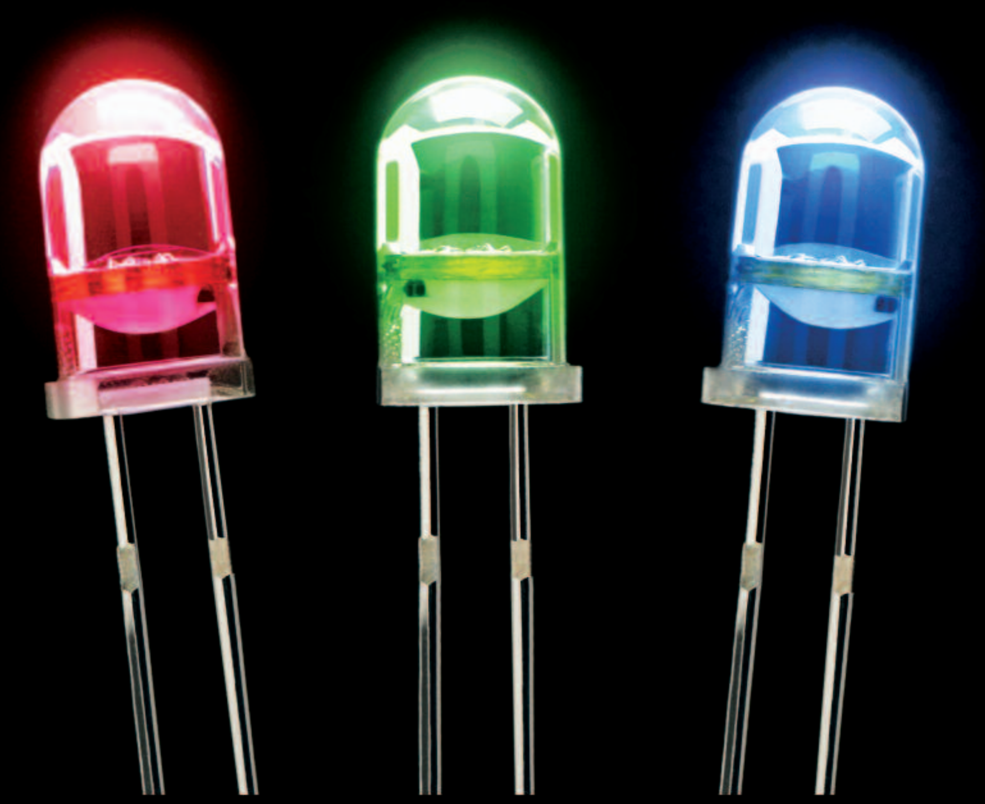
Measuring Planck's Constant



PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Introduction

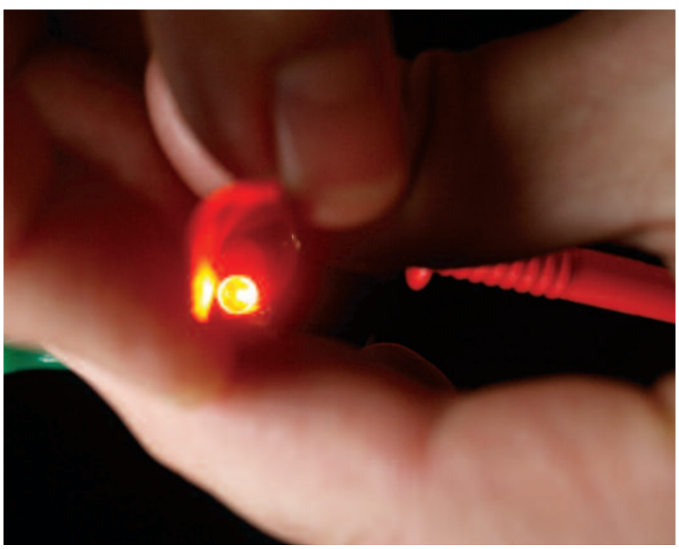
Outline

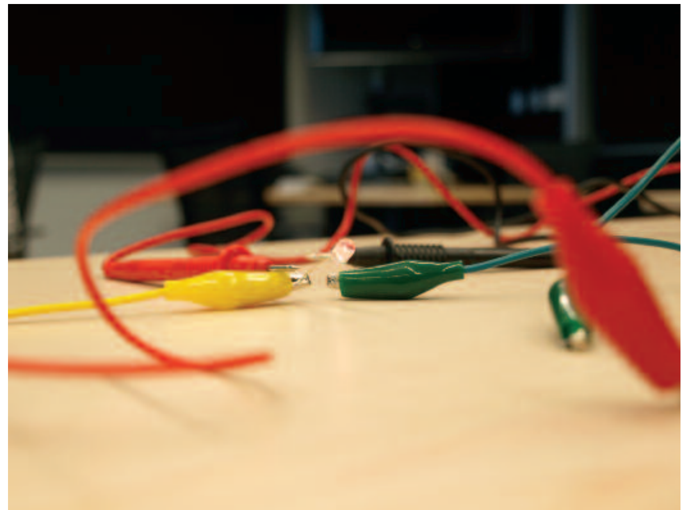
Planck's constant (h = 6.63 x 10^{-34} Js) is a universal constant that lies at the heart of quantum physics. It defines the scale of this theory just as the speed of light (c = 3.00 x 10^{8} m/s) defines the scale of special relativity.

This resource centres around a laboratory activity in which students measure Planck's constant using a simple electronic circuit. The circuit is inexpensive and contains only a 6-volt battery, an LED, a resistor, a voltmeter, a few wires, and a potentiometer (variable resistor).

When the circuit is used to apply a potential difference across the LED, current flows once the potential difference is large enough. The electrical energy lost by each electron that crosses the LED is converted into the energy of an individual photon. The energy E of this photon is