ELE 110
Introduction to Electrical Engineering

http://www.ee.hacettepe.edu.tr/~usezen/ele110/

Textbooks

Electrical Circuits (first 4-5 weeks):

- J.W. Nilsson, S.A. Riedel, *Electric Circuit*s, Pearson-Prentice Hall, 2011 (it is also the text book of "ELE203 Circuit Theory I" and "ELE220 Circuit Theory II" courses).

Semiconductors:

- C. C. Hu, *Modern Semiconductor Devices for Integrated Circuits*, 2010.
- B. Streetman and S. Banerjee, *Solid State Electronic Devices*, 6th ed, 2009.

Contents

- Ohm's Law, Energy and Power
- Circuit Analysis Techniques: Kirchoff's Voltage Law (KVL) and Kirchoff's Current Law (KCL)
- Thévenin's, Norton's and Superposition Theorems
- Mesh and Nodal Analysis

- Introduction to Semiconductors (atoms, bonding, electrons and holes, intrinsic semiconductors, doping, p-type and n-type semiconductors)
- Electrons and Holes in Semiconductors (effective mass, energy bands, Fermi distribution)
- Motion and Recombination of Electrons and Holes (mobility, conductivity, drift and diffusion current)
- PN junctions (equilibrium, reverse bias, forward bias, diode equation, solar cells, lasers, tunnel diode)
- Bipolar Junction Transistors (BJT)

Part I

Electrical Circuits

SI Units

Quantity	Quantity symbol	Unit	Unit symbol
Capacitance	*C*	Farad	F
Charge	*Q*	Coulomb	C
Current	*I*	Ampere	A
Electromotive force	*E*	Volt	V
Frequency	*f*	Hertz	Hz
Inductance (self)	*L*	Henry	H
Period	*T*	Second	s
Potential difference	*V*	Volt	V
Power	*P*	Watt	W
Resistance	*R*	Ohm	Ω
Temperature	*T*	Kelvin	K
Time	*t*	Second	s

Common Prefixes

Prefix	Name	Meaning (multiply by)
P	peta	10^{15}
T	tera	10^{12}
G	giga	10^{9}
M	mega	10^{6}
k	kilo	10^{3}
m	milli	10^{-3}
μ	micro	10^{-6}
n	nano	10^{-9}
p	pico	10^{-12}
f	femto	10^{-15}

Ohm’s Law, Energy and Power

Review of *V, I,* and *R*

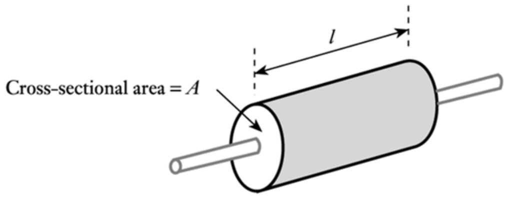
Voltage is the amount of energy per charge available to move electrons from one point to another in a circuit and is measured in volts.

Current is the rate of charge flow and is measured in amperes.

Resistance is the opposition to current and is measured in ohms.

Resistors

- resistance of a given sample of material is determined by its electrical characteristics and its construction
- electrical characteristics described by its **resistivity** ρ or its **conductivity** σ (where $\sigma = 1/\rho$)



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

Conductance

Inverse of resistance is called **conductance**. The lower the resistance means the higher the conductance.

$$G = \frac{1}{R}$$

Unit of conductance is called **siemens** (S).

Several different symbols are used interchangeably to denote the unit of conductance:

$$\Omega^{-1},\ \mho,\ \mathrm{S},\ \mathrm{mho}$$

Ohm's law

The most important fundamental law in electronics is **Ohm's law**, which relates voltage, current, and resistance.

Georg Simon Ohm (1787-1854) formulated the equation that bears his name:

$$I = \frac{V}{R}$$

Question:

What is the current in a circuit with a 12 V source if the resistance is 10 Ω? 1.2 A

If you need to solve for voltage, Ohm's law is:

$$V = IR$$

Question:

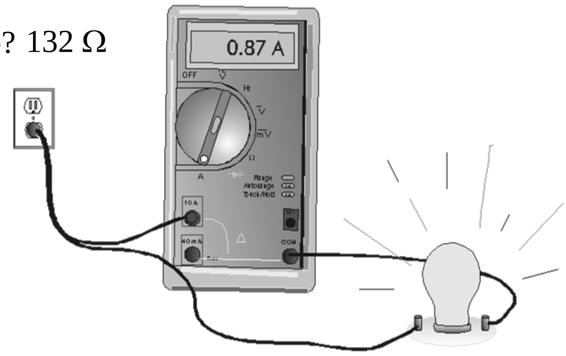
What is the voltage across a 680 Ω resistor if the current is 26.5 mA? 18 V

