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Introduction to Bioelectricity Part I

Sabato Santaniello

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What is “bioelectricity”?

- It studies the electric phenomena produced by or occurring within living organisms

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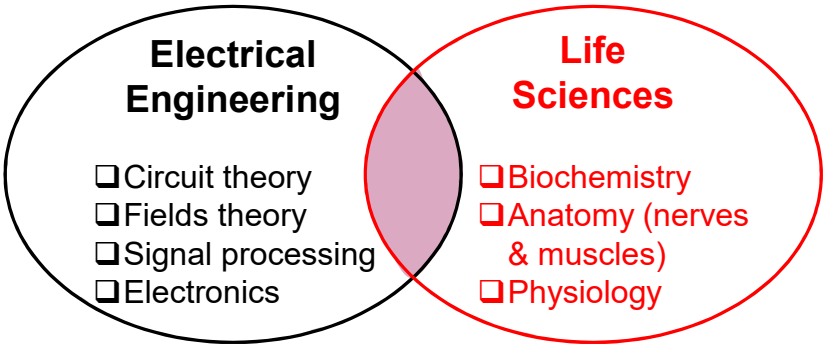
- It studies the electric phenomena produced by or occurring within living organisms
- It combines Engineering and Life Sciences



Bioelectricity: areas of interest

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To measure the electric signals produced by the activity of living tissues

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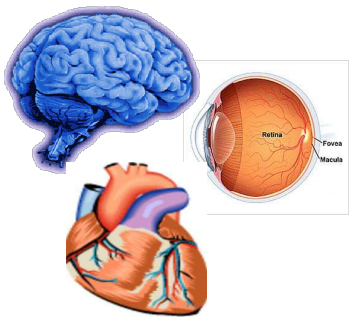
Bioelectricity

To measure the electric signals produced by the activity of living tissues

- ❑ Electroencephalography (EEG)
- ❑ Eectroretinography (ERG)
- ❑ Electrocardiography (ECG)
- ❑ electromyography (EMG)



Bioelectricity: areas of interest

Bioelectricity

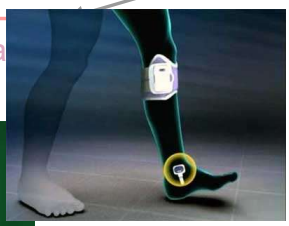
To measure the electric signals produced by the activity of living tissues

To study the effect of electric fields due to an external device on tissue

Bioelectricity: areas of interest

Bioelectricity

To mea
signals



To study the effect of electric fields due to an external device on tissue

- ❑ Deep brain stimulation (DBS)
- ❑ Functional stimulation (FES)
- ❑ Cardiac defibrillation (CDF)

Bioelectricity: key concepts

Electricity

The set of physical phenomena associated with the presence and flow of electric charge

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Electricity

The set of physical phenomena associated with the presence and flow of electric charge

- Charge $\stackrel{\text{def}}{=}$ *A property of subatomic particles determining their electromagnetic interactions*

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Electricity

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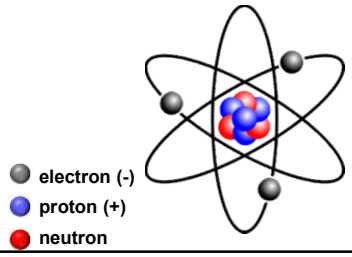
Atoms have particles with positive (**protons**) and negative (**electrons**) charge



Bioelectricity: key concepts

Electricity

The set of physical phenomena associated with the presence and flow of electric charge

- Charge $\stackrel{\text{def}}{=}$ *A property of subatomic particles determining their electromagnetic interactions*
- Electric current $\stackrel{\text{def}}{=}$ *A movement or flow of electrically charged particles through a medium*

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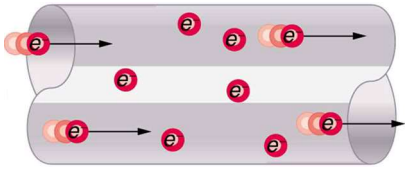

e^- $\stackrel{\text{def}}{=}$ electron

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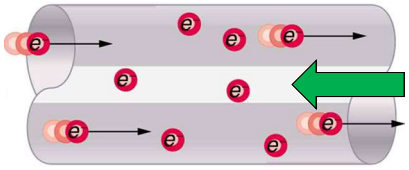

By definition, the direction of the current i_E is given by the direction of positive charges

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Bioelectricity: key concepts

