

Electricity, Magnetism, and Motors

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Welcome

- This workshop is intended to provide some ideas to K-12 teachers (especially K-6) for introducing electricity, magnetism, and motors.
- We will begin with background for the teachers then move to examples for the students.

For the teachers

- A bit of background: I am an engineer and teach engineering at the university level.
- I saw very little of what I would now consider engineering topics in my K-12 experience. Instead, I was exposed to them via my engineer father.
- I realize how difficult it can be to introduce these complex topics into the curriculum, especially for the youngest students, and hope to offer a path for easing their introduction.

STEM

- I expect most of you are familiar with the STEM acronym:
 - Science
 - Technology
 - Engineering
 - Math
- Greater exposure of students to these subject areas at all levels will support a better understanding of the challenges facing our world and help produce a strong, vibrant workforce.

Scientists and Engineers

- If a student asks you, “What does a scientist do?” or “What does an engineer do?”, how would you answer?
- These can be tough questions to answer even for engineers and scientists.
- Part of the difficulty is how broad the terms “scientist” and “engineer” are. They cover a huge range of activities.
- For example, electrical engineering alone ...

The Institute of Electrical and Electronics Engineers



IEEE

- IEEE Aerospace and Electronic Systems
- IEEE Antennas and Propagation
- IEEE Broadcast Technology
- IEEE Circuits and Systems
- IEEE Communications
- IEEE Components, Packaging and Manufacturing Technology
- IEEE Computer
- IEEE Consumer Electronics
- IEEE Control Systems
- IEEE Dielectrics and Electrical Insulation
- IEEE Education
- IEEE Electromagnetic Compatibility
- IEEE Electron Devices
- IEEE Engineering in Medicine and Biology
- IEEE Engineering Management
- IEEE Geoscience and Remote Sensing
- IEEE Industrial Electronics
- IEEE Industry Applications
- IEEE Information Theory
- IEEE Instrumentation and Measurement
- IEEE Lasers and Electro-Optics
- IEEE Magnetics
- IEEE Microwave Theory and Techniques
- IEEE Neural Networks
- IEEE Nuclear and Plasma Sciences
- IEEE Oceanic Engineering
- IEEE Power Electronics
- IEEE Power Engineering
- IEEE Product Safety Engineering
- IEEE Professional Communication
- IEEE Reliability
- IEEE Robotics and Automation
- IEEE Signal Processing
- IEEE Social Implications of Technology
- IEEE Solid State Circuits
- IEEE Systems, Man and Cybernetics
- IEEE Ultrasonics, Ferroelectrics, and Frequency Control
- IEEE Vehicular Technology
- Intelligent Transportation Systems Council
- Sensors Council
- Superconductivity Council



Models

- Scientists attempt to understand the way the world works.
- Engineers attempt to take the best understanding of the way the world works to design and build things to make life better.
- A common factor between scientists and engineers is their use of models to make things easier to understand.

