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Light-Emitting Diodes: Solving Complex Problems

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This is the fourth paper in our Light-Emitting Diodes series. The series aims to create a systematic library of LED-based materials and to provide readers with the description of experiments and the pedagogical treatment that would help their students construct, test, and apply physics concepts and mathematical relations. The first paper[1] provided an overview of possible uses of LEDs in physics courses. The second paper[2] discussed how one could help students learn the foundational aspects of LED physics through a scaffolded inquiry approach, specifically the ISLE cycle. The third paper[3] showed how the physics inherent in the functioning of LEDs could help students deepen their understanding of sources of electric power and the temperature dependence of resistivity, and explore the phenomenon of fluorescence also using the ISLE cycle.[4] The goal of this fourth paper is to use LEDs as black boxes that allow students to study certain properties of a system of interest, specifically mechanical, electric, electromagnetic, and light properties. The term "black box" means that we use a device without knowing the mechanism behind its operation.

In this paper we will mostly work with application experiments. These are usually experimental problems where students need to combine several qualitative and quantitative ideas to produce a solution. When LEDs are used as black boxes, the following properties are important. LEDs glow when the currents through them are small (a few milliamps) and in a particular direction, and when the voltage across them is higher than the turn-on voltage. LEDs turn on and off almost instantly and produce almost monochromatic light[5] in the wide range of frequencies including UV and infrared.

Below we describe four investigations that students might conduct using LEDs as black boxes (the summary of the activities is provided in Table I). The investigations are in order of increased sophistication both in terms of physics involved and the details of experimentation. Activities described in the paper have been used with high school students, freshman undergraduate physics majors, pre-service physics teachers, middle and high school physical science/physics teachers in professional development programs, and physics teacher educators.

Table I. Summary of the activities in which LEDs are used as black boxes.

Activity	Content area	Role played by the LED	Prerequisite knowledge
Recording and analyzing motion	Kinematics, dynamics, energy	Light source of variable intensity	None
Why do we use LEDs to light up our homes?	Electric current	Light source with a specific mechanism of light generation	Voltage, current, power
Exploration of sunscreen lotions	Wave optics, chemistry, living organisms	Monochromatic light source	Wavelength of light, electromagnetic spectrum
Electromagnetic induction	Electromagnetism	Indicator of current presence and direction	Magnetic field and electromagnetic induction; LEDs glow when the current is in one direction and the voltage exceeds opening voltage.

Recording and analyzing motion

There are many ways of keeping records of moving objects—ticker tape, motion detector, video analysis—but one of the simplest ways is to use a blinking light source in combination with long time exposure photography.[6] LEDs are an ideal solution for making blinking light sources for the following reasons: they have a very short response time, they need very little electric power, and they can be very bright.

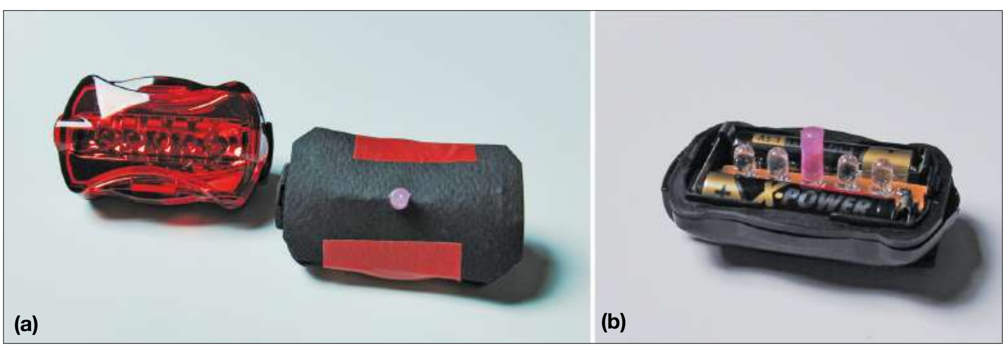

Fig. 1. Making a blinking point-like source out of a bicycle lamp: (a) covering all LEDs but one; (b) diffusing light from the remaining LED using a short piece of a plastic straw.

