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One Fish, Two Fish, Catch Me with a Blue Fish? A "Design a Lure for Depth" Challenge

ACTIVITIES AND PROGRAM MODELS

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LISA ANNE PIKE
JESSICA REICHMUTH
*Author affiliations can be found in the back matter of this article

ABSTRACT

Fishermen who understand the science behind underwater vision may have an edge when catching fish. Colors are less intense, and water depth has a profound impact on what colors are visible. Even in the ultra-clear waters of our tropical oceans on a sunny day, light penetrates a surprisingly short distance into the depths. Lure colors that look so bright and alluring in sunlight to the human eye can look drab underwater to the fish we are targeting. In this classroom extension, suitable for middle school marine biology, ecology, physics, or art classrooms, students investigate how colors changes with depth and use that information to color a lure appropriate for a target fish.

CORRESPONDING AUTHOR:
Lisa Anne Pike
Francis Marion University, US
lpike@fmarion.edu

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Fishing is not just a hobby but an intricate blend of skill, patience, and understanding of both the environment and the species being targeted. Lures are used to attract fish and so must mimic prey in color, pattern, and/or movement to get the target fish to bite and make capture possible. One of the key elements that separate an experienced angler from a novice is the ability to choose the right fishing lure, particularly when it comes to selecting the color. Color plays a significant role in attracting fish, and understanding how fish perceive color, how the color changes in different types and depths of water, and which colors are most effective for specific species (as all fish do not see color equally) can be the difference between a successful fishing trip and an unsuccessful one. In this paper I describe an extension to a lesson about the properties of light in water, where students design an appropriate fishing lure. This lesson is NGSS aligned and appropriate for middle school (Table 1).

Table 1 NGSS middle school standards that best apply to this lesson.

CLASSROOM ACTIVITY: THE "WHAT"	STUDENT LEARNING OBJECTIVES: THE "WHY"	SCIENCE AND ENGINEERING PRACTICES: THE "HOW"	DISCIPLINARY CORE IDEAS	CROSSCUTTING CONCEPTS
Students do the Monterey Bay "Light in the deep sea" activity, or NOAA's "Investigation: the science of light and color in the deep ocean" prior to this activity. They collect and use both qualitative and quantitative data and graphically compare deep sea organisms which are red with those that are bioluminescent.	Students will explain how the visible light spectrum changes (or attenuates) as a function of depth.	Developing and Using Models Analyzing and Interpreting Data	MS-PS4-2 Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.	Patterns
Students work in groups to research a target fish, then color a lure designed to best attract that fish in a given water depth, using what they have learned about the attenuation of light with depth.	Students will differentiate between freshwater, coastal ocean, or open ocean patterns of light attenuation. Students will correlate available light as a function of depth and turbidity, and using that correlation will design a lure to attract a specific target fish.	Asking Questions Constructing Explanations and Designing Solutions	MS-ETS1-1 Engineering Design ETS1.B Developing Possible Solutions.	Cause and Effect Structure and Function
Students do a gallery walk to see how each group designed a lure for a specific target fish and water depth. Groups explain their color choices, and there are opportunities to place lure designs under dishes of blue water to see what the lure will look like.	Students will select the best colors for a lure to stand out, in terms of visibility, at a given depth and turbidity. Students will explain, using natural selection principles, that prey fish (or lures) that are camouflaged have a better chance of survival, leading to an increase in that allele in the population. Lures that are visible will result in capture.	Engage in Argument from Evidence	MS-LS2-5. Evaluate competing design solutions for maintaining biodiversity and ecosystem services. MS-LS4-4 Construct an explanation based on evidence that describes how genetic variations of traits in a population increase some individuals' probability of surviving and reproducing in a specific environment.	Systems and System Models

BACKGROUND

The light that humans see, the visible light spectrum, is just a small part of the total electromagnetic radiation that is received from the sun. It lies roughly between 400–700 nm. The longer wavelengths are red and orange; the shorter wavelengths are green, blue, and violet Humans, and some fish, are trichromatic, with pigments in the rods and cones of the eye that are sensitive to red, green, and blue light. Some fish, carp for example, can even see colors that we do not, including ultraviolet (Avery et al. 1982; Hawryshyn & Harosi 1991; Levine & MacNichol 1982). Other fish are monochromatic and see fewer colors than humans. Skipjack tuna are monochromatic and tend to approach prey from below, so prey are backlit - presenting as a single dark color - so seeing fewer colors doesn't present a problem. And, as bass fishermen worldwide seem to know, other fish are dichromatic, lacking cones to detect blue light, but highly sensitive to red light. In fact, experiments using both microspectrophotometry to look at the rods and cones and behavioral training with food rewards for approaching pipettes painted in different colors, indicate that that largemouth bass have rods and cones sensitive to reds and