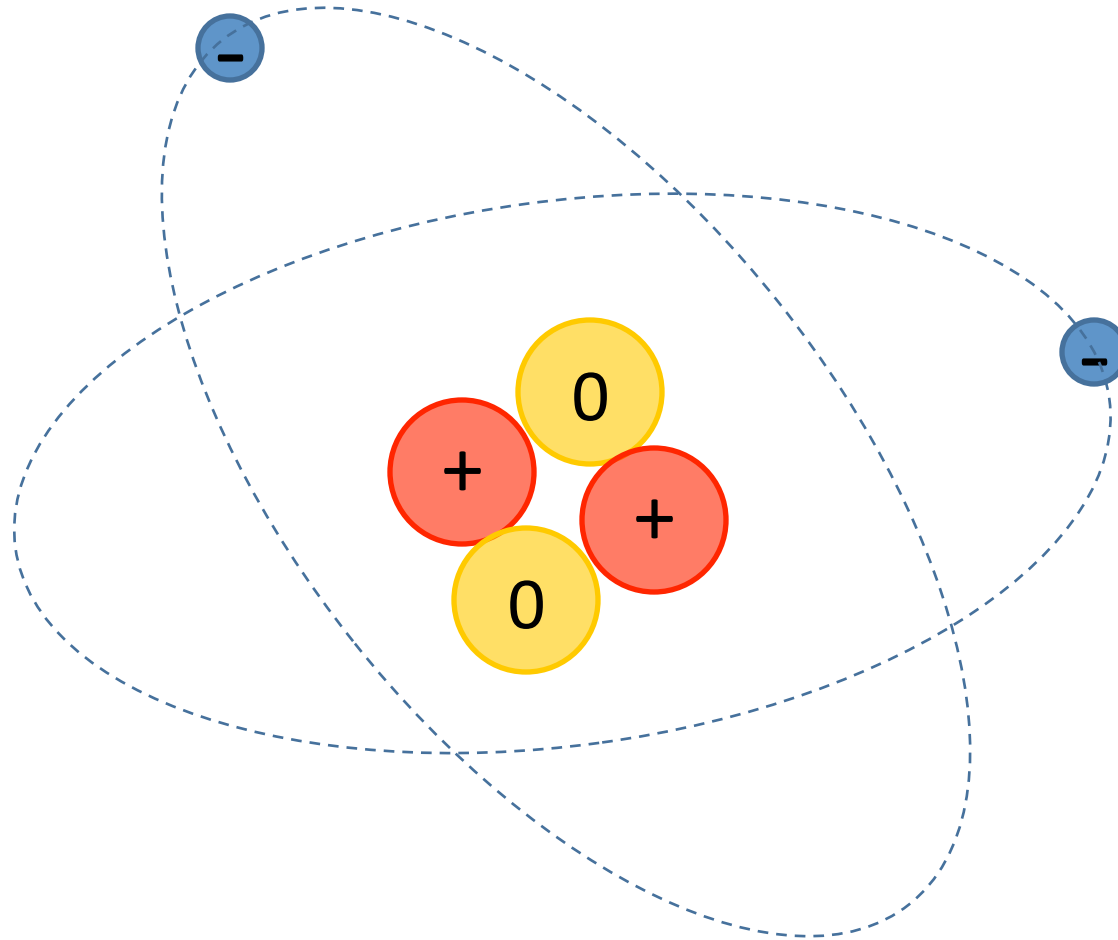
Using models

- An architect's plan for a house is a model. It can help us understand what the house should be like but it can't capture every detail about the house.
- What we will be looking at over the next few minutes is a model for electricity and magnetism. This model helps us understand but it can't capture every detail either.

A model for matter

- Matter is made of atoms.
- Atoms are made of three types of particles: protons, neutrons, and electrons
- Protons and neutrons cluster together to form a central core and the electrons orbit around the core.
- Part of our model is a quantity we call “charge”.
- We model protons with a charge of +1, neutrons with charge of 0, and electrons with charge of -1.

Atom Model

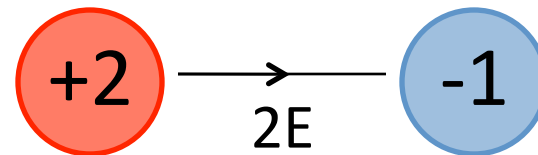
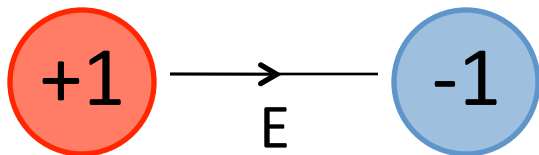


Properties of electric charge

- All electrical charges exert force on all other electrical charges.
- Charges with like polarity repel each other. Positive repels positive and negative repels negative.
- Charges with opposite polarity attract each other. Positive attracts negative.

Electric force is affected by charge

- The force exerted between electric charges is proportional to the amount of charge involved.
 - The electric field between an object with charge +2 and an object with charge -1 is twice the force of an object with +1 and an object with -1.



