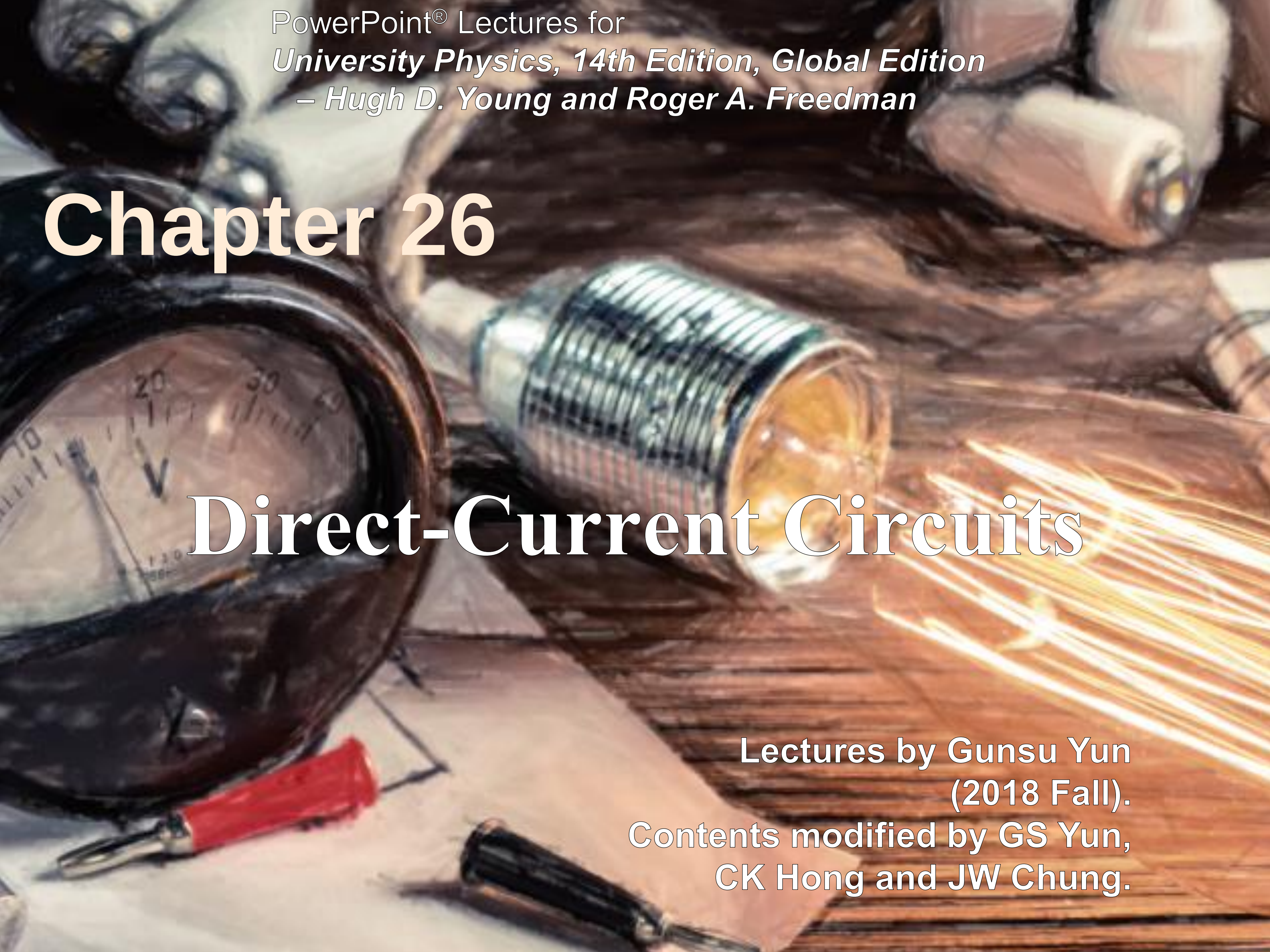

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– Hugh D. Young and Roger A. Freedman

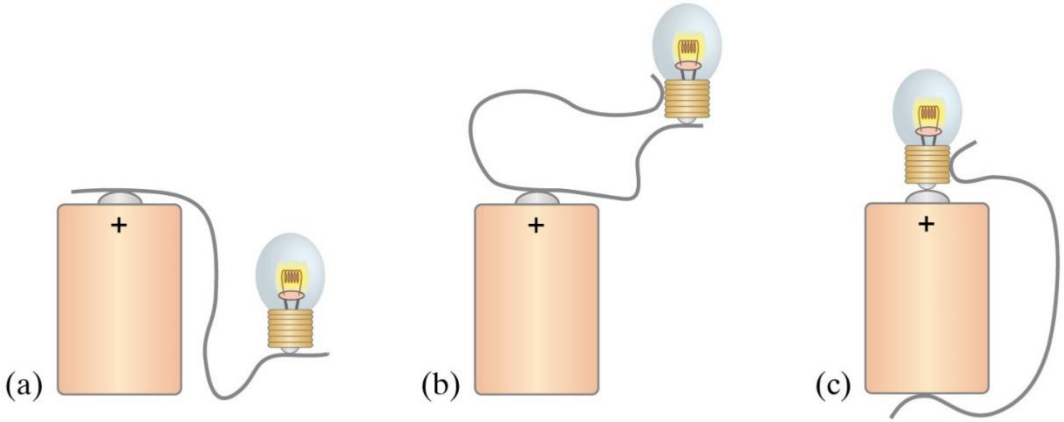
Chapter 26

Direct-Current Circuits

Lectures by Gunsu Yun
(2018 Fall).
Contents modified by GS Yun,
CK Hong and JW Chung.

Goals for Chapter 26

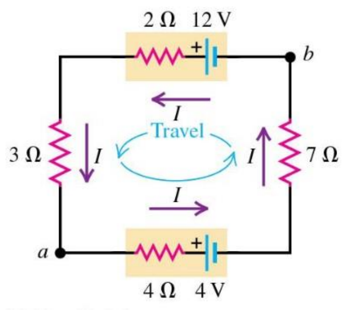
- **Direct current (**cf. alternating current)
- **Resistors** in series and parallel
- **Kirchhoff's rules**
- **R-C circuits**
- Electrical power distribution

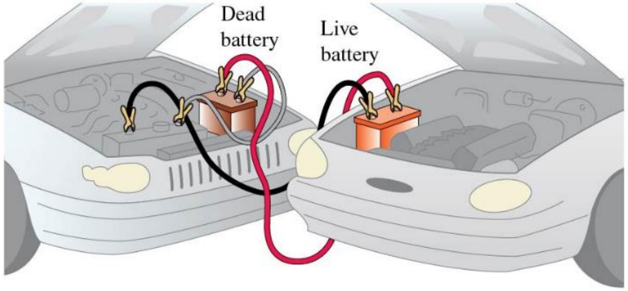


dc versus ac

- **Direct-current (dc)** – the direction of the current does not change with time.

  Ex. Flashlights, automobile wiring systems





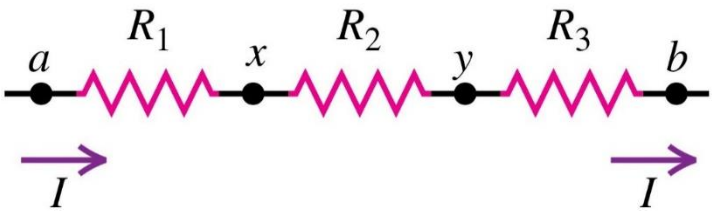
- **Alternating current (ac)** – the current oscillates back and forth.

  Ex. household electrical power

- The same principles for analyzing networks apply to both kinds of circuits.