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greens, but not blue (Mitchum et al. 2019). Interestingly, many fish have photoreceptors in their eyes that match the usual colors in their aquatic environments; that is the photoreceptors have visual pigments whose absorbance spectra matches the colors of the ambient downwelling light (Warrant & Johnsen 2013). Levine and MacNichol (1982) suggest that fish have evolved so that if they live in deep dark waters, their visual pigments have the greatest sensitivity at wavelengths matching the colors of light present in their surroundings, which maximize contrast in darker environments. Conversely, fish that live at shallow depths have multiple pigments and pigments that are slightly off with the maximum sensitivity not quite matching their ambient light, which aids in maximizing visual contrast when in environments with more light surrounding a prey item.

Fishermen who understand the science behind underwater vision may have an edge when catching fish. Colors are less intense underwater, and that is because there is less light beneath the water surface. Even in the ultra-clear waters of our tropical oceans on a sunny day, light penetrates a surprisingly short distance into the depths. Lure colors that look so bright and alluring (pun intended) in sunlight to the human eye can look drab underwater to the fish we are targeting. Fish eyes, like our own with rods and cones for color vision, need light to detect color, but the color also must be there to detect. The problem is, the amount of light available to fish varies with many factors, including time of day and season of the year, whether the fish is in deep water or at the surface, and if the water is clear or filled with plankton, tannins, or sediment.

The amount of light decreases with depth, so as you go deeper it gets darker, and colors are dimmer. This is because light shining on water is either reflected or it penetrates (is transmitted). Reflection is greater when the sun's rays are at an angle (early morning, higher latitudes). When light penetrates the water, its intensity quickly decreases and its color changes. These changes are called attenuation. Attenuation is the result of two processes: scattering and absorption (Jerlov 1976; Warrant & Johnsen 2013; Levine & MacNichol 1982; McFarland & Munz 1975). The famous graphic from Levine and MacNichol (1982) shows a representation of colors at different depths underwater; Marshall (2017) has a more modern version of this - I show these to my students. Ultraviolet, with its short wavelength, scatters the most easily, and reds, with the longer wavelengths, are absorbed more easily in clear water, leaving the greens and especially the blues to penetrate the deepest (Jerlov 1976). This is why clear water appears blue to our eyes (Levine & MacNichol 1982). But how deep? There is no clear answer - at what depth red light becomes fully absorbed is different at different times of day, seasons, and it depends on water clarity (Figure 1). Most temperate lakes and coastal waters have higher nutrient and sediment inputs leading to higher phytoplankton growth and higher loads of dissolved organic material. All colors are absorbed more strongly when there is "stuff" in the water to absorb the light, so light won't penetrate as deeply. Coupled with phytoplankton absorption of blue and red wavelengths preferentially, for photosynthesis, it is the greens and yellows that make it the deepest, which, again, is not as deep as light would penetrate in clear water. This makes most lakes, as opposed to the low nutrient open ocean, look green, not blue, to our eyes (Levine & MacNichol 1982). In swamps and marshes, with high tannin levels, it is red light that penetrates the deepest (Levine & MacNichol 1982).