Electricity

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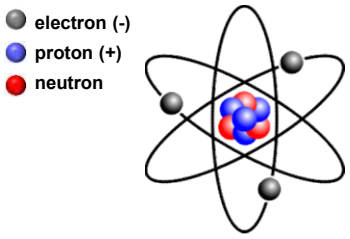
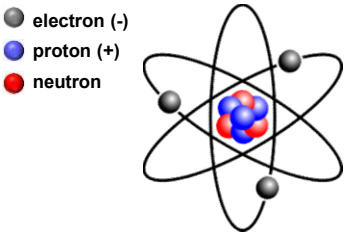
- Charge $\stackrel{\text{def}}{=}$ *A property of subatomic particles determining their electromagnetic interactions*
- Electric current $\stackrel{\text{def}}{=}$ *A movement or flow of electrically charged particles through a medium*
- Voltage $\stackrel{\text{def}}{=}$ *The work required to move a unit charge between two points*

Electric charge



Electric charge

It is **quantized**, i.e., it comes in integer multiples of an individual small unit called "**elementary charge**" ***e***



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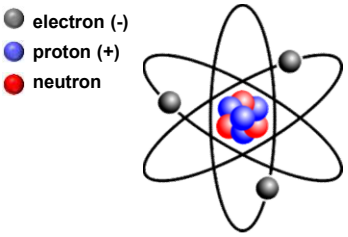
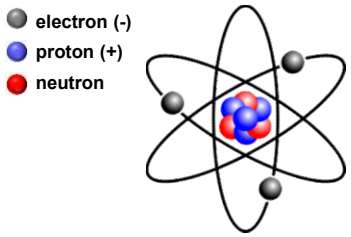


In the SI, it is measured in **Coulomb** (**C**)

Electric charge



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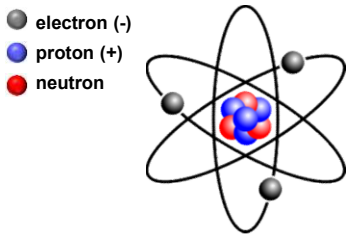
$\boldsymbol{e} \cong 1.602 \times 10^{-19}$ **C**

1 **C**$= \boldsymbol{e}/(1.602 \times 10^{-19}) \cong 6.241 \times 10^{18}\boldsymbol{e}$

Electric charge



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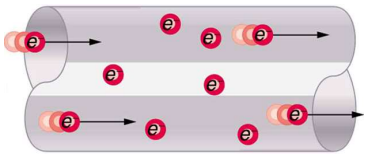
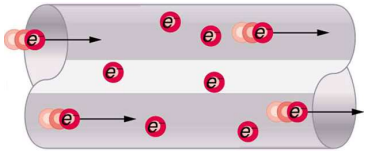
An electron and a proton have both the charge of 1 $\boldsymbol{e}$ but opposite sign ($\boldsymbol{e}^-$ and $\boldsymbol{e}^+$, respectively)

Electric current



Electric current

It is caused by moving electrons (e.g., in a circuit), ions (e.g., in a battery), or both (e.g., in plasma)



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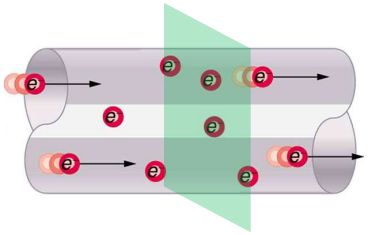

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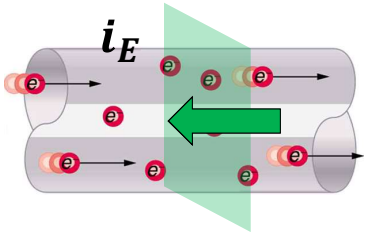

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A convention is that a **positive current** flows in the same direction as **positive charges** and vice versa

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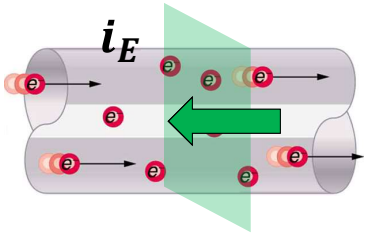

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1 **A**= 1 **C** / 1 **s**

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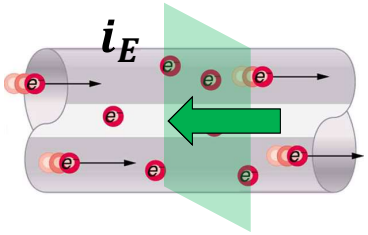

