Grass Roots GK-12 Laboratory Activity

Title:	Shake Light – A Model of Electromagnetic Induction
Initial Version: Revision:	August 2014 Rev. 1 – February 2015
Authors:	Robert Bell, Michael Mangini and Ray Kaschalk
Course & Appropriate Level:	Regents and AP Physics, STEM (Grades 10-12)
Abstract:	This series of activities is designed to develop the student's understanding of how voltage is generated via electromagnetic induction and how simple circuits can be constructed to store the energy produced and rectify the alternating current produced by a simple "shake-light" AC generator. Advanced students will also determine the mathematical relationship between induced voltage in a similar coil and the speed with which a magnet passes through it to derive Faraday's Law of Electromagnetic Induction.
Time Required:	160 minutes
NY Standards Met:	**Standard 4 Performance Indicators:** 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 mat 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. **Standard 4 Process Skills:** • Recognize and describe conversions among different forms of energy in real or hypothetical devices such as a motor, a generator, a photocell, a battery. • Measure current and voltage in a circuit.

	• Compare the power developed when the same work is done at different rates. **Standard 1 Key Ideas** M1.1 Use algebraic and geometric representations to describe and compare data. • Construct graphs of real-world data. • Manipulate equations to solve for unknowns. M2.1 Recognize patterns and mathematical relationships. • Interpret graphs to determine the mathematical relationship between the variables.

Student Learning Outcomes:

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

- Explain how voltage is generated via electromagnetic induction.
- Determine the direction (polarity) of a voltage generated via electromagnetic induction.
- Predict the shape of the voltage-time graph for the given coil/magnet configuration.
- Predict the shape of the voltage-time graph for an alternative coil/magnet configuration.
- Sketch a circuit that uses four one-way diodes to rectify an AC input into a DC output
- Understand how AC voltage is converted into electrical power.
- Build a basic LED circuit (Diode Bridge) that rectifies alternating (AC) current into DC.
- [AP Physics] Apply the universal right hand rule to solve problems involving the relative motion of conductors and magnetic fields.
- Use capacitors to modify the shake light power output.
- [AP Physics] Determine the mathematical relationship between induced voltage and relative speed between a coil of wire and a moving cylindrical magnet to develop Faraday's Law of Electromagnetic Induction.

Class Time Required:

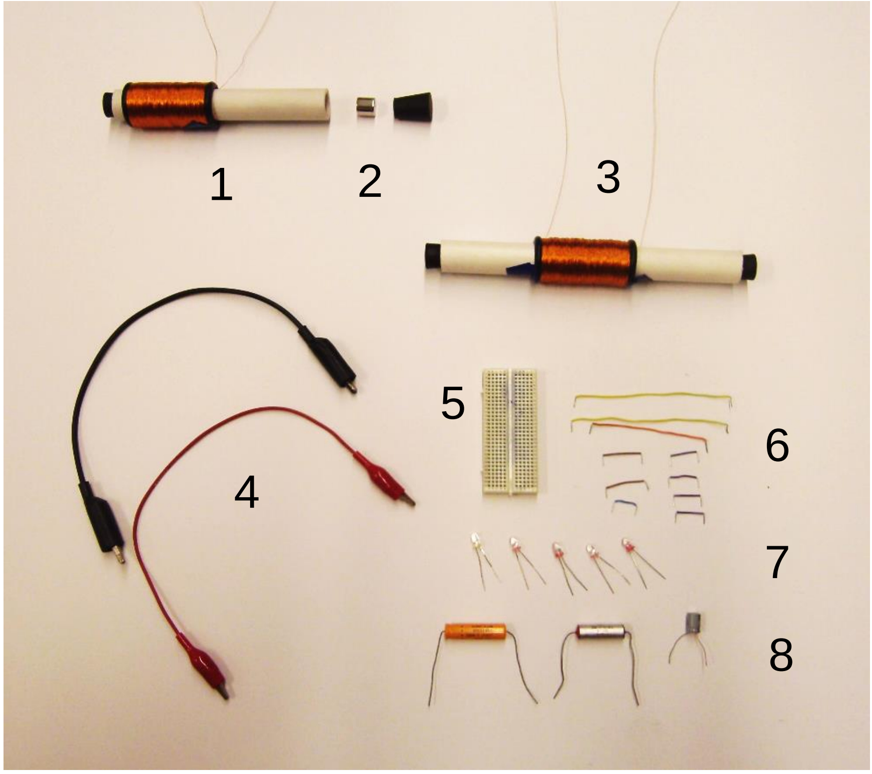
- Four 40-minute periods. Add another 40-minute period if you have the students construct the coils themselves.

Teacher Preparation Time:

- 20 minutes to lay out materials for lab groups.

<u>Part 1 - Shake Light Challenge Introduction</u>:

In this investigation, students construct a basic "shake light" flashlight and use the apparatus to learn how voltages are produced by relative motion between magnets and wires. This method, called electromagnetic induction, is the most common method for producing power.



<u>Materials List</u>:

1. Coil Apparatus 1 (Short body tube – 100m magnet wire coil, wound near one end, with #1 rubber stoppers at each end)
2. slug magnet (3/8" x 1/2")
3. Coil Apparatus 2 (Long body tube – similar coil, but center-wound magnet wire)
4. alligator to alligator clip cables
5. small bread board
6. set of small bread board wires
7. LEDs (3mm – one yellow, 4 red)
8. various capacitors

Tips for the Teacher:

- Use only red LEDs for the shake light diode bridge circuit, as these require the least voltage to light. We experimented with different color LEDs and found that it is increasingly difficult to get them to illuminate in the rectifier circuit as you increase the frequency of emitted light.
- The magnet wire that comprises the coil is coated. If the ends of the wire coming from the coil break off, you will need to remove this coating to make good electrical contact again. The coating is easily burned off in a small flame or sanded off; DO NOT USE WIRE STRIPPERS.

Assumed Prior Knowledge of Students:

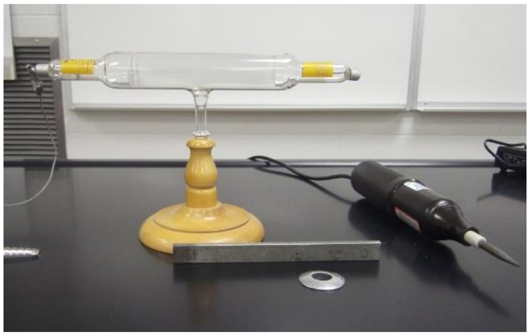
- Mechanical energy concepts, i.e. work and power, and Law of Conservation of Energy.
- Basic electricity, including Ohm's Law, series and parallel DC circuits, electrical energy and power.
- Magnetic fields and field strength units ($T = N/A \cdot m$), magnetic flux units ($\Phi = T \cdot m^2$).
- [optional, for AP Physics] Capacitance and circuits with capacitors in series and parallel.
- [optional, for AP Physics] Electromagnetism, up through force on a current-carrying conductor. AP Students should have learned about the right hand rule for magnetic force on a current carrying conductor (the first half of the universal right hand rule – motor action). The pre-lab activity is designed to help students see that the rule is reversible and set up the basic understandings necessary to understand how the shake light works and how AC voltage is generated.

