Lights, Physics, Action: The Science of Theater Lighting Design

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A physics professor (DS) and a theater technical instructor (BC) came together in 2018 to plan a general education course on the Physics of Theater Stagecraft. This is less surprising than it sounds, because theatrical lighting design had been Smith's hobby for almost 30 years, and he has always felt that his understanding of physics helped him better implement the art of stage lighting. In 2019, Guilford College launched a new instructional calendar,[1] and we worked together to offer this interdisciplinary general education course for the first three-week class session. We agreed that our priority was that the students would learn by doing, rather than reading and homework. We spent mornings in the physics lab and afternoons in the theater. There was no final exam—the practical task of creating a design for an actual performance was students' opportunity to show what they had learned.

This term had 16 days of instruction from late August 2019. For the first 10 days, the students had physics labs in a morning three-hour time block. Every afternoon we spent in the theater on the tools of lighting design. For the last five days, our class merged with a performance class that had spent the three weeks developing a one-hour musical for children. Our students designed the lights for their performance. In the last few days of the course, our local professional theater company, Triad Stage in Greensboro, opened a production of Albee's "Who's Afraid of Virginia Woolf." We required our students to attend a performance and write a short reaction paper on how they observed the principles they learned in the course being implemented by a professional lighting designer.

We did not use a textbook. Although some books have been written about the physics of the theater, [2] no one has written specifically about the physics of theater lighting.[3] Some books instruct on the engineering of stage electricity,[4] and there is a website that comes close to what we hoped to do,[5] but we could not find any single book that connects the fundamental physics of light, electricity, optics, and color[6] with the art and craft of stage lighting design. The Physics Classroom has a tutorial on the physics of stage lighting[7] that is limited to subtractive color. There has been very little published in *The Physics Teacher* about the physics of theatrical lighting design.[8] We therefore thought an article outlining our experiences could be of interest to other teachers who are looking for novel applications of physics concepts.

Theater design activities

On day one, we taught the students about the angles of lighting an actor: front, side, back, top, etc., and we discussed how those angles affect audience reaction. We challenged the students to use three instruments to light and color a person in such a way as to evoke a particular emotion.

Fig. 1. The Art Card Assignment. The group of students was given a printout of Edward Hopper's "Summer Evening" (top) and tasked to recreate the scene on our stage (lower). They felt challenged to match the levels and directions of the light and shadows in this piece. They found they needed four spotlights to simulate the single bulb in the painting.

The rest of the class guessed what emotion was being represented. Anger, fear, and joy worked well, but they struggled with confusion.

Further activities included how to create and read a light plot, how to hang, cable, and focus lights (one "quiz" challenged them on day three to wire up a complete circuit—if the instrument turned on when power was supplied, they passed!), and how to deal with a set. They also learned how to design cues and program them into the light board. We gave each group of students a painting, and they were challenged to reproduce this painting in the theater. Figure 1 shows an example of the students' recreation of Edward Hopper's "Summer Evening." They were startled to realize that to create the effect of the single light bulb in the painting, they needed four lights on stage. This forced them to think about geometry and hold ray-tracing diagrams in their heads.

As their final project, they had to design the lights for a separate class's production of "Free to Be You and Me." We split our class into four groups, and each group designed 15 minutes of the performance. They had to choose color schemes, instruments, angles, specials, and the timing of cues. In addition, they had to coordinate with each other to avoid conflict and not demand too many instruments.

Ten physics labs

We designed 10 laboratory experiences to encourage the students to explore the basic physical principles behind modern stage lighting design. Each day we provided an electronic instructions document that contained questions for them to answer and tasks for them to carry out. They filled out their answers as they went and submitted their reports at the end of the session. Their submissions were graded and returned later that day. We decided to emphasize four topics: the electricity to generate the light, the control circuitry to dim and brighten the instruments, the optics to direct the light, and how the nature of color can impact the audience.

The students began with some static electricity experiments, to show that charges can be used to affect macroscopic objects (they particularly enjoyed the hair-raising experience of a Van de Graaff generator). They then used batteries and bulbs to explore the properties of DC circuits, current, and resistors. They also used hand-crank generators to viscerally feel how it takes more work to illuminate incandescent bulbs than LED bulbs.[9]

Theatrical lighting runs on AC current, so we spent a day using function generators and oscilloscopes. The main goal was for them to build a toy model of how a modern Silicon Controlled Rectifier theatrical circuit dimmer works[10]: by changing the duty cycle of an oscillation cycle, first at 1 Hz and then ramping up to 60 Hz, they could see how one can make a light look dimmer by having it be off for a larger fraction of the cycle, rather than by changing the peak voltage.

Once they had used electricity to generate light, they moved on to the question of how to direct that light. They learned how to make ray-tracing diagrams (using the Physlet[11] app[12]) and how to find the focal point of a concave mirror. The next day they carried out similar activities with lenses. They learned about images and what it means to be in focus. On the third day of optics, they integrated these concepts to build toy models of PAR Can[13] and ellipsoidal instruments. An example of one group's PAR Can is shown in Fig. 2. With their ellipsoidals, some of them succeeded in projecting the shadow of a cut-out pattern (called a gobo) onto a screen, a common theatrical technique. It was very difficult for them to align the optics and figure out where the focal points were (especially the *two* focal points of an ellipsoidal mirror). This struggle gave them an appreciation for the engineering that went into the stage instruments. In future versions of the class, I hope to have the models a bit more preassembled, so they can spend less time fighting with the equipment and more time figuring out what it's doing.

