Building Intuition for In-Water Optics and Ocean Color Remote Sensing

Spectrophotometer Activity with littleBits™

By Stephanie Schollaert Uz

PURPOSE OF ACTIVITY

This activity demonstrates optical properties of water: that different constituents in water affect the transmission, absorption, and scattering of different colors in the visible light spectrum. Inexpensive, off-the-shelf components are used to build a light sensor and source, creating a simple spectrophotometer that can measure light absorption. In the second part of this activity, principles of ocean color remote sensing are applied to measure reflectance. Using components that are clearly visible allows students to configure them in different ways. Playing with the instrument design gives students a practical understanding of spectrophotometers, in-water optics, and remote sensing. Students are encouraged to think about how ocean color is used to estimate the concentration of chlorophyll, colored dissolved organic matter, and suspended sediments.

AUDIENCE

This activity includes two parts. The first one builds intuition about in-water optics as a basic demonstration of spectrophotometry. It is suitable for everyone and is especially recommended for graduate- and undergraduate-level students, especially science and engineering students. It has been tested in education settings ranging from formal graduate level courses and K–12 science teacher professional development to informal outreach events attended by families. With appropriate instructional scaffolding, it can engage K–12 students as well. The second part of the activity includes several extensions to demonstrate how satellites measure optical properties of water for more advanced audiences with an interest in ocean color remote sensing or engineering of optical instruments.

BACKGROUND

What Color is the Ocean?

Our perception of color depends on the relative intensity of light reflected at different wavelengths. The qualities of the light illuminating the water, light absorption by the water itself, and light scattering and absorption by water and the constituents in the water all affect how the water looks. That is why very clean water can look deep blue and why water with an abundance of microscopic plants called phytoplankton can appear very green. In coastal and inland waters, dissolved organic matter such as that produced by decaying leaves can color the water brown. Beyond describing it, scientists quantify color by measuring light intensity at different wavelengths and creating a spectrum. The instrument that does that is called a spectrophotometer. Differences in the shape of the spectrum can be used to determine what is in the water, such as how much of the green plant pigment chlorophyll is present.

Why Does the Color of the Ocean Matter?

The capability to detect what is in the ocean has a broad range of applications for society at large and for addressing climate science questions. Phytoplankton form the base of the marine food web, and major fisheries around the world are located in water with high chlorophyll concentrations. Optical measurements of coastal waters are used to monitor and regulate water quality (e.g., runoff, sewage leaks), preserve estuarine ecosystems that protect coastal communities from erosion and storm surge, and identify oxygen minimum zones (a.k.a. dead zones) and harmful algal blooms that can negatively impact fisheries. Globally, phytoplankton play a key role in the carbon cycle; thus, monitoring their abundance and changes over time with the broad coverage enabled by satellites is crucial for quantifying that role.

How Do We Measure the Color of Water?

Here, light transmission at different wavelengths (red, green, blue) is measured through samples of colored water. Clear water is used as the control to characterize the light source and normalize the other samples, blue water represents open-ocean areas with very little productivity (e.g., subtropical gyres), green water represents productive water where phytoplankton are blooming, and water with tea in it represents coastal or estuarine water with dissolved organic material (such as that leached from

