Grass Roots GK-12 Laboratory Activity

Title:	**Turning on the Lights!**
Initial Version: **Latest Revision:**	7/25/2013 7/15/2015
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Course & **Appropriate Level:**	Regents, AP and IB Physics
Abstract:	Students compare and contrast different types of power production identifying the turbine/generator as a common part. Students will explain how electricity is produced and how the turbine speed, number of loops, and number of magnets affects the induced EMF.
Time Required:	120 minutes
NY Standards Met:	4.1 Students can observe and describe transmission of various forms of energy. 4.1b Energy may be converted among mechanical, electromagnetic, nuclear, and thermal forms. 4.1j Energy may be stored in electric or magnetic fields. This energy may be transferred through conductors or space and may be converted to other forms of energy. 4.1k Moving electric charges produce magnetic fields. The relative motion between a conductor and a magnetic field may produce a potential difference in the conductor. 4.1n A circuit is a closed path in which a current can exist. (*Note: Use conventional current.*)
Special Notes:	This laboratory activity was created via Cornell University's NSF GK12 Grass Roots Program: Award 1045513

Student Learning Outcomes:

Upon completion of this lab activity, students should be able to:

- Explain how electricity is produced
- Explain how speed, number of loops, and number of magnets affect the voltage / power produced.

Class Time Required:

- 120 minutes

Teacher Preparation:

The following materials need to be secured/prepared:

Typically, students make generators in a group of two. Per generator, you need:

Item	**Per generator**	**Cost**	**Source**
LED 5mm red	1	0.03	http://www.taydaelectronics.com/led-5mm-red.html Tayda is a great electronics source.
LED 5mm yellow	1	0.03	http://www.taydaelectronics.com/led-5mm-yellow.html
Magnet Wire, 32 AWG	~ 200 feet	0.73	http://www.amazon.com/gp/product/B0082CUR1K/ Elektrisola has been reliable.
Neodynium Magnets disc 1/2 x 1/8 (inch)	4	1.16	http://www.magnet4less.com/product_info.php?products_id=119 Part number ND031. Also check amazon; Bykes and Applied Magnets are good suppliers, and the cheapest options on Amazon change frequently
50 mL centrifuge tube, pill bottle or PVC tube (~1 inch inner diameter)	1	0.34	ebay ("50 mL centrifuge tubes"), roughly $10 / 25, or $30 / 100.
Jumbo paper clip	1	0.01	
Pinwheel on transparency	1	0.05	4 pinwheels fit on a transparency sheet

Common supplies:

Item	Number	Reason
LabQuest / Vernier LabPro + voltage probe	Ideally 1 per group	Measure voltages produced by generator. A multimeter is not a good substitute, because the voltage produced is low frequency AC—neither AC or DC setting captures the voltage produced very well.
Multimeter	2+	Measure resistance of wire to determine length of wire wrapped.
Plastic tweezers	1 per 1-2 groups	Helpful to have non-magnetic tweezers for getting the magnets onto the paper clip; see the picture in the student handout.
Needle-nose pliers	2+	Helpful to bend the end of the paper clip after attaching pinwheel
Masking tape	Few rolls	Taping wire in place on generator, taping LEDs to generator
Sandpaper, rough or	1x1” square per group	Rubbing the insulation off the magnet wire

medium grit		
Sticky tack	1 piece per group	Hold paper clip pieces in place for wire-winding
Thumb tack	Few	Poke holes in pinwheel
Straws	1 box	May be easier to blow on the pinwheel with a straw
Hand / power drill (optional)	1+	Useful to spin generators at a consistent speed, or spin generators at all of the paper clip is very bent.

Tips for the Teacher:

- **Pre-lab preparation:**
  - A hole should be drilled through the 50 mL centrifuge tubes at the 40 mL line. This will be used for the shaft of the generator.
  - Straighten out 4 paperclips and cut them into small strips approx. ¾" long (Students could also cut their own paper clip pieces)
  - Cut the sand paper into 1"x1" pieces.
  - Place the following materials inside the 50 mL tubes:
    - 1 paperclip
    - 2 paperclip pieces
    - LEDs (1 red and 1 yellow, twisted together, with one long lead twisted with one short lead on each side)
  - One ~30 foot long length of wire per group should be cut off, made into a loop, and have the ends scraped off before class.
- **Introduction of the activity:**
  - Students can be assigned to research how electrical power is generated during a first class period. Alternatively, the activity can be introduced with the included PowerPoint presentation. The simulation of electromagnetism / an electrical generator from phET may also be helpful.[1]
- **During the activity:**
- In order to light the LEDs, students should wrap at least 150 feet of magnet wire around the tube. Timing students taping wire for about 8 minutes works well; the length of wire used can be measured by using a multimeter to measure its resistance.
- Typically the activity is done in groups of 2. This works out well because it can be helpful to have an extra pair of hands for holding something when attaching the magnets or spinning the generator.
- If LabQuests are used, they should be set up to collect 50 to 100 points / second for 3 or 5 seconds (3 seconds for original LabQuests, 5 seconds for LabQuest 2; this should be a high enough rate that the AC voltage generated is measured accurately, but low enough that the LaqQuest display will still update in real-time). **The default setting of 10 samples / second will not capture the waveform (which can be 5–15 Hz).**