given by the formula $E = hf$, where f is the photon's frequency. By measuring the potential difference across a number of different LEDs, students can calculate h. Typically, they can complete this laboratory activity within an hour and measure Planck's constant to within an accuracy of 20%.

Curriculum Links: Quantum nature of light, $E = hf$.





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Measuring Planck's Constant: Student Worksheet

Aim

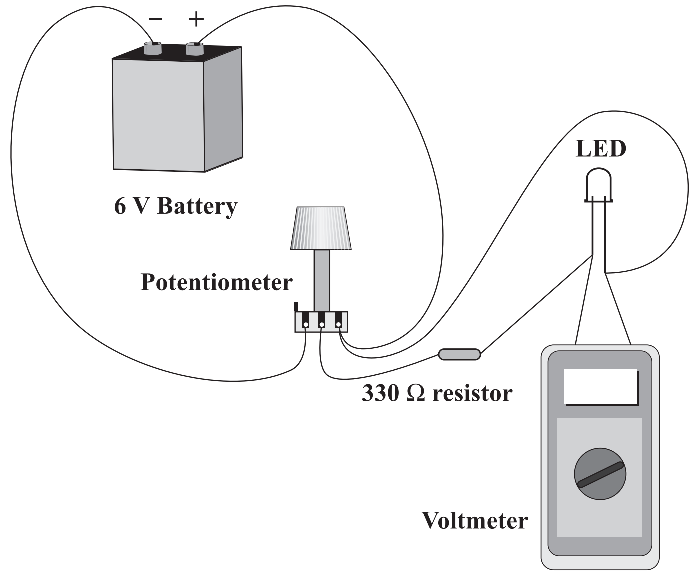
To demonstrate the quantization of light and to measure Planck's constant (h).

Background

The energy lost by a single electron that passes through a light-emitting diode (LED) is converted into the energy of one photon.

$$e\Delta V = hf$$

e = elementary charge = 1.6×10^{-19} C
ΔV = potential difference across LED
f = frequency of a photon emitted by LED



Materials

Set of 5 LEDs
6 V battery
1 kΩ potentiometer
330 Ω resistor
voltmeter
5 connecting leads

Procedure

CAUTION: Do not stare *directly* at a *brightly* lit LED.