Shake Light Challenge (Part 1) Overview:

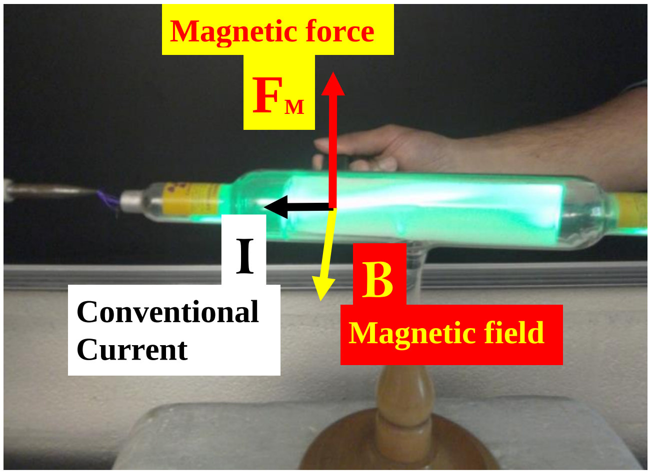
Students build a shake light apparatus that does not allow a magnet to pass through the induction coil completely. The pre-lab is designed to introduce students to the functionality of an LED and to illustrate that the LED only lights up when the magnet either goes in or comes out of the induction coil on apparatus 1. This sets them up for the circuit design challenge, which asks students to build a circuit out of four additional LEDs that would make the LED light up when the magnet passes into and out of the induction coil (essentially, students build a full-wave four diode bridge rectifier on a bread board). Once students handle this challenge, they are tasked with devising a way to use the assortment of capacitors at their station to store the energy generated in the apparatus along with a switch to turn it on and off. Student groups compete for five bonus points by building the circuit that makes the LED light continuously for the greatest length of time.

Upon completion of the circuit design challenge, students construct apparatus 2, which has the induction coil wound around the center of a longer piece of PVC pipe, so that the magnet may pass through it entirely. Students hook up apparatus 2 to the voltage sensor and produce another induced voltage-time graph. This time, they see both a positive and a negative voltage peak when the magnet slides completely through the coil. Students are then asked to speculate what effect this might have on the LED, and then test their hypotheses. They find that the LED lights up each time the magnet passes through the induction coil. Students realize that their rectifying circuit is no longer necessary to light the LED up with each transition through the coil, but are now asked to determine whether it would still perform some useful function. This is the moment we've been waiting for. Some brief experimentation is sufficient for them to realize that it is not only easier to light their LED, but it is noticeably brighter. The students discover that their rectifiers harness the energy of both the positive and the negative voltages induced as the magnet passes through the induction coil instead of just one or the other. The students learn that by using their rectifiers they increase the amount of energy produced in the same amount of time, thereby increasing the power. They have also begun the process of understanding AC power generation via electromagnetic induction.

Shake Light Lab Sequence Instructions:



A. Introductory Demonstration or Video: Use a Vacuum Tube Demonstration similar to the one shown at right to show that moving charges experience a magnetic force if there is relative motion between the charges and a magnetic field. [NOTE: For AP students, this presents an opportunity to review the universal right hand rule for determining the direction of magnetic force on charges/ conductors moving through a magnetic field, where the thumb is the input (conventional) current direction, the index finger is the direction of the magnetic field and the palm is the direction of the magnetic force the charges feel.]



In this case, the charges move relative to the magnet. If you do not have a hand-held Tesla Coil and a vacuum tube like the one pictured, show the videos below. [It may help to pause video 2 to review the right hand rule.]
H:\GK-12 2014\pics\Right Hand Rule Demo 1.AVI

GK-12 2014\pics\Right Hand Rule Demo 2.AVI

Once students have viewed the demonstration (and reviewed the right hand rule if applicable), pose the following question: "If it is possible for charges (and current-carrying conductors) in a magnetic field to move due to magnetic forces, is it possible for a conductor to move through a magnetic field in such a way as to produce current?" Accept student responses and then demonstrate that it is possible by moving a magnet through a small coil of wire connected to an ammeter, using an apparatus similar to the one pictured above. Note: Only pass the magnet through one of the coils, so that students can determine the effect of a larger coil on induced voltage later on. Explain that this phenomena is called electromagnetic induction and that the purpose of the series of activities about to be undertaken is discover what factors effect it and learn how it can be used to produce electrical power. [For AP students, Handout the Electromagnetic Pre-lab Activity and separate them into small groups. Have students whiteboard answers to the questions as they go so you can easily monitor their progress, then have groups pair up to compare answers and argue which ones are correct. Correct discrepancies/incorrect responses before moving on.]

B. Shake light Assembly. Set out the materials necessary to construct the shake light, and have students assemble Shake Light Apparatus 1, using the instructions found in the student section entitled *III. Shake Light Assembly Instructions.* It is imperative that the students make their coils at one end of the short PVC pipe so that the magnet can only go into and then back out of the coil. The number 1 rubber stopper at that end should actually extend into the bottom of the coil inside the PVC pipe. For a successful pre-lab, this is necessary to ensure the LED only lights up going in or coming out of the coil, NOT BOTH.

C. Once student groups have completed apparatus number one, conduct the Shake Light Pre-Lab. Start with a brief introduction to a light-emitting diode (LED). Ensure students understand that it essentially a one-way street for current flow by hooking it up to a battery. Illustrate that the long side is the positive lead and that the short side is the negative lead. The LED will allow current to flow through it in one direction but not the other if the leads are reversed. It is also helpful to suggest to students that they mark the positive (longer) lead with a marker before they begin constructing their circuits, as it may become difficult to tell which lead is which once they are bent and inserted into the boards.

D. Handout section *IV. Shake Light Pre-Lab – Exploration of Coil Apparatus 1*. The students will hypothesize what is going on with the induced voltage and then attach the coil to a voltage sensor to see the induced voltage. After that, they should understand how to manipulate either the orientation of the magnet or switch the leads on the LED to get the LED to light up on the opposite half of the shake.

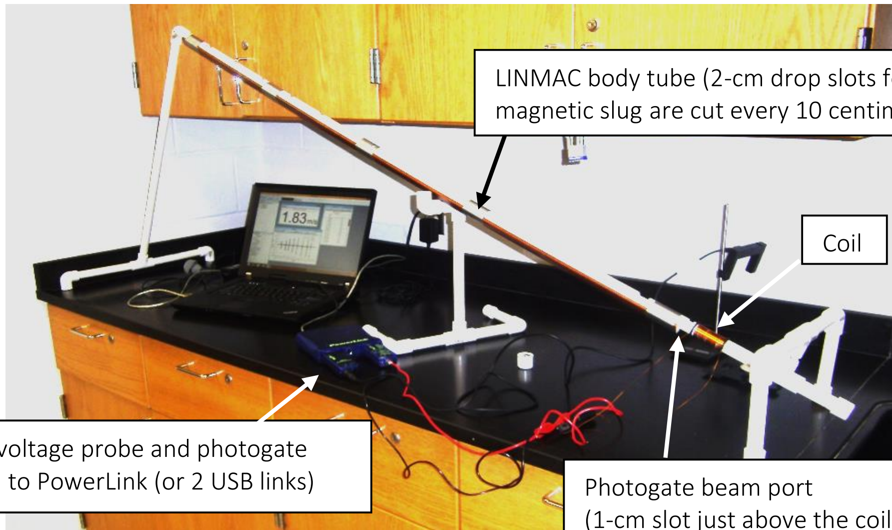
E. Once student groups have demonstrated to the instructor that they can cause the LED to light on the opposite transition in or out of the coil, give them the *V. Shake Light Circuit Design Challenge* handout. The handout will provide some instruction on using the breadboards and guide them through the activity. Students may experience some difficulty designing the rectifier, so use the following analogy and question to help guide them: Diodes allow current to flow in only one direction, like a one way street permits traffic flow in only one direction – How would you design a series of one-way streets that would take traffic going in opposite directions and redirect them in the same direction down another street?

