Document ID: 09_07_05_1
Date Received: 2005-09-07 **Date Revised**: 2005-10-21 **Date Accepted**: 2005-10-24
Curriculum Topic Benchmarks: S11.3.2, S11.3.6, S12.3.3, S10.4.1, S10.4.2, S11.4.6, S11.4.7
Grade Level: Middle & High School [6-12]
Subject Keywords: light, color, spectrum, spectral analysis, blackbody
Rating: Advanced

Color and Spectrum

By: Stephen J Edberg, Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, M/S 301-486, Pasadena CA 91011
e-mail: Stephen.J.Edberg@jpl.nasa.gov

From: The PUMAS Collection http://pumas.jpl.nasa.gov
©2005, Jet Propulsion Laboratory, California Institute of Technology. ALL RIGHTS RESERVED.

Human beings' color vision allows us to distinguish both large and subtle differences between objects of similar color. Consider a forest, with its multitude of greens. But objects with similar colors are not necessarily the same, as the jade and seaweed found on some Pacific coast beaches illustrate. Researchers, chemists, criminalists, and many other investigators study and compare objects and learn about their compositions by breaking the light down into its composite colors, a technique called spectroscopy (pronounced spek-TRAH-skah-pee). Most people are familiar with a natural presentation of the spectrum (plural: spectra) of the Sun: we call it a rainbow.

In this lesson, students will examine the spectra of three sources of light that have very similar colors. But these sources generate their light by three different mechanisms – electrons changing levels in individual atoms, electrons changing levels in a bulk solid, and a bulk solid heated to incandescence (by electrons passing through it) whose light is then filtered. Light generation is discussed in more detail below in Appendix 1, "Underlying Principles."

The study of spectra, whether from sources that emit light or objects that reflect light, is a very powerful technique. It is used for learning about the compositions and sometimes even the textures of objects, even when they are studied at astronomical distances.

Extensions to this lesson are found in Appendix 2.

OBJECTIVE: Demonstrate that similar-appearing lights can be distinctly different, suggesting that the light emitted is generated in different ways.

APPARATUS: Three different sources of orange light are recommended for this demonstration. All can be purchased at department or electronics stores.

(1) A small **neon hallway light** (sometimes called a guide light). These operate from standard electric outlets and can be found at many discount department stores for less than $5. If possible, remove the diffuser packaged around the neon bulb (the diffuser absorbs a lot of the already-weak light generated by the bulb).

(2) An **orange holiday light** fitted into a standard electric nightlight. Both are available from many discount department stores for less than $10 total. The diffuser/shade that usually comes with the nightlight will not be used.

(3) An **amber light emitting diode (LED)**, current limiting resistor, and suitable low voltage power supply (battery and holder or plug-in transformer). Solder the LED and resistor in series and attach leads to the power supply. An electronics store worker can help you find the right parts. The cost should be less than about $10, depending on the parts purchased.

(4) **Transmission-type diffraction gratings**. These are relatively inexpensive and can be purchased mounted in 35 mm slide frames. Sources for gratings include:

a) Rainbowsymphony.com:
http://store.yahoo.com/rainbowsymphony/difgratslidl.html,

b) learningtechnologiesinc.com:
http://www.learningtechnologiesinc.com/productCat52734.ctlg,

c) scientificsonline.com:
http://scientificsonline.com/product.asp_Q_pn_E_3001307 or
http://scientificsonline.com/product.asp_Q_pn_E_3054509, and

d) sciencekit.com:
http://sciencekit.com/category.asp_Q_c_E_439536.

Choose a grating with 750 – 1000 grooves/mm; fewer gr/mm will work, but the colors will not be as well separated, and differences between light sources may be harder to discern.

Alternatively, you can purchase a sheet of diffraction grating material and slide mounts, from a camera store or on-line, to cut and mount the material yourself.

