Conceptual Physics
Electric Potential
Circuits
Magnetism

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Last time

- waves
- sound
- electric charge
- electric field

Overview

- electric potential
- circuits, current, resistance
- magnets and magnetic field

Warm Up Question

Object A has a charge of $+2\ \mu\text{C}$, and object B has a charge of $+6\ \mu\text{C}$. Which statement is true about the electric forces on the objects?

(A) $\mathbf{F}_{A\to B} = -3\mathbf{F}_{B\to A}$

(B) $\mathbf{F}_{A\to B} = -\mathbf{F}_{B\to A}$

(C) $3\mathbf{F}_{A\to B} = -\mathbf{F}_{B\to A}$

(D) $\mathbf{F}_{A\to B} = 3\mathbf{F}_{B\to A}$

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[1] Serway & Jewett, 9th Ed, page 696, Quick Quiz 23.3.

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Newton's 3rd Law!

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[1]Serway & Jewett, 9th Ed, page 696, Quick Quiz 23.3.

Sparking: Electrical Breakdown

Electric fields can cause forces on charges.

If the field is very strong, it begins to accelerate free electrons which strike atoms, knocking away more electrons forming ions. This starts a cascade, forming a spark.

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The air along the spark becomes a **plamsa** of free charges and can conduct electricity.

Sparks look like bright streaks because the air molecules becomes so hot. Accelerating charges radiate, so lightning can also cause radio interference.

Faraday Cages

A conducting shell can shield the interior from even very strong electric fields.

[1]Photo from Halliday, Resnick, Walker

Faraday Cages

[1]Photo found on TheDailySheeple, credits unknown.

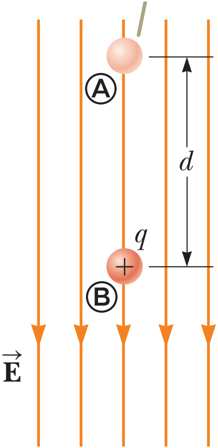
Electric Potential Energy

A ball on a high shelf has the potential to fall, gaining speed and kinetic energy.

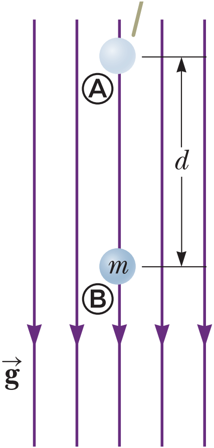
The energy the ball stores is gravitational potential energy.

Two unlike charges held apart also store electric potential energy U_E, since if they are released they will accelerate towards each other.

Energy of a charge in a uniform E-field



$$\Delta U_E = qEd$$



$$\Delta U_g = mgd$$

Electric Potential

Electric potential is a new quantity that relates the effect of a charge configuration to the potential energy that a test charge would have in that environment.

It is denoted V.

electric potential, V

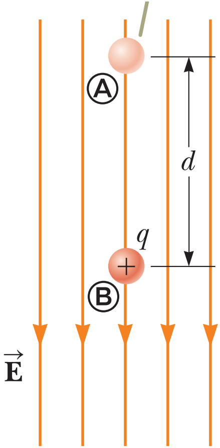
the potential energy per unit charge:

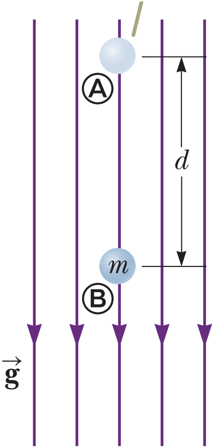
$$V = \frac{U_E}{q}$$

V has a unique value at any point in an electric field.

It is characteristic only of the electric field, meaning it can be determined just from the electric field.

Potential in a uniform E-field





$\Delta V = Ed$

$\Delta(\text{grav. ptl.}) = gd$

Electric Potential

Potential is potential energy per unit charge:

$$V = \frac{U_E}{q}$$

The units are Volts, V.

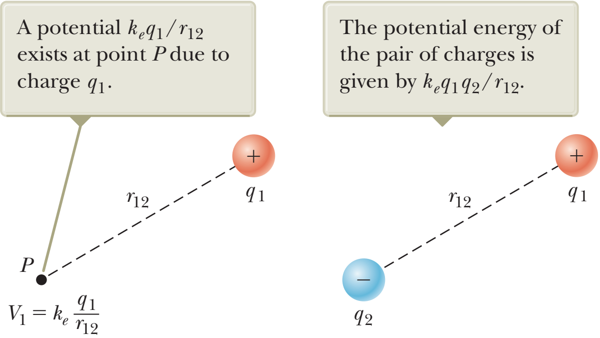
$1 \text{ V} = 1 \text{ J/C} = 1 \, \frac{\text{kg m}^2}{\text{A s}^3}$

Volts are also the units of **potential difference**, the change in potential: ΔV.

