NGSS Engineering Practices in Physics Instruction: Building a Night Light

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Many physics teachers have experienced the challenges of implementing the Next Generation Science Standards (NGSS) in their high school curricula. These standards, based upon the Framework for K-12 Science Education, were intended to shift science instruction towards an interdisciplinary focus on three-dimensional learning, phenomena anchored explorations, and developing solutions for technological problems.[1,2] The present paper describes a collaboration between electrical and computer engineers and physics educators, whereby a physics unit was created to embed engineering practices in the design of a night light. Although the project also incorporates aspects of crosscutting concepts and disciplinary core ideas, we focused on engineering practices since more educational resources are needed that illustrate this aspect of NGSS-aligned teaching and learning. The unit was piloted with over 1500 high school students in an informal outreach program, as well as professional development workshops for 100 secondary science teachers, with the intent that teachers would incorporate this and other engineering projects in their physical science classrooms.

Several physics and engineering educators have proposed curricular innovations to meet the challenges of NGSS-based instruction, for example, cell phone units that examine analog-to-digital voice transmissions,[3] project-based units on designing and navigating a robotic vehicle,[4] and university-based outreach experiences where students build home security systems.[5] A major challenge in NGSS adoption is the incorporation of engineering practices in physics instruction; teachers have reported a lack of confidence in defining and integrating engineering design in their classrooms since pre-service programs have typically not prepared prospective educators for these reforms.[6,7] In addition, many curricula used in science instruction have shown weak connections to engineering skills such as defining a problem, testing a prototype, and optimizing designs through iterative processes.[8]

Design process and disciplinary connections

A *night light*, as suggested by the name, is an electronic device utilized at night for visionary purposes. This practical device is popular due to its function of providing light in darkened settings. The present design mainly consists of two basic components found in almost every other electronic device used in our daily lives—light-emitting diodes (LEDs) and resistors. Such a device may be constructed in many ways.

This activity was designed as an embedded engineering activity for middle and high school students studying basic physics concepts. The primary focus was on electronic concepts related to voltage, current, and resistance, and theoretical concepts related to Ohm's law, voltage dividers (splitting voltage across various components in the circuit), and energy flow and transfer. In addition, students learned the basics of color theory since they chose the light patterns for their devices. Students viewed the 1931 CIE (Commission Internationale de l'Eclairage) chromaticity diagram to explore human perception and how specific combinations of red, green, and blue LED light would produce desired spectral hues (Fig. 1).[9] They were encouraged to think about these combinations as they constructed their night lights.

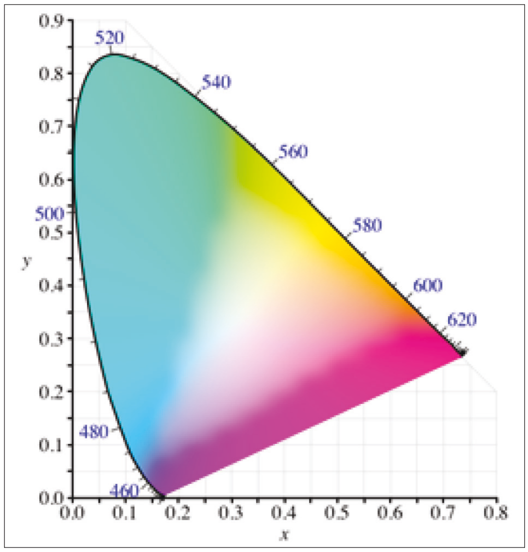

Fig. 1. 1931 CIE chromaticity diagram.[8]

The students used red, green, and blue (RGB) LEDs and controlled the current flow passing through the LEDs in a two-part experiment. First, students were introduced to basic design concepts in electronics such as circuits, electric potential, charge flow, Ohm's law ($V = IR$), and infinite current phenomena. Instructional tools included PowerPoint slides and reference sheets that summarized the performance and other technical characteristics of the night light components.[10] For instance, an RGB LED has specific voltage and current characteristics that need to be met in a circuit design for the night light to function properly. While designing the night light, students were encouraged to think critically about the technical constraints and physics concepts such as Kirchhoff's voltage law, which states if a battery in a closed loop circuit generates a set voltage, the sum of the voltages across all electronic components in the circuit must be equal to the total voltage of the source. While an in-depth treatment of Kirchhoff's law is often beyond the scope of high school curricula, it is taught as an extension of the idea of energy conservation, that is, voltage represents the electric energy per unit charge and this energy can neither be created nor destroyed. Circuit schematics were introduced as a visual guide for using models to build and test a design, and these same models were modified to illustrate energy flow and transfer (Fig. 2).