Make sure you buy a single, linear grating. Some sources offer two-dimensional gratings that generate spectra in a cross pattern or starburst pattern; these will prove quite confusing to users. Mounted gratings cost from about $0.40 to $4.25 each, depending on quality and type of mounting. Cost for an adequate setup should be less than about $40 all together.

The light sources should be mounted together so they are oriented along a vertical line. This allows for easier, direct comparison of their spectra. Mask the neon light and holiday light with black electrical tape, or mount them behind black-painted cardboard, wood, or foam-core with suitable holes cut in it, so the visible parts of the bright, emitting areas match that of the smaller LED in size and shape.

Set up the light source board as far from the first row of students as is practical.

PROCEDURE: Discuss with the students their assumptions about light and color and their origins. Talk about lights in the classroom, traffic signals, streetlights, store sign lights, party lights, campfires, and candles. Discuss the colors, heat generated, and sources of the light.

Now darken the room and examine all three light sources at the same time. Start by comparing the orange lights by eye, without using the diffraction grating. The students should note any differences in the colors of the three sources.

(a) (b)

This figure illustrates (a) the light sources and (b) their respective spectral signatures. For this photograph, slots were made with electrical tape over the circular holes normally used for visual studies so that the spectra would be more distinctive. Observed from student seating, the circular holes should be adequate for discerning the spectral differences.

(a) The left side of the figure shows the three light sources, neon, amber LED, and orange light bulb (top to bottom) and their similar colors. Even though there is little difference between them as recorded by the camera, a careful visual examination of the actual lights shows slightly different shades of orange for each.

(b) The spectrum of each source is displayed to its right. The different appearance of each indicates a different source for the light emission. Note the different "textures" of the spectra and their different extents toward the green and red. Orange is not a "pure" color.

Once everyone has studied the sources alone, the gratings should be used. Orient them so the spectra extend right and left. Students will see spectra going both right and left, and may see more than one spectrum in each direction. Depending on the grating type, either the left or right spectrum may be brighter. To make discussion easier, ask the students to rotate their grating so that the brightest spectrum is to the right or left, as you specify.

Have the students describe what they see and offer their ideas for why similar-appearing sources look so different when their light is spread out.

ACKNOWLEDGEMENTS: This publication was prepared by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

Appendix 1

THE UNDERLYING PRINCIPLES: All the light sources rely on the current of electrons coming from the wall outlet and/or a battery to excite or heat the actual light emitter within each source.

The Neon spectrum is created by the energy released when electrons, excited first by the electric current to higher energy levels, drop back to less excited states within the neon atoms. These levels can be thought of as steps in a ladder, though the separation between steps varies. Each transition from a higher energy step to a lower step emits light, called a spectral line, at a wavelength that depends on the separation between the steps. With many excited atoms, many electrons are moving between steps having different separations and a variety of wavelengths is emitted. Quantum mechanics explains that for each type of atom, the relative positions of the steps are fixed, so distinct wavelengths of light, characteristic of the atoms involved, are emitted. The fundamental equation, discovered in the early part of the twentieth century by Max Planck, is usually written simply as $E = h\upsilon$. Here, E is the energy of the electron's transition, υ is the frequency of the light emitted, and h is a constant called Planck's constant in honor of the discoverer.

In a light emitting diode, electrons within the solid material of the LED also drop from a higher level of excitement to a lower level. Instead of having the multiple, distinct, narrow energy levels of gaseous neon, which limit the wavelengths of light that can be emitted, the complex LED material has a broad upper level and a broad lower level, like two ramps, one above a curb and the other below a curb. Electrons in the LED can jump from any part of the higher ramp to any part of the lower ramp, permitting the emission of light at all possible wavelengths for transitions between the range of energy states within the higher level and the range of states within the lower level.

The light bulb spectrum is emitted by a hot metal, tungsten, with a color pattern filtered by the orange paint on the glass envelope surrounding it. The emission process, also explained by Max Planck, is totally different for this source; it relies on the bulk properties of the atoms in the metal to spread light across the spectrum. The orange paint absorbs much of the blue-end radiation.

