Light-Emitting Diodes: A Hidden Treasure

Gorazd Planinši and Eugenia Etkina

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Light-Emitting Diodes: A Hidden Treasure

Gorazd Planinšič, University of Ljubljana
Eugenia Etkina, Rutgers, The State University of New Jersey

LEDs, or light-emitting diodes, are cheap, easy to purchase, and thus commonly used in physics instruction as indicators of electric current or as sources of light (Fig. 1). In our opinion LEDs represent a unique piece of equipment that can be used to collect experimental evidence, and construct and test new ideas in almost every unit of a general physics course (and in many advanced courses) either (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 an astonishing amount of physics that they usually do not encounter in a regular introductory physics course, and (III) as non-traditional devices that allow students to construct concepts that are traditionally a part of a general physics course.

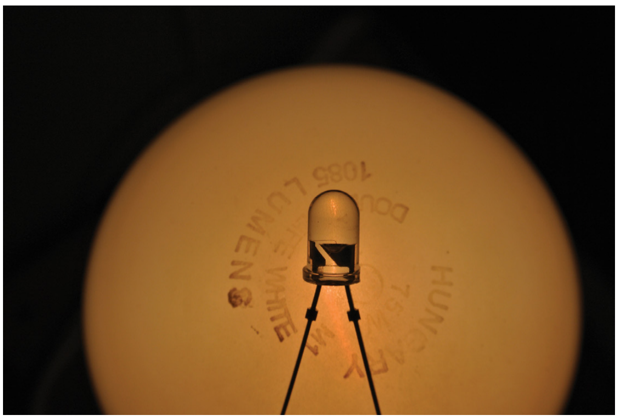

Fig. 1. The LED is eclipsing the incandescent bulb in many ways.

In this paper, we provide a classification of different uses of LEDs in a physics classroom according to the three directions noted above, including a brief description of relevant experiments (some already published and some new) and the questions that students or teachers might pose or that students would be able to answer after conducting these experiments and analyzing data. Future articles will describe experiments and reasoning related to the physics behind the LEDs that is accessible for high school and introductory college students. (We found that different aspects of the functioning of an LED can be used to help students learn concepts in at least 11 curriculum units of the general physics course, where an example of a unit is energy, or geometrical optics, or dc circuits.) In addition, future articles will describe how the physics inherent in the functioning of an LED can help students learn new physics (in nine curriculum units), and how an LED can be used as a black box device (in 12 units). The goal of the series of papers is to create a systematic library of LED-based materials for all curriculum topics and provide readers with the description of experiments and pedagogical treatment that would help their students construct, test, and apply physics concepts and mathematical relations.

History: science and education

A light-emitting diode was invented by Russian technician Oleg Losev in 1927.[1] Nick Holonyak at General Electric developed the first practical visible-spectrum (red) LED in 1962. Soon after that, LEDs became available as electronic components and thus they gained the attention of the physics teaching community. The first paper on LEDs in *The Physics Teacher* appeared in 1974. In *TPT* alone, more than 20 papers dedicated to teaching with LEDs have been published (in this number we did not include the papers that employ LEDs simply as light indicators).

Awareness that LEDs can be used in teaching several introductory physics topics emerged as early as in 1991.[2] Jewett's article describes a number of activities with LEDs in the areas of electricity, optics, and modern physics. Since then many things have changed: technological inventions and improvements resulted in much brighter LEDs, more efficient LEDs, LEDs that cover a wide range of wavelengths including blue and UV, LEDs that emit white or pink light, etc. (see Fig. 2). At the same time important changes occurred in our knowledge of how students learn and, consequently, in how we teach. We have evidence that students' active participation in experiments (not mere observation) make the use of experiments productive in education, and we have also developed general frameworks for the fuller use of experiments in physics instruction.[3] Both technological advances and educational innovations inspired our series of articles about LEDs described above.

