DIRECT CURRENT FUNDAMENTALS

CURRENT AND CHARGE

An electric current consists of electric charges moving in a wire.

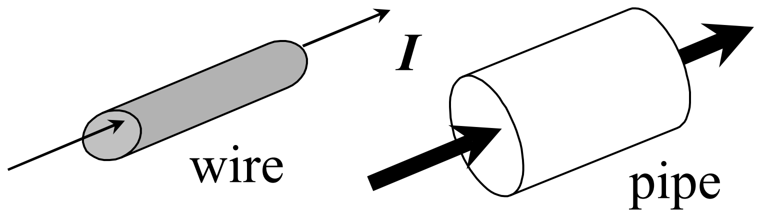


Fig. 1 Wire carrying current *I* (left) and its **water model** (right).

Electric Current => **I**
Electric Charge => **Q**

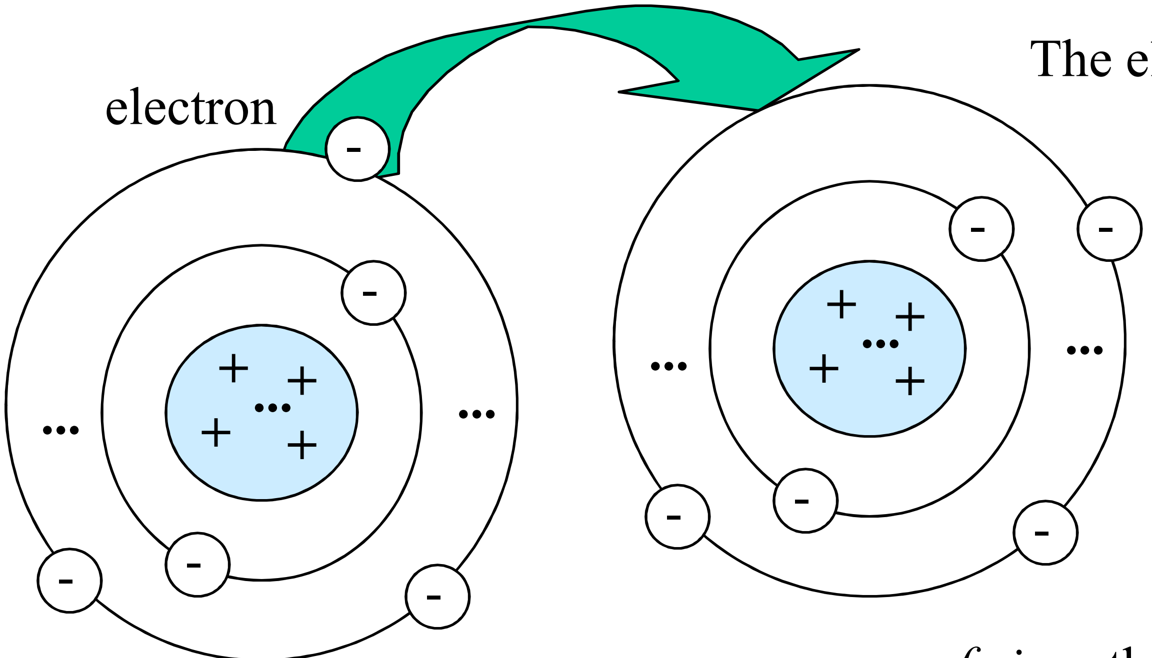
•*Flow of water*: [molecules/s], [l/s]

•*Electric current*: [Ampere]=[**A**]

$$I = \frac{dQ}{dt}$$

1 Ampere = 1Coulomb/s

1 **A** = 1 **C**/**s** = 6.3 x 10^{18} **elementary electric charges**/s



The elementary electric charges that are actually moving are **electrons** which jump between external orbits of **adjacent atoms**.

⇩

From a *physical point of view*, the **electric current** flowing through a wire is like a **river of electrons**.

However as the the electrons are "negative electric charges" (due to some odd historical reasons!), from a *technical point of view*, these **flow of electrons is considered a negative current**!!

Small … and big currents

Engineering Unit Prefixes

Prefix	Abbr.	Value
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
milli	m	10^{-3}
micro	❍	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}

0.067 A = 67 mA

73,500 A = 73.5 kA

$$I = \frac{dQ}{dt}$$

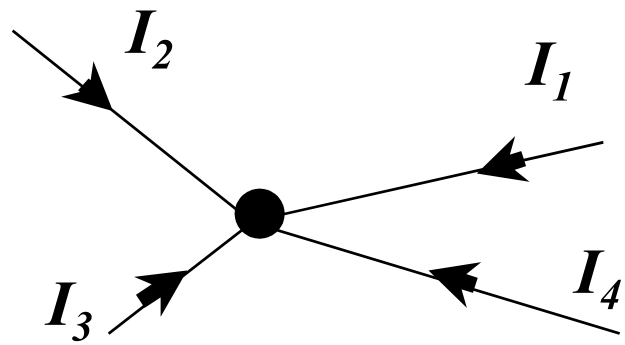
Electrical charge Q_1 that flows over the time t_1 is the integral of the current from the time zero to time t_1.

$$Q_1 = \int_0^{t_1} i(t) \bullet dt$$

Kirchhoff's Current Law

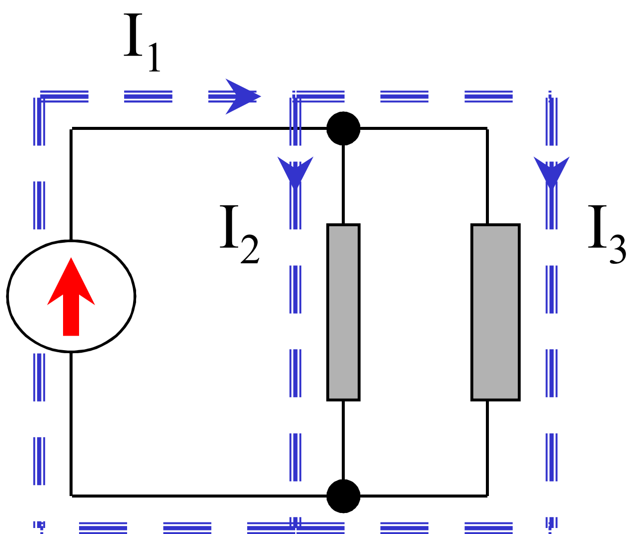
- The **indestructibility of electrical currents** is expressed by Kirchhoff's Current Law (KCL), which states that **the sum of all the currents into a node is zero**.