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$$\boldsymbol{i_E}(t) = \lim_{\Delta t \to 0} \frac{\Delta Q(t)}{\Delta t} = \dot{Q}(t)$$

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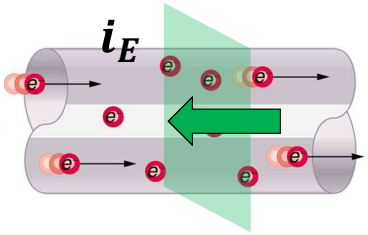

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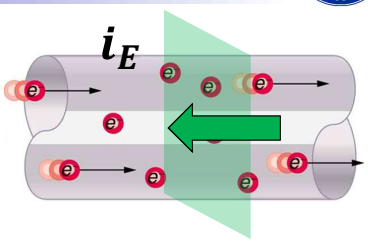
It's a derivative!

Electric current

We usually consider two classes of electric currents:



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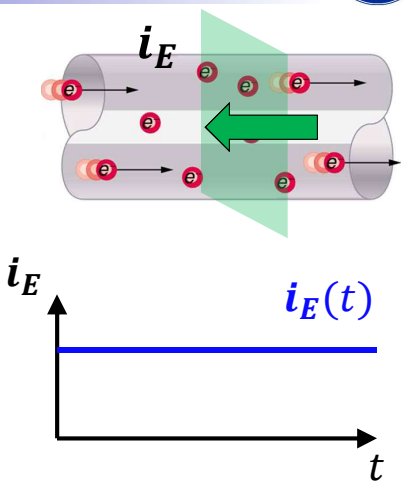
- **Direct (DC)**, i.e., the flow of charge is **unidirectional**



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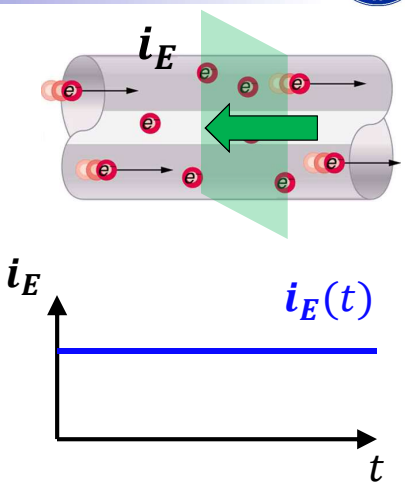
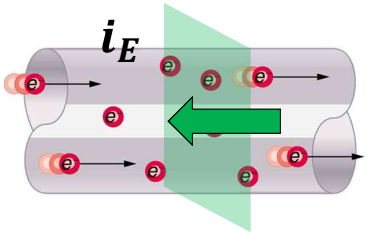
It is produced by sources like batteries, thermocouples, solar cells, and commutator-type electric machines of the dynamo type

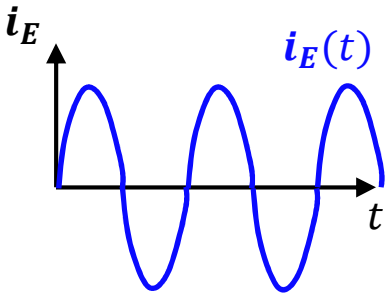


Electric current

We usually consider two classes of electric currents:

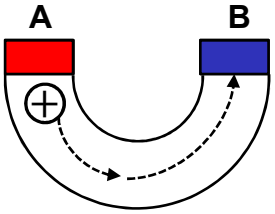
- **Direct (DC)**, i.e., the flow of charge is **unidirectional**
- **Alternating (AC)**, i.e., the movement of the charges **periodically reverses** direction





Voltage

It is the work associated with moving a unit charge between two points along a circuit



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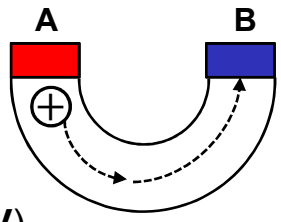

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1 **V** = 1 **J** / 1 **C** **J** = joule

Voltage

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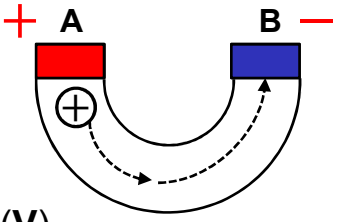

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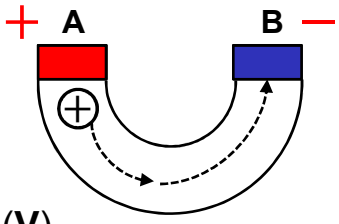