Electric Potential and Potential Energy

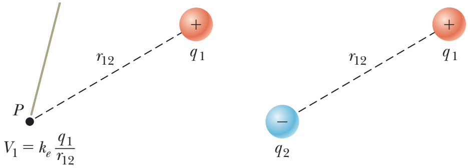
Electric potential gives the potential energy that would be associated with test charge q_0 if it were at a certain point P.

$$U_{E,q_0} = q_0 V_P$$



[1]Figure from Serway and Jewett, 9th ed.

Electric Potential and Potential Energy



The closer two positive or two negative charges are, the **higher** the potential energy.

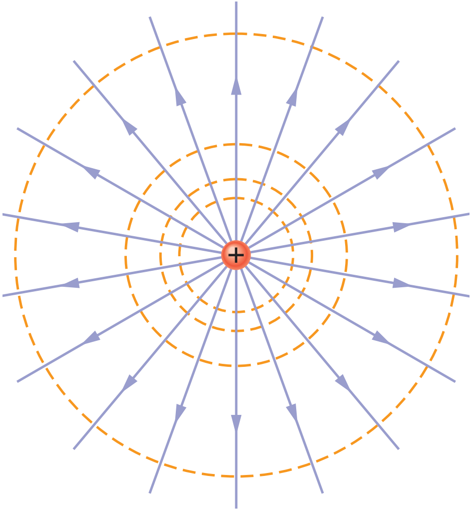
The closer a positive charge is to a negative charge, the **lower** the potential energy.

By convention, we say that the electric potential V is positive close to a positive charge and negative close to a negative charge.

A **potential difference**, ΔV, will cause free charges to move.

Electric Potential

A contour plot of electric potential (dashed lines) around a point charge:



Electric Field and Electric Potential

Potential, V, is potential energy per unit charge:

$$U_E = qV$$

Electric field, $\mathbf{E}$, is force per unit charge:

$$\mathbf{F} = q\,\mathbf{E}$$

Notice the relation! Both quantities are defined so that we can predict physical quantities associated with putting a charge at a certain point.

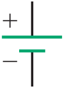
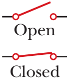
Circuits

Circuits make use of potential differences to create currents.

Circuits consist of electrical **components** connected by wires.

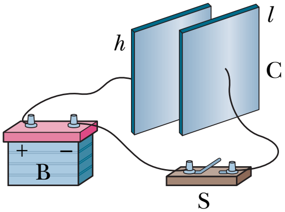
Some types of components: batteries, resistors, capacitors, lightbulbs, LEDs, diodes, inductors, transistors, chips, etc.

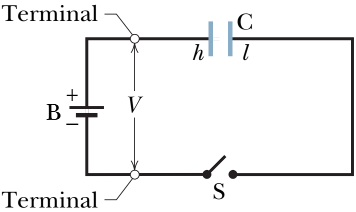
Circuit component symbols

battery	ΔV	
capacitor	C	
switch	S	
resistor	R	
inductor	L	

Circuits

The different elements can be combined together in various ways to make complete circuits: paths for current to flow from one terminal of a battery or power supply to the other.





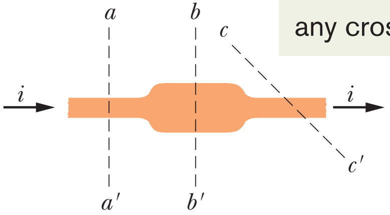
This circuit is said to be incomplete while the switch is open.

Electric Current

Electric current, I, is the rate of flow of charge through some defined plane (cross section):

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

q is an amount of charge and t is a time interval.



The current is the same in any cross section.

Coulombs and Ampères

The unit for current is the Ampère, or more commonly, “Amp”.

Using the definition for current, 1 A = 1 C / 1 s.