$$\sum_{n=1}^{N} I_n = 0$$

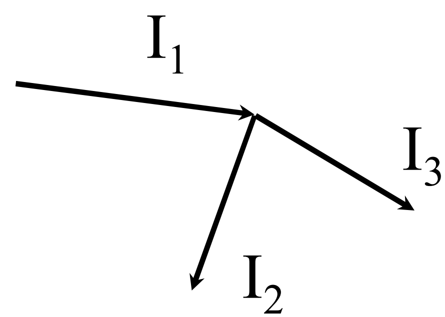


=> *Some currents should be flowing into the node while other currents should come out of the node*

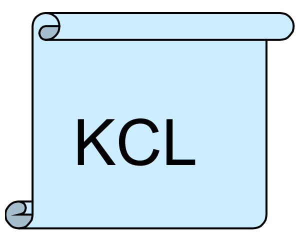
•Currents flowing into the node are considered "**positive.**"
•Currents coming out are considered "**negative**."



A current splits to enter two parallel circuit elements



- Currents flowing into the node are considered "**positive**" : I_1
- Currents coming out are considered "**negative**": I_2 and I_3.



$$I_1 - I_2 - I_3 = 0 \quad \Rightarrow \quad I_1 = I_2 + I_3$$

CONDUCTORS, INSULATORS, SEMICONDUCATORS, AND SUPERCONDUCTORS

CONDUCTORS ….. materials through which electric currents flow relatively easily.

Metals are good conductors

- *silver* (tarnishes ! =>limited practical use);
- *gold* (expensive! => used as a coating to protect other metals in connectors);
- *copper* and *aluminum* (mostly used for wiring; aluminum surface oxidizes rapidly but it is considerably less expensive and lighter than copper);

Solder ⇨ an amalgam of **tin** & **lead**, having a relatively low melting temperature, used to connect electrical components

INSULATORS …. materials that do not conduct electricity:

* **vacuum** * dry air* ceramics * glass * plastic *rubber*dry paper*

→ *Most wires are coated with a layer of insulation to prevent current from finding unintended paths*

SUPERCONDUCTORS … very special materials which, when cooled below their critical temperature (from a few deg. K up to more than 100^0 Kfor the "high-temperature superconductors")

→ *…are used to generate the very strong magnetic fields required for nuclear magnetic resonance imaging, and may even be used in electric motors and for levitating trains.*

SEMICONDUCTORS

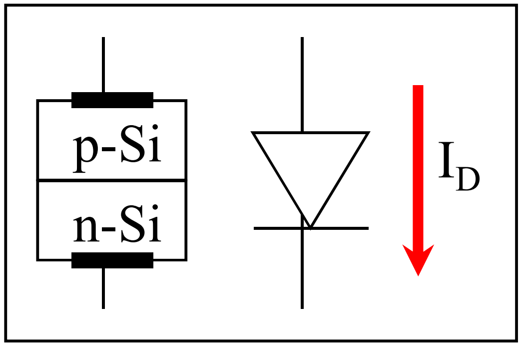
… materials such as *silicon* (**Si**) and *germanium* (**Ge**) which are relatively poor conductors until they are "doped" with trace quantities of other materials such as *arsenic* (**As**), *phosphorous* (**P**), or *boron* (**B**).

Portion of the periodic table of the elements near the element **Silicon**.

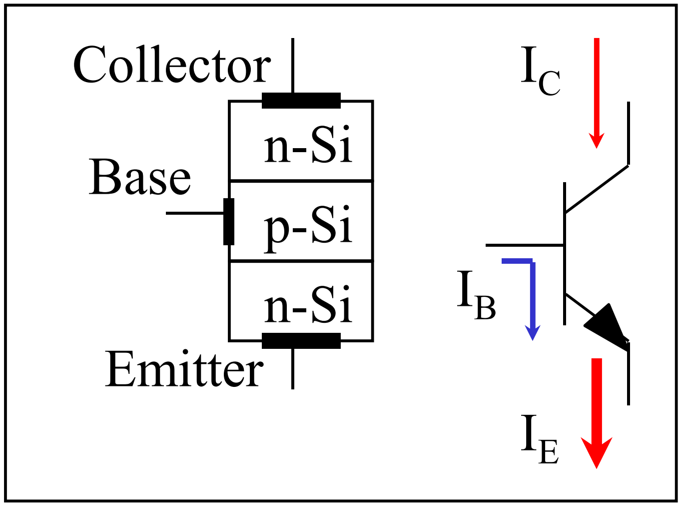
GROUP III	GROUP IV	GROUP V
B *BORON* valence +3 atomic no. 5	**C** *CARBON* 5	**N** *NITROGEN* 7
Al ALUMINIUM 13	**Si** *SILICON* valence +4, -4 atomic no. 14	**P** *PHOSPHORUS* valence +5 atomic no. 15
Ga *GALLIUM* 31	**Ge** *GERMANIUM* 32	**As** *ARSENIC* valence +5 atomic no. 33

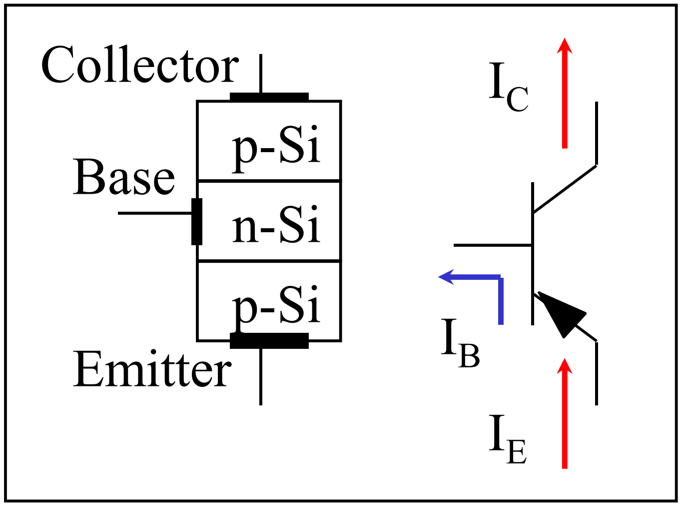
- Impurities from Group V (P, As) are called donors as they contribute more free electrons to the silicon, resulting in an **n-type** silicon (in which the majority current carriers are electrons).