Electric force is affected by distance

- The force exerted between electric charges is inversely proportional to the square of the distance between them.
 - If you double the distance between charges you reduce the force to $\frac{1}{4}$



A model for electricity

- When stable, the number of protons and electrons in an atom are equal so the net charge for a stable atom is zero.
- If enough energy impacts an atom, it can dislodge an electron leaving the atom with a net positive charge and the electron free to move.
- *Electricity is the movement of charge.* Since electrons move much more easily than atoms, electricity is primarily the movement of electrons.

Measuring electricity

- Electricity is one form of energy.
- We measure electricity using a few interrelated quantities.
 - Current – the number of charges (usually electrons) moving
 - Voltage – the average amount of energy carried by each of the charges
 - Energy – the total potential for work in the moving charges
 - Power – energy carried during a particular period of time
 - Resistance – measures how easily current flows in a given material

Current

- Electricity is defined as the movement of charge.
- We call the movement of charge “current” and engineers use the symbol “ I ”.
 - “ I ” comes from the French term *intensité* in honor of the term used by André-Marie Ampère, the scientist who first quantified electric current.
- The units for current are also named amperes (A).
- 1 Ampere = 1 Coulomb of charges per second
- 1 Coulomb = 6,241,507,648,655,549,400 charges
- $\therefore 1 \text{ A} = 6,241,507,648,655,549,400 \text{ charges/s}$

Voltage

- Electric charges only move as current if the charge carriers (*e.g.* electrons) are imbued with energy.
- We call the amount of energy per charge voltage with the symbol “V” and units of volts.
 - Voltage is named for Alessandro Volta, the Italian scientist who invented the modern battery.
- 1 Volt = 1 Joule of Energy per 1 Coulomb of charge

Energy

- Energy is measured in joules (J) named for James Prescott Joule.
- 1 Joule of energy is roughly the amount of energy needed to lift an apple 1 meter.
- It takes 4184 joules to heat 1 liter (1 kilogram) of water by 1°C
- We often see the energy needed for a task indirectly measured as power.

Power

- Power is the amount of energy expended in a given amount of time.
- For electricity, power is measured in watts (W) named for James Watt.
- 1 watt = 1 joule per second
- A 100W light bulb uses 100 joules/second
- 1 horsepower = 746 W

Resistance

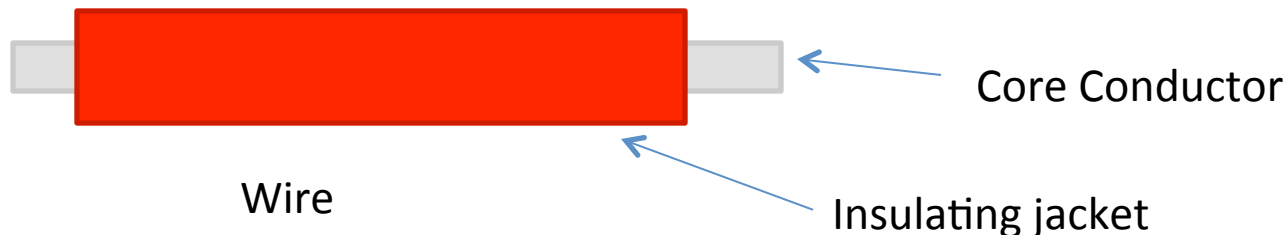
- Resistance in materials is measured in units of ohms (Ω) named for Georg Simon Ohm.
- Resistance is measured as the amount of current that flows as a result of applied voltage.
- 1 ohm = 1 volt per 1 ampere
- $1 \Omega = 1V/1A$
- Resistance is low for conductors and high for insulators

The rules

- All electricity follows a few simple rules:
- Ohm's Law
 - $V=I*R$ or $V/I=R$ or $V/R=I$
- Kirchoff's Laws
 - The sum of all voltage changes around any closed path is 0
 - The sum of all currents entering a given point is equal to the sum of the currents leaving that point.
- Power
 - Power = Voltage * Current or $P=V*I$

Conductors and insulators

- In some materials, notably most metals, it is easy to dislodge electrons so electricity flows easily. These materials are called conductors.
- In other materials, such as rubber and plastic, it is difficult to dislodge electrons so electricity flows poorly. These are called insulators.