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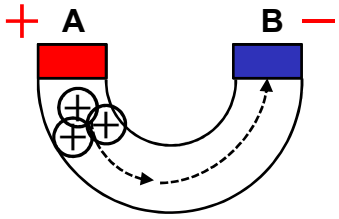
Current flows from lower voltage to higher voltage only when a source of energy "pushes" it (**battery**)

Electric power

It is the **rate** at which work is done along a circuit

Electric power



It is the **rate** at which work is done along a circuit

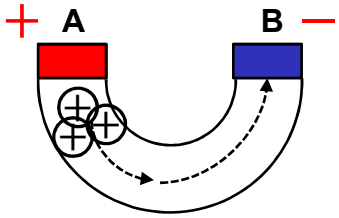
$\Delta q \stackrel{\text{def}}{=}$ amount of charge moved from A to B

$\Delta W \stackrel{\text{def}}{=}$ work done moving Δq from A to B

$\Delta t \stackrel{\text{def}}{=}$ time to do work ΔW

$$\boldsymbol{P = \frac{\Delta W}{\Delta t}}$$

Electric power



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$$\boldsymbol{P = \frac{\Delta W \cdot \Delta q}{\Delta q \cdot \Delta t}}$$

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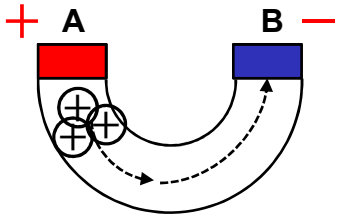

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voltage

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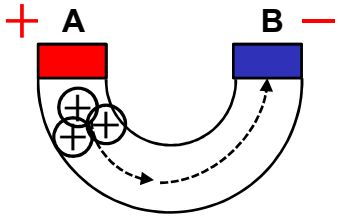

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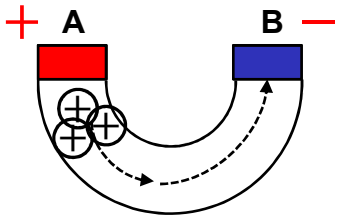

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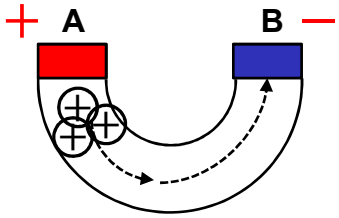
$$\boldsymbol{P = v \cdot i}$$

Electric power



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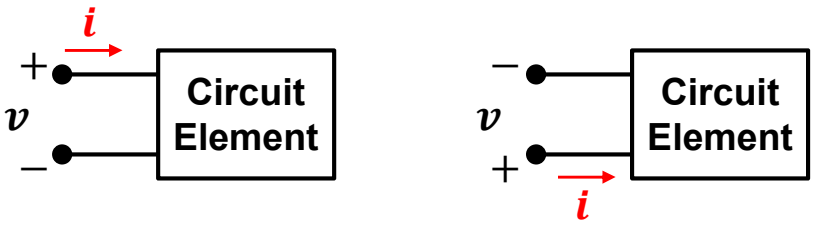
In the SI, it is measured in **Watts** (**W**)

$1\ \mathbf{W} = 1\ \mathbf{J} / 1\ \mathbf{s} = 1\ \mathbf{V} \times 1\ \mathbf{A}$

Polarity of power



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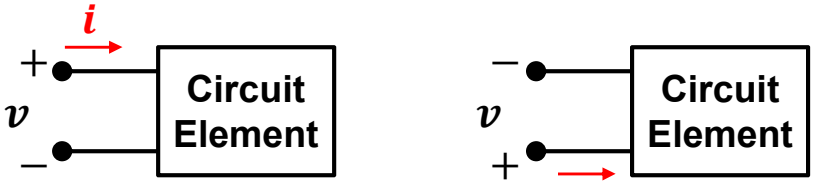
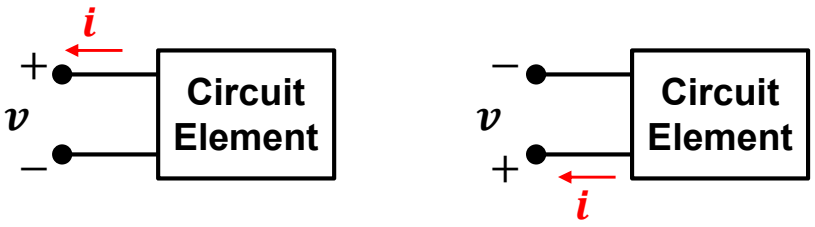


