CNS Institute for Physics Teachers

Title:	**Light Emitting Diodes**
Revision:	October 30, 2004
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Appropriate Level:	Regents Physics, Engineering
Abstract:	Light emitting diodes (LEDs) are increasingly being used as indicators in electronic devices and as efficient light sources such as traffic lights. Using super-bight LEDs, students investigate the conversion of electrical energy into light and vice versa. By measuring and comparing the energy lost by each electron with the frequency of the emitted light for several LED colors students estimate Plank's constant, a fundamental number of quantum mechanics.
Time Required:	Two 45-minutes periods
NY Standards Met:	● 4.1a All energy transfers are governed by the law of conservation of energy. ● 4.1o Circuit components may be connected in series or in parallel. Schematic diagrams are used to represent circuits and circuit elements. ● 4.1p Electrical power and energy can be determined for electric circuits ● 5.3c On the atomic level, energy is emitted or absorbed in discrete packets called photons. ● 5.3d The energy of a photon is proportional to its frequency.
Special Notes:	"Light Emitting Diodes" is a kit available through the CIPT equipment lending library.

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TEACHER SECTION

Objectives:

- To explore the conversion of electrical energy into light energy using LEDs and that this process is reversible.
- To measure electrical energy lost and frequency of light emitted in LEDs of different color and use this data to estimate Plank's constant.

Class Time Required:
Two 45-minute periods.

Teacher Preparation Time:
5—10 minutes to set out supplies.

Materials Needed:
The equipment listed below is available from the CIPT equipment lending library as the "Light Emitting Diodes" kit. Visit www.cns.cornell.edu/cipt/ for on-line access.

Each student group needs:

- set of eight super-bright LEDs of different colors
- 2 9V batteries
- 2 battery clips with 300Ω resistor
- voltmeter
- 100 kΩ resistor
- spectrometer (diffraction grating with scale)

Purchasing materials:
The following materials can be purchased on-line from: www.newark.com

Item	Quantity	Catalog number	Cost
Green LED	1 ea.	95B1796	$2.94
Infrared LED	1 ea.	06F6935	$0.59
Red LED	1 ea.	92F2465	$0.23
Orange LED	1 ea.	34C1544	$0.32
Yellow LED	1 ea.	34C1534	$0.32
Blue LED	1 ea.	27C2763	$0.68
Violet LED	1 ea.	34C1518	$0.39
9V Battery Clip	2 ea.	16F433	$0.41
Alligator Clip	4 ea.	90F7188	$0.26
300 Ω resistor	2 ea.	84N1622	$0.03
Red Insulator	1	BU-32-2	$0.19
Black Insulator	1	BU-32-0	$0.19

The UV LED can be purchased on-line from: www.superbrightleds.com

Item	Quantity	Catalog number	Cost
Ultraviolet LED	1 ea.	RL5-UV2030	$1.35

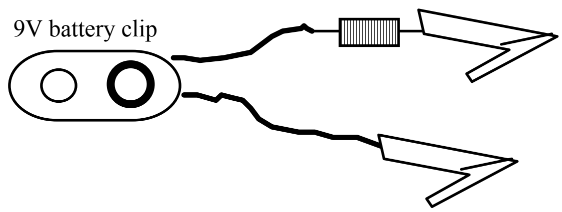
The spectrometer can be purchased on-line from: www.borealis.com

Item	Quantity	Catalog number	Cost
Handheld Spectrometer	1 ea.	WW1652500	$7.95

The multimeter can be purchased on-line from: www.kelvin.com

Item	Quantity	Catalog number	Cost
Multimeter, 50LE	1 ea.	990177	$7.95

To assemble the battery clip, solder the 300 Ω resistor to either wire. Then slip the insulator of the appropriate color over each wire and solder one alligator clip to the resistor and one alligator clip to the remaining wire.