Using LEDs in a general physics course

The goal of this section is to provide a reader with a systematic review of the existing LED-related ideas and to show how LEDs can be used in almost every unit of a physics course (such as kinematics, energy, electric field, etc.). In the subsections we briefly describe experiments using LEDs in different units and questions that teachers and students might pose and answer while observing the experiments, collecting data, and analyzing and interpreting data (commonly the questions are posed after the students observe the experiments; in a few cases where the question/task comes before the experiment, we note this change). There are 13 subsections, one for each of the relevant units. In each subsection there is a table that has three rows demonstrating how to use LEDs in three different ways.

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- ***Row I*** treats LEDs as black box devices used to help students make a connection to relevant physical phenomena.
- ***Row II*** helps students understand unit-relevant aspects of physics (that students investigate in row I) that explain how an LED works. Most of the experiments in row II are qualitative and focus on the conceptual aspects of LED physics.
- ***Row III*** focuses on the new physics that students can develop after they understand LED physics in row II. Experiments and questions in row III ask students to collect more data about the same phenomenon to investigate it at a quantitative level.

Basically, in most cases each subsequent row goes deeper and deeper into the same phenomenon. Row I shows the fact of the existence of a phenomenon, row II goes into a description and a conceptual explanation, and row III calls for a more rigorous description and a deeper explanation. Note that not every table has all three rows; the presence of a particular row depends on the unit.

In this paper we provide an outline of the experiments to be performed; the reader may need to consult the references mentioned for details about how to conduct the specific experiments that were proposed before. Further details regarding the original experiments suggested by the authors of this paper and details of the pedagogical treatment will be included in the subsequent articles.

Here, we provide an overview and some questions that teachers or students might pose or should be encouraged to pose about the experiments. In most cases the questions come after the experiment; blue arrows [⬅] in the tables indicate the cases when the question comes before the experiment. Double asterisks [**] indicate cases that are (to our best knowledge) new.

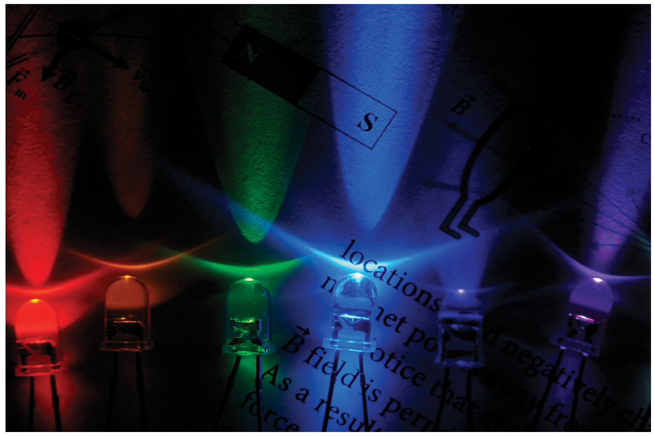

Fig. 2. A rainbow of LEDs: red, yellow, green, blue, ultraviolet, pink, and white.

Summary

We invite readers to try the experiments and assemble a set of equipment that can be used in most of the experiments. Creating containers with all of the materials for groups of students is the most helpful way to keep track of everything that one can do with LEDs. Once students start working with the LEDs, they will generate their own questions and design their own experiments. In future papers we will elaborate on the specific experiments and their pedagogical treatment consistent with inquiry-based instruction. We will provide instructional sequences with supporting questions that will allow your students to observe a phenomenon, to analyze it and propose multiple explanations for the mechanism, and finally test those explanations in new experiments.[41]

Unit 1. *Table I. Kinematics*

	Experiments	Questions that teachers/students should pose
I	Use long-exposure photos of moving objects that are illuminated by or carry periodically flashing LEDs (such as a bicycle light).[4]	What type of motion did the object undergo? Represent the motion with a motion diagram. How is the motion diagram related to real motion? If the frequency of flashing and the scale of the picture are known, what are the speed and/or acceleration of the moving object?