Assumed Prior Knowledge of Students:

- For magnets, like charges, like poles repel, and opposite poles attract.
- Electricity involves moving charges

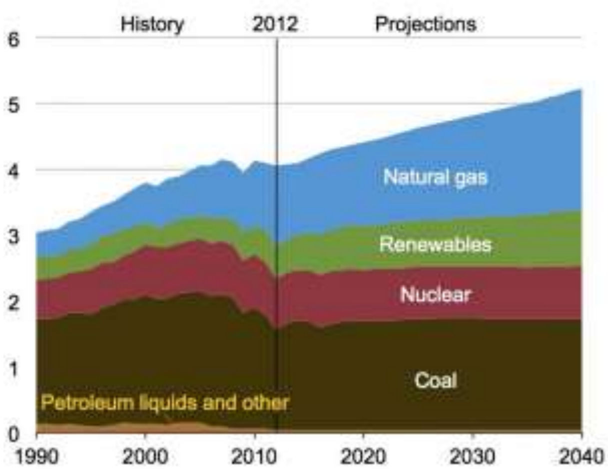
[1] http://phet.colorado.edu/en/simulation/generator

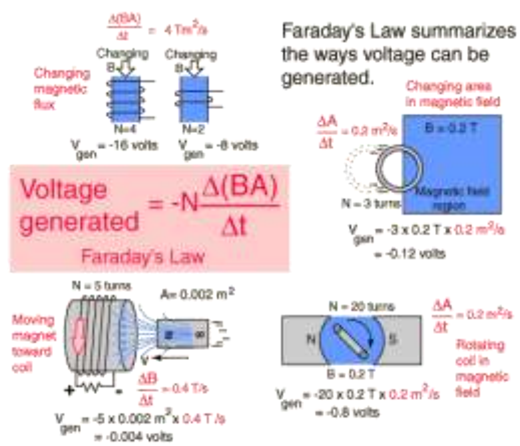
Background Information for Teacher:

Question: How do we convert heat, mechanical motion to electricity?

The United States uses about 125 mega-joules (MJ) of electricity per person per day; that is the energy in 1 gallon of gasoline or 50 hamburgers (to produce this amount of electricity would require roughly 3 gallons of gasoline or 150 hamburgers, since power plants are about 33 percent efficient).[2] Another way of looking at it is that the United States is constantly using 1500 watts per person, or about 100 CFL light bulbs worth.

Figure ES-5. Electricity generation by fuel in the Reference case, 1990-2040 (trillion kilowatthours)





To produce this electricity, the U.S. relies on natural gas, coal, nuclear, and renewables, with renewables dominated by hydroelectric and wind production. All of these power plants use generators to convert the energy in rotating turbines to electricity. Generators do this by utilizing electromagnetic induction: due to the relationship between electricity and magnetism, a conductor in a changing magnetic field will produce a current.

Electromagnetic induction can be described mathematically by Faraday's Law $\varepsilon = -N\frac{d\Phi}{dt} = -N\frac{d(BA)}{dt}$, where ε is the electromotive force (emf), N the number of loops of the conductor, Φ the magnetic flux, B the magnetic field, A the area of the loop made by the conductor, and t time. See the picture above for examples.[3]

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[2] http://en.wikipedia.org/wiki/Energy_in_the_United_States#Current_consumption, http://www.eia.gov/forecasts/aeo/er/pdf/0383er(2014).pdf p17.

[3] http://hyperphysics.phy-astr.gsu.edu/hbase/electric/farlaw.html and http://hyperphysics.phy-astr.gsu.edu/hbase/electric/farlaw2.html

The voltage produced by the generator can be explained qualitatively in terms of Lenz's law[4]:

> "An induced electromotive force (emf) always gives rise to a current whose magnetic field opposes the original change in magnetic flux."

The specific type of generator created in this activity is a magneto. Its operation is very simple; a permanent magnet rotates in loops of a conductor, which induces a current in the conductor. Since the direction of the magnetic field is constantly changing, an alternating current is produced. An alternator, the design used in power plants, differs in that it uses electromagnets rather than permanent magnets to create the magnetic field.

An electrical motor is just the reverse process: electrical energy is converted into mechanical energy by running a current through a conductor to induce motion in a magnet. For this reason, electrical motors can be used as generators; for example, electric and hybrid cars recharge their batteries during braking (regenerative braking).[5]

Now that rare earth neodymium magnets are widely available, magneto generators have become more common, especially for home-built or easily portable designs. They are especially well suited for off-the-grid applications since they do not require an external alternating current to begin producing power.[6]

Acknowledgements:

This activity is loosely based on an activity by Grzegorz F. Wojewoda.[7]

Technical Details:

It can be difficult to pull the magnets apart. Try sliding one magnet off at a time using a lateral motion, as shown in the video from K&J Magnetics.[8]

Pre-lab activity ideas:

- Short research assignment (pre-class or during class) on "How is electricity produced?" (possibly also, "What is electricity?") and class discussion of answers. This should lead students to the idea that a generator is required to turn energy from coal, wind, water, nuclear, etc. into electricity (and even solar in thermal solar power plants).
- Demonstrate Lenz's law with magnets, a coil of wire, and galvanometer: will the magnets and coil of wire produce current? When is the current positive? When is the current negative? How does it change when the magnets are moved or slower?