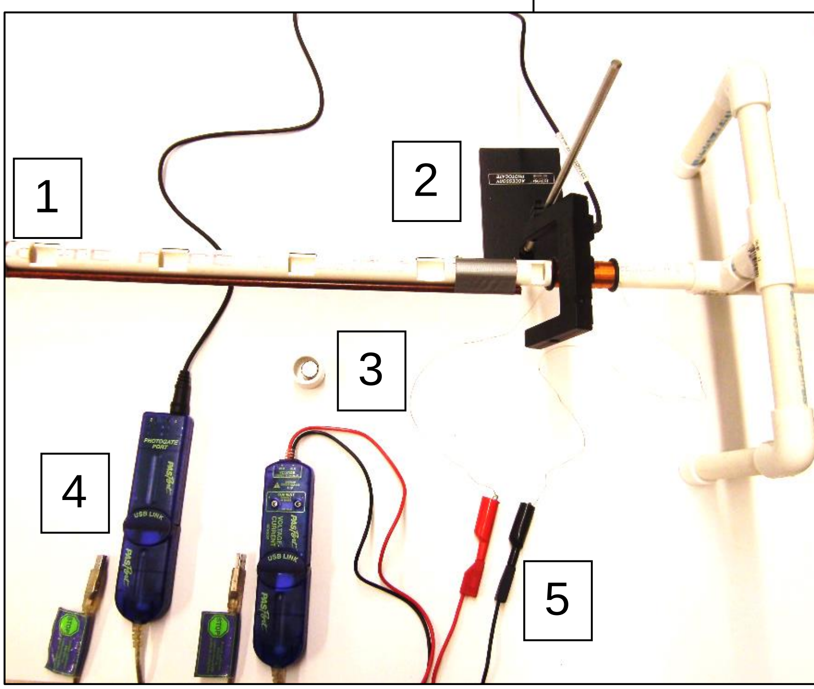
F. Have students answer the questions on the section *VI. Shake Light Post-Lab Analysis* handout.

Part 2 - The LINear Magnet Accelerator (LINMAC) Investigation Introduction:

Picking up where the Shake Light Challenge left off, the LINMAC is designed to more fully develop students understanding of how power is generated via electromagnetic induction by allowing students to derive Michael Faraday's Law of Electromagnetic Induction, on a coil similar to that of the shake light.

LINMAC Apparatus:





1. LINMAC body tube with coil
2. photogate
3. 2-cm slug magnet (3/4"x 9/16" neodymium cylindrical magnet)
4. photogate port with USB link (Pasco)
5. voltage/current sensor with USB link (Pasco)

The LINMAC (Part 2) Overview

The LINMAC was designed to facilitate derivation of Faraday's Law of Electromagnetic Induction. Students initially construct a limited model of electromagnetic induction by deriving the relationship between maximum induced voltage and the speed of a magnet as it enters a coil of wire. Students will derive an equation to successfully predict the maximum induced voltage for a given magnet speed through the coil. During this initial investigation, students are asked to determine the significance of the slopes of their graphs. They will derive the generalized equation: $\mathcal{E} = B\ell v$, ($\mathcal{E}$ = induced voltage, B = magnetic field strength, ℓ = the length of wire in the coil and v = the speed of the magnet) where students will believe that their slope equals the product $B\ell$. Students will likely think this because they used the same magnet in each trial and the same length of wire, and the units of the slope work out to T·m. The magnetic field strength, however, is not constant - changing continuously as the magnet passes through the coil. As a consequence, students are not sure of what the slope represents, necessitating further refinement of their model.

Examining the limitations of this model provides an excellent opportunity to teach students about motional EMF and sets up the subsequent investigation to derive Faraday's Law of Electromagnetic Induction. The students are asked if the voltages calculated with their equation would be useful for determining the amount of electrical energy produced by the coil as the magnet slides through at a particular speed. They should realize, based on their previous experience in the Shake Light Challenge, that the magnet induces voltage for the entire duration that it interacts with the coil, which can be used to produce energy. The maximum induced voltage at a given instant, therefore, is not a practical value to calculate the energy produced. Thus, it becomes clear that if one were to obtain a practical value, it would be necessary to have relative motion characterized by constant velocity between a given length of wire and a constant magnetic field to produce a constant induced voltage (this allows discussion of the requirements and more appropriate use of the motional EMF relationship) or determine the average induced voltage for the duration of the interaction.

Upon further investigation, the students graph average induced EMF versus time using their original data gathered with the voltage sensor. The graph is inverse and is then linearized, which allows students to determine the correct relationship. The students discover that the slope of their linearized graph is the total change in the flux of the magnet multiplied by the number of turns in the coil and then derive Faraday's Law of Electromagnetic Induction. They come to the realization that the importance of the relative velocity of the coil and the magnet is to determine the rate of change of magnetic flux through the coil. They now have an operational understanding of electromagnetic induction.

LINMAC Lab Sequence Instructions:

A. Introductory Demonstration for LINMAC Investigation - Revisit the Shake Light:
   Ask students to observe the shake light LED once again. Slowly and gently tilt the apparatus so the magnet slides SLOWLY through the coil. Students should see that the LED does not light or just barely lights. Ask students what you could do to get the LED to light up or be brighter. They will immediately suggest that you must shake the apparatus harder (since that's what they had to do when they conducted the previous experiment). Then ask, "What variable are we changing in our apparatus by shaking harder?" Accept

student responses, but guide them carefully to the idea that shaking harder changes the speed with which the magnet passes through the coil. Then ask, “What kind of relationship must there be between the induced voltage and the speed of the magnet through the coil, if the LED lights more brightly when we shake harder?” Students should suggest a direct relationship of some sort. “What kind of measurements would we need to take in order to determine this relationship mathematically?” Students should suggest measuring the voltage of the coil in a manner similar to that of the shake light lab and that speed of the magnet would need to be varied and measurable. Present the goal for the investigation, which is to answer the following question: What is the mathematical relationship between induced voltage in a coil of wire and the relative speed of a magnet passing through the coil?

B. Then familiarize the students with the apparatus as you see fit. This can be rather open-ended, since most students at this level probably are familiar with collecting and organizing data. You could just provide the apparatus and sensors and tell them to figure it out, or vary how much you tell them in the interests of conserving time. For the convenience of the instructor, Student Section *VII. The LINMAC – (LINear Magnet ACcelerator) Investigation* is included in this lab so students can set up the sensors on their own. Note: be sure not to give this to students until after going through the demo and establishing the lab question.

