PHYSICS OF LIGHT

Light, Energy, and Color

NGSS HIGH SCHOOL LESSON PLAN

Why do we see color? This lesson is designed to help teachers educate students about the connection between energy, light, and the colors we see.

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Image (cover): Gummy bears come in many different colors and flavors. What colors do the gummy bears absorb and which do they reflect? We can predict these properties based solely on the color of the bear in this lab developed by Caltech scientist Astrid Mueller!

Before You Start

1. What do I know about light and solar cells?

Evaluate your prior knowledge of light, energy, and color. This short assessment is meant to help you identify what you *already* know about light and what you might want to review.

Pre-lab Assessment

1. What is light?
    a. A wave
    b. A particle
    c. A force
    d. Both (a) and (b)
2. Mark the following sentences as true or false.
    a. Blue light is more energetic than red light.
    b. Humans can see all wavelengths of light as different colors.

Assessment key:

1. D, light has properties of both a wave and a particle. The light particle is referred to as a photon.

2a. True, blue light has a shorter wavelength and is more energetic than red light.

2b. False, humans can only see less than 5% of the wavelengths of light in the electromagnetic spectrum. These wavelengths are known as visible light and are seen as the colors of the rainbow.

How did you do? Identify the material you need to review from the questions you missed and continue on to #2.

2. Why do we see color?

Now that you've identified what you need to review, take some time to read through the background information on the next few pages. This information should serve to fill in any knowledge gaps you may have identified in #1. Once you are done, continue on to #3.

3. Identify 3-4 learning objectives that connect the background information to the standards.

After reading through the four next generation science standards on page 9, what would you like your students to learn from this lab? To help prompt your thoughts, we've provided example objectives using language directly from the NGSS table.

Example objectives:
Students should be able to:

- Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media
- Evaluate the idea that electromagnetic radiation can be described either by a wave model or a particle model
- Evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter
- Communicate information about how some devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy

What objectives would you like your students to be able to complete?

4. Read through the lab procedure.

After you read through the procedure, check out our demonstration video for a quick refresher. Any questions or concerns? Contact a Caltech scientist! We'd love to answer your questions or clarify any instructions.

5. Assess what you have learned.

At the end of this lab, your students (and you too!) should be able to fulfill all the objectives listed above in #3 along with any alternative or additional objectives you have identified from the NGSS standards. We have suggested some questions to assess what your students have learned. Feel free to use these questions or write your own.

Background Information

The Electromagnetic Spectrum

Light makes up more than just the visible colors that we can see with our eyes. Light can refer to any type of electromagnetic radiation from radio waves to gamma rays. Much of this light is invisible to the human eye, but we can sense it using special detectors like an x-ray machine or a radio.

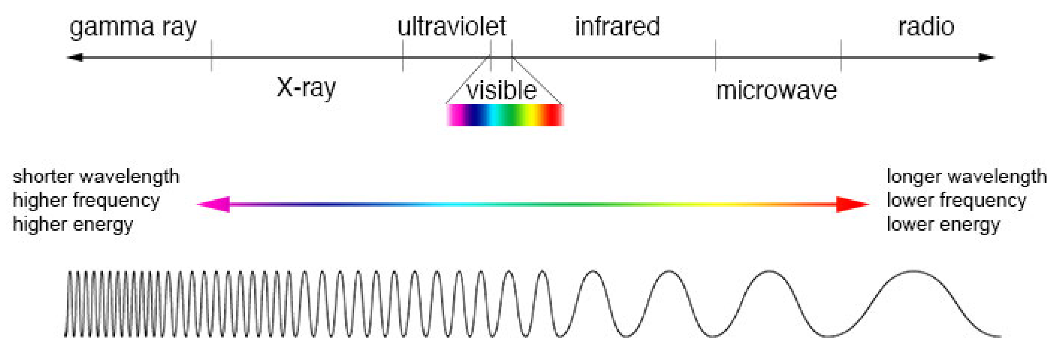


Figure 1. The electromagnetic spectrum

Light can be thought of as both a wave and a particle. In certain instances, light acts like a particle. It only travels in straight lines, can bounce off surfaces and does not need a medium to travel through. However, light also acts as a wave in that light waves can interfere with each other, either adding or subtracting to create diffraction patterns. Light wavelengths also account for the various types of light, their energies, and the colors we see.