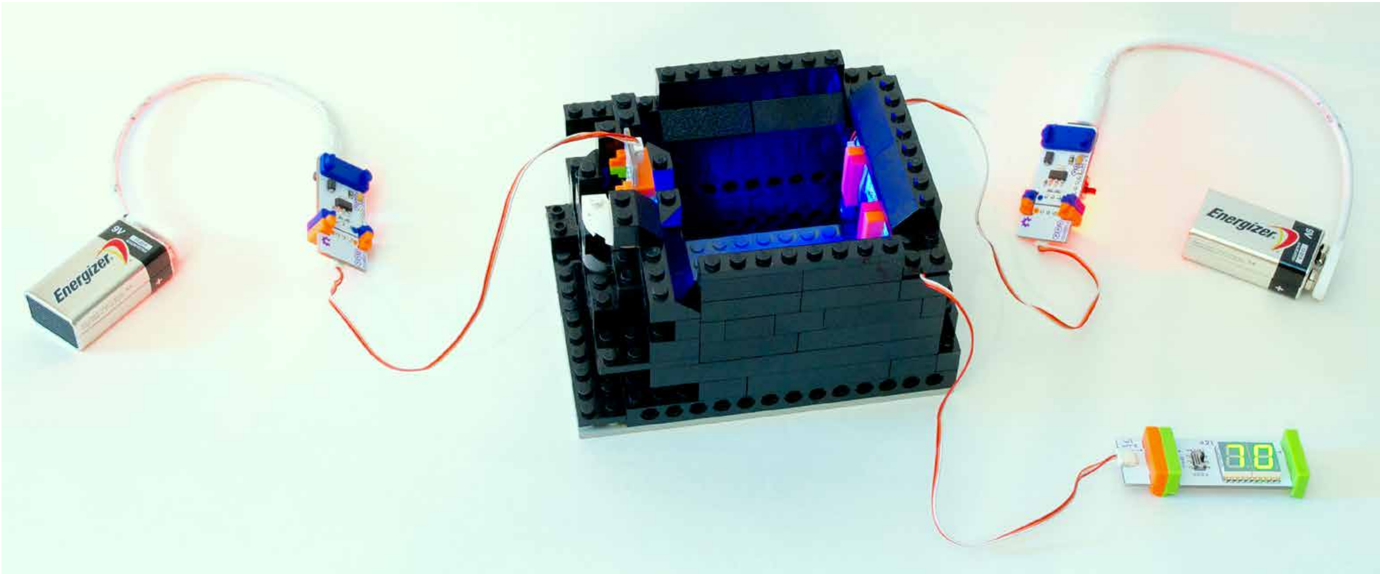

FIGURE 1. The spectrophotometer base is made of Legos® with a gap for the LED light to easily slide in and out.

decaying leaves and soil). The spectrum for each sample demonstrates that the most light transmitted through a medium corresponds most closely to the color of its constituents; the other colors are preferentially absorbed. In other words, blue water transmits the most blue light and absorbs green and red light. A laboratory spectrophotometer is much more sensitive than the one created in this activity and allows measurement at precisely controlled wavelengths (i.e., colors across the entire visible spectrum with tight spectral resolution). However, its optical hardware is hidden and may seem like a black box, whereas all of the littleBits™ components are out in the open here. While a lab spectrophotometer is essential for obtaining accurate scientific measurements, the focus of this activity is not on accuracy but on encouraging students to play with different configurations of the instrument to build intuition about how light is transmitted and absorbed in the world ocean.

How Does This Activity Relate To Satellite Ocean Color Measurements?

Satellites measure backscattered and reflected light from the ocean to derive the concentration of chlorophyll in phytoplankton and other constituents in water. In the second part of the activity, the source-and-sensor configuration is changed to mimic remote sensing. Milk is added to the water samples to increase backscattering. The clear water with milk added is used as the control to characterize the light source, backscattering, and reflectance of the water and other materials (e.g., shiny container), and to normalize the colored water samples. Analogies and differences from ocean color remote sensing are explored.

MATERIALS

- littleBits™ components or their equivalents:
  - 2x battery + cable (http://littlebits.cc/accessories/battery-plus-cable)
  - 2x power bit (http://littlebits.cc/bits/littlebits-power)
  - 3x rgb LED (http://littlebits.cc/bits/rgb-led)
  - 3x wire (http://littlebits.cc/bits/wire-bit)
  - 1x light sensor (http://littlebits.cc/bits/light-sensor)
  - 1x number output (http://littlebits.cc/bits/number-plus)
- Two batteries
- Four square, clear containers of clean tap water
- Blue food dye
- Green food dye
- Cooled tea (e.g., black tea made with a tea bag or strained to remove tea leaves)
- Calculator to divide colored sample values by the clear sample values
- Black cloth to cover water sample being analyzed and minimize ambient light during measurements
- A black base into which the square water containers fit. Secure the LED light on one side of the base and the light sensor directly across (Figure 1). *Note: A simple Lego® structure is used here. A more durable structure could include littleBits™ brick adapter Lego® connections that attach the light and sensor more securely and stay in place while the different water samples are being placed in the holder.*

