# Frogs, Torpedo Fish, and the Pile

- Around 1780, Luigi Galvani and Alessandro Volta were doing something similar to this:

  https://www.youtube.com/watch?v=MpJfGIjwZfE

- The origin of "animal electricity" was hotly contested: Galvani believed that it was from within the animal and was therefore a special type of electricity. Volta believed it was electricity from outside the animal causing it to twitch.

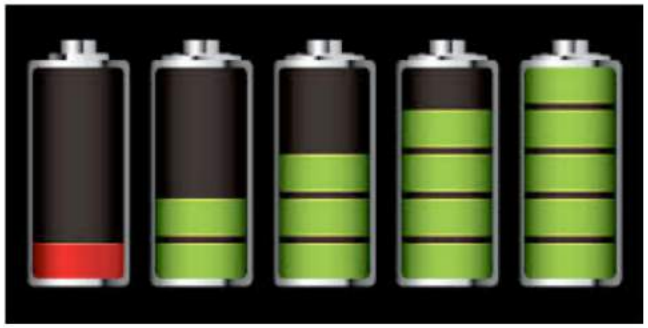
- Other types of electricity generation in animals had been found before, such as in torpedo fish, for example. The origin of this animal electricity was unexplained.


BBC The Story of Electricity, Ep.1, 46:00-52:00

# The first battery was born

- Volta proved there was only one kind of electricity. Animal electricity was no different than what could be generated by a Hauksbee machine and stored in a Leyden jar.
- Thanks to the torpedo fish, through his invention of the pile Volta had also invented the first battery! This was an early example of technology arising from biomimicry.


Biomimicry — an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies.

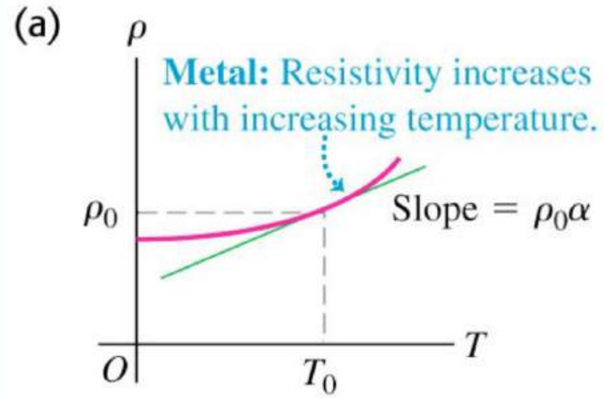
# Resistivity

- The *resistivity* of a material is the ratio of the electric field in the material to the current density it causes: $\rho = E/J$.
- The *conductivity* is the reciprocal of the resistivity.
- The table below shows the resistivity of various types of materials.

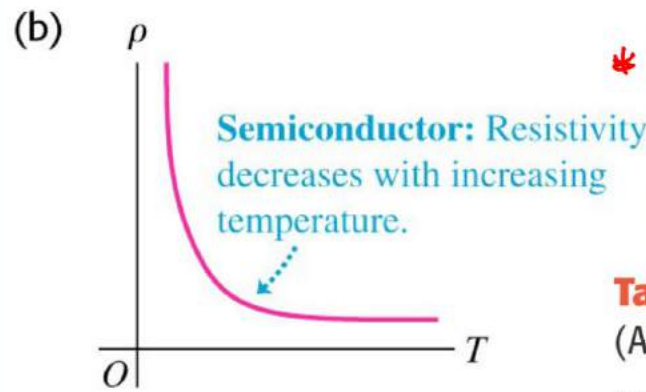
**Table 25.1** Resistivities at Room Temperature (20 °C)

| | Substance | $\rho\,(\Omega \cdot m)$ | Substance | $\rho\,(\Omega \cdot m)$ |
|---|---|---|---|---|
| **Conductors** | | | **Semiconductors** | |
| Metals | Silver | $1.47 \times 10^{-8}$ | Pure carbon (graphite) | $3.5 \times 10^{-5}$ |
| | Copper | $1.72 \times 10^{-8}$ | Pure germanium | 0.60 |
| | Gold | $2.44 \times 10^{-8}$ | Pure silicon | 2300 |
| | Aluminum | $2.75 \times 10^{-8}$ | **Insulators** | |
| | Tungsten | $5.25 \times 10^{-8}$ | Amber | $5 \times 10^{14}$ |
| | Steel | $20 \times 10^{-8}$ | Glass | $10^{10}–10^{14}$ |
| | Lead | $22 \times 10^{-8}$ | Lucite | $>10^{13}$ |
| | Mercury | $95 \times 10^{-8}$ | Mica | $10^{11}–10^{15}$ |
| Alloys | Manganin (Cu 84%, Mn 12%, Ni 4%) | $44 \times 10^{-8}$ | Quartz (fused) | $75 \times 10^{16}$ |
| | Constantan (Cu 60%, Ni 40%) | $49 \times 10^{-8}$ | Sulfur | $10^{15}$ |
| | Nichrome | $100 \times 10^{-8}$ | Teflon | $>10^{13}$ |
| | | | Wood | $10^{8}–10^{11}$ |

# Resistivity and temperature



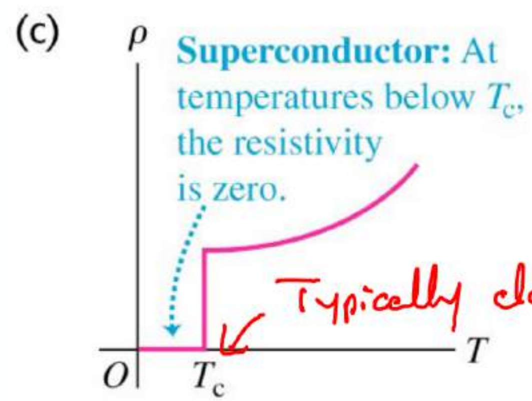

- Resistivity depends on temperature. In metals, higher temperatures increase the probability of electrons colliding with the vibrating ions.
- Table 25.2 shows some temperature coefficients of resistivity.




* The electrical properties of a semiconductor material can be modified by controlled addition of impurities, or by the application of electric fields or light. They can therefore be used to make transistors, which amplify and switch electronic signals.

