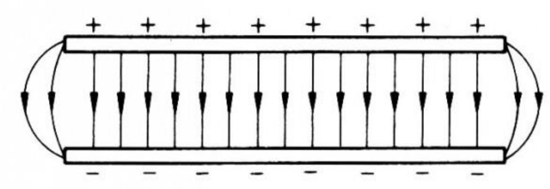
Fixed Capacitor Polarized Capacitor Variable Capacitor

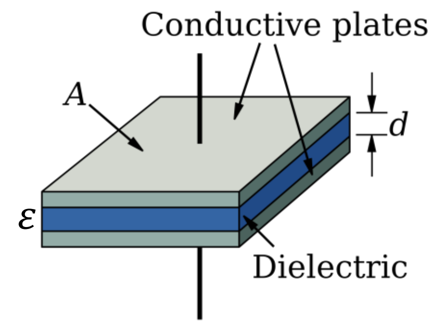
Capacitor

Current does not flow through a capacitor; rather, charges are displaced from one side of the capacitor through the conducting circuit to the other side, establishing the electric field.

$$V(t) = \frac{1}{C}\int_0^t I(\tau)\mathrm{d}\tau = \frac{q(t)}{C}$$

$$I(t) = C\frac{\mathrm{d}V}{\mathrm{d}t}$$





C is the **Capacitance** measured in farads (F=C/V).

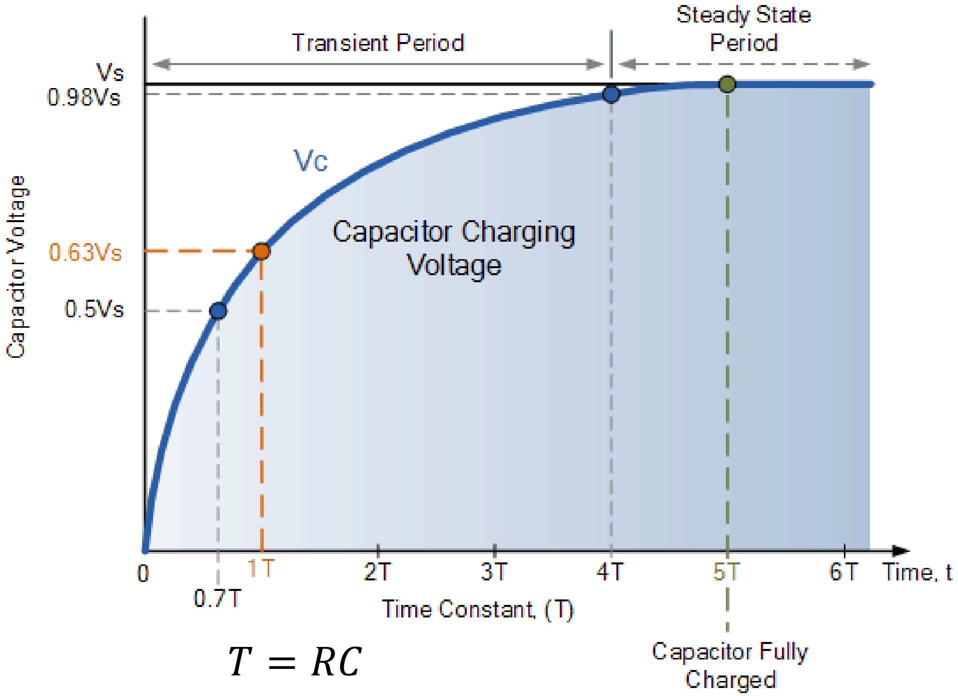
$$C = \frac{\varepsilon A}{d}$$

ε: permittivity

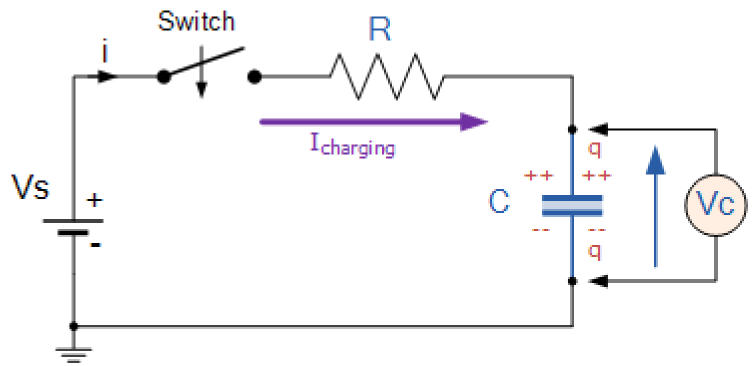
Capacitance is a property of the **dielectric material**, **plate geometry** (A), and **separation** (d). Values for typical capacitors range from 1 pF to 1000 μF.