<u>Assumed Prior Knowledge of Students</u>:

- Conservation of energy
- Relationship between frequency and wavelength ($f = c/\lambda$)
- Relationship between energy and frequency of a photon ($E = hf$)
- Relationship between electric potential and electric potential energy ($E = qV$)
- Interpretation of circuit diagrams to build circuits
- Measurement of voltage

Background Information for Teacher:

Figure 1 shows the structure of a *light-emitting diode* (LED)—a device that emits light when electric current is made to flow through it. Unlike a lightbulb, the conversion of electrical energy into light energy in an LED takes place at an interface between two different semiconducting materials called a *p-n junction*. The reason for this name is that one of the materials has a chemical composition that furnishes excess mobile electrons (the *n-type* material), while the other has a different composition with a deficiency of mobile electrons (the *p-type* material).

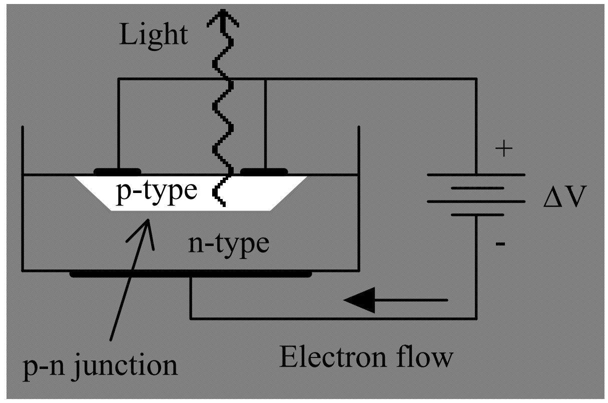


Figure 1. A light-emitting diode (LED).

The goal in this lab is to study the energy conversion process:

Electrical energy ⇔ Photons (bundles of light energy),

<u>not</u> to do a detailed investigation of the structure and mechanisms of the p-n junction. However, a simple physical model can help explain how the junction works. At the junction some electrons diffuse across the interface from the n-type to p-type material, leading to the situation shown in Figure 2—a slight excess of negatively charged ions (with bound electrons) on the p-side and a slight excess of positively charged ions (missing electrons) on the n-side. The curve shows the potential energy of mobile electrons on both sides and in the junction region.

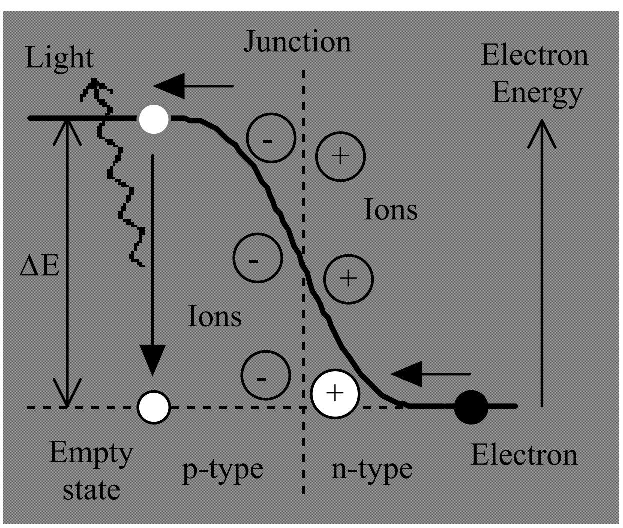


Figure 2. Operation of an LED.

Mobile electrons on the p-side of the junction occupy energy levels that lie an amount ΔE above empty energy states there. When a large enough external voltage difference ΔV is applied to the junction with the proper polarity, mobile electrons from the n-side can be driven up the energy hill and across the interface to the p-side. When an electron finds an empty state there and falls into it, the electron loses energy ΔE. This energy can then be carried off by a *photon* of light, provided that competing processes don't absorb the energy and that the p-type layer is thin enough for the light to escape. The key idea here is that $E_{photon} = |\Delta E_{electron}|$.

If the external voltage is applied to the LED with the opposite polarity, no electron current flows because electrons on the n-side are now driven away from the junction rather than across it. This one-way current flow leads to another important use of the p-n junction—a one-way *rectifying* device called simply a *diode*. The light-emitting diode or LED combines these two properties: Electric current can flow across the junction only in one direction, and when it does, the energy $e\Delta V$ gained by an electron from the applied voltage ΔV can be released as a photon of light. This simple model leads to the expectation that if we gradually increase the applied voltage ΔV, light should appear when $e\Delta V = \Delta E$, and the frequency f of the light should follow the relationship $\Delta E = hf$, where h = Planck's constant.