**Table 25.2** Temperature Coefficients of Resistivity (Approximate Values Near Room Temperature)

| Material | $\alpha\,[(°C)^{-1}]$ | Material | $\alpha\,[(°C)^{-1}]$ |
|---|---|---|---|
| Aluminum | 0.0039 | Lead | 0.0043 |
| Brass | 0.0020 | Manganin | 0.00000 |
| Carbon (graphite) | −0.0005 | Mercury | 0.00088 |
| Constantan | 0.00001 | Nichrome | 0.0004 |
| Copper | 0.00393 | Silver | 0.0038 |
| Iron | 0.0050 | Tungsten | 0.0045 |

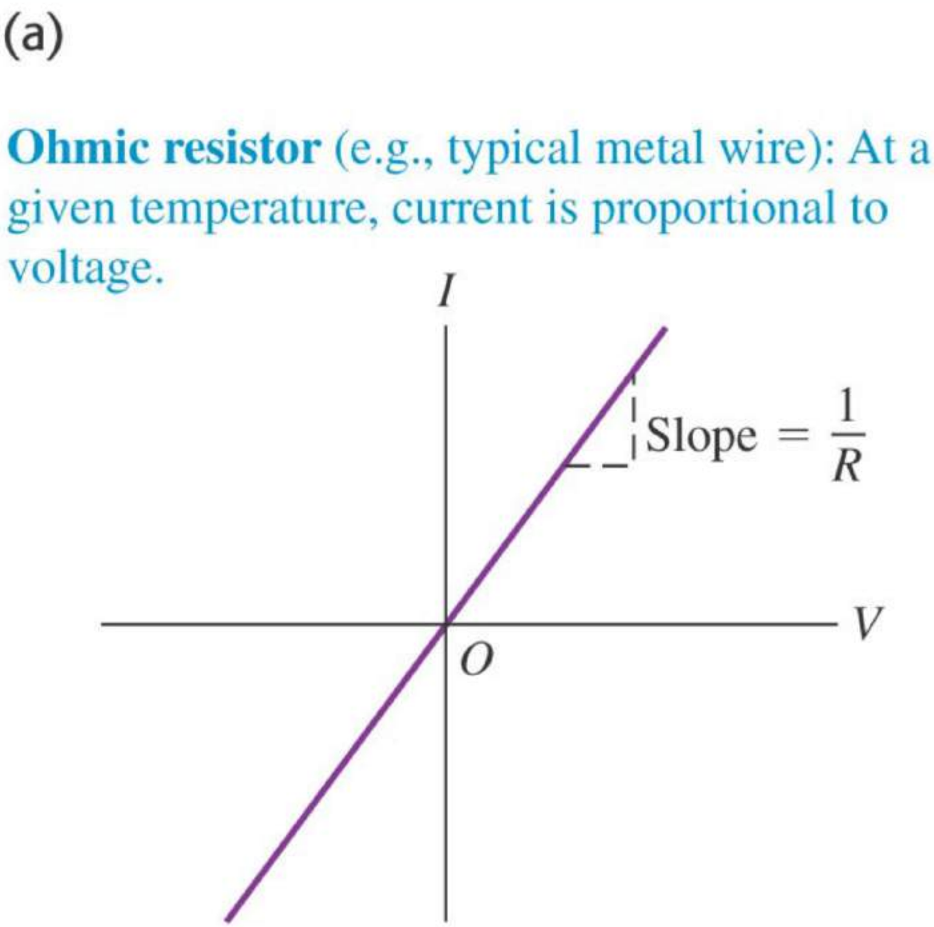


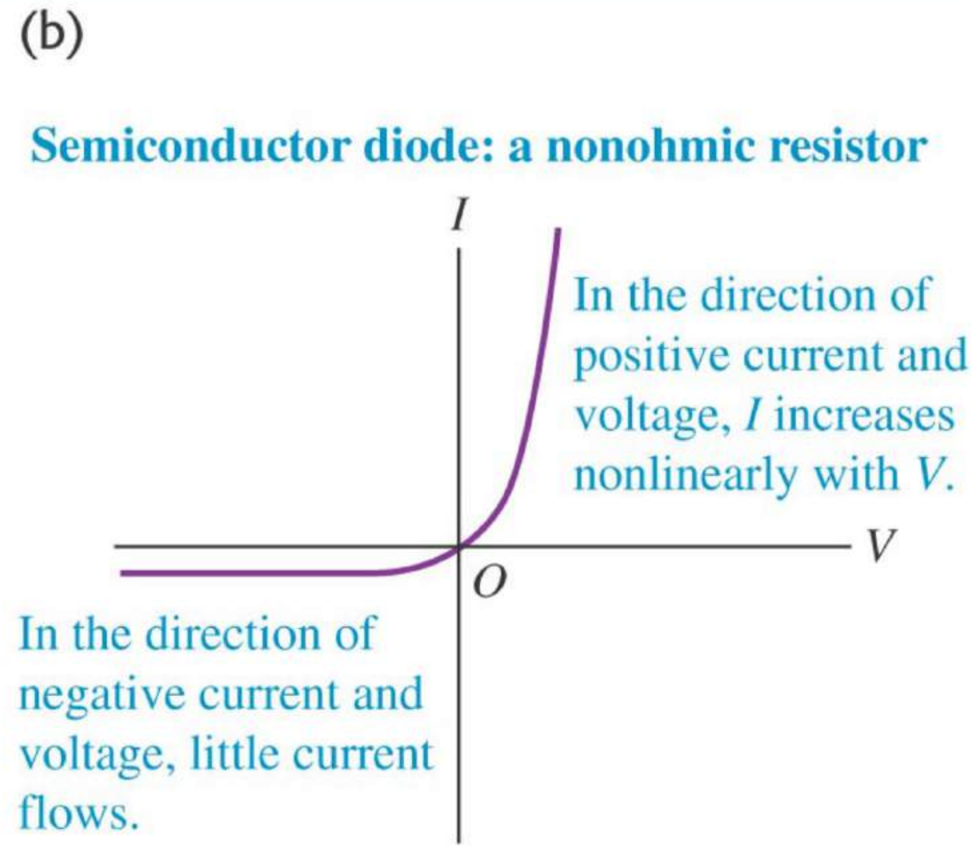

Typically close to 0K.

"High" $T_c$ now ~138 K.

# Resistance

- The *resistance* of a resistor is $R = \rho L/A$. (resistivity; L - conductor length; A - cross sectional area)
- The potential across a resistor is $V = IR$. (Ohmic resistor)
- If $V$ is directly proportional to $I$ (that is, if $R$ is constant), the equation $V = IR$ is called *Ohm's law*. Unit of resistance is the ohm.



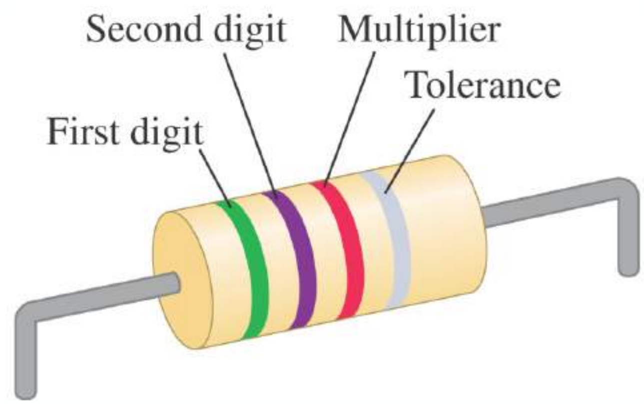



# Resistors are color-coded for easy identification

- This resistor has a resistance of 5.7 kΩ with a tolerance (precision) of ±10%.