- Impurities from Group III (B) are called acceptors as they contribute more positively charged holes to the silicon, resulting in a **p-type** material (in which the majority current carriers are holes).

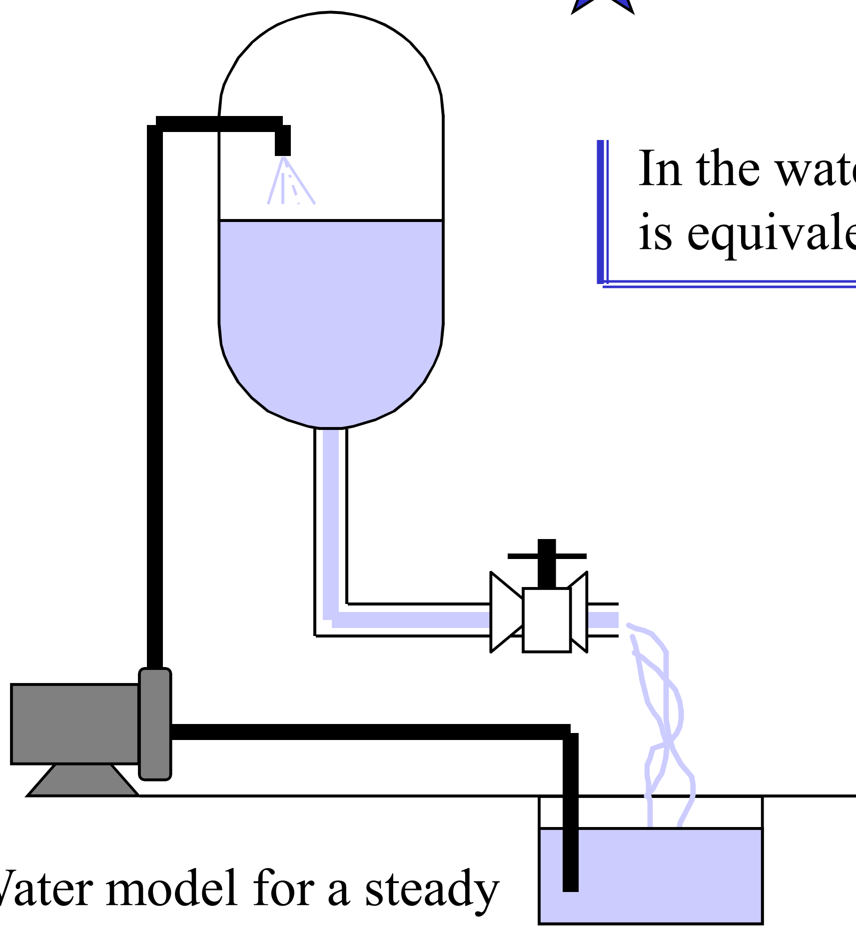


→ *Semiconductors are used to form electronic devices such as **diodes** and **transistors*** (BJT = Bipolar Junction Transistor).





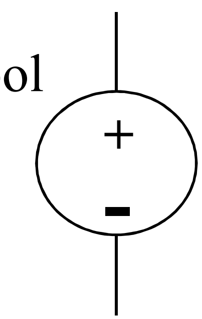
★ VOLTAGE



Water model for a steady voltage source

In the water model, the **electric voltage** is equivalent to the **water pressure**.

Schematic symbol for the steady voltage source



The measurement unit for voltage is the *Volt* [**V**].

RESISTANCE

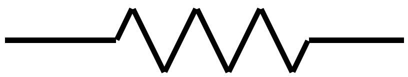
WATER MODEL ==> Any pipe hooked up to a source of water offers some resistance to the flow which goes through it. Different pipe construction parameters will affect the degree of resistance. A small-diameter pipe will offer a bigger resistance than a large-diameter one.

Similarly, the wires and other circuit components offer some *resistance to the passage of electric current* through them.

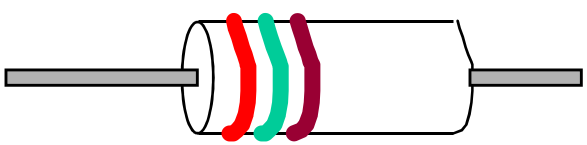
The magnitude of this **resistance** depends on the different construction parameters of these wires and other electric circuit components:

- a small-*diameter* wire will offer a bigger resistance than a large-diameter one;
- a *long* wire will offer a bigger resistance than a short wire;
- the nature of the *material* also affects the amount of this resistance.

The measurement unit for resistance is the *Ohm* [Ω].



Schematic symbol



Resistor's value marked with colored bands.

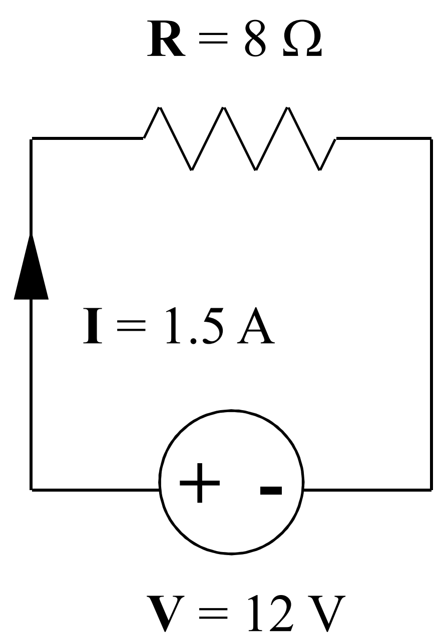
Band color	*Significant digit*	*Multiplier*	*Tolerance*
Black	0	1	-
Brown	1	10	1%
Red	2	100	2%
Orange	3	1,000	3%
Yellow	4	10,000	4%
Green	5	100,000	-
Blue	6	1,000,000	flame proof
Violet	7	10,000,000	-
Gray	8	-	-
White	9	-	-
Gold	-	0.1	5%
Silver	-	0.01	10%
No band	-	-	20%