A nice thing about LEDs is that by changing the materials of which the p-n junction is made, the value of ΔE can be "tuned" to give different colors in the ermitted light. This is because the height ΔE of the energy hill depends on the material. ed LEDs (and red lasers) are made from the material gallium arsenide (GaAs) with small concentrations of phosphorus impurity added. The blue LEDs are made from a different material.

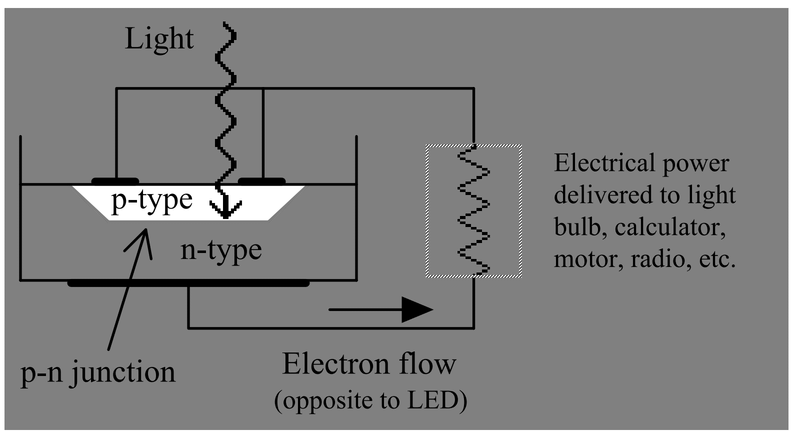


Figure 3. A solar cell.

The *solar cell* is a wonderfully simple variation on the LED. In a solar cell, light directed at the very thin top layer of a p-n junction penetrates to the junction interface. Here, if the photon energy E_{photon} (= hf) is equal to (or greater than) the electron energy level difference ΔE, then *bound* electrons on the p-side can absorb these photons and be freed, that is, raised in energy by $\Delta E_{electron} = E_{photon}$ to become *mobile* electrons which are then driven *down* the energy hill shown in Figure 2. This is opposite to the direction of electron flow that makes an LED light up. In other words, *a solar cell is an LED run backwards*. The electric current (that is, "photocurrent") produced by a solar cell depends on the intensity of light illuminating it.

Answers to Questions:

Prelab

a. What is the relationship between electric potential and electric potential energy? Electric potential multiplied by charge equals electric potential energy. $E = qV$.

b. How much electric potential energy does each electron lose when passing through the resistor? $E = qV = (1.6\times10^{-19}\text{ C})(5\text{ V}) = 8\times10^{-19}\text{ J}$

c. What is the relationship between f and λ? Frequency equals speed of light divided by wavelength. $f = c/\lambda$.

d. What is the relationship between energy E of a photon and frequency f of light? Energy of a photon equals Planck's constant multiplied by frequency. $E = hf$.

e. Calculate the energy of a photon of wavelength 500 nm. (1nm = 10^{-9}m)
$f = c/\lambda = (3.0\times10^{8}\text{ m/s})/(500\times10^{-9}\text{ m}) = 6.0\times10^{14}\text{ Hz}$
$E = hf = (6.6\times10^{-34}\text{ Js})(6.0\times10^{14}\text{ Hz}) = 4.0\times10^{-19}\text{ J}$

f. If electrons flowing in a circuit were to lose an amount of energy equal to the photon energy of part (b), what would be their change in voltage?
$V = E/q = (4.0\times10^{-19}\text{ J})/(1.6\times10^{-19}\text{ C}) = 2.5\text{ V}$

Making LEDs Light Up

1. Try hooking up the positive and negative leads both ways to the LED. Does it matter which way you hook them up? Yes, the LED will not light if the polarity of the leads is not correct.

2. What is the voltage across the red LED when it is lit? The voltage across the red LED is about 1.8 V.

3. What is the voltage across the blue LED when it is lit? The voltage across the blue LED is about 3.6 V.

4. Given your voltage measurements on the red LED and the blue LED, in which LED does an electron lose the most energy? The greater voltage drop across the blue LED indicates that an electron loses the most energy in the blue LED.

5. Using your knowledge of photons, which color of light (red or blue) contains photons of greater energy? Blue light contains photons of greater energy.