1. Orient the potentiometer so that the terminals are pointing towards you. Turn the knob fully clockwise. Connect the negative terminal of the battery to the left-hand terminal of the potentiometer and the positive terminal of the battery to the right-hand terminal of the potentiometer, as shown in the diagram.
2. Connect any one of the LEDs to the 330 Ω resistor using a wire. Connect both of these components between the central and right-hand terminals of the potentiometer as shown in the diagram (with the *longer* wire of the LED attached to the *right-hand* terminal).
3. Connect the voltmeter across the LED.
4. Slowly increase the potential difference across the LED by turning the potentiometer knob counterclockwise until the LED **just begins** to glow. Record the potential difference at which this happens. Go backwards and forwards past the point at which the LED just begins to glow a few times to locate it as accurately as possible.
5. Repeat Step 4 for all the other LEDs. Always turn the potentiometer knob fully clockwise before changing LEDs so the initial voltage across each LED is 0 V.
6. Summarize your results in a table similar to the following:

Colour of LED	Red	Amber	Yellow	Green	Blue
Frequency (x 10^{14} Hz)	4.54	5.00	5.08	5.31	6.38
Potential Difference (V)					

Analysis

1. Plot a graph of potential difference (y-axis) versus frequency (x-axis).
2. Draw the line of best fit and measure its slope. Use this slope to calculate Planck's constant by using the equation $e\Delta V = hf$.

Questions

1. What is the percentage error in your calculated value for Planck’s Constant?
2. A green laser pointer produces 530 nm light with a power rating of 1.0 mW. How many photons does the laser produce each second?
3. Weather reports monitor ultraviolet (UV) light levels. Why is UV light a concern?

Measuring Planck's Constant: Teacher’s Notes

Curriculum Links

Quantum nature of light, particle model of light.

Equipment needed

6 V battery

1 kΩ potentiometer

330 Ω resistor

voltmeter

five connecting leads

set of LEDs that produce five different colours of light in the visible spectrum, eg. Knight Lites KSB-1372, KSB-1393, KSB-1356, KSB-1337 and KLL-5058A.

Viewing tube (optional, see Appendix for details)

Experiment Set Up

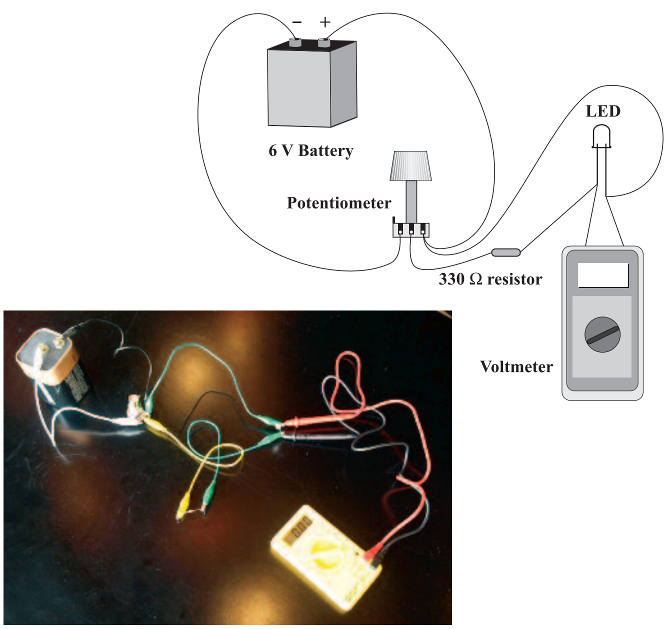


Figure 1: Diagram and photo of circuit used.

Background Information

What is a potentiometer? What is an LED? See Appendix.

Purchasing LEDs and Potentiometers

LEDs are inexpensive and readily available. They often cost less than a dollar and can be purchased from many electronic stores or ordered online. Most brands of LEDs are suitable for use in this laboratory activity. Any size of LED is also suitable but one of the most common sizes is 5 mm in diameter. Potentiometers are also inexpensive and readily available. The most common type has three terminals (see Figure 7 in the Appendix) and this is the type used in this lab activity.

