Electricity

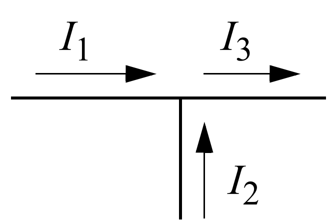
Electric Charge

- Unit of charge: coulomb (C)
- Charge of an electron: $Q_e = -1.6 \times 10^{-19}$ C
- Conservation of charge:

  The total charge in a closed system is constant.

Electric Current

- Unit of electric current: ampere or amp (A) = C/s
- A positive current reflects the direction of positive charge motion.
- A positive current can also be due to negative charges moving in the opposite direction.
- From conservation of charge: *the sum of all currents at a point is zero.*



Current is conserved

$$I_3 = I_1 + I_2$$

Voltage

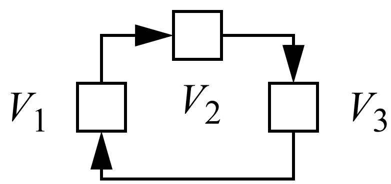
Charge and Work

- Unit of work: joule (J) = N m
- Work is independent of the path taken by a charge.
- Conservation of electrical energy:

  The work done on an electric charge along a closed path is zero.

Electric Potential

- Unit of electric potential: volt (V) = J/C
- From the conservation of electrical energy: *the sum of voltages around a closed loop is zero*.



Voltage is conserved

$$V_1 + V_2 + V_3 = 0$$

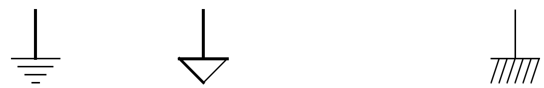
Power

- Unit of power: watt (W) = J/s
- In circuits, a watt equals a volt-amp. $P = IV$

Ground

- Work is defined relative to the starting point on a path.
- The starting point depends on the situation.

- Electric potential is defined relative to a starting point.
- A common starting point used in a circuit is called *ground*.
- In a circuit, ground is given a special symbol.

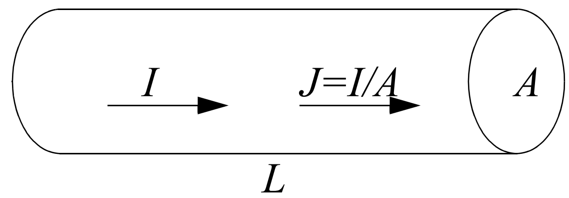


chassis grounds *earth grounds*

- Circuits may not show ground.
- Voltage can be given or measured between any two points, not just to ground.
- If voltage is given at just one point, then it is assumed to be with respect to ground.

Conductivity

- Current density is the flux of current per unit area: $\boldsymbol{J}=\boldsymbol{I}/A$



- *Conductivity* is the relation between current density and the applied electric field: $\boldsymbol{J} = \sigma \boldsymbol{E}$.
- Conductivity can depend on the material, field, temperature, pressure, or other physical properties.
- Assume an electron is has constant acceleration from an electric field for time τ, then it collides with an atom and starts over.
- With constant acceleration, the electron's velocity is $v = \frac{eE\tau}{m}$.
- If the number of electrons in the conductor is n, then the current density is $J = nev = \frac{ne^2\tau E}{m}$
- The conductivity depends on the number of electrons and mean time between collisions:

$$\sigma = \frac{ne^2\tau}{m} = ne\mu$$

Where μ is the *mobility*.

Resistivity

- *Resistivity* is the inverse of conductivity: $\rho = 1/\sigma$.
- *Resistance* measures the integrated resistivity per cross-sectional area over a length of conductor:

$$R = \int \frac{\rho}{A} dl$$

- For a uniform material of length L, $R = \rho L/A$.
- Unit of resistance: ohm (Ω) = V/A
- Units of resistivity are Ω-m.
- *Conductance* is the inverse of resistance.
- Unit of conductance: mho or siemen = Ω^{-1}

Resistivity in Copper

$n = 8.5 \times 10^{22}$ e/cm^3

$ne = 1.36 \times 10^4$ C/cm^3

$\rho = 1.7 \times 10^{-6}$ Ω-cm, so $\mu = 1/ne\rho = 43$ cm^2/V-s.

A large current density is 100 A/cm^2,

so $E = \rho J = 1.7 \times 10^{-4}$ V/cm, and $v = J/ne = 7.3 \times 10^{-3}$ cm/s.

Solving for $\tau = mv/eE = 2.4 \times 10^{-14}$ s.

Ohm's Law

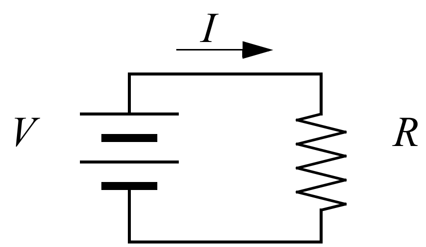
- In a normal uniform conductor, the resistivity is independent of the field or current density.

$$J\rho = E$$

$$\left(\frac{I}{A}\right)\left(\frac{RA}{l}\right) = \left(\frac{V}{l}\right)$$

$$IR = V$$

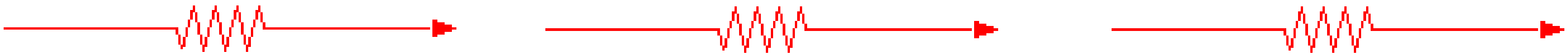
- In a circuit Ohm's law includes a voltage source and a resistance.