$P = vi > 0$ $P = vi > 0$

A positive value for power indicates that power is being absorbed (or consumed) by the circuit element

Polarity of power



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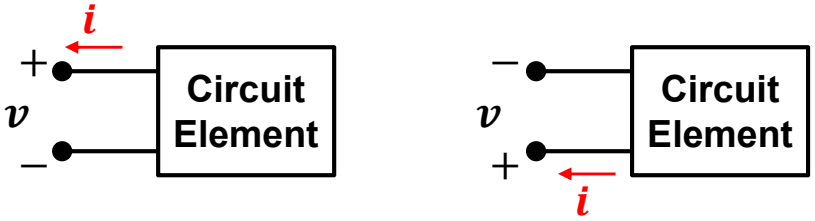


$P = -vi < 0$ $P = -vi < 0$

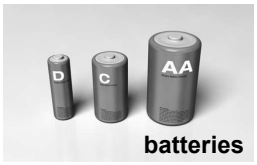
A negative value for power says that power is being generated by (or extracted from) the circuit element (e.g., **battery**)

A circuit element is…

- **Active**

$P < 0$, i.e., it can generate energy

voltage generator



batteries

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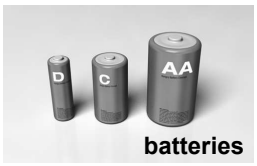
$P < 0$, i.e., it can generate energy

voltage generator



batteries

- **Passive**

$P \geq 0$, i.e., it dissipates or stores energy

resistor

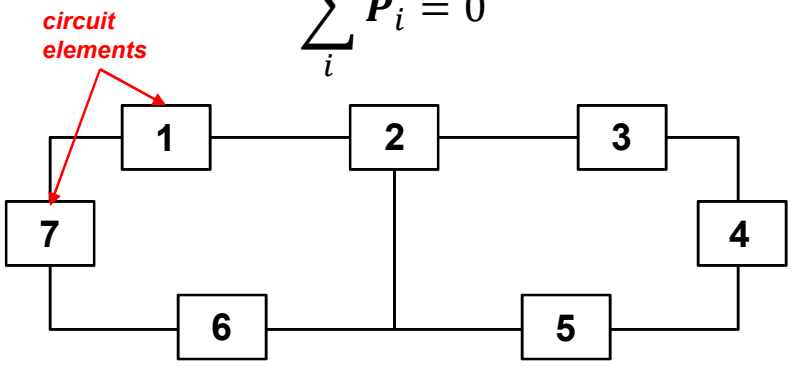
capacitor

inductor

Remember…

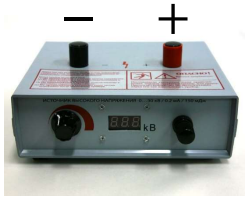
In any **closed electric circuit** the amount of power that is supplied must be equal to the amount that is absorbed

$$\sum_i \boldsymbol{P}_i = 0$$



Source

- It is an **active** circuit element with **two terminals** that provides energy to the circuit



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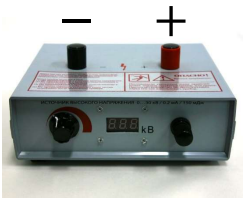
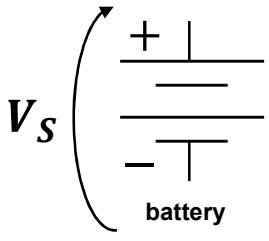
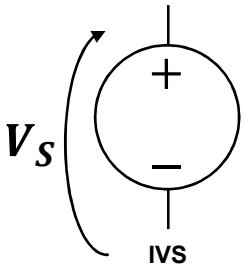


- There is no direct voltage-current (v-i) relationship for a source. v and i depend on the type of circuit

Ideal sources

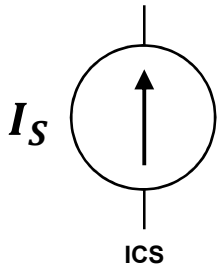
An **ideal voltage source (IVS)** generates a prescribed voltage at its terminals **regardless of the current flow**





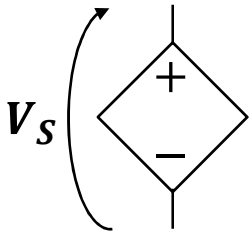
Ideal sources

An **ideal current source (ICS)** provides a prescribed amount of current **regardless of the voltage** at its terminals