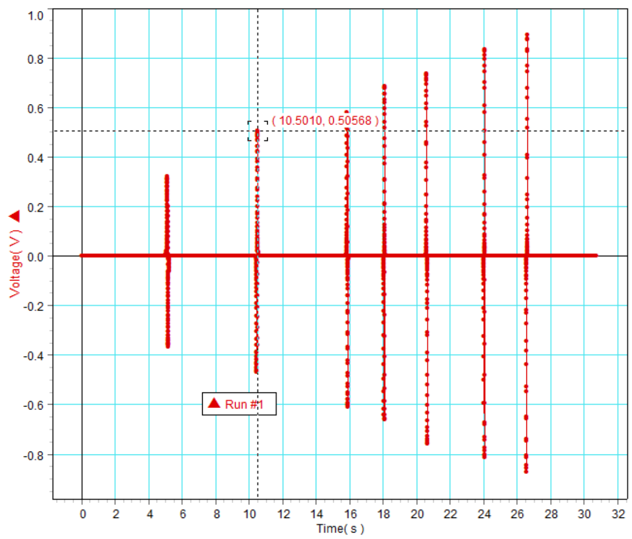
C. Data Collection Setup. The LINMAC is used to vary the speed with which a cylindrical magnet passes through a coil of magnet wire. Drop slots are cut along the length of the device so that a cylindrical magnet can be inserted into the body tube. To increase the speed of the magnet, students simply insert the magnet at a higher drop slot. The constant slope of the ramp insures a fairly consistent acceleration, while dropping the magnet in at higher position simply allows the acceleration to occur for a slightly longer duration, producing higher speeds.

   A 1-centimeter photogate slot is cut just above the coil. Adjust the photogate stand so that the beam of the photogate passes through the slot. The speed of the magnet just as it enters the slot can then be found by dividing the length of the magnet, .02m, by the time it takes the magnet to pass through the beam. Note: if using DataStudio® and a Pasco photogate you can select velocity in gate in the setup menu (see The LINMAC, student section VII).

   Use a voltage/current sensor connected to the ends of the magnet wire coming from the coil to measure voltage and produce a voltage versus time graph. It is essential that the sample rate be 1000 Hz to see the entire AC waveform. Have students obtain the maximum induced voltage from the second peak. This one will consistently be higher since the magnet is speeding up as it goes through the coil. Some of the peaks may be positive and some negative, since students may flip the orientation of the cylindrical magnet when they drop them into the slots. Inform students that, for the purposes of graphing, that they simply need the magnitude of the induced voltage. Detailed setup instructions for the Pasco voltage/current sensor in DataStudio® can also be found in *The LINMAC, student section VII*).

<u>Important Note</u>: **Ensure students only collect data from the seven slots closest to the photogate.**

D. Data Collection: Once students have followed the instructions to set up data collection, it may be helpful to suggest that they conduct all of their trials at once, rather than one at a time, so that they can compare the peaks on the same voltage-time graph. It should appear similar to the one shown at right. They hypothesized that there is some sort of direct relationship between higher relative speeds and induced voltage, so they should see larger peaks as they release the magnet from the higher drop slots, as shown in the diagram. If peaks appear the same height, it is likely that students released the magnet from the same slot. Since the magnet goes completely through the coil, students will obtain a voltage waveform with a positive and negative peak, similar to the one they observed using the apparatus 2 shake light. Students should use the smart cursor to determine the maximum induced voltage on the second peak, since the velocity of the magnet does increase slightly as it passes through the coil. Also, have them double click on the data set under "Summary" and select the "numeric" tab, then set "fixed decimals" to 4 digits to the right of the decimal prior to improve data precision.



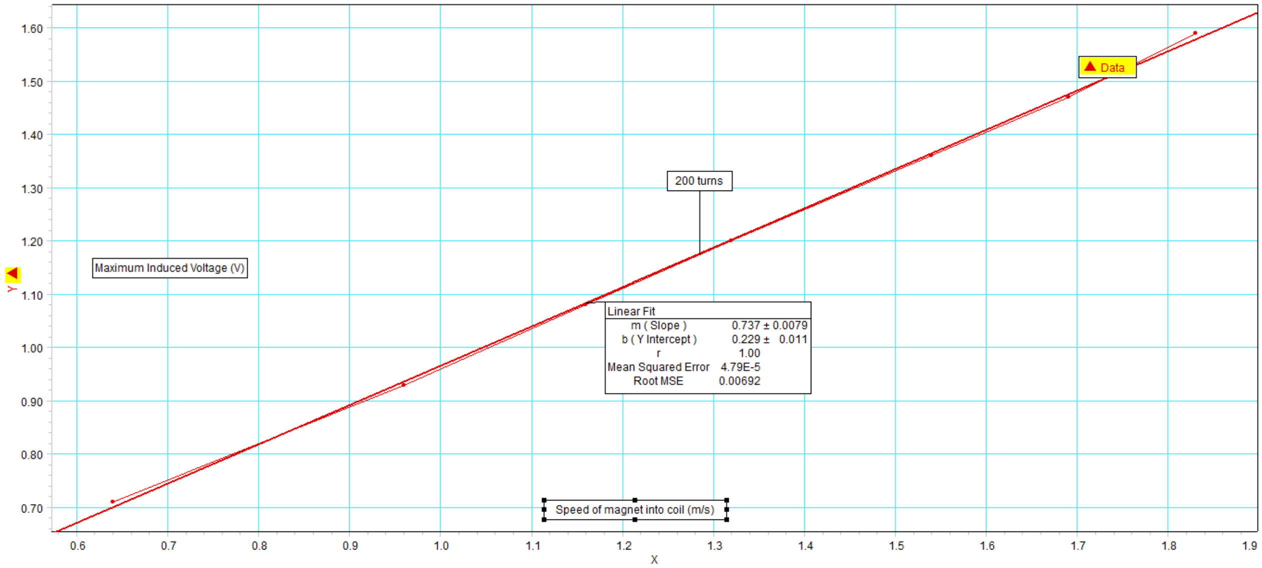
<u>Important Note</u>: **Make sure students do not delete this graph!**

E. Model Development - Initial Analysis of Data: Students should create a data table and ensure that the magnet speed and its corresponding voltage peak for the same drop slot are recorded together, similar to the one below.

Magnet velocity (m/s)	Max Induced Voltage (V)
.64	.71
.96	.93
1.16	1.08
1.32	1.20
1.54	1.36
1.69	1.47
1.83	1.59

To then find the mathematical relationship between the maximum induced voltage and the speed of the magnet, students should then graph the maximum induced voltage versus the magnet velocity.