26.1 Resistors in series and parallel

- **Resistors in series**: same current



- **Equivalent resistance:**

Resistors in series:

$$R_{\text{eq}} = R_1 + R_2 + R_3 + \cdots$$

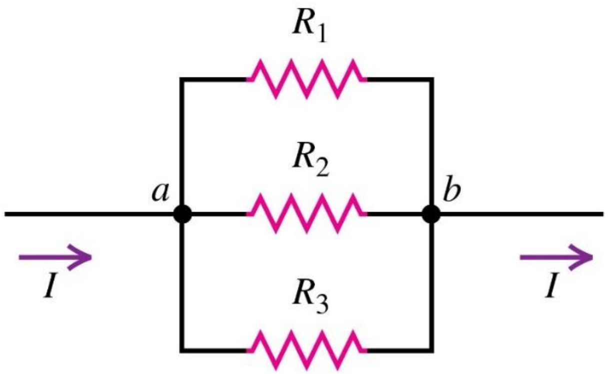
Equivalent resistance of series combination

Resistances of individual resistors

$$
\begin{aligned}
V_{ab} &= V_{ax} + V_{xy} + V_{yb} \\
IR_{\text{eq}} &= IR_1 + IR_2 + IR_3 = I(R_1 + R_2 + R_3)
\end{aligned}
$$

Resistors in parallel

- **Resistors in parallel**: same potential difference



- **Equivalent resistance:**

Resistors in parallel:

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

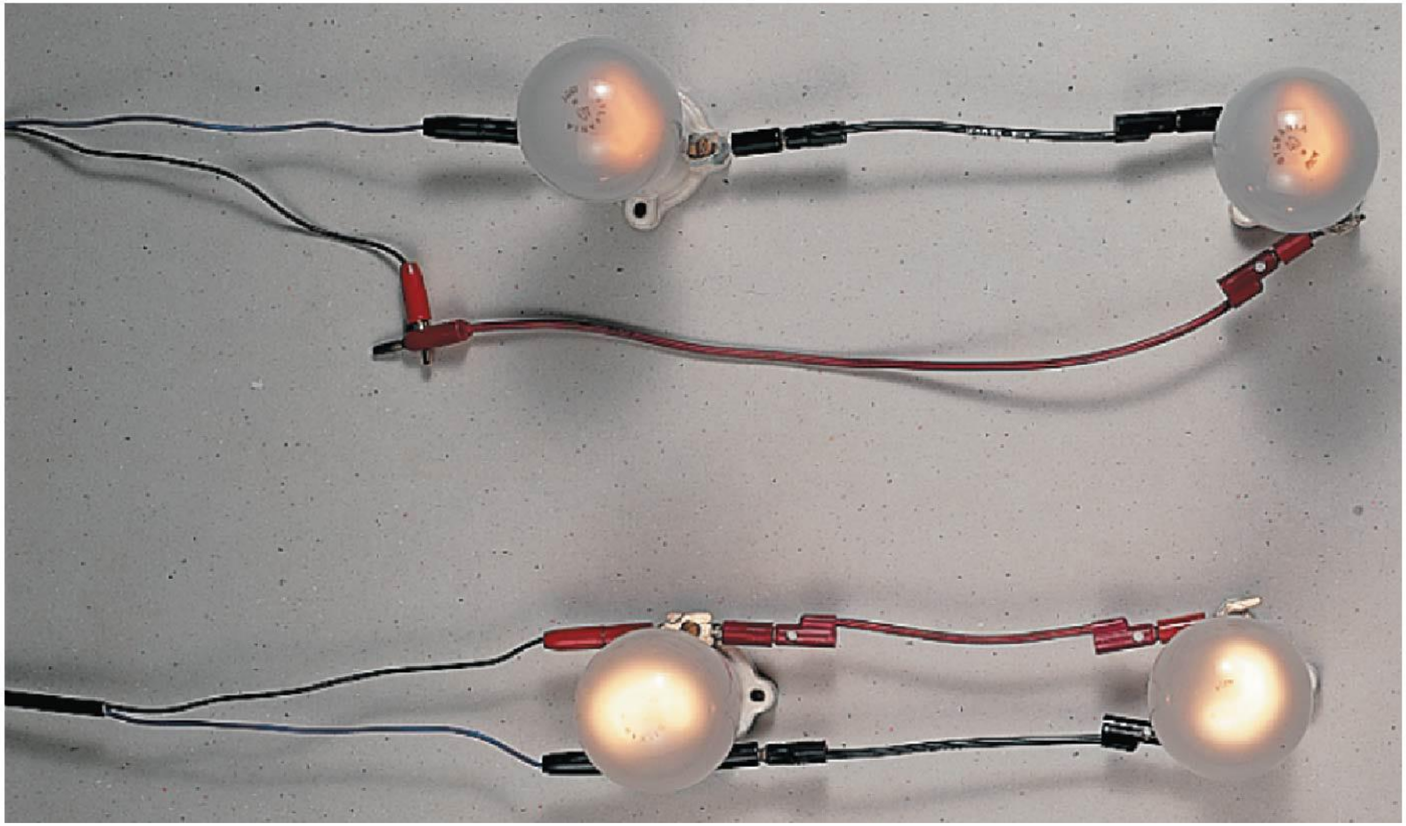
Equivalent resistance of parallel combination

Resistances of individual resistors

$$\begin{aligned} I &= I_1 + I_2 + I_3 \\ \frac{V_{ab}}{R_{eq}} &= \frac{V_{ab}}{R_1} + \frac{V_{ab}}{R_2} + \frac{V_{ab}}{R_2} \end{aligned}$$

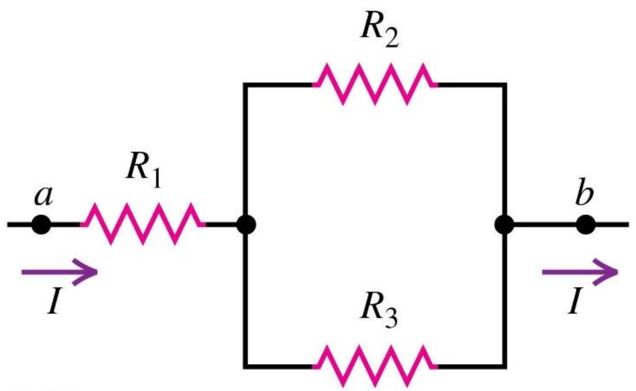
Series versus parallel combinations

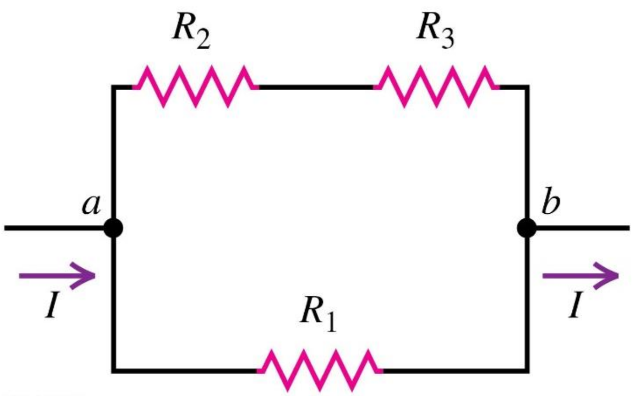
When connected to the same source, two incandescent light bulbs in series draw less power and glow less brightly than in parallel.



Series and parallel network

- Resistors can be connected in **combinations** of series and parallel.
- Reduce the circuit to series and parallel combinations step by step.