Capacitor

It can be inferred that the **voltage across a capacitor cannot change instantaneously** because it is the integral of the displacement current. It takes time to increase or decrease the voltage across a capacitor. Thus, **capacitors can be used for timing purposes** in electrical circuits using a simple RC circuit, which is a resistor and capacitor in series.



$$T = RC$$



$$V(t) = \frac{1}{C}\int_0^t I(\tau)\mathrm{d}\tau = \frac{q(t)}{C}$$

$$I(t) = C\frac{\mathrm{d}V}{\mathrm{d}t}$$

Common Types of Capacitors

Common types of capacitors are (1) **aluminum electrolytic capacitors**, (2) **tantalum electrolytic capacitors**, (3) **ceramic disk capacitors**, and (4) **mylar capacitors**.

aluminum electrolytic capacitors

tantalum electrolytic capacitors

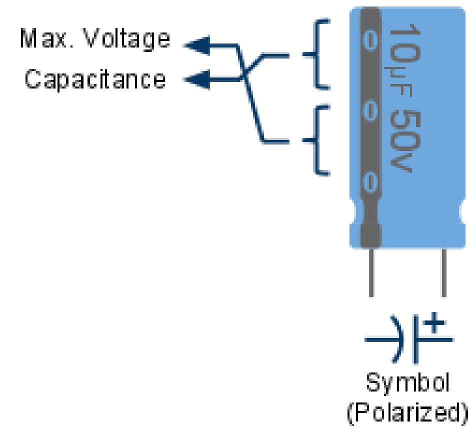
ceramic disk capacitors

mylar capacitors

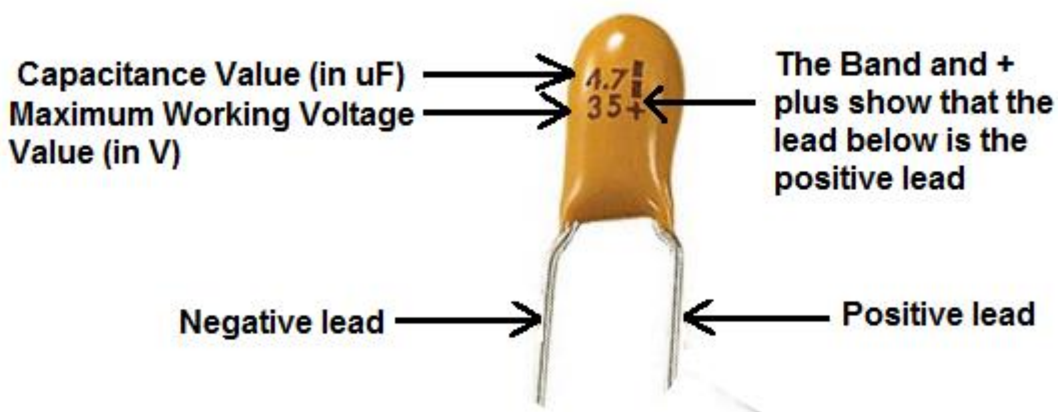
Electrolytic capacitors are polarized, meaning they have a **positive** end and a **negative** end. The positive lead of a polarized capacitor must be held at a higher voltage than the negative side; otherwise, the device will usually be damaged. Improper polarity can cause the cap to become shorted or it can also result in gas formation internally that can cause the cap to explode.

Aluminum & Tantalum Electrolytic Capacitors

Since **aluminum electrolytic capacitors** are usually larger, the capacitance is printed directly on the component, including the unit prefix (typically in μF or pF).

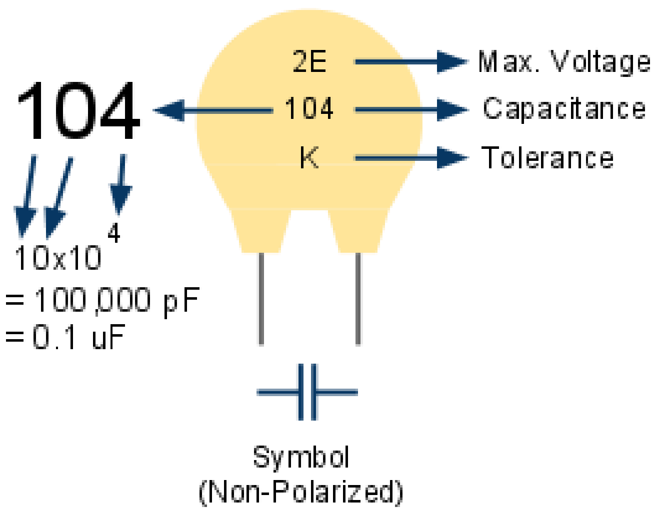


Tantalum electrolytic capacitors:



Ceramic & Mylar Capacitors

Since **ceramic and mylar capacitors** are usually smaller, the capacitance is printed in a three-digit code. The first two digits are the value and the third is the power of 10 multiplied times picofarads (e.g., 102 implies 10×10^2 pF = 1 nF). If there are only two digits, the value reported is in picofarads (e.g., 22 implies 22 pF).