The induced voltage is the dependent variable and should be graphed on the Y-axis and the magnet velocity is the controlled variable, and should be plotted on the X-axis. The graphs will be linear, so students should use the equation for a straight line to determine their mathematical relationship: **y = mx + b**



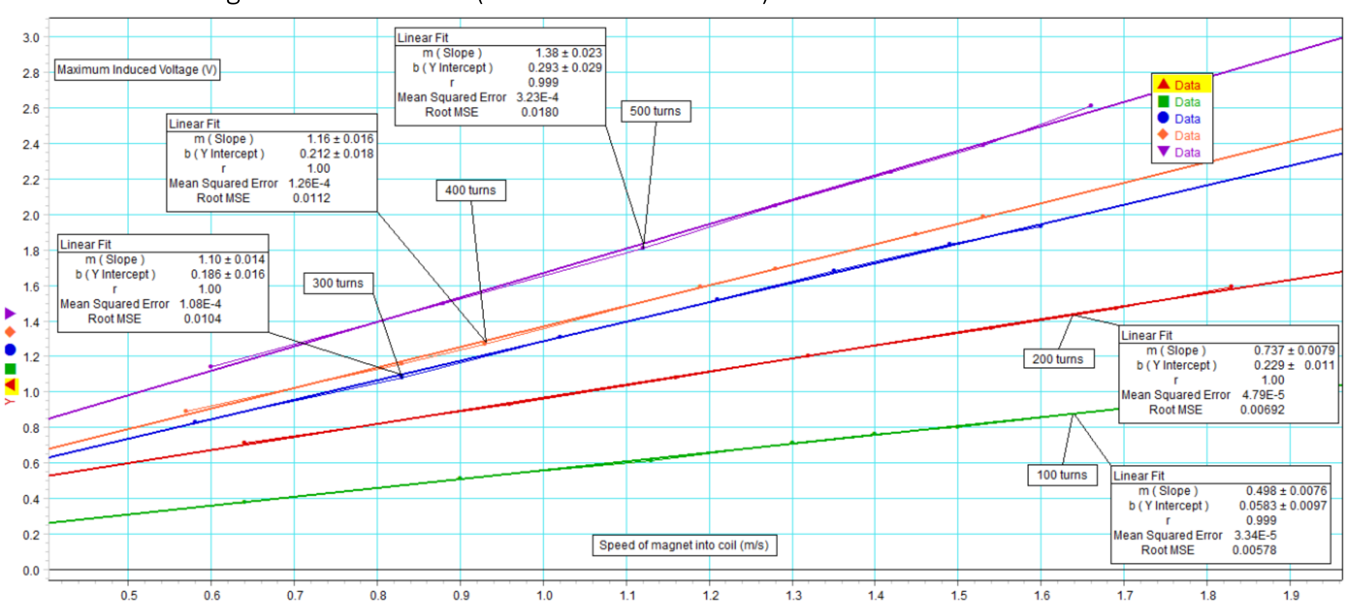
The y-intercept is not significant in this case, since no voltage would be induced if the speed of the magnet was zero (there must be relative motion between the coil and the magnet for voltages to be induced).

$$y = mx$$

$$\mathcal{E} = (.737 V/m/s)v$$

(Where Ɛ = the maximum induced voltage and v = the speed of the magnet into the coil)

Since each group's LINMAC coil was wound with a different amount of wire, the slopes of the graphs will all be different. The graph below is for the instructor. It shows the maximum induced voltage versus magnet speed for each of the five different coil windings on the LINMACs (100 turns – 500 turns).



Have students test their relationship. Tell them to pick one of the unused higher drop slots, and perform one more trial. Have them collect the velocity of the magnet and then calculate the maximum induced voltage using their equation and compare it to the actual maximum induced voltage by calculating the percent error. Have students compare their results and discuss the validity of the relationship. Then ask them to determine the significance of the slope.

Students will struggle with the significance of the slope, since the units of the slope will initially seem unfamiliar. It may help to have students whiteboard sketches of their graphs and mathematical relationship derivations, then have them walk around and compare their graphs and equations with those of the other groups. They should note that larger coils produced larger slopes. Remind them that slopes of linear graphs usually represent something constant in the relationship (or combinations of constants). Ask them, "What was constant in the experiment each trial?"

Students will most likely identify two constants; the amount of wire in the coil and the strength of the magnet. It may be necessary to provide units for magnetic field strength for inexperienced students [1 Tesla (T) = 1 N/A·m]. Encourage them to analyze the units of their slope and try to come up with a plausible explanation of what the slope might represent. Here's an example of what to expect:

$$\frac{V}{m/s} = \frac{J/C}{m/s} = \frac{N\cdot m}{m\cdot A} = \frac{N}{A\cdot m}\, m = T\cdot m$$

Students will likely believe that their slope equals the product of the magnetic field strength measured in Teslas (T) and the length of wire in the coil in meters (m), because they used the same magnet and the same length of wire in each trial. Upon generalizing the relationship the students will obtain the following relationship:

$$\boldsymbol{\mathcal{E} = B\ell v},$$

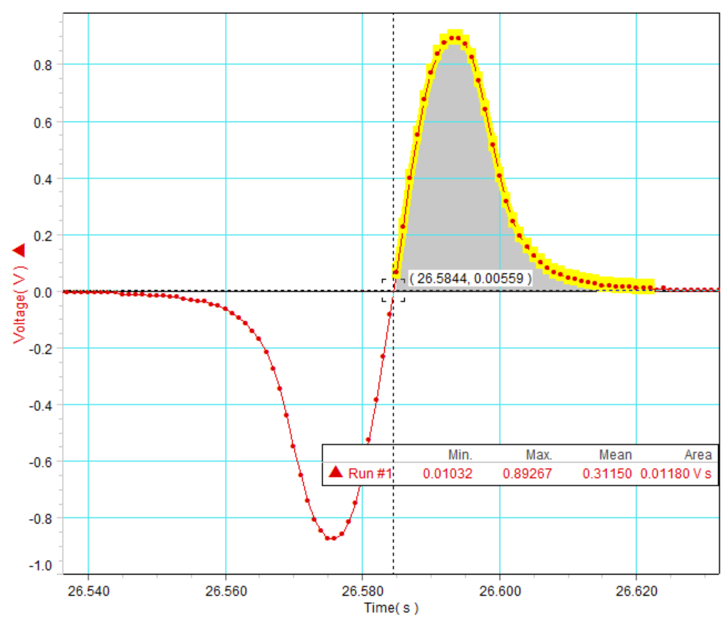
(Where $\mathcal{E}$ = induced voltage, B = magnetic field strength, ℓ = the length of wire in the coil and v = the speed of the magnet)

Their assumption is not correct, however, because the magnetic field strength is NOT constant, rather, it is changing continuously with respect to the coil as the magnet passes through it.

Note: more experienced students may not derive this relationship. They may realize that there is no way the magnetic field strength was constant, in which case the instructor can proceed to the follow-up investigation.

