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Light-Emitting Diodes: Exploration of Underlying Physics

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Light-Emitting Diodes: Exploration of Underlying Physics

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This paper is the second in the series of LED-dedicated papers that have a goal to systematically investigate the use of LEDs in a general physics course. The first paper, published in the February 2014 issue, provided an overview of the course units where LEDs can be used and suggested three different ways of utilizing LEDs in an introductory physics course: (I) as "black boxes" that allow students to study certain properties of a system of interest, (II) as physical systems that allow students to learn a large amount of physics not usually encountered in a typical introductory course, and (III) as non-traditional devices that allow students to construct concepts that are traditionally a part of a general physics course.[1] The present paper focuses on LED physics and how students can learn this physics through a guided inquiry approach (section II in the classification above). Specifically, we will: (1) introduce the Investigative Science Learning Environment (ISLE) approach,[2] which we will use as a framework for student learning of the physics of the LEDs; (2) discuss the most important aspects of LED physics that students can learn in a general physics course; and (3) describe in detail classroom activities that follow the ISLE approach which will lead the students to the "discovery" of LED physics described in (2).

LED physics in an introductory physics course (high school honors, AP, or college physics)

There are several important ideas related to the physics of LEDs that students can learn at an introductory level. The prerequisite for the understanding of basic LED physics is the knowledge of electric field and the motion of charged particles in electric fields, dc circuits, photons, and photoelectric effect. In addition, it would be helpful if students have a qualitative understanding of semiconductors.

What do we want the students to understand about LEDs at the end of this sequence of activities?

Complete LED physics is rich and complex. It is well beyond the scope of a high school or introductory college physics course. The purpose of this section of the paper is not to delve into the physics details of the LED operation but to summarize what we hope the students will know if they work through the sequences of activities described in this paper.

a) An LED, like any diode, is an electronic element with an asymmetrical *I-V* curve (see Fig. 3). This means that the dc resistance of an intact LED is much larger for the current in one direction than in the opposite direction (assuming that the voltage is larger than turn-on voltage and smaller than the breakdown voltage). The asymmetrical *I-V* curve is the result of the internal structure of an LED.

b) The main part of an LED consists of two layers of different semiconductors (p-n junction). The top layer is very thin and can emit light when the anode of the LED is connected to a higher potential than the cathode. Light emitted by an LED is the result of electron and hole recombination between well-defined energy bands and not the result of radiation due to high temperature of the p-n junction. Color LEDs emit (relatively narrow) band spectra that can be explained in terms of the energy band structure. A visible glow of an LED starts at certain turn-on voltage that is typically between 1 V and 3 V. The turn-on voltage of an LED is related to the energy of the photons emitted by the LED. LEDs convert electrical energy into light energy, but they can also convert light energy into electric energy, just like solar cells do.[3]

The ISLE cycle

The Investigative Science Learning Environment (ISLE)[2] is an educational framework that can guide the design of instruction and student learning. ISLE engages students in the processes that mirror scientific practice to help them learn physics. Specifically, students start learning a new concept by observing a few very simple experiments (called "observational experiments"). They then identify patterns, develop multiple explanations for those patterns, and, finally, test the explanations (with the purpose of ruling them out). The testing involves designing a new experiment (called a "testing experiment"), the outcome of which they can predict using the

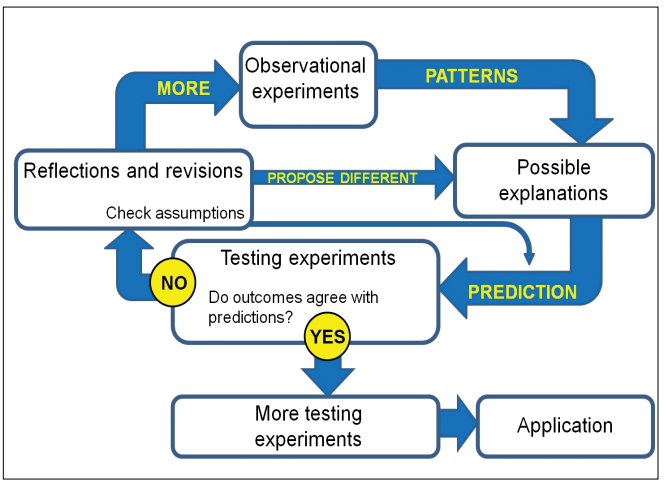

Fig. 1. Elements and the flow of the ISLE cycle.