PART I: SPECTROPHOTOMETER ACTIVITY

Instructor Pre-setup

- Tune one LED light to red (tune up r with the littleBits™ screwdriver, tune down g and b), tune one LED to green (tune up g, tune down r and b), and tune one LED to blue.
- Test the sensitivity of the lights and sensor by securing the light sensor on one side of the black base and the LED light source directly across on the other side.
- *Make sure the LED light is not too bright. Adjust the three light sources and/or the sensitivity of the detector so that the light sources put out distinct colors and read up to 98 when transmitted through clear water. Green values filled in on the example shown for Data Table 1 (online Supplemental Materials) are low but adequate. Keep the same settings for the entire experiment.*

Student Setup and Investigation

- Build a light sensor with battery + power + orange wire + sensor + number display.
- Put together a light circuit with power + bright LED.
- Attach the light sensor to one side of the black base and put the LED light source on the other.
- Use four containers of water (Figure 2). Keep one clear. Put one drop of blue food dye in one, one drop of green food dye in another, and some tea (no leaves) in the last. Mix well.
- Put the clear sample into the base and turn on the first LED light and make sure the sensor value increases (Figure 3). If not, dim any overhead lights in the room or cover the spectrophotometer and water sample with a black cloth to minimize background light.
- Record the LED value in Data Table 1 (online Supplemental Materials) for clear water and the corresponding light color (blue, green, or red). *Note: These values are only used to normalize the colored water samples so do not place much importance on them or how they compare to each other, but do ensure they are less than 99, as tuned prior to having students conduct the experiment.*
- *Note: Shining the LED light directly across the water sample to the light sensor in the exact same location for all samples is essential for consistency and meaningful results.*
- Replace the clear water sample with the blue, then green, then tea samples.
- Place each water sample into the holder and shine the different colored lights through them.
- Record all LED values in Data Table 1 (online Supplemental Materials) for the corresponding light color and water sample color.
- Investigate different colored water samples and how the visible light spectrum varies for each.
- Divide each value by the clear water value for that colored light and multiply it by 100 to get the percentage of light transmitted. Record percentage in Data Table 2 (online Supplemental Materials).
- Plot the three water samples on Graph 1 (online Supplemental Materials): the color of light versus the light transmitted (%).

FIGURE 2. Water samples in straight-sided containers (i.e., not curved).