Ohm's Law

- Ohm's Law states that **the voltage V drop over a resistance is equal to the value of that resistance R multiplied by the current I which goes through it**.

$$V = I \bullet R$$

$\mathbf{I} = \mathbf{V} / \mathbf{R} = 12\ \text{V} / 8\ \Omega = 1.5\ \text{A}$

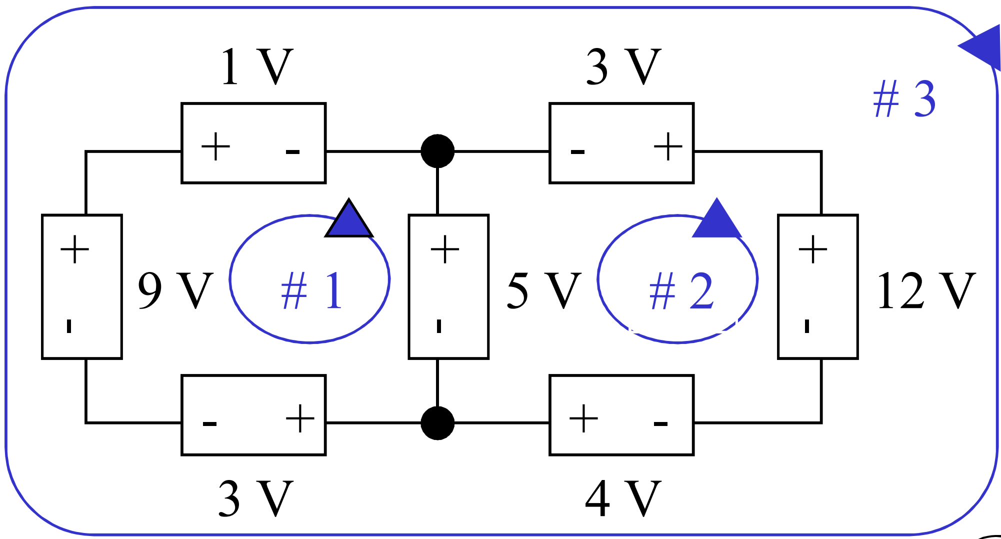


Kirchhoff's Voltage Law

- Kirchhoff's Voltage Law (KVL) states that **the sum of all the voltages around any closed circuit is zero**.

$$\sum_{n=1}^{N} V_n = 0$$

This means that as follow around any loop in a specific direction, some of the voltages across components will be negative and some will be positive, but when we have closed the loop the sum of all voltages will be zero.



Move around the loop summing the voltage drops. The sign which is encountered first when reaching a component tells what to do (+ or -) with the voltage drop over that component.

Loop #1:
$1V + 5V + 3V - 9V = 0$

Loop #2:
$-3V + 12V - 4V - 5V = 0$

Loop #3:
$1V - 3V + 12\ V - 4V + 3V - 9V = 0$

Power

WATER MODEL ==> When water flows over a water wheel to power a mill, both the amount of water flowing (the equivalent of the electric current) and the height of the fall (the equivalent of the voltage) determine the power that is delivered. The product of these two parameters gives the amount of power.

- Similarly, the electric power **P** delivered by a steady voltage **V** source providing a current **I** is expressed by the formula:

$$P = I \bullet V$$

The measurement unit for power is the *Watt* [**W**].
1 **W** = 1 **A** · 1 **V**

★ Energy

A charge moving through an electric field in a vacuum converts the potential energy to kinetic energy in its motion. The quantity of energy can be expressed by the formula:

$$U = Q \bullet V$$

The measurement unit for energy is the Joule [**J**].
1 **J** = 1 **C** · 1 **V**

Energy **U** can also be expressed as an integral of the power **P** over an interval of time **T**:

$$U = \int_0^T I(t) \bullet V(t) \bullet dt$$

If the voltage **V** and current **I** are constant in time the energy produced over the interval of time **T** is :

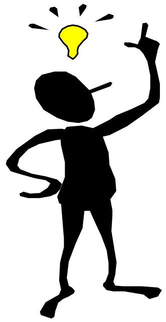
$$U = I \bullet V \bullet T$$

1 **J** = 1 **C** · 1 **V =**

1**A** · 1 **s** · 1 **V =** 1 **W** · 1 **s**

Energy delivered by the Hydro electric utility is measured in **kilowatt-hours**:

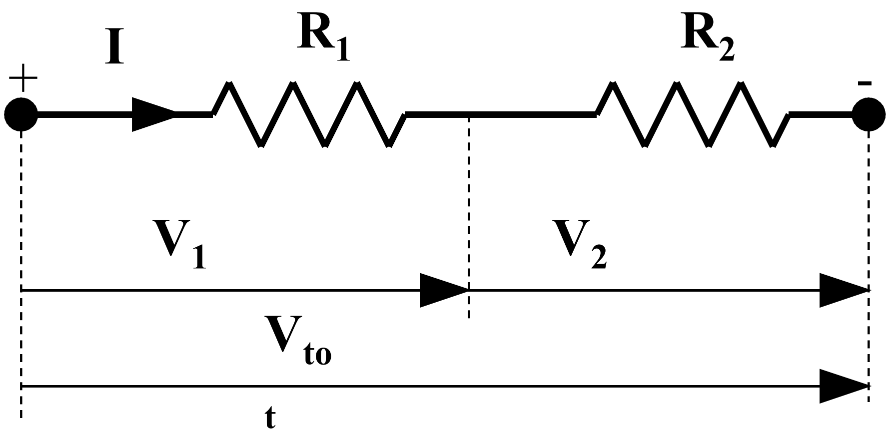
1 **kWh** = 1,000 **W** · 3,600 **s** = 3,600,000 **J**



Resistors Connected in Series

Connected “in series” means that the same current flows through all these resistors …no leaks happens.