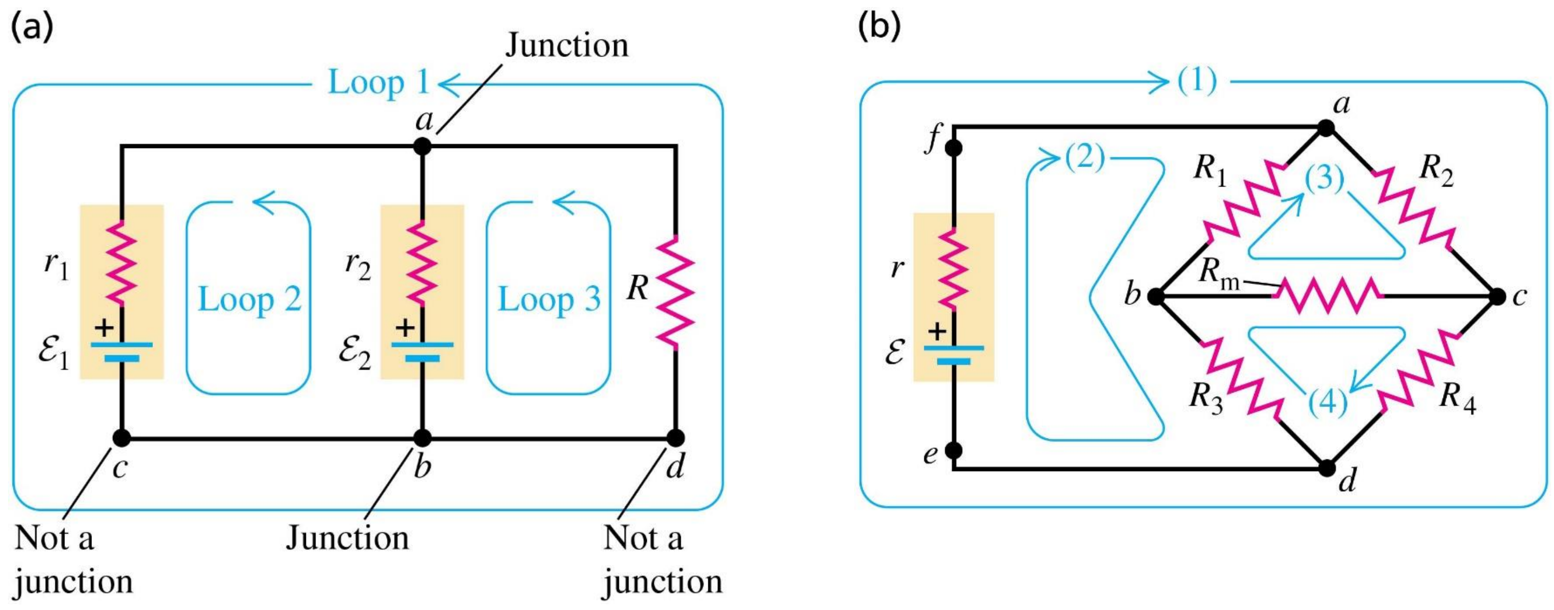


$$\begin{aligned} R_{\mathrm{eq}} &= R_1 + (R_2 || R_3) \\ &= R_1 + \left(R_2^{-1} + R_3^{-1}\right)^{-1} \end{aligned}$$

$$\begin{aligned} R_{\mathrm{eq}} &= R_1 || (R_2 + R_3) \\ &= \left(R_1^{-1} + (R_2 + R_3)^{-1}\right)^{-1} \end{aligned}$$

26.2 Kirchhoff's rules

- Many practical resistor networks cannot be reduced to simple series-parallel combinations.
- **Kirchhoff's two rules** are applied to analyze these networks.

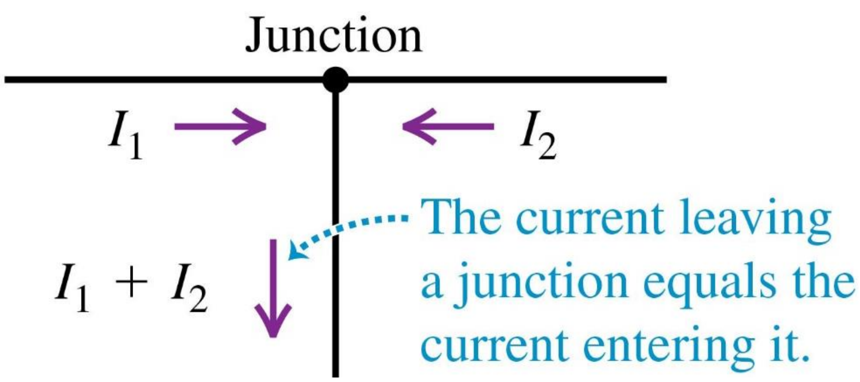


Kirchhoff's junction rule

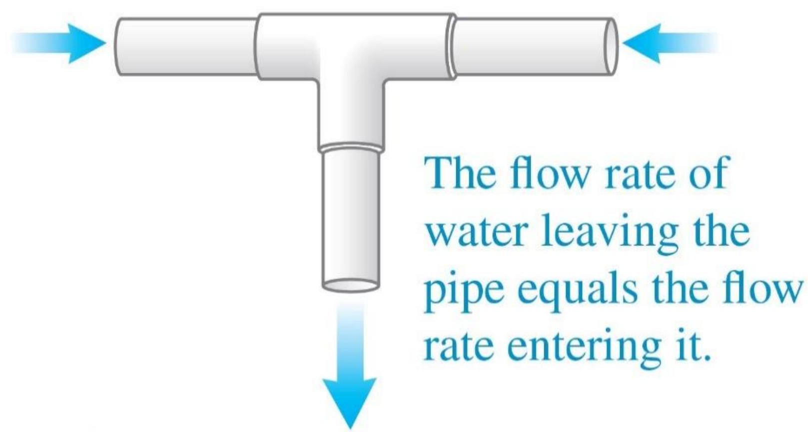
- A **junction** is a point where three or more conductors meet.
- **Kirchhoff's junction rule**:

Kirchhoff's junction rule (valid at any junction):

$$\overbrace{\sum I}^{\text{The sum of the currents into any junction ...}} = 0 \quad \text{... equals zero.}$$



Water pipe analogy:

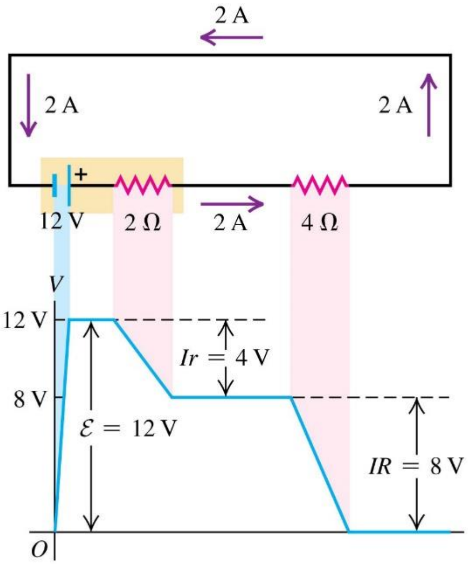


Kirchhoff's loop rule

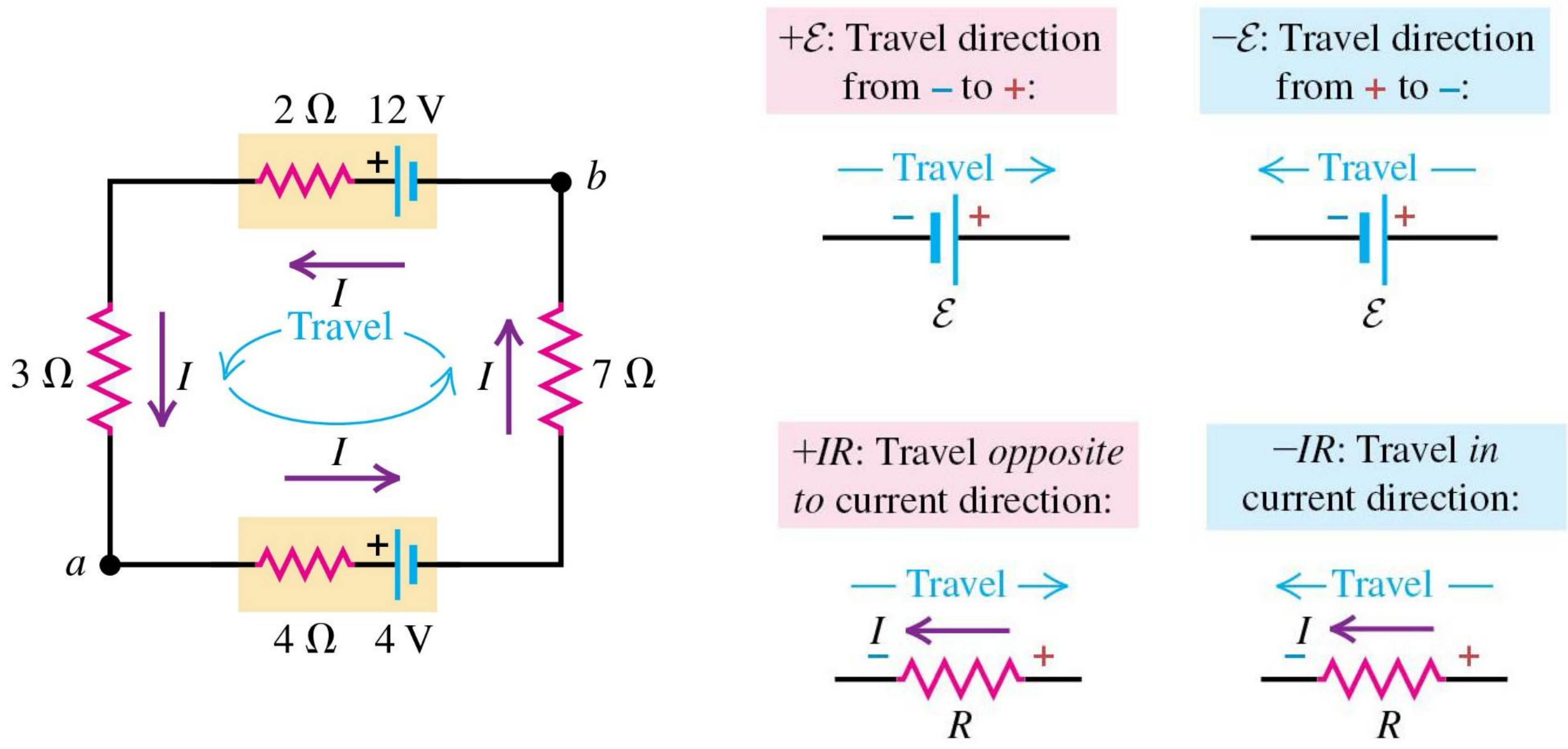
- A **loop** is any closed conducting path.
- **Kirchhoff's loop rule**:

> The sum of the potential differences around any loop ...
>
> **Kirchhoff's loop rule** (valid for any closed loop): $\underbrace{\sum V}_{\text{The sum of the potential differences around any loop ...}} = 0$ ... equals zero.

- The loop rule is a statement that the electrostatic force is conservative.

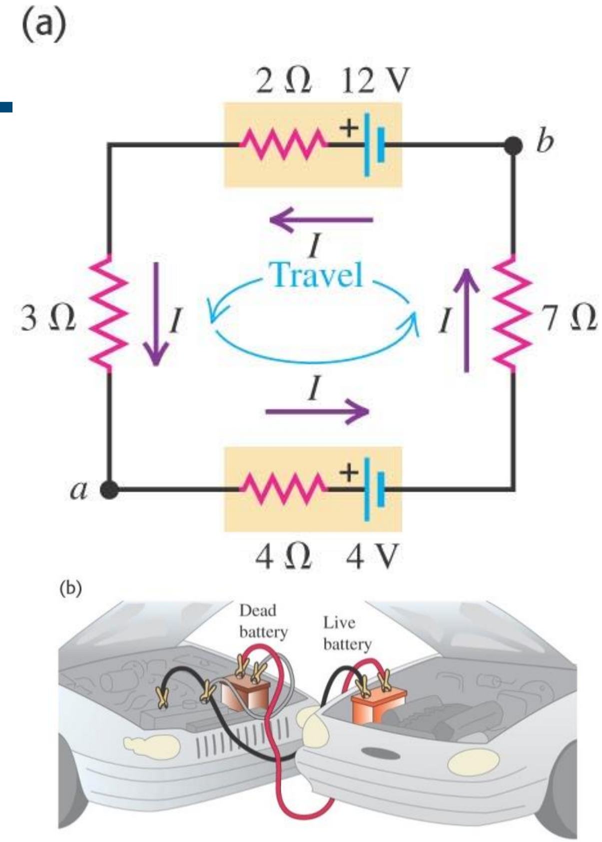


Sign conventions for the loop rule



- In each part of the figure, "Travel" is the direction that we imagine going around the loop, which is not necessarily the "true" direction of the current.

A single-loop circuit



The circuit shown in Fig. 26.10a contains two batteries, each with an emf and an internal resistance, and two resistors. Find (a) the current in the circuit, (b) the potential difference V_{ab}, and (c) the power output of the emf of each battery.

a) Starting at *a*,

$$\begin{aligned} 0 &= -I(4) - 4 - I(7) + 12 - I(2) - I(3) \\ &= -I(4+7+2+3) - 4 + 12 \\ I &= +0.5[A] \end{aligned}$$

b) Starting at *b* toward *a*, $V_{ab} = 0.5(7+4) + 4 = 9.5\ [\mathrm{V}]$

c) The power outputs of the emf of the 12-V and 4-V batteries are

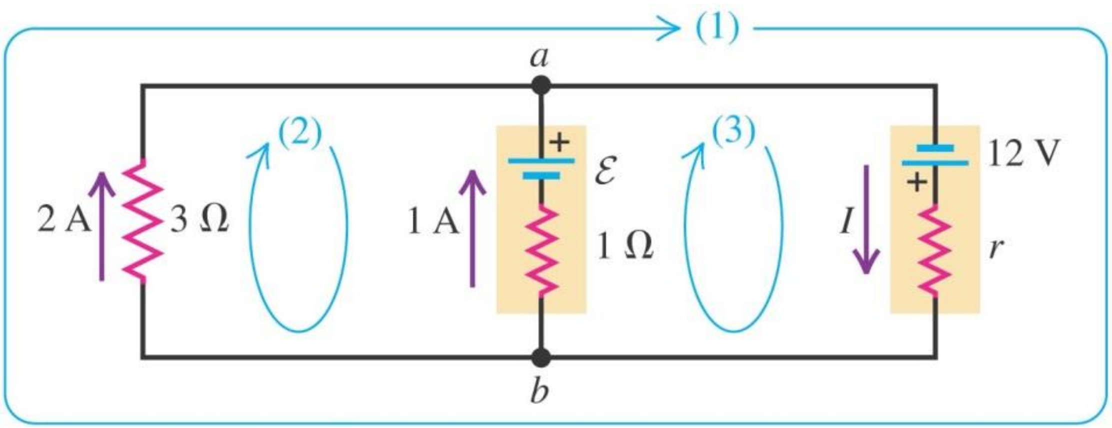
$$\begin{aligned} P_{12\mathrm{V}} = \mathcal{E}I &= (12\ \mathrm{V})(0.5\ \mathrm{A}) = 6\ \mathrm{W} \\ P_{4\mathrm{V}} = \mathcal{E}I &= (-4\ \mathrm{V})(0.5\ \mathrm{A}) = -2\ \mathrm{W} \end{aligned}$$

The negative sign in $\mathcal{E}$ for the 4-V battery appears because the current runs from the higher-potential side of the battery to the lower-potential side.

The negative value of P for the 4-V battery means that it is receiving the energy (coming from the 12-V battery). It will be *recharged* if it is rechargable; otherwise, it will be destroyed.

Charging a battery

In the circuit shown in Fig. 26.11, a 12-V power supply with unknown internal resistance r is connected to a run-down rechargeable battery with unknown emf $\mathcal{E}$ and internal resistance 1 Ω and to an indicator light bulb of resistance 3 Ω carrying a current of 2 A. The current through the run-down battery is 1 A in the direction shown. Find r, $\mathcal{E}$, and the current I through the power supply.



At junction a, $-I + 1 + 2 = 0 \rightarrow \quad I = 3$ [A].

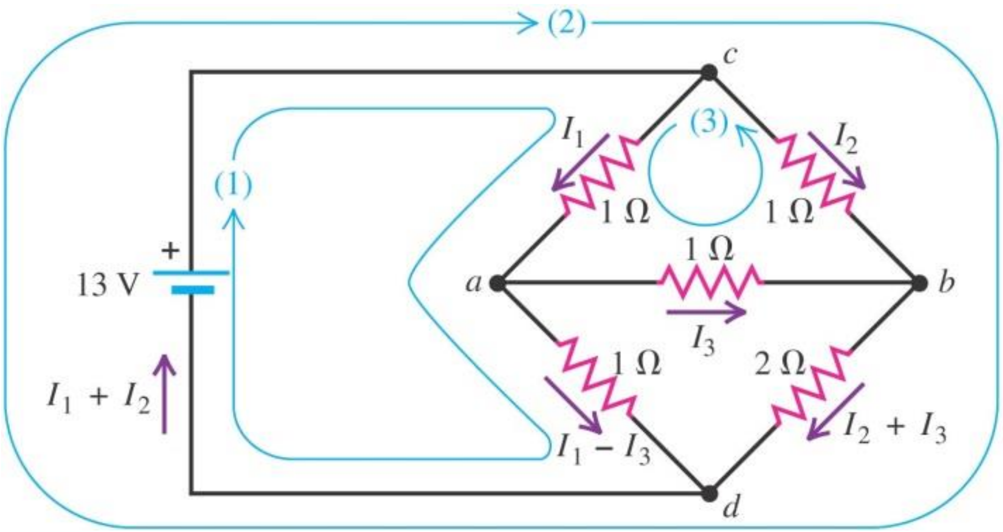
For loop (1), $12 - (3)r - (2)(3) = 0 \rightarrow \quad r = 2$ [Ω].