Wavelength and energy

Light and electricity deliver energy in very different ways. Electricity has a ba sic unit called an electron. The basic unit contained in light is called a *photon* whose energy (E) is $E = hv = hc/\lambda$, where h is the Planck's constant, c is the speed of light, and v and λ are the frequency and wavelength of light as an electromagnetic wave, respectively. Based on this equation, light with higher frequencies or shorter wavelengths will have more energy. Blue light has higher frequencies (shorter wavelengths) and therefore photons with higher energy, whereas red photons have less energy stored in them. Radio waves have very large wavelengths and therefore the least amount of energy, while gamma rays have tiny wavelengths and massive amounts of energy.

The Solar Spectrum

Sunlight consists of a vast amount of photons each at a different energy. About half of solar photons are in the visible range of light and appear to us as "white light," or a combination of all the colors of the rainbow (red, orange, yellow, green, blue, indigo, violet). The other half of the sun's photons are in the infrared region of the electromagnetic spectrum (noticeable to us in the form of heat). There are also a small percentage photons in the ultra-violet region (which are responsible for sun burns). The graph below shows the relative intensity of the different wavelengths of light we receive from the sun.

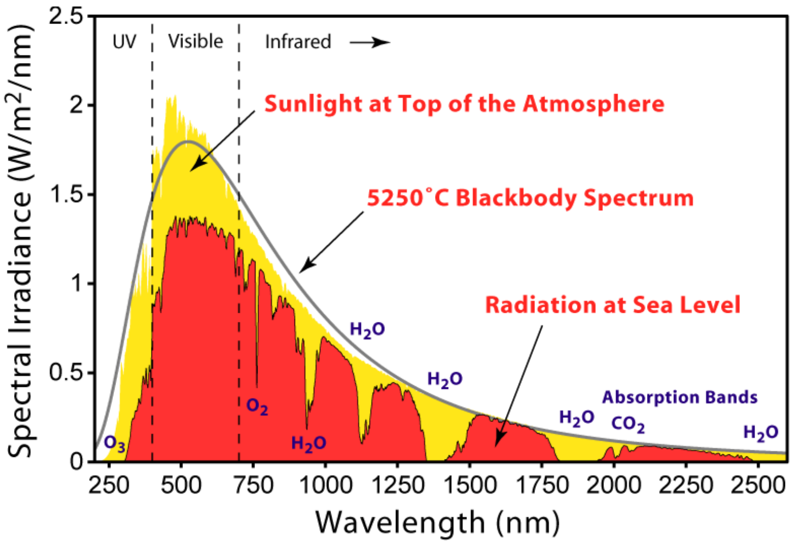


Figure 2. Relative intensities of various wavelengths of light emitted by the sun.

Solar cells

The rate at which photons reach the earth is termed the photon flux (q) Photon flux (q) can also be thought of as the intensity of the sunlight, or how sunny it is. The power (P) of sunlight is the product of the energy and the flux, or $P = E \cdot q$ (typical units are: P is Watts, E is joules/mole, and q is moles/sec). Remember that $E = hv = hc/\lambda$, so $P = hvq = hcq/\lambda$. Depending on its intensity or flux, less energetic light can be just as powerful as more energetic light at lower intensity; i.e. intense red light can be just as powerful as less intense blue light.

Solar cells are ultimately trying to convert solar power into electricity. In order for this conversion to happen, the solar cell must first be able to absorb all of the photons it possibly can, then the cell converts the energy of the photons into electrical energy. One of the simplest ways to improve the power output of a solar cell is to increase the number of photons the cell is able to absorb from sunlight.

The graphs below show the overlap of wavelengths a silicon photovoltaic cell can absorb vs the total solar spectrum and a typical leaf vs the solar spectrum.