Although one can make her own electric circuit for making a blinking LED,[7] we decided to use a simple LED-based blinking bicycle lamp. Bicycle lamps usually contain several LEDs blinking simultaneously, each emitting light in a narrow cone. For recording motion one needs a point-like light source that blinks with a constant frequency and can be visible from a wide range of viewing angles. In

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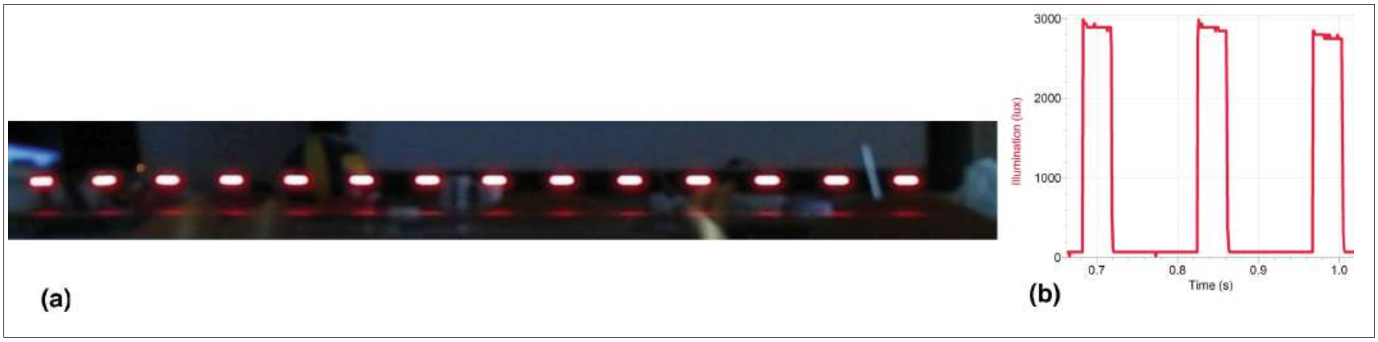

Fig. 2. (a) Photo of a blinking LED that is fixed on a cart which moves with constant speed. Knowing the exposure time (2 s), one can estimate the blinking period (145 ms); (b) measurements of a blinking LED duty cycle using a Vernier light sensor (period 143 ms; 39 ms ON and 104 ms OFF).

order to make a bicycle lamp satisfy all three conditions, we need to 1) block all but one LED, for example, by using black masking tape, and 2) diffuse light emitted by the LED, for example, by putting a plastic straw on the LED and filling it with glue-gun plastic (see Fig. 1). Below we describe two possible activities for the students. Activity 1 teaches them how to collect data using a blinking LED attached on a moving object. Activity 2 presents a challenging problem: investigating and explaining how a pullback car works.

Equipment: a modified LED-based bicycle lamp, a digital camera fixed on a stand (the camera should allow manual setting of the exposure time), any moving car or cart on a track (to make quantitative measurements, use a constant motion vehicle), a pullback car, and Plasticine or some other material for fixing a blinking LED on a moving object.

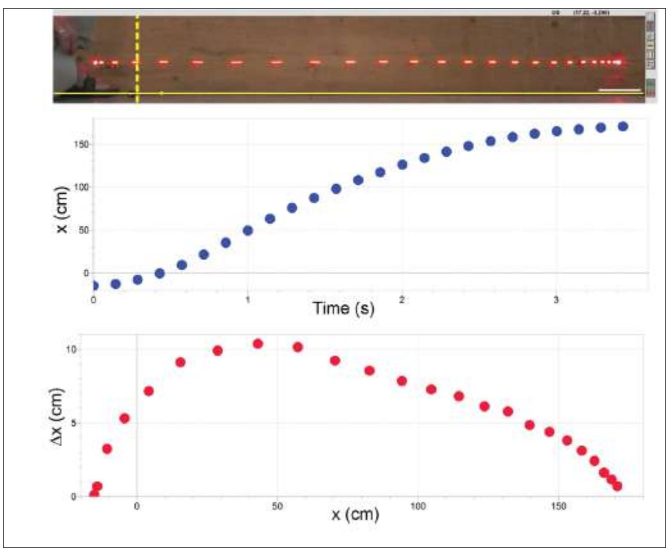

Fig. 3. Analysis of the photo of the blinking LED fixed on the pullback car. We used Logger Pro software to make position-vs-time $x(t)$ and displacement-vs-position $\Delta x(x)$ graphs for the motion of the car after it had been pulled back from initial position at $x = 0$. The clock readings for the beginning of each bright trace data point on the top graph were determined using the period of the LED blinking. On the second graph, the Δx coordinate represents the displacement during the time interval when the LED is off (104 ms in our case). Note that the scale of the horizontal axis of the $\Delta x(x)$ graph matches the situation shown in the photo. The graph $\Delta x(x)$ can be easily converted into $v(x)$ graph for the same motion.