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explanation. After they conduct the experiment and compare the predictions to the outcomes of the testing experiment, they make a judgment about the explanation (see Fig. 1).

This purposeful testing of proposed explanations using hypothetico-deductive reasoning is one of the most important features of ISLE, which in turn directly reflects common reasoning in science and, in particular, in experimental physics. (Sometimes when it is impossible for the students to perform the experiments themselves, they can find the descriptions of similar experiments done by other people.) Often an unexpected outcome of a testing experiment turns this testing experiment into an observational experiment for a new cycle. The ISLE cycle can serve as a guide for designing whole units and individual lessons. For every idea that an instructor wishes his or her students to learn, the instructor needs to find simple experiments that students can observe to conceive this idea, and the experiments whose outcomes students should be able to predict using their newly invented idea, as well as the experiments that students can use to apply this new idea in combination with other ideas. In this paper we will use the ISLE cycle as a framework through which the students can learn LED-related concepts discussed earlier.

Helping students master LED physics via the ISLE cycle

In this section we will describe ISLE cycles (starting from simple observational experiments to pattern identification, explanations, testing experiments, and application experiments) that can be used to help students master LED physics concepts listed in the previous section. For each cycle we describe the concept that we wish the students to construct, necessary equipment, the sequence of pedagogical moves that match the elements of the ISLE cycle, and what students will do in the classroom. We also provide photos of the experimental setup and outcomes where appropriate, as well as tables of collected data for your convenience.

It is important to discuss the equipment. Make sure you are using clear plastic LEDs (not LEDs that are made of colored plastic). Also make sure you do not exceed the forward dc current through an LED recommended by the manufacturer (typically from about 20 mA to 70 mA) or maximum (breakdown) reverse voltage (typically about 5 V to 30 V). In most of our experiments we are using a 3-V voltage source made from two 1.5-V batteries in series.

How to light an LED

The main concept that students should construct in this cycle is the idea that an LED is a unidirectional current device.

Equipment: For each group, the students will need one red LED, a 3-V source, a 100-Ω resistor, wires, and a voltmeter. Leave the length of the LED leads as they are, so students can see that one lead is longer than the other.

Students work in groups of three to perform the following activities:

1. ***Observational experiments.*** Obtain an LED, a 3-V voltage source, a 100-Ω resistor, and wires. Connect all the elements in series. The goal is to light an LED using different circuit combinations. Investigate how the order and orientation of the elements affect the outcome.
2. ***Patterns and explanations.*** Describe the patterns that you found. If you can provide an explanation, please do so.
3. ***Testing experiments.*** Propose experiments to test your explanations. Use the explanations to make predictions of the outcomes of these experiments before you perform them and then compare the actual outcomes to the predictions.

Students work in groups to light an LED; they discover that the LED lights only when its long lead connects to the positive terminal of the battery and the short one to the negative terminal, and that the order of elements in the circuit does not matter. They might propose at least two explanations. E1: the LED has a finite resistance when connected in one direction and an infinite (or very large) resistance when connected in the opposite direction; E2: the resistance is the same in both directions, but the LED only glows when the current through it is in a particular direction. To test these two explanations, students might suggest using a voltmeter to measure the voltage across the resistor for different orientations of the LED.

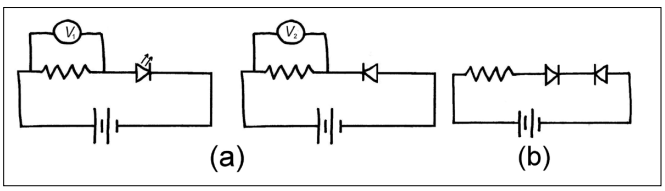

Fig. 2. Electric circuits and predictions for experiments that test explanations E1 and E2. (a) If E1 is correct, then we should observe that $V_2 \approx 0$; if E2 is correct, we should observe that $V_1 \approx V_2 \neq 0$. (b) If E1 is correct, LEDs should not glow; if E2 is correct, the one LED should glow.

Figure 2(a) shows the circuits and the prediction made for each based on the explanations E1 and E2. The experiments show that $V_2 = 0$. Thus, based on the outcomes of the experiments, students are led to reject explanation E2 and do not reject E1. Another experiment that students might suggest is to take two LEDs and connect them in series in opposite orientations [see Fig. 2(b)]. Explanation E1 predicts that none will glow, explanation E2 predicts that one of them will glow. When we conduct the experiment, we observe that none of the LEDs glow. The outcome of the experiment is again consistent with the explanation E1. Thus it survives the experimental tests and is kept.