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4 http://en.wikipedia.org/wiki/Lenz%27s_law
5 http://auto.howstuffworks.com/auto-parts/brakes/brake-types/regenerative-braking.htm
6 http://www.scoraigwind.com/axialplans/index.htm
7 http://www.euhou.net/index.php/exercises-mainmenu-13/classroom-experiments-and-activities-mainmenu-186/273-simple-model-of-a-generator
8 http://www.youtube.com/watch?v=QRjCNe88xpg,

- Have students determine when voltage is produced from magnets and wire using a coil of wire, magnet, and voltage probes (LabQuest or computer data collection)
- Demonstrate Lenz's law / eddy currents with a copper pipe (see http://www.coolmagnetman.com/magpipes.htm for an example)
- Homopolar motor (http://en.wikipedia.org/wiki/Homopolar_motor)
- Act out Lenz's law (usually done after some large-class demonstration or small-group exploration)
  - Introduce a right or left hand rule (left hand if thinking in terms of electrons, right hand if thinking in terms of conventional current) describing the magnetic field produced by a current through a wire
  - "Current in wire always *opposes* a change in magnetic field"
  - Get students to be atoms, electrons (we gave the electrons tennis balls), and one student to be / hold a magnet (we use a shoebox labeled N / S)
  - So, can our magnet-holder start moving the magnet away from the wire? Use your thumb to show where the magnetic field is pointing. Okay, what direction do the electrons want to move, using the left-hand rule?
  - Eventually, have the magnet-holder *slowly* turn the magnet; as it spins, the electrons will spin clockwise, counter-clockwise, clockwise…demonstrating an alternating current.

Extensions:

- Try different materials / sizes / designs for the pinwheel
- Try using cool setting of a hair dryer to spin pinwheels with a consistent speed
- Try using different magnets: magnet4less.com has a variety of strength magnets in the same size
- Try different diameter tubes
- Try different color LEDs, connecting LEDS the same direction or opposite: when do the different LEDs light up (cell phone video of the LEDs could be helpful here)

Other Resources:

http://en.wikipedia.org/wiki/Eddy_current_brake Applications of eddy current brakes, and other lab ideas.

http://phet.colorado.edu/en/simulation/generator A very nice customizable simulation of a generator.

http://physics.stackexchange.com/questions/5573/whats-the-core-difference-between-the-electric-and-magnetic-forces

"Electric forces are created by and act on, both moving and stationary charges; while magnetic forces are created by and act on only moving charges."

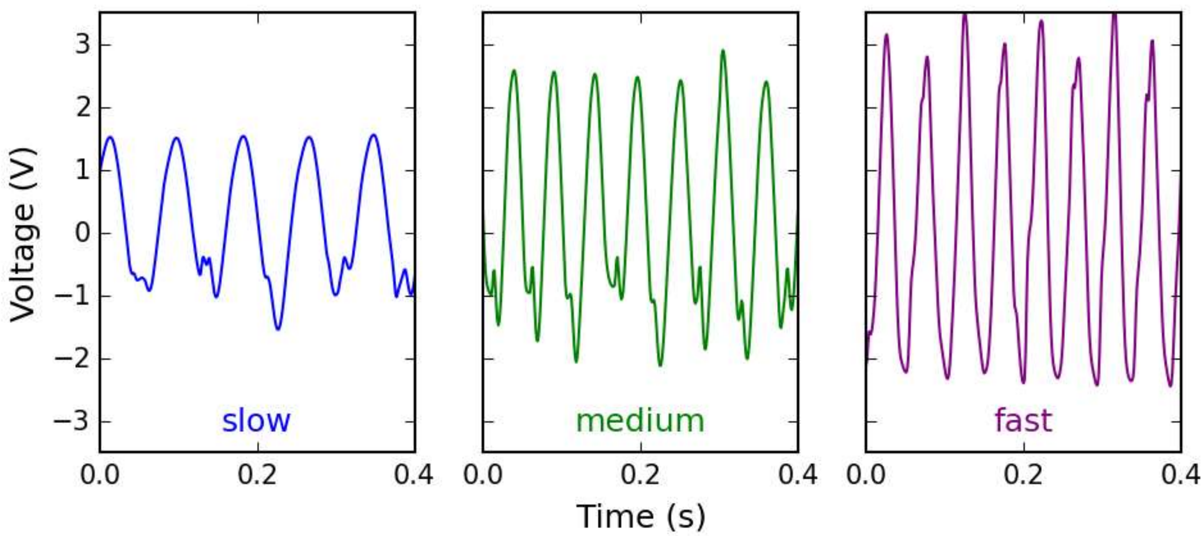
Discrepant Event:

- Electricity and magnetism are closely related, as we will discover in this lab. Magnetic forces are created by and act on moving charges.
  - What is electricity?
    - Moving charges!