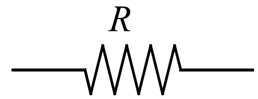
- Ohm's law allows power to be expressed in terms of resistance.

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

Resistors



- Schematic symbol:

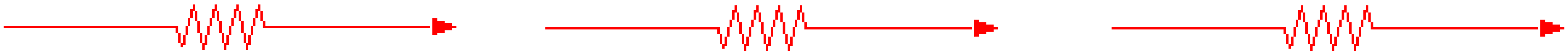


- Resistors are measured in ohms (Ω) in the range 0.01 to 10^{12} Ω.
- Resistors come with power ratings from 1/8 to 250 W.
- Resistors are made with accuracies from 0.01 to 20%.

- Scientific notation is generally avoided for resistors less than 10^{12} Ω.
- Preferred units are 1-999 Ω, 1-999 kΩ, 1-999 MΩ, 1-999 GΩ.

- Wire-wound resistors have high precision (0.01-1%), high power ratings and are often bulky, inductance prevents use at high frequencies (1 kHz).
- Metal-film resistors are precise (0.1-1%) and stable, but capacitance prevents use at high frequencies (1 MHz).
- Carbon-composition resistors are common, cheap and work over a wide range of frequencies, but not particularly precise (5-20%) or stable.

Resistor Values



- Resistor values are coded by

1. Size

   Power ratings for carbon-composition resistors are standard sizes for 1/8, 1/4, 1/2, 1, 2 W.

2. Number

   With three digits, the first two are a number and the last is an exponent for a power of 10.

   Example: $103 = 10 * 10^3 = 10\ k\Omega$.

   Standard two digit numbers go in steps of about 10%:

   10, *11*, 12, *13*, **15**, *16*, 18, *20*, **22**, *24*, 27, *30*,

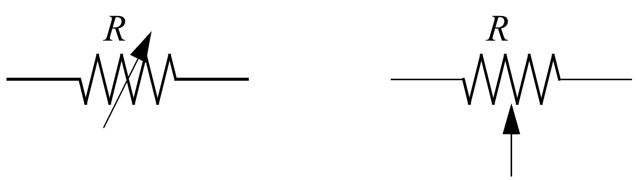
   33, *36*, 39, *43*, **47**, *51*, 56, *62*, **68**, *75*, 82, *91*

3. Color (instead of number)

   0:black, 1:brown, 2:red, 3:orange, 4:yellow, 5:green, 6:blue, 7:violet, 8:grey, 9:white

   A fourth band is for precision: none=20%, silver=10%, gold=5%.

- Variable resistors and potentiometers



R refers to maximum resistance

Thermal Effects

Temperature Variations

- Thermal motion of atoms changes the drift of electrons between atoms.
- Resistance is dependent on temperature.

$$R_T = R_0(1 + \alpha\Delta T) = R_0(1 + \alpha T - \alpha T_0)$$

Temperature is measured with respect to a reference - typically 300 K.

- Elemental metals have values of α from 0.003 to 0.007 K^{-1}.
- Some materials, such as carbon, have a negative dependence.

Resistance Thermometer

- Pure platinum is used as a standard from -190 C to +600 C.
- A precise current and precision voltmeter are used to make a thermometer.

Thermistor

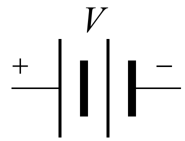
- Made from alloys or metal oxides, sometimes encased in glass.
- Strong negative dependence on temperature

$$R_T = R_0 e^{A(1/T - 1/T_0)}$$

- Wide range of resistances available: 30 Ω to 20 MΩ.

Voltage Sources

- Schematic symbol:



- Ideally provides constant voltage for any load.

Batteries

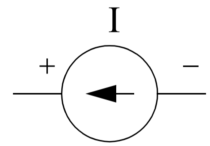
- Chemical batteries are typically available from 1-15 V.
- Chemical type determines energy density and lifetime available: zinc-carbon, alkaline, mercury, nickel-cadmium, lithium, etc.
- High energy density means small batteries.
- Lifetime measures current available for a period of time (Ah).

Power Supplies

- Uses 120 V AC or other power source to create specific voltage.
- AC voltage requires transformer, rectifier, and regulator to create DC.
- Rating includes maximum voltage and current.

Current Sources

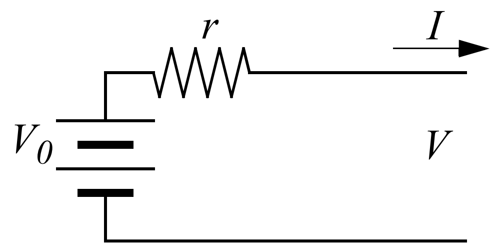
- Schematic symbol:



- Ideally provides constant current for any load.

Internal Resistance

- Real supplies have some resistance inside.
- Voltage sources behave like there is a series resistance.



- Current sources behave like there is a parallel resistance.