Title:	**Power to the People! (Transformers – More V, Less Heat and I!)**
Original: **Revision:**	7 August 2008 28 July 2009
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Appropriate Level:	Regents, Honors, or AP Level Physics
Abstract:	Students will learn what transformers are and how to construct one, analyze what factors affect the power loss of a transmission line, and explore some of the differences between AC and DC electricity.
Time Required:	60 Minutes
NY Standards Met:	Standard 4_Key Idea 4 Standard 1_Key Idea 1 Standard 6_Key Idea 2 Standard 6_Key Idea 3 Standard 6_Key Idea 6 Standard 7_Key Idea 1
AP Physics Standards Met:	III. Electricity and Magnetism • C. Electric circuits ○ Current, resistance, power • E. Electromagnetism Electromagnetic induction
Special Notes:	**Transformers** is a kit available from the CIPT Equipment Lending Library, Xraise.classe.cornell.edu. Created by the CNS Institute for Physics Teachers via the Nanoscale Science and Engineering Initiative under NSF Award # EEC-0117770, 0646547 and the NYS Office of Science, Technology & Academic Research under NYSTAR Contract # C020071

Cognitive Objectives:

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

- Make measurements of AC voltage with a multimeter
- Assemble a transformer and explain how it functions
- Compare and contrast AC and DC electricity
- Solve problems relating to high tension lines and power loss
- Teach electrical safety to younger students

Class Time Required:

60 minutes

Teacher Preparation Time:

10 minutes

Tips for the Teacher:

Double check all wiring between classes to ensure the boards and wands are safe for student use. If you have the equipment, attach the LabQuest of Logger pro to a computer and/or projector so students will be able to see the readings more easily.

Assumed Prior Knowledge of Students:

Students should be facile with Ohm's Law and the power formulae for electricity. The power point presentation of *Power Equals* I^2R by Joshua Buchman and Jim Overhiser is included on the CD. The song sets the formulas for electrical power to the music of *Twinkle, Twinkle, Little Star*. Feel free to use the song and the lyrics in your classroom. It is also helpful if your students have had some experience with electromagnets, but it is not necessary.

Background Information for Teacher:

Electricity is often generated quite far from the point of use. This results in a relatively large resistance because of the long length of the power lines. By transmitting power at high voltage and low current, power losses during transmission can be minimized.

Note: Present the following the day before the students will be doing the actual lab.
If you are brave enough (and do not suffer from hyperhydrosis), you can open this lab with an exciting demonstration. (I preface the demonstration by telling the class that my original dream was to be the conductor of the NY Philharmonic. But after I auditioned I was told that I was terrible, and that I should NEVER bother them again! I was disappointed, but realized after the experience that I could do something that most people would never consider doing!) Plug the demonstration transformer (which is a step down transformer) into the wall. Show the students that you can hold the ends of the wires with no discomfort. Then brush the frayed ends of the wires against each other. They will zap and pop! (If you told my story, you can then ask why you were able to touch the wires without getting shocked. The answer, of course, is that you are a terrible conductor!) Ask the students if they would like to know the secret to that miracle. Explain that they will learn the secret during the lab.
Next, explain that the lab begins with a short video clip. Show the Braniac Electric Fence segment which is available on the CD that comes with the lab (or on You Tube).

When the segment is over, explain that if anyone ever has to check a wire with his or her hand then a safer technique is to touch the BACK of the fingers to the wire so that the hand will jerk AWAY from the wire. (An even safer technique is to use a meter!)

Then ask how the electric fence can deliver thousands of volts when it is only plugged into a 120 V line. Explain that the rest of the lab will help them to understand this…and then assign the pre-lab sheet. ☺

When you do the hands on portion of the lab, there are three activities. You will lead the students through the first activity, and then you can turn them loose on the second two.