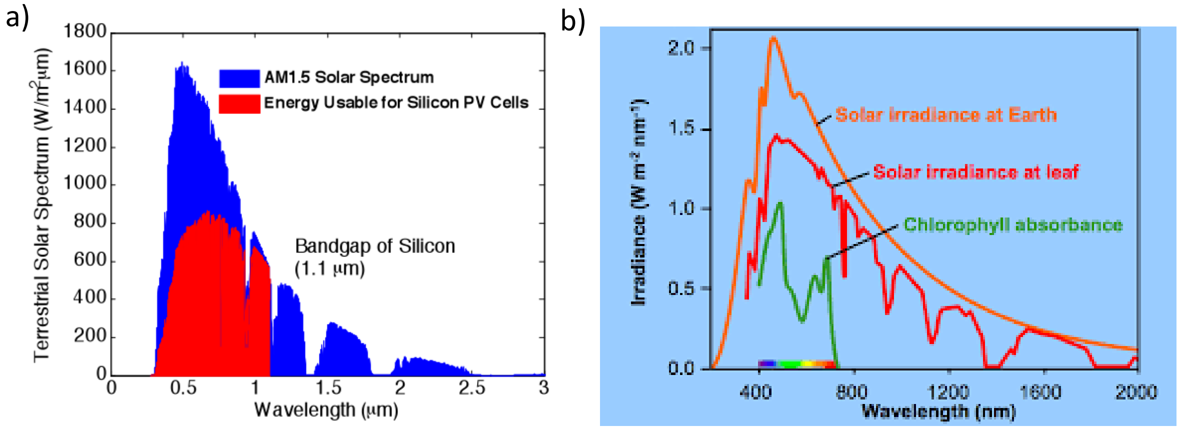


Figure 3. (a) Red shows the total light a silicon photovoltaic can absorb vs. the blue of the total solar spectrum. (b) Green line shows the light absorbed by chlorophyll vs. red of the total solar spectrum.

As you can see, silicon solar cells do a good job of absorbing photons produced by sunlight, but they fail to capture all of them. This is one of the reasons solar cells cannot have 100% efficiency in converting solar energy into electricity. Chlorophyll in leaves absorbs even less photons than silicon solar cells, meaning even nature has not found a way to efficiently convert solar energy into usable fuel.

Light Absorption and Reflection

The radiation from light can be absorbed or reflected. Depending on the material irradiated by the light, the substance can either absorb the radiation and the energy associated with that wavelength of light, or it can reflect the light and its energy back. For example, classic sunscreens contain compounds like oxybenzone or avobenzone, which *absorb* UV light, protecting our skin underneath which would also gladly absorb the radiation. Mineral sunscreens with compounds like zinc oxide or titanium dioxide *reflect* UV light, bouncing it away from our skin. The different ingredients react differently to the same wavelengths of light (though thankfully both materials protect our skin, each in their own way).

Why we see color

A much more obvious example of light being absorbed or reflected by objects around us is color. Depending on the wavelengths of visible light being absorbed or reflected, we will see different colors. If an object reflects all wavelengths of visible light, it will appear white; ie all the colors of the rainbow are reflected back to our eye giving the appearance of white. If an object absorbs all the wavelengths of visible light, it will appear black. No light is reflected back to the eye for us to see a color. The energy of the light is absorbed too, which is why you'll want to wear white rather than black on a warm, sunny day to keep cool.

When only certain wavelengths of light are absorbed and others are reflected, this gives rise to color. Think back to the example of black and white. We see the light that is reflected back into our eye, *not* what is absorbed by the object. Therefore, if an object appears red, that means the object is reflecting red light but absorbing all other colors.

Lights and Pigment

It is important to remember here that light and pigment combine together differently. Light is additive, pigment is subtractive. The primary colors of light are red, green and blue. Any combination of these primary colors of light can generate the other colors- yellow, cyan, magenta and of course white.

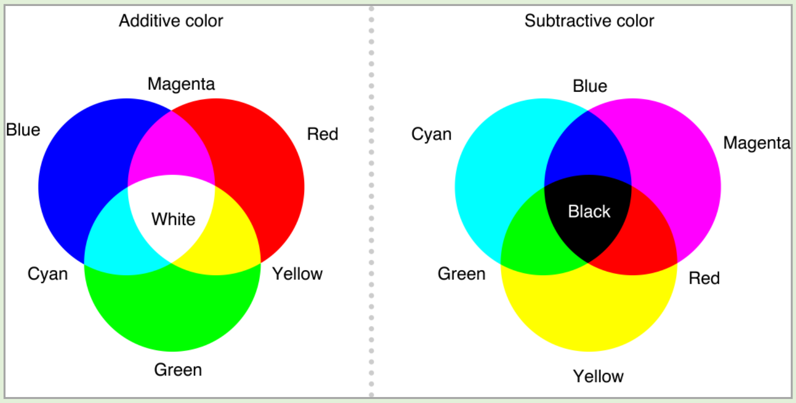


Figure 4. (a) Light is additive color with red, blue, and green as the primary colors. (b) Pigment is subtractive with magenta, yellow, and cyan as the primary colors.

As depicted in the diagram below, an object will reflect back the color or colors that add up to what we see. The remaining color or colors are absorbed. Red objects reflect back only red light, absorbing blue and green. Magenta objects reflect back both red and blue, only absorbing green.