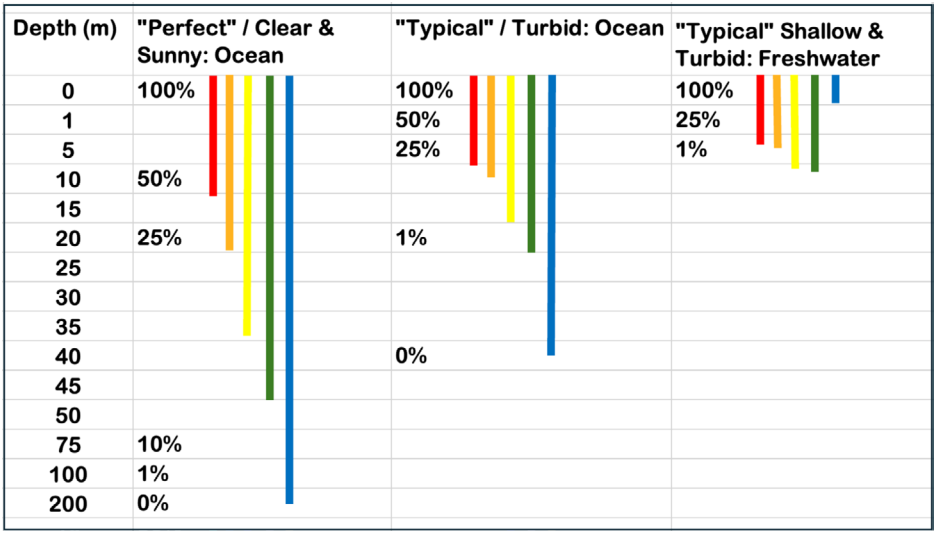


Figure 1 A representation of the maximum depth at which different colors are no longer visible in water under different conditions. The percentage of surface light reaching a depth is also shown.

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Can we put numbers to this? In clear water, at 10 meters deep, only about 50% of the surface light remains, and almost all the red light has been absorbed, although in the clear water of the open ocean, on a clear day near noon, red may penetrate up to 25–30 meters. At 75 meters deep, only 10% of the surface light remains, and, in clear tropical waters at 100 m deep, only about 1% of the sunlight remains, and it is just the blue wavelength. Sunlight won't make it below 200 m deep, and even then, only in clear ocean waters does it ever reach this depth. This attenuation has a direct bearing on how a fish perceives a lure. At a depth of 10 meters, a red lure appears gray, and it eventually appears black as the depth increases. With the increasing depth in oceans, the now dimming light becomes bluish and eventually black when all the other colors are absorbed (Warrant & Johnsen 2013; Levine & MacNichol 1982; McFarland & Munz 1975). Not only does the quantity of light decrease with depth, but so does the quality - it has fewer colors.

Typically, we call the marine zone from 200 m – 1000 m the twilight zone, where the water is clear and the light is dim and blue, and insufficient for photosynthesis. In the open ocean, below 1000 m is called the aphotic zone, where it is always dark. These depths (and the color that penetrates the deepest) are reduced in coastal areas and in temperate lakes, both of which have higher turbidity and higher phytoplankton loads; depths are also reduced in early mornings, on overcast days, or in the late evening. For fishermen, this means that in low light situations, color is less important that other cues like contrast and movement (Olander 2019).

The change in quantity and quality of light with depth is an important concept to teach in your marine science classrooms, as well as your physics or art classrooms. Prior to this 'design a lure' activity, I spend a day doing a hands-on activity to illustrate this concept, using either the Monterey Bay Aquarium's NGSS aligned lesson "Light in the deep sea" or the NOAA investigation 'The science of light and color in the deep ocean' (Monterey Bay Aquarium 1999–2025; NOAA n.d.). These lessons drive home the idea that light influences the coloration patterns of marine organisms: if you are in dim light where only the blue wavelengths penetrate, being red in color makes you appear dark brown or black, camouflaging you. If there is no red wavelength to be reflected into your eyes, you won't see red - unless you bring to those depths your own light, using the flash of a camera or a dive light.

DESIGN A LURE ACTIVITY

I begin the lure activity by showing a photo of a small cut on a SCUBA diver's hand, bleeding slightly. At 10 m under water, blood looks green instead of red. Then I show a quick YouTube video of colorful objects being lowered into deeper water - on video you can see how the non-fluorescent colors dim and disappear. One example of such a video is found at https://www.youtube.com/watch?v=AAJjdA6b4Ts&t=13s (Roberg 2017). This video also includes a fluorescent pink tube which stays bright while red and purple tubes fade to dark as they are lowered. For students who ask why, explain that UV light is absorbed quickly in oceans, but near the surface, in low light UV wavelengths are dominant and can activate fluorescent lures. The fluorophores in fluorescent materials absorb UV, exciting photons of light. These photons quickly return to their normal energy state, releasing light of a slightly longer (more visible) wavelength as they do so. These are my "hooks" for this lesson. My goal for the end of the unit is to get students to understand that color loss at depth is an important consideration when trying to choose appropriate fishing lures. Matching a red or orange jig-head with a gray tail looks like good contrast on the surface but may be a bad move when fishing in deeper water as the jig-head's color will fade to gray or black at depth, and all contrast is lost.

