Electric Current
and
Direct Current Circuits

Chapter 19

- Electric Current
- Resistance and Ohm's Law
- Power in Electric Circuits
- Direct Current Circuits
- Combination Circuits

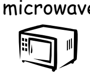
Part 1

Electric Current

Real life is mostly dynamic

Chapters 17 and 18: Electrostatics - charges at rest
Chapter 19: Charges in motion
Examples of electric current
Small currents: nerve currents, …, computers (laptops),


Larger currents: microwave, dishwashers, …,




Very large current: lightning strokes, …

Electric current is a stream of moving charges

Important to know!
A net electric charge moving through a surface is not zero

Examples:

- Current: An electric bulb – the net transport of charge is not zero.
- No Current: The flow of water through a garden hose (water molecules are neutral) . There is NO net transport of charge.

What particles are moving?

In most cases (electric current in a wire) the charge is carried by electrons moving through a metal wire.

In liquids the charge is often carried by positive ions.

Most important applications – **electronics** (moving electrons)

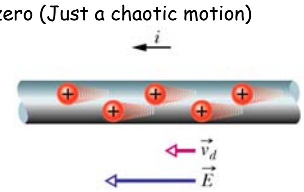
"Electricity is actually made up of extremely tiny particles called **electrons**, that you cannot see with the naked eye unless you have been drinking."
Dave Barry

What "pushes" particles?

Electric potential – electromotive force

External electric field (or electric potential) "pushes" electrons.

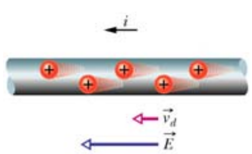
In the absence of electric potential the net transport of charge is zero (Just a chaotic motion)

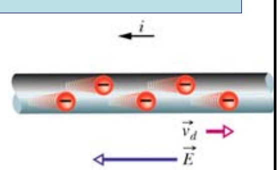


The directions of current

That is just an agreement to draw diagrams

A current is drawn in the direction in which positive charges carries would move, even if the actual charge carries are negative (electrons) and move in the opposite direction

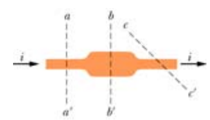




A mathematical definition for electric current

If charger Δq passes through a plane in time Δt, then the current I through that plane is define as

$$I = \frac{\Delta q}{\Delta t}$$



SI unit: coulomb per second = ampere (A)
1 ampere = 1 A = 1 coulomb per second = 1 C/s

?

Conceptual question

Current is a measure of:

A) force that moves a charge past a point
B) resistance to the movement of a charge past a point
C) energy used to move a charge past a point
D) amount of charge that moves past a point per unit time
E) speed with which a charge moves past a point

Part 2

Resistance and Ohm's Law

First Newton's Law

If there is no net force on a body, the body must remain at rest if it is initially at rest, or move in a straight line at constant speed if it is in motion

However - No electromotive force (or electric potential) and the net transport of charge is zero, or electric current is zero

Is there a contradiction?

Ideal wires vs. real wires

Motion of electrons (or other charged particles) in real wires is similar to motion with air resistance (frictional force!)

Example: a car

Atomic structure of real wires

Interactive simulations from the Physics Education Technology project at the University of Colorado
http://www.colorado.edu/physics/phet/

Resistance

In order for a current I to flow through a material there must be a potential difference, or voltage V, between the two ends of the material.
We define the resistance, R, of a material to be:

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

SI unit: volt per ampere
1 ohm = 1 Ω = 1 volt per ampere = 1 V/A

Ohm's Law: The electric current is always directly proportional to the potential difference

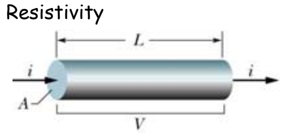
$$I = \frac{V}{R}$$

Resistance and Resistivity

Resistance (R) is a property of an object
Resistivity (ρ) is a property of a material

Calculating Resistance from Resistivity

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

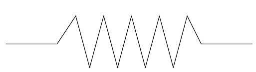


L – length of a wire
A – the cross sectional area of a wire

It does not depends on the shape of the area A!