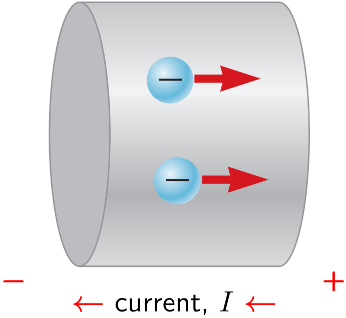
Therefore, we can formally define the unit of charge in terms of the unit of current:

1 C = (1 A)(1 s)

Flow of charge in a circuit

Conventional current is said to flow from the positive terminal to the negative terminal.

However, actually it is negatively charged electrons that flow through metal wires:



[1]Figure from Serway and Jewett, 9th ed.

Electric Current

There are two modes for electric current in use:

- Direct Current (DC)
- Alternating Current (AC)

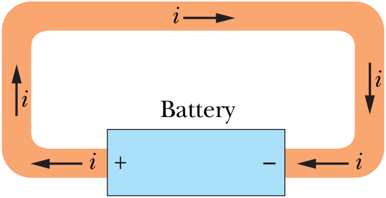
Direct current flows only in one direction through a wire. A typical source of DC is a battery.

Alternating current flows back and forth. It alternates its direction. Household electricity is AC.

Current

Charge will only move when there is a net force on it. A supplying a potential difference across two points on a wire will do this.

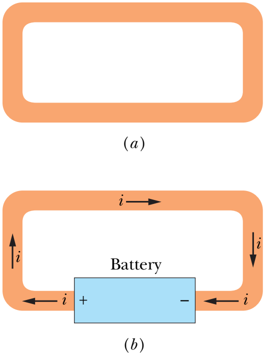
(a)



(b)

Resistance

When a potential difference is applied across a conductor, current begins to flow.



However, different amounts of current will flow in different conductors, even when the applied potential difference is the same. What is the characteristic of the conductor which determines the amount of current that will flow?

[1] Figure from Halliday, Resnick, Walker, 9th ed.

Resistance

Resistance

The resistance of a conductor is given by the ratio of the applied potential to the current that flows through the conductor at that potential:

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

The units of resistance are Ohms, Ω, symbol is the capital Greek letter "Omega". $1\ \Omega\ = 1$ V/A

We can think of a high resistance as *resisting*, or impeding, the flow of current.

Ohm's Law

Ohm's Law

The current through a device is directly proportional to the potential difference applied across the device.

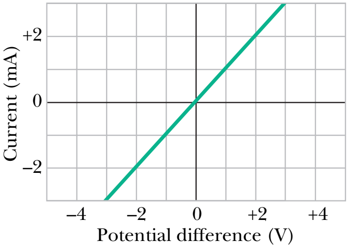
Not all devices obey Ohm's Law!

In fact, for all materials, if V is large enough, Ohm's law fails.

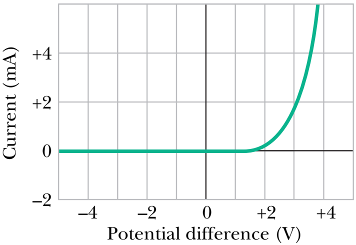
They only obey Ohm's law when the device's **resistance is independent of the applied potential difference**.

Ohm's Law

Obeys Ohm's law:



Does not obey Ohm's law:



We can write this linear relationship as $V = IR$ if and only if R is constant and independent of V.

However, notice that we can always define $R(V) = \frac{V}{I}$ even when resistance does depend on V.

Exotic Conductors

Conductors

materials through which charge can move readily

Insulators

(also called nonconductors) are materials that charge cannot move through freely

Semiconductors

are materials with behavior between that of conductors and insulators, *eg.* silicon and germanium

Suprerconductors

materials that (in the right circumstances) allow charge to flow without any resistance

Semiconductors

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Semiconductors have resistivities between those of conductors and insulators.

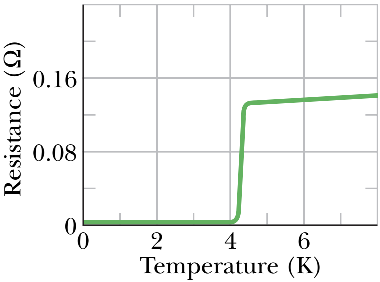
However, their resistivities can be controlled by several different means (depending on the type of semiconductor):

- by adding impurities during manufacture
- by electric fields
- by light

This allows for many new kinds of components in circuits: ones that amplify currents, emit light, are light sensitive, implement switching, *etc.*

Superconductors

Superconducting materials are elements, alloys, or compounds that exhibit a remarkable property: below some *characteristic temperature* the resistivity of the material is effectively zero.