For loop (2), $-\mathcal{E} + (1)(1) - (2)(3) = 0 \rightarrow \quad \mathcal{E} = -5$ [V].

The negative value for ε means the actual polarity is opposite to that in the figure and the battery is being recharged.

A complex network

Figure 26.12 shows a "bridge" circuit of the type described at the beginning of this section (see Fig. 26.6b). Find the current in each resistor and the equivalent resistance of the network of five resistors.



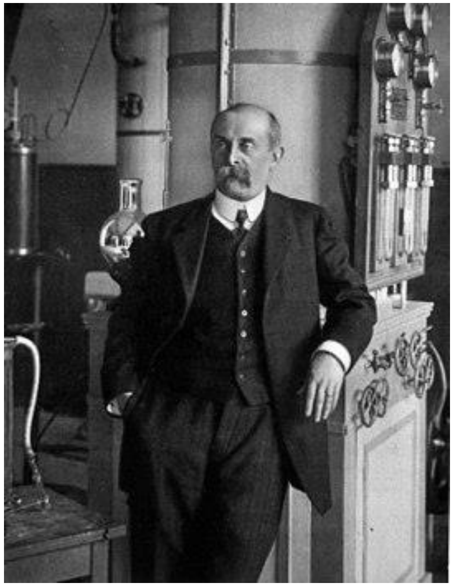
$$
\begin{aligned}
\text{(loop 1)}\ 0 &= 13 - I_1(1) - (I_1 - I_3)(1) \\
\text{(loop 2)}\ 0 &= 13 - I_2(1) - (I_2 + I_3)(2) \\
\text{(loop 3)}\ 0 &= -I_1(1) - I_3(1) + I_2(1)
\end{aligned}
$$

$$\Rightarrow \quad I_1 = 6 \text{ A},\ I_2 = 5 \text{ A},\ I_3 = -1 \text{ A}.$$

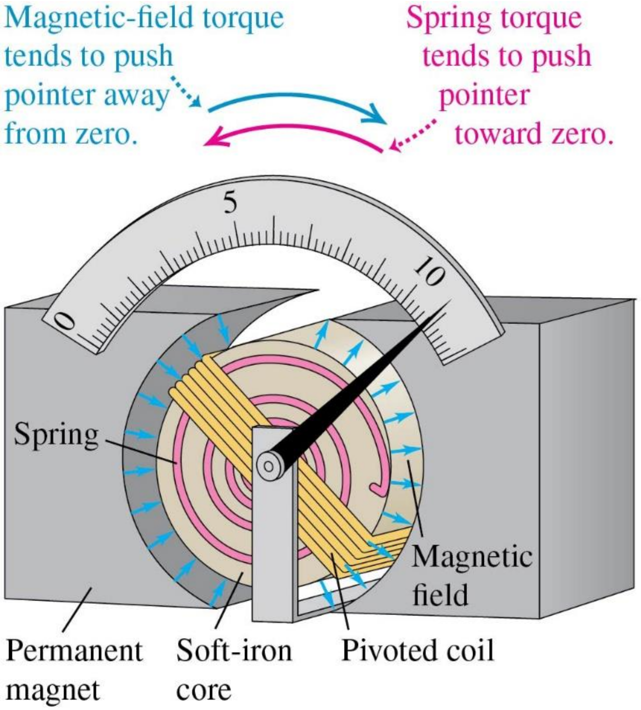
$$\Rightarrow \quad R_{\text{eq}} = \frac{13 \text{ V}}{I_1 + I_2} = \frac{13 \text{ V}}{11 \text{ A}} \approx 1.2\,\Omega$$

26.3 Electrical measuring instruments

- D’Arsonval (다송발) **galvanometer** measures the current that passes through it.
- Many electrical instruments, such as ammeters and voltmeters, use a galvanometer in their design.

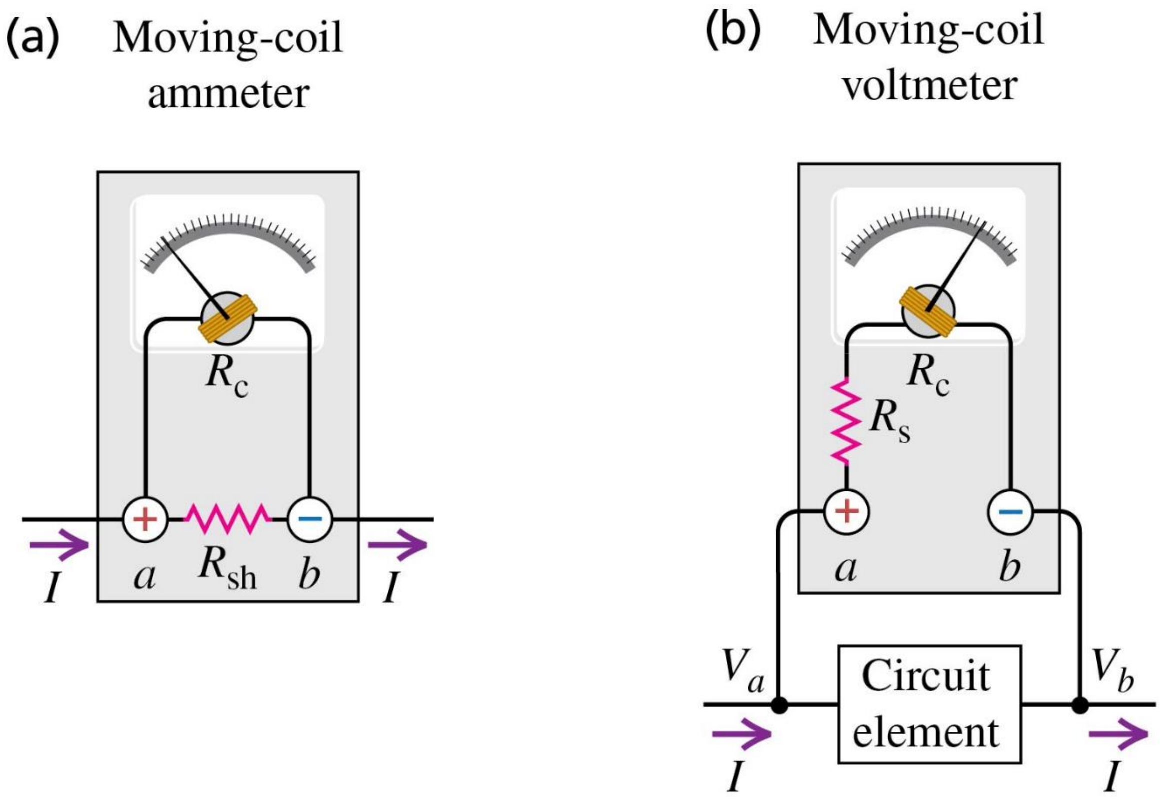


Jacques-Arsène d'Arsonval
(☼1851, †1940)
Electrophysiology



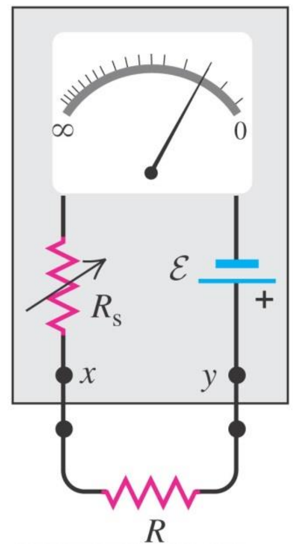
Ammeters and voltmeters

- An **ammeter** measures the current passing through it.
- A **voltmeter** measures the potential difference between two points.

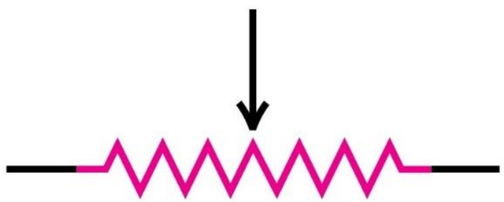


Ohmmeter, potentiometer, and digital multimeter

- An **ohmmeter** consists of a meter, a resistor, and an emf source connected in series.