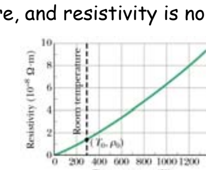
Resistance and Resistivity

An object which provides "resistance" to current flow is called a resistor.

The symbol for a resistor is 

Variation with temperature

The values of most physical properties vary with temperature, and resistivity is no exception.

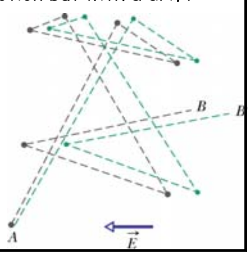


Superconductivity – resistivity drops to ZERO at very small temperatures

Drift speed

No electric field – random motion (but very fast)
v ~10^6 m/s

Electric current – still random motion but with a drift speed
v_d~10^{-4} m/s



Conceptual question

?

If the potential difference across a resistor is doubled:

A) only the resistance is doubled
B) only the current is halved
C) only the current is doubled
D) only the resistance is halved
E) both the current and resistance are doubled

Conceptual question

?

A cylindrical copper rod has resistance R. It is reformed to twice its original length with no change of volume. Its new resistance is:

A) R
B) 2R
C) 4R
D) 8R
E) R/2

Part 3

Power in Electric Circuits

Energy and Power

When a charge Δq moves across a potential difference V, its electrical potential energy U changes by the amount

$$\Delta U = \Delta q V$$

Power is the rate of electric energy transfer

$$P = \frac{\Delta U}{\Delta t} = \frac{\Delta q V}{\Delta t} = IV$$

SI unit: watt, W
1 V·A = (1J/C)(1C/s) = 1 J/s = 1 W

Resistive Dissipation

Since

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

The rate of electric energy dissipation due to resistance

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

Caution

There is a difference between two equations for power

$P = IV$ applies to electric energy transfer of all kinds

$P = I^2R = \frac{V^2}{R}$ apply only to the electric energy transfer to thermal energy in a device with resistance

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?

Power

It is better to send 10,000 kW of electric power long distances at 10,000 V rather than at 120 V because:

A) the insulation is more effective at high voltages
B) the resistance of the wires is less at high voltages
C) more current is transmitted at high voltages
D) there is less heating in the transmission wires
E) the iR drop along the wires is greater at high voltage

More efficient power lines?
A) USA
B) Europe

?

Power

You buy a "75 W" light bulb. The label means that:
A) no matter how you use the bulb, the power will be 75 W
B) the bulb was filled with 75 W at the factory
C) the actual power dissipated will be much higher than 75 W since most of the power appears as heat
D) the bulb is expected to "burn out" after you use up its 75 watts
E) none of the above

Energy usage

1 kilowatt-hour = (1000 W)(3600 s) =
= (1000 J/s)(3600 s) = 3.6×10^6 J

?

Buying electricity

What do you buy from the power company?

A) Only energy
B) Electrons and energy
C) Only electrons

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problem

Simple problem

Suppose the electric company charges 10 cents per kW×h. How much does it cost to watch a TV (250 watt) 4 hours a day for 30 days?

A) $1.50
B) $3.0
C) $30.0
D) $150.0
E) none of these

problem

Problem

Problem 3. (25 points)
A 280 W High Definition TV is plugged into a standard 120 V outlet.
(a) How much does it cost per month to watch the TV continuously?
Assume electric energy cost 10¢/kW•h.
(b) What is the resistance of the TV?
(c) How much current flows through the TV?
(d) How many electrons pass through the TV in 1 second?
(e) If the energy supplied to the TV could be converted entirely to gravitational potential energy, how high an aircraft carrier of 98,600 tonnes would be uplifted from water?

a) cost = $\frac{P \cdot \text{time (hours)}}{1000} \cdot 10$ ¢/kWh = \$ 20.16
e) $P \cdot t$ (joules) = mgh $h = 0.75$ m
b) $P = \frac{V^2}{R}$ or $R = \frac{V^2}{P} = 51\ \Omega$
c) $I = \frac{V}{R} = 2.33$ A
d) $I = \frac{\Delta Q}{\Delta t}$ or $n_e q_e = I \Delta t$ $n_e = \frac{I \Delta t}{q_e} = 1.46 \cdot 10^{19}$ electrons