Tolerance

Code	Percentage
B	± 0.1 pF
C	±0.25 pF
D	±0.5 pF
F	±1%
G	±2%
H	±3%
J	±5%
K	±10%
M	±20%
Z	+80%, -20%

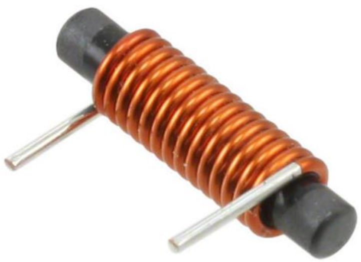
Max. Operating Voltage

Code	Max. Voltage
1H	50V
2A	100V
2T	150V
2D	200V
2E	250V
2G	400V
2J	630V

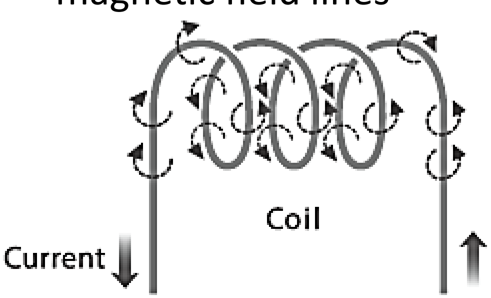
Inductor

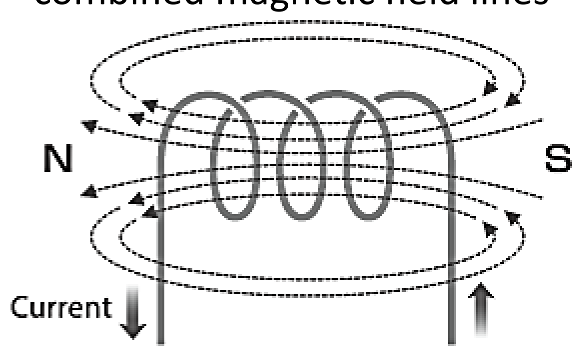
Inductor store energy in the form of magnetic field. The simplest form of an inductor is a **wire coil**, which has a tendency to maintain a magnetic field once established. The inductor's characteristics are a direct result of **Faraday's Law of Induction**:

$$V(t) = \frac{\mathrm{d}\Phi}{\mathrm{d}t}$$

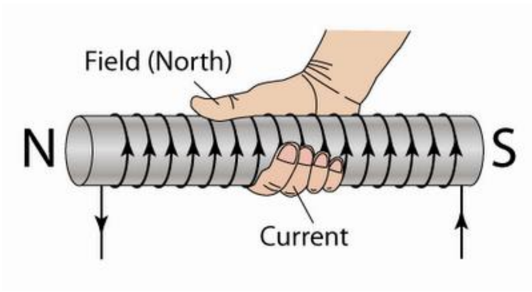


Φ: total **magnetic flux** through the coil windings due to the current (**unit**: weber (Wb)).





right-hand rule for a coil:

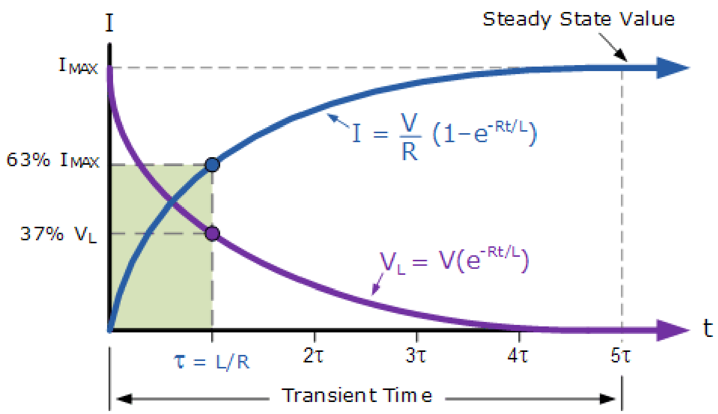


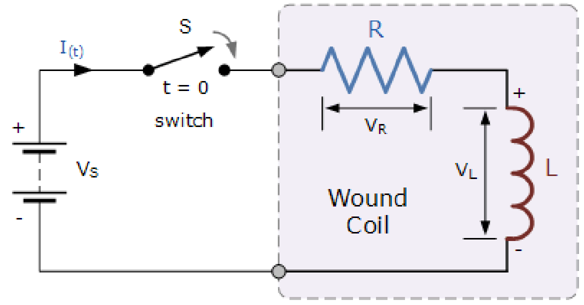
Inductance

$$V(t) = \frac{d\Phi}{dt} \xrightarrow{\text{for an ideal coil}} \Phi = LI \longrightarrow V(t) = L\frac{dI}{dt} \quad \text{or} \quad I(t) = \frac{1}{L}\int_0^t V(\tau)d\tau$$

L: **inductance** of the coil, which is assumed to be constant (**unit**: henry (H=Wb/A)).

It can be inferred that the **current through an inductor cannot change instantaneously** because it is the integral of the voltage. It takes time to increase or decrease the current flowing through an inductor. **Thus**, it is difficult to start or stop motors, relays, and solenoids very quickly.