•*Activity 1:*

The students working in groups are given the following challenge: "Using a blinking LED and a digital camera, design a procedure that will allow you to investigate the motion of the vehicle and represent this motion graphically and mathematically."

Students need to do three main steps in the procedure: 1) calibrate the blinking LED (how often it blinks), 2) record the motion, and 3) analyze data to produce a desired representation. Depending on how you run your classroom, you might either let them figure these steps on their own or provide the information about the steps before they proceed. Below we describe one possible procedure to solve the problem.

Procedure: Use a low-friction cart on a horizontal track. Fix the blinking LED on the cart and put the camera on a stand several meters away from the track, facing the middle of the track (use zoom). Set the camera exposure time to two seconds. Put the cart on one end of the track, gently push it so it starts moving, and then press the camera switch to collect the image. (The procedure needs to be repeated several times to estimate uncertainty.) The photo is shown in Fig. 2(a). From the image one can determine the on and off time of the LED [this can be checked with a light sensor later, see Fig. 2(b)] and the velocity of the vehicle. We can also draw motion diagrams, $v(x)$ graphs, and traditional $x(t)$ and $v(t)$ graphs. Students might also discuss what determines the uncertainties in the data and how to minimize them.[8]

Activity 2:

The students working in groups have the following challenge: "Use the blinking LED to record the motion of a pullback car and use the data to pose and answer any questions you can about the car."

Procedure: Fix the blinking LED on the pullback car. Mark the initial position of the car, pull it back, start image acquisition, and let the car go. Possible questions that the students might pose and answer:

a) How can we use the obtained image and data to represent the motion of the car with motion diagrams and with $x(t)$, $v(t)$, and $v(x)$ graphs?

b) How can we represent the motion of the car with energy bar charts[9] (for example, compare different types of energies in the moments just before the car is released, when the car moves with the largest speed, and when the car stops).

c) What can you say about the operation of the pullback car based on the energy analysis? Describe all the assumptions that you made.

Figure 3 shows the analysis of data collected in Activity 2. The vertical yellow dashed line indicates the initial position of the car before it was pulled back. The lower graph shows how the displacement of the car changed during each time interval when the LED was off. Note that this graph is equivalent to the $v(x)$ graph. The students can use this graph to compare the distance that the car was pulled back to the distance during which the car sped up after it had been released (in our case the latter is about three times longer than the former). Using the work-energy principle, students can estimate the ratio of the maximum force exerted by the person on the car during the winding of the car and the maximum force exerted by the floor on the car while it was speeding up. From the $\Delta x(x)$ graph the students can conclude that the car's "engine" should employ some kind of a gear that makes more rotations per traveled distance during spring winding and fewer rotations per traveled distance when the car is speeding up. The students can test their explanations in a separate investigation by opening the car mechanism and studying how it works.

Why do we use LEDs to light our homes?

It is well known that LEDs are the most efficient light emitters on the market. Incandescent light bulbs were first improved as halogen bulbs and then replaced by fluorescent bulbs. Now LEDs are becoming more and more popular. But how much better are LEDs compared to the traditional incandescent light bulbs when we want to illuminate our house? The following activity will help our students answer this question quantitatively. The goal of this activity is to design a procedure for a quantitative comparison of performance of an LED and an incandescent light bulb as light sources from the energy perspective.[10]

Equipment: A modified white LED[11] (see instructions below for the modifications of the LED), a small incandescent light bulb,[12] two white Ping-Pong balls, two 3-V battery sources (make sure the batteries are fresh!), an ammeter, and a voltmeter. *Optional*: two variable dc voltage sources and a light sensor with spectral sensitivity similar to human eye.[13]

The students working in groups are given the following challenge: "Compare the efficiency of conversion of electric energy to light energy of an incandescent light bulb and a white LED." Give students the data about the normal operating voltage for both light sources (in our case about 3 V) and maximum allowed currents.

The students should realize that to compare a white LED and a light bulb correctly, they need to be able to control for electric power delivered by the voltage source and the region of the space (solid angle) into which the device emits light. It is easier to compare the light sources when both emit light equally in all directions (as point light sources). A small incandescent light bulb is a good approximation of a point light source, but most commercially available LEDs have a plastic body with a lens above the p-n junction, which directs most of the light they emit into a narrow cone. To eliminate this problem, cut off the lens and change the LED into a (semi-) point-light source[14] [see Fig. 4(a)].