If you need to solve for resistance, Ohm's law is: $R = \frac{V}{I}$

Question:

What is the (hot) resistance of the bulb? 132 Ω

115 V



Example:

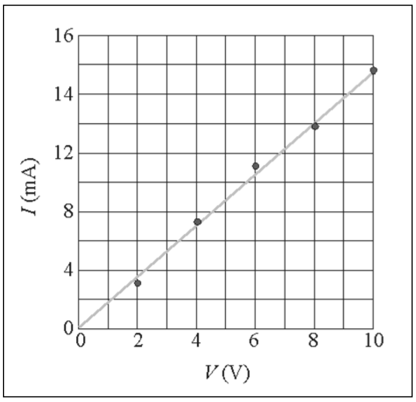
A student takes data for a resistor and fits the straight line shown to the data. What is the conductance and the resistance of the resistor?

The slope represents the conductance.

$$G = \frac{14.8\text{ mA} - 0\text{ mA}}{10.0\text{ V} - 0\text{ V}} = 1.48\text{ mS}$$

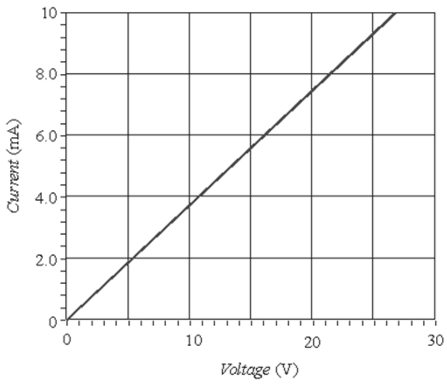
The reciprocal of the conductance is the resistance:

$$R = \frac{1}{G} = \frac{1}{1.48\text{ mS}} = 676\,\Omega$$



Graph of Current versus Voltage

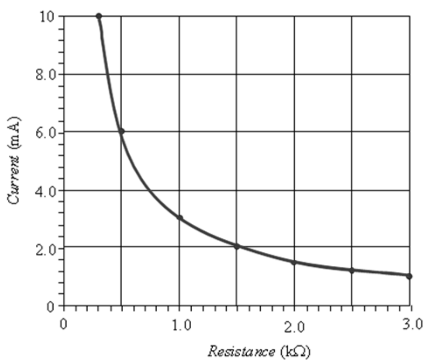
Notice that the plot of current versus voltage for a fixed resistor is a line with a positive slope. What is the resistance indicated by the graph? 2.7 kΩ



What is its conductance? 0.37 mS

Graph of Current versus Resistance

If resistance is varied for a constant voltage, the current versus resistance curve plots a hyperbola.



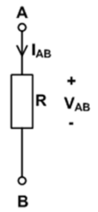
Question:

What is the curve for a 3 V source?

Voltage Polarity and Current Direction

The direction of the current and polarity of the voltage across a resistor are also related. If a **voltage** value is **negative**, it means that its **polarity is reverse**.

Current flows from a higher potential to a lower potential. If a **current** value is **negative**, it means that it is actually flowing in the **reverse direction**.



$$V_{AB} = I_{AB}R$$

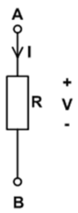
$$V_{BA} = I_{BA}R$$

$$V_{AB} = V_A - V_B$$
$$V_{BA} = V_B - V_A$$

$$V_{BA} = -V_{AB}$$

$$I_{BA} = -I_{AB}$$

Examples:

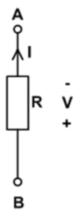


$I_{AB} = I$ $\quad$ $I_{BA} = -I$

$$V_{AB} = I_{AB}R = IR$$

$$V_{BA} = I_{BA}R = -IR$$

$$V = V_{AB} = IR$$



$I_{AB} = -I$ $\quad$ $I_{BA} = I$

$$V_{AB} = I_{AB}R = -IR$$

$$V_{BA} = I_{BA}R = IR$$

$$V = V_{BA} = IR$$

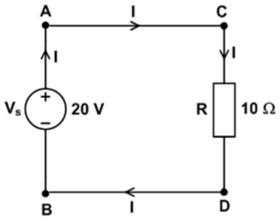
Example: In the circuit below

A, B, C and D represents the connection points (i.e., nodes).