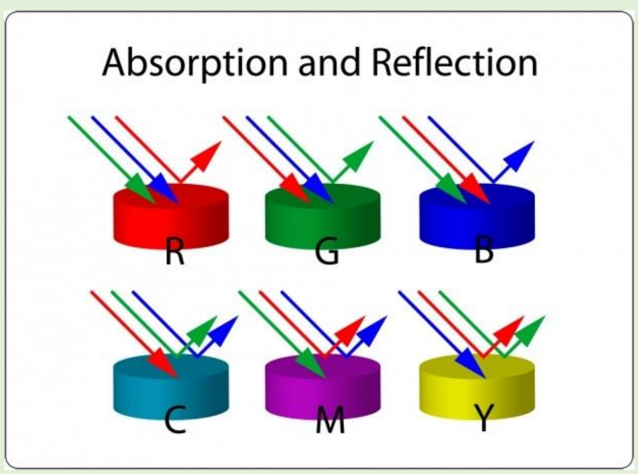


Figure 5. Colored objects reflect back the primary color (or colors that add up to a secondary color) that we perceive.

Next Generation Science Standards

HS-PS4-1. **Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media.** [Clarification Statement: Examples of data could include electromagnetic radiation traveling in a vacuum and glass, sound waves traveling through air and water, and seismic waves traveling through the Earth.] [*Assessment Boundary: Assessment is limited to algebraic relationships and describing those relationships qualitatively.*]

HS-PS4-3. **Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than the other.** [Clarification Statement: Emphasis is on how the experimental evidence supports the claim and how a theory is generally modified in light of new evidence. Examples of a phenomenon could include resonance, interference, diffraction, and photoelectric effect.] [*Assessment Boundary: Assessment does not include using quantum theory.*]

HS-PS4-4. **Evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter.** [Clarification Statement: Emphasis is on the idea that photons associated with different frequencies of light have different energies, and the damage to living tissue from electromagnetic radiation depends on the energy of the radiation. Examples of published materials could include trade books, magazines, web resources, videos, and other passages that may reflect bias.] [*Assessment Boundary: Assessment is limited to qualitative descriptions.*]

HS-PS4-5. **Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.*** [Clarification Statement: Examples could include solar cells capturing light and converting it to electricity; medical imaging; and communications technology.] [*Assessment Boundary: Assessments are limited to qualitative information. Assessments do not include band theory.*]

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
<u>Using Mathematics and Computational Thinking</u> Mathematical and computational thinking at the 9-12 level builds on K-8 and progresses to using algebraic thinking and analysis, a range of linear and nonlinear functions including trigonometric functions, exponentials and logarithms, and computational tools for statistical analysis to analyze, represent, and model data. Simple computational simulations are created and used • Use mathematical representations of phenomena or design solutions to describe and/or support claims and/or explanations. (HS-PS4-1) **<u>Engaging in Argument from Evidence</u>** Engaging in argument from evidence in 9–12 builds on K–8 experiences and progresses to using appropriate and sufficient evidence and scientific reasoning to defend and critique claims and explanations about natural and designed worlds. Arguments may also come from current scientific or historical episodes in science. • Evaluate the claims, evidence, and reasoning behind currently accepted explanations or solutions to determine the merits of arguments. (HS-PS4-3)	**<u>PS3.D: Energy in Chemical Processes</u>** • Solar cells are human-made devices that likewise capture the sun's energy and produce electrical energy. *(secondary to HS-PS4-5)* **<u>PS4.A: Wave Properties</u>** • The wavelength and frequency of a wave are related to one another by the speed of travel of the wave, which depends on the type of wave and the medium through which it is passing. (HS-PS4-1) • Information can be digitized (e.g., a picture stored as the values of an array of pixels); in this form, it can be stored reliably in computer memory and sent over long distances as a series of wave pulses. (HS-PS4-2),(HS-PS4-5) • [From the 3–5 grade band endpoints] Waves can add or cancel one another as they cross, depending on their relative phase (i.e., relative position of peaks and troughs of the waves), but they emerge unaffected by each other (Boundary: The discussion at this grade level is qualitative only; it can be based on the fact that two different sounds can pass a location in different directions without getting mixed up.) (HS-PS4-3) **<u>PS4.B: Electromagnetic Radiation</u>** • Electromagnetic radiation (e.g., radio, microwaves, light) can be modeled as a wave of changing electric and magnetic fields or as particles called photons. The wave model is useful for explaining many features of electromagnetic radiation, and the particle model explains other features. (HS-PS4-3)	**<u>Cause and Effect</u>** • Empirical evidence is required to differentiate between cause and correlation and make claims about specific causes and effects. (HS-PS4-1) • Cause and effect relationships can be suggested and predicted for complex natural and human designed systems by examining what is known about smaller scale mechanisms within the system. (HS-PS4-4) • Systems can be designed to cause a desired effect. (HS-PS4-5) **<u>Systems and System Models</u>** • Models (e.g., physical, mathematical, computer models) can be used to simulate systems and interactions—including energy, matter, and information flows—within and between systems at different scales. (HS-PS4-3) -------------- ***Connections to Engineering, Technology, and Applications of Science*** <u>Interdependence of Science, Engineering, and Technology</u> • Science and engineering complement each other in the cycle known as research and development (R&D). (HS-PS4-5) **Influence of Engineering, Technology, and Science on Society and the Natural World** • Modern civilization depends on major technological systems. (HS-PS4-2),(HS-PS4-5)