Part 4

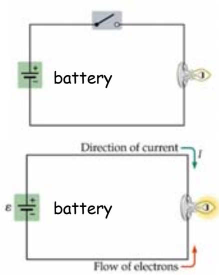
Direct Current Circuits

Direct Current (DC) Circuits

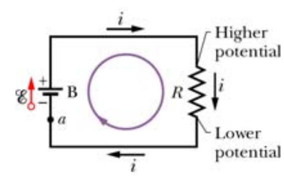
A circuit is a loop comprised of elements like resistors and capacitors around which current may flow.

For current to continue flowing in a circuit with non-zero resistance, there must be an energy source. This source is often a battery.

The light bulb in this circuit is the resistor. The wires that connect the battery to other circuit elements are assumed to have zero resistance.



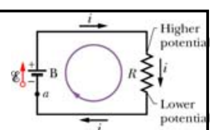
A single-loop circuit



a simple equation $i = \frac{\varepsilon}{R}$

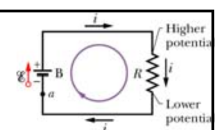
where ε is electromotive force (emf)
The potential difference between the terminals of an ideal emf device is equal to the emf of the device

A single-loop rules



Loop rule: The algebraic sum of all changes in potential encountered in a complete traversal of any loop of a circuit must be zero (Kirhhoff's loop rule).
Resistance Rule: For a move through a resistance in the direction of the current, the change in potential is -iR; in the opposite direction +iR.
EMF Rule: For a move through an ideal emf device in the direction of the emf arrow, the change on the potential is +ε; in the opposite direction is -ε

A single-loop rules (cont.)



EMF Rule + Resistance Rule + Loop Rule

Clockwise $\varepsilon - iR = 0$

Counterclockwise $iR - \varepsilon = 0$

problem

Electric hazard in heart surgery

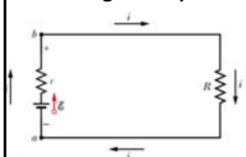
A a patient is undergoing open-heart surgery. A sustained current as small as 25 μm ($25*10^{-6}$ A) passing through the hart can be fatal. Assume that the heart has a constant resistance of 250 Ω; determine the minimum voltage that posses a danger to the patient.

V = IR = 6.25 mV

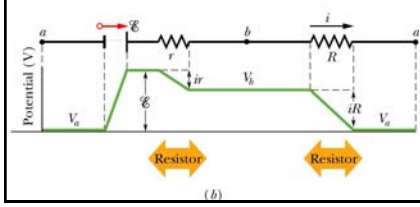
Part 4a

Resistors in series

A single-loop with resistors in series

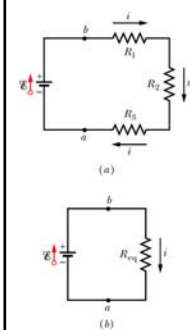


When a potential difference ε is applied across resistances connected in series, the resistance have identical currents i.



The sum of the potential differences across the resistances is equal to the potential difference ε

Resistors in series



$$\varepsilon - iR_1 - iR_2 - iR_3 = 0$$

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

with a single equivalent resistance

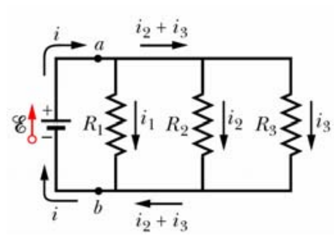
$$i = \frac{\varepsilon}{R_{eq}}$$

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

Part 4a

Resistors in parallel

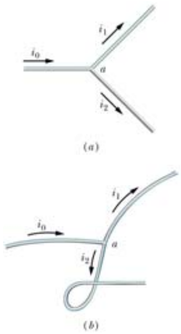
Resistances in Parallel



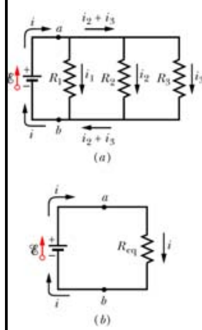
Multiloop Circuits

Junction rule: The sum of the current entering any junction must be equal to the sum of the currents leaving that junction
(Kirhhoff's junction rule)