Ohm’s law



$$V_1 = I \cdot R_1 \qquad V_2 = I \cdot R_2$$

$$V_{tot} = V_1 + V_2 = I \cdot R_1 + I \cdot R_2$$

$$V_{tot} = I \cdot (R_1 + R_2)$$

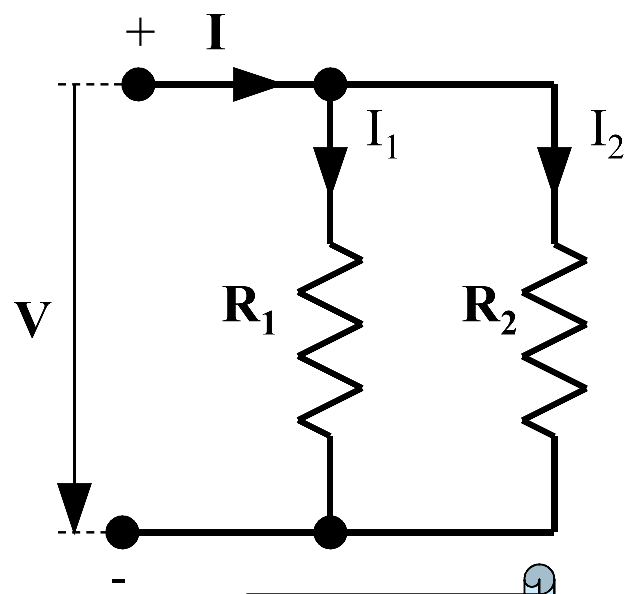
$$R_{tot} = V_{tot} / I = R_1 + R_2$$

The **effective resistance** of the two resistors connected in series:

$$\mathbf{R_{tot} = R_1 + R_2}$$

Resistors Connected in Parallel

Connected "in parallel" means that the current entering the node splits as a river that branches in more channels.



$I = I_1 + I_2$ ⇐ KCL

$\begin{cases} I_1 = V / R_1 \\ I_2 = V / R_2 \end{cases}$ ⇐ $\begin{cases} V = I_1 \cdot R_1 \\ V = I_2 \cdot R_2 \end{cases}$ ⇐ Ohm's law

$I = V / R_1 + V / R_2 = V \cdot (1 / R_1 + 1 / R_2)$

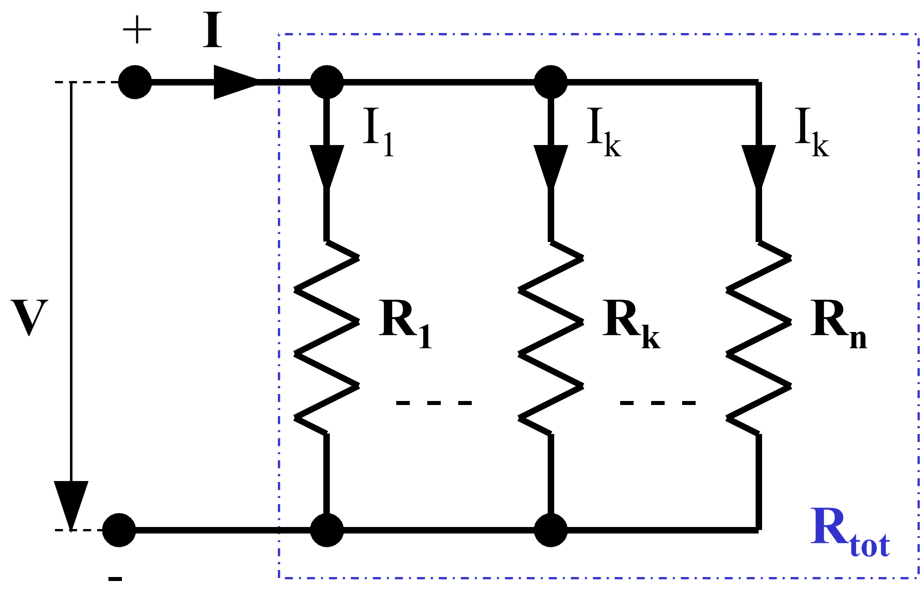
$I / V = 1 / R_1 + 1 / R_2$

$$\mathbf{1 / R_{tot} = 1 / R_1 + 1 / R_2}$$

The **effective resistance**:

$$R_{tot} = \frac{R_1 \bullet R_2}{R_1 + R_2}$$

Generalization => "*n*" resistors in parallel



$I = I_1 + \ldots + I_k \ldots + I_n$

$I_k = V/_{Rk}$; $k = 1, 2, \ldots, n$

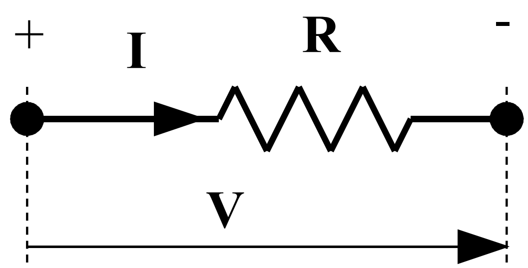
$V = I \cdot R_{tot}$

$V/R_{tot} = V/R_1 + \ldots + V/R_k \ldots + V/R_n$

$1/R_{tot} = 1/R_1 + \ldots + 1/R_k \ldots + 1/R_n$

R_{tot} = the **effective resistance** of the *n* resistors in parallel: $\{R_k ; k = 1, 2, \ldots, n\}$