First Activity notes:

- Notes regarding the voltage probe:
    - The interface has been set to obtain the largest possible sampling rate for the voltage probe. (For the Vernier LabQuest, this would be 100 samples/second.) A high sampling rate will increase the odds that rapid changes in voltage will be "caught" by the computer.
    - The interface has been set to create a graph of voltage vs. time.
    - The circuitry of the LabQuest creates an artificial voltage offset of 3 volts when the probes are not connected to anything. But when the probes are touched together they should provide a reading of approximately 0 volts. (If this is not so, the LabQuest needs to be re-zeroed.)
    - The probes should NOT be attached to a potential difference that is greater than 10 V. But since you are going to use a AA cell, the probes can't possibly produce more than 1.5 volts, right? ☺
    - To record data, click on START. Click on STOP each time you finish testing an arrangement.

For the first activity, you will be following student suggestions regarding the optimal design for a step-up transformer. You are going to start by creating the absolute lamest step-up transformer. (Sorry, folks. But your students already KNOW that you are super-smart, right?)

- Begin by demonstrating the LabQuest (attached to a computer and projected, if possible). Turn it on by pressing the large silver button in the upper left corner.
- Plug the voltage probes into one of the analog ports (i.e. CH 1). The LabQuest should recognize that you have connected a voltage probe. Don't be thrown by the 3.3 volt reading. This offset value shows up when the probes are not attached to anything, but the probes will give you correct values when you actually use them. The offset is an artifact of the circuitry built into the LabQuest, but only a really slow learner would continually zero it out and then wonder why the readings were so messed up. Ummm…never mind about that. (But a big "Thank you!" to the Vernier staff for their quick response to my query.)
- Show the students that when you touch the probes together, the voltage falls to zero.

- Now show the students that when you touch the probes to the terminals of the AA cell, the reading is approximately 1.5 volts.
- Explain that you are trying to "catch" any voltage changes that occur, so you are going to set the LabQuest to take 100 measurements a second. Click on the word **Sensors**. Then click **Data Collection…** on the pull down menu. Change the **Rate** setting to 100 samples/s. (When you click into the **Rate** box, it will bring up a keyboard so that you can input 100 and then hit **OK**.)
- Click on the graph icon to bring up the graphical display.
- Now you are going to set-up a step-up transformer. (Well, kind of…) Have the transformer coils and core on the table where you are demonstrating the LabQuest.
- To set up the "lame" step-up transformer, attach the computer probes to the leads of the 100 wind coil. (Is it really 100 winds? I have no idea! But use the coil that has *fewer* winds.)
- Nest the coils together.
- Next, attach the AA cell to the leads of the 500 wind coil. (Is it really…? Oh, never mind… Just use the coil that has the *greater* number of winds.) After a moment or two, disconnect the cell. Repeat this several times, rescaling the graph if necessary.
- Have students record their observations.
- Challenge them to create the optimal step-up transformer. Do your best to follow the suggestions that they offer. If necessary, ask them leading questions, but in my experience, no leading questions were required here. (Patience, on the other hand, turned out to be quite useful!)
- **Make sure that the students notice that the computer only records momentary changes in potential as you connect to the cell or break contact with the cell. (i.e. Potential difference is only created in the secondary when the current is *changing* in the primary coil.)**
- If you have time, direct the students to check out: http://micro.magnet.fsu.edu/electromag/java/transformer/.

For the second activity, the students will use the power line boards. They will take measurements and answer questions. When they are done, you can give them some time to run their calculations. (Side note: If students look under the power line board they may wonder why line B's bulb has a resistor in parallel with it. This was done to create a model that started at the power station with similar power values in each of the lines. Without the resistor, the lab might have *looked* fairer that it does now, but it would not have *been* as fair.)

For the third activity, the students will begin by experimenting with LEDs. (The LEDs will serve as a vehicle for better understanding AC electricity.) Have each group of students experiment with a 9V battery, the holiday bulbs, and the LED. **Make sure the students notice that the holiday bulbs light no matter which way the current flows and that the LEDs only light (i.e. current only flows) when battery is connected with the "correct" terminal orientation.** (You could point out that this is true for diodes in general, but that LEDs are very efficient at emitting light and this lets us know when current is flowing.) (If they ask, explain that the resistors in series with the bulbs and the LEDs are there to keep the bulbs and LEDs from being damaged.) Then show them the paired

LEDs, and point out that only one of the LEDs is lit by the 9V battery for any given arrangement. Finally, let the students experiment with the power wands. Have them study the still wands for a little while. Then have them wiggle the wands quickly. They will probably have a lot of fun with them, especially if you are willing and able to lower the light level of the room. Just be sure to remind them that they should be careful to avoid collisions!