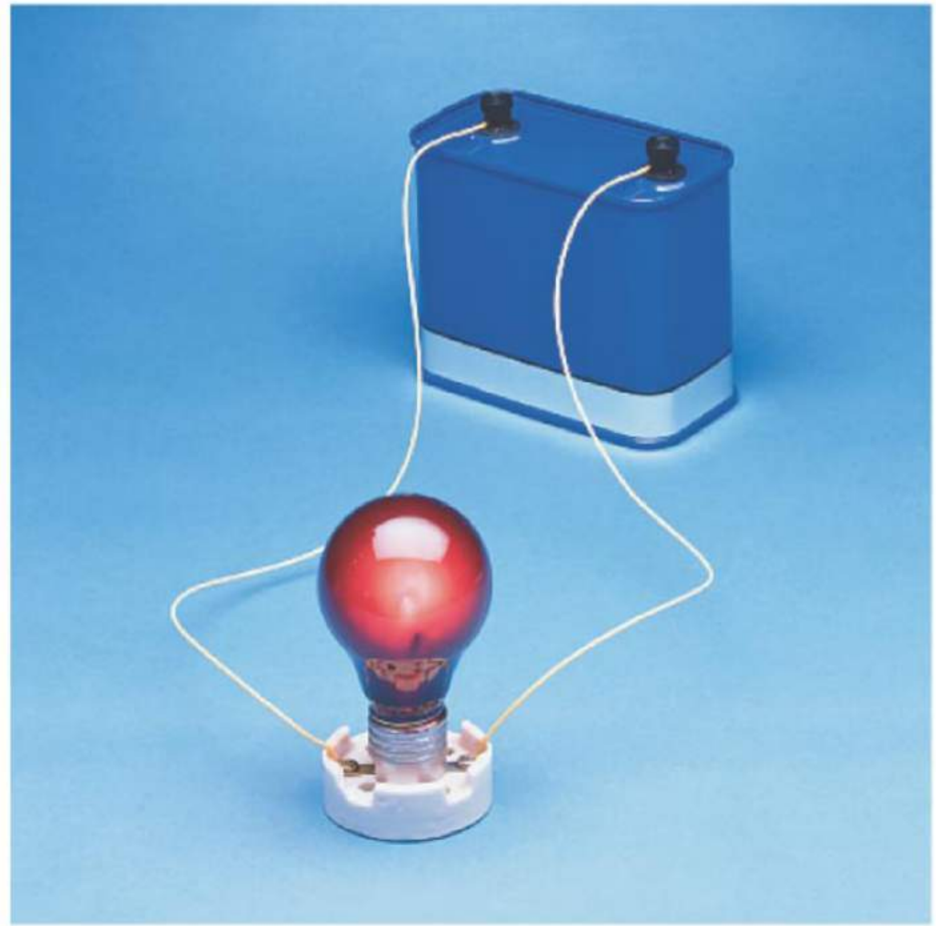
**Table 25.3** Color Codes for Resistors

| Color | Value as Digit | Value as Multiplier |
|---|---|---|
| Black | 0 | 1 |
| Brown | 1 | 10 |
| Red | 2 | $10^2$ |
| Orange | 3 | $10^3$ |
| Yellow | 4 | $10^4$ |
| Green | 5 | $10^5$ |
| Blue | 6 | $10^6$ |
| Violet | 7 | $10^7$ |
| Gray | 8 | $10^8$ |
| White | 9 | $10^9$ |



# emf and internal resistance

- An *electromotive force* (*emf*) makes current flow. In spite of the name, an emf is *not* a force.
- Note that potential is not necessarily the same as emf. Real sources of emf actually contain some *internal resistance r*.
- The *terminal voltage* of an emf source is $V_{ab}$.