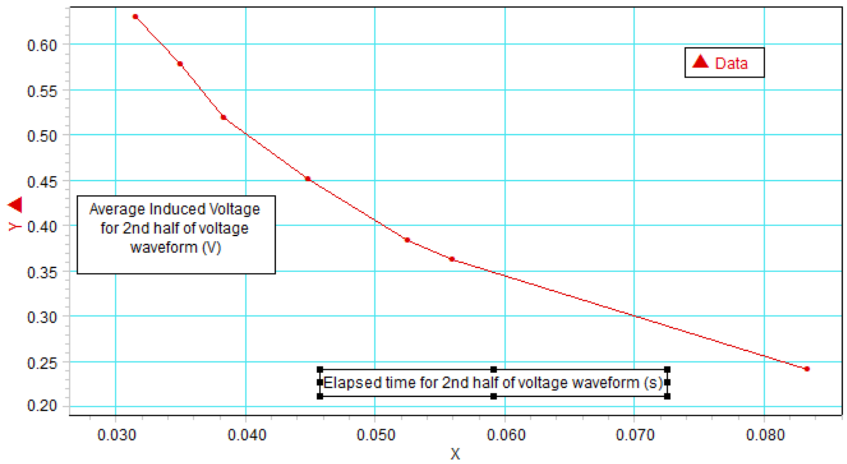
F. Model Refinement – Subsequent Data Analysis: Once students obtain the relationship above and/or realize that they cannot completely verify the significance of their slope, tell them that it is true that the magnetic field of the magnet is constant with respect to the magnet, but ask them whether they think the field of the magnet stays constant with respect to the coil as it passes through. This should get them thinking that the flux of the magnet would definitely change as it moves to different positions with respect to the coil. It is that change in the flux that is of interest. You may want to visit https://phet.colorado.edu/sims/faradays-law/faradays-law_en.html to help students visualize this. Pose this question: How would increasing the speed affect the rate of change of the flux? Students should suggest that, the faster the magnet, the faster the flux changes. Ask them if that would affect the total amount of flux change. Not as long as the magnetic field strength is constant. The next important question: What would that mean about the time for the flux change? It would take less time for the change to happen. This develops the idea that changing the speed of the magnet through the coil changed the time over which the change in flux happened.

Once students reach this point, have them go back to their original voltage-time graph and collect data to compare induced voltage versus time. Show students how to highlight an induced voltage pulse and use the scale to fit button to obtain a view of the pulse similar to the one shown below.

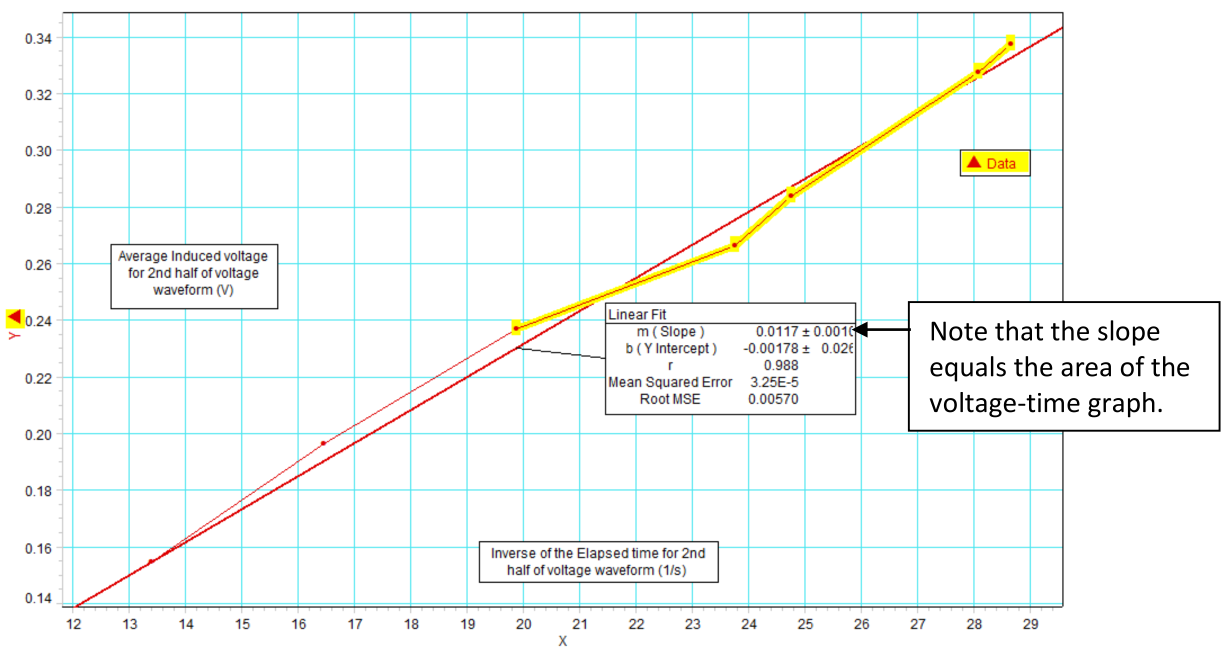


Since we know the flux changes as the magnet passes through the coil, the induced voltage is also constantly changing. They initially collected maximum induced voltage, which is an instantaneous voltage. Ask students what might be a better data value to obtain from this graph. Since it was previously discussed, students should suggest finding the average voltage. Point out that there is a positive peak and a negative peak, and ask, "What is the average very likely to be?" The answer is very small (10^{-5}V). Then ask what could be done to collect meaningful data. Lead students to the idea of finding the average voltage for the duration of the second half of each pulse. Direct students to highlight the entire second pulse and click on the Σ button to obtain the Mean, as shown in the graph above. Calculate the change in time (Δt) by using the smart cursor to find t_1 at the beginning of the pulse and t_2 at the end of the pulse and find the difference ($t_2 - t_1$).

Have students graph average induced voltage versus elapsed time for the second half of the voltage waveform. Their graph will be inverse, similar to the one shown below.



The students should linearize by inverting their elapsed time data on the horizontal axis and obtain the final graph:



The students will then determine the mathematical relationship as before:

$$\mathbf{y = mx}$$

$$\boldsymbol{\mathcal{E}_{AVG} = (.0117 V\cdot s)\ 1/\Delta t}$$

This time, the students will find that the units of the slope are the units for magnetic flux:

$$V\cdot s = \frac{J}{C}\cdot s = \frac{(N\cdot m)}{C}\cdot s = \frac{N\cdot m}{A} = \boxed{\frac{N\cdot m\ (\cdot m)}{A\ \ (\cdot m)}} = T\cdot m^2$$

In all likelihood, the instructor will need to provide the suggestion that students multiply the top and bottom by “meter” in order to derive the correct units for magnetic flux.

The students will then generalize and produce the following relationship:

$$\varepsilon_{AVG} = \Delta\Phi/\Delta t$$

They are almost there, but this is still not the complete relationship. Ask students to once again compare their slopes. They will see that the larger coils have steeper slopes. Since all the magnets have identical magnetic fields, the change in flux should be the same. See if the students can determine why the slopes are different. They will most likely suggest that it is the differing amounts of wire in each of the coils. Be sure to note that if that were the case, the units of the slope would have had to have been V·s·m, which was not the case. At this time, it may be helpful to remind students that the units for magnetic flux are derived from B·A, where B is the magnetic field strength (concentration of flux lines) and A is the area of the surface the magnetic field lines are penetrating. In terms of the apparatus, the simplest area through which the flux is changing is simply the area of one loop of the coil. The flux isn't just changing through one loop of the coil, however, it's changing through all of them at the same time. It is the number of loops (turns) of the coil that is different for all the induction coils. The slope is the number of turns of coil multiplied by the change in flux. Have students determine the change in flux of each of their induction coils by dividing the slope by the number of turns and compare them. What they will find is that the values for ΔΦ are very close to $1\text{x}10^{-4}$V·s, but decrease slightly as the number of turns increases (see the table below).