Notes: 1) We used bright red LEDs that are rated for the forward current of 70 mA.[4] Such LEDs will not burn even if the LED is connected for a short time directly to the 3-V battery, without the resistor. 2) If students are concerned that no glow in the experiment shown in Fig. 2(b) is due to a small battery voltage, you can use a 9-V battery instead and there will still be no glow.

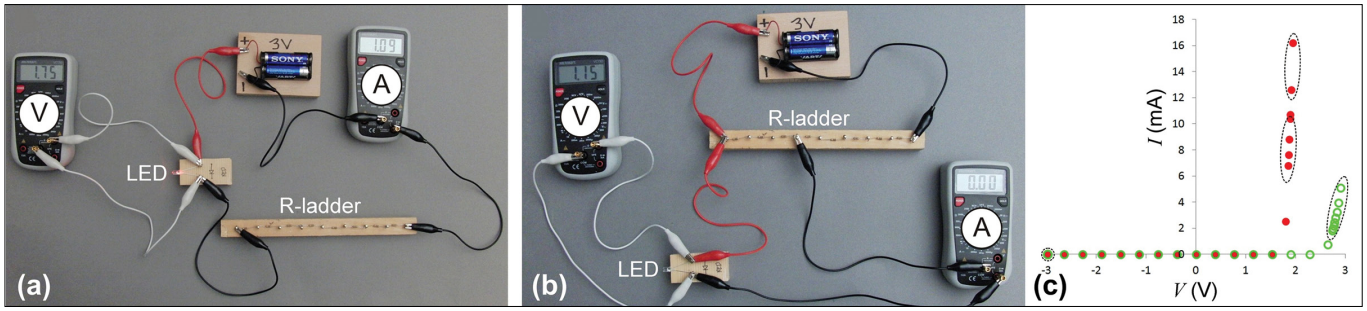

Fig. 3. Obtaining the *I-V* curve for an LED. Measure the voltage across and current through the LED (a) by connecting resistors in series with the LED and (b) by using a potential divider. (c) The *I-V* curve for a red (filled circles) and a green (empty circles) LED. Points that can be measured with the R-ladder in series are circled with dotted line. The rest of the points were measured using potential divider.

How are the current through an LED and voltage across it related?

The students now are convinced that the resistance of an LED is much larger in one direction than in the other direction. Next we want them to learn that at a particular voltage in the positive direction the resistance of the LED starts to decrease rapidly with increasing current, and for any voltage lower than that, and for any voltage in the opposite direction the resistance is very large (about 10 MΩ). We also want them to learn the difference between the *I-V* curve for a commercial resistor, an incandescent light bulb (we assume they know these from previous lessons), and an LED.

Equipment: A red and green LED, a 3-V battery, a resistor ladder (R-ladder; we used eight 22-Ω resistors connected in series), wires, ammeter, voltmeter, a 9-V ac voltage transformer, and a 300-Ω resistor.

Students work in groups of three to perform the following activities:

1. Draw a current-versus-voltage graph for a commercial resistor; draw a current-versus-voltage graph for an incandescent light bulb. Such graphs are called *I-V* curves.
2. ***Observational experiments.*** Using the following equipment (red LED, R-ladder, wires, 3-V battery, ammeter, voltmeter), design an experiment (or set of experiments) in which you can vary voltage across the LED[5] in the range of -3 to +3 V. Then use this experiment to investigate how the current through the LED depends on the voltage across it. Make measurements and draw the *I-V* curve for the LED.
3. ***Patterns.*** Describe the patterns in the graph that you found. What can you infer about the resistance of the LED from the graph?
4. ***Application experiment.*** Use what you have learned about the LED's resistance to explain the following experiment: You connect the LED and a 300-Ω resistor to a 9-V ac transformer in series. Observe what happens when you move the LED back and forth across about 0.5-m distance in a dark room and explain your observation.[6]
5. ***Application experiment.*** Repeat the investigations you performed in #2 but this time use a green LED. What can you infer from the *I-V* curves of the green and red LEDs?