<u>Obtaining, Evaluating, and Communicating Information</u> Obtaining, evaluating, and communicating information in 9–12 builds on K–8 and progresses to evaluating the validity and reliability of the claims, methods, and designs. • Evaluate the validity and reliability of multiple claims that appear in scientific and technical texts or media reports, verifying the data when possible. (HS-PS4-4)) • Communicate technical information or ideas (e.g. about phenomena and/or the process of development and the design and performance of a proposed process or system) in multiple formats (including orally, graphically, textually, and mathematically). (HS-PS4-5) **--------------** ***Connections to Nature of Science*** <u>Science Models, Laws, Mechanisms, and Theories Explain Natural</u> <u>Phenomena</u> • A scientific theory is a substantiated explanation of some aspect of the natural world, based on a body of facts that have been repeatedly confirmed through observation and experiment and the science community validates each theory before it is accepted. If new evidence is discovered that the theory does not accommodate, the theory is generally modified in light of this new evidence. (HS-PS4-3)	• When light or longer wavelength electromagnetic radiation is absorbed in matter, it is generally converted into thermal energy (heat). Shorter wavelength electromagnetic radiation (ultraviolet, X-rays, gamma rays) can ionize atoms and cause damage to living cells. (HS-PS4-4) • Photoelectric materials emit electrons when they absorb light of a high-enough frequency. (HS-PS4-5) **<u>PS4.C: Information Technologies and Instrumentation</u>** • Multiple technologies based on the understanding of waves and their interactions with matter are part of everyday experiences in the modern world (e.g., medical imaging, communications, scanners) and in scientific research. They are essential tools for producing, transmitting, and capturing signals and for storing and interpreting the information contained in them. (HS-PS4-5)	

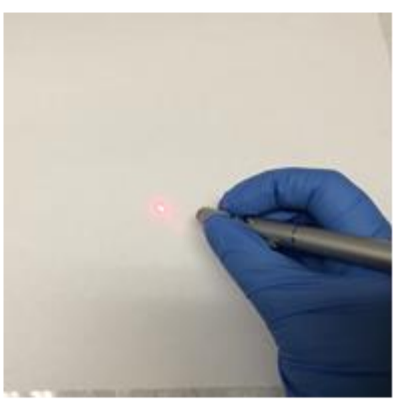
Procedure

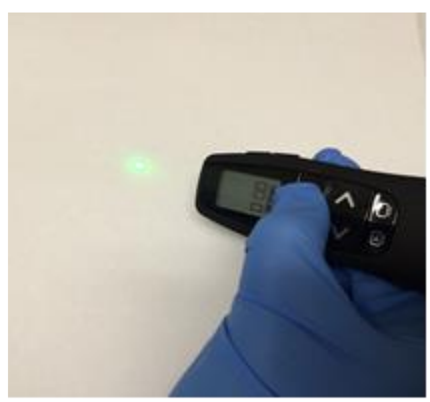
Materials and Supplies

- Gummy bears (red, green, and any other colors)
- Red laser pointer
- Green laser pointer
- White background surface for testing (paper, whiteboard, desk, etc)