6. Qualitatively, explain the relationship between voltage drop across an LED and the color of the light it emits. The greater the voltage drop across an LED, the greater the frequency of the light it emits or the bluer the color.

LEDs in Reverse

1. Adjust the two LEDs until you find the maximum voltage across the red LED with green light shining into it. What is this value? About 1.4 V.

2. If you disconnect the battery from the green LED, now what is the voltage across the red LED? Typical answers will be a few hundredths of a volt, depending on the amount of background light in the room and the orientation of the LED to the background light source.

3. Can you explain your voltage measurements from (1) and (2)? When the green light entered the red LED, electrons in the red LED absorbed the photons and gained electric potential energy, creating a voltage across the red LED.

4. What is the voltage across the green LED with the red light shining into it? No change in voltage is observed across the green LED when red light enters it.

5. Can you explain your observations from (4)? The red photons do not have enough energy to get absorbed by the electrons in the green LED. (This is due to a larger band gap in the green LED. See "Background Information for Teacher.")

6. Predict what will happen if you shine ultraviolet light into the green LED. The ultraviolet light will have enough energy to get absorbed by electrons in the green LED, causing an increase in voltage across it.

7. Try the experiment from (6). Were your predictions correct? Answers will vary.

Measuring Planck's Constant

The LED voltages below were measured with a 0.010 mA current through the LEDs.

LED	LED voltage (V)	Energy lost (J)
infrared	1.12	1.79×10^{-19}
red	1.44	2.30×10^{-19}
orange	1.53	2.45×10^{-19}
yellow	1.62	2.59×10^{-19}
green	2.33	3.73×10^{-19}
blue	2.37	3.79×10^{-19}
violet	2.52	4.03×10^{-19}
ultraviolet	2.81	4.50×10^{-19}

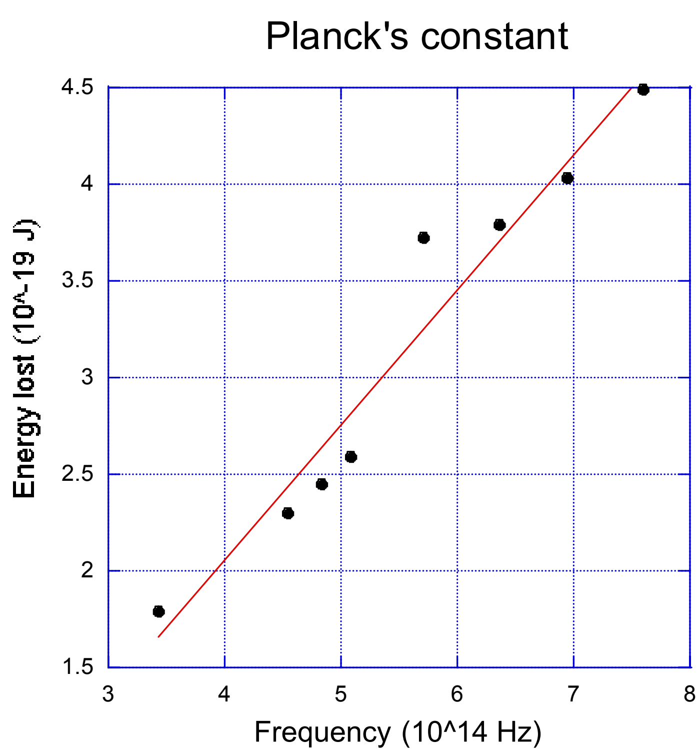
The LED wavelengths below are at the peak intensity of the LED output spectrum provided by the manufacturer.

LED	**λ (nm)**	**λ (m)**	**f (Hz)**
infrared	875	8.75×10^{-7}	3.43×10^{14}
red	660	6.60×10^{-7}	4.55×10^{14}
orange	620	6.20×10^{-7}	4.84×10^{14}
yellow	590	5.90×10^{-7}	5.08×10^{14}
green	525	5.25×10^{-7}	5.71×10^{14}
blue	472	4.72×10^{-7}	6.36×10^{14}
violet	432	4.32×10^{-7}	6.94×10^{14}
ultraviolet	395	3.95×10^{-7}	7.59×10^{14}

1. Compare the voltages of the different LEDs with the frequency of the light emitted by the LED. What trend to do observe? The voltage across the LED increases with the frequency of the light emitted.