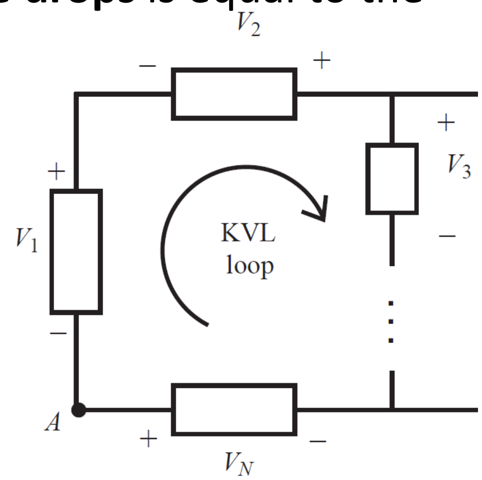
Kirchhoff's Laws

Kirchhoff's Voltage Law (KVL)

Basic laws governing electrical circuits are **Kirchhoff's Current and Voltage Laws**.

Kirchhoff's Voltage Law (KVL) or **Loop Law**: The algebraic sum of the voltages around any closed loop in an electrical circuit is zero (or the sum of the voltage **drops** is equal to the sum of the voltage **rises** around a loop).

$$\sum_{i=1}^{N} V_i = 0$$



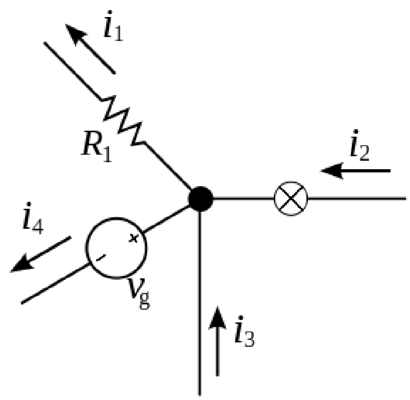
- Assume a current direction on each loop of the circuit.
- If polarities are not given, assume that the voltage drops across each passive element in the direction of the loop current.
- The polarity of voltage across a voltage source and the direction of current through a current source must always be maintained as given. The voltage rises (from - to +) or drops (from + to -) across an element (like voltage source).

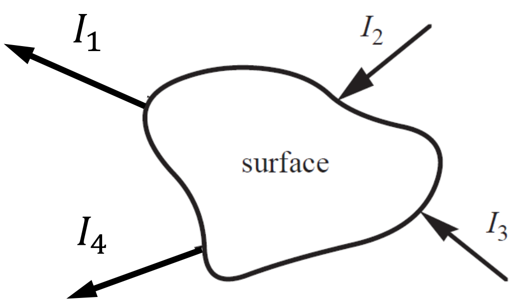
$$\Rightarrow \quad V_1 + V_2 - V_3 + \cdots + V_N = 0$$

Kirchhoff's Current Law (KCL)

Kirchhoff's Current Law (KCL) or **Node Law**: The algebraic sum of all currents entering and leaving a node (or a closed surface) is zero (or the sum of currents entering a node is equal to the sum of currents leaving the same node).

$$\sum_{i=1}^{N} I_i = 0$$





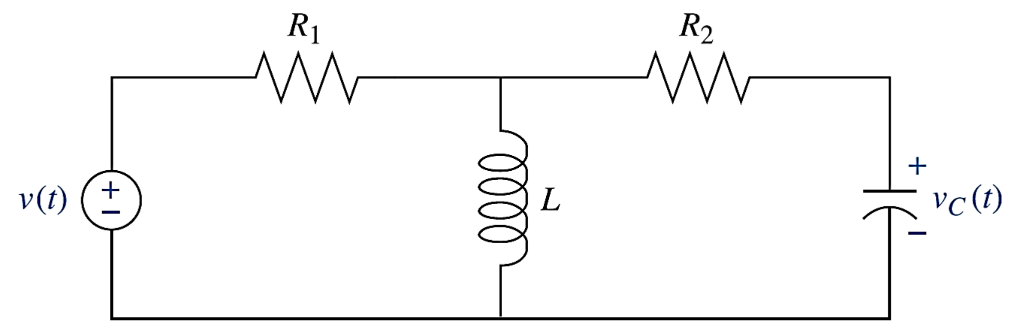
- The **currents entering** a node or surface are assigned a **positive** value, and **currents leaving** are assigned a **negative** value.

$$\Rightarrow \quad i_2 + i_3 - i_1 - i_4 = 0$$

Note: Since the current directions are assumed arbitrarily, if the calculated result for a current is negative, the current actually flows in the opposite direction.

Example

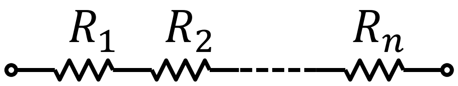
Find the circuit equations.