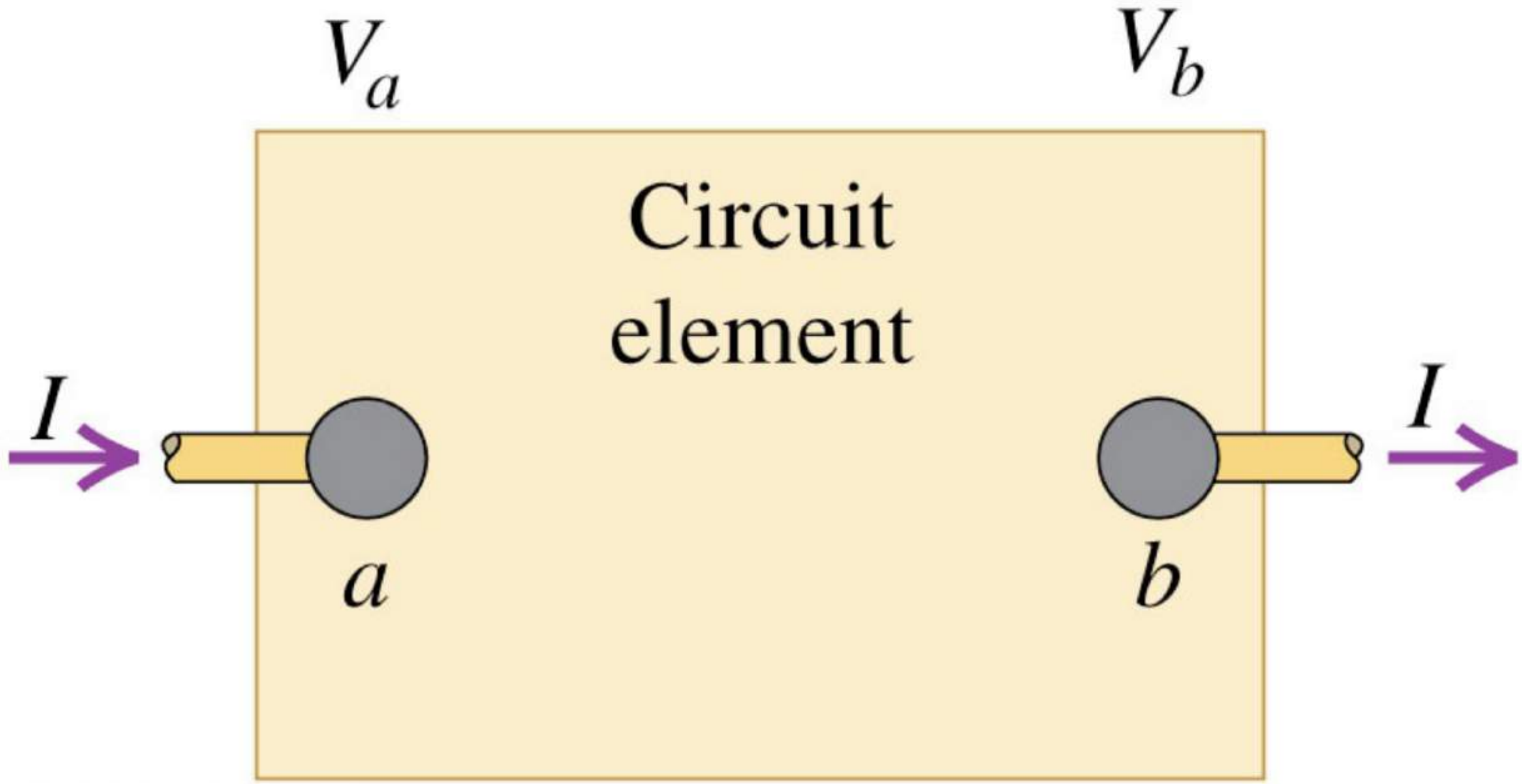


$V_{ab} = \mathcal{E} - Ir$

emf

internal resistance of battery

# Power and Energy





Power: Rate at which energy is delivered to or extracted from a circuit element

$$P = (V_a - V_b)I = V_{ab}I$$

Resister : $V = IR \Rightarrow P = I^2 R$

$$E = Pt$$

EXAMPLE: A 25.0 Ω bulb is connected across the terminals of a 12.0 V battery having 3.50 Ω of internal resistance. What percentage of the power of the battery is dissipated across the internal resistance and hence is not available to the bulb?

$$P = I^2 R$$

$$\frac{P_r}{P_{TOT}} = \frac{I^2 r}{I^2 (R + r)}$$

$$= \frac{r}{R + r}$$

$$= \frac{3.5\ \Omega}{28.5\ \Omega}$$

$$= \underline{12.3\ \%}$$

EXAMPLE: A copper transmission cable 100 km long and 10.0 cm in diameter carries a current of 125 A.

a) What is the potential drop across the cable?

b) How much electrical energy is dissipated as thermal energy every hour?

a) R?

$$R = \frac{\rho L}{A} = \frac{(1.72 \times 10^{-8}\ \Omega \cdot m)(100 \times 10^{3}\ m)}{\pi (0.050\ m)^2}$$