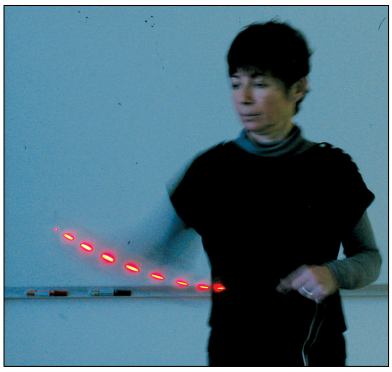

Fig. 4. Photo of light traces produced by a moving LED that is connected to an ac transformer.

The students will probably first try to vary the voltage across the LED by connecting the R-ladder in series with the LED [See Fig. 3(a)].[7] They will observe that the LED glows dimmer and dimmer as they increase the resistance, but it never stops glowing. The measurements of voltage across the LED show that using this method, it is impossible to achieve voltage across a red LED lower than about 1.3 V even if we use very large resistors (as the lower the current the larger the resistance of the LED, one cannot make the product $R_{LED}I$ too small). In order to measure the low voltage points on the curves, the students either need to invent a potential divider themselves or the instructor needs to explain to them how to do it [Fig. 3(b)]. At the end of this part of the activity, students should devise a graph [Fig. 3(c)].

The students can infer from the shape of the graph in Fig. 3(c) that the LED has a variable resistance. They can apply this inference to explain the experiment in part 4 in which they observe traces of light along the path of the LED (Fig. 4). The last experiment with the green LED allows the students to come up with the idea that the color of the LED and the opening voltage (approximate potential difference across the LED when we first observe it glow) are related.

How does an LED produce light?

So far the students have observed the unidirectional electric properties of an LED and the asymmetrical nature of its *I-V* curve. However, they have not investigated the mechanism by which an LED produces light. The goals of this cycle

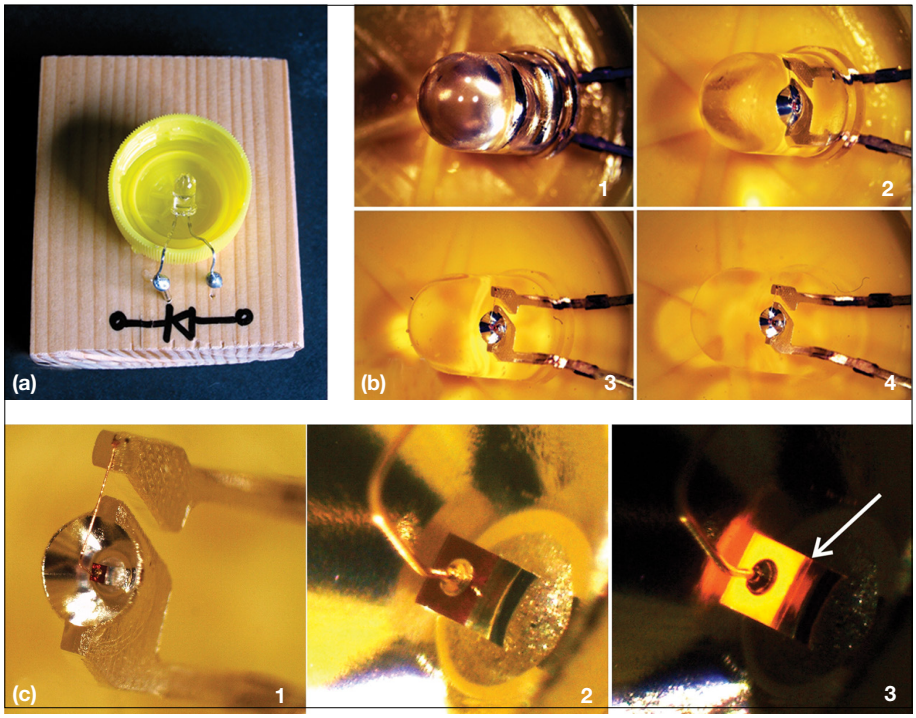

Fig. 5. An LED under a microscope; (a) the setup; (b) The LED, slightly magnified, as seen in air (1), water (2), glycerin (3), and silicon oil (4); (c) closer view of a yellow LED's p-n junction sitting in the metal reflector when it is switched off (left – medium magnification and middle – large magnification) and when the current through the LED is about 0.2 mA (right – also large magnification). The arrow points to the glowing p layer. The photos were obtained using the Leica EZ4HD school microscope, but you can obtain similar photos using any handheld USB microscope.

are to help students learn (1) that the element of an LED that emits light consists of two layers, and that the top layer of the element is very thin and it emits light when the LED is properly connected to a battery, and (2) that emitted light is the result of changes in the electric energy of interaction between the electrons and the lattice inside the semiconductor (photons are produced when free electrons recombine with holes). As the light-emitting part of the LED cannot be seen clearly due to its being surrounded by the layer of plastic, one of the main difficulties of this investigation is to figure out how to eliminate the optical distortions due to plastic.