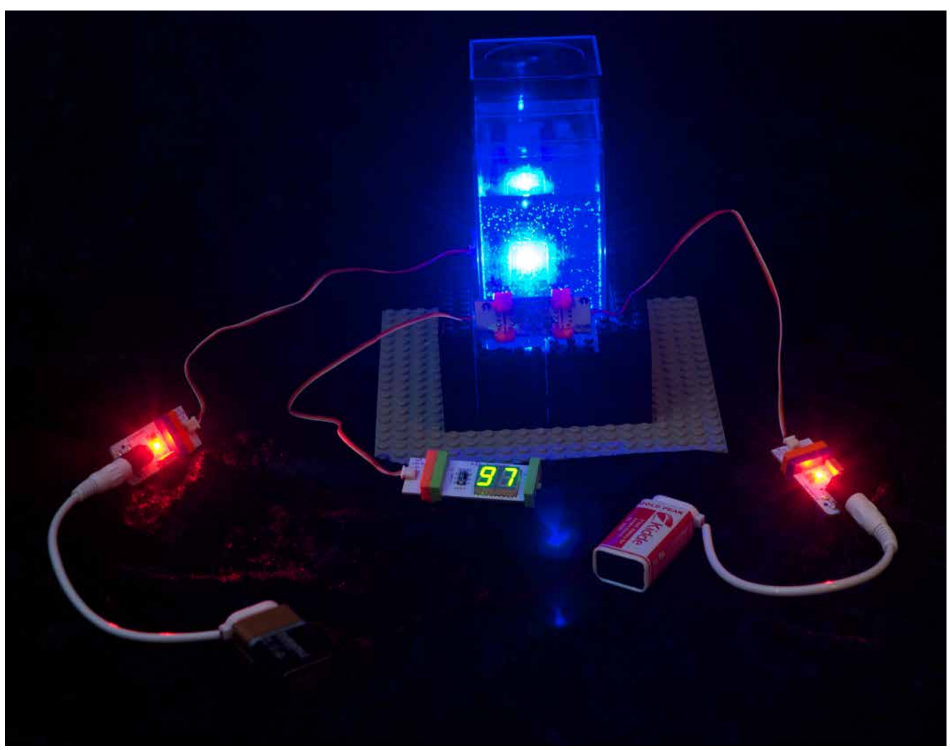

FIGURE 3. Blue LED through clear water, light sensor reading 97.

- Draw a line between the three colors of light for each sample to get the spectrum of that water sample.
- Note the differences between the three water samples tested.

Results

The color of the water affects how much light is transmitted or absorbed. Help students notice that the color of light closest to the color of the water has the greatest percentage of light transmitted and other colors of light are absorbed more. Shine red, green, and blue lights through the blue water sample and notice that the blue light is transmitted most while red and green light are absorbed more. A spectrum is a range of electromagnetic waves in order of wavelength. In the visible light spectrum, red light has the longest wavelength and blue/violet light has the shortest wavelengths. The blue water spectrum has the greatest percentage of light transmitted through it at the blue wavelength; the green water spectrum peaks at green light; the tea water spectrum peaks at red light. These are called spectral signatures.

Extension Questions

- Is water in nature ever colored like this and what could cause it? Have you ever seen blue water, perhaps if you've been to Florida or the Caribbean?
- What do you see when the light shines through the water samples?
- Does the colored light look different depending upon what color water it shines through?
- How sensitive are the results to the distance between the sample and the sensor?
- What happens if a lens is placed in front of the light source to make the light beam more parallel? What if laser pointers are used as the light source?

Real-World Examples

Water that receives abundant sunlight but contains a scarcity of nutrients tends to be blue because the nutrients have been used up (e.g., Figure 4, left). Nutrients that fertilize phytoplankton blooms reach ocean surface waters through river runoff, wind-blown minerals or dust, and upwelling from the deep ocean where there is no sunlight. These processes cause phytoplankton blooms or green water (e.g., Figure 4, right). In addition to nutrients, runoff from land contains colored dissolved organic matter, including tannins derived from dead leaves that make the water look tan or brown.

Optical sensors on ocean color satellites collect information about how Earth looks at different wavelengths of light. Such spectral signatures yield useful information, such as where phytoplankton are located in the world ocean (e.g., Figure 5) and how their abundance changes over time. Transmission, absorption, and scattering of light through water or the atmosphere are used to analyze data collected by satellites. Ocean color satellite sensors measure reflected light, not light that is transmitted all the way across the water sample as a spectrophotometer does.

FIGURE 4. Mediterranean water (left) lacks nutrients and looks blue while the productive Black Sea (right) is green.

FIGURE 5. SeaWiFS satellite image showing the Mediterranean and the Black Seas, where the Figure 4 underwater photographs were taken. Notice the green and brown swirls caused by phytoplankton in the Black Sea.

PART II: OCEAN COLOR REMOTE SENSING ACTIVITY

The second part of this lab simulates ocean color remote sensing with both source and detector on the same side of the container, first by demonstrating how little light is detected when there is no backscattering, then adding paper behind the container to increase reflection, and finally by performing the activity with the addition of a scattering medium.