$$= 0.219\ \Omega$$

$$V = IR$$

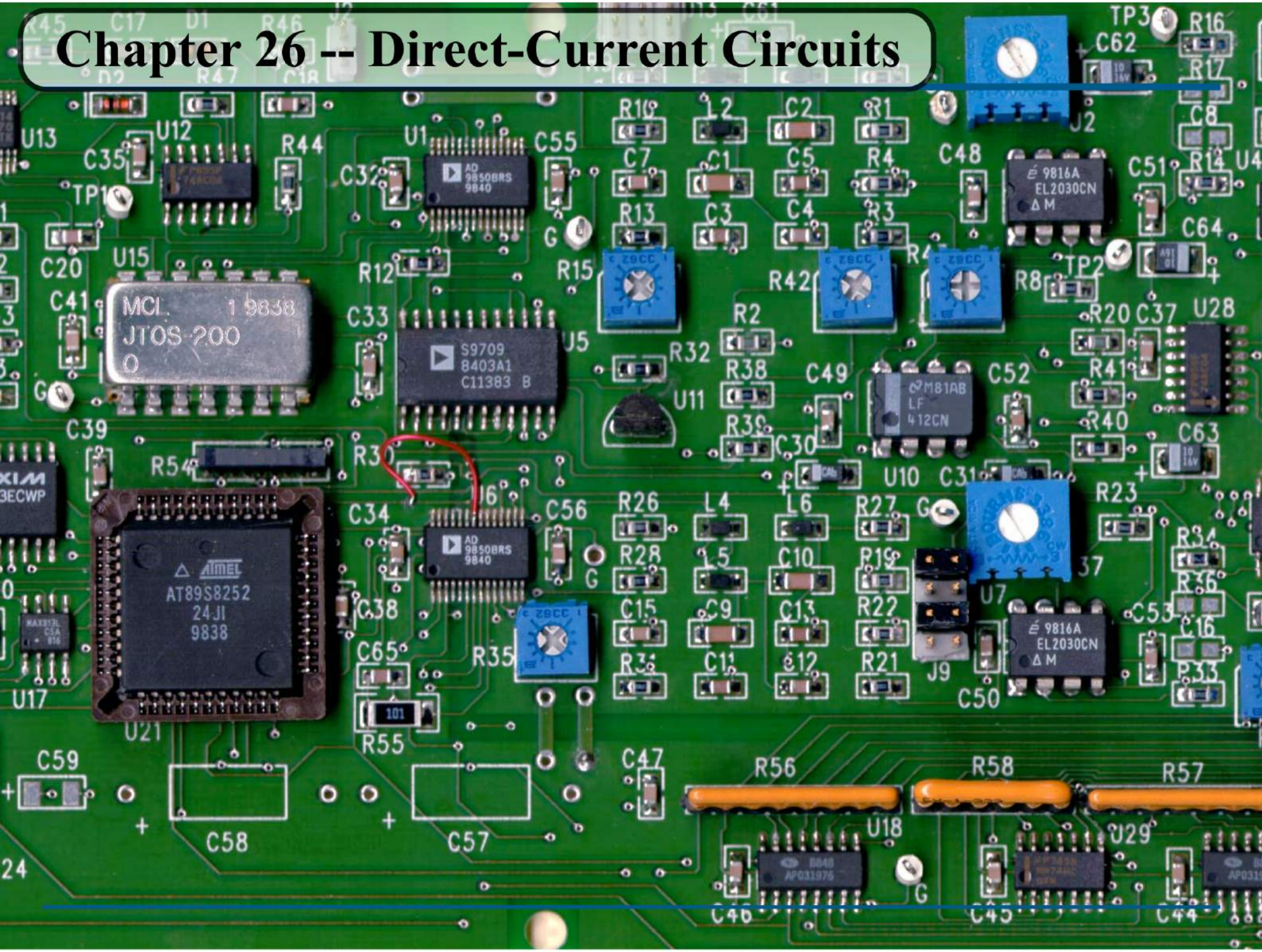
$$= (125\ A)(0.219\ \Omega)$$

$$= 27.4\ V$$

b) $P = IV = (125\ A)(27.4\ V) = 3422\ W$

$$E = Pt = \left(3422\ \frac{J}{s}\right)(3600\ s) = 1.23 \times 10^{7}\ J$$

# Chapter 26 -- Direct-Current Circuits

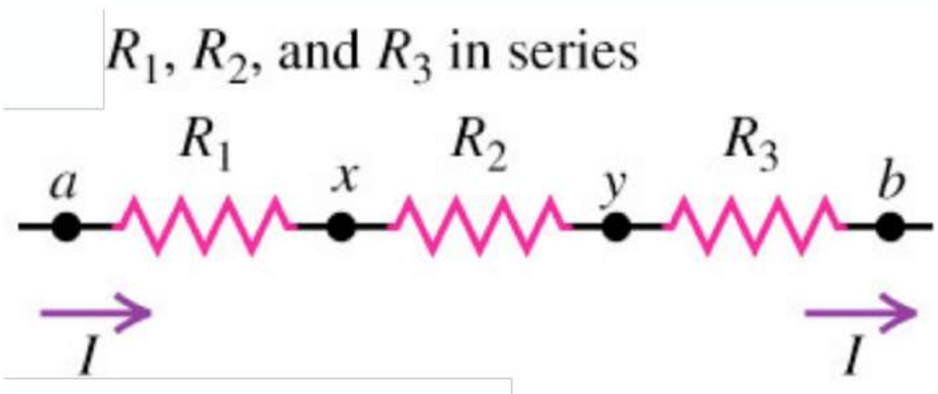


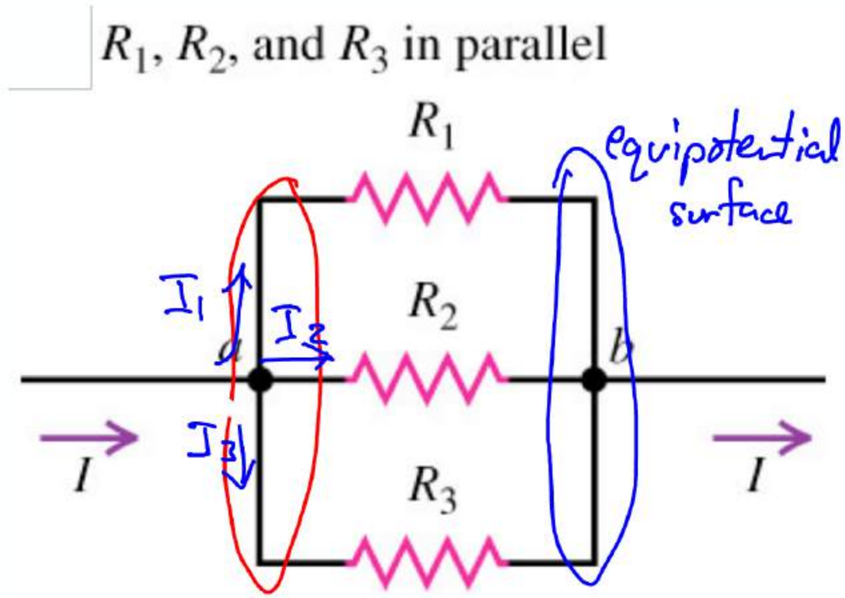
# Goals for Chapter 26

- To analyze circuits having resistors in series and parallel
- To apply Kirchhoff's rules to multiloop circuits
- To analyze circuits containing capacitors and resistors

# Resistors in series and parallel

- Resistors are in *series* if they are connected one after the other so the current is the same in all of them (see left figure below).
- The *equivalent resistance* of a series combination is the *sum* of the individual resistances: $R_{eq} = R_1 + R_2 + R_3 + \ldots$
- Resistors are in *parallel* if they are connected so that the potential difference must be the same across all of them (see right figure below).
- The *equivalent resistance* of a parallel combination is given by $1/R_{eq} = 1/R_1 + 1/R_2 + 1/R_3 + \ldots$



## SERIES

$$V_{ax} = I R_1$$

$$V_{xy} = I R_2$$

$$V_{yb} = I R_3$$

$$V_{ab} = V_{ax} + V_{xy} + V_{yb}$$

$$= I ( R_1 + R_2 + R_3 )$$

$$\frac{V_{ab}}{I} = R_1 + R_2 + R_3$$

$$R_{eq} = R_1 + R_2 + R_3$$

## PARALLEL

$$I = I_1 + I_2 + I_3$$

$$I_1 = \frac{V_{ab}}{R_1} , I_2 = \frac{V_{ab}}{R_2}$$

$$I_3 = \frac{V_{ab}}{R_3}$$

$$I = \frac{V_{ab}}{R_1} + \frac{V_{ab}}{R_2} + \frac{V_{ab}}{R_3}$$

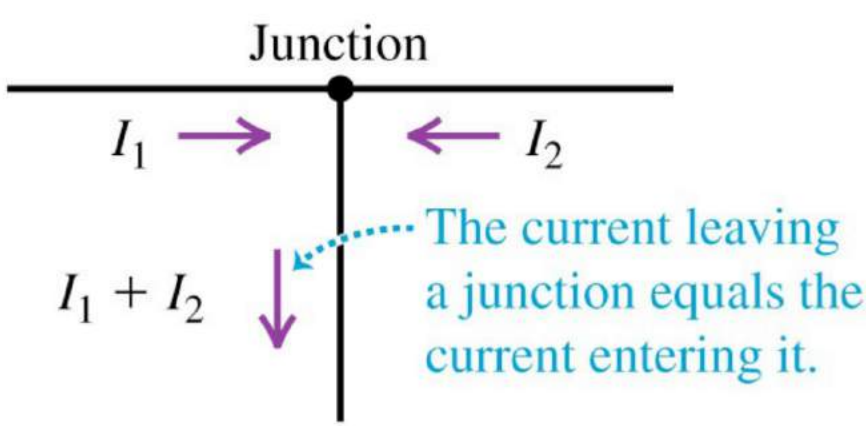
$$\frac{I}{V_{ab}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

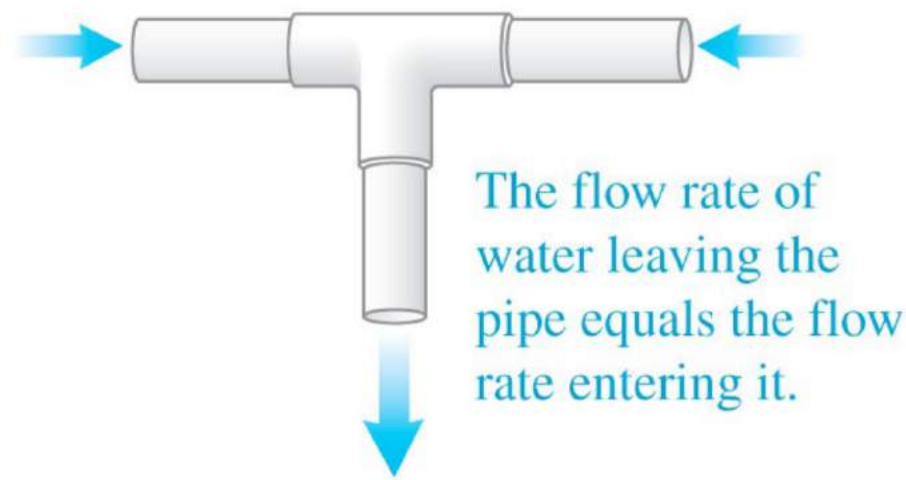
# Kirchoff's Rules

- Kirchhoff's *junction rule*: The algebraic sum of the currents into any junction is zero: $\Sigma I = 0$. Charge cannot accumulate at a junction.
- Kirchhoff's *loop rule*: The algebraic sum of the potential differences in any loop must equal zero: $\Sigma V = 0$.
For every closed loop energy must be conserved.