Design procedure

In the first part of the experiment, students were introduced to breadboards and techniques to wire the components

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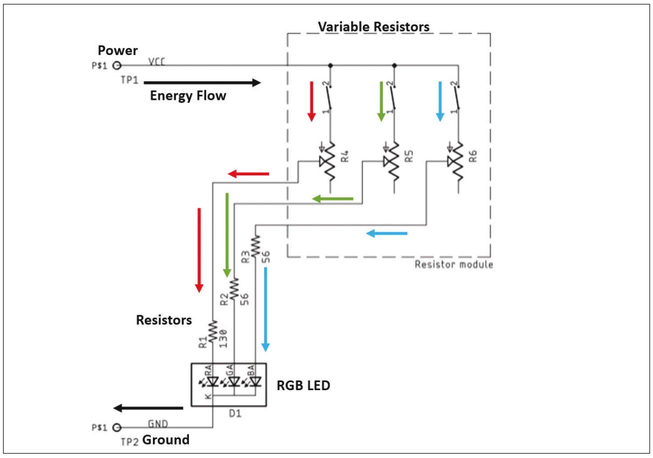

Fig. 2. Night light schematic with energy flow diagram and red, green, and blue LEDs. Note: R1=130 Ω; R2=R3=56 Ω

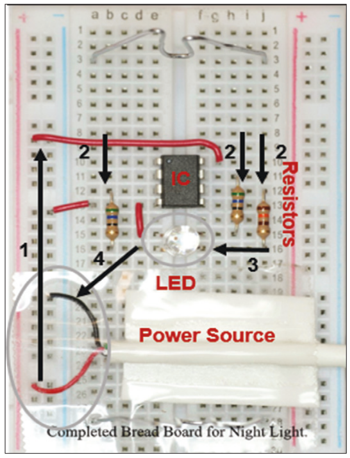

Fig. 3. Student-built device with energy flow diagram.

properly. They first put together a rudimentary device based upon a simple schematic where a battery source was connected to three resistors (R1, R2, R3) separately connected in series with three LEDs. In the present activity, red, green, and blue LEDs were infused into one LED bulb with four pinouts (D1) and to a ground source to provide a closed circuit. To optimize the design, students were asked to connect an extra potentiometer in series with each of the original resistors (resistor module R4, R5, R6) as shown in Figs. 2 and 3. The potentiometers were controlled through switches. Increasing resistance, according to Ohm's law, reduces the current flowing through circuit components, resulting in diminished power and a dimmer light pattern. If the potentiometer switch were fully on (infinite resistance), the LED would be off; otherwise, if the potentiometer switch were fully off (zero resistance), only the original resistance (R1, R2, R3) in the circuit would be in effect and the LED would be on. Each color could be controlled separately, creating different patterns of light. This feature was important so students could customize their designs to create their desired light patterns.

The subsystems of the device presented several constraints and opportunities to adjust functionality. The LEDs presented a constraint in that students had to choose modifications based upon different combinations and/or possible potentiometer combinations to adjust brightness. They also had the opportunity to select resistors to adjust the flow of current and brightness. The schematic was presented as a model for energy transfer throughout the circuit, illustrating conservation of energy and the multiple pathways for the flow of current. Students and teachers created their own devices to take home; however, participants sat in pairs at lab tables where discussion and collaboration were encouraged.