Equipment: clear plastic LED [use the type of LED with a single wire connecting at the top layer of the p-n junction, see Fig. 5(c)], microscope, water, silicon oil, glycerin, 3-V battery, R-ladder, and connecting wires.

Students work in groups performing the following activities:

1. ***Observational experiment.*** Observe a non-glowing LED under a microscope (students will not be able to see much because of the plastic cover).
2. ***Explanation.*** Why is the image highly distorted?
3. ***Testing experiment.*** Design an experiment to test an explanation of why the image is distorted and come up with a way to see inside the plastic dome clearly.
4. ***Observational experiment.*** Observe the inside of the LED when it is glowing (after "canceling out" the plastic dome effect).
5. ***Explanation.*** What is the mechanism of the glow? Consider a possible explanation: there is a metal inside and it gets very hot when there is current through it.
6. ***Testing experiment.*** Develop a method to rule out the "hot metal" explanation using existing data.

Refraction on the transparent plastic prevents us from seeing what is inside the plastic dome. The index of refraction of plastic is about 1.5–1.6. One way to reduce the distortion is to submerge the LED in a fluid with a similar index of refraction (index matching). See the setup for the experiment in Fig. 5(a). We found that the best liquid is silicon oil [Fig. 5(b)], but Johnson's® Baby Oil also works reasonably well. The students can submerge the LED in different fluids and observe it under a microscope until the small part of the LED inside the plastic becomes clearly visible. Our students typically try air (the natural environment), water, glycerin, and then silicon oil. Once the image is clear (in silicon oil), the students connect the LED to a battery and observe it while it is glowing (while it is still submerged in the silicon oil). We ask them to draw a picture of the interior structure of the LED. They need to focus on the thin top glowing layer and the bottom layer that is thicker and the electrical connections leading to both layers [Fig. 5(c)].

The next step for the students is to figure out the mechanism behind the glow. As the students are familiar with incandescent bulbs, they might offer a "hot metal" explanation. However, they should be able to rule it out using their knowledge of the resistance of the LED, which decreases with the current as opposed to the bulb, whose resistance increases. There are many other reasons that the students should list for why these materials could not be two metals. If students are unfamiliar with the semiconductors, here is the point when you can tell them that inside the plastic cover there is the junction of two differently doped semiconductors—a p-n junction. Use your own judgment and the knowledge of the level of your students to decide how much to tell here about the junction and the semiconductor band structure. The key idea that they need to understand is that the photons of light emitted by the LED are produced when the electric energy of the electron-crystal system decreases (often this is explained

as a recombination of electrons and holes, but we think that the general energy-based explanation is sufficient). Use references[8] for help. Students should also question why LEDs are so small. The top layer of the p-n junction should be very thin so the produced photons can come out of the material. Light is produced at the p-n junction and is emitted by the whole volume of the top layer.

LED and energy conversions

Now the students know that inside an LED there is a p-n junction and understand the mechanism of the production of light by the p-n junction. The next step is to immerse themselves into the energy aspect of LEDs. Specifically we want them to discover that LEDs not only convert electrical energy into light energy, but they also can convert light energy into electric energy. It will be helpful if prior to this lesson students learn about the photoelectric effect and how a solar cell converts light energy into electric energy. You can assign them to research solar cells on their own.

Equipment: Two red LEDs, two green LEDs, voltmeter, various resistors, wires, and battery. We recommend using LEDs that are made by the same manufacturer, and have the same power angle and approximately the same nominal luminous intensity.[9]

1. ***Observational experiment.*** In a bright room, connect an LED to a voltmeter (no battery) and observe the reading on the voltmeter.
2. ***Explanation.*** Devise an explanation for a non-zero reading of the voltmeter although it is not connected to a battery.
3. ***Testing experiment.*** Design experiment/experiments to test your explanations.
4. ***Application experiment.*** Use the explanation that you have not ruled out in step 3 and what you know about red and green LEDs to investigate how the color of light and the intensity of light incident on an LED (detector) affects the voltage across the LED. Investigate what happens when you shine red LED (source) on a red LED (detector), green LED on a red LED, red LED on a green LED, and green LED on a green LED (in every case the LED on which the light is shining is connected to a voltmeter). Conduct the experiments and compare the outcome to the prediction. Reconcile the discrepancies.