Additional Materials

- White piece of paper
- Milk

Student Setup and Investigation

- Position the light sensor and LED light source on the same side of the black base and make the same measurements as before (Figure 6). Are there differences among the measurements for the different colored samples?
- Next, put a white piece of paper behind the container, across from the light and the detector. Does this increase the difference between the water samples and different colors of light? Obviously, this method would not work when measuring the ocean from satellites.
- How do satellites measure reflectance from the ocean? Satellite sensors rely on things like particles in the ocean to scatter and reflect the light back toward space.
- Add one teaspoon of milk to the water in each of the four containers so that one has milk, one has milk + blue, one has milk + green, and one has milk + tea. Mix well.
- Measure the values for all four water samples using the three different colored lights, as before, and record in Data Table 3 (online Supplemental Materials).
- Divide each measured value by the milk-only value for that colored light and multiply it by 100 to get the percentage of reflected light that was not absorbed by the pigments. Record the percentage in Data Table 4 (online Supplemental Materials).
- Plot the three water samples on Graph 2 (online Supplemental Materials): the color of light versus the light reflected (%).
- Plot the spectrum for each water sample.
- Note the differences between the three milky colored water samples tested. Compare these spectra to the graph from Part I of the spectra of light transmitted through the plain colored water samples.

Results

With the light detector and the source positioned on the same side of the container, the amount of light reflected or absorbed by the water depends largely upon backscattering by small particles in the water. In this experiment, backscattering is introduced by adding milk. Clear water with only milk added serves as the control and accounts for backscattering from the water and the container. Water with milk plus colors represents ocean water that contains phytoplankton and other constituents. Satellite measurements cannot normalize with an unpigmented sample at each location, so their algorithms for estimating chlorophyll often use band ratios to normalize the spectrum with a

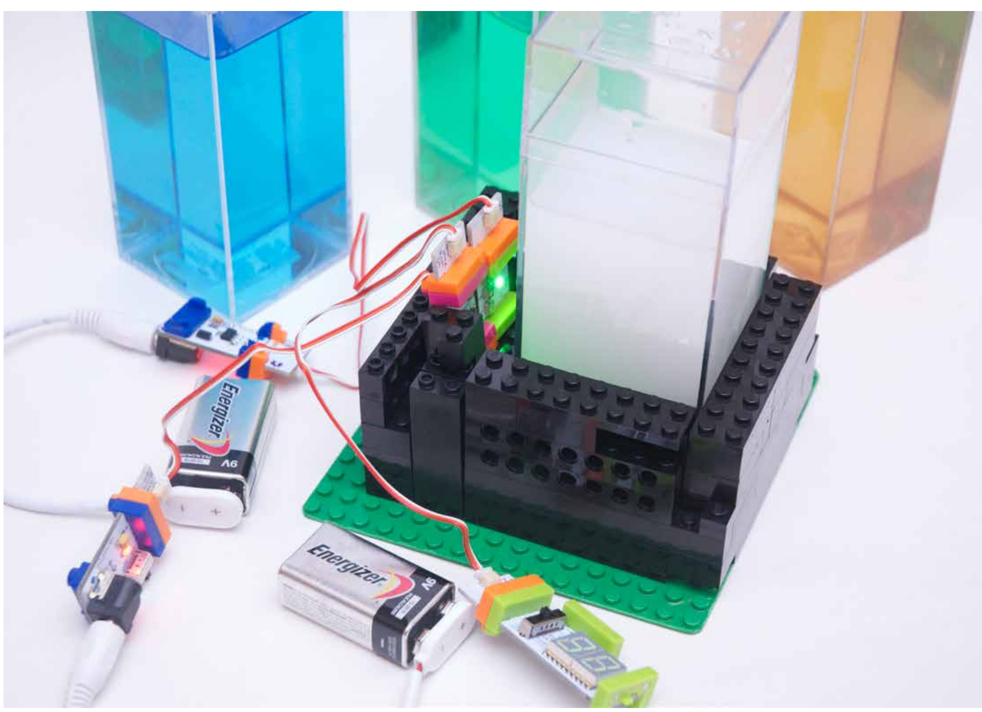

FIGURE 6. LED light source and sensor placed side by side in the base. Milk is added to the water to increase backscattering.

green wavelength where chlorophyll absorption is weakest. In situ sampling is limited by the size of the ocean and the expense of ship time, but measuring the transmission and absorption of light through ocean water samples is important for calibrating satellite measurements. In these activities, the main point is to show students that the color spectrum of the reflected light is largely determined by the spectrum of the pigments in the water. Also note that reflectance measurements are more complicated than absorption and transmission measurements: the measured light level is smaller, making it more sensitive to artifacts such as variations in the amount of milk and ambient light.