Passive Elements in Series

The total resistance of resistors connected in **series** is the sum of their individual resistance values.

$$R_{\text{eq}} = R_1 + R_2 + \cdots + R_n = \sum_{i=1}^{n} R_i$$



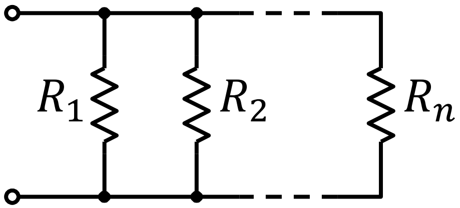
- Same **current** flows through all resistors.

❖ How about **capacitors** and **inductors** in **series**?

Passive Elements in Parallel

The total resistance of resistors connected in **parallel** is the reciprocal of the sum of the reciprocals of the individual resistors.

$$\frac{1}{R_{\mathrm{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n} = \sum_{i=1}^{n} \frac{1}{R_i}$$

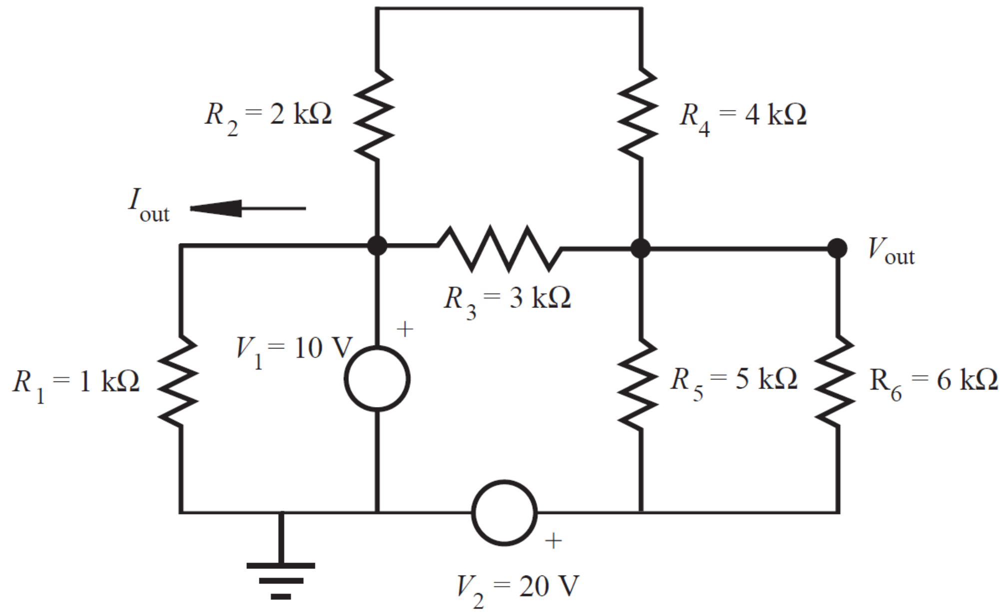


- Same **voltage** appears across all resistors.

❖ How about **capacitors** and **inductors** in **parallel**?

Example

Find I_{out} and V_{out}.



Power

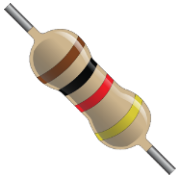
The power **consumed** or **generated** by an element is simply the product of the voltage across and the current through the element.

$$P = VI$$

Unit: watt (W = J/s)

The **instantaneous** power dissipated by **resistive components** in the form of heat can be expressed as

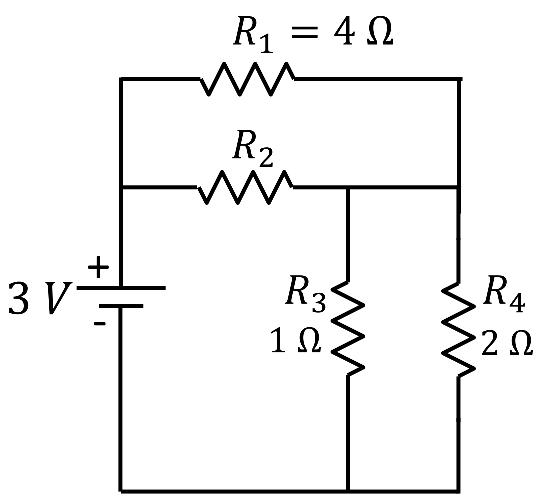
$$P = VI = RI^2 = \frac{V^2}{R}$$



Because increased power is associated with increased heat dissipation, components generally have a **maximum power rating** to avoid **overheating**.

Example

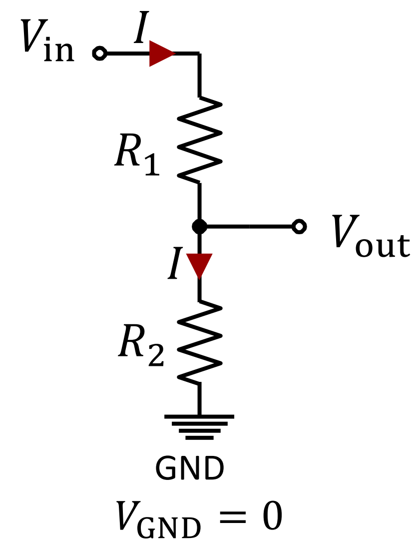
Resistor R_2 is rated for 1/2 W and has resistance of 2 Ω. What can you say about this circuit when it is turned on?