Number of Turns	Change in Flux (ΔΦ)
100	.000118
200	.000102
300	.000091
400	.000074
500	.000071

This is due to the fact that the area of the coil is wider for the larger coils. Thus the final equation, Faraday's Law of Electromagnetic Induction, can be attained by adding the symbol N as shown below, to represent the number of turns in the coil. Note that the negative sign has not yet been included, but could be added after a group discourse on how the polarity of the induced voltage produces a current direction that produces an opposing magnetic force.

$$\varepsilon_{AVG} = N\ (\Delta\Phi/\Delta t)$$

G. Deployment of the relationship: Tell them to pick one of the unused higher drop slots, and perform another trial. Have them determine the elapsed time for the second voltage peak and then calculate the average induced voltage using their equation and compare it to the Mean voltage on the graph. Then have students complete the Post Analysis Questions.

Answers to questions during the Shake Light Pre-lab:

2. [When does the LED light up?]

   The LED will light up when the magnet either slides into the induction coil or out of it.

3. [What makes the LED light up?]

   Relative motion between the magnetic field and the induction coil.

4. [Hypothesize why the LED only lights up in one direction.]

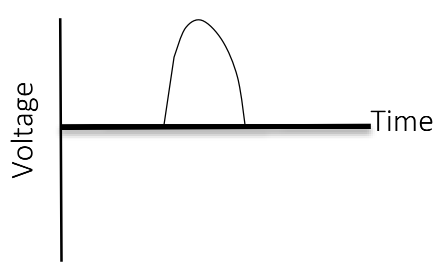
   The induced voltage switches polarity when it moves in and out of the coil, and the LED only allows current to flow when that induced voltage has the proper polarity.

5. [Sketch what you think is happening with voltage on the graph axes below:]

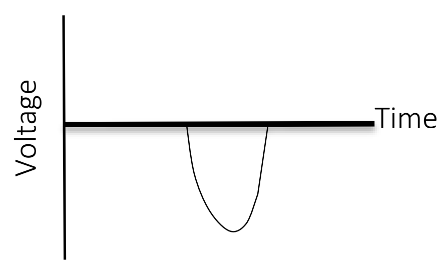
   Student answers will vary. They will see the correct graphs in the next step.

6. [… Sketch what is happening with voltage on the corresponding graph below. Then tilt the apparatus in the opposite direction so that the magnet comes out. Sketch what is happening with voltage on the corresponding graph below.]

Magnet going into coil



Magnet coming out of coil



7. [Is your hypothesis from question 4 supported by the graphs?]

   Answers will vary depending on what the hypothesis was in #4.

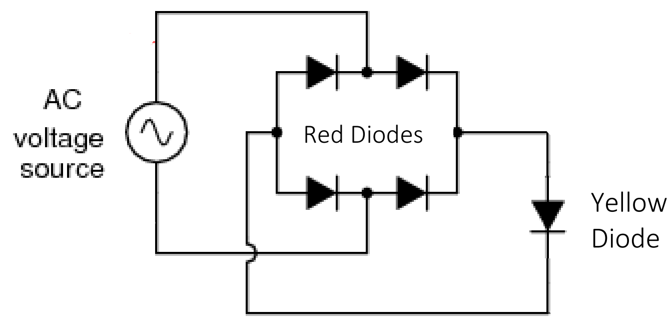
8. [What could you do to make the LED light up in the other direction?]

   Students should indicate that switching the leads of the LED or turning the magnet around will cause this.

Answers to questions during the Shake Light Circuit Design Challenge:

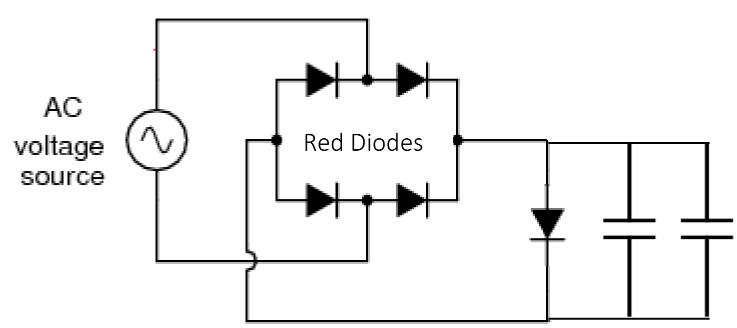
3.

Circuit diagram 1 – example of 4-diode rectifier circuit.

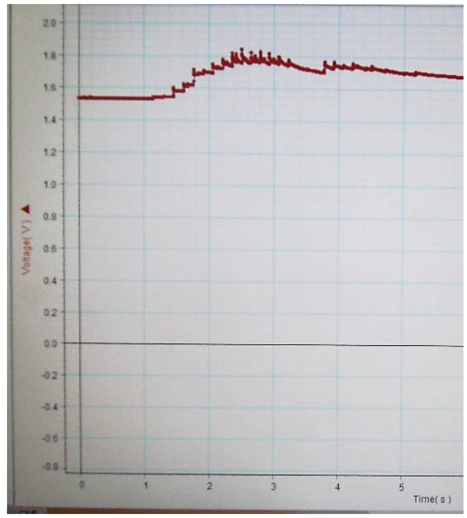


5.

Circuit diagram 2 – example with capacitors properly added (in parallel with the yellow LED).



6. [Observe the voltage output across the terminals of the yellow LED with the voltage sensor. Sketch the pattern you see on the graph below:]



   Students will produce a DC ripple voltage graph like the one shown, and should sketch something similar.

7. [Your shake magnet outputs an AC voltage, i.e. +voltage peaks when the magnet moves into the coil and –voltage peaks when the magnet moves out of the coil. How do the voltages on this graph compare to the shake light coil output?]

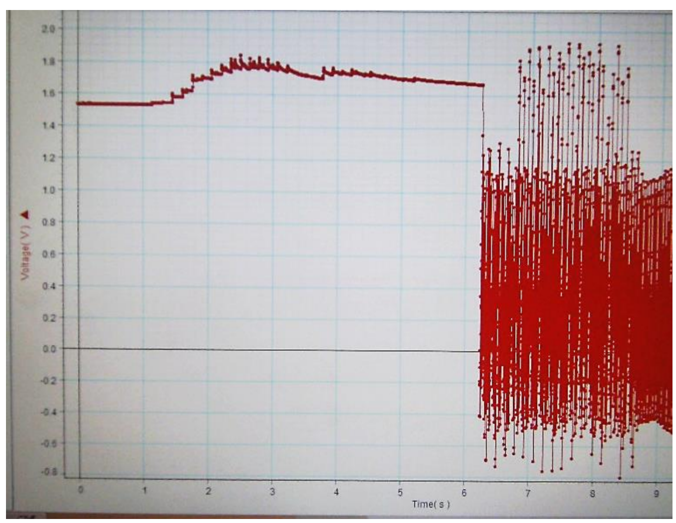
   Students should indicate that they are getting either a positive or negative DC voltage output.

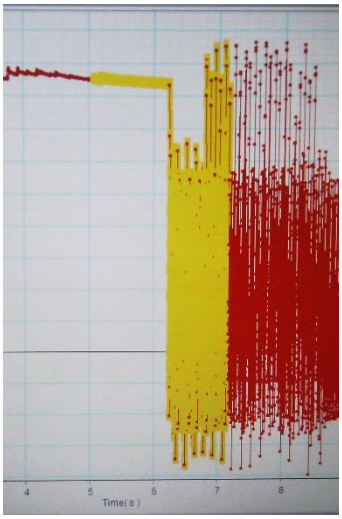
8. [Explain what you think your circuit is doing to produce this waveform.]