For honors classes, you could show that the LabQuest gives different values for the voltage across the holiday bulb (that is in the "house" on the power lines board) than the multimeter because the multimeter gives V_{rms} values for AC voltage. So the peak values shown by the LabQuest should be higher (by about a factor of radical two) than those shown by the multimeter.

After the lab, show the video clip "High Voltage Cable Inspection". Point out that the cables are THICK to minimize resistance, but that also makes them rather heavy. (Weight matters, because as the weight/length density increases the power company needs to provide more poles to support the wires against sagging. Aluminum is often used because it provides a reasonable compromise between the resistance and density values.)

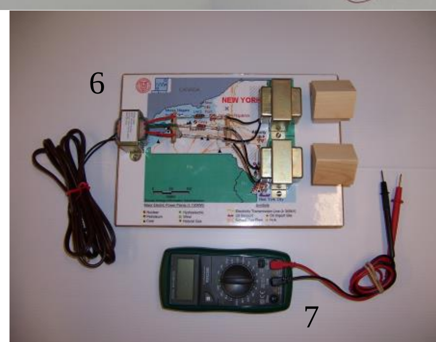
Now, you might want to revisit the original "terrible conductor" demonstration. After all of these experiences, your students are ready for a rather discrepant question. Challenge them to explain how you could touch the bare wires safely, but those same wires snapped, crackled, and popped when they were touched to each other! Your students will likely be able to tell you that there was a transformer involved. (Well, I hope so, anyway!!! What was the name of this lab, again???) They also might try to tell you that you used a step up transformer. But think about it. Did YOU fry? Since you didn't, the voltage involved could not have been enough to cause a large current to flow through the resistance of your body. But when you caused a short, the tiny voltage offered by the step down transformer was able to cause a large current to flow through the negligible resistance of the bare wire, and the step down transformer was able to deliver that current. There was easily enough *power* to produce heat, sparks, and pops, despite the fact that there was not enough *voltage* for you to be hurt by it…or even to feel it!

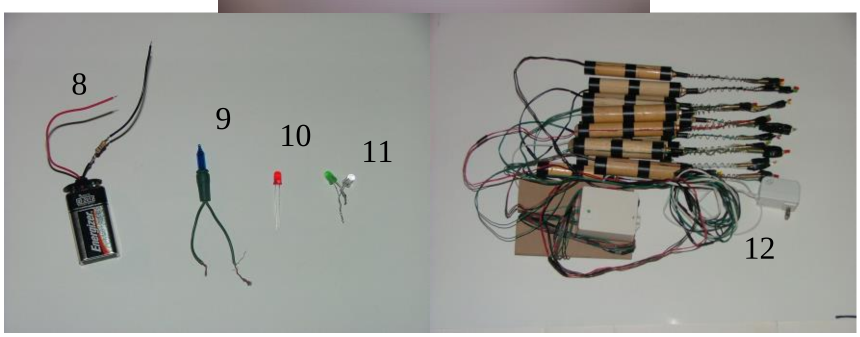
References:

Map source: http://tonto.eia.doe.gov/state/state_energy_profiles.cfm?sid=NY
Schematic information: http://www.tpub.com/neets/book2/5d.htm

Answers to Questions*: send email to cipt_contact@cornell.edu to request answers*

Power to the People!
(Transformers – More V, Less Heat and I!)





Equipment

Pre-lab	1. Braniac Electric Fence, High Voltage Cable Inspection, Power Equals I^2R CD
	2. Intro Demo Device
Activity 1	3. LabQuest, Power cord, Computer Link, and Voltage Probe
	4. Demonstration transformer (i.e. solenoids and core) and wires
	5. AA cell
Activity 2	6. Power lines board
	7. Multimeter
Activity 3	8. 9 volt battery with resister in detachable leads
	9. Holiday bulb
	10. LED
	11. LEDs in parallel (but with opposite orientations)
	12. Power wands (aka AC Demo Devices)

POWER TO THE PEOPLE
(Transformers – More V, Less Heat and I!)