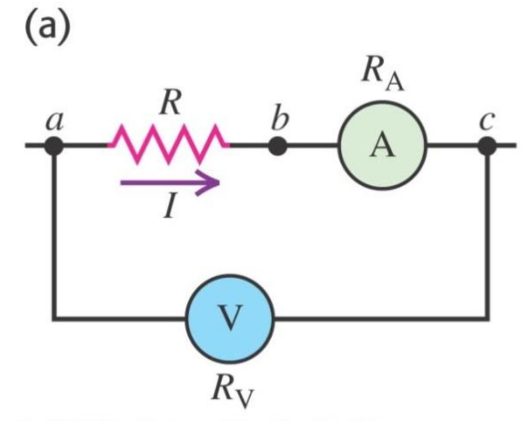
- A **potentiometer** is a variable resistor.



- A digital multimeter can measure voltage, current, or resistance over a wide range.

Ammeters and voltmeters in combination

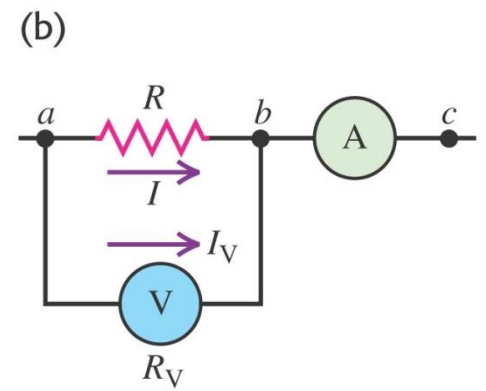
The voltmeter in the circuit of Fig. 26.16a reads 12.0 V and the ammeter reads 0.100 A. The meter resistances are $R_V = 10{,}000\ \Omega$ (for the voltmeter) and $R_A = 2.00\ \Omega$ (for the ammeter). What are the resistance R and the power dissipated in the resistor?



$$
\begin{aligned}
V_{bc} &= IR_A = (0.1)(2.00) = 0.200\ [\mathrm{V}] \\
V_{ab} &= V - V_{bc} = 12.0 - 0.200 = 11.8\ [\mathrm{V}] \\
R &= \frac{V_{ab}}{I} = \frac{11.8}{0.100} = 118\ [\Omega] \ll R_V
\end{aligned}
$$

The power dissipated in the resistor is

$$P = V_{ab}I = (11.8)(0.100) = 1.18\ [\mathrm{W}]$$



Suppose the meters of Example 26.10 are connected to a different resistor as shown in Fig. 26.16b, and the readings obtained on the meters are the same as in Example 26.10. What is the value of this new resistance R, and what is the power dissipated in the resistor?

$$
\begin{aligned}
I_V &= V/R_V = (12.0)/(10{,}000) = 1.20\ [\mathrm{mA}] \\
I &= I_A - I_V = 100 - 1.2 = 98.8\ [\mathrm{mA}] \\
R &= \frac{V_{ab}}{I} = \frac{12.0}{98.8 \times 10^{-3}} = 121\ [\Omega]
\end{aligned}
$$

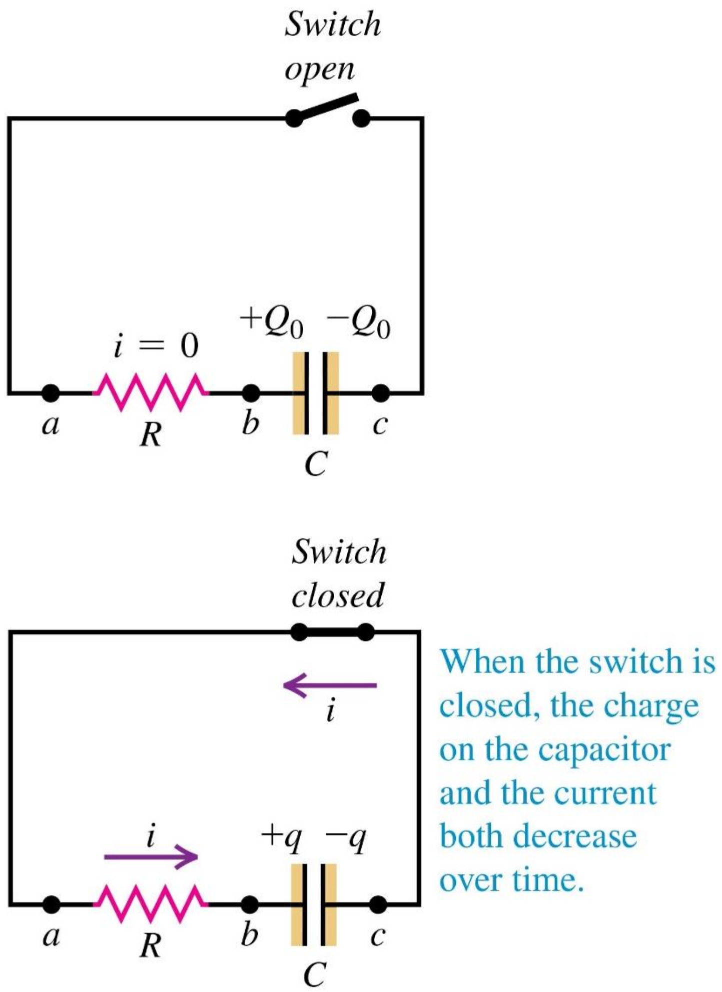
The power dissipated in the resistor is

$$P = V_{ab}I = (12.0)(0.0988) = 1.19\ [\mathrm{W}]$$

26.4 *R-C* circuits

Discharging a capacitor:

Before the switch is closed, the capacitor charge is Q_0.



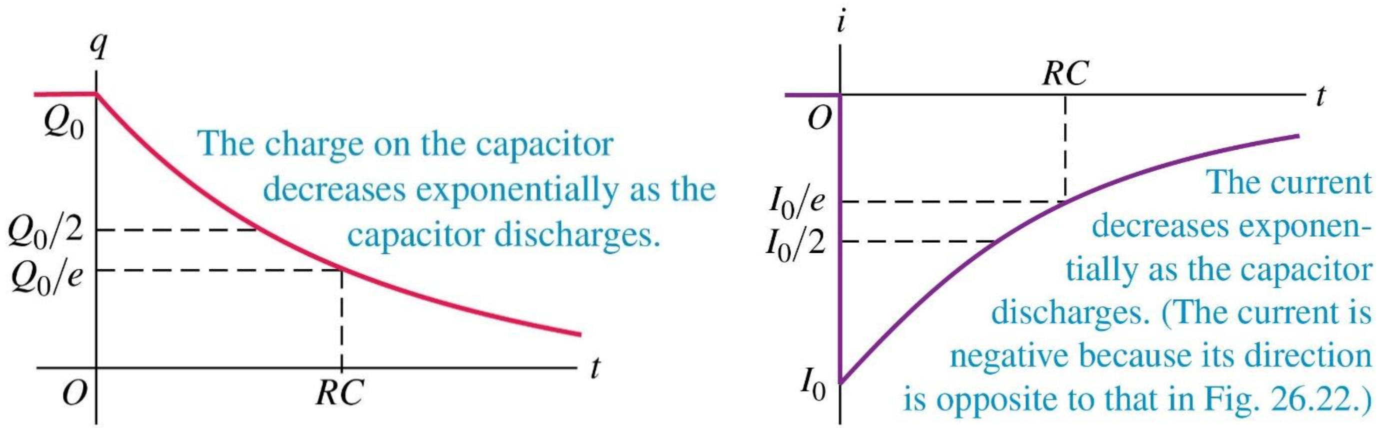
$$\begin{aligned} 0 &= -iR - \frac{q}{C} \\ i &= \frac{dq}{dt} = \frac{-q}{RC} \end{aligned}$$

$$\begin{aligned} q(t) &= q(0)\exp\left(-\frac{t}{RC}\right) = Q_0 \exp\left(-\frac{t}{RC}\right) \\ i(t) &= \frac{dq}{dt} = -\frac{Q_0}{RC}\exp\left(-\frac{t}{RC}\right) \end{aligned}$$

$\tau \equiv RC$: time constant for R-C circuit.

Note: The negative current at the capacitor means it is discharging.