Resistive Voltage Divider

A **Resistive Voltage Divider** is a simple circuit which turns a large input voltage (V_{in}) into a smaller one (V_{out}), which is a fraction of V_{in}.

$$V_{\text{out}} = \frac{R_2}{R_1 + R_2} V_{\text{in}}$$

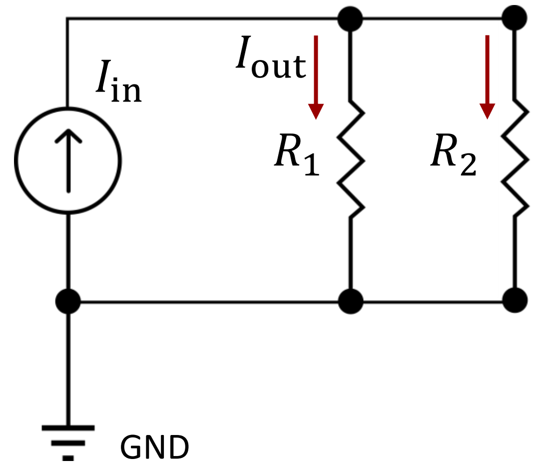


- **Note**: Loads attached to V_{out} affect the voltage references produced with the dividers.

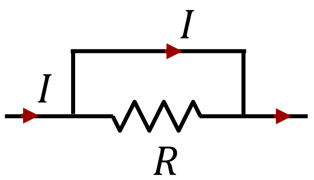
Resistive Current Divider

A **Resistive Current Divider** is a simple circuit which turns a large input current (I_{in}) into a smaller one (I_{out}), which is a fraction of I_{in}.

$$I_{\text{out}} = \frac{R_2}{R_1 + R_2} I_{\text{in}}$$



Note: Current will always follow the path of least resistance in a circuit.



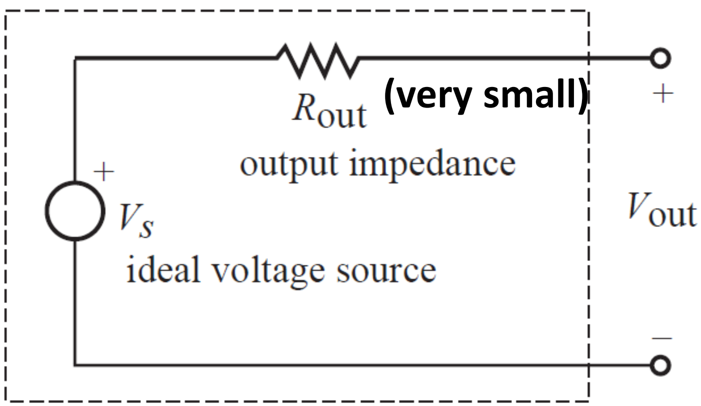
Short Circuit!

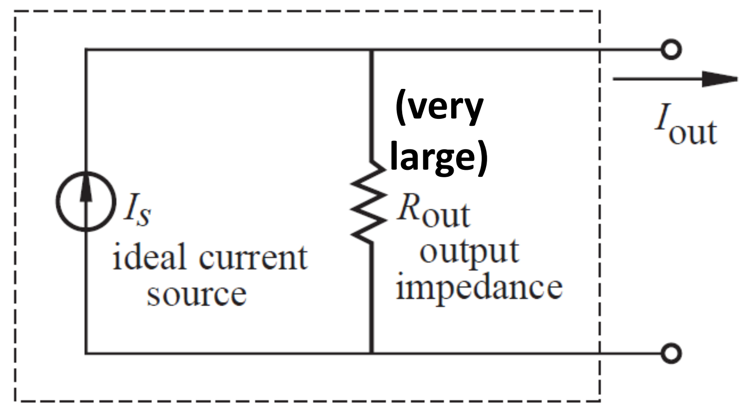
Voltage and Current Sources and Meters

Voltage & Current Sources

- An **Ideal Voltage Source** has **zero** output resistance and can supply **infinite current**.
- An **Ideal Current Source** has **infinite** output resistance and can supply **infinite voltage**.

A **Real Voltage [Current] Source** can be modeled as an ideal voltage [current] source in series [parallel] with a vey small [large] resistance called the **Output Impedance** of the device.