Power Dissipated in a Resistor

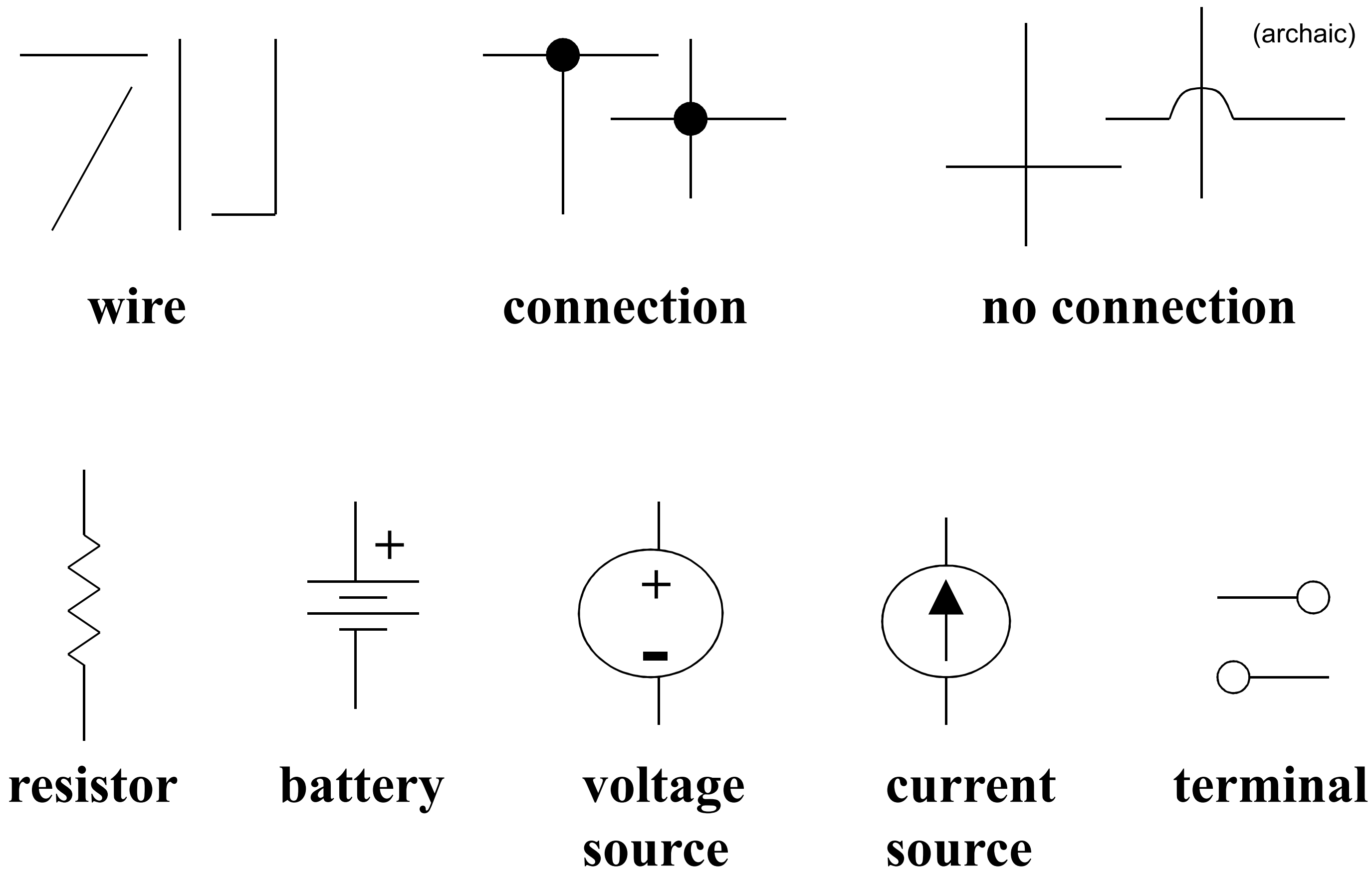


$$P = I \cdot V \quad \text{and} \quad V = I \cdot R \quad \Rightarrow$$

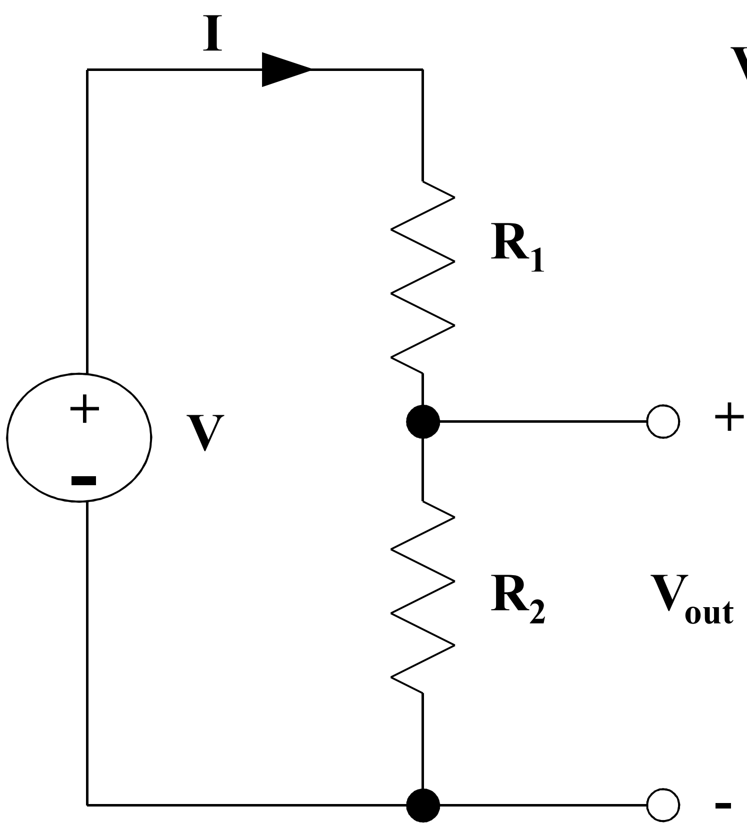
$$\mathbf{P = I^2 \cdot R}$$

$$\mathbf{P = V^2 / R}$$

Schematics


(archaic)
wire
connection
no connection
resistor
battery
voltage source
current source
terminal