Semiconductors?

- Semiconductors, such as silicon, in pure form are generally poor conductors.
- With the addition of additional materials, called dopants, semiconductors can be transformed into good conductors.
- In certain configurations, semiconductors can be switched between being insulators and conductors with an applied voltage.

“Static” electricity

- Mechanical movement of electrons in normally insulating material separates positive and negative charges
 - shuffling your feet across a carpet then touching a doorknob
 - rubbing silk across a glass rod
 - Rubbing a balloon on your hair and sticking it to a wall
 - Lightning (movement of water particles in air)

Chemical electricity

- The result of certain chemical reactions knocks electrons loose from their host atoms and imbues them with energy.
- All batteries produce electricity this way.
- The battery chemistry determines the voltage produced by the battery.
 - An alkaline battery produces approximately 1.5 V per cell



Direct Current

- Batteries produce a constant voltage (well, nearly so until the chemicals all react)
- Constant voltage leads to constant current in a given load.
- We call this “direct current” or simply “dc”
- Let’s look at an example.

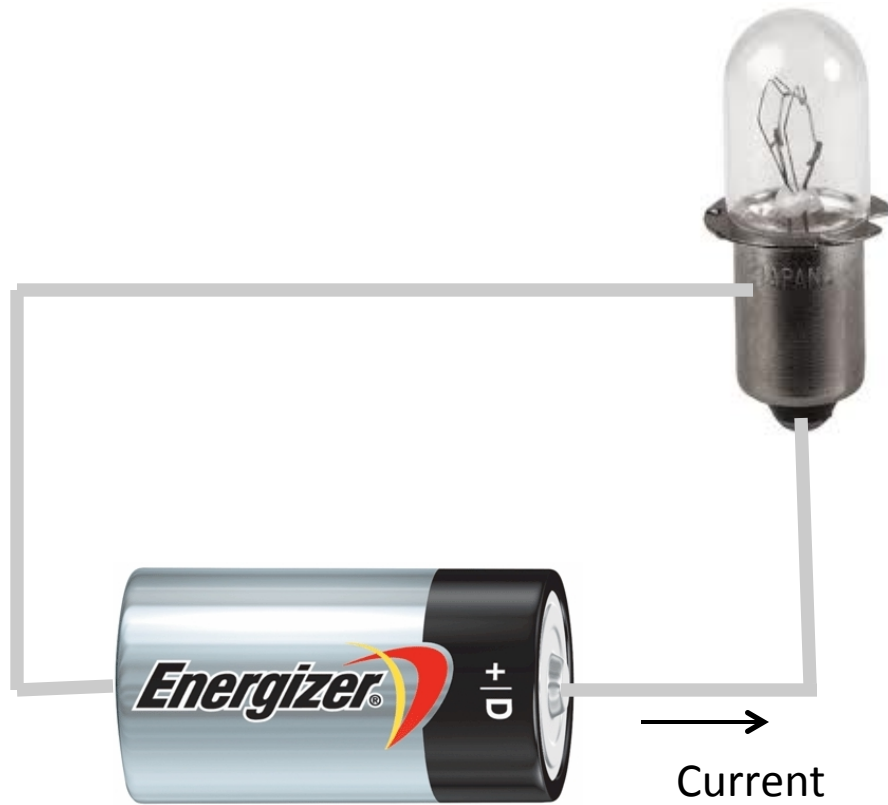
For the students

- What follows is a series of ideas for early introduction of electricity and magnetism topics.
- This will lead up to a simple electric motor.

A simple electric circuit

- Electricity is the movement of charge through conductors.
- This is analogous to the flow of water through pipes.
- To be sustainable, all of the electricity must flow in a closed path.
- To induce flow, a voltage source, acting as a “pump,” must add energy to the system.

A simple electric circuit



Things to consider

- What happens if you put two batteries back to back in series with the bulb?
- What happens if the batteries are opposite polarities?
- What about two batteries in parallel?
- What about multiple bulbs?