Theory

- When we apply a large enough potential difference across a light-emitting diode (LED), it emits photons that all have the same frequency.
- When the LED just begins to glow, the energy E lost by each electron as it passes through the LED is converted into the energy of a single photon.
- The energy lost by each electron is $E = e\Delta V$, where e is the elementary charge (1.6×10^{-19} C) and ΔV is the potential difference across the LED.
- The energy E of a photon of frequency f is $E = hf$, where h is Planck’s constant ($h = 6.63 \times 10^{-34}$ Js).
- Equating the two energies yields $e\Delta V = hf$
- Plotting ΔV against f for LEDs of several different colours produces a straight line of slope h/e.
- Measuring the graph’s slope and multiplying it by e yields Planck's constant.

Useful Constants

$c = 3.0 \times 10^{8}$ m/s

$e = 1.6 \times 10^{-19}$ C

$h = 6.63 \times 10^{-34}$ Js

Cautions

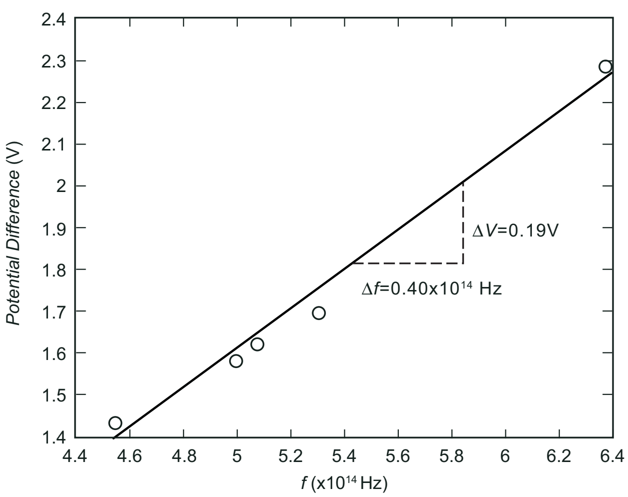
1. **Students should not stare directly at LEDs when they are brightly lit.** LEDs are safe when they just begin to glow, but they quickly become bright as the potential difference across them increases above the threshold value. **Be especially careful with the blue LED** as the upper part of its frequency spectrum is very close to the ultra-violet region which can cause permanent eye damage. Students should not stare at the blue LED even when it is dimly lit.
2. **LEDs can be destroyed if the current flowing through them is too large.** The purpose of the 330 Ω resistor connected in series with the LED is to limit the current flowing through the LED. This current should be no more than about 50 mA.
3. **The potentiometer can be destroyed if wired incorrectly.** Students should be careful when wiring the potentiometer. If they wire it incorrectly, they can create a short circuit which leads to a large potential difference across a low resistance. This can result in the

potentiometer heating up rapidly, producing a visible quantity of smoke and ceasing to function. To prevent problems from occurring, you may wish to inspect your students' circuits before allowing them to connect the battery. You may also wish to give your students extra assistance by labelling the terminals of the potentiometer and the LED (with tape, for example, or by colour-coding them with paint) to indicate where they should be connected.

Sample Results:

Colour of LED	Red (KSB-1372)	Amber (KSB-1393)	Yellow (KSB-1356)	Green (KSB-1337)	Blue (KLL-5058A)
Frequency (x 10^{14} Hz)	4.54	5.00	5.08	5.31	6.38
Potential Difference (V)	1.43	1.58	1.62	1.69	2.29

Graph



Analysis

- slope of graph = h/e = (0.19 V)/(4.0 x 10^{13} Hz) = 4.75 x 10^{-15} Js/C
- h = (4.75 x 10^{-15} Js/C) (1.6 x 10^{-19} C) = 7.6 x 10^{-34} Js

This result is 15% above the true value, which is reasonable for this lab. Errors of 15-20% are common.

Note that the graph has a false origin. If the line of best fit is extended to the left it does not pass through the origin, but instead intercepts the ΔV axis at -0.80 V. One reason for the intercept not being 0 V is the fact that the formula $e\Delta V = hf$ is only approximate. In reality, $e\Delta V < hf$ as electrons in the LED have some thermal energy. When the potential difference across the LED is less than hf, this thermal energy can provide enough extra energy for a photon with frequency f to be created. Note, however, that the thermal energy of electrons is typically significantly less than $e\Delta V$ and so cannot account for the entire deviation of the intercept from the origin.