$i_0 = i_1 + i_2$



Resistances in Parallel



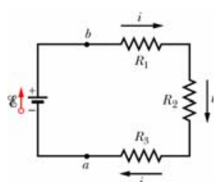
when a potential difference V is applied across resistances connected in parallel, the resistances all have that same potential difference

$$i = i_1 + i_2 + i_3 = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

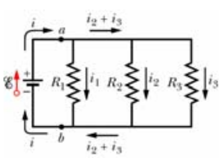
$$i = \frac{V}{R_{eq}}$$

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

Resistors in series and parallel (reference set)



$$\varepsilon = V_1 + V_2 + V_3$$
$$I = I_1 = I_2 = I_3$$
$$R = R_1 + R_2 + R_3$$



$$\varepsilon = V_1 = V_2 = V_3$$
$$I = I_1 + I_2 + I_3$$
$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

problem

Resistance

Give an example how four resistors of resistance R can be combined to produce an equivalent resistance of R.

?

Electric current

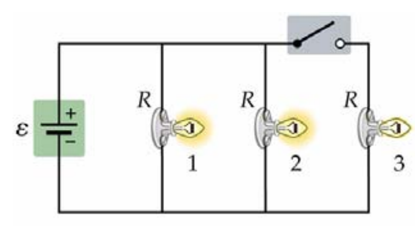
Two 110-V light bulbs, one "25 W" and the other "100 W", are connected in series to a 110 V source. Then:

A) the current in the 100-W bulb is greater than that in the 25-W bulb
B) the current in the 100-W bulb is less than that in the 25-W bulb
C) both bulbs will light with equal brightness
D) each bulb will have a potential difference of 55 V
E) none of the above

?

Conceptual Question

Consider the circuit shown in the figure, in which three lights, each with a resistance R, are connected in parallel. What happens to the intensity of light 3 when the switch is closed? What happens to the intensities of lights 1 and 2?



?

Electric current

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D) each bulb will have a potential difference of 55 V
E) none of the above

?

The resistance of resistor 1 is twice the resistance of resistor 2. The two are connected in parallel and a potential difference is maintained across the combination. Then:

A) the current in 1 is twice that in 2
B) the current in 1 is half that in 2
C) the potential difference across 1 is twice that across 2
D) the potential difference across 1 is half that across 2
E) none of the above are true

?

Electric current

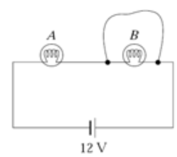
A 120-V power line is protected by a 15-A fuse. What is the maximum number of "120 V, 500 W" light bulbs that can be operated at full brightness from this line?

A) 1
B) 2
C) 3
D) 4

problem

Electric current

Two light bulbs A and B are connected in series to a constant voltage source. When a wire is connected across B as shown, bulb A

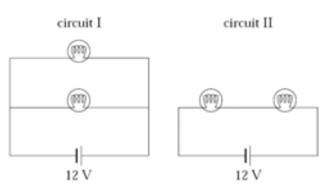


1. burns more brightly.
2. burns as brightly.
3. burns more dimly.
4. goes out.

problem

Electric current

If the four light bulbs in the figure are identical, which circuit puts out more light?



1. I.
2. The two emit the same amount of light.
3. II

?

Christmas tree

Old-time Christmas tree lights had the property that, when bulb burned out, all the lights were out.

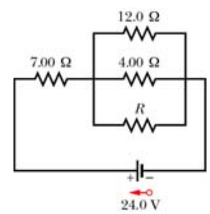
How were these lights connected?

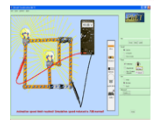
How could you rewire them to prevent all the lights from going out when one of them burned out?