Voltage Dividers



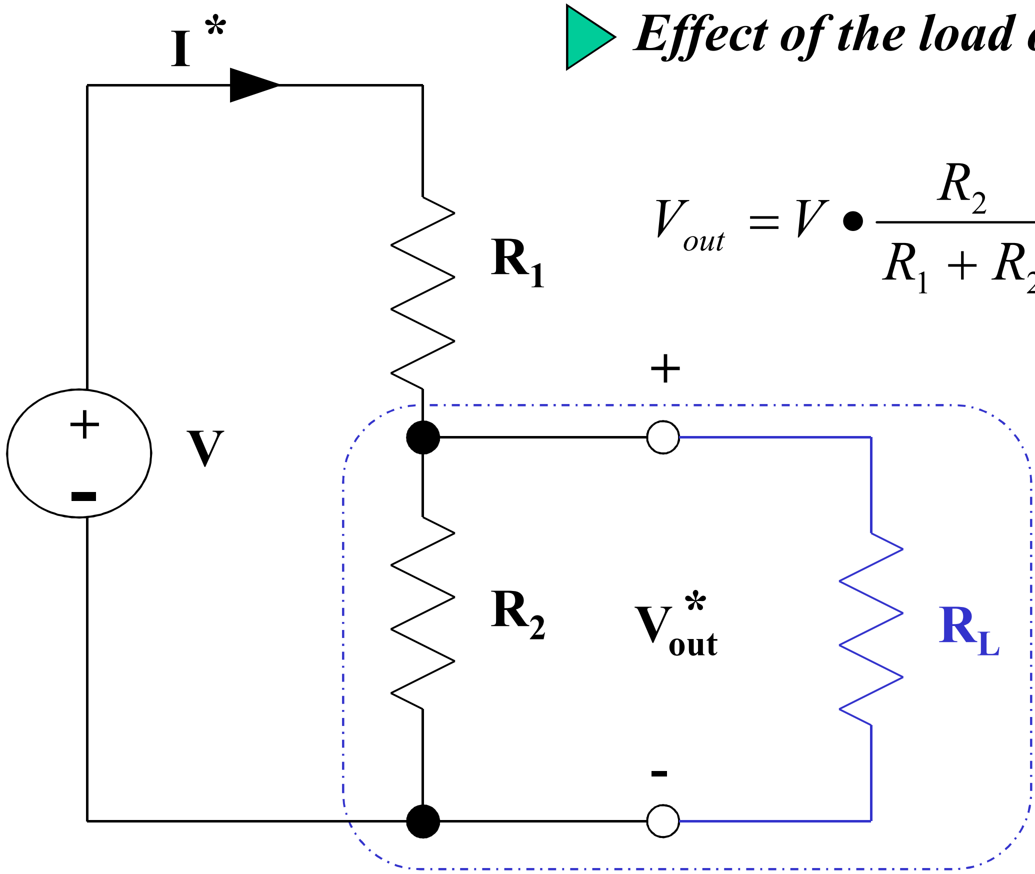
$$V = I \cdot (R_1 + R_2)$$

$$I = V / (R_1 + R_2)$$

$$V_{out} = I \cdot R_2$$

$$V_{out} = V \bullet \frac{R_2}{R_1 + R_2}$$

Effect of the load on the voltage divider's output



$$V_{out} = V \bullet \frac{R_2}{R_1 + R_2}$$

$$I^* = \frac{V}{R_1 + \{R_2 \| R_L\}}$$

$$V_{out}^* = I^* \bullet \{R_2 \| R_L\}$$

$$V_{out}^* = V \bullet \frac{\{R_2 \| R_L\}}{R_1 + \{R_2 \| R_L\}}$$

$$\{R_2 \| R_L\} = \frac{R_2 \bullet R_L}{R_2 + R_L}$$

$$V_{out}^* = V \bullet \frac{R_2 \bullet R_L / (R_2 + R_L)}{R_1 + R_2 \bullet R_L / (R_2 + R_L)} = V \bullet \frac{R_2 \bullet R_L}{R_1 \bullet R_L + R_2 \bullet R_L + R_1 \bullet R_2}$$

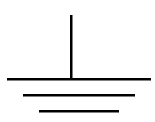
$$V_{out}^* = V \bullet \frac{R_2}{R_1 + R_2 + R_1 \bullet R_2 / R_L} \Rightarrow V_{out}^* \le V_{out}$$

Ground

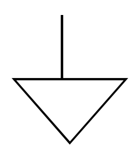
In the early days of the telegraph only a single wire was used to carry the current. The return path was provided by making a connection to the **ground** on both ends: emission and reception. This does make sense because the moisture and the ion content allows the soil to conduct electricity.

The term ***ground*** *has come to mean any common connection point to which other points in an electric circuit are referenced*.

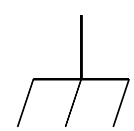
- In a circuit schematic drawing all the nodes that are drawn using the same same type of ground symbol are connected to a common conductor.This saves having to draw all of these wires, which might clutter the schematic.
- Voltages marked on a schematic are usually referred to ground.
- Some electronic devices housed in metal enclosures or chassis make use of what is known as a *chassis ground*.



Digital ground

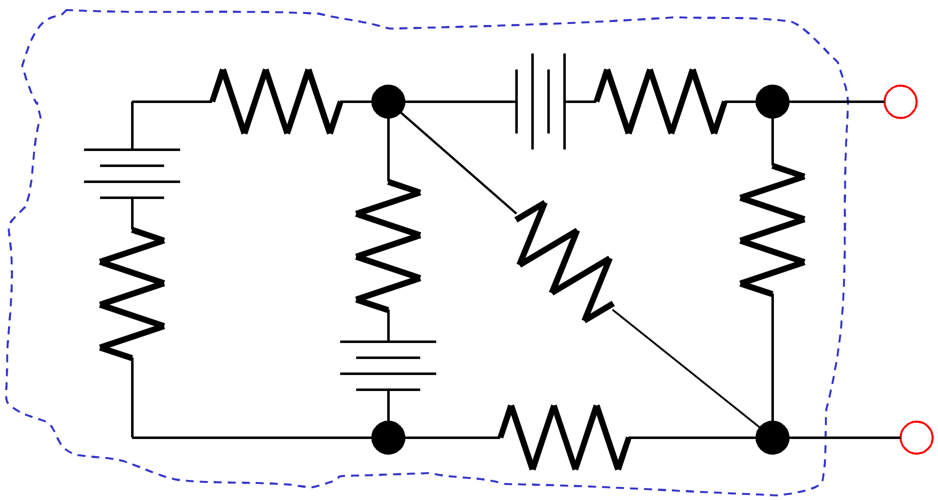


Analog ground



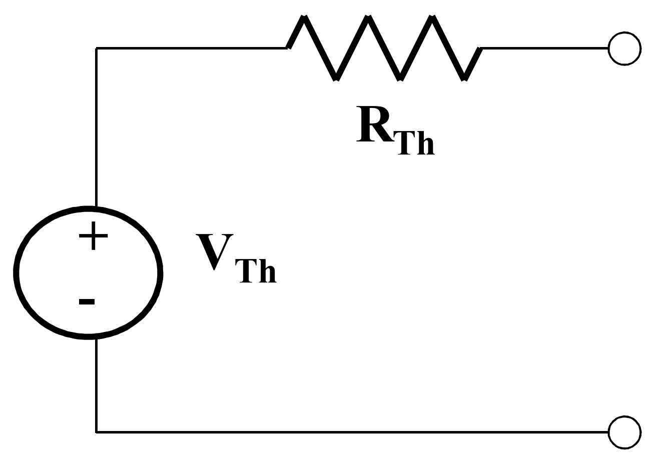
Chassis or earth ground

Thévenin Equivalent Circuits



??? For any given circuit (even a very complex one) what would be the voltage and the resistance which a user can see looking from outside at these two terminals ???