When each light source is inserted into a white Ping-Pong ball, the emitted light is even more isotropic and the comparison of brightness is easier[15] [see Fig. 4(b)].

Procedure: The students might start by first connecting each light source separately to the 3-V voltage source. They will find out that the white LED emits light of bluish-white color and the light bulb emits light of reddish-white color. Although the difference in color shades might confuse them at the beginning, they will soon agree which light source appears brighter and how to make them look more equally bright (by adjusting the voltage if they are using a variable voltage source or by adding resistors in series to one of the light sources if they are using batteries). Then they can measure the current through the devices and the voltage across them and compare the power. They will immediately see that the power consumed by the LED-ball is much smaller. To make a quantitative comparison between the performance of these two light sources, students will need to objectively compare the intensities of both light sources in visible range. There are many ways to do it and we will leave to your students to figure out the procedure. Table II shows our measurements. Note that the light sensor can be used only as a device that helps determine when the light sources are equally bright, but it is essential to use the light sensor whose spectral sensitivity is similar to that of a human eye. The students don't need to know how the light sensor works or how the unit lux is defined, but they need to learn that the distance between the sensor and the source has to be the same in both cases.

The pattern is clearly visible from the table: the white LED consumes about 10 times less electric power while emitting

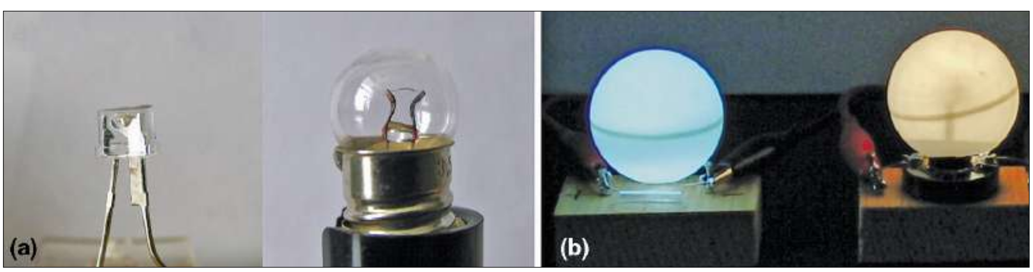

Fig. 4. A white LED and a light bulb: (a) The LED with the lens cut off and the light bulb as point-like sources; (b) white LED (left) and the light bulb inside Ping-Pong balls for comparison of brightness.

Table II. The measurements of current through, voltage across, electric power, and the brightness of the two light sources measured on the surfaces of the Ping-Pong balls. All measurements have about 10% uncertainty.

	V/V	*I* (mA)	*P* (mW)	*B* (lux)*
White LED	3.1	20	62	450
Inc. light bulb	3.6	190	680	450

* measured at the surface of the Ping-Pong balls.

light of approximately the same brightness as the incandescent light bulb. The students might come up with an explanation for the observed difference if they simply touch both devices—the LED feels cold and the bulb is warm.

Although the measurements described above are rather simple, there are a few things about LEDs that we would like to warn you about. Since the LEDs have very steep *I-V* characteristics, even a small change in voltage across the LED can result in significant change of current through the LED and consequently in the change of the LED brightness. There are two things that are important to note: 1) If the students connect a light bulb and an LED in parallel to the battery, they might observe a notable decrease in LED brightness compared to the case when they connect the LED alone. This is the result of decreased voltage across the loaded battery due to its internal resistance. The effect is small for fresh batteries, but it can be quite large for used ones. 2) When the students include an ammeter in the circuit in order to measure the current through the LED, they might observe a decrease in the LED's brightness. This is the result of the internal resistance of the ammeter. This effect is smaller if the ammeter is set to a larger range (for example, use 200 mA range instead of 20 mA).

Exploration of sunscreen lotions

Sunscreen lotions are a part of our lives, but we rarely think of them as materials for learning physics. In this activity students will devise a procedure to compare the transmittance[16] of different sunscreen lotions in different wavelength regions: from near infrared (near IR) to ultra-violet (UV).

To investigate the transmittance as a function of wavelength, one needs sources that emit light in a wide range of wavelengths. LEDs are perfect for this purpose as they are almost monochromatic sources of light and are available not only in different visible colors but also in UVA and in near IR wavelength region. The activity provides an excellent practice for controlling variables strategy in a meaningful context.