V_s is a voltage source whose value is 20 V.

R is a resistor whose value is 10 Ω

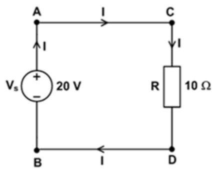
I is the current through the circuit



What is the value of the circuit current I?

What are the values of the voltages and currents between all the nodes?

Solution: $I = \frac{V_s}{R} = \frac{20}{10} = 2\,\mathrm{A}$



$V_{AB} = V_s = 20\,\mathrm{V}$ $\quad V_{BA} = -V_s = -20\,\mathrm{V}$

$V_{CA} = 0\,\mathrm{V}$ $\quad V_{AC} = 0\,\mathrm{V}$

$V_{CD} = 20\,\mathrm{V}$ $\quad V_{DC} = -20\,\mathrm{V}$

$V_{DB} = 0\,\mathrm{V}$ $\quad V_{BD} = 0\,\mathrm{V}$

$I_{BA} = I = 2\,\mathrm{A}$ $\quad I_{AB} = -I = -2\,\mathrm{A}$

$I_{AC} = I = 2\,\mathrm{A}$ $\quad I_{CA} = -I = -2\,\mathrm{A}$

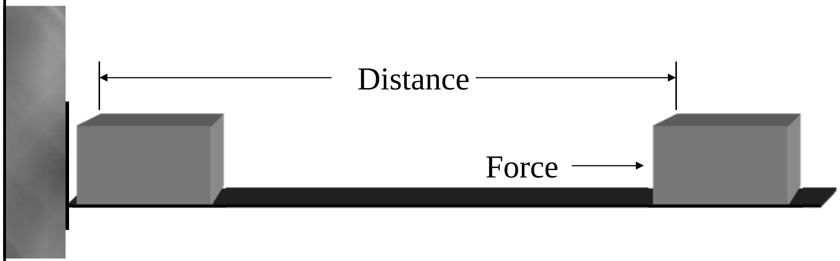
$I_{CD} = I = 2\,\mathrm{A}$ $\quad I_{DC} = -I = -2\,\mathrm{A}$

$I_{DB} = I = 2\,\mathrm{A}$ $\quad I_{BD} = -I = -2\,\mathrm{A}$

Energy and Power

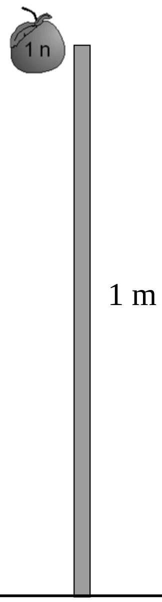
When a constant force is applied to move an object over a distance, the work is the force times the distance.

The force must be measured in the same direction as the distance. The unit for work is the newton-meter (N-m) or joule (J).



One joule is the work done when a force of one newton is applied through a distance of one meter. A joule is a small amount of work approximately equal to the work done in raising an apple over a distance of 1 m.

The symbol for energy, *W*, represents work, but should not be confused with the unit for power, the watt, W.



Energy is closely related to work. Energy is the ability to do work. As such, it is measured in the same units as work, namely the newton-meter (N-m) or joule (J).

Example:

What amount of energy is consumed in sliding a box along a floor for 5 meters if the force to move it is 400 N?

$$W = Fd = (400 \text{ N})(5 \text{ m}) = 2000 \text{ N-m} = 2000 \text{ J}$$

Power is the rate of doing work. Because it is a *rate*, a time unit is required. The unit is the joule per second (J/s), which defines a watt (W).

$$\boxed{P = \frac{dW}{dt} = \frac{\Delta W}{\Delta t}}$$

Example:

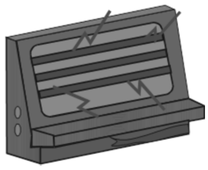
What power is developed if the box in the previous example is moved in 10 s?

$$P = \frac{\Delta W}{\Delta t} = \frac{2000\,\mathrm{J}}{10\,\mathrm{s}} = 200\,\mathrm{W}$$

The kilowatt-hour (kWh) is a much larger unit of energy than the joule. There are 3.6 x 10^6 J in a kWh. The kWh is convenient for electrical appliances.

Question:

What is the energy used in operating a 1200 W heater for 20 minutes?