More on conductors vs. insulators

- The kit contains a bag of various items which are made of different materials.
- Disconnect one wire from the first circuit.
- Touch the wire and bulb to the various items and make two lists. If the bulb lights, the item is a conductor. If not, the item is an insulator.
- What happens if the bulb lights but only dimly?

Things to consider

- Some materials are insulators to low voltage but conductors at high voltage
- Dry skin is an insulator, wet skin is a conductor
- Once skin begins conducting, it becomes a better conductor
- Jewelry is an excellent conductor and should not be worn when working with electricity

SAFETY WARNING

- Jewelry is an excellent electrical conductor.
- Before working with electricity, it is safest to remove all rings, watches, bracelets, necklaces, etc.
- Even a single battery cell has enough power to heat a piece of jewelry to the point of causing a severe burn in a matter of seconds.

Alternating Current

- The other form of electricity which is very commonly experienced is the household wall plug which provides “alternating current” or “ac”
- Alternating current is produced using a combination of mechanical and magnetic action

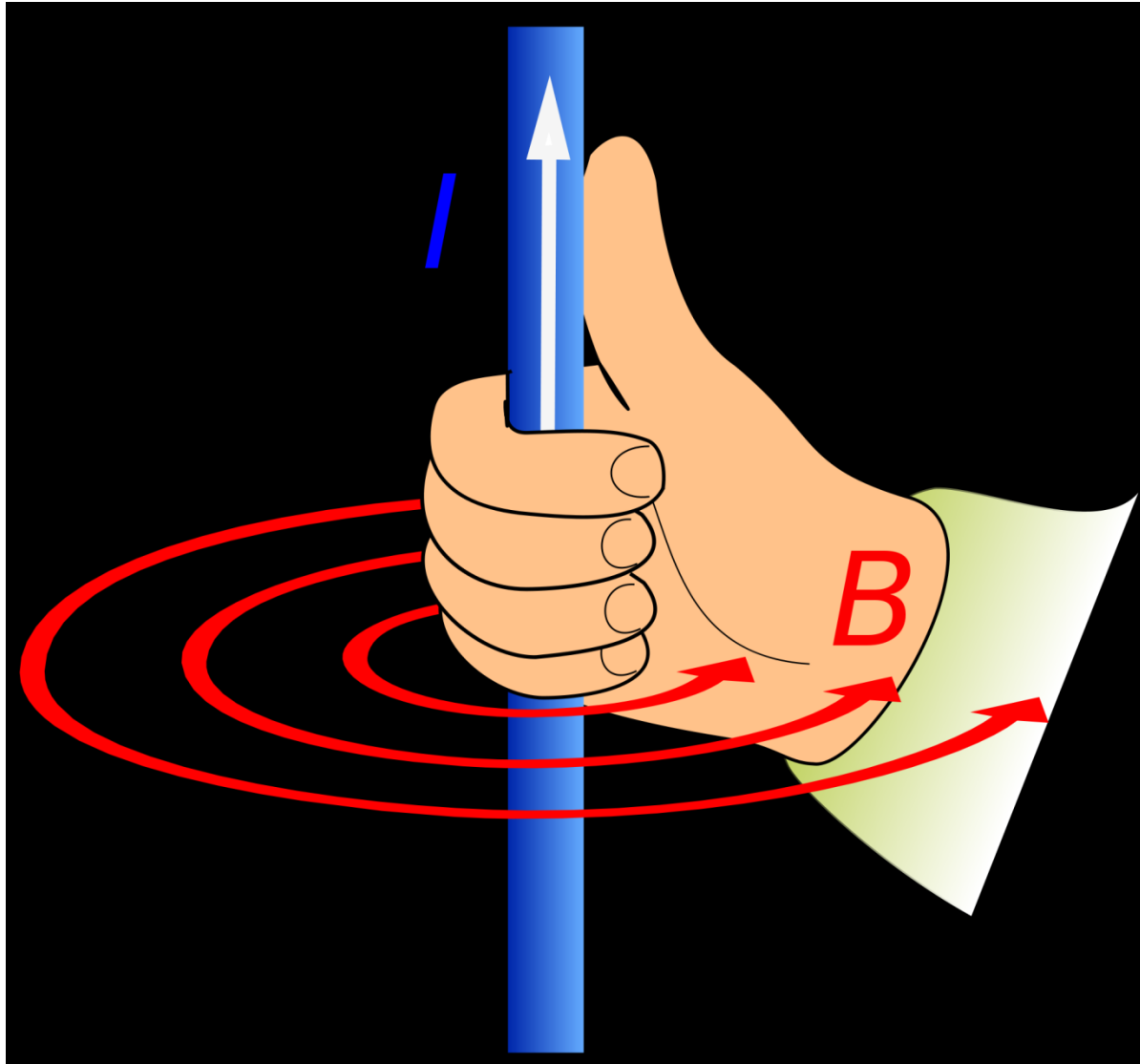
SAFETY WARNING

- The amount of power which can be provided by a battery cell is limited so handling a battery is relatively safe
- The amount of power which can be delivered by a household ac plug is much greater and is potentially lethal
- **DO NOT** repeat the dc experiments from earlier with the ac socket!

Electricity and Magnetism

- Electricity and magnetism are closely related.
- The flow of electricity is called “current” and has the symbol “ I ”.
- Whenever electric current flows, it generates magnetic fields, which have the symbol “ B ”.