Equipment: different LEDs (near IR,[17] red, green, blue,[18] and UVA[19]), a light sensor,[20] microscope slides, different sunscreen lotions (we used two lotions, one with SPF[21] 20 and another with SPF 30), regular hand cream (no SPF), a variable dc voltage source, and lab stands. *Optional:* a UVA light sensor.[22]

The students working in groups are given the following challenge: "Devise a procedure to compare the fraction of the original light intensity transmitted through sunscreen lotion in different parts of the electromagnetic spectrum. Specifically, figure out how to identify the relevant parameters and find the ways to control for them."

Procedure: One way to approach the problem is to place a light source that emits light of one color and a light sensor[23] at a fixed distance and to measure the light sensor response to light emitted by the LED with and without a layer of sunscreen placed between the LED and the sensor. The ratio of these two measurements is transmittance. There are several important issues that students have to consider in order to get meaningful data:

- Any ambient light may spoil the measurements. It is necessary to check whether the ambient light affects sensor reading and if it does, they need to reduce it.
- The light sensor might not be equally sensitive to light emitted by all LEDs. Light sensors typically have poor sensitivity in the UVA region, thus students might need to use a UVA sensor for more accurate measurements with the UV LED.
- As any lotion might absorb light, not just sunscreen, it is useful to have a reference sample—a lotion or a cream that has no Sun protection factor (we used a regular hand cream).
- If the students are using microscope slides to put the sunscreen on, they need to think about their effects on measurements. They might take as a reference measurement the light sensor response when two clean microscope slides are placed between the source and the sensor (see the next item for the explanation for why two slides are needed).
- One of the most difficult issues is the control for the thickness of the samples. The students need to figure out how to make the thickness of all samples as equal as possible. One solution is to place about equal amount of lotions on one microscope slide [Fig. 5(a)] and then press the second slide on it to spread the lotions in a thin layer [Fig. 5(b)]. This method also allows the students to estimate the thickness of the lotion layer using a caliper (about 0.05 mm in our case). Remind students to make several (at least three) samples to be able to check how reproducible the measurements are and to estimate the uncertainty of the measured values.
- The students should discuss how the position of the sample relative to the light source and light sensor affect the measurements and where it is best to place the sample. Let them test their ideas experimentally. They will find out that it is best to place the sample right in front of the sensor and to place the light source not too close to it [Fig. 5(c)]. In this way light emitted by the source is more uniform at the position of the sample and the sensor captures most of the light scattered after it exits the sample. In addition they need to place the sample consistently in the same way for every measurement.

After collecting the data and calculating the transmittance, the students may represent their results with graphs such as the graph in Fig. 6.

Encourage the students to describe the main differences and similarities between the samples that can be inferred from the graphs. Here are some that are most important: hand cream's transmittance is the largest of all and does not vary much with wavelength; the transmittance of both sunscreen lotions decreases with decreasing wavelength; the sunscreen lotion with higher SPF has a smaller transmittance at all wavelengths covered in the measurement; the ratio of the transmittances of the sunscreen lotions at 400 nm roughly matches the inverse ratio of their SPF values; and the transmittance of all samples has peak value for green light.

The next step is to come up with several explanations/interpretations of the observed patterns. Here are some questions that may come up through the discussion of the graphs:

- How do sunscreen lotions work?
- What happens to light that does not get transmitted through the sample? Students may come up with two explanations: light that does not penetrate through the sample is absorbed or light is reflected. Students should note that based on their measurements it is impossible to decide which of these explanations is correct (in fact both mechanisms are used in sunscreen lotions[24]).
- Why is the green light transmitted best? We could not find an expert answer to this question. (We did not find an expert answer to this question, but leave it to you and your students to explore it further.)

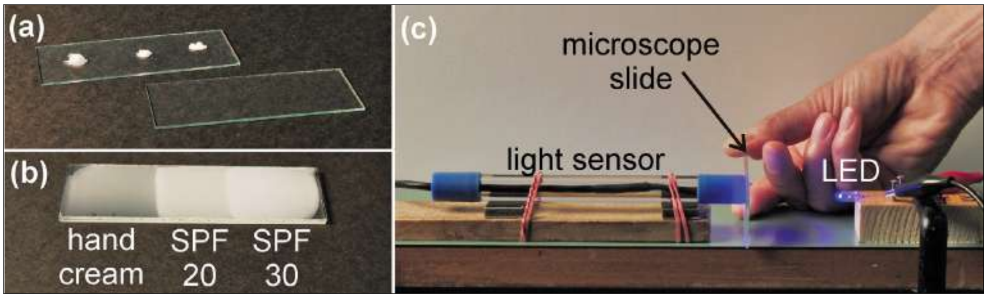

Fig. 5. (a and b) Preparation of the sample. (c) Setup for taking measurements. The LED is connected to a variable dc voltage source and the light sensor is connected to a data logger.