Errors

There are several possible sources of error in this experiment. First, there is the human error associated with seeing the point at which the LED just begins to glow. The results obtained can vary depending on whether or not a viewing tube is used to block out other sources of light, whether or not room lights are on, etc. For optimal results, using a viewing tube is recommended.

Another source of error is the fact that LEDs do not emit a single frequency of light. Instead, they emit a narrow spectrum with a width of approximately 60 nm. The frequency values plotted on the horizontal axis are the central frequency emitted by the LEDs, but when the LEDs just begin to glow, we typically see slightly lower frequencies.

Answers to Questions in the Student Instruction Sheet

1. The sample result of h = 7.6 x 10^{-34} Js is 15% greater that the known value.

2. The frequency of green light is given by the following equation:

$$f = \frac{c}{\lambda} = \frac{3.00\times10^{8}\ \text{m/s}}{530\times10^{-9}\ \text{m}}$$
$$= 5.66\times10^{14}\ \text{Hz}$$

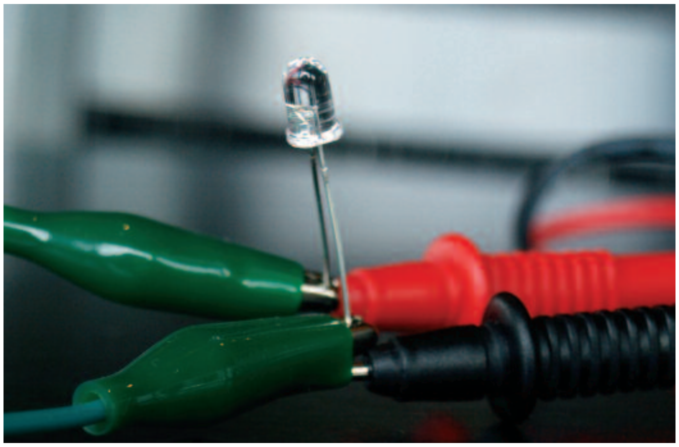
Energy of a green photon:

$$E = hf$$
$$= (6.63\times10^{-34}\ \text{Js})\,(5.66\times10^{14}\ \text{Hz})$$
$$= 3.75\times10^{-19}\ \text{J}$$

The number of photons emitted by the laser each second is:

$$\frac{\text{energy emitted each second}}{\text{energy of a single photon}} = \frac{1.00\times10^{-3}\ \text{J}}{3.75\times10^{-19}\ \text{J}} = 2.66\times10^{15}$$

3. Ultra-violet light has a higher frequency than visible light and so, using the formula $E = hf$, ultra-violet photons have more energy than visible ones. Thus, ultra-violet photons can cause more damage to the cells in our bodies when they impact on them.



Structure of a light-emitting diode (LED)

An LED consists of two different types of semiconducting materials that are joined together and cased in plastic. One of the materials (A) contains a number of electrons that are free to move throughout it. The other (B) has a number of vacant spaces where electrons could be found but are not. Instead, there is the absence of an electron that is called an electron *hole*.

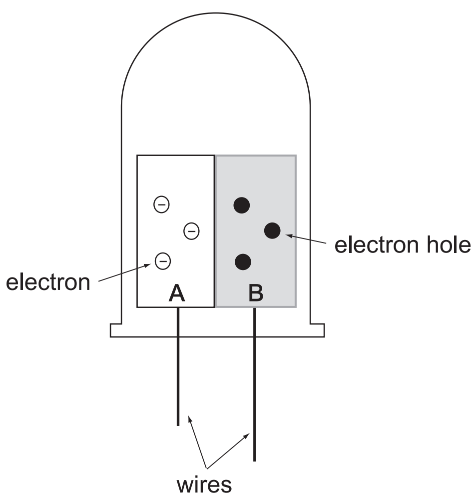


Figure 2: Schematic diagram of an LED made from two different semiconductors (represented by white and grey rectangles).

At the boundary between the two semiconductors, some of the free electrons in material A move into holes in material B as this reduces their energy (Figure 3).