- Similarly, magnetic fields generate electricity.
- The relative directions of the electric current and the magnetic field are related by the “right hand rule”.

Right hand rule



Right hand rule

- In the right hand rule diagram, a linear current, I , is encircled by a magnetic field, B .
- If you switch I and B in the diagram, it is also correct.
- Current flowing in a circular path generates a magnetic field aligned along the axis of the circle.
- This relationship is critical to electrical engineering.

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Magnetic fields

- Magnetic fields are always polarized such that there are two ends of the field with opposite polarity.
- We call these “north” and “south” because the earth has an intrinsic magnetic field aligned from north to south poles.
- As with electricity, opposite polarities attract and like polarities repel.

Seeing the effects of magnetic field

- From the kit you will need:
 - A ferrite magnet
 - Compass
- Bring the magnet close to the compass.
- One end of the compass needle should swing toward the magnet. Turn the magnet around and the needle should reverse.
- Move the compass slowly around the magnet and the needle will stay aligned with the magnetic field.

What makes a permanent magnet?

- Electrons spinning around the core of every atom generate magnetic fields.
- So, why isn't everything magnetic?
- For most materials, the atoms are arranged so that the magnetic fields of the various individual atoms are arranged randomly and, on average, cancel one another out.
- In ferromagnetic materials, the atomic structure allows the magnetic fields to align and be held aligned without external energy applied.
- Iron, nickel, and cobalt are good ferromagnets