In step 1 students observe that when a red LED is connected to a voltmeter (assuming that the lights are on in the room or there is natural light), the voltmeter shows a non-zero reading. A possible explanation is that an LED now works as a solar cell. To test this explanation, they can change the brightness of light incident on the LED and predict that if the LED works as a solar cell, the voltage across it should change (step 3). They will observe that increasing the brightness of light

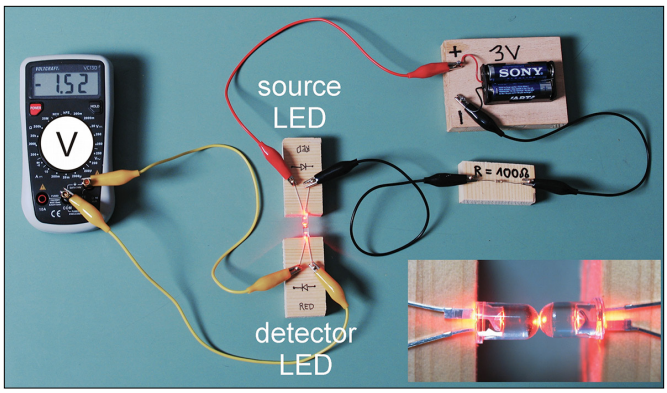

Fig. 6. Experimental setup for investigating the dependence of the voltage across the LED on the color of incident light. By moving the source and detector LED with respect to each other, one should find the position for the maximum voltage reading. The inset shows the close view of the LEDs during the measurement.

Table I. Interactions of a red and a green LED. In the experiment we used LEDs with the same nominal brightness values. In all cases the current through the emitting LED was set to the dc forward current recommended by the LED manufacturer (in our case 70 mA).

		Detector LED	
		Red	Green
Source LED	Red	1.60 V	0 V
	Green	1.52 V	1.78 V

incident on the LED leads to the increase of the voltage and decreasing the brightness leads to the decrease in the voltage. Now that the students know that an LED behaves like a solar cell, they can investigate the effects of the color of the source LED on the voltage across the detector LED using a simple setup (Fig. 6). In order to investigate the effect of the color alone, one needs to keep the brightness of the source LED constant. In practice this requires advanced measurements, but for our purpose it is enough to keep the current through the source LEDs equal to the dc forward current recommended by the LED manufacturer (using an appropriate resistor in series with each LED). Depending on the conceptual understanding of energy bands of your students, you can ask them to explain the interaction of green and red LEDs or leave the discussion at the level of phenomena. Table I presents the results of those interactions.

From the data similar to that presented in Table I, the students can infer that the detector LED has the largest voltage across it when it is illuminated by light of the same color that it produces when it is attached to a battery. Note that in this activity we are not interested in the ability of an LED to drive current through a load but merely in the ability to create potential difference, which is also a good estimate for the characteristic energy associated with the p-n junction.

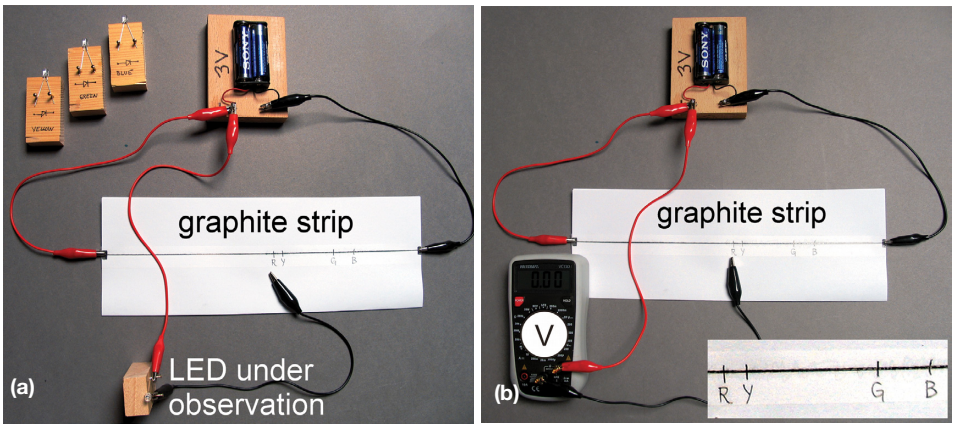

Fig. 7. Setup for measuring the turn-on voltages of color LEDs. (a) Finding the position on the graphite strip when LED starts to glow, (b) measuring the voltages at marked positions. Inset shows the detail of the graphite strip with marked positions for red, yellow, green, and blue LED.