- Whenever we have electricity, we also have magnetic fields, and we can use that effect, and things that produce magnetic fields can also produce electricity
- Event: Take a neodymium magnet and drop it down a copper tube. Why does it slow down? Why doesn't it stop completely?
    - Changes flux creates a magnetic field which exerts an upward force on the magnet (opposing the change in magnetic field). If the magnetic stopped completely, there would be no change in flux to create a magnetic field; it instead reaches equilibrium at a certain velocity where the magnetic force (from the current through the copper tube) on the magnet is equal and opposite to the gravitational force on the magnet.

Experimental Data:

- Sample data, spinning a generator with 4 magnets and 156 ft of wire:



Answers to lab questions:

- The coil of wire and magnets produce electricity when one moves relative to the other, especially when the motion is fast or moves the magnets in / through the center of the coil of wire.
- Example: R = 26.6 Ω, length of wire = 26.6 Ω · 100 ft / 17 Ω = 156 ft.
    - *100 to 200 feet of wire in 8 minutes of fast wire wrapping is typical*

Generator Experiment 1: Explore how the number of magnets affects the voltage produced

- Adding more magnets should produce greater voltage.
- Example: 1.02 V RMS, 1.82 V peak
- Example: 1.95 V RMS, 3.48 V peak
- Our data showed that adding more magnets produced greater voltage, consistent with our hypothesis.

Generator Experiment 2: Explore how the pinwheel spin speed affects the voltage produced

- Spinning the pinwheel should produce greater voltage.

Example:

pinwheel spin speed	RMS voltage (V)
slow	0.97
medium	1.55
fast	2.14

- Our data showed that spinning the pinwheel faster produced more voltage, consistent with our hypothesis.

Generator Experiment 3: Explore how the wire length affects the voltage produced

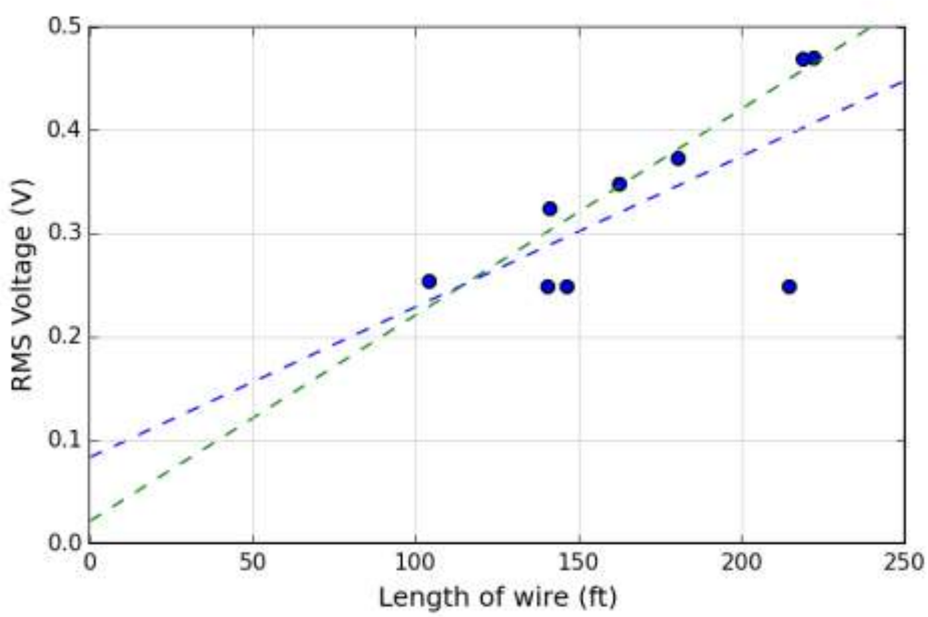
- A longer length of wire should produce greater voltage.
- Example: 1.51 V RMS, 2.25 V peak. Yes, it lights both LEDs.
- *It takes about 1.6 V to light a red LED, 1.8 V to light a yellow LED, so an RMS voltage of about 1.2–1.3 volts is enough to light the LEDs dimly; any additional voltage will increase the current and make the LEDs brighter.*

11. Our data showed that a longer length of wire produced more voltage, consistent with our hypothesis.
    - *This will depend a lot on how well controlled the spin speed is; if using a hand / power drill and counting revolutions carefully, the results should be quite good. If just blowing on the pinwheel, the results will be quite inconsistent, since the spin speed can vary dramatically.*

<u>Answers to post-lab questions:</u>

1. Provide your data to the class to create a complete plot of voltage output vs. wire length (use the 1 rev. / second or medium speed data). Sketch the plot below.

Example plot, for *well-controlled spin speed* (3 revolutions / second, with a hand drill):



The green line excludes the 3 possible outliers. If the spin speed is not well controlled, little or no effect will be seen, because the fastest speed achievable with a turbine can vary by a factor of 2 or 3 depending on how straight the paper clip is.