Examples of these materials are mercury and lead. Not all materials do this! Copper does not.

Mercury is superconducting below 4 K. (-269° C)

Superconductors

Before 1986, it seemed we had a good idea about how this happened and why.

[1] Drozdov, *et al.* (2015). Nature 525 (7567): 73-6. arXiv:1506.08190

Superconductors

Before 1986, it seemed we had a good idea about how this happened and why.

Then "high temperature" superconductors were found.

These are ceramics. One is yttrium barium copper oxide (YBCO).

The highest critical temperature, T_c, at atmospheric pressure found so far is ~ 138 K.

We do not really understand why these ceramics are superconductors.

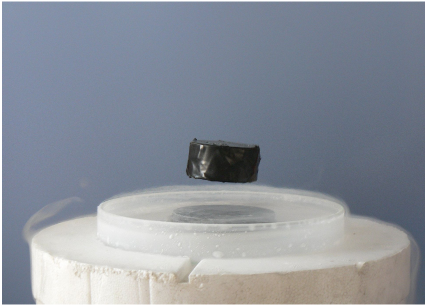
Hydrogen sulfide becomes a solid metal at extremely high pressures. It has $T_c = 203$ K at around 150 gigapascals pressure.[1]

[1] Drozdov, *et al.* (2015). Nature 525 (7567): 73-6. arXiv:1506.08190

Superconductors

Superconductors must be cooled to their critical temperature, however, they make excellent powerful electromagnets.

They are used as electromagents in MRI scanners, mass spectrometers, and particle accelerators.



[1]Magnet photo by Mai-Linh Doan, Wikipedia; Frog photo by Lijnis Nelemans/High Field Magnet Laboratory/Radboud University Nijmeg.

Magnets

Like charges, magnets also interact at a distance.

They can either attract or repel.

Similarly to charges, they can also effect certain kinds of nearby material by *magnetizing* it. (*cf.* polarization)

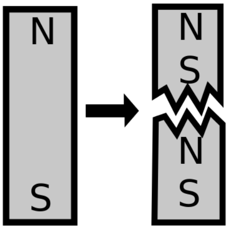
Magnets and electrostatics

Magnets have similarities to electric charges but also have an important difference from electric charges.

It is possible for a positive or negative electric charge to be found on its own: *eg.* electrons, protons.

Magnetic charges are **never** found on their own.

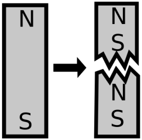
Magnets have a North pole and a South pole. If you break a magnet in two, new North and South poles form:



[1]Figure from Wikipedia.

Lack of Magnetic Monopoles

Breaking a magnet in two:



It is impossible to separate a North pole from a South pole.

Lack of Magnetic Monopoles

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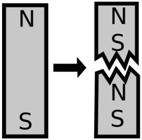

It is impossible to separate a North pole from a South pole.

It is unclear at this time why magnetic monopoles do not exist, but they have never been conclusively observed.

Some (unconfirmed) theories predict them, and they may have existed in the early universe. Other theories attempt to explain why they do not exist. None are yet confirmed.

As we understand it, magnets always behave similarly to electric dipoles.

The Magnetic Field

The magnetic field is written **B**.

The units are:

$$1 \text{ Tesla} = \frac{1 \text{ Newton}}{(1 \text{ Coulomb})\ (1 \text{ m/s})} = 1 \text{ N A}^{-1} \text{ m}^{-1}$$

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The Tesla is abbreviated to T. It is a really big unit: 1 T is already a stronger field than you encounter except in extreme circumstances.

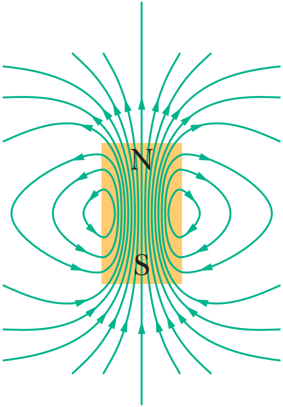
A more convenient unit (but not an SI unit) is the Gauss:

$1 \text{ Gauss} = 10^{-4} \text{ Tesla}$

Magnetic Field Lines

Draw magnetic field lines similarly to E-field line: lines emerge from North pole, enter South pole, denser lines means a stronger field.