1200 W = 1.2 kW

20 min = 1/3 h

1.2 kW x 1/3 h = 0.4 kWh

In electrical work, the rate energy is dissipated can be determined from any of three forms of the power formula.

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

Together, the three forms are called **Watt's law**.

Example 1:

What power is dissipated in a 27 Ω resistor if the current is 0.135 A?

Solution:

Given that you know the resistance and current, substitute the values into $P = I^2R$.

$$P = I^2R$$
$$= (0.135\ \text{A})^2 (27\ \Omega)$$
$$= 0.49\ \text{W}$$

Example 2:

What power is dissipated by a heater that draws 12 A of current from a 120 V supply?

Solution:

The most direct solution is to substitute into $P = IV$.

$$P = IV$$
$$= (12\ \text{A})(120\ \text{V})$$
$$= 1440\ \text{W}$$

Example 3:

What power is dissipated in a 100 Ω resistor with 5 V across it?

Solution:

The most direct solution is to substitute into $P = \frac{V^2}{R}$.

$$P = \frac{V^2}{R} = \frac{(5\ \text{V})^2}{100\ \Omega} = 0.25\ \text{W}$$

It is useful to keep in mind that small resistors operating in low voltage systems need to be sized for the anticipated power.

Power Between Two Nodes of a Circuit

Power between two nodes A and B is equal to the voltage across the nodes multiplied by the current from one node to the other

$$P_{AB} = V_{AB} I_{AB}$$
$$P_{BA} = V_{BA} I_{BA}$$
$$P_{AB} = P_{BA}$$

A **positive** value for the **power** indicates that it is a **dissipated power**.

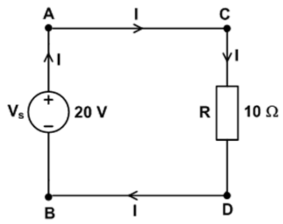
Note: Power over a resistor is always positive.

A **negative** value for the **power** indicates that it is a **generated power**.

Total power in an electrical circuit is zero, i.e., generated power is equal to the dissipated power. This is due to the conservation of energy law.

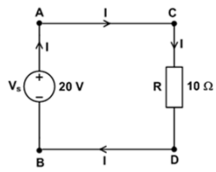
Example 4: In the circuit below

A, B, C and D represents the connection points (i.e., nodes).



Calculate the power across all the nodes.

Solution: $I = \frac{V_s}{R} = \frac{20}{10} = 2\,\mathrm{A}$



$$P_{AB} = P_{BA} = V_{AB} I_{AB} = 20V \times (-2A) = -40\,\mathrm{W}$$

Power is generated

$$P_{AC} = P_{CA} = V_{AC} I_{AC} = 0V \times 2A = 0\,\mathrm{W}$$

$$P_{CD} = P_{DC} = V_{CD} I_{CD} = 20V \times 2A = 40\,\mathrm{W}$$

Power is dissipated

$$P_{DB} = P_{BD} = V_{DB} I_{DB} = 0V \times 2A = 0\,\mathrm{W}$$

Total Generated Power = 40 W

Total Dissipated Power = 40 W

Resistor failures

Resistor failures are unusual except when they have been subjected to excessive heat. Look for discoloration (sometimes the color bands appear burned). Test with an ohmmeter by disconnecting one end from the circuit to isolate it and verify the resistance. Correct the cause of the heating problem (larger wattage resistor?, wrong value?).

Normal

Overheated

Ampere-hour Rating of Batteries

Expected battery life of batteries is given as the ampere-hours specification. Various factors affect this, so it is an approximation (factors include rate of current withdrawal, age of battery, temperature, etc.) .

Question:

How many hours can you expect to have a battery deliver 0.5 A if it is rated at 10 Ah?

20 h

Troubleshooting

Some questions to ask before starting any troubleshooting are:

1. Has the circuit ever worked?
2. If the circuit once worked, under what conditions did it fail?
3. What are the symptoms of the failure?
4. What are the possible causes of the failure?

Plan the troubleshooting by reviewing pertinent information:

1. Schematics
2. Instruction manuals
3. Review when and how the failure occurred.

You may decide to start at the middle of a circuit and work in toward the failure. This approach is called half-splitting.

Based on the plan of attack, look over the circuit carefully and make measurements as needed to localize the problem. Modify the plan if necessary as you proceed.

After solving the problem, it is useful to ask, "How can I prevent this failure in the future?"