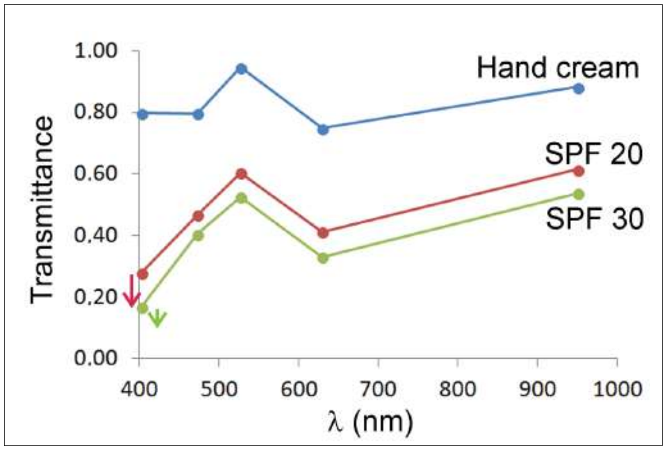

Fig. 6. Transmittance of regular hand cream and two sunscreen lotions [as shown in Fig. 5(b)] for light of different wavelengths. The thickness of the lotion layer was about 0.05 mm. The arrows indicate the shift of the measured points in UV region, if a UVA sensor is used instead of the light sensor. Transmittance was obtained as the ratio between the two sensor readings: the reading with the lotion and two glass slides and the reading with two glass slides only.

Electromagnetic induction

In this section we provide a sequence of activities that will lead students to revisit their understanding of EM induction, magnetic field lines around a disk magnet, and LEDs, and to apply this understanding to solve qualitative and quantitative problems. The students will also learn how to evaluate assumptions.

Prerequisite knowledge: changing magnetic field induces electric current in a coil; LEDs glow when the current through them is in one direction and start to glow when the voltage across them is about 2 V.

The activity is designed as an online lab where students either use online high-speed videos of the experiments or sequences of photos taken from such videos. However, if you have the equipment listed below, you can turn this activity into a lab. Note the important advantage of using LEDs as current indicators in these experiments compared to other methods for measuring currents. Having LEDs, the coil, and the magnet in the same video frame allows frame-by-frame observation of the presence/direction of the current through the coil, as well as motion/position of the magnet relative to the coil. All these data are needed if one wants to explain the observed phenomena.

Equipment: red and yellow LEDs,[25] a small coil with many turns (data for our coil: outer diameter 30 mm, inner diameter 10 mm, height 13 mm, 900 turns, made of 0.2-mm thick insulated copper wire, resistance 30 Ω), a strong neodymium magnet (data for our magnet: diameter 18 mm, height 7 mm, the maximum magnitude of the magnetic field B at the center of the coil when the magnet is placed on top of the coil is B_{max} = 0.1 T), a plastic CD cover, and a high-speed camera.[26]

All the experiments use the following setup. A small coil with many turns is glued to a half of a plastic cover box for a CD [Fig. 7(a)]. The coil is connected in parallel to red and yellow LEDs oriented in the opposite directions [see the circuit diagram in Fig. 7(b)] that are also fixed on the CD cover. Four legs (cut from a sponge) are glued on the bottom side of the plastic cover to keep the setup stable on the table.

Activity 1: Investigation of coil-magnet interaction

Observational experiment: A teacher (or a student) holds the magnet right above the coil, with the north pole of the magnet facing down. Then the experimenter quickly pushes the magnet down so that the magnet starts moving and finally stops by hitting the plastic cover. The procedure is recorded with a high-speed camera (see http://youtu.be/PxqcL5NMZ18). The video shows that the yellow LED flashes for a

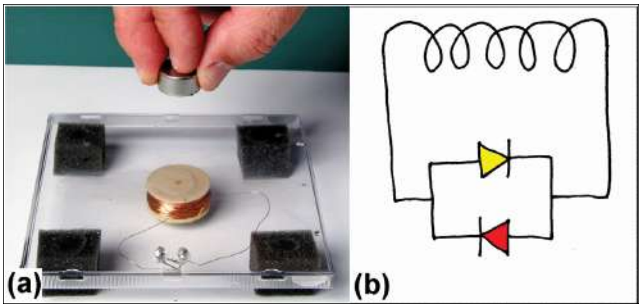

Fig. 7. Coil-magnet interaction: (a) Experimental setup and (b) circuit diagram.

moment, just before the magnet hits the plastic cover.