2. Can you explain the trend that you noted in (1)? A greater voltage means that an electron is loses more energy, which allows a photon of greater energy and frequency to be created.

Plot the energy lost by an electron versus the frequency of the light emitted for all the LEDs on a separate piece of graph paper or on a computer.



3. What do you measure for the slope of the graph? Answers will vary within 20% of the accepted value for Planck's constant (6.6×10^{-34} Js). The slope of the graph shown above is 7.0×10^{-34} Js. Note that there is some scatter in the data and not all points fall on a straight line. This is because the assumption that the energy lost by the electron equals the energy of the emitted photon is not entirely true. The interaction takes place inside of a solid state material, and other processes occur that affect the energy of the photon emitted.

4. What is the meaning of the slope? The slope is an estimate for Planck's constant.

Tips for the Teacher:

- For the activity, "LEDs in Reverse," make sure the students align the two LEDs coaxially so that one LED is shining its light directly into the tip of the other as shown and described in the worksheet. The LEDs are highly directional in their output, and this directionality applies to their input as well.

Annotated References:

Basics of LEDs:
- http://hyperphysics.phy-astr.gsu.edu/hbase/electronic/leds.html
- http://mrsec.wisc.edu/edetc/LED/

Explanation of Planck's constant estimation method:
- F. Herrmann, D. Schatzle, "Measuring Planck's constant by means of an LED," American Journal of Physics. vol. 64, p. 1448 (1996).
- R. Morehouse, "Answer to Question #53. Measuring Planck's constant by means of an LED," American Journal of Physics. vol. 66, p. 12 (1998).

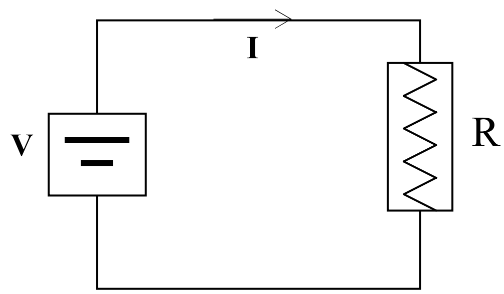
Historical information, applications and purchasing info on LEDs:
- http://www.ledmuseum.org/

Good chemistry activity with LEDs:
- G. Lisensky, et. al., "Periodic Properties in a Family of Common Semiconductors," Journal of Chemical Education. vol. 69, pp. 151-156 (1992).\

General integrated circuit explanation/history:
- http://www.nobel.se/physics/educational/integrated_circuit/history/index.html

Light Emitting Diodes—Prelab

Consider the following circuit with a battery V = 5V and resistor R = 100 Ω.



g. What is the relationship between electric potential and electric potential energy?

h. How much electric potential energy does each electron lose when passing through the resistor?

Now consider light of frequency (f), wavelength (λ) and velocity (c).

i. What is the relationship between f and λ?

j. What is the relationship between energy E of a photon and frequency f of light?

k. Calculate the energy of a photon of wavelength 500 nm. (1nm = 10^{-9}m)

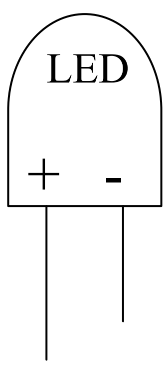
l. If electrons flowing in a circuit were to lose an amount of energy equal to the photon energy of part (b), what would be their change in voltage?

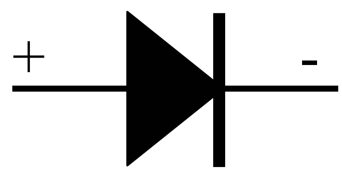
Light Emitting Diodes

Light Emitting Diodes (LEDs) can be found everywhere you look—in digital clocks, appliances like TVs, VCRs, coffee makers and electronic devices like cell phones and computers. LEDs emit light by converting the electrical potential energy into light energy. This property is what makes LEDs useful as indicators. The color of light that an LED emits depends on the material that it is made of. By lighting up LEDs of different color and measuring some of their electrical and optical properties, you will be able to estimate the value of Plank's constant at the end of this lab.

