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# Color Mixer for Every Student

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**T**his paper describes the construction and use of a color light mixer that uses different color LEDs. The idea was partly inspired by two papers.<sup>1,2</sup> The first one describes how a standard LED can be converted into a point-light source, and the second one explains how a Ping-Pong ball can be used to mix polarized color light from two lasers.

It was Sir Isaac Newton about 300 years ago who first proved that white light, such as sunlight, is really a mixture of colors that we perceive as white. We simplify the problem by saying: Let's pick three colors from the rainbow and see if we can get white light by adding them together (we may skip the discussion on what "adding the colors" means at this point). Then we show one of the many versions of the "R+G+B=W" experiment. If you ever tried to do this experiment, you know how difficult it is to obtain a white color that would convince the students. In principle, three flashlights and three colored filters should work, but in practice it is much harder to obtain the desired results than one would expect, because flashlights produce light spots of nonuniform intensity. Slide projectors do a good job producing a light spot with uniform brightness, but the experiment requires three slide projectors, careful choice of the filters, and fine adjustment of the color intensities by varying the distance from each projector to the screen.

Modern technology offers a simpler solution. The obvious choice today seems to be the use of red, green, and blue light-emitting diodes (LEDs). Though the

idea is straightforward, it requires some tricks to make it work properly. Here are instructions on how to make a simple and reliable light mixer that you can carry in one hand and does not require complete darkness in the classroom to obtain a convincing result. In addition, this experiment is useful in introducing topics such as emission light spectra, filters, and human perception of colors.

## Making a Point LED Source

Most commercially available LEDs have an epoxy-drop lens above the PN junction — the light-emitting element. These LEDs suffer from the same problem as a torch: They give a light spot with nonuniform brightness. The problem can be eliminated by changing the LED into a (semi) point-light source. Start with red, green, and blue LEDs that are encased in clear plastic.<sup>3</sup> Using a hacksaw, carefully saw off the part of the LED body that makes the lens. Make sure that you do not cut too close to the PN junction (1 mm away is OK). If we want to make light propagate out from the plastic without being scattered by scratches, we have to brush and polish the sawed surface. Use fine water sandpaper starting from lower grades (such as grade 600) and finishing with higher grades (grade 1200). After this you have to polish the surface with an abrasive polishing paste (a white toothpaste also works well) until the surface looks clearly transparent. Repeat this procedure with all three LEDs.

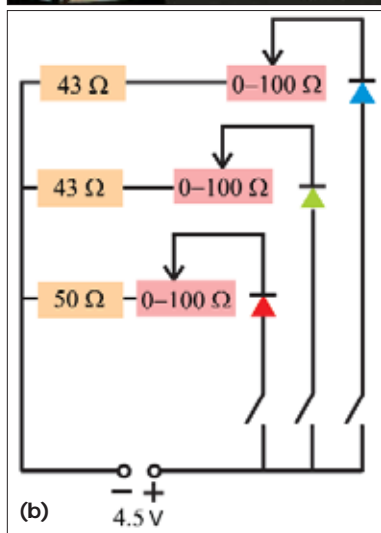
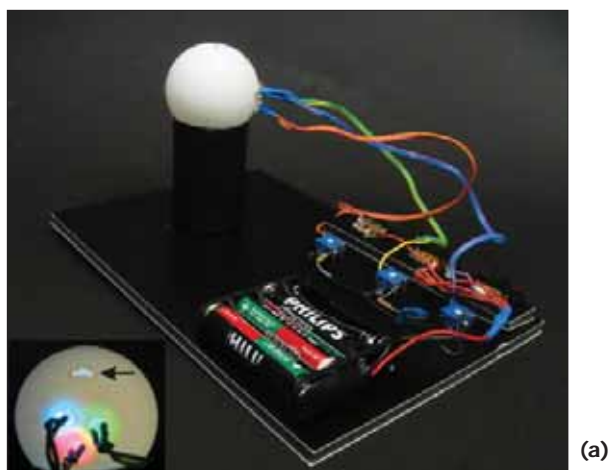


Fig. 1(a) The completed diode light mixer. The inset at the bottom of the photo shows the back view of the light mixer with LEDs switched on; the arrow points to the slit, which is used in the experiment with light shadows. (b) Electronic circuit of the diode light mixer; the suggested resistor values refer to the LEDs specified in the references.