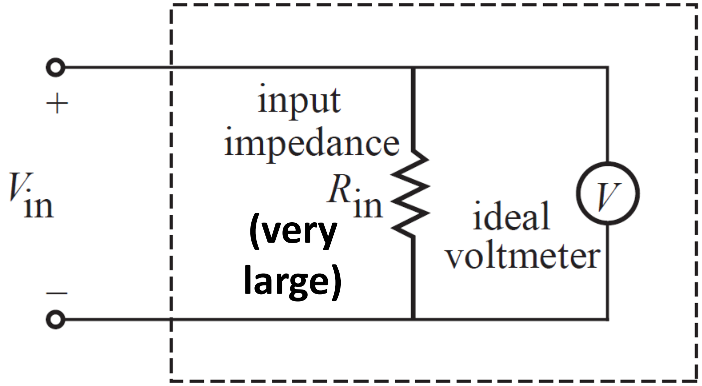


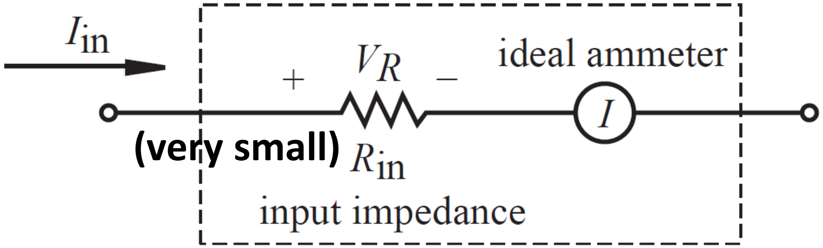
❖ The **output impedance can be important** when driving a circuit with a small [large] resistance because this impedance affect the resistance of the circuit.

Voltage & Current Meters

- An **Ideal Voltmeter** has **infinite** input resistance and draws no current.
- An **Ideal Ammeter** has **zero** input resistance and no voltage drop across it.

A **Real Voltmeter [Ammeter]** can be modeled as an ideal voltmeter [ammeter] in parallel [series] with a very large [small] resistance called the **Input Impedance**.





❖ The **input impedance can be important** when making a voltage [current] measurement across [through] a circuit branch with large [small] resistance because this impedance would result in significant error in the measured value.

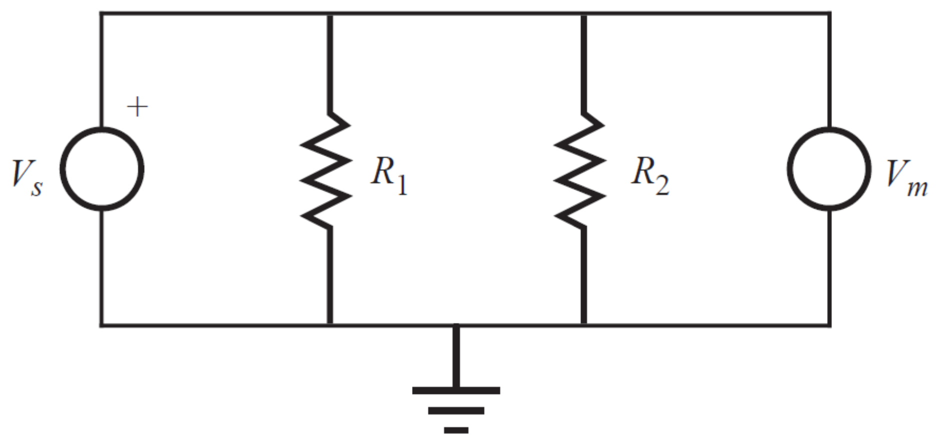
Example

Consider the effects of source and meter output and input impedance on making measurements in a circuit. V_s is a voltage source and V_m is a voltmeter.

$$R_1 = R_2 = 1\ \text{k}\Omega,$$

$$V_s = 10\ \text{V}$$

$$R_{V_m} = 1\ \text{M}\Omega, \qquad R_{V_s} = 50\ \Omega,$$



Sources and Meters

Sources:
Power Supplies and Function Generators
Impedance: about 50Ω

Function Generator

For generation of different types of electrical waveforms, e.g., sine, square, triangular, and sawtooth shapes

Meters:
Digital Multimeters (DMMs) and Oscilloscopes
Impedance: 1 to 10 MΩ

Oscilloscope

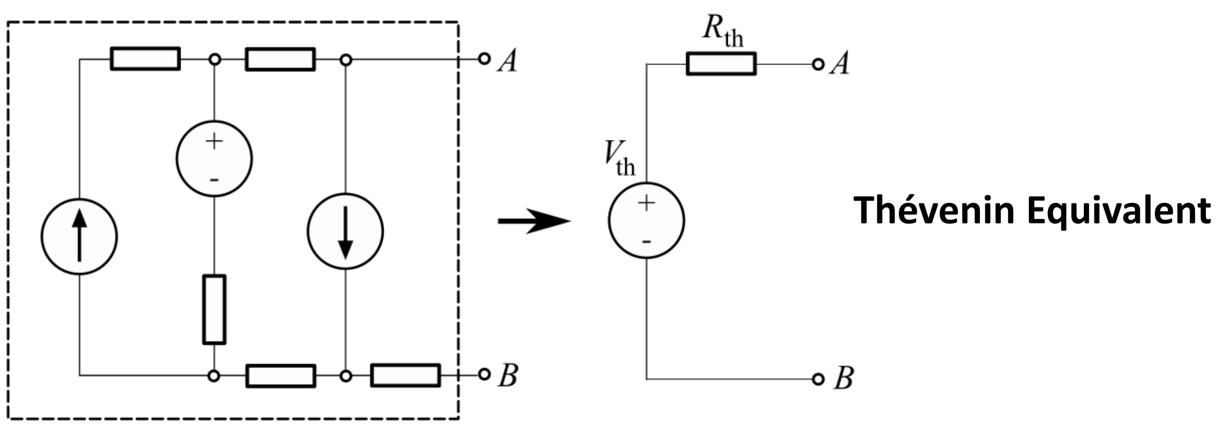
For observation of constantly varying signal voltages