Photo credit:
Oak Ridge National Laboratory

** In this lab you will learn what transformers are and how to construct one, analyze what factors affect the power loss of a transmission line, and explore some of the differences between AC and DC electricity. **

<u>Pre-lab Assignment</u>

1. What do people mean when they say that power lines are "high tension wires"?

2. In class, we often assume that bare wires have essentially no resistance. Why is this assumption *incorrect* when it comes to power lines?

3. Do you have any "wall warts" in your house? (A wall wart is a transformer that plugs into the wall to turn the normal 120 V AC into a smaller value of either AC or DC in order to power an electronic device.) If so, list a few of the devices they are powering?

Introduction

Electricity is delivered to your neighborhood at a higher voltage than you use in your home. In fact, the voltage in a transmission line often needs to be stepped down twice before it becomes safe to use! Why does the electric company bother to raise the voltage so high for the transmission lines? What benefit is worth creating such a dangerous situation? And how does the electric company get the voltage so high, anyway? You will find the answers to these, and many other questions, as you explore the science of transformers!

A transformer is a device that either raises or lowers voltage. The primary coil is the coil attached to the power source. As the current changes in the primary coil, a changing magnetic field is created. This changing magnetic field induces a voltage in the secondary coil.

Activity 1: How do transformers work?

For this activity, your class is provided all the equipment you need to build a transformer that will raise the voltage provided by the source (a AA cell, in this case) to a higher voltage. You will monitor the voltage induced in the secondary via a voltage probe and a computer interface.

Note: Do NOT connect the voltage probe to a potential difference greater than 10V.

Procedure:

- Your goal is to create a "step up" transformer. (i.e. You want to create the *largest* possible voltage in the secondary coil (the coil that you attach to the probes) when you apply a voltage to the primary coil (the coil that you touch to the cell). Unfortunately, the instructions for the best way to assemble the materials were lost. Your teacher has created a transformer for a starting point, but between us…there is room for a lot of improvement. Good luck!
- The interface has been set to collect voltages at 100 samples/second. A high sampling rate will increase the odds that rapid changes in voltage will be "caught" by the computer.
- The probes should NOT be attached to a potential difference that is greater than 10 V. But since you are going to use a AA cell, the probes can't possibly produce more than 1.5 volts, right? ☺
- Note that in the original configuration the computer probes were attached to the leads of the 100 wind coil and the terminals of the AA cell were connected to the leads of the 500 wind coil.
- If the maximum voltage measured in the secondary was significantly less than 1.5V then change the configuration and try again.
- Answer all questions in the Student Data Packet for this activity.

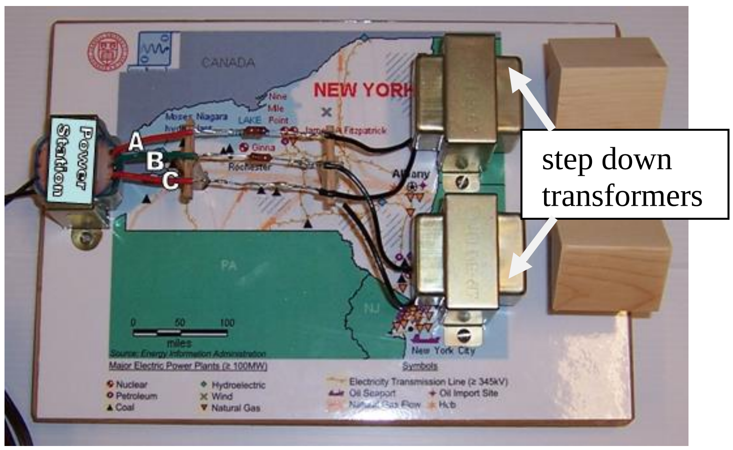
- If you enjoyed this section of the lab, check out: http://micro.magnet.fsu.edu/electromag/java/transformer/.

Activity 2: Why are transmission lines at such a high voltage?

In this activity you will examine what happens to the voltage and the power of two different transmission lines.