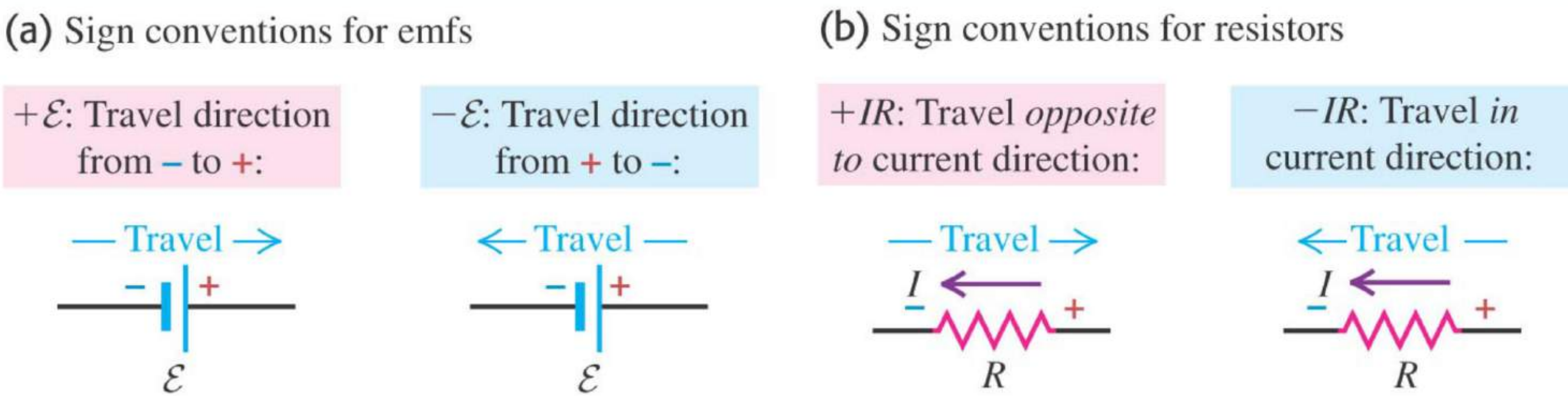
(a) Kirchhoff's junction rule

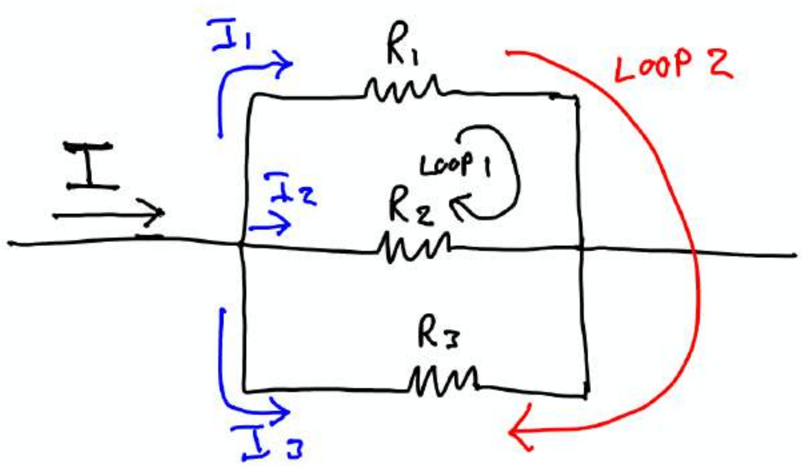



(b) Water-pipe analogy



# Sign convention for the loop rule



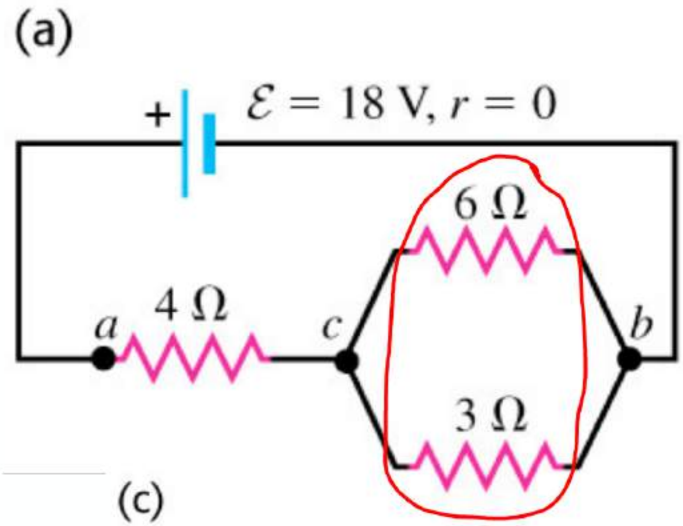




$$\sum V_1 = -I_1 R_1 + I_2 R_2 = 0$$

$$\sum V_2 = -I_1 R_1 + I_3 R_3 = 0$$

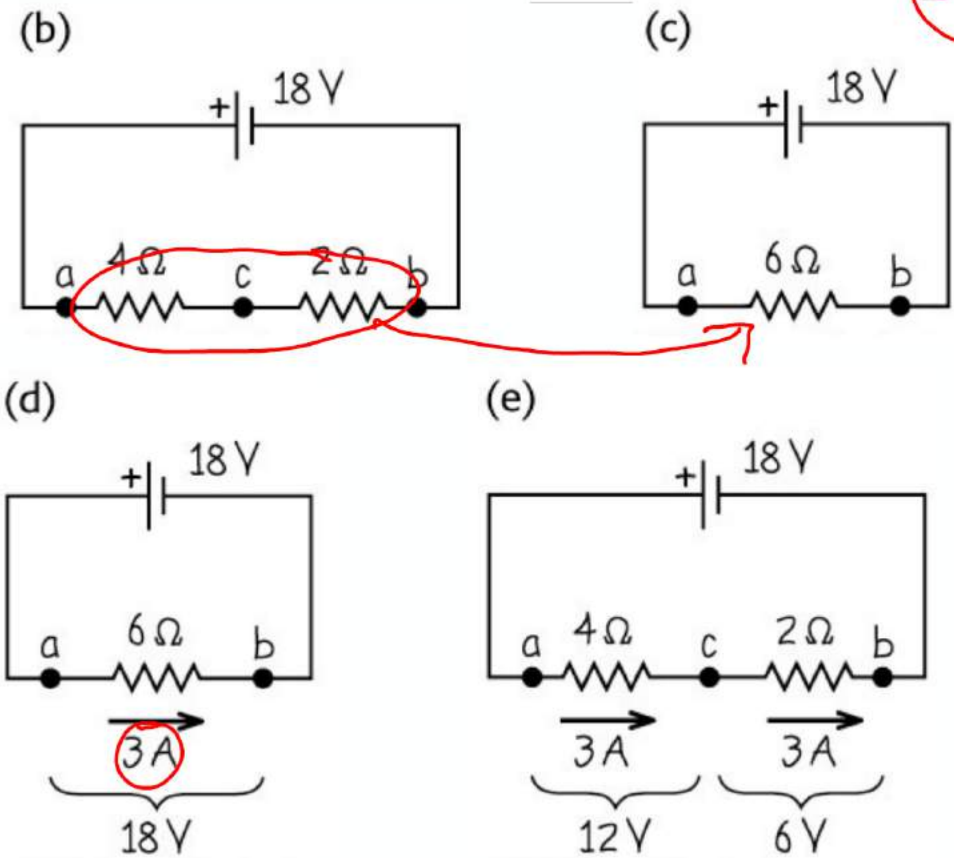
# Equivalent resistance

Find the equivalent resistance of the network and the current in each resistor.