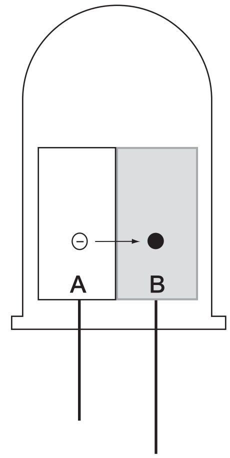


Figure 3: Electron moving into a hole.

After a short period of time, the region in material B near the boundary becomes negatively charged, and the region in material A near the boundary becomes positively charged (as a number of electrons have left). This produces an electric field $\vec{E}$ that exerts a force $\vec{F}_e$ on electrons in material A in a direction away from the boundary, as shown in Figure 4. The field acts as a potential barrier that prevents any more electrons from crossing.

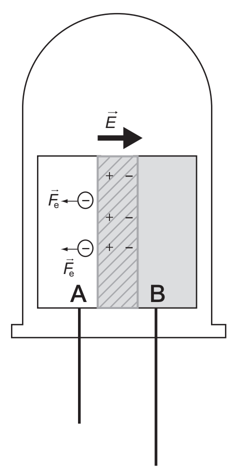


Figure 4: After a number of electrons have crossed the boundary, an electric field $\vec{E}$ builds up that prevents more electrons from crossing. The diagonal lines ▨ represent the barrier created by this field.

Connecting the LED to a circuit

When we connect the LED to a voltage source so that material A is connected to its negative terminal, electrons in this material are attracted to the boundary, as shown in Figure 5. The LED is said to be in 'forward bias' and current flows when the potential difference is large enough to overcome the barrier created by the electric field.

When electrons cross the boundary and move into holes, they move from higher-energy states to lower-energy ones. In doing so, they emit energy in the form of photons which causes the LED to shine.

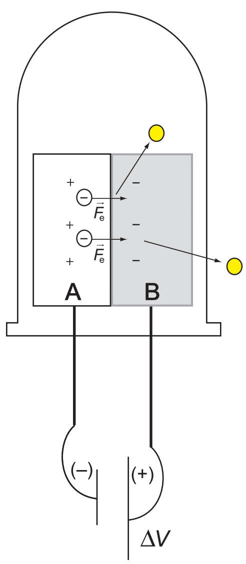


Figure 5: When we connect material A to the negative terminal of a voltage source (forward bias), current flows through the LED once the potential difference reaches a certain threshold voltage ΔV. When this happens, the LED emits photons (represented by ◯).

Mathematical Analysis

When the LED just begins to glow, electrons crossing the boundary move through a potential difference ΔV. In doing so, they lose an energy equal to $e\Delta V$, where e is the elementary charge (e = 1.6 x 10^{-19} C). This energy is converted into the energy E of a photon where E is given by the equation $E = hf$, where h is Planck's constant and f is the photon's frequency. Equating E to the energy lost by each electron yields $e\Delta V = hf$, the equation used in this laboratory activity.

Connecting the LED the 'wrong' way

When we connect the LED to a voltage source so that material A is connected to its positive terminal, the applied potential difference across the LED repels electrons in material A from the boundary. This has the effect of increasing the size of the existing potential barrier in the vicinity of the boundary and so no current flows. The LED is said to be in 'reverse bias'.

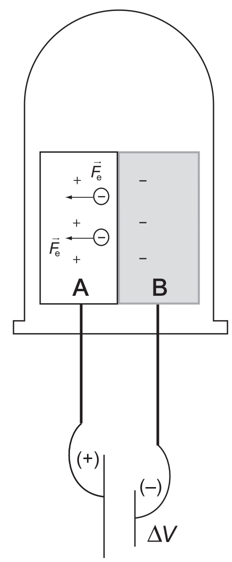


Figure 6: Connecting material A to the positive terminal leads to a force on electrons directed towards the left (reverse bias). Current does not flow through the LED.

Appendix

What is a potentiometer?

A potentiometer is a device that allows the user to vary the resistance between two electrical contacts or terminals by some means, such as turning a knob. Many potentiometers have three terminals (see Figure 7) with the left and right-hand terminals being connected to either end of a fixed resistor. The central terminal is connected partway along the resistor with its exact position depending on the orientation of the knob. This provides a variable resistance between the central terminal and the other two terminals.