Materials:

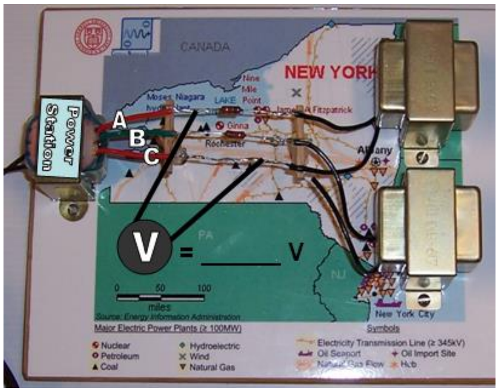
- New York State Power Lines activity board (shown below)
- multimeter

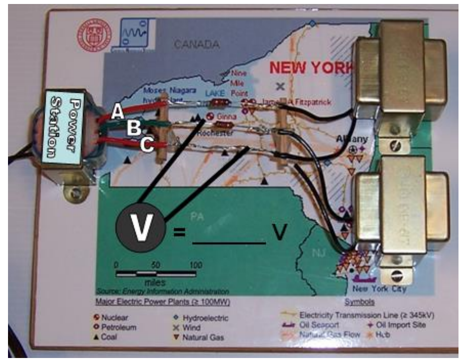


Procedure:

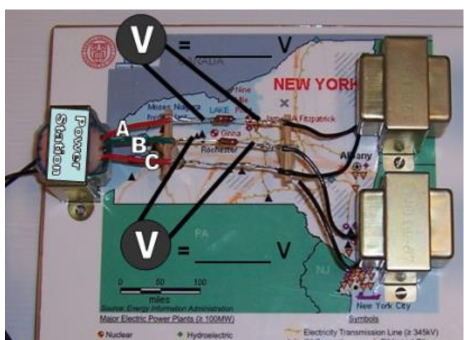
- Look at the power lines board. It models power transmission across New York State. The transformer on the left represents a power station at which electricity is generated and raised to high voltage (i.e. stepped up) for transmission across the state. The two transformers on the right reduce the voltage (i.e. step it down) for use in homes.
- The power line board contains three lines.
  - Transmission lines A and B are at different voltages so you can compare their relative power losses.
  - Line C is the ground line that is maintained at zero voltage.
- Notice that the power lines on this model differ from real power lines in a few crucial ways. In a real power line:
  - Transmission lines A and B would be at much higher voltages than you will use.
  - The top three power lines on a pole are usually all at a high voltage.
  - The ground lines are usually located vertically below the high voltage lines.
  - Wires are usually attached to the power poles using strain insulators.
- In addition to answering questions in the Student Data Packet, **record all voltage data (and current and power values) on the separate Power Lines Board Schematic sheet** as you work through the rest of the lab.

- Set the voltmeter to read AC voltage. (That is usually indicated on the meter with a little wave symbol.)
- Use the voltmeter to measure the voltage of each line leaving the power station.
  - Determine the voltage of transmission line A. (This is V_1 on the schematic.)
    - Touch one voltage probe to line A and the other to line C (the ground wire).
    - Note: Connect the multimeter to line A **on the left side of the resistor**.





  - Determine the voltage of transmission line B. (This is V_2 on the schematic.)
    - Touch one voltage probe to line B and the other to line C (the ground wire).
    - Note: Connect the multimeter to line B **on the left side of the resistor**.
- Measure the voltage *drop* in each transmission line A as it traverses New York State. This models the electrical losses that occur during power transmission.
  - The resistance due to the enormous length of a real transmission line is being modeled by using a 100. Ω resistor.
  - Measure the voltage drop along line A by measuring the voltage **across the resistor** on line A. (This is V_3 on the schematic.)



  - Measure the voltage drop along line B by measuring the voltage **across the resistor** on line B. (This is V_4 on the schematic.)
- Calculate the current running through each transmission line. Show your work in the Student Data Packet and write the current value for each line in the appropriate space on the schematic.

*****A Very Important Point To Consider*****

There are two voltage values associated with each line: the *voltage above ground* and the *voltage drop in the transmission line.* Consider carefully which voltage is more appropriate to use with the resistance value (provided above) in order to calculate the current in the line.