The students need to give a qualitative explanation of the observed experiment and then use the explanation to predict outcomes of the follow-up experiments in which orientation of the magnetic poles and/or direction of magnet motion are changed (for example, the magnet rests on the plastic cover right above the center of the coil, with the north pole of the magnet facing down; the experimenter lifts the magnet vertically upward as fast as possible; see video at http://youtu.be/-loaJXJoUAU). Note that the students do not predict what they will see in the observational experiment, but they do predict the outcomes of the follow-up experiments based on the ideas they proposed explaining the observational experiment.

Activity 2: Quantitative analysis/explanation

Students watch the high-speed video of the following experiment (see http://youtu.be/m-z9fOahfxU; for frame-by-frame analysis, download the video "Activity 2" in QuickTime format from http://www.fmf.uni-lj.si/~planinsic/PEMbG.htm).

The magnet rests on the left side of the plastic cover. The experimenter slides the magnet along the plastic cover from left to right so that it moves fast across the center of the coil. The video shows that when the magnet passes across the first half of the coil's cross section, the yellow LED flashes, and when it passes across the second half, the red LED flashes. Both LEDs are off while the magnet is moving above the center of the coil (see Fig. 8). When the magnet is moved right to left, the LEDs flash in the same order as before.

The students need to find out which pole of the magnet is facing down and to estimate the induced emf in the coil during this experiment. The data for the magnet and the coil are provided at the beginning of this activity; the turn-on voltages for LEDs are as follows: red V_{on} = 1.5 V, yellow V_{on} = 1.6 V. They also need to list any assumptions they made in their estimations.

Procedure: Combining the knowledge gained from the observational experiment in Activity 1, the students should be able to say which magnetic pole was facing down (north pole in our case). They should realize that when the magnet was moving across the edge of the coil (from either side), the magnetic flux through the coil first increased. When the magnet was above the center of the coil, the flux stayed constant, and when the magnet was moving across the other edge, the flux decreased.[27] The students need to acknowledge several assumptions in order to make the calculation:

- The coil can be approximated with a single layer coil with the diameter equal to the mean diameter of the actual coil (in our case 20 mm).
- The maximum value of the magnetic flux through the coil (when the magnet is placed right above the center of the coil) can be estimated from the given B_{max} = 0.1 T when the magnet is placed on top of the coil and the dimensions of the coil and the magnet (note that in our case the magnet's cross section is smaller than the cross section of the coil). In our case we get $\Phi_{m\_max} = 2.3\ 10^{-2}$ Wb.
- Magnetic flux through the coil changes from zero to maximal value in the time needed for the magnet to pass the edge of the coil. By analyzing the high-speed video, frame by frame, students find out that in our case this happens during 12 video frames, which is equal to 10 ms.

Using Faraday's law the students can now estimate value of emf (about 2.3 V in our case). They need to realize that this emf is large enough to make either of the LEDs glow.

Summary

This paper concludes our four-item series on using LEDs in teaching and learning physics. Here we showed examples of using LEDs as black boxes that help students study mechanical, electric, electromagnetic, and light phenomena. In addition to exploring the physics of the above phenomena, LEDs in this paper help students connect classroom investigations to the devices they use every day (light bulbs) and to materials that are not commonly associated with physics (sunscreens). In addition to the benefits of LEDs, this paper takes advantage of high-speed video recording, the field where our students are becoming so much more proficient than their teachers.