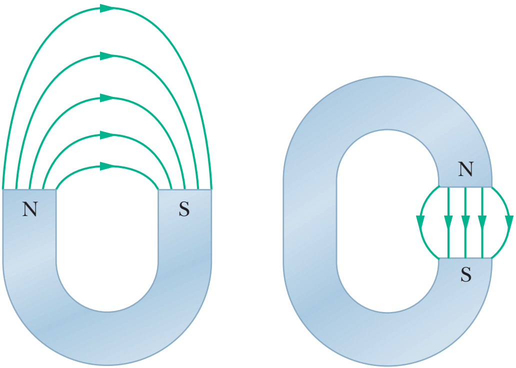
A bar magnet is a like a magnetic dipole:



[1]Figure from Halliday, Resnick, Walker, 9th ed.

Magnetic Field Lines

Magnetic fields for a horseshoe magnet and a C-shape magnet:



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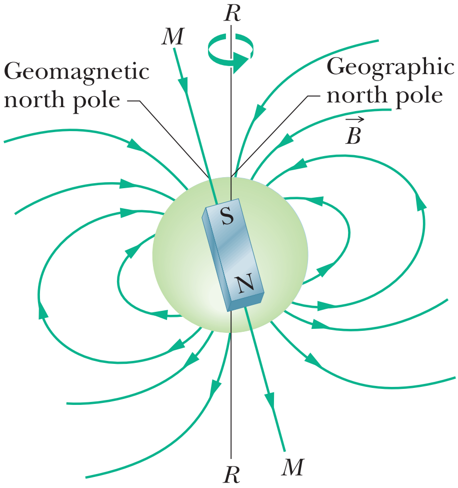
Compasses and the Earth's Magnetic field



[1]Figure from Halliday, Resnick, Walker, 9th ed, pg 870.

Compasses and the Earth's Magnetic field

North poles of magnets point northward, so the magnetic pole that points (roughly) North is a south pole

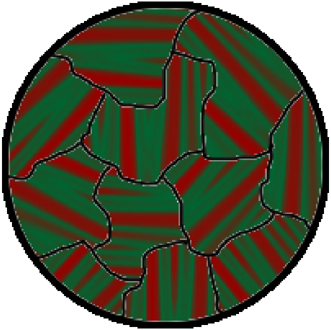
The poles of magnets are perhaps more accurately called:

- north-*seeking* pole
- south-*seeking* pole

but almost always they are just called "north" and "south" poles.

Why are some objects magnetizable?

Microscopic view of ferrous metal:



The different red and green regions are magnetic domains.

Within each domain are atoms with their outermost electrons aligned (green) or oppositely aligned (red).

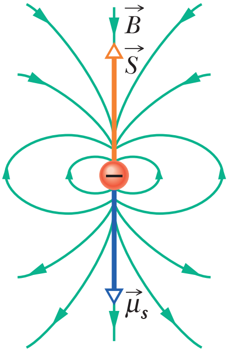
Electron magnetic effects come from two properties.

[1]Figure from Wikipedia, by Ra'ike.

Electron Spin Angular Momentum

Electrons have *intrinsic angular momentum*. This is also called "spin" and is the main source of magnetism.

Spin is an inherent property of all electrons. It cannot be understood with classical mechanics.



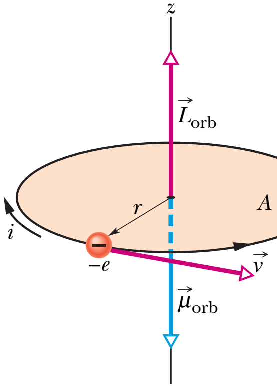
[1] Figure from Halliday, Resnick, Walker, 9th ed.

Electron Orbital Angular Momentum

Electrons can be thought of as orbiting the nucleus. (In actual fact, this is not such an accurate picture.)

If you have a current around a loop you get a magnetic field.

The electron in its orbit is like current in a loop: it creates a magnetic field (as we shall see later).



Summary

- electric field and potential
- circuits, current, resistance
- magnetism

Homework

- Prepare a 5-8 minute talk for next week. Tuesday, Aug 8.
- 3 worksheets (due Monday)

Hewitt,

- Ch 22, onward from page 403. Exercises: 50 & 51; Probs: 7
- Ch 23, onward from page 421. Exercises: 5; Problems: 1, 3

Will be set on Monday:

- Ch 24, onward from page 437. Exercises: 21, 37
- Ch 25, onward from page 452. Exercises: 25, 39