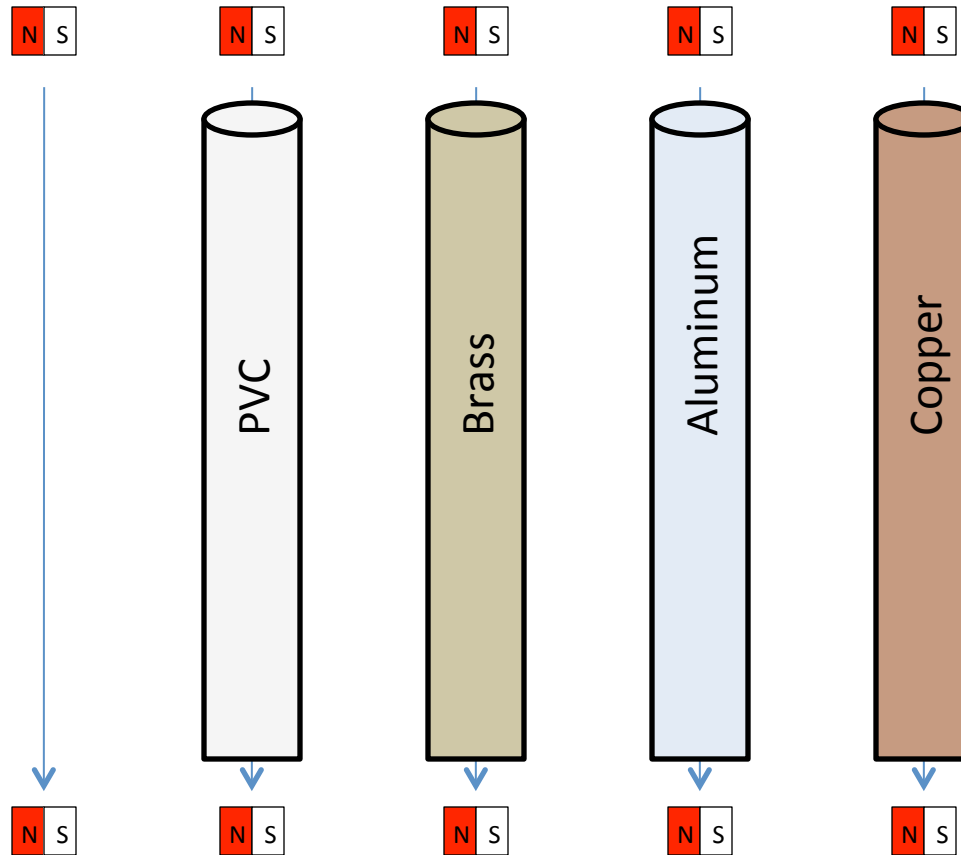
Magnets generate electricity

- Whenever an electrical conductor is placed in a changing magnetic field, electrical current is induced in the conductor.
- A fixed magnetic field produces zero current.
- The amount of current is proportional to the rate of change of the magnetic field.
- This can be demonstrated with a strong magnet and a length of pipe.

Magnetic “braking” supplies

- You will need:
 - A strong magnet (preferably Neodymium Iron Boron rated N40 or higher)
 - The ferrite magnets in the kits are probably too weak to notice the effect
 - Lengths of pipe made of non-conductive PVC and conductive copper (brass and aluminum are also interesting)
 - The magnets should fit as snugly as possible through the pipe without binding.

Magnetic “braking”



Drop a magnet in free air and it falls quickly to the ground.
Drop through non-conductive PVC and it falls just as fast.
Drop through a poor conductor, brass, and the magnet takes a bit longer to fall
Drop through good conductor, aluminum, and the magnet takes significantly longer to fall
Drop through excellent conductor, copper, and the magnet takes very long to fall

What is happening?

- As the magnet moves down the axis of the conductive tube it is creating an electric current that rotates around the circumference of the tube.
- The circular current produces a magnetic field in the same polarity as the falling magnet thereby repelling it and slowing the magnet's fall.
- The better the conductor, the more it “brakes” the falling magnet.

Things to consider

- Magnetic braking operates without the need for contact or friction so parts do not wear.
- Instead of a moving magnet and stationary conductor, you can use a stationary magnet to slow a moving conductor.
- Magnetic brakes are commonly used on roller coasters and monorail trains which have copper fixtures on the bottom of the cars.
- An electromagnet can be used instead of a permanent magnet so you can choose to brake or not and how strongly.

What makes an electromagnet?

- Since electric current in a wire generates a magnetic field, we can create a magnet when desired.
- Current flowing in a circle generates a linear magnetic field.
- Wrapping many turns of wire around the same axis reinforces the magnetic field with each turn of wire.

Making an electromagnet

- Take several feet of wire and strip the insulation from the last $\frac{1}{2}$ inch of the two ends
- Using a pencil or pen as a form, wrap the wire snugly around the shaft leaving a few inches free at each end
- Connect the ends of the wire to the battery and bring the coil near the compass
- The compass should react as it did to the permanent magnet
- Disconnect the battery and the magnet should ignore the coil of wire

Things to consider

- The strength of an electromagnet depends on the product of the current carried by the wire and the number of turns of the wire.
- If you double the current, you double the magnetic field
- If you double the number of turns of wire, you double the magnetic field.

Further considerations

- Wrapping the wire coils of an electromagnet around a ferromagnetic material such as iron will concentrate the generated magnetic field within the “core.”
- This has the effect of making the magnet stronger at close range but weaker at long distances.