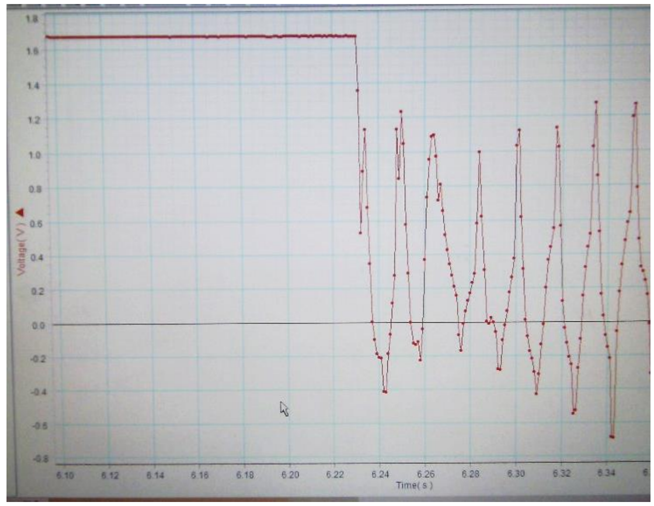
   The circuit is rectifying the opposite pulses so that they are all either positive or negative going through the yellow LED. The capacitors are shaping the output by increasing the time of discharge so the voltage varies much less.

9. [Start the voltage probe again and after a few seconds, disconnect the capacitor(s). Sketch the pattern you see on the graph below:]

   Students should see the peaks return. Have them highlight the area at the time the capacitors were disconnected to see the pattern more clearly.



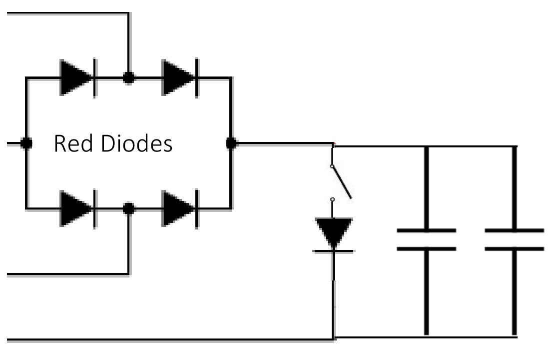




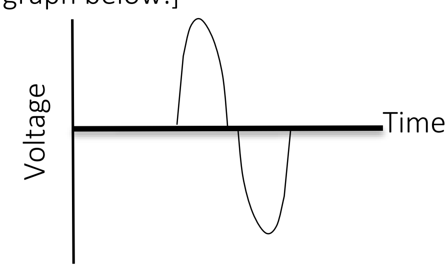
10. [Hypothesize why this pattern is different.]

    Since the capacitors are no longer connected, they can no longer shape the output by discharging over time, so the output now shows the rectified voltage peaks of the shake light across the yellow diode.

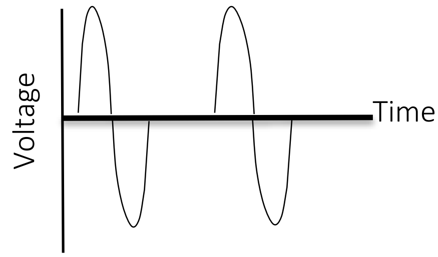
11. Circuit diagram 3 – example of switch properly added (in series with yellow LED).



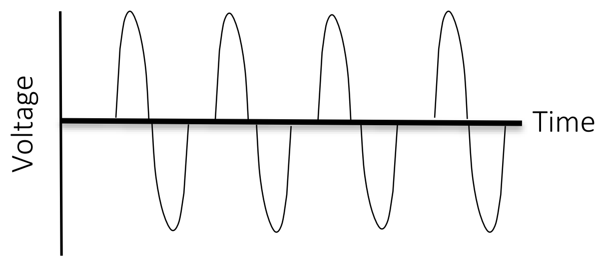
12. [Hypothesize what would happen if the magnet was allowed to pass completely through the coil, instead of going in and coming out. Sketch what you think the output voltage signal would look like on the graph below:]



14. Hook up apparatus 2 to the voltage sensor. Tilt the apparatus so the magnet passes through the coil and then back one time and sketch the actual signal on the graph:



15. Now repeatedly shake the body tube back and forth. Sketch what the signal looks like on the graph below:



16. […predict what would happen if you were to connect a single LED to it. When would the LED light?]

    The LED will light every time the magnet passes through the coil, since both a positive and negative voltage peak is generated with each passage.

17. [Test your prediction by hooking up one of the red LEDs to apparatus 2 and shake at a low frequency, to see when the LED lights up. Record what you see below:]

    The LED lights up every time the magnet passes through the induction coil.

18. [Is the LED circuit you designed for apparatus one still necessary to get the LED to light up with each shake? Explain why you think so.]

    No. The LED lights up every time the magnet passes through the induction coil.

19. [Is the LED circuit still useful if connected to apparatus 2? … and explain why you chose your answer.]

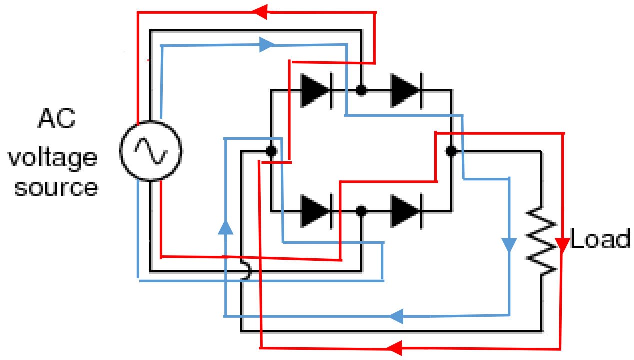
    Students should note that it was easier to light the yellow LED and that it was noticeably brighter using apparatus 2. If just the yellow LED were to be hooked up to the shake light, it would act as a half wave rectifier. In other words, half the induced voltage signal would be useless since the LED only allows current flow in one direction. The circuit is rectifying the entire effectively uses all of the induced voltage signal waveform and thus increases the power output from the apparatus.

Answers to the Shake Light Post-Lab Analysis:

1. […Which apparatus produced greater power in conjunction with your LED circuit?]

   Apparatus 2. Since the magnet was allowed to pass through completely, both a positive and negative voltage pulse were produced every time the magnet passed through the coil, as opposed to just a positive or negative pulse in apparatus one. The rectifier circuit allowed both pulses to send current through the LED, increasing the power per shake.

2. […use two different colors pens/pencils to illustrate the current loops for both positive and negative voltage inputs from the AC source.]



3. [Why do you think this is this called a "full-wave" rectifier? The single LED you used initially also rectified your output from apparatus 1. What might be a good name for the apparatus 1 "rectifier?"]

   Because both positive and negative voltage peaks cause current to flow through the Load LED. Half-wave rectifier. The single LED cuts off half the signal.

4. [What circuit element…could…increase the duration the LED lights? Sketch how that circuit element would need to be attached in the circuit diagram above, using an appropriate schematic symbol.]

   A rechargeable battery, also connected in parallel to the yellow LED.