2. Which variable was observed to have the weakest effect on voltage generated? Why do you think that is?

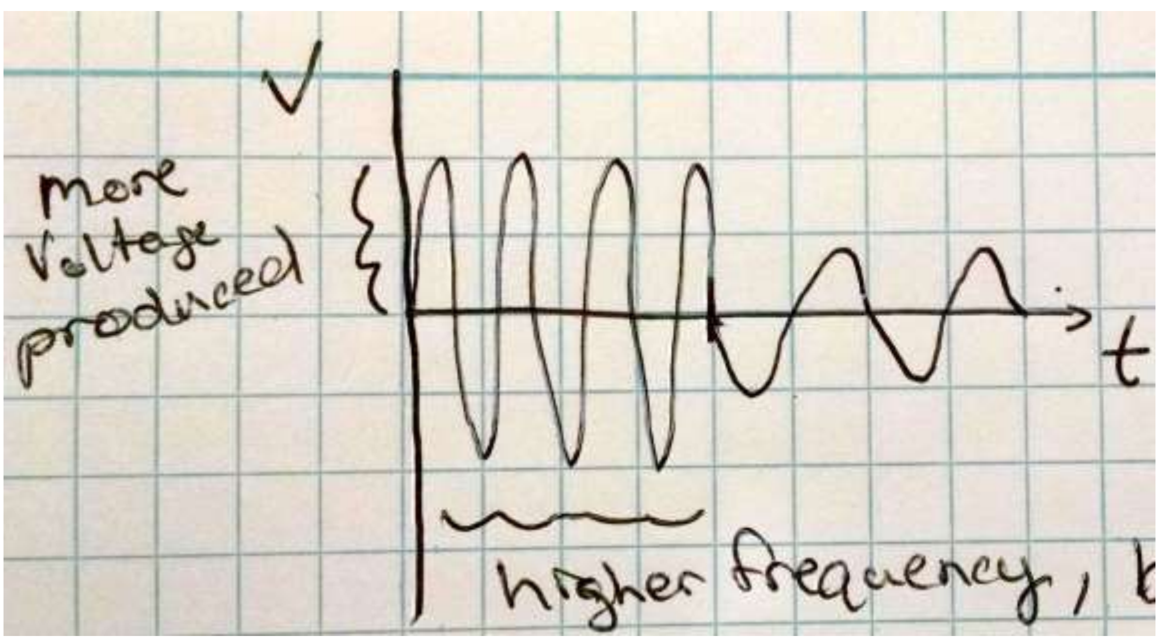
Length of wire, most likely. There are a variety of explanations:

- Differences in spin speed (very important if the spin speed was not well-controlled).
- Length of wire requires comparing between different generators, different groups. Any differences in how the wire was wound (how much overlap, how far away from the magnet) will affect the voltage vs. length of wire plot, but not the others. Location of the magnets in the tube is another factor; when the magnets are closer to the edge of the tube, somewhat more voltage is produced.

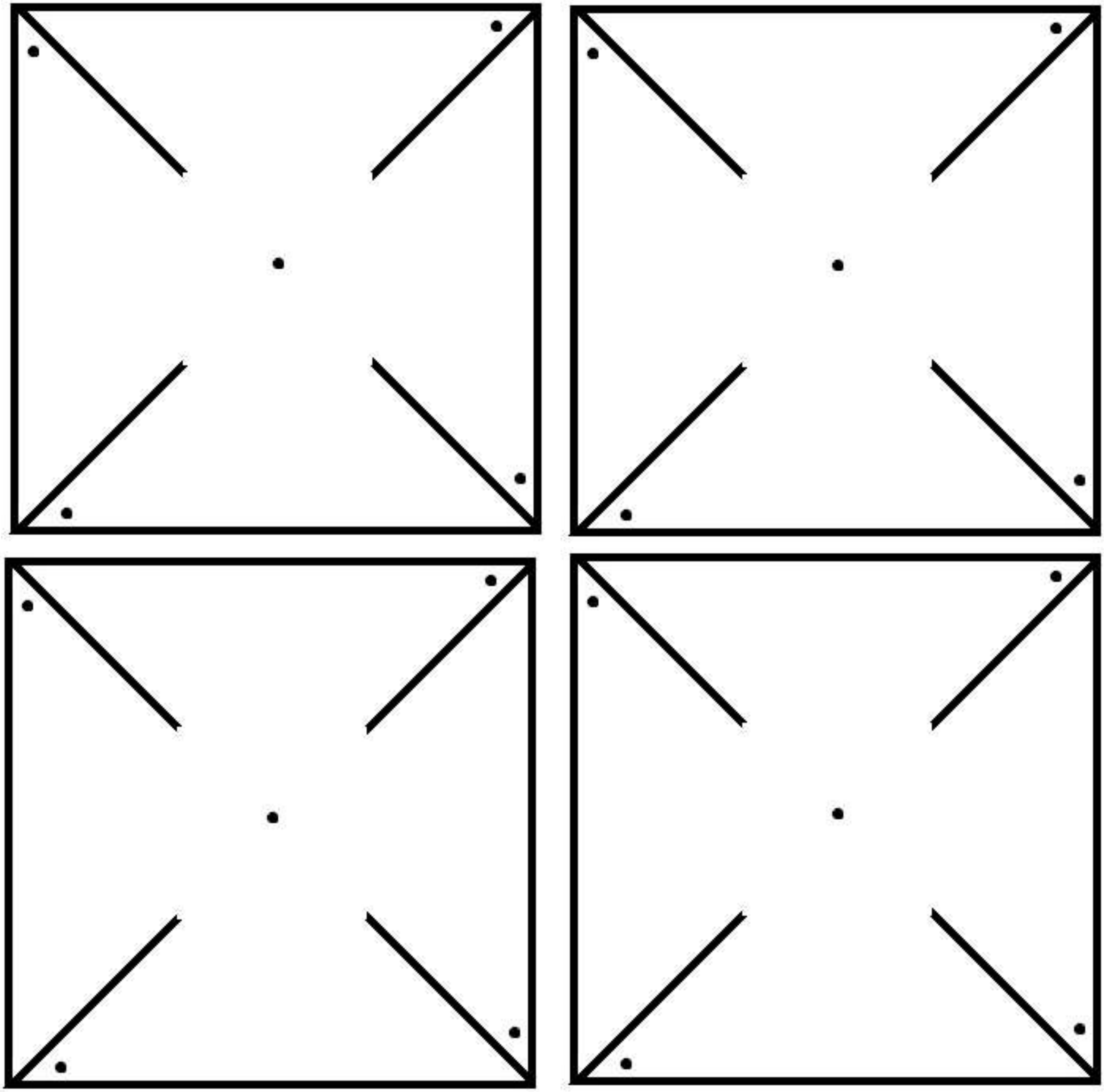
3. Why does the voltage alternate between positive and negative?