The LED

Familiarize yourself with the LED. Unlike resistors, the LED has a polarity. The LED only allows current to flow in one direction, from positive to negative.





Symbol used to represent LEDs in circuit diagrams

You should have a small strip of circuitboard with eight different superbright LEDs in it. Each LED has been marked at its base according to the color of light it emits. The following chart explains the color code:

color code (at base of LED)	color of light emitted by LED
brown	infrared
red	red
orange	orange
yellow	yellow
green	green
blue	blue
violet	violet
black	ultraviolet

Making LEDs Light Up

Use a 9V battery and battery clip to light up the red LED.

1. Try hooking up the positive and negative leads both ways to the LED. Does it matter which way you hook them up?

2. What is the voltage across the red LED when it is lit?

Now use the 9V battery and battery clip to light up the blue LED.

3. What is the voltage across the blue LED when it is lit?

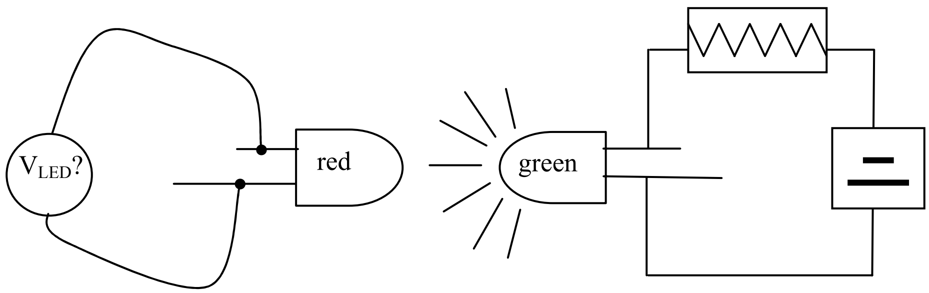
4. Given your voltage measurements on the red LED and the blue LED, in which LED does an electron lose the most energy?

5. Using your knowledge of photons, which color of light (red or blue) contains photons of greater energy?

6. Qualitatively, explain the relationship between voltage drop across an LED and the color of the light it emits.

LEDs in Reverse

Use the 9V battery and battery clip to light the green LED. Place the voltmeter across a separate red LED (not in the same strip as the green LED).



Orient the two LEDs so that light from the green LED can shine directly into the tip of the red LED as shown.

1. Adjust the two LEDs until you find the maximum voltage across the red LED with green light shining into it. What is this value?

2. If you disconnect the battery from the green LED, now what is the voltage across the red LED?

3. Can you explain your voltage measurements from (1) and (2)?

Now hook the battery to the red LED and the voltmeter to the green LED.

4. What is the voltage across the green LED with the red light shining into it?

5. Can you explain your observations from (4)?

6. Predict what will happen if you shine ultraviolet light into a green LED.

7. Try the experiment from (6). Were your predictions correct?

Measuring Planck's Constant

Connect the eight LEDs, two 9V batteries with battery clips and the 100 kΩ resistor in series. You should see most of the LEDs just barely emit visibly emit light.

Measure the voltage across each LED and write it in the table below. Then calculate the energy each electron loses when it passes through the LED in the "Energy lost" column.

LED	LED voltage (V)	Energy lost (J)
infrared		
red		
orange		
yellow		
green		
blue		
violet		
ultraviolet		

Now attach the strip of eight LEDs to the spectrometer box. Light the LEDs with the two 9V batteries in series across the six visible LEDs only (do not include the ultraviolet or infrared LEDs).

In the column marked "λ," write the central wavelength of each LED. Convert the wavelength to meters and calculate the corresponding frequency *f*.

LED	λ (nm)	λ (m)	f (Hz)
infrared	875		
red			
orange			
yellow			
green			
blue			
violet			
ultraviolet	395		

1. Compare the voltages of the different LEDs with the frequency of the light emitted by the LED. What trend to do observe?

2. Can you explain the trend that you noted in (1)?

Plot the energy lost by an electron versus the frequency of the light emitted for all the LEDs on a separate piece of graph paper or on a computer.

3. What do you measure for the slope of the graph?

4. What is the meaning of the slope?

Graph Paper