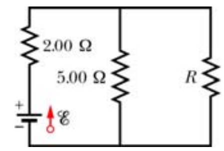
Part 4c

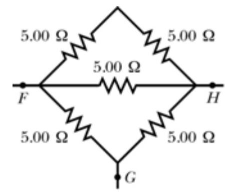
Combination Circuits

Combination Circuits





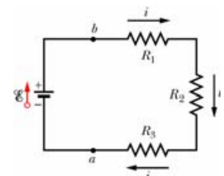




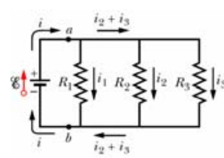
Part 4c (1)

Equivalent resistance

Resistors in series and parallel (reference set)



$$\varepsilon = V_1 + V_2 + V_3$$
$$I = I_1 = I_2 = I_3$$
$$R = R_1 + R_2 + R_3$$



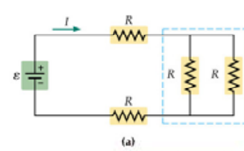
$$\varepsilon = V_1 = V_2 = V_3$$
$$I = I_1 + I_2 + I_3$$
$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

A key idea for solving combination circuits (equivalent resistance)

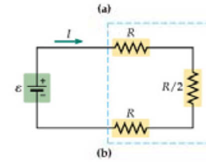
1. Select a group of resistors connected in either series or parallel.
2. Calculate the equivalent resistance for the group.
3. Go to the first step - Select a group of resistors connected in either series or parallel in the new loop
4. Keep going till you get what you want

Simple analysis:
all resistors are the same

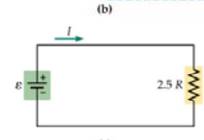
(a) The two vertical resistors are in parallel with one another, hence they can be replaced with their equivalent resistance, R/2.



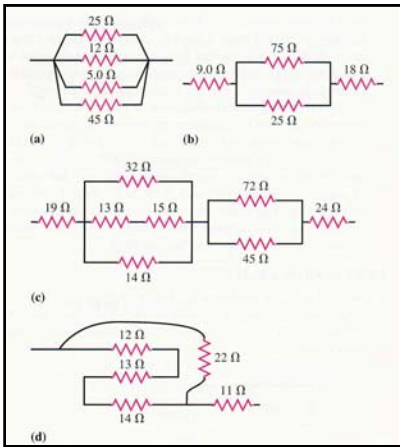
(b) Now, the circuit consists of three resistors in series. The equivalent resistance of these three resistors is 2.5 R.



(c) The original circuit reduced to a single equivalent resistance.



problem

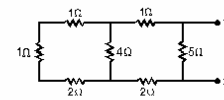


Find the equivalent resistance of each combination

problem

Simple problem

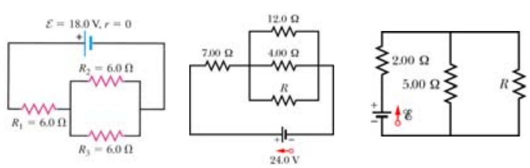
The equivalent resistance between points A and B of the circuit shown is:



A) 4 Ω
B) 4.5 Ω
C) 6 Ω
D) 3 Ω
E) 2.5 Ω

Part 4c (2)

Single battery case



Key ideas for solving combination circuits

1. When a potential difference is applied across resistances connected in series, the resistance have identical currents i.
2. When a potential difference V is applied across resistances connected in parallel, the resistances all have that same potential difference
3. Junction rule: The sum of the current entering any junction must be equal to the sum of the currents leaving that junction

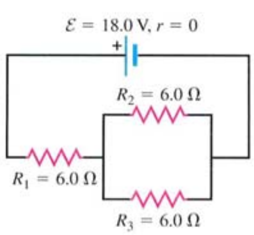
problem

A resistor network

Three identical resistors with resistance of 6 Ω are connected to a battery with an emf of 18 V