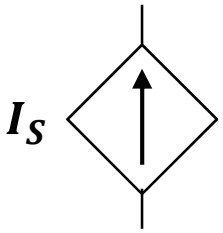


Controlled sources

A voltage or current source is **controlled** if its output (voltage or current) depends on the voltage or current somewhere else in the circuit

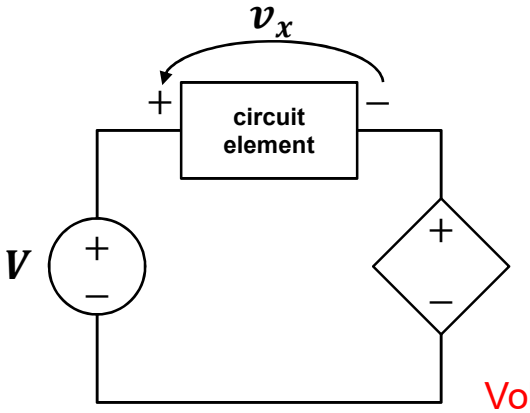


Controlled Voltage Source



Controlled Current Source

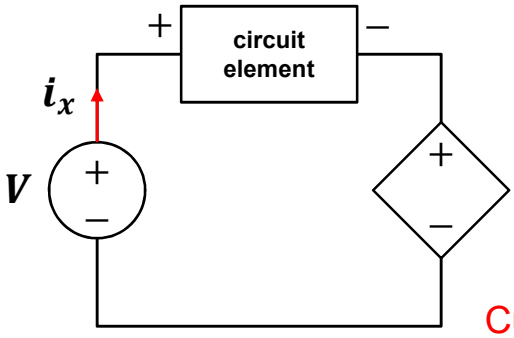
Examples



$V_d = f(v_x)$

Voltage-controlled voltage source

Examples



$V_d = g(i_x)$

Current-controlled voltage source

Resistor

A circuit element that limits the flow of current through it, i.e., it opposes the current by producing a voltage drop between the terminals

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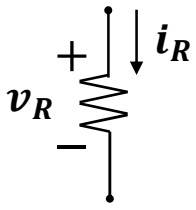
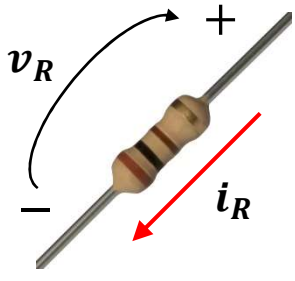
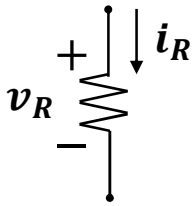




Resistor

A circuit element that limits the flow of current through it, i.e., it opposes the current by producing a voltage drop between the terminals

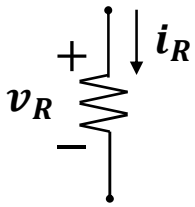


The ability to impede current is called **resistance (R)** and is measured in **ohms (Ω)**

$1\ \mathbf{\Omega} = 1\ \mathbf{V} / 1\ \mathbf{A}$

Resistor

A circuit element that limits the flow of current through it, i.e., it opposes the current by producing a voltage drop between the terminals

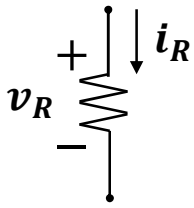


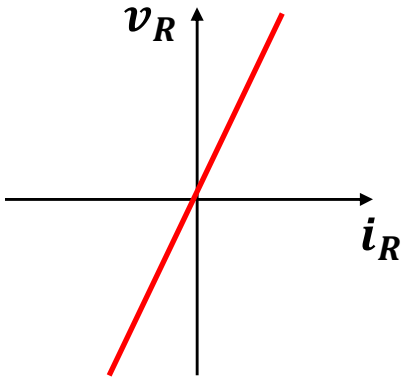
The inverse of the resistance is the **conductance (G)** and is measured in **siemens (S)**

$1\ \mathbf{S} = 1\ \mathbf{A} / 1\ \mathbf{V}$

Ohm's law

- An ideal resistor is characterized by a **linear** voltage-current relationship