In the second part of the experiment, students were introduced to programmable integrated circuits (IC) chips. Instead of controlling the light patterns of the LED manually with a switch, the IC performed this function by changing the resistance in the circuit in an automated fashion. The IC chips were pre-programmed (see appendix[11] for full programming code, which took about 30 seconds to load onto each IC chip). If time permitted, students were introduced to some basic coding skills to change the light patterns by alternating some lines of code in the pre-programmed IC chip. In terms of differentiation among age groups, the middle school students used pre-programmed IC chips, while high school students could use the pre-programmed chips or modify the program to alter functionality (this took approximately 30 additional minutes). For the older students, the IC chip code presented an opportunity for optimization since it could be changed to produce desired

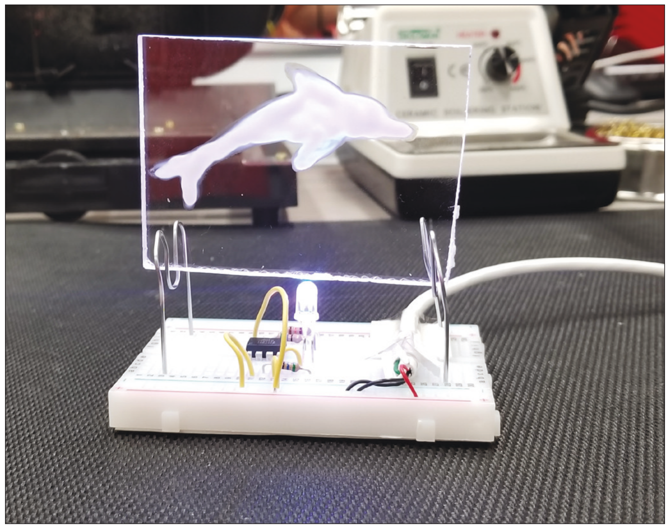

Fig. 4. Night light device with painted acrylic design.

light patterns. In the last part of the activity, students placed acrylic glass with their own hand-painted designs above their designated light pattern to create a full night light device, as shown in Fig. 4. Metal clips were positioned in the breadboard to mount the acrylic glass.

Engineering practices

The implementation of engineering practices presents a challenge for physics teachers. NGSS has advanced precollege science instruction beyond the notion of inquiry—whereby students pose questions and answer questions through investigations—to student engagement with engineering practices, where they simultaneously solve technological problems and refine skills that are dependent upon specific disciplinary knowledge (see Table I for examples of NGSS alignment).[1] The night light device prototype was designed as an example of technological advancement based upon physics principles related to direct current. The design team incorporated opportunities for students to employ engineering practices, for example, using models to test and build a design, revising designs to meet constraints, optimizing performance, and

Table I. Examples of night light alignment with NGSS.[1]

3D Focus	NGSS Standard	Student Task(s)
Engineering Practices	• Make and use a model to test a design, or aspects of a design, and to compare the effectiveness of different design solutions. • Construct a device or implement a design solution. • Read scientific and engineering text, including tables, diagrams, and graphs, commensurate with their scientific knowledge, and explain the ideas being communicated.	• Building breadboard device using the schematic as a model. • Demonstrating ability to optimize performance by changing resistors or reprogramming the IC
Crosscutting Concepts	***Energy and Matter: Flows, Cycles, Conservation*** • Tracking fluxes of energy and matter into, out of, and within systems helps one understand the systems' possibilities and limitations. ***Structure and Function*** • The way in which an object or living thing is shaped and its substructure determine many of its properties and functions.	• Explaining how energy is transferred throughout the circuit (potential, electrical, light). • Applying principles of electrostatics, Ohm's law, and circuit construction when analyzing and altering designs, troubleshooting, and testing devices. • Examining how variations in voltage and/or current affected design functionality.
Disciplinary Core Ideas	***PS3B: Conservation of Energy and Energy Transfer*** • Energy cannot be created or destroyed, but it can be transported from one place to another transferred between systems. ***PS3C: Relationship between Energy and Forces*** • Electric force fields contain energy and can transmit energy across space from one object to another.	

adjusting functionality.[1] The team developed several ways for students to change device performance, such as changing resistor values manually, and altering the code within the programmable IC chip. With these modifications, students observed a change in performance of the LED, since changing resistor values modified the voltage across the LED, resulting in a different brightness, while changing the code on the IC changed both brightness and the LED light patterns. Optimization opportunities in engineering design projects are important for promoting student creativity, autonomy, and critical thinking.[5,8,12-15]

During our workshops with teachers, we developed assessment rubrics for measuring students' ability to define the design problem, evaluate competing designs, and develop a process for optimization; these constructs were aligned with NGSS[1] (see Table II for an example of a physics rubric). The rubric may be modified for different engineering activities, since specific design skills may be more appropriate depending on the physics ideas involved.