$$\frac{1}{R_{eq}} = \frac{1}{6\Omega} + \frac{1}{3\Omega} = \frac{3}{6\Omega}$$

$$R_{eq} = 2\Omega$$

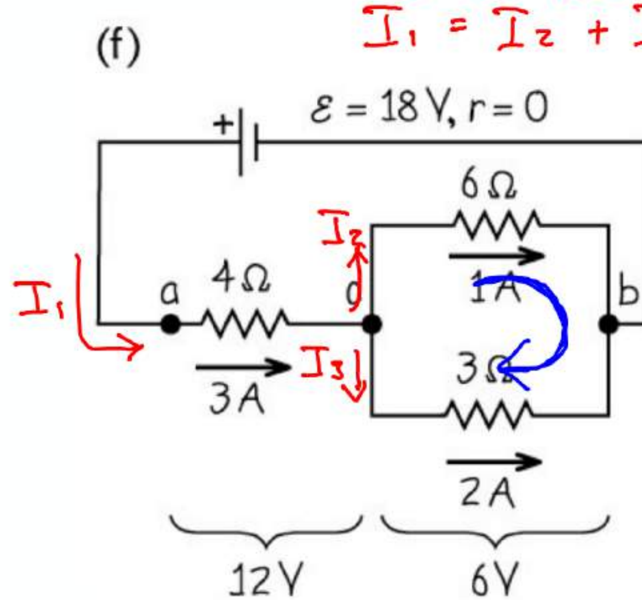



$V = IR$

$I = \frac{V}{R} = \frac{18V}{6\Omega} = 3A$

JUNCTION RULE:

$I_1 = I_2 + I_3$



JUNCTION RULE: $I_2 = 3A - I_3$

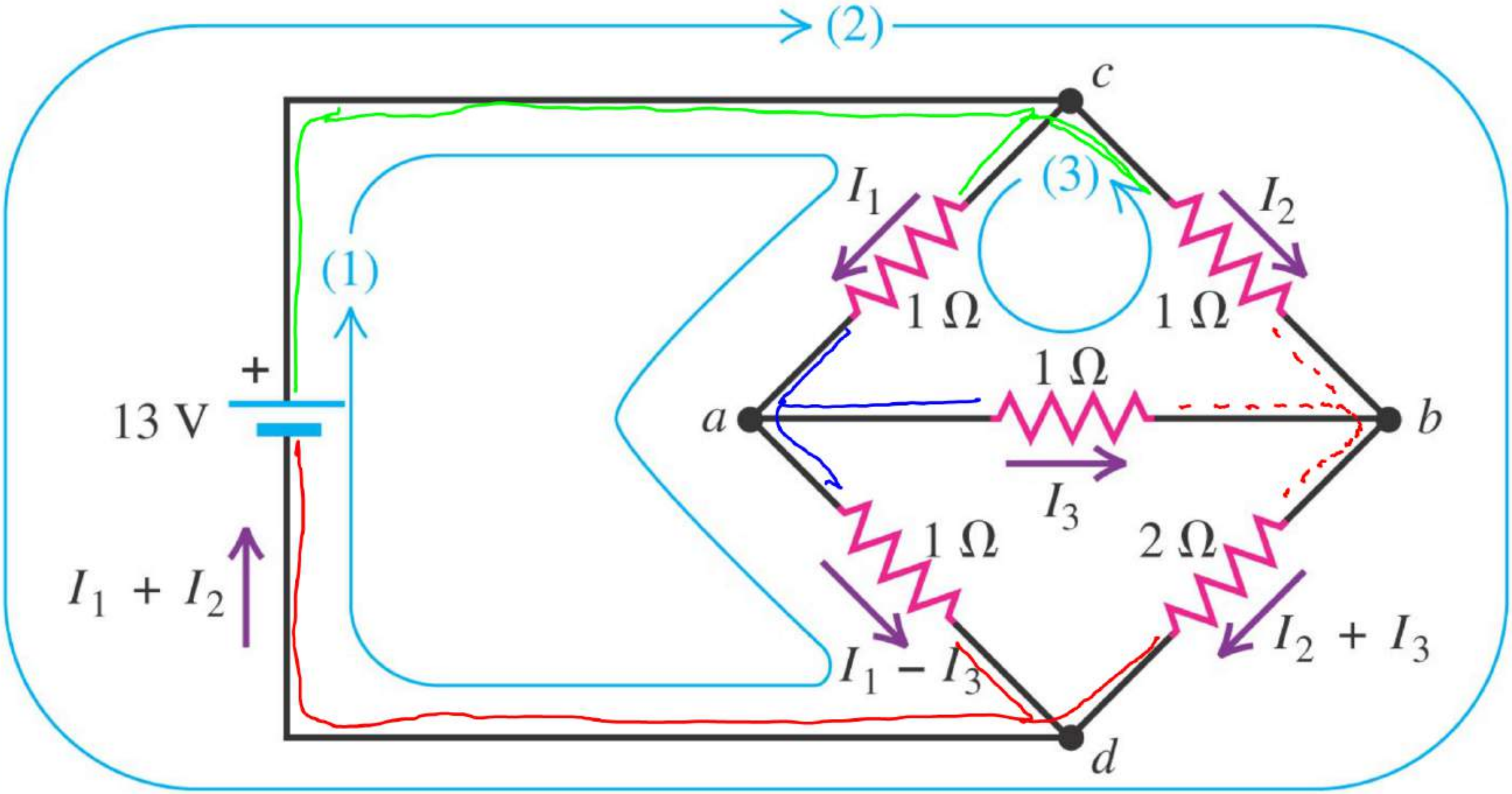
LOOP RULE: $-I_2(6\Omega) + I_3(3\Omega) = 0$