- Calculate the power loss across each 100. Ω resistor using at least two different techniques. The answers should be reasonably close. If they are quite different, you are most likely making an error.
- If you are super motivated, make a third calculation for the power loss of each line.
- Note that each line carries approximately the same power (about 0.4 Watts) when the power leaves the power station.
- You now have enough information to calculate the approximate voltage of each line to the right of its resistor. (Note that for the sake of this lab, you are only going to do this with line B.) Calculate the expected voltage of line B (relative to ground) to the right of its resistor.
- Now measure the voltage of line B relative to ground. (This is V_5 on the schematic.)

Note: By now you should be able to refer to the schematic for guidance.

- Use the measured value V_5 (and the hint provided in Question 10) to calculate the power remaining in line B to the right of the resistor.
- Think about this: Could you have determined the power remaining in line B in another way?
- You have not measured the voltage of line A to the right of the resistor, but you should be able to calculate the power remaining in line A anyway.
(Note: Calculating the voltage of line A to the right of the resistor is "cheating" for the sake of this problem.) Show your work in the Student Data Packet.

(Hint: Think conservation of energy.)

The transformers to the right of the power lines board are "step down" transformers. They drop the voltage of the high tension lines down to voltages that are suitable for household use. Assuming that they operate at about 100% efficiency (Commercial transformers come close to this!), they will be able to deliver nearly all of the power remaining in the lines to the houses on the right side of the board.

- Determine the voltage to the right of the step down transformer by lifting the houses and measuring the potential difference between the two brass bolts.
- Answer the rest of the questions for this activity in the Student Data Packet.

This stuff is shocking!

Source:
http://www.crazy-jokes.com/pictures/cartoons_424.shtml

Activity 3: A.C. power coming out of the wall!

In this activity, you will experiment with light emitting diodes (LEDs). You will then use LEDs to analyze the nature of household electricity.

Materials:

- 9 volt battery with resistor in detachable leads
- holiday bulb
- single LED
- LEDs in parallel (but with opposite orientations)
- power wands (AC Demo Devices)

Procedure:

- Diodes have an interesting electrical property. Try lighting the LED using the 9 volt battery. Does the LED light up no matter which way you touch the terminals? An incandescent light bulb would light up no matter which way the electricity was directed through it. (You can prove that to yourself by experimenting with the holiday light.) Determine if this is also true for the LED, and record your results in the Student Data Packet.
- Now look at the paired LEDs. They are oriented so current will flow through them in opposite directions. Touch the paired LEDs to the battery. One of the LEDs should light. Now reverse the battery and record your observations in the Student Data Packet.
- Now we are going to use this electrical property of LEDs (that they only pass current in one direction) to analyze household electricity. Hold the power wand (i.e. the AC demo device) as still as you can. Look carefully at the LEDs on the tip of wand and record what you see in the Student Data Packet.
- Now wiggle the power wand rapidly and record what you see in the Student Data Packet. Note that the two LEDs are attached in parallel, but they are paired in opposite directions of current flow.
- Answer the final two questions for this activity.
- If you enjoyed this section of the lab, check out: http://micro.magnet.fsu.edu/electromag/java/generator/ac.html and http://www.walter-fendt.de/ph14e/generator_e.htm for more details about the functioning of both AC and DC generators.

Now use what you have learned in this lab to complete the Post-Lab Analysis questions.

POWER TO THE PEOPLE!
(Transformers – More V, Less Heat, and I!)

Student Data Sheet

Name____

Activity 1: How do transformers work?

1. Did a large voltage result in the secondary of the original configuration? ____

2. When exactly did the spikes in voltage occur? (You may need to wait to answer this question.)

3. What was the largest voltage you were able to obtain in the secondary? ___________

4. What configuration allowed you to produce the largest voltage in the secondary?

(If you have not yet answered Question 2, go back and answer it now.)

Activity 2: Why are transmission lines at such a high voltage?

5. What is the value of the resistor being used in each power line? ___________

6. Calculate the current running through each line. Show your work!

Current running through line A **Current running through line B**

7. Calculate the power loss across each 100. Ω resistor. Show your work!

Power loss along line A (Way 1) **Power loss along line B (Way 1)**

Power loss along line A (Way 2) **Power loss along line B (Way 2)**

Power loss along line A (Way 3) **Power loss along line B (Way 3)**

8. The initial power in the transmission lines is roughly equal: Line A starts with a relatively high voltage relative to ground and a relatively small current while line B starts with a relatively __________ voltage relative to ground and a relatively __________ current.