Crosscutting concepts and disciplinary core ideas

Some thematic crosscutting concepts such as energy transfer and the structure and function of components within a system were crucial in understanding the night light design. More specifically, the middle school progression of the crosscutting concept of "Systems and System Models" states that "models can be used to represent systems and their interactions —such as inputs, processes, and outputs—and energy and matter flows within systems."[1] The high school progression advances this goal by stating that "… the boundaries and initial conditions of the system need to be defined" and "systems can be designed to do specific tasks."[1] In terms of disciplinary core ideas, electric potential is a common topic found in physical science and foundational in understanding electrical engineering. Knowledge of electrostatics concepts facilitates an understanding of energy flow and transformation. Both Figs. 2 and 3 show the energy flow in the night light device, and they illustrate how Kirchhoff's voltage law might be applied as an extension of crosscutting concepts and disciplinary core ideas related to energy conservation. The closed structure of the device and transfer of energy through these sub-systems was essential for students to test and troubleshoot their products. The use of LEDs and ICs, which are found in nearly every electronic device, presents an opportunity to introduce more sophisticated electrical components while learning physics concepts.

This activity incorporated other key disciplinary core ideas related to transfer of energy in the form of light. By exploring color formation based on the triadic nature of the LED and the chromaticity diagram, the students applied the concept of electrical energy transfer to light energy in their designs. This feature was an opportunity for them to customize their designs. It also provided a relevant context for students to consider color combinations to meet desired functionality.

Logistics and advantages of project design

The time required for this activity was approximately 2.5 hours, which included both the instructor's introduction of physics concepts and the construction and testing of the device, with an extra 30 minutes needed if students modified the program on their IC chips. In addition to a lead instructor, there were graduate teaching assistants available in the workshops to answer technical and conceptual questions (one for every 10 participants). Most materials for this activity were purchased from a standard electronic supply shop (breadboards, resistors, LEDs, pinouts, ground source, potentiometers, IC chips). The acrylic panes and paints were purchased from an art supply store. The metal clips were available from an office supply store; in later iterations of the activity, we used a 3D printer to create clips that were easier to manipulate. The cost was approximately $6/kit, which is reasonable for allow-

Table II. Rubric for Assessing Engineering Tasks.[1]

	Exceeds Expectations (3)	Meets Expectations (2)	Developing (1)	Missing (0)
Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.				
Define criteria/ constraints				
Apply science principles				
Consider impacts				
Evaluate competing design solutions using a systemic process to determine how well they meet the criteria and constraints of the problem.				
Evaluate alternative solutions				
Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.				
Test alternative solutions				
Analyze data from solution testing				
Optimize solution				
Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.				
Design a model				
Test a model				

ing students and teachers to bring their night lights home after they designed, constructed, and tested them. The materials were provided in the workshops—the teachers' professional development was funded by the National Science Foundation (NSF BPE 7686640) and National Grid, and these funders also subsidized the costs of attendance for high-need middle and high school students. Other students/schools paid a small fee to cover the materials when attending the workshops at the university. We strived to maximize cost efficiency while developing a simple project for integrating engineering practices in physics instruction.

The night light activity was aligned with NGSS to establish its applicability and usefulness in teaching physical science concepts at multiple levels of complexity. We addressed several constraints in the project development, including age appropriateness, cost, and practicality. The project was tested with students from ages 11 to 18, as well as high school teachers from many schools in the region. Most students were familiar with the basic idea of a night light, and they were intrigued by building and modifying their designs. The activity incorporated basic electronics principles and skills yet allowed for creativity. By modifying the core design and building the device, students developed a stronger grasp of physics concepts, engineering design, and the value of science in developing technological solutions to everyday problems.

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