Unit 2. *Table II. Energy*

	Experiments	Questions
I	Connect an incandescent light bulb to a battery and observe it glow. Repeat with an LED to a battery and a resistor and observe it glow.[5]	Describe macroscopically the energy flow and energy conversions in these experiments. Compare and contrast these processes for the two cases.
II	Connect an LED to a battery and a resistor and observe it glow. Then take the LED alone and connect it to a voltmeter. Shine white light on it and observe a non-zero voltmeter reading.[6]	Explain microscopically the energy flow and energy conversions in these experiments. Compare and contrast these processes for the two cases.
III	Connect an LED alone to a voltmeter (use red, green, or blue LED). Shine different color lights on the LED and observe voltmeter reading. The LED produces highest voltage when it is illuminated by light of its characteristic wavelength. This potential difference can even power another LED. **	What are the patterns in your observations? What general rule relating the voltage produced by an LED and the intensity and color of light incident on the LED can you suggest?

Unit 3. *Table III. Electric field*

	Experiments	Questions
I	Put an LED into water between two conductive strips connected to a battery spreading its legs in a horizontal plane. Observe the LED glow when at certain orientations and not glow in others. Use the LED as a visual indicator of the component of electric field in electrolytes.[7]	Draw electric field lines for the electric field between the conductive strips that are connected to a battery. What happens to the direction of the field lines when the polarity of the battery is reversed?
II	(Same setup as I above) Investigate the dependence of LED intensity on separation and length of legs.[7]	Why does the brightness of an LED submerged in the water depend on the separation between the end points of its terminals?

Unit 4. *Table IV. DC circuits*

	Experiments	Questions
I	Use an LED as a visual indicator of small currents (for example, current produced by a lemon cell).[8]	What are the conditions necessary for electric current to be in a circuit?
II	a) Use an LED, a variable voltage source, and various resistors /potential dividers to measure LED's *I-V* characteristic.[9] b) Measure *I-V* characteristic of parallel/series LEDs.**	a) What *I-V* curve characterizes an LED? Is it an ohmic or a non-ohmic device? How do you know? b) What *I-V* curve characterizes an arrangement of parallel/series LEDs?
III	a) Connect an LED to resistor and illuminate the LED with white light. Measure potential difference and current produced by an LED for different load resistors. ** b) Build two electric circuits to measure voltage across and current through a white LED and an incandescent light bulb.	a) How is the LED illuminated by constant source of light different from a regular battery in terms of potential difference across it and current through it? b) Design an experiment to compare electric power of a white LED and of an incandescent light bulb that appear equally bright.

Unit 5. *Table V. Capacitors*

	Experiments	Questions
II	Charge a capacitor and discharge it through a resistor. Measure time dependence of voltage across the capacitor. Then repeat the experiment, this time discharging the capacitor through an LED.**	How is the discharge of the capacitor through the LED different than the discharge through the resistor? Explain the reasons for these differences. Based on your explanations predict how the voltage across the capacitor will change if you connect it to the LED and resistor in series or in parallel.

Unit 6. *Table VI. AC circuits*

	Experiments	Questions
II	Connect an LED and a resistor in series to a low-voltage ac source. Use an oscilloscope to compare electric current through the LED (by measuring the voltage across the resistor) and the voltage across the source. Repeat measurements with different color LEDs.	Explain observed time dependence of current through an LED and reconcile it with the *I-V* curve of an LED.
III	a) Connect an LED and a resistor in series to a low-voltage ac source (students should not know what kind of source it is). Move the LED back and forth and use it as a visual indicator of ac current. Repeat the experiment, only this time use paired LEDs (two LEDs in parallel but connected in opposite directions) instead of a single LED.[10,22] b) Connect an LED (or two paired LEDs) and a resistor in series and use the LED as a visual indicator of the direction of electric current (for investigating piezoelectric effect, e/m induction, and so on).[11-13]	a) Based on an *I-V* curve of an LED, explain why it changes brightness when you move it back and forth. b) Based on an *I-V* curve of an LED, what can you say about the voltage across the devices under investigation?