Discharging a capacitor



***R-C* circuit, discharging capacitor:**

Capacitor charge

Initial capacitor charge

$$q = Q_0 e^{-t/RC}$$

Capacitance

Time since switch closed

Resistance

***R-C* circuit, discharging capacitor:**

Current

Initial capacitor charge

Capacitance

$$i = \frac{dq}{dt} = -\frac{Q_0}{RC} e^{-t/RC} = I_0 e^{-t/RC}$$

Time since switch closed

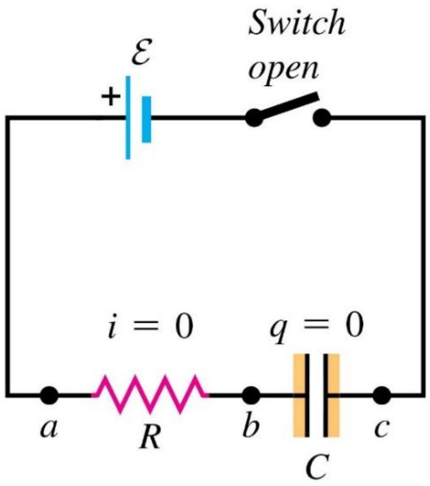
Rate of change of capacitor charge

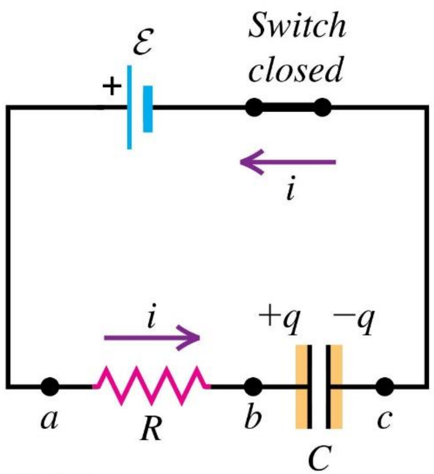
Resistance

Initial current $= -Q_0/RC$

Charging a capacitor

The capacitor is initially uncharged.





When the switch is closed, the charge on the capacitor increases over time while the current decreases.

$$
\begin{aligned}
0 &= \mathcal{E} - iR - \frac{q}{C} \\
i &= \frac{dq}{dt} = \frac{1}{R}\left(\mathcal{E} - \frac{q}{C}\right) = \frac{-1}{RC}\left(-C\mathcal{E} + q\right)
\end{aligned}
$$

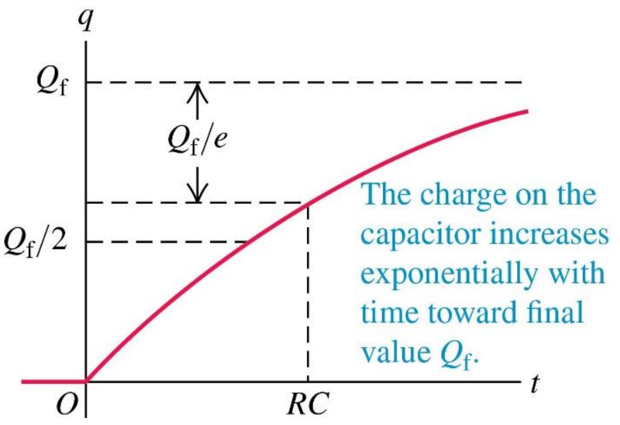
Let $q' = q - C\mathcal{E}$. (Note $dq'/dt = qd/dt$.)

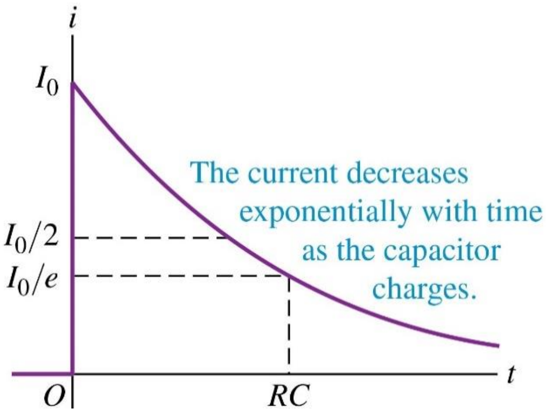
$$
\frac{dq'}{dt} = \frac{-1}{RC} q'
$$

$$
\begin{aligned}
q'(t) &= q'(0)\exp(-t/RC) = -C\mathcal{E}\exp(-t/RC) \\
q(t) &= q' + C\mathcal{E} = C\mathcal{E}\left(1 - \exp(-t/RC)\right) \\
i(t) &= \frac{dq}{dt} = \frac{dq'}{dt} = \frac{\mathcal{E}}{R}\exp(-t/RC)
\end{aligned}
$$

$\tau \equiv RC$: time constant for R-C circuit.

Charging a capacitor





R-C circuit, charging capacitor:

Capacitor charge, Capacitance, Final capacitor charge $= C\mathcal{E}$

$$q = C\mathcal{E}\left(1 - e^{-t/RC}\right) = Q_f\left(1 - e^{-t/RC}\right)$$

Battery emf, Time since switch closed, Resistance

R-C circuit, charging capacitor:

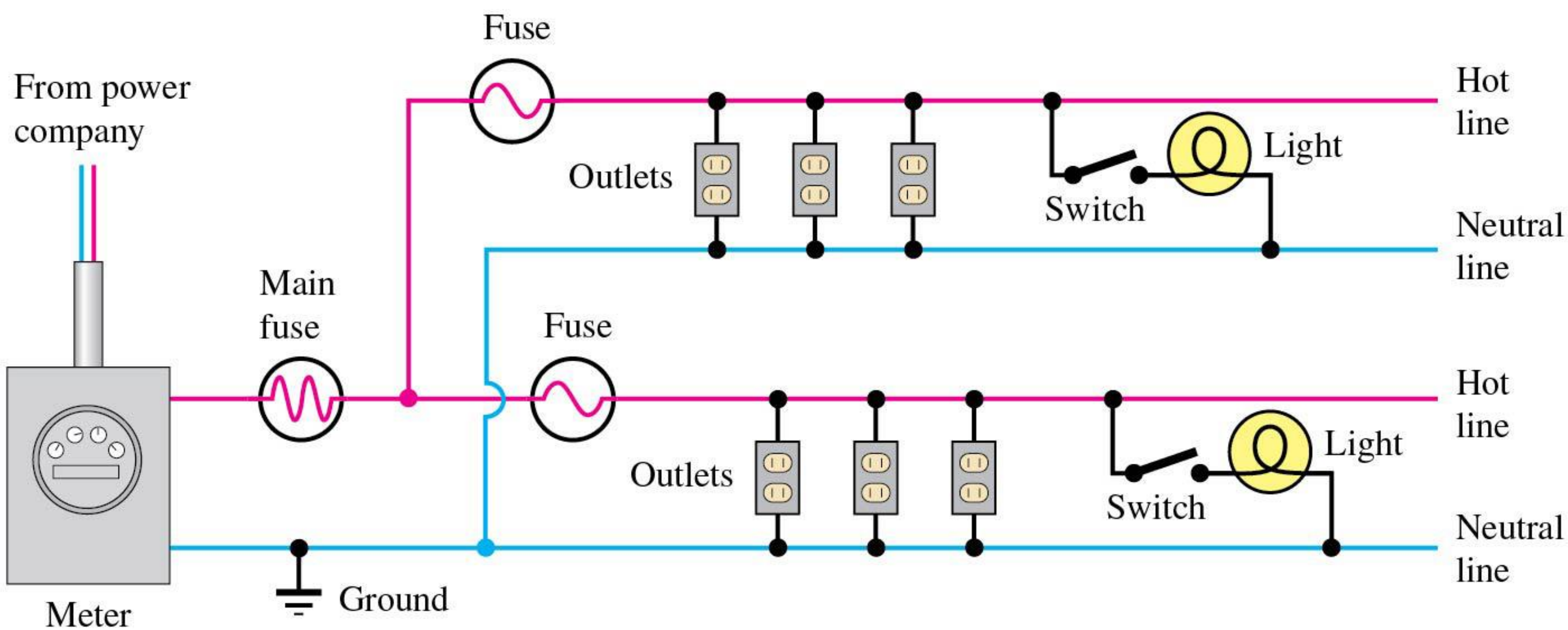
Current, Battery emf, Time since switch closed, Initial current $= \mathcal{E}/R$