Lenz's law; the current through the wire is always opposing the change in magnetic field; as the magnetic field decreases in the +z-direction, a counterclockwise conventional current through the wire creates a magnetic field in the +z-direction. As the magnetic field increases in the +z-direction, the clockwise conventional current through the wire creates a magnetic field in the –z-direction.

4. A student spins a generator quickly for 1 second, then slowly for 1 second. Sketch what the voltage produced by the generator would look like on the following graph.



Note both the frequency and amplitude change at slower spin speeds!

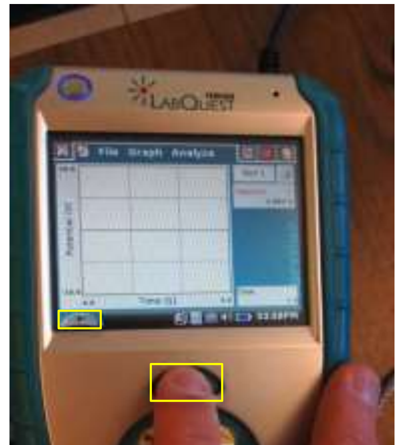


Pinwheel cutout. Print on transparency instead of white paper, if possible.

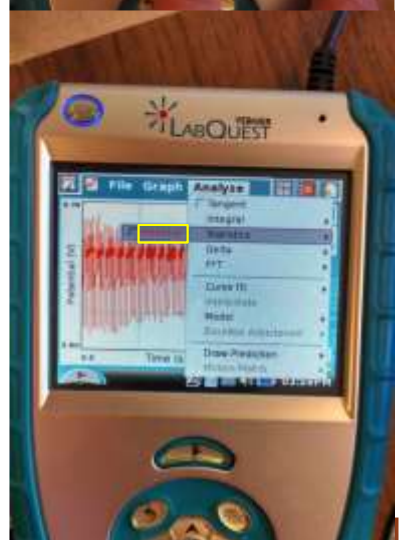
Cutout from http://blog.homeseasons.com/2012/05/23/fun-diy-pinwheel-project-for-4th-of-july/

Using the LabQuest and voltage probes:

- First, hook up a voltage probe lead (the black or red piece) to each end of the wire or generator. Make sure the lead is touching exposed wire, rather than the coating on the wire.
- Press either the physical or touch screen “play” buttons to begin collecting data.



- When data collection has finished, navigate to Analyze > Statistics, and press potential.



- The standard deviation (std. dev.) is a good measure of the average voltage or power produced by your generator, so report that on your lab handout. It should be in units of volts.

Grass Roots GK-12 Laboratory Activity

Turning on the Lights!

Name ________________________

Introduction

In this activity, you will build a homemade generator that produces electricity in the same way as power plants. Using the generators, you can explore voltage and power generated, and even power red and yellow LEDs!

Warm-up Activity

Materials:

- coil of wire
- Labquest or Vernier voltage probe
- magnet

Attach a voltage probe to each end of the wire, and collect data with the Labquest or Vernier voltage probe. Explore how voltage can be generated using only the wire and a magnet.

1. When do a coil of wire and magnets produce electricity?

Building your generator

Materials needed to build your generator:

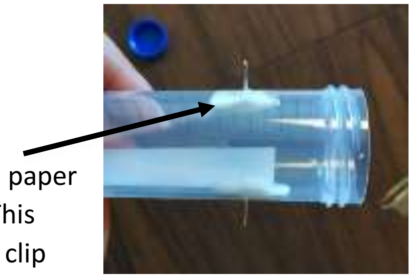
- Magnet wire
- Pinwheel transparency pattern
- 4 neodymium magnets
- 5 mm T-1 3/4 red and yellow LEDs
- 50 mL plastic centrifuge tube
- Paper clip

You should also have available:

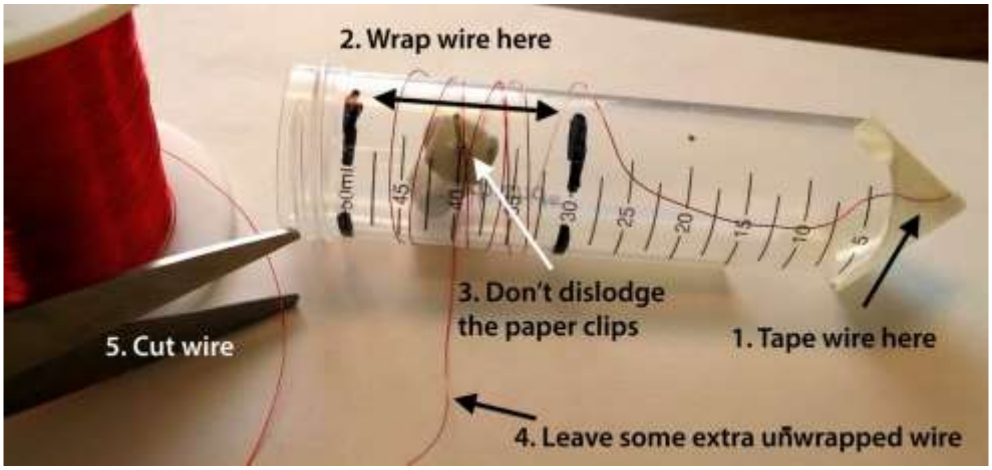
- Sticky tack
- Plastic tweezers
- Sandpaper
- Tape
- Thumb tack
- Needle-Nose pliers
- Straws
- LabPro / Vernier voltage probes

Instructions to build your generator

- Empty the contents of your plastic tube. You should have:



- Place the sticky tack inside the tube, covering the two holes. Put the paper clip pieces into the holes so they are firmly stuck in the sticky tack. This will prevent you from covering the holes, so you can put your paper clip and magnets in later.
- Follow the picture below to wind wire for your generator.

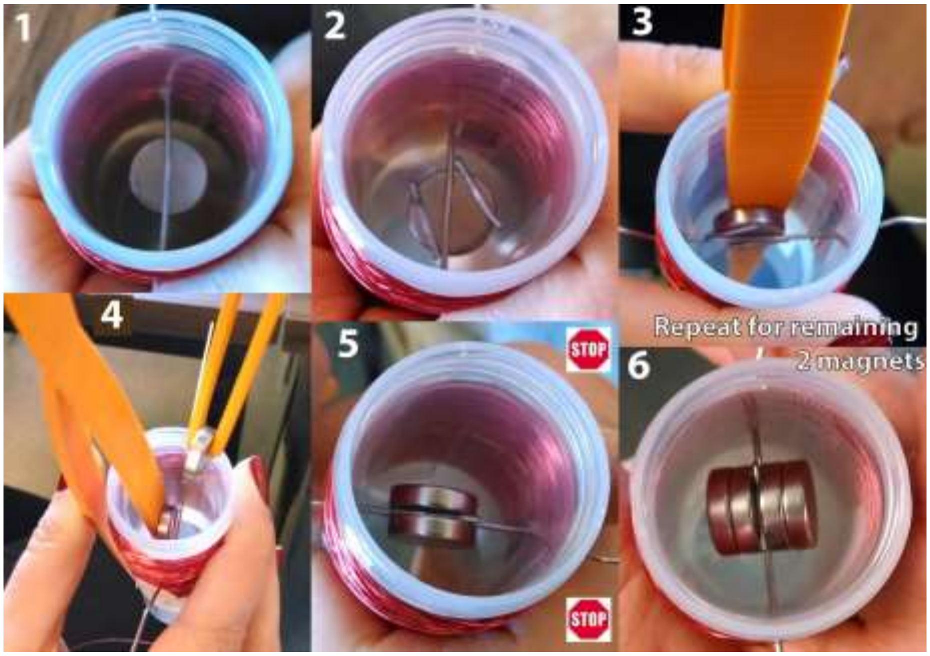


- Put some tape around the bottom of the wire on your generator to secure it in place.
- Scrape the (red) enamel coating off the two ends of the wire using sandpaper. Make sure all the enamel is removed from the ends of the wire, since it does not conduct electricity and will prevent you from measuring voltage or powering your LED.
- Carefully straighten your paper clip. Wiggle the paper clip pieces so there is room to insert the straightened paper clip. Remove the sticky tack and paper clip pieces, and slide the flattened paper clip through the tube.

2. Determine the length of wire by connecting the generator to a multimeter set as a resistance meter and using the equation below.