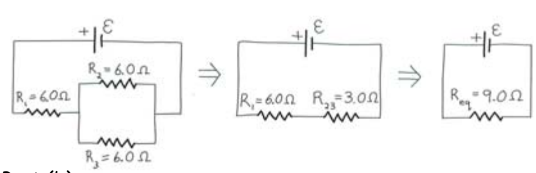
a) find the equivalent resistance of the resistor network

b) Find the current in each resistor

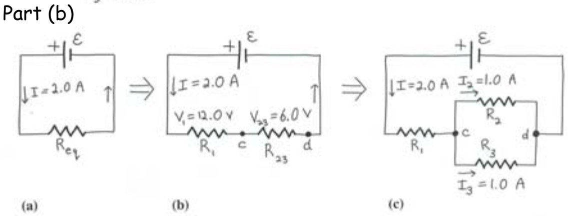


problem

Part (a)



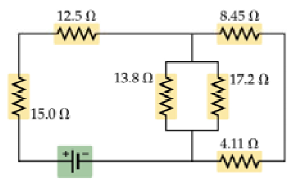
Part (b)



problem

problem

The current in the 13.8 Ω resistor is 0.750 A.
Find the current in the other resistors in the circuit.



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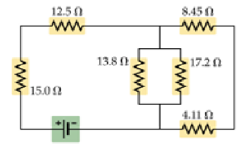
problem



$$\boxed{I_{13} = 0.75\text{ A} \quad \text{given}}$$

$$V_{drop} = I_{13} \times 13.8 = 0.75 \times 13.8 = 10.35$$

$$V_{drop} = I_{17} \times 17.2 = 10.35$$

$$\boxed{I_{17} = 0.6\text{ A}}$$

$$V_{drop} = I_{8+4} \times (8.45 + 4.11) = 10.35$$

$$\boxed{I_{8+4} = 0.824\text{ A}}$$

$$I_{total} = I_{13} + I_{17} + I_{8+4}$$

$$I_{total} = 0.75 + 0.6 + 0.824$$

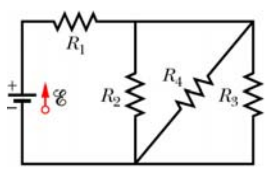
$$\boxed{I_{total} = 2.174\text{ A}}$$

---

problem

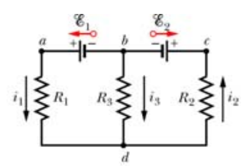
Electric current

(a) What is the equivalent resistance of the network shown?
Put R1=10.0 Ω, R2=R3=50.0 Ω, R4=25.0 Ω, and E=6.0 V; (assume the battery is ideal.)
(b) What is the current in resistors R1 and R4?



Part 4c (2)

Networks that can not be reduced to simple series-parallel combinations of resistors



For solving any combination circuit …

1. If a circuit can be simplified by replacing resistors in series or parallel with their equivalents, do so
   Case One or "work forward": reduce the circuit to a single loop
   Case Two or "work backward": undoing the resistor simplification processes to find current or potential difference for a particular resistor
2. If a circuit cannot be to a single loop, use Kirchhoff's rule (the junction rule and the loop rule) to write a set of simultaneous equations. You need have only as many independent equations as there are unknowns

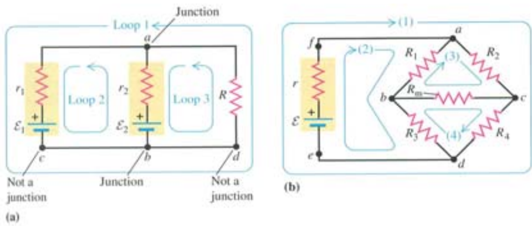
---

Kirhhoff's rules

1. Junction rule: The sum of the current entering any junction must be equal to the sum of the currents leaving that junction
2. Loop rule: The algebraic sum of the potential differences in any loop must equal zero

problem

Complex networks



▲ **FIGURE 19.23** Two networks that cannot be reduced to simple series–parallel combinations of resistors.

?

A two-cell flash light

In a two-cell flash light , the batteries are normally connected in series. Why not connect them in parallel?