$$i = \frac{dq}{dt} = \frac{\mathcal{E}}{R}e^{-t/RC} = I_0 e^{-t/RC}$$

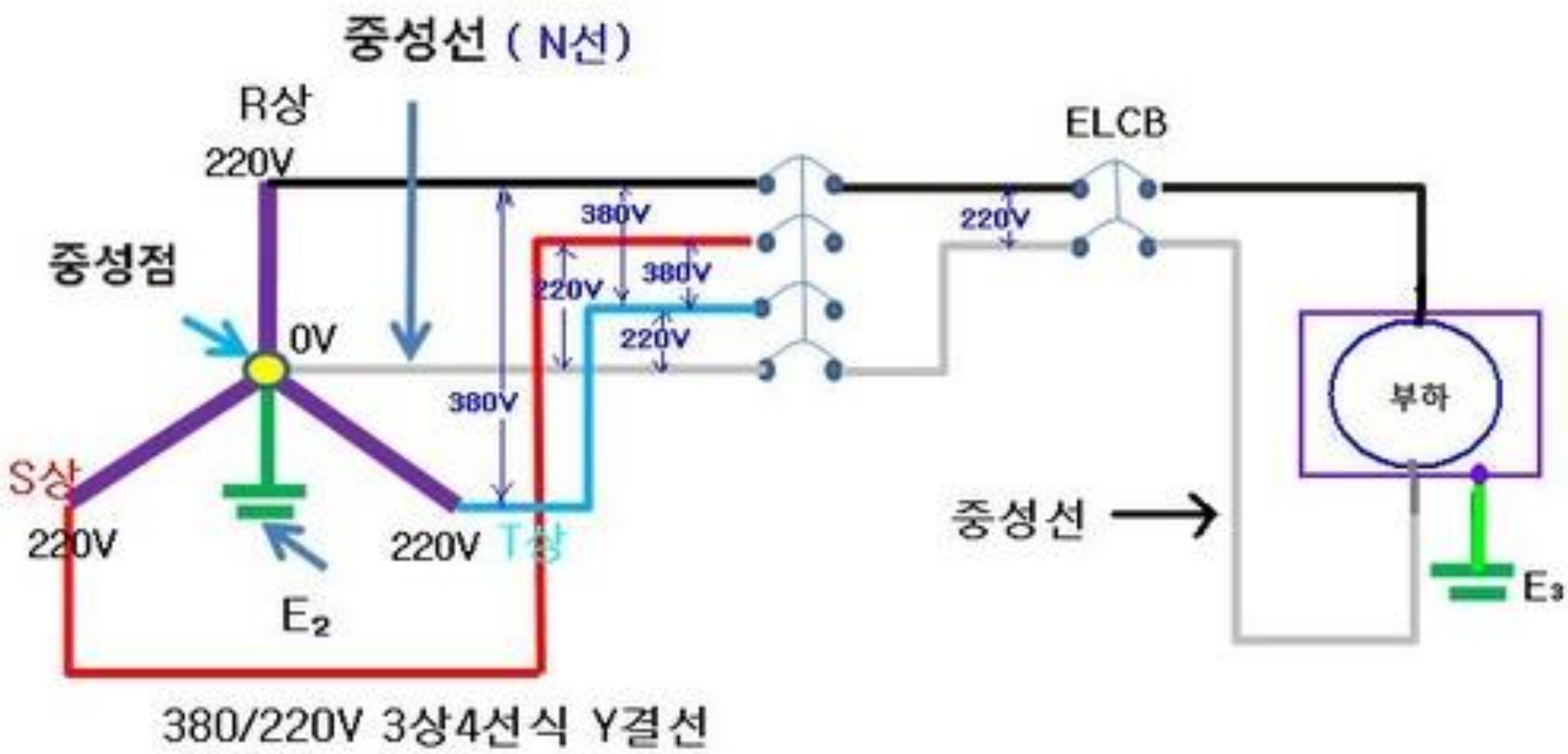
Rate of change of capacitor charge, Resistance, Capacitance

26.5 Power distribution systems*

- Basic house wiring
- The "**hot line**" has an alternating sinusoidal voltage with a root-mean-square value of 120 V.
- The "**neutral line**" is connected to "**ground**," which is usually an electrode driven into the earth.



220V distribution systems*



$$\begin{aligned} V_S &= V_0 \sin(2\pi f t + 2\pi/3) \\ V_R &= V_0 \sin(2\pi f t) \\ V_T &= V_0 \sin(2\pi f t - 2\pi/3) \end{aligned}$$

$$\begin{aligned} (V_S - 0)_{\mathrm{rms}} &\equiv \left\langle |V_R|^2 \right\rangle^{-1/2} = V_0/\sqrt{2} = 220 \text{ [V]} \\ (V_S - V_R)_{\mathrm{rms}} &= \sqrt{3}(V_0/\sqrt{2}) = 380 \text{ [V]} \end{aligned}$$

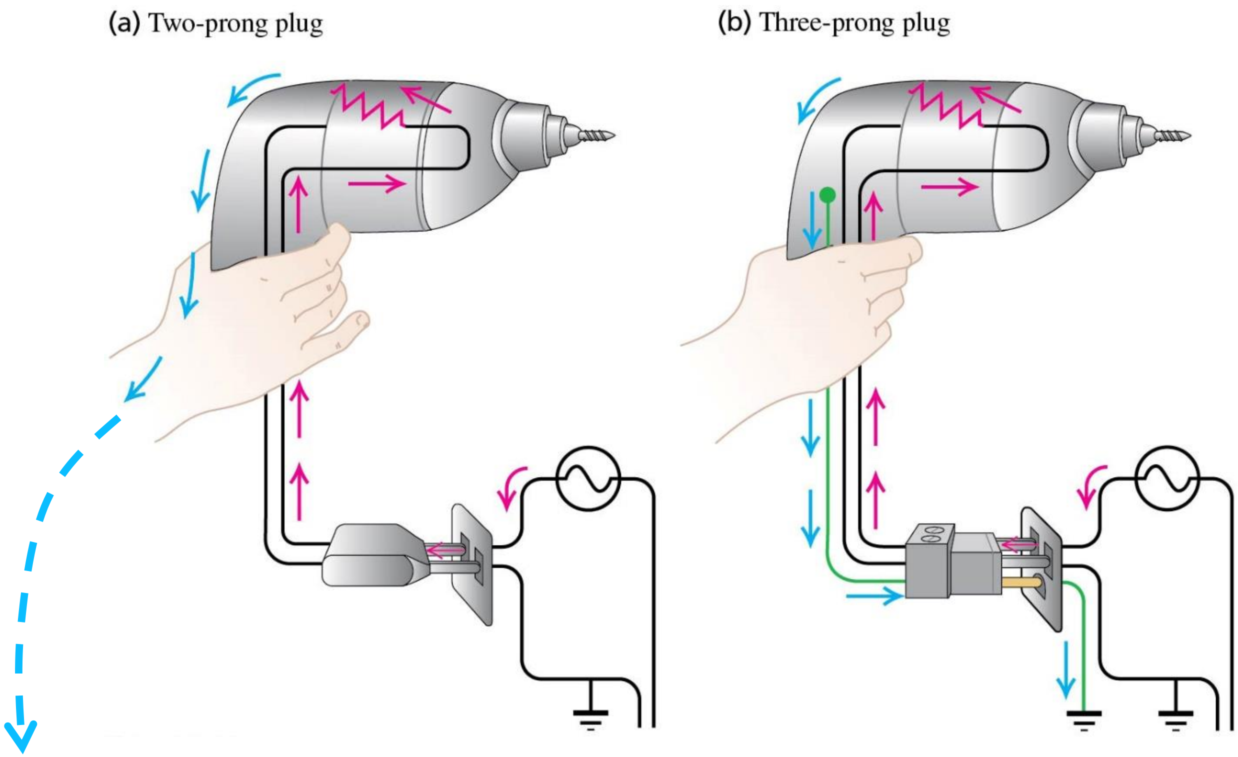
Circuit overloads

- A **fuse** (Figure a) contains a link of lead–tin alloy with a very low melting temperature; the link melts and breaks the circuit when its rated current is exceeded.
- A **circuit breaker** (Figure b) is an electromechanical device that performs the same function, using an electromagnet or a bimetallic strip to “trip” the breaker and interrupt the circuit when the current exceeds a specified value.
- Circuit breakers have the advantage that they can be **reset** after they are tripped, while a blown fuse must be replaced.

(a)

(b)

Why it is safer to use a ground plug



26 Summary

- **Resistors in series and parallel**
- **Kirchhoff's rules**
- **Electrical measuring instruments**
- ***R-C* circuits**
- **Electrical power distribution**