What makes an electric motor?

- One type of electric motor uses a combination of a permanent magnet and an electromagnet to produce motion.
- The permanent magnet is placed in a fixed position next to a coil of wire.
- Passing current through the wire coil will produce a magnetic field that will either be attracted to or repelled by the magnet.

What makes an electric motor?

- The attractive or repulsive force will cause the coil to move to align the two magnetic fields.
- If we are careful, we can create a situation in which the coil's motion causes the current to be reversed as the coil aligns.
- Momentum will carry the coil past this position.
- With the current reversed, the coil will try to reverse orientation so the coil will spin in a full circle and repeat the process as long as power is available.

Build your own dc motor

- Building a dc motor is relatively easy.
- The following Wikipedia page is a good illustration:
- [http://en.wikipedia.org/wiki/Brushed DC electric motor](http://en.wikipedia.org/wiki/Brushed_DC_electric_motor)

DC motors

- The kits contain small dc motors.
- Connect the dc motor to the battery and the drive shaft will spin.
- Reverse the battery leads and the motor will spin in the opposite direction.
- The speed of the shaft varies with load.
- The amount of electric current needed to turn the motor varies with load.

Reversing the motor process

- If we put electric current into a motor, we get mechanical movement out as a result of the interacting magnetic fields of the permanent magnet and electromagnet.
- If we mechanically spin the motor, the coil moving through the field of the permanent magnet will produce electric current.
- The magnitude and orientation of the current is proportional to the position of the coil relative to the permanent magnet.

Generator

- Mechanically spinning a motor to create current makes the device a “generator”
- Because the coil is constantly changing alignment with the permanent magnet, the resulting current constantly varies between a maximum positive and maximum negative value.

Practical generators

- Most electrical power supplied to the home wall sockets is produced by large generators.
- These may be turned by a variety of mechanical power sources.
- The “alternator” in your car is a form of generator optimized for producing power that can easily be converted to a form that can be used to charge the car battery.

Resources and Ideas

- Free Textbook – Lessons In Electric Circuits
 - <http://openbookproject.net/electricCircuits/>
- “All about Circuits” Forum
 - <http://forum.allaboutcircuits.com/>
- MIT K-12 videos: Exploring Circuits”
 - <http://k12videos.mit.edu/content/exploring-circuits>
- <http://www.discovercircuits.com/>

Resources and Ideas

- <http://www.teachengineering.org/>
- “Squishy circuits”
 - <http://shiftingphases.com/2012/04/15/k-12-engineering-squishy-circuits-tips-and-tricks/>
- Electricity Interactive: Fun for Kids
 - <http://www.vrml.k12.la.us/curriculum/quicktip/science/electricity/elec.htm>
- NeoK12 Educational videos
 - <http://www.neok12.com/Electricity.htm>

Resources and Ideas

- Science Toys - <http://scitoys.com/>
- Battery Stuff - <http://www.batterystuff.com/>
- Pololu Robotics and Electronics
 - <http://www.pololu.com/>
- Educational Innovations
 - <http://www.teachersource.com/>
- How Stuff Works: Motors
 - <http://electronics.howstuffworks.com/motor1.htm>

Resources and Ideas

- Super Magnet Man
 - <http://www.supermagnetman.net/>
 - <http://www.youtube.com/user/SuperMagnetMan>
 - http://www.engconcepts.net/Magnet_University.html
- *Disclaimer: SuperMagnetMan is George Mizzell. His daughter was one of my favorite students and a talented engineer. I am not impartial in recommending his site. Nevertheless, he does have some very nice magnet videos.*

Places to purchase parts

- <http://www.jameco.com>
- <http://www.digikey.com>
- <http://www.mouser.com>
- <http://www.alliedelec.com>
- <http://www.mcmaster.com>
- <http://www.mpja.com>
- <http://www.goldmine-elec.com>
- <http://www.sparkfun.com>
- <http://www.makershed.com>
- <http://www.geeks.com>
- <http://www.eio.com>