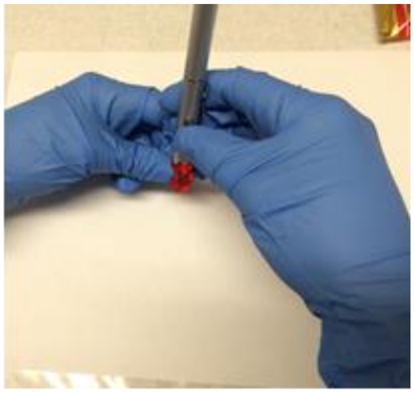
Testing light absorption

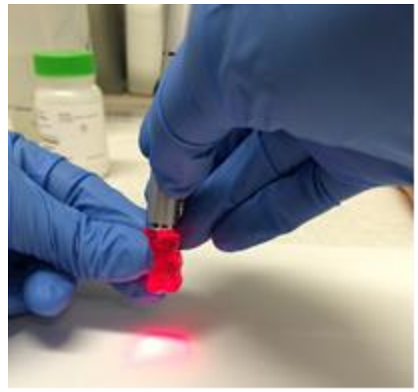
1. Shine the red laser pointer onto the white background to see what the light looks like. Do the same with the green laser.



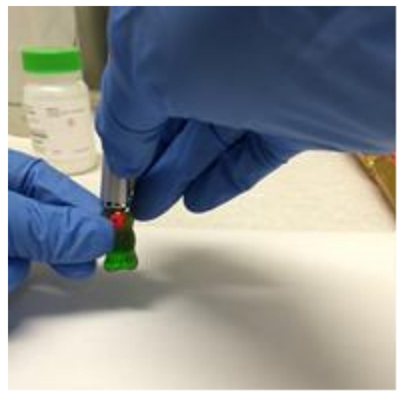


2. Take a red gummy bear and hold it about 1 foot away from the white background surface. Shine the red laser though it. Take note of how the light looks coming through onto the white surface.





3. Next, shine the green laser through the red bear and take note of how the light looks.



4. Repeat steps 2 & 3 on the green gummy bear, shining the red laser and then the green laser through it. Take note of the light coming through the bear.

5. Finally, predict what will happen when you shine the red or green laser through the other colored gummy bears. Test your hypothesis by shining the lasers through the remaining colored gummy bears.

Review questions

1. Write a short description of why the red gummy bear transmits the red light but the green bear absorbs the red light.

2. If you could have a blue laser pointer and a blue gummy bear, what do you expect would happen if you shined the laser on it? What if the blue light was shined on the red and green gummy bears?

3. Let’s relate this experiment to colors we see all around us: Sunlight shines onto a brand new car that we can see as red. Which kinds of light and wavelengths are shining from the sun onto the car? Which wavelengths are absorbed and which are reflected?

4. If you did this experiment with thin plastic light filter instead of a gummy bear, what do you expect to happen? Think about the depth of material that can absorb. (Bonus: try it for yourself!)

5. Now think about solar cells and their dark color- Silicon solar cells you see on rooftops are a dark blue and the blackberry DSSC is a dark purple. Why are solar cells designed to be these dark colors? What does this mean about the light (and therefore energy) that they absorb?

Optional analysis

How do we evaluate whether or not students can successfully fulfill the objectives we set out at the beginning of the lesson? Here are some sample assessment activities based on our example objectives.

Example Objectives:
Students should be able to:

1. Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media

   Have small groups calculate the energy and frequency of the red laser pointer (671 nm) and the green laser (520 nm) in air, using the equation $E = h\nu = hc/\lambda$, where h is the Planck's constant and c is the speed of light. Ask the class to predict if the speed of light be the same in the gummy bears. What might slow light down in the gummy bears? Introduce the idea of refraction: light can be deflected by small particles in the air, slowing its speed slightly.

   Given that the index of refraction (n) of a gummy bear is around 1.5, what is the speed of light in a gummy bear? Remember that $n = c/\mathrm{v}$, where n is index of refraction, c is the speed of light in a vacuum, and v is the speed of light in a gummy bear.

2. Evaluate the idea that electromagnetic radiation can be described either by a wave model or a particle model

   As an extension of #1, have students explain how the concept of refraction supports that electromagnetic radiation behaves as either a particle or a wave. If light can be deflected by small particles, such as the densely packed molecules in a gummy bear, is that a wave or particle property?

3. Evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter

   After the lab, organize students into groups and have them discuss the following questions: What range of light does the human body absorb? Why does the frequency and wavelength of light matter in predicting whether a colored object will absorb it or not? Show the class an article on the effects of UV radiation on skin. Let them come to their own conclusions before asking if there ranges of electromagnetic radiation that are detrimental to human health.

4. Communicate information about how some devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy

   In concert with the DSSC lab, have your students write a summary of how a solar cell works to capture light and convert it to usable energy.