## Ping-Pong Ball as a Light Mixer

A white Ping-Pong ball has a special property: Light scatters off the interior surface of the ball with equal intensity regardless of viewing direction. Surfaces exhibiting this property are called Lambertian surfaces.

Some light is transmitted through the ball wall because it is thin and not perfectly opaque. Therefore, the external appearance of the ball is the same color as the light illuminating the interior. If we put the glowing point LED source inside the Ping-Pong ball, the ball will appear equally bright from all directions. Make three holes in the ball wall by using the hot tip of a soldering iron. The holes should be just big enough for the LEDs to sit in without falling into the ball. In order to obtain a decent white color, a fine adjustment of the current through each LED is required.

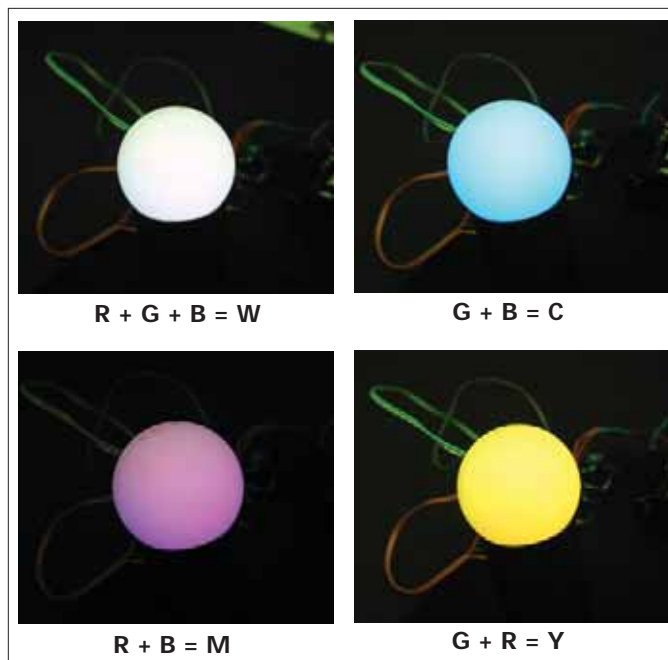
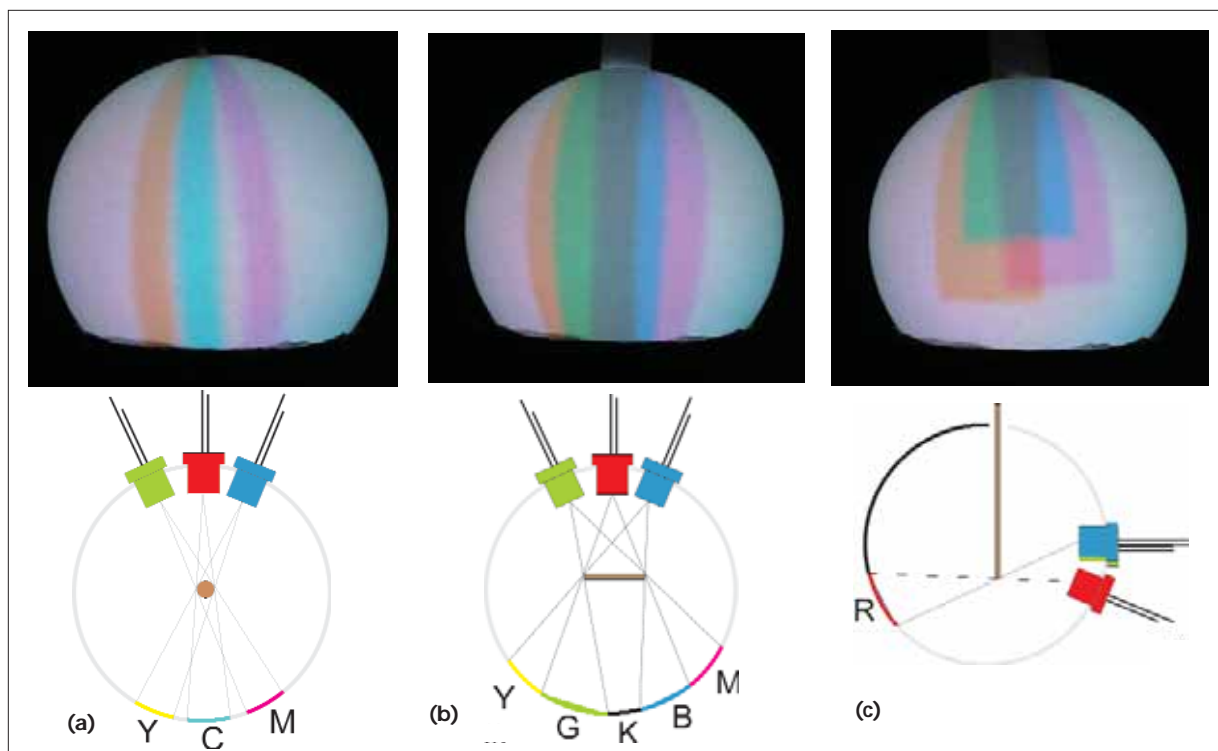