Thevenin and Norton Equivalent Circuits

Thévenin's Theorem

Any linear electrical network with voltage and current sources and resistances only can be replaced at terminals A-B by an **equivalent** ideal voltage source V_{th} in series connection with an equivalent resistance R_{th}.

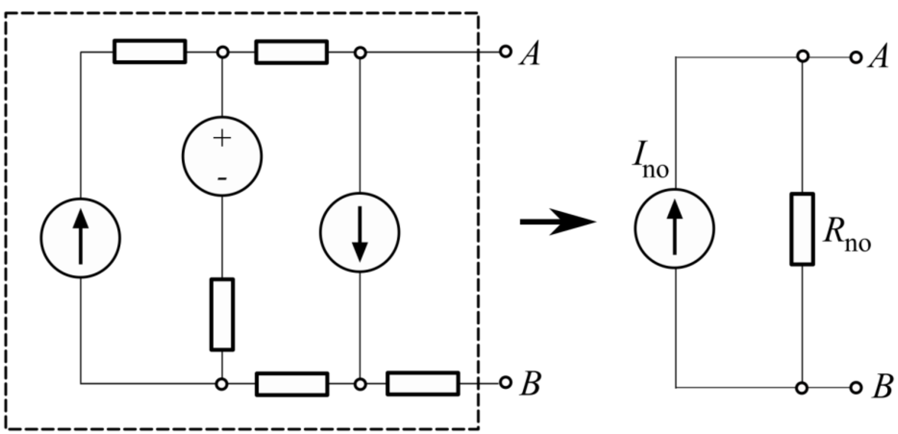
- V_{th} is the voltage obtained at terminals A-B of the network with terminals A-B open circuited.
- R_{th} is the resistance that the circuit between terminals A and B would have if all ideal voltage sources in the circuit were replaced by a short circuit and all ideal current sources were replaced by an open circuit.



Norton's Theorem

Any linear electrical network with voltage and current sources and resistances only can be replaced at terminals A-B by an **equivalent** ideal current source I_{no} in parallel connection with an equivalent resistance R_{no}.

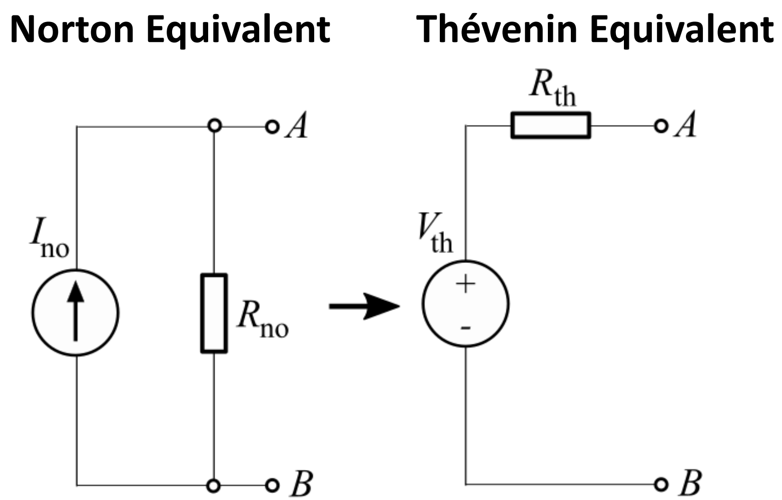
- I_{no} is the current flowing from A to B, if terminals A and B are connected to one another.
- R_{no} is the resistance that the circuit between terminals A and B would have if all ideal voltage sources in the circuit were replaced by a short circuit and all ideal current sources were replaced by an open circuit.



Norton Equivalent

Thévenin & Norton Equivalents

A Norton equivalent circuit is related to the Thévenin equivalent by



$$R_{th} = R_{no}$$
$$V_{th} = I_{no} R_{no}$$
$$I_{no} = V_{th}/R_{th}$$

- The Thevenin and Norton equivalents are widely used **to make circuit analysis simpler**.
- They are **independent of the remaining circuit network representing a load**. Therefore, it is possible to **make changes in the load** without reanalyzing the Thevenin or Norton equivalent.

Example

Find the Thévenin and Norton equivalents.