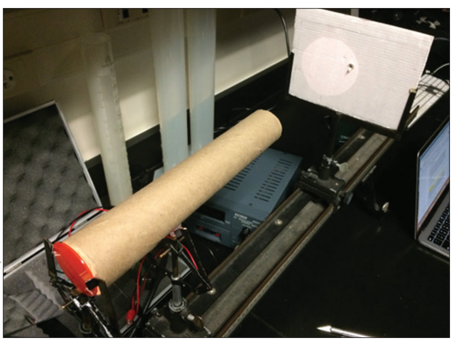

Fig. 2. The students' toy model of a PAR Can theatrical light. A concave mirror (colored orange at the left) is mounted behind a collimating tube. The students had to figure out where to cut a hole in the tube to place a light bulb at the focal point (the hole is on the bottom of the tube, not shown in the figure), such that the light rays came out (mostly) parallel on the right.

Finally, we spent a few days on color.[15] The color the audience perceives is a function of four elements: the spectrum of the emitted light, the reflective properties of the object on stage, the detection efficiency of the eye, and the psychology of the brain.[16] We spent time on each of these steps in the process, so the students would understand how the physics of light and color can alter the emotions of a watching human being.

Many stage instruments are being made from LED bulbs now, and the color of the beam is generated by mixing primary red, green, and blue. Traditional stage lights use incandescent bulbs, and each instrument is assigned a single color by putting translucent gel in the beam. The students therefore learned about the visible and infrared spectrum, how spectrometers measure light, and how the spectra of LEDs and incandescent bulbs[17] are different. Gel manufacturers provide a transmission function for each color,[18] and the students compared these graphs to observed spectra when they shone white light through the gel. This impressed upon them the fact that perceived color is a process, not a property, because their observed spectra often shared only the most gross features with the manufacturers' graphs: their "white" bulbs did not provide a flat source spectrum, and the sensitivity of their detectors was not uniform, either. Both of these effects distorted the observed spectra, but they could see how the spectral colors combined to make complex colors. We used a yellow laser to demonstrate the difference between pure yellow and the yellow you get from mixing red and green. Students mixed pure red and green to match the laser, and found that not everyone agreed on the same relative amounts of each. Perception is subjective.

To demonstrate subtractive color, we followed Lincoln[19] by shining both the yellow laser and the red and green LEDs on a rainbow of colored candies. The students were shocked at how different the reflected colors looked to them. They also were given a sheaf of colored construction paper and challenged to predict how the paper would look when illuminated with incident light of different colors. This activity was not as straightforward as we hoped, because even the paper that looked to be "pure" colors turned out to have other colors mixed in, which complicated the perceived color of the reflected light. It was also much harder than expected to detect the reflected light with the spectrometer—the signal was often contaminated by specular reflection off the paper (shininess) so that magenta light reflected off blue paper was not, in fact, pure blue, but still had red light in it. The reality was much more complicated than the simple theory, and this interfered with the students' understanding of the phenomena. The next time we teach this course, we hope to find objects that reflect purer colors than craft store construction paper.

Student reactions

The physics labs were a mixed success. During some activities, students clearly puzzled over their observations and argued about how to interpret what they were seeing, as we hoped they would. However, the design of the instructions had an unanticipated flaw. The instructions were written as a series of questions to answer, in the hopes of sparking their curiosity. We found that in many cases it had the opposite effect—students focused on getting the answers and moving on to the next question, without thinking about the implications of their answers. The dimmer activity allotted two hours for them to explore the workings of function generators and oscilloscopes, and there is no evidence that any of them did anything beyond the bare minimum they needed to get the result. If they were not explicitly asked to do something, they generally didn't do it. For future iterations of the course, we hope to gamify the process, articulating goals and puzzles rather than questions, in the hopes that they will explore more.

Although they did apply what they were learning in the lab to the theater, concepts didn't necessarily carry over from one lab to the next. They spent a session figuring out the focal lengths of concave mirrors, and then a session figuring out the focal lengths of convex lenses, but when we asked them to put the two together and make a toy model of a theatrical spotlight, many of them were confused and claimed to have no idea what a focal length was. On the other hand, it was clear that they could make the connection between building a small circuit on the lab bench and wiring up a circuit across the ceiling of the theater.

The students were generally positive in their reactions to the class. Some students struggled to find motivation to stay engaged for up to six hours a day, especially during activities that were limited by space or equipment (only a few people could operate our single light board). However, most found the hands-on learning engaging. One student wrote: "Almost all of the learning was hands-on and interactive, keeping me engaged for the ~6 hours I spent in class every day." For at least one student, it was a revelation: "Science has always felt impossible for me to wrap my head around, and I assumed I was going to have to grin and bear some class like molecular biology. 'The Physics of Theatre Lighting' [sic] made me realize that science isn't just some daunting subject in school. It showed me that science is the basis of everything—even artistic endeavors! I felt so lucky to have learned that science and art aren't mutually exclusive." What more could we have asked for?

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Reference

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