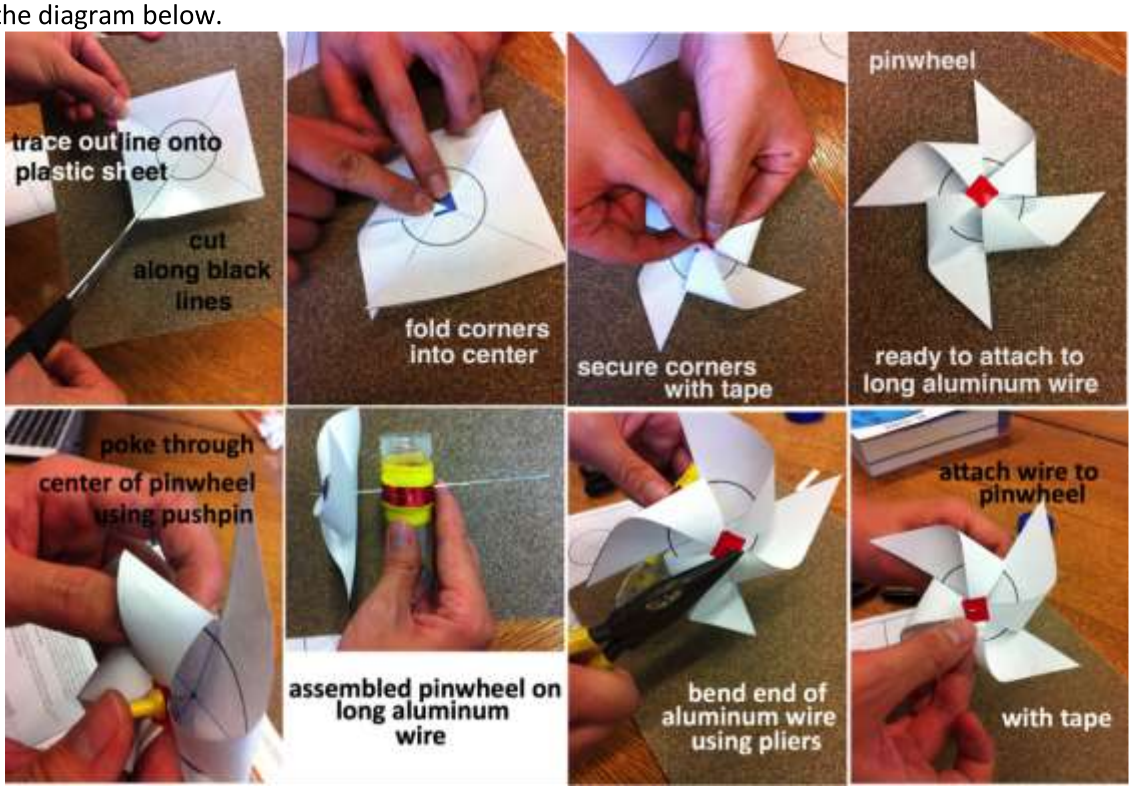
Resistance of generator ______
Length of wire ______

$$\text{length of wire} = \frac{(\text{resistance})}{17\,\Omega} \times 100 \text{ feet}$$



IMPORTANT: The magnets will be strongly attracted to one another! Always use a paper clip or tweezers when attaching the magnets to avoid pinching your fingers.

- Add two magnets to your generator, following the pictures. **1.** Add the 1st magnet. **2.** Add the paper clip pieces so that when you add the next magnet, the magnets don't slide off the paper clip. **3.** Use the tweezers to hold the paper clip so that the next magnet goes on the other side. **4.** Drop the second magnet in. **5.** Stop with 2 magnets for now.
- Make a pinwheel from the provided transparency and attach it to the generator according to the diagram below.



Generator Experiment 1: Explore how the number of magnets affects the voltage produced

3. Write out your hypothesis regarding how the voltage depends on the number of magnets:

- Test it! Hook your generator up to the LabQuest voltage probes. Blow on the pinwheel using a straw and record data.

4. What is the largest voltage produced by your generator with 2 magnets? _________V

- Add the remaining 2 magnets to the generator. Blow on the pinwheel again and record your data.

5. What is the largest voltage produced by your generator with 4 magnets? _________V

6. Revisit your hypothesis. Based on your data, what do you now conclude regarding the mathematical relationship between the voltage generated and the number of magnets?

Generator Experiment 2: Explore how the pinwheel spin speed affects the voltage produced

7. Write out your hypothesis regarding how the voltage depends on the pinwheel spin speed:

- Blow on the pinwheel at a slow, medium, and fast speed. Record data using the LabQuest.

pinwheel spin speed	**RMS voltage (V)**
slow	
medium	
fast	

8. Revisit your hypothesis. Based on your data, what do you now conclude regarding the relationship between the voltage generated and the pinwheel spin speed?

Generator Experiment 3: Explore how the wire length affects the voltage produced

9. Write out your hypothesis regarding how the voltage depends on the wire length:

- Attach your LEDs to the generator.

10. The largest RMS voltage produced by your generator when blowing on the pinwheel = ______V
    Does it light the LEDs?

- Plot your largest voltage produced and length of wire on the blackboard. Your fellow students will also add their data to this plot.

11. Based upon the data of the entire classroom, what is your conclusion regarding the relationship between the length of wire and voltage generated by your generator (be as mathematically precise as you can in describing this relationship)?

Post Lab Analysis

1. Provide your data to the class to create a complete plot of voltage output vs. wire length (use the 1 rev. / second or medium speed data). Sketch the plot below.

2. Which variable was observed to have the weakest effect on voltage generated? Why do you think that is?

3. Why does the voltage alternate between positive and negative?

4. A student spins a generator quickly for 1 second, then slowly for 1 second. Sketch what the voltage produced by the generator would look like on the following graph.