Although in this paper LEDs were used as black boxes or as indicators to investigate particular phenomena, each of the experiments can be used to investigate the physics of LEDs. For example, comparison of the efficiency of LEDs

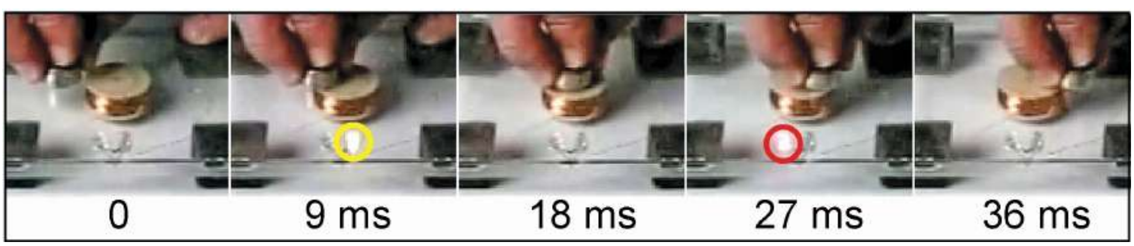

Fig. 8. Photos from the high-speed movie of the experiment where the experimenter moved the magnet across the coil from left to right. Note that the magnet's axis is parallel to the coil axis. Red and yellow circles indicate the color of the flashing LED.

and incandescent light bulbs can continue to the questions concerning the mechanisms behind light emission of both sources. The black box approach also offers opportunities for connections, comparisons, and contrasts of LEDs with other physics devices. For example, we used LED-based blinking bicycle lights to investigate motion. Why couldn't we use a blinking incandescent light bulb for the same purpose? When the students use the LED to study electromagnetic induction, the same question arises—why not use a light bulb?

To summarize, the LEDs are a hidden treasure for a physics teacher and we invite all of you to explore and utilize their properties to inspire your students.

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5. White and magenta LEDs employ blue LEDs covered with phosphor coating. Mixing blue light with the light emitted by the phosphor produces light that appears white or magenta. The activity in which students discover this mechanism is described in paper #3 from our series.
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8. Students should realize that the uncertainty of the period is smaller if exposure time is larger and that the cart need not move with constant speed in order to determine the period.
9. For energy bar charts, see Chapter 6 in Etkina, Gentile, and Van Heuvelen, *College Physics* (Pearson, 2014).
10. A comparison of efficency of light bulbs and LEDs was published before: James A. Einsporn and Andrew F. Zhou, "The 'Green Lab': Power consumption by commercial light bulbs," *Phys. Teach*. **49**, 365–367 (Sept. 2011). However, our approach is sufficiently different experimentally and pedagogically to be reported here.
11. We used OptoSupply white LED OSPW5111P.
12. We used a conventional flashlight bulb with the following data: 3.8 V, 0.3 A.
13. We used Vernier Light Sensor LS-BTA.
14. Using a hacksaw, carefully saw off the part of the LED body that makes the lens, then brush and polish the sawed surface using a fine water sandpaper and finally a white toothpaste until the surface looks clearly transparent [see also Gorazd Planinšič, "Color mixer for every student," *Phys. Teach.* **42**, 138–142 (March 2004)].
15. The Ping-Pong ball scatters light off the interior surface of the ball with equal intensity regardless of viewing direction, making the ball appear equally bright from all directions. However, note that some light is absorbed by the ball (i.e., light energy is converted into thermal energy).
16. Here we define transmittance as a fraction of the energy of incident light at a specified wavelength range that passes through a sample.
17. We used LD 271, which has the peak wavelength at 950 nm and can stand maximal forward current 130 mA.
18. We used Optosupply LEDs: red OSHR5111P, green OSPG5111P, and blue OSUB5111P.
19. The spectrum of our UV LED had the peak wavelength at 400 nm (visible range) and extended to about 380 nm in UV region. These are typical data for commonly available UV LEDs.
20. We used Vernier Light Sensor LS-BTA.
21. Sun protection factor (SPF) X means that using this sunscreen you can stay X times longer in the Sun to burn the same way as without the sunscreen.
22. We used Vernier UVA Sensor UVA-BTA.
23. Using the LED as a detector in this case would not give useful measurements because of the lens, which modifies the intensity of light that scatters on the sunscreen layer.
24. Doris Kimbrough, "Photochemistry of sunscreens," *J. Chem. Educ*. **74**, 51–53 (Jan. 1997).
25. We used Optosupply LEDs: red OSHR5111P and yellow OS5YKA5111P.
26. We made videos at 1200 frames per second using a Casio Exilim camera.
27. Some students may realize that due to the shape of the dipolar field of the magnet, there is also a small change of the magnetic flux through the coil (and consequential induced voltage) when the magnet is outside the coil and approaching the coil region. This is true and it is a sign of deeper understanding of the topic. However, the induced voltage in this case is far too small to turn on the LED, but it can be measured using an oscilloscope.

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