9. To the right of the resistor, the potential of line B is likely to be about ______ V relative to ground. Show your work.

10. Remember that along line B, ___________________ would be the same no matter where you placed your ammeter.

11. Calculate the power remaining in line B to the right of the resistor. Show your work.

Power remaining in line B

12. Could you have determined the power remaining in line B in another way? _____

13. Calculate the power remaining in line A. (Remember that calculating the voltage of line A to the right of the resistor is "cheating" for the sake of this problem.)

Power remaining in line A

14. Since the voltage went **________** going from the left to the right of the step down transformer, there must be more winds on the **________** side of the transformer.

15. [Circle the correct answer in each case.] When the electricity left the power station, the power carried by lines A and B were (**about the same**/**significantly different**). But by the end of the transmission line, the power carried by line B was (**about the same**/**significantly less**/**significantly greater**) than the power carried by line A.

16. [Circle the correct answer.] Which is more efficient at carrying a given amount of power, **a high voltage line with low current** or **a low voltage line with high current**? (Note: This is most easily seen with $P = I^2R$. The more charge you need to force through the line, the greater the loss of power!) Explain why you chose the answer that you circled.

17. Where did the "lost power" of the lines go?

<u>Activity 3: A.C. power coming out of the wall!</u>

18. Does the LED light up no matter which way you touch the terminals?

    An LED will light up (**either way**/**only one way**).

19. What happens when you touch the paired LEDs to the battery and then switch the leads and touch the opposite terminals of the battery?

20. When holding the LED power wand still, do the LEDs look as if they are on all of the time, or do they look like they are flickering on and off?

21. When rapidly wiggling the LED power wand, do the LEDs look as if they are on all of the time, or do they look like they are flickering on and off?

22. [Circle the correct answer.]
    The paired LEDs **(are on at the same time/alternate being on)** when connected to an AC circuit.

23. What does your answer to the previous question tell you about the nature of AC current?

Post-lab Analysis

- **Questions associated with Activity 1:**

1. Which of the following set-ups would produce the highest voltage to the secondary? [Circle the correct answer.]
   - 20 winds in the primary, 40 winds in the secondary, air core
   - 20 winds in the primary, 40 winds in the secondary, iron core
   - 40 winds in the primary, 20 winds in the secondary, air core
   - 40 winds in the primary, 20 winds in the secondary, iron core

2. When was there a voltage reading in the secondary? [Circle the correct answer.]
   - When the DC source circuit was closed only
   - When the DC source circuit was left connected for an extended period of time
   - When the DC source circuit was opened only
   - Whenever the voltage across the primary changed

- **Questions associated with Activity 2:**

1. What is the power loss if a line carries 2.00 amperes at 120,000 volts (initially, anyway) along a 200.0 km line that has a total resistance of 0.60 Ω? [Show all calculations and circle your final answer.]

2. If a high tension power line is at 150,000 V, why can a pigeon sit on it safely? Under what circumstances might it be dangerous for a bird to sit on a power line?

3. What are some reasons that birds sit on power lines?

4. You see that a high tension power line has fallen onto the road during a storm. You should… [Note: Choose the better of the two choices.]
   - grab the line and pull it off to the side of the road. It is insulated and therefore safe to handle.
   - keep away from it! The insulation is designed to protect the line against the weather, but it will NOT protect you! Notify the power company immediately!

Questions associated with Activity 3:

1. In what way are AC and DC electricity similar? (Remember that AC electricity came from the wall, while DC electricity came from the battery.)

2. In what way are AC and DC electricity different?

3. What is an advantage of using AC electricity when using transformers?

4. The primary of a transformer is attached to a 60 V AC source. What will the voltage of the secondary be if a transformer has 100 winds in the primary and 1000 winds in the secondary? You should assume that the transformer is 100% efficient. (Industrial transformers are pretty close!) [Show all calculations and circle your final answer.]

5. Some generators in the U.S. used to cycle at 25 Hz. What disadvantage might this have for lighting when compared to the electricity produced by the 60 Hz generators in use today?