Fig. 2. Combining red (R), green (G), and blue (B) lights with the ball light mixer, white (W), cyan (C), magenta (M), and yellow (Y) color can be produced.

I used a simple circuit shown in Fig. 1(b) with a 4.5-V voltage source (three AAA batteries) and 100- $\Omega$  variable resistors. The value of the fixed resistors should be chosen so that the current through each LED does not exceed the forward current as specified by the manufacturer (normally 20–30 mA) at the lowest setting of the variable resistor. The values of fixed resistors that are indicated in the figure refer to my choice of LEDs. The power rating of all the resistors is 0.25W. I used a plastic film container as a stand for the ball and fixed all the elements on a black foam board with a glue gun [see Fig. 1(a)]. Make a slit at the top of the light ball [see inset in Fig. 1(a) photo] again by using the hot tip of a soldering iron. This slit will be useful for experiments, which I will address later.

## Additive Color Mixing

When the color mixer is completed, switch on all three LEDs. The colored lights are mixed and the ball glows in the resulting color shade, appearing approximately equal in brightness from all directions. Adjust the variable resistors until you obtain the best white (W) color (see Fig. 2). It is instructive to slightly change the current through one diode and show stu-



**Fig. 3.** The color patterns are produced when (a) a wire or (b) a paper strip is inserted all the way through the ball and (c) when a paper strip is inserted about half the way through the ball (the sketches below show the situation in the central cross section of the photos above). The colors on the sketches are indicated with the usual letters (K means black).

dents how the human eye is sensitive to a minute change in color proportions when the resultant color is close to white.

By switching on two LEDs at the same time in different color combinations, you can produce cyan (C), magenta (M), and yellow (Y) and check the basic rules for additive mixing of colors (Fig. 2). The white shading in the center of the cyan ball is photographic artifact.

Here comes the puzzle for the students. Insert a wire through the slit on the top of the light ball (an extended paper clip works well) all the way down into the ball. The colored shadows should appear on the ball wall, opposite to the LEDs [see photo in Fig. 3(a)]. Repeat the same with a paper strip (about 4 mm wide) and you will observe a different color pattern [photo in Fig. 3(b)]. Pull the paper strip half way out of the ball and notice a different color pattern. Ask students to explain the formation of the colors in all cases.

In order to give the right explanation, the students

should understand how the light emitted by the point-light source propagates, how it forms the shadows, and how the rules of additive color mixing operate. They should also take into account the arrangement of the LEDs in the ball [see inset photo in Fig. 1(a)]. The corresponding explanations of the observed colored patterns are given schematically below the photos. More pretty color patterns can be obtained by making a second slit on the side of the ball and inserting two (or more) objects into the ball (see cover photos).

### Complementary Colors

Two colors are said to be complementary if they produce white when they are mixed together. Which color is complementary to green? First switch on all three LEDs to obtain white. The complementary color to green is the color that remains when you switch off the green LED. It is magenta. In a similar way you can show that yellow is complementary to blue and cyan is complementary to red.