Turning the potentiometer knob fully clockwise results in the resistance between the central and right-hand terminals becoming 0 Ω. Turning the knob counter-clockwise increases the resistance between the central and right-hand terminals up to some maximum resistance (1 kΩ in the lab) and the potential difference across them.

When the LED is connected in parallel with the central and right-hand terminals, the potential difference across the LED-resistor combination is equal to the voltage across these two terminals. So, as we turn the knob counter-clockwise, we increase the potential difference across the LED.

What is an LED?

A *diode* is an electronic component that has very low resistance when a current flows through it in one direction and very high resistance when it flows through in the other direction. It acts similarly to a one-way valve that allows water to flow through a pipe in only one direction. A *light-emitting diode* (LED) is a diode that converts electrical energy into visible electromagnetic radiation and thus emits light with a narrow frequency range when sufficient current flows through it in the low-resistance direction. LEDs are more energy efficient and have longer lifetimes than conventional incandescent light bulbs. They are used in devices such as traffic lights, digital alarm clocks, and TV remote controls.

What is a viewing tube?

A *viewing tube* is a small tube made of rubber (or anything else) that can be used to block out light from other sources when students are attempting to see when an LED just begins to glow. To use a viewing tube, place one end of it over the LED and look through the other end as shown in Figure 8.

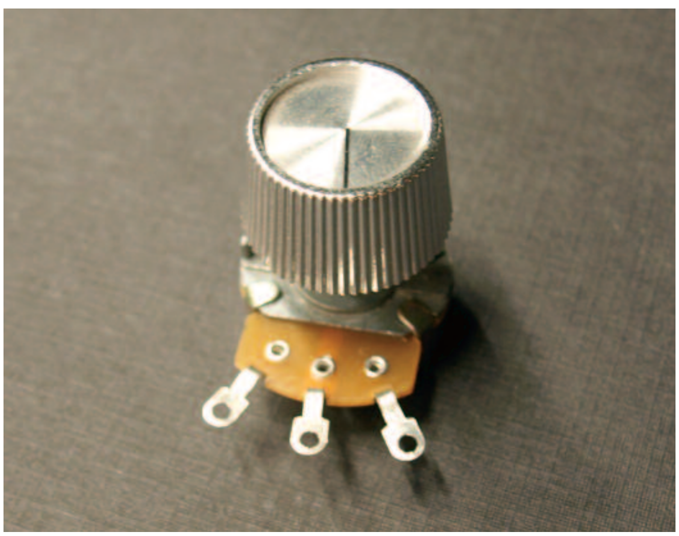


Figure 7: A potentiometer.

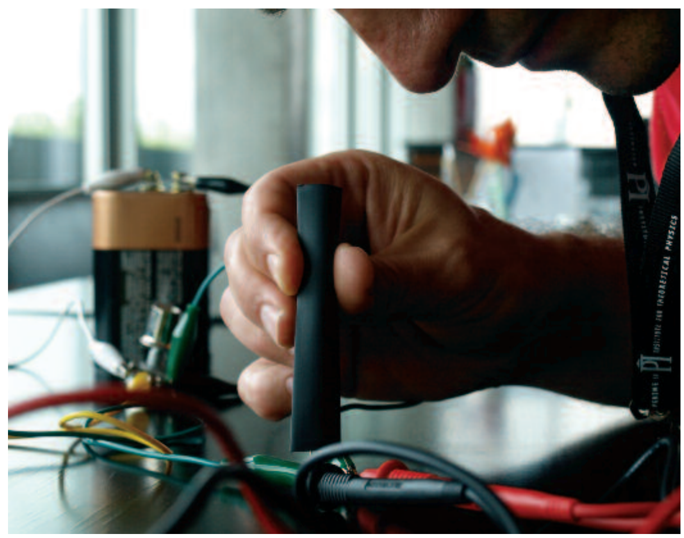


Figure 8: Looking at an LED through a viewing tube.

Perimeter Institute for Theoretical Physics
31 Caroline Street North
Waterloo, Ontario, Canada N2L 2Y5
Tel: (519) 569-7600 Fax: (519) 569-7611

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