$$-(3A - I_3)6\Omega + I_3(3\Omega) = 0$$

$$I_3 = \frac{18\,V}{9\Omega} = \underline{2A}$$

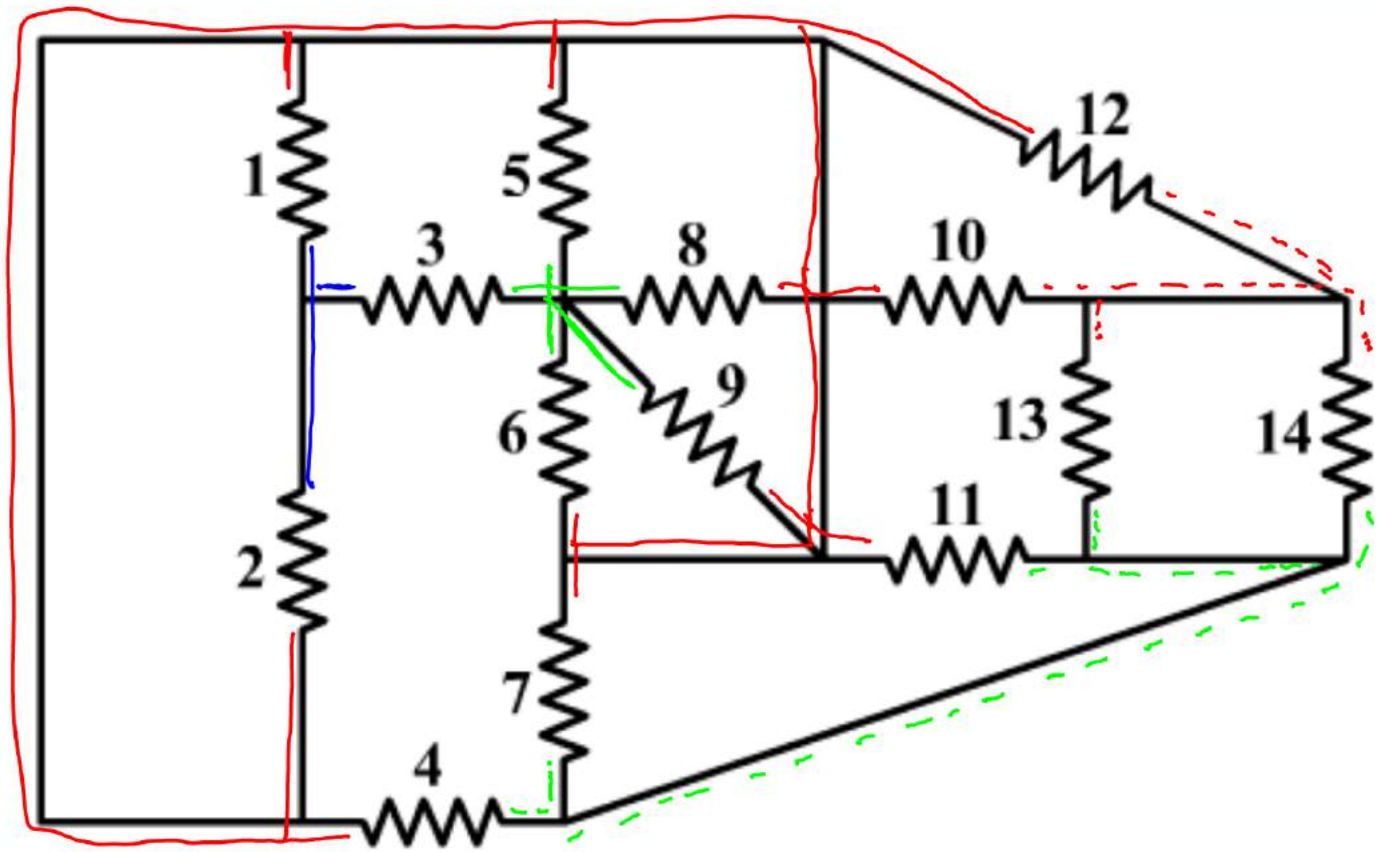
$$I_2 = \underline{1\,A}$$

# A complex network -- can't be reduced!



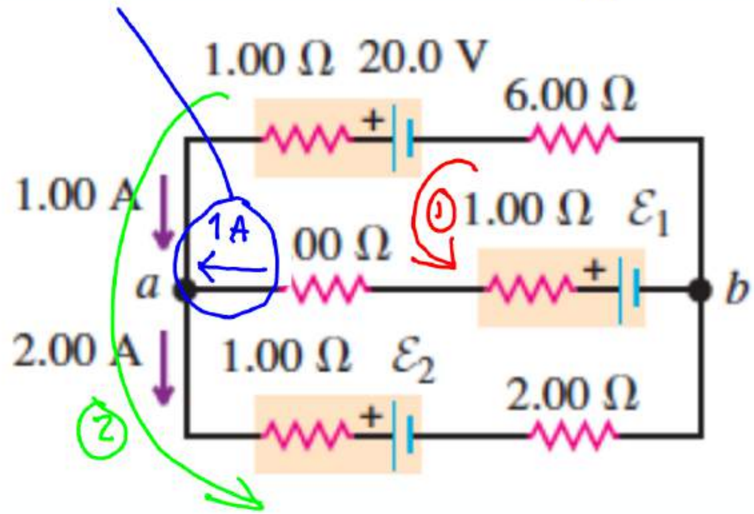
# Which one of these resistors are in parallel?

1 : 2
3 : none
4 : 7, 11
5 : 6, 8, 9
10 : 12
13 : 14



# Example

**26.26** • Find the emfs $\mathcal{E}_1$ and $\mathcal{E}_2$ in the circuit of Fig. E26.26, and find the potential difference of point $b$ relative to point $a$.




LOOP 1

$$20.0\ V - (1.00\ A)(1.00\ \Omega) + (1.00\ A)(4.00\ \Omega) + (1.00\ A)(1.00\ \Omega) - \mathcal{E}_1 - (1.00\ A)(6.00\ \Omega) = 0$$

Solving the above equation gives: $\mathcal{E}_1 = 18.0\ V$

LOOP 2

$$20.0\ V - (1.00\ A)(1.00\ \Omega) - (2.00\ A)(1.00\ \Omega) - \mathcal{E}_2 - (2.00\ A)(2.00\ \Omega) - (1.00\ A)(6.00\ \Omega) = 0$$

$$\mathcal{E}_2 = 7.0\ V$$

To find $V_{ba}$, start at a and add potential changes on the path towards b. Moving along the lower branch:

$$V_{ba} = V_b - V_a = -(2.00\ A)(1.00\ \Omega) - 7.0\ A - (2.00\ A)(2.00\ \Omega)$$
$$= -13.0\ V$$

(b is at 13.0 V lower potential than a)