Now that we have investigated how going deeper underwater affects the visibility of color, we discuss how fish benefit from color, making color an adaptation for deep sea fish. Down deep, red can be a color of camouflage, but it isn't only deepwater fish that are red. On coral reefs, where there are colorful red and orange and yellow sponges and branching tree-like corals, red colors and patterns like red striping are common adaptations that aid by camouflaging fish (for example, the northern red snapper *Lutjanus campechanus*, the red grouper *Epinephelus morio*, and the red-banded wrasse *Pseudolabrus biserialis*). Even in less colorful shallow environments, red fish are present, but these fish are often nocturnal, for example, many squirrelfish (genus *Holocentrus*) and soldierfish (genus *Myripristis*) are red (and have large eyes), because whether in a dimly lit area due to depth or time of day, red is seen as dark gray or black in darkness, making it a perfect camouflage color. Other fish have markings that are also adaptive camouflage elements, like eye spots (the foureye butterflyfish, *Chaetodon*

capistraetus) or stripes (particularly stripes running through the eye, rendering the eye invisible, like the eight banded butterflyfish, *Chaetodon octofasciatus).* The copperband butterflyfish (*Chelmon rostratus*) has both an eyespot and stripes, including one which obscures the eye. Still other fish, usually open water surface dwellers, are silvery in color from guanine crystals (in cells called iridiphores) which reflect sunlight and thus can also camouflage fish (Levy-Lior et al. 2008). Countershading is another camouflage pattern, where fish have a dark colored back and a lighter colored belly. When viewed from above, or below, the countershading helps fish blend in with the background light.

Switching topics to fishing, and how color is a large part of fishing lure design, I wonder out loud if fishermen need to match lure colors with the depth at which they are fishing. Indeed, lure color selection is based on several factors, including water clarity, light conditions, fishing depth, and the color spectrum available to the fish.

My first question for students is: what do the lures mimic? The answer is smaller prey fish, crustaceans, amphibians, or insects - lures are designed to attract a target fish and you want the target fish to think the lure is food so that they bite and get hooked. I ask, what makes a good lure? Students know that shape and motion are important, but the number one answer is what the lure looks like - colors and patterns. The right color and pattern can enhance the visual appeal of the lure to fish, increasing the chances of a successful strike. Drawing the target fish's attention is important, and contrast can do this - that's why wild colors like neon green and pink don't imitate nature but still get bites. In fact, with the way colors change underwater, sometimes contrast is more important. Additionally, many prey fish show contrast, such as with striping patterns or countershading, and matching that contrast with more lifelike lures can draw the target fish's attention.

There is both scientific and anecdotal evidence for which lure colors work for which fish. Hseih et al. (2001) found that transparent lures were chosen less frequently than colored lures, and, at roughly 20–70 m deep on longlines, mackerel preferentially chose red and black lures over transparent, blue or purple ones, and chose yellow-green and yellow-orange, pink, and white lures over transparent or purple ones (there was no difference in red or black versus pink, white, or the shades of yellow). They felt that mackerel were choosing lures based on sight, and that in the mid-depth waters the low hooking rate was correlated with lures made of the least visible materials, i.e., the transparent lures. Red and black lures were seen as dark silhouettes and that contrast helped catch more fish. Ajik et al. (2023) trolled for fish in the Philippines using just blue or green lures. Over 1,000 fish were caught, representing nine species (including 5 species of tuna) and the 66% of the fish chose green lures over blue, although the catch per unit effort results were not significant. Their study used multiple lures on each line and lures were approximately 70–90 m deep. Tester and Nakamura (1957) and Wilde et al. (2003) similarly found no color preference for lures, although Tester and Nakamura, who fished for tuna, did note that tuna are color blind. Wilde et al. (2003) fished for bass, as did Moraga et al. (2015) and they note that bass are dichromatic and have difficulty distinguishing blue from green. Wilde et al. used lures patterned to mimic shiners, trout, and fathead minnows, and did find that catch rates were significantly lower for a lure that was green and black striped, but other color/pattern combinations showed no difference. Moraga et al. (2015) captured bass using worm shaped plastic lures that were classified as "dark", "natural", or "bright", and did not find that any one-color category caught more fish. Other research indicates that in shallow murky environments, bright and contrasting colors, such as neon green or orange, can enhance the catch rate because they stand out better against the dark background of murky water; however turbidity due to algae or sediment showed different lure color success where black lures had more success in algal blooms and yellow and gold lures worked better when the water had a lot of sediment (Nieman et al. 2020). Visibility of lures is crucial, they state, as fish rely on their sight for hunting, especially in reduced visibility conditions. Conversely, during sunny days in clear waters, natural-colored lures, like silver or blue, can be more successful, appealing to the fish's natural feeding instincts by mimicking their prey (Ajik et al. 2023). It does make sense that in bright light conditions, shiny colors that reflect sunlight and can be seen from far away work well, and that in low light or deeper waters, darker colors like dull gray or plain white work by creating a silhouette that's easy for the fish to spot (Ajik et al. 2023). It is important to note that there are inconsistencies in the literature, as well as among fishermen, regarding color preferences for individual species. Table 2 gives a few recommendations that I have collated from a variety of fishermen friends.