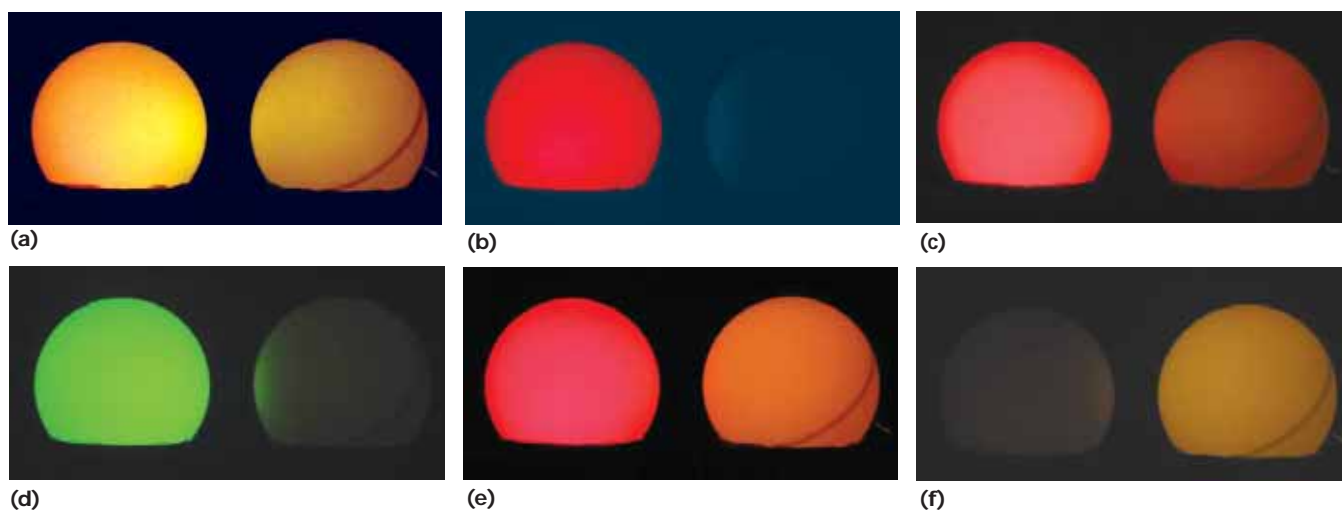


Fig. 4. Red-green yellow ball (on the left) and “proper” yellow ball (on the right) as seen under different conditions: (a) with no added filter, and when observed through the following filters: (b) red filter, (c) magenta filter, (d) green filter, (e) orange filter, and (f) green and orange filter together. The photos from (a) to (e) were obtained with exposure time of 1/6 s and aperture 8, while (f) was obtained with the exposure time of 4 s and aperture 8.

## The Two Yellows?

Somebody may ask now “But you can also buy a yellow LED. Can we make the color white just by using the yellow and the blue LED?” Yes, we can. Prepare the yellow LED as described before and fix it into the ball together with the blue LED. After some fine adjustment of the currents you should get the white color as in the previous experiment.

At this point, signs of confusion may be noticed on some students’ faces. What is the difference between the “proper” yellow light and the red-green yellow, which is really the mixture of red and green light? Are there two yellows, or only one? How can our eyes perceive both yellows as the same color shade?

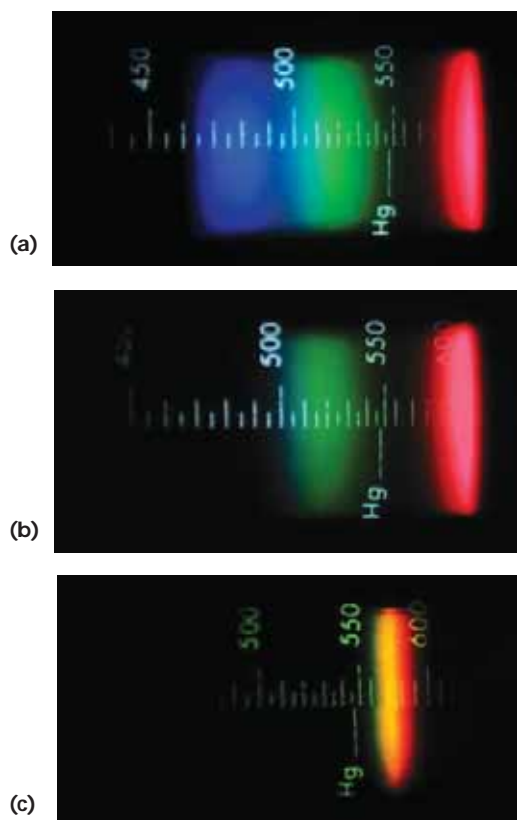
As we know, the cones in the retina are responsible for color sensation in human eyes. In the simplified explanation, there are three types of cones that are most sensitive to red, green, and blue light respectively. The sensitivity curves are broad and their tails overlap. There are no “yellow cones.” The sensation of yellow appears when the red and green cones are about equally stimulated. This can be done in two ways — either by the mixture of red and green light, or by a light with a wavelength that falls between the red and green where the corresponding sensitivity of red and green cones is about the same. This happens for the (proper) yellow light of the wavelength around 570 nm.