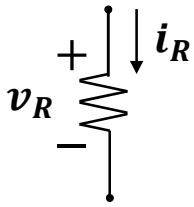


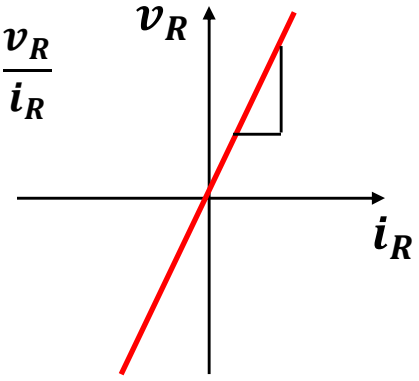


Ohm's law

- An ideal resistor is characterized by a **linear** voltage-current relationship
- The slope is the resistance:

$$R = \frac{v_R}{i_R}$$

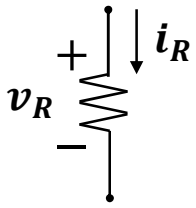


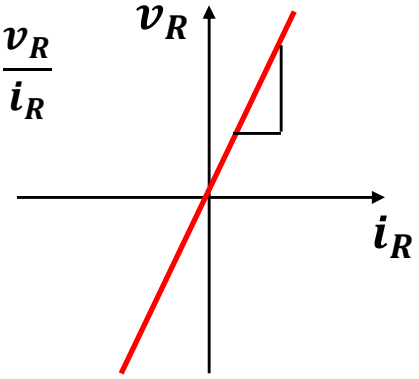


Ohm's law

- An ideal resistor is characterized by a **linear** voltage-current relationship
- The slope is the resistance:

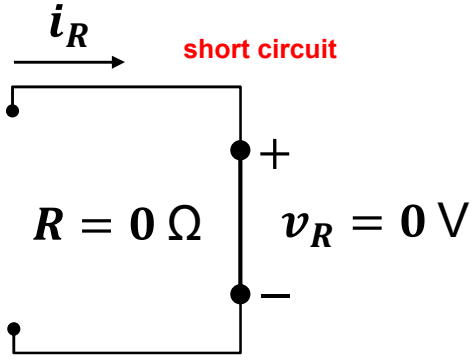
It is constant! $R = \frac{v_R}{i_R}$





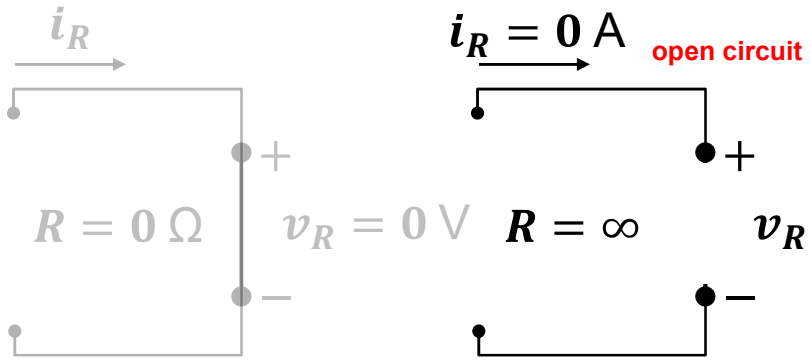
Ohm's law ($v_R = R \cdot i_R$)

- An ideal bare wire connecting circuit elements together has resistance $R = 0\ \Omega$

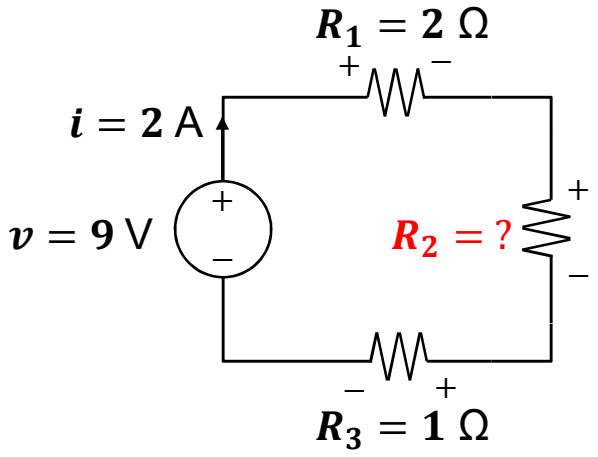


Ohm's law ($i_R = v_R/R$)