Appendix 2

EXTENSIONS: (1) Set up a clear night light bulb with the same wattage as the orange bulb. Use a dimmer or potentiometer (from a hardware or electronics store) to control the voltage passing through the filament. Have the students look at the bulb and its spectrum at full brightness. Ask them to predict what they will see when the voltage is reduced so the filament glows dull orange, matching as closely as possible the orange holiday light. With the room very dark (since the filament will not be bright when it glows orange), reduce the voltage so the clear bulb's filament glows orange. Have the students compare this with the other orange light sources.

This new source will exhibit a full, near-blackbody spectrum spanning violet to red, unlike the orange light bulb, which shows no violet or blue and little green. Even though the orange-filtered bulb at full voltage, inside its envelope, produces large amounts of green, blue, and violet, the orange paint on that bulb's envelope specifically absorbs light with wavelengths shorter than the green that is seen. The clear bulb at full voltage shows what the orange bulb's filament emits before it passes through the orange paint filter.

(2) Have students observe lights around them at night. Storefront lighting exhibits a wide variety colors and sometimes of spectra. "Fluorescent" lights (which are really phosphorescent lights) can now generate colors besides the "cool" (light blue tinted) white that is often used for room illumination. Internally, all fluorescent lights produce the same mercury emission spectrum of traditional fluorescent bulbs (it is visible with a diffraction grating and very different from neon), but a continuous spectrum of light is broadcast as well thanks to the internal phosphorescent coating. The general color of the continuous spectrum from these lights is determined by the phosphor coating on the interior of the tube. Some of the colors now generated by fluorescent lights were once generated with neon and other gases.

Streetlights generate light using high pressure sodium, low pressure sodium, mercury (compare the emission pattern with fluorescent lights), and tungsten. For daylight scouting in advance, golden yellow low-pressure sodium streetlights are built with a rectangular luminaire, whereas the "cobra head" luminaire is more commonly used with orange-pink high pressure sodium or pale blue mercury streetlights. It is interesting to compare the golden yellow color of low pressure sodium streetlights and the similar yellow shade of a tungsten traffic signal (the newer LED traffic signal's shade of yellow may be different). This comparison will demonstrate great differences in their spectral signatures, just as the neon guide light and orange holiday bulb do.

(3) The orange sources in this lesson and the yellow of low pressure sodium street lights and traffic signals are convenient coincidences. Other light sources, especially LEDs and filtered tungsten (colored by [a] the bulb envelope's coloring, [b] with filters used for

photography, [c] made from cellophane wrapping plastic, or [d] plastic report covers) expand the sources that can be compared. Some LED night lights shift colors over a cycle a few tens of seconds long and are very instructive in studies of color.

(4) A hardware store torch or a Bunsen burner will provide a clean flame suitable for studying the emission spectra of some elements. Place a little of the chemical in a wire loop (or on a screwdriver blade) and insert it into the flame. The flame will change color and spectrum. Chemicals to try, individually, include:

Copper chloride, $CuCl_2$ – mixed spectrum; a good light show
Lithium chloride, LiCl – good red spectral line with some continuum
Sodium sulfite, Na_2SO_3 – strong yellow spectral line (sodium is also often seen by placing any metal with sodium contamination in a flame, including a common screwdriver)
Strontium nitrate, $Sr(NO_3)_2$ – yellow, orange, and red spectral lines

(5) Measurements of color extents and spectral line wavelengths can be quantified with tabletop spectroscopes commonly found in high school laboratories or with handheld spectroscopes. Visit these vendors for suitable apparatus:

a) learningtechnologiesinc.com:
http://www.starlab.com/psprod.html (about 1/3 down the web page, cardboard and plastic handheld spectroscope options)

b) sciencekit.com:
http://sciencekit.com/search.asp?t=ss&ss=spectroscope&c=0&x=8&y=10 (for a variety of handheld and tabletop spectroscopes)