The explanation calls for more experiments that can be used either as an illustration of the phenomena, or the evidence that supports the explanation.

Following the instructions from the first paragraph, make a light ball using three yellow LEDs. Connect the yellow LEDs *in a series* to a 9-V battery following the instructions from the first paragraph. For my choice of LEDs,<sup>3</sup> I used a 100- $\Omega$  variable resistor in series with 120- $\Omega$  (0.25 W) fixed resistor. Switch on the yellow light ball and the color mixer from the previous experiment with only the red and green LEDs on. Adjust the currents in the setups so that the yellow lights emitted by both balls look as equal as possible [Fig. 4(a)].

Take different acetate color filters and observe the balls through them. Try red, green, magenta, and other filters. You will notice that for most color filters the “proper” yellow ball appears to glow dimmer, or may even look like it’s been switched off, while the red-green yellow ball appears to glow in different colors [Fig. 4(b-e)]. For these filters the transmittance of the yellow light is low, but it increases for longer or for shorter wavelengths making the red-green yellow ball look redder or greener, respectively.

Ask students at this point what kind of a color filter would cause the red-green yellow ball to glow dimmer than the proper yellow ball. Obviously, this would be the filter that blocks the light from the red-green ball



**Fig. 5.** (a)–(b) the spectra of white and yellow glowing RGB light mixer and (c) the spectrum of yellow LED. The scale shows the wavelength in nm.

and passes the “proper” yellow light through (a band-pass filter). But, since acetate filters are very broad, one realizes after some experimentation that there is no single filter that would meet this requirement. However, combining two filters, one that cuts wavelengths below the yellow (orange filter) and one that cuts above the yellow (green filter), may give the desired result [Fig. 4(f)]. Of course, the price we pay is low light intensity, because the transmittance of acetate filters is slowly changing with the wavelength and that causes the overlapping of the tails. That is why the exposure time for the last photo in Fig. 4 needed to be so much longer.

The described experiments and related concepts become even clearer if students can observe the emission spectra of the LED color mixer. Spectra of white, red-green yellow and “proper” yellow light from the experiments are shown in Fig. 5. The spectra have been obtained with a pocket prism spectrometer.<sup>4</sup>

### Note about the photos:

All photos have been made with a Canon Power Shot G2 digital camera. The colors on the photos are as obtained with the camera and have not been post-processed. The colors and contrasts on the photos are equal or less pronounced than those observed with a naked eye. In particular, photographing the magenta light often resulted in obtaining a white color on the photo. The problem can be solved by reducing the light level (short exposure time, small aperture value), resulting, of course, in a darker background (compare photos in Fig. 2)

### References

1. G.T. Gillies, “Altered light-emitting diode point source emitter,” *Am. J. Phys.* **48**, 418–419 (May 1980).
2. A.A. Middleton and S. Sampere, “Color mixing via polarization,” *Phys. Teach.* **39**, 123–124 (Feb. 2001).
3. I used the following LEDs from Kingbright : red L-53SEC-H, green L-53VGC-E, and yellow L-53SYC-H, and blue NSPB500S from Nichia. Kingbright: <http://www.kingbright-led.com/> Nichia: [http://www.nichia.co.jp/index\\_eng.html](http://www.nichia.co.jp/index_eng.html).
4. You can get one for about \$50 U.S. from Educational Innovations (see <http://www.teachersource.com/>).

PACS codes: 42.66, 42.10D, 85.60

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