Unit 7. *Table VII. Electromagnetic oscillations*

	Experiments	Questions
I	Build a circuit that consists of a coil of specific dimensions (size and the number of turns) and an LED, and position the circuit near a cell phone. Change the orientation of the cell phone with respect to the coil. Observe the glow of the LED for certain orientations.[14]	Describe a pattern in the relative orientations of the coil and the cell phone when the LED is glowing and propose explanations for the observed phenomenon.

II	Connect an LED to a small coil and drive this circuit inductively with another coil that is connected to a sine generator. In a certain frequency range of the generator, the LED glows.**	Use your knowledge of capacitance and electromagnetic oscillations to explain the observations. Based on your explanations predict what will happen if you connect to the coil two LEDs in series or in parallel.
III	Same experiment as in 7.II. In addition the inductance of the coil connected to the LED should be known.	Estimate the effective capacitance of the LED (assuming the inductance of the coil is known).

Unit 8. ***Table VIII. Geometrical optics***

	Experiments	Questions
I	Use a bright LED as a point-like source in various experiments in geometrical optics.[15,16]	Pose questions about the relationships between the size of the shadow and size of the object and about image formation with lens and mirrors.
II	Submerge a clear LED in small cup filled with silicone oil and observe from above the size and structure of the p-n junction using a microscope.**	What is the shape and what are the dimensions of the p-n junction? How do the shape and dimensions of the p-n junction relate to the purpose of the LED to be a source of light? Why is p-n junction embedded in plastic? Why did we need to submerge the LED into oil to see the p-n junction? What other liquid would be useful for the same purpose?
III	Observe the deflection of a laser beam when it passes through a clear LED. Repeat the experiment, this time submerging the LED in liquids of known indices of refraction.**	Design an experiment to estimate the index of refraction of the plastic enclosure of the LED. Why is plastic used for the enclosure, not glass, for example?

Unit 9. ***Table IX. Color and wave optics***

	Experiments	Questions
I	a) Use red, green, and blue LEDs and a Ping-Pong ball to construct a simple color mixer.[17] b) Use an LED as a monochromatic source of visible light in various experiments on interference, diffraction,[18,19] and light scattering.[20]	a) What are the patterns in additive color mixing? b) Pose questions about the relationships between the wavelength of the light and observed diffraction patterns or intensity of scattered light.
II	Observe spectra of different color LEDs, an incandescent lamp, a fluorescent bulb, a laser, and the Sun using a grating or a spectrometer.[21]	Investigate the spectra of different color LEDs and compare them with spectra of an incandescent lamp, a fluorescent light bulb, a laser, and the Sun. Explain major differences and connect them with typical applications.
III	Connect a bi-colored (red-green) LED to low-voltage ac source and show that it appears yellow.[22, 23]	Manufacturer claims that this is a bi-colored LED made of red and green LEDs. Design a simple experiment to test this claim.

Unit 10. ***Table X. Electromagnetic radiation and photons (row II repeats row II in Table IX)***

	Experiments	Questions
I	a) Use an LED as light detector. a1) Measure light intensity at various distances from a small lamp.[24] a2) Measure intensity of light emitted by an incandescent lamp as a function of angle between two polarizers that are placed between the lamp and the LED.[24] a3) Modulate current through a glowing LED with an audio signal (for example, signal from an MP3 player) and use another LED of the same color as a detector (connect it to input of the audio amplifier-speaker system).[25,26] b) Use near-IR and UV LEDs to investigate properties and application of “invisible light.” b1) Use cell phone camera to observe diffraction patterns produced by a grating and a near-IR LED.[27] b2) Use a near-IR LED and cell phone camera to explore near-IR optical properties of different materials.[28] b3) Using a UV LED, determine UV-A absorption rate of different sunscreens.**	a1) Represent data in a log-log graph and compare it with the theoretical prediction ($1/r^2$ dependence). a2) Compare the measured data with theoretical prediction (law of Malus). a3) Using LEDs design a simple experiment to show transmission of data (music, for example) with light. b1) Compare the effects of different wavelengths of light on the diffraction patterns. Compare the effects of near-IR light to the effects of visible light. b2), b3) Investigate optical properties of different materials in near-IR and UV region and suggest practical applications.