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shallow = bright, vibrant colors like pink, gold, bright yellow-green	turbid (from algae) = black
clear = bright, vibrant colors like pink, gold, bright yellow-green	turbid (from sediment) = yellow-greens, golds
sunny/bright: shiny, silver, gold, blue	low-light = darker colors or plain white
deep = blues, greens, silver, white	cloudy/overcast = fluorescent

Table 2 Fishermen recommendations for lure colors when water and light conditions are as shown. This information was obtained through personal communication with a variety of fishermen as well as scientific literature.

I give student groups different scenarios such as in Figure 2, then challenge them to make an appropriately colored lure for a specific situation, and students color a lure template and design a poster to explain their choices. Students will need to research their fish (particularly the diet of adult fish, and if the fish tend to choose realistic lures), design a lure to match the depth and water clarity specifications, and defend their design during a gallery walk, usually done Day 2. The gallery walk could include larger clear bowls filled with blue water that you place over each lure. Having bowls that contain a different number of drops of blue food coloring allow you to see what happens to lure colors as the lure goes progressively deeper, because deeper water will be darker blue. There isn't going to be a "correct" answer; this activity is more about letting students do some research and then defend their choices by arguing with evidence. If you have the opportunity to get on the water, there is a device called a "color c-lector" which has a probe you can lower; it will tell you what color is the most visible to the fish at that depth under the present water and light conditions. Did students choose the "correct", i.e., most visible, colors? Another twist is to require students to ask an AI platform to suggest colors for a specific fish at a specific depth and then find the flaws in the AI answer. I've had ChatGPT, in the same "document", advise that red and oranges are filtered out by 15 meters deep, then also say that at 15 meters in freshwater to use bright colors "like red" to attract prey. It is a good lesson on not taking everything from an AI generator as the truth, as well as a lesson on the importance of critical thinking skills. I've thought about secretly telling one group to make a lure design the exact opposite of what they think it should be, then challenge the class to discover the lure that likely won't work. Last, I bring in real lures (Figure 3) as a show and tell.

You work for Lakeshore Anglers as a fishing lure designer. Your boss has a lure design template, and you must color the lure so it will attract your target fish. You will need to defend your design choices to the Board of Directors. Use non-fluorescent colors and add markings as needed.

Your target fish is the ___speckled sea trout___, found at ___6-15 meters___ depth, in the ocean near shore where water conditions are murky and there are sand and seagrass flats.

Figure 2 Sample scenario given to students with the instruction to design a lure that fits these specifications.



Figure 3 Assorted fishing lures showing color and pattern differences.

There are many ways to incorporate this extension, time permitting. In addition to independent research, arguing from evidence, collaborating with a group, and critical thinking, this extension offers opportunities to collaborate with art teachers and community members. Students can make a physical (art) model of the lure instead of a poster. Students who fish have an opportunity to act as the classroom expert, or you can bring in a professional sport fisherman (or fisherwoman), a fishing industry representative, or representatives from the schools fishing club to talk or to judge student posters. Fly fishing clubs often have introductory classes and could bring some fly rods to the class for students to try out, and this adds a twist to an assessment opportunity: design the best fly to catch salmon in the Great Lakes in June (and defend your choice). With older students I may delve into the scientific literature on colors versus catch rate, and use real data to teach interpretation skills. While not all students are interested in fishing, there is enough in this lesson to "catch" most of your class.

To conclude, students participating in the activity develop a deeper understanding of the implication of light attenuation, especially in cases of environmental monitoring (for example, sedimentation due to land use changes, or the presence of oil due to spills, can affect light attenuation, which in turn affects biological processes like photosynthesis). From an engineering standpoint, aquatic monitoring equipment is now based on optical measurement techniques, but surface waves and clouds can affect how well the probes can function. This activity helps students understand why photosynthesis occurs in the surface waters, and why the ability to detect prey (or predators) can change on a daily, or even hourly, basis.

COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR AFFILIATIONS

Lisa Anne Pike orcid.org/0000-0002-0463-5869
Francis Marion University, US
Jessica Reichmuth orcid.org/0009-0003-7515-9964
Francis Marion University, US

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