Extension Questions

- One complication in this experiment is the reflection off of the container, which is analogous to the sun glint problem in ocean color remote sensing. One possible solution to the glint problem is to wipe the front side of the container with acetone to make it less shiny. *Note that rubbing with acetone will give the side a permanently frosted sheen.*
- The distance that light travels from the ocean to the satellite is immense compared to that in this lab (e.g., 700 km for the satellite and at least seven orders of magnitude less for this activity). What do you think is the biggest complication added to ocean color remote sensing by the extreme distance? *(Hint: Subtracting the intervening atmosphere, which accounts for about 90% of the signal received by the satellite sensor.)*

Precautions

If you get unexpected results that are wildly different from the example at the end, there are a few possible reasons:

- *Is too much ambient light reaching the sensor?*
  First ensure that the sensor is facing toward the water sample and not away from it. Ideally, the only light seen by the sensor should be coming from the colored source after it has passed through the water sample. If too much light from the room is reaching the sensor, you are mostly measuring the ambient light instead of what passes through the sample. Try dimming the room, shielding the experiment with a piece of cardboard, or draping something dark behind or around the experiment. When you turn off the light source, the sensor should show a small number.
- *Are your water samples colored too light or too dark?*
  If your sample is too diluted, the differences in how it absorbs different color lights will be very small. If the sample is too dark, very little light will make it across to the sensor. In either case, you would need a more sensitive instrument to reliably measure the differences.
- *Did you tune the LED light sources too far down in order to get a reading of less than 99 with clear water?*
  If your red light reads 99 with clear water, you can make that number smaller by turning down the r setting on that LED bit. Notice that if you turn down the r too much, the color might look washed out (pink instead of a deep red). That is because the other two color sources (g and b) do not really go down to zero even when turned all the way down, and if r is not turned up to a high enough value, they can compete and produce pink instead of red. Turn up r until the light looks as red as possible, then adjust the sensor sensitivity to get the value below 99.
- *Did you adjust the light sources or the sensor sensitivity partway through the experiment?*
  You are comparing the light levels measured with different color sources through different water samples. It is important that all of your data be measured with the same instrument settings. If you need to change any setting during the experiment, redo all of your measurements, including those with clear water.

SUPPLEMENTAL MATERIALS

The online supplemental materials are available online at http://dx.doi.org/10.5670/oceanog.2016.01 and include:
- Data Tables 1–4 and Graphs 1–2
- Examples of how data tables and graphs might look

ADDITIONAL ONLINE RESOURCES

- What color is the ocean—and why do you need a satellite to tell you?
  http://oceancolor.gsfc.nasa.gov/SeaWiFS/TEACHERS/sanctuary_3.html
- Optical properties of water
  http://misclab.umeoce.maine.edu/boss/classes/RT_Weizmann/Chapter3.pdf
  http://misclab.umeoce.maine.edu/documents/BossOPN.pdf
- Ocean Optics Web Book
  http://oceanopticsbook.info

REFERENCE

Mobley, C.D. 1994. *Light and Water: Radiative Transfer in Natural Waters*. Academic Press, San Diego, 592 pp.

ACKNOWLEDGMENTS

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AUTHOR

Stephanie Schollaert Uz (stephanie.uz@nasa.gov), Senior Support Scientist, Global Science & Technology Inc., works with the new ocean color satellite mission, PACE, and the Earth Science Division at NASA Goddard Space Flight Center in Greenbelt, MD, USA.

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