Spectra and quantum optics

By now the students probably noticed that there is a pattern between the turn-on voltages and LED color. Now they will investigate this pattern deeper.

Equipment: red, yellow, green, and blue LEDs, battery, resistors, graphite strip, and spectroscope.

1. ***Observational experiment.*** Observe glowing red, yellow, green and blue LEDs with a spectroscope.[10] Describe the patterns in your observations.
2. ***Explanation.*** Explain the similarities and the differences in the spectra.
3. ***Testing experiments.*** Predict the relative values of turn-on voltages (a turn-on voltage is the smallest voltage across the LED when a naked eye can see it glow) for the LEDs of different colors. Use your knowledge of electric energy and photon energy to make the prediction. After you make the prediction, conduct the measurements in the following way. Measure the turn-on voltage for each LED using the potential divider circuit [see Fig. 3(b)] only this time use a graphite strip instead of the R-ladder.[11] Slide a free wire that is connected to the LED [black wire in Fig. 7(a)] along the graphite strip while observing the LED. Work in a darkened room. First mark the position on the graphite strip at which you see each LED start glowing [Fig. 7(a)] and then measure the corresponding voltages [Fig. 7(b)]. To make your own graphite strip, draw a 2-mm thick line with a 6B pencil on a piece of Scotch tape that you previously taped on a sheet of paper. The resistance of the whole strip should be about 1 to 2 MΩ.

Table II. Typical measurements of the peak wavelengths and turn-on voltages for the red, yellow, green, and blue LED. The peak wavelength was measured by the Vernier spectrometer.

	Peak wavelength	Turn-on voltage
Red	629 nm	1.51 V
Yellow	590 nm	1.57 V
Green	527 nm	2.03 V
Blue	473 nm	2.23 V

The cycle starts with the students observing spectra of red, yellow, green, and blue LEDs. They should explain the similarities in the spectra using the energy bands model from the section "How does an LED produce light?" They already know that the color of the emitted light and the energy of the emitted photons are related, which, in turn, is related to the turn-on voltage of the LED (see Table II for typical values). Here you need to remind them of this knowledge and lead them to connect it to the frequency of the emitted light. Using the values in Table II, readers can verify that the work done by electric field on an electron when moving it across the turn-on potential difference ($V_{\text{turn-on}}e$) is systematically smaller than the energy of the emitted photons with the peak wavelengths ($E = hc/\lambda$). One reason for this is that the LEDs have band spectra and the peak value is somewhere in the middle of this band. Other reasons why the product of $V_{\text{turn-on}}e$ differs from the value of E are discussed in Ref. 12. However, the difference between $V_{\text{turn-on}}e$ and E is

approximately the same for the LEDs from the same producer when the current is smaller than 0.1 mA.

Summary

The goal of this paper was to help the reader learn how one can engage students in guided inquiry while learning the most fundamental concepts of LED physics. We described the materials to use in the activities, questions to pose for the students, and possible scenarios of student participation. We hope that the provided information is sufficient for the reader to implement these activities in the classroom.

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3. LEDs that emit light of a continuous spectrum (such as white or pink LED) utilize a secondary mechanism such as fluorescence in addition to the one described. The role of the fluorescent paint is to convert higher energy photons emitted by the p-n junction into the photons with a spread of lower energies.
4. We used LEDs from OptoSupply with power angle 15° and luminous intensity 50 cd.
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9. See Ref. 4.
10. See also tutorial "The Light Emitting Diode," http://web.phys.ksu.edu/vqm/VQMNextGen/App&ModelBuilding/led.pdf and "Spectroscopy Lab Suite," http://web.phys.ksu.edu/vqm/software/online/vqm/ at Visual Quantum Mechanics website.
11. Alternatively you can use your own body as a large resistor in series with an LED and the battery. You can adjust the series resistance (and therefore the brightness of an LED) by varying the pressure exerted by your fingers on the connecting wires.
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