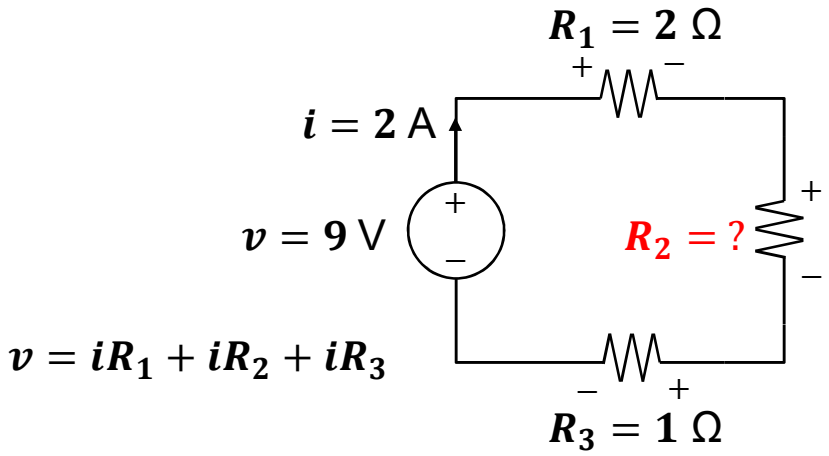
- An ideal bare wire connecting circuit elements together has resistance $R = 0\ \Omega$
- A gap between circuit elements has $R = \infty$



An example

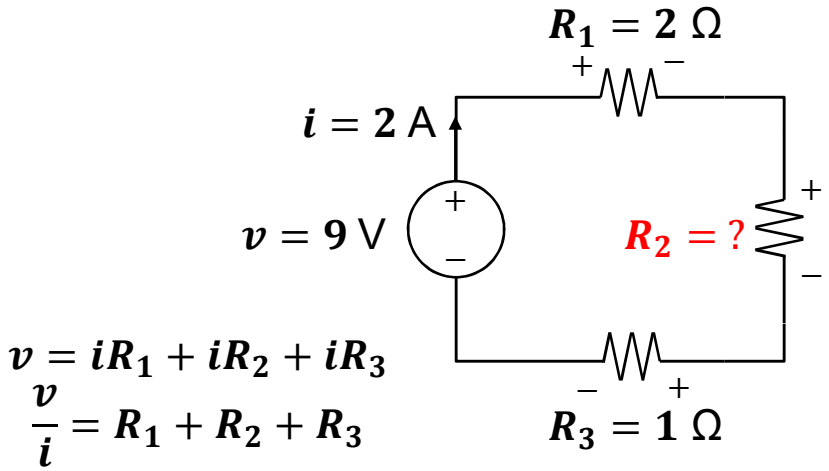


An example



$$v = iR_1 + iR_2 + iR_3$$

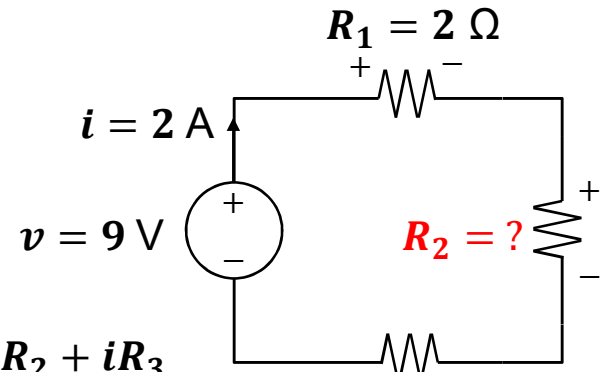
An example



$$v = iR_1 + iR_2 + iR_3$$

$$\frac{v}{i} = R_1 + R_2 + R_3$$

An example



$$v = iR_1 + iR_2 + iR_3$$

$$\frac{v}{i} = R_1 + R_2 + R_3$$

$$R_2 = \frac{v}{i} - R_1 - R_3 = 1.5\ \Omega$$

Power and Ohm's law

For an ideal resistor the power is:

$$P = v_R \cdot i_R = (i_R R) \cdot i_R = i_R^2 R$$

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- $P > 0$ independently of the signs of i_R and v_R (i.e., power is always absorbed)

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For an ideal resistor the power is:

$$P = v_R \cdot i_R = (i_R R) \cdot i_R = i_R^2 R$$

- $P > 0$ independently of the signs of i_R and v_R (i.e., power is always absorbed)
- The resistor dissipates the absorbed power as heat

Exceptions to Ohm's law

- Ohm's law does not apply at very high voltages and currents (nonlinear $\boldsymbol{i}$-$\boldsymbol{v}$ relationships occur)
- Many physiological systems only follow Ohm's law in a narrow range of voltages. Outside this range the model is nonlinear
- Different materials exhibit different resistances. Some materials exhibit linear behavior over a limited range of voltage and current values