The <u>Thevenin equivalent circuit</u> can represent any collection of DC voltage sources and resistors as an *equivalent circuit* that consists of a single voltage V_{Th} and a single resistor R_{Th}.



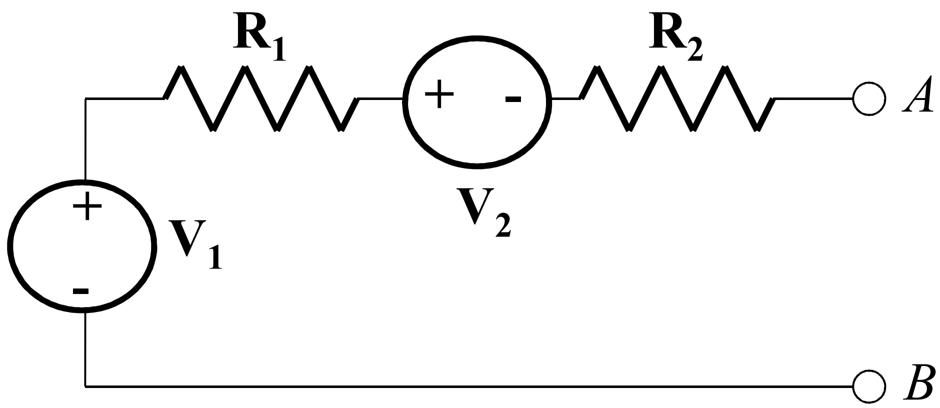
Measurement approach to find the Thevenin equivalent circuit:

- connect a voltmeter (having a very high internal resistance so it consumes a practically negligible current from the tested circuit) across the two output terminals to measure the *open-circuit voltage*, $\mathbf{V_{oc}}$;
- replace the voltmeter with an ammeter (which has a practically negligible internal resistance) to measure the *short-circuit current*, $\mathbf{I_{sc}}$;
- calculate the *Thevenin voltage*, $\mathbf{V_{Th}} = V_{oc}$, and the *Thevenin resistance* $\mathbf{R_{Th}} = V_{Th}/I_{sc} = V_{oc}/I_{sc}$.

N.B. - This method allows to see the effects of a load resistance across two points in a given circuit.

- It is an easy to apply method if you have a physical circuit measure, or if V_{oc} and I_{sc} can be easily calculated from the schematic.

Example

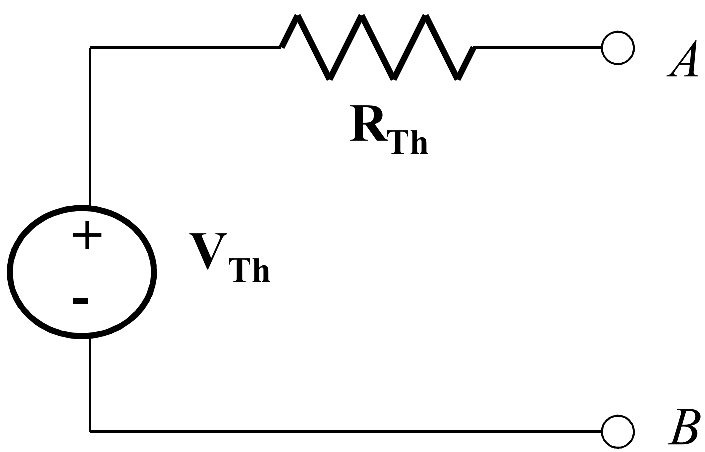


$V_1 = 12\ V$

$V_2 = 8\ V$

$R_1 = 6.8\ \Omega$

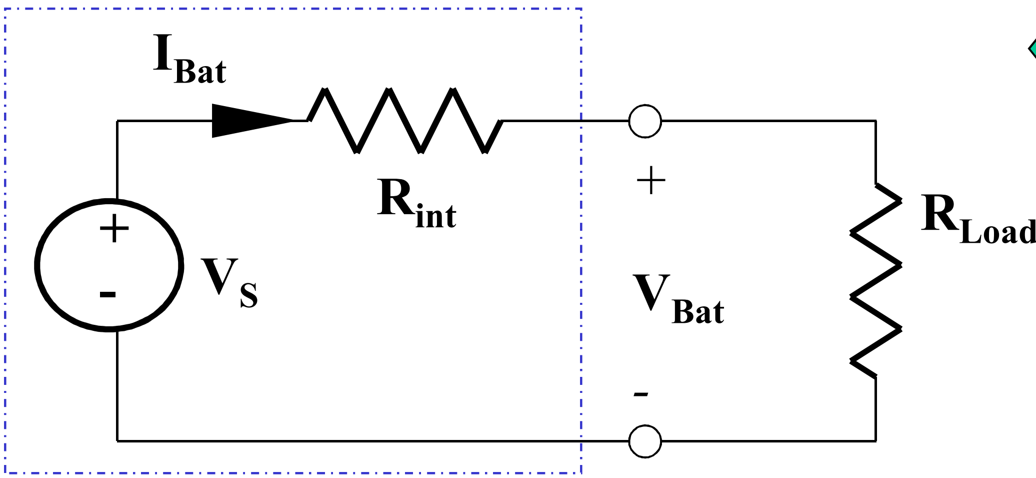
$R_2 = 5.2\ \Omega$



$$V_{Th} = -V_2 + V_1 = -8V + 12V = 4V$$

$$R_{Th} = R_2 + R_1 = 5.2\ \Omega + 6.8\ \Omega$$

The Load Line and Your Car Battery



Thevenin equivalent circuit for a real battery with load.

- If $R_{load} = R_{int}$ then $V_{bat} = V_S /2$.

- What would happen if you connect a light-emitting diode (LED) across the terminals of your car battery?