III	Measure a turn-on voltage for LEDs of different colors and measure the wavelength of LEDs using the spectrometer. Plot graph of turn-on voltage vs light frequency. A simplified approach is described in Refs. 29 and 30, an in-depth approach is in Refs. 31 and 32.	Use the graph to estimate the Planck's constant.

Unit 11. ***Table XI. Semiconductors and p-n junctions***

	Experiments	Questions that teachers/students should pose
III	a) Connect a small incandescent light bulb (MAGlite) to a battery and submerge it in liquid nitrogen. Observe that the brightness of the light bulb does not change notably. Connect green or red LED in series with a suitable resistor to a battery. Submerge the LED into liquid nitrogen and observe decrease in the brightness of the LED. ** b) Submerge red or yellow LED into liquid nitrogen and observe change in the color of light emitted by LED (red color LED becomes orange, yellow color LED becomes green).[33]	a) What can we infer about the electric properties of the semiconductors from this experiment? Compare and contrast the outcomes of both experiments. b) Use your knowledge of energy bands in solids and thermal expansion to explain the change in color of the LED in the experiment.

Unit 12. ***Table XII. Photoelectric effect***

	Experiments	Questions
I	a) Use different color LEDs to observe photoelectric effect in a vacuum phototube.[34] b) Connect an LED, a neon bulb, and an ac voltage source in series. Adjust voltage slightly below the level when the neon bulb and the LED start to glow. Then illuminate the dark neon bulb with visible light. The LED starts to glow, indicating the presence of the photocurrent produced by the photoelectric effect in the neon bulb.[35]	a) Describe the pattern between the color of light illuminating the phototube and the presence/absence of the electric current. b) Explain why there is current in the circuit illuminated by light. What is the role of each element (neon bulb, LED, and ac voltage source) of the circuit in this experiment? Could you perform the same experiment with a dc voltage source?
II	Same experiment as in 2.III.	How does an LED convert light into electric current?

Unit 13. ***Table XIII. Nature of light emission, fluorescence, and phosphorescence***

	Experiments	Questions
I	a) Shine an LED on a fluorescent material and observe it glow; compare the color of the LED light to the color of light emitted by the material. Qualitative comparison can be based on the naked eye observation or using a simple grating; quantitative comparison can be made using a simple spectrometer. One can also investigate plants such as peppers, kiwis, and bananas.[36,37] b) Shine an LED on a phosphorescent material and observe the afterglow; compare the color of the LED light to the color of light emitted by the material. Qualitative comparison can be based on naked-eye observation and quantitative comparison can be done using a simple spectrometer.[38]	1. Describe what happens when some materials are being irradiated with light of different colors. 2. How long does the effect last? 3. Compare the wavelength of the emitted light to the wavelength of the incident light. Propose a rule summarizing the patterns.
II	Measure current-voltage, light output-voltage, and light output-current characteristics of an LED and a semiconductor laser.[39]	How are laser diodes different from LEDs? How do laser diodes produce light?
III	Use a spectroscope to compare the spectra of light emitted by red, green, and blue LEDs to the spectra of light emitted by white and pink LEDs.[40]	How can an LED produce light with a continuous spectrum (such as white or pink light)?

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Gorazd Planinšič *is a professor of physics in the faculty of mathematics and physics, University of Ljubljana, Slovenia. He also works at the Ljubljana House of Experiments. He leads a physics education program for future high school physics teachers and a continuing education program for in-service physics teachers in Slovenia. His main interest is in development and educational applications of simple experiments.*
gorazd.planinsic@fmf.uni-lj.si

Eugenia Etkina *is a professor of science education at Rutgers University, GSE. She works with pre- and in-service high school physics teachers and develops physics curriculum materials. She is one of the creators of the Investigative Science Learning Environment (ISLE) and a co-author of the recently published* College Physics *textbook. Her research is in helping students develop "scientific habits of mind."*
eugenia.etkina@gse.rutgers.edu