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There's More to Light Than Meets the Eye

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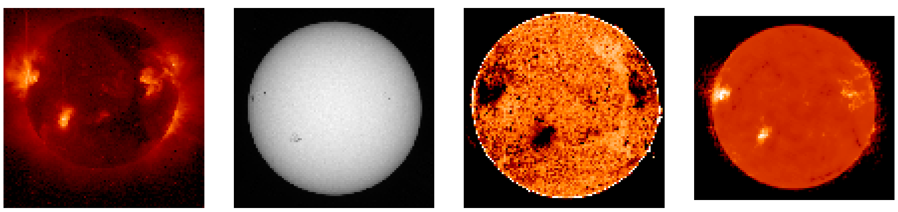


Bionic eyes. If our eyes could see in different wavelength bands, this is what the Sun would look like. From left to right, these images show the Sun at x-ray, visible, infrared, and radio wavelengths. Photos courtesy of Yohkoh, BBSO, NSO, and Nobeyama Radio Observatory.

If you want to reduce your class size, try sending a note home with your students asking for parental permission to conduct classroom experiments with electromagnetic radiation. It is probably the "radiation" part that would induce fear. The word has long been associated with lead suits and red buttons, accidents and bombs whose emitted radiation is hazardous.

But not all radiation is dangerous. Visible light, crucial to photosynthesis, is a type of radiation. So what is this phenomenon that both gives and takes life?

Over the past 100 years, there has been a revolution in our ability to understand light and its sibling forms of radiation. At the heart of this revolution is the recognition that light travels as a wave. It sounds simple enough, but this basic realization has rippled throughout our society. It has unleashed whole new technologies, from radio transmitters to lasers. It has infused new scientific theories that, in turn, have led to other technologies, including electronics. And it has helped to push astronomy from an intriguing pursuit, akin to stamp collecting, to an analytical science.

The information riding on waves of light tell us what stars are and, ultimately, what we are. Light reveals how far away stars are, how fast they move, what chemical elements they contain, how massive they are, and whether they have planets. One day, maybe soon, the faint light from a planet may bring the news that we are not alone.

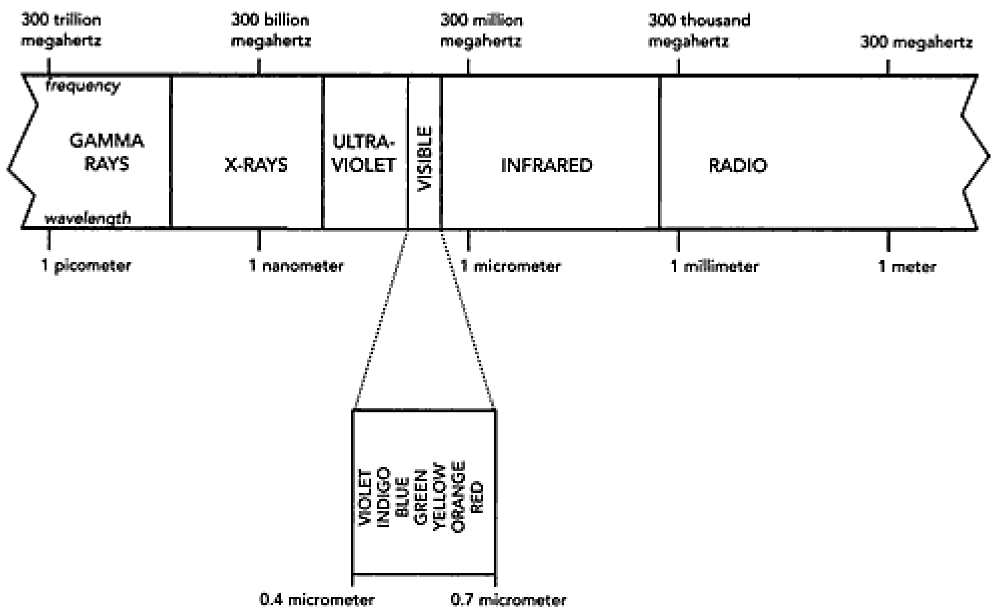
For teachers, one of best things about light is that it is cheap. Light experiments are easy to carry out in the classroom and can be adapted to a broad range of student abilities (see activity). Students can make rainbows. They can learn why mixing red, green, and blue pigment makes black paint, whereas mixing red, green, and blue light makes white light. They can learn not only about light, but also about the methods of science.

Catch the Wave

Our peephole to the universe was once the visible window the relatively small range of light wavelengths to which human eyes are sensitive. In the last 50 years, new instruments, such as radio telescopes and ultraviolet detectors, have become our seeing-eye dogs outside that window. Now we are experiencing the once-invisible phenomenon of the universe: the birth of stars, the munchings of cannibalistic galaxies, the afterglow of the Big Bang. The broad range of invisible and visible wavelengths through which we now view the universe has that descriptive, if awkward, 10-syllable name: *electromagnetic radiation.*

Electromagnetic radiation is one of the many forms that energy can take. As the name implies, this energy has two components: electric and magnetic. The components themselves are invisible; they exist in the form of electric and magnetic fields (see *Dreams of Fields*).

Like runners in a three-legged race, the two fields are locked together. Together they urge each other on, radiating, or traveling, through space. Like runners, the fields vary in strength. They weaken, then regain strength, then weaken again, and so on. When the electric field is strongest, so is the magnetic. When the electric field sags, so does the magnetic. When you combine these two basic ideas motion and oscillation - you have the very definition of a wave. There are other kinds of waves, such as sound waves and water waves, but they involve vibrations in solids and fluids, rather than in electric and magnetic fields. The oscillation of the fields happens at a regular rate, known as the *frequency.* By the time the fields go from strong to weak and back to strong, the wave has moved a certain distance, known as the *wavelength.*



The many hues of light. Our eyes are sensitive to just a small portion of the total grandeur of electromagnetic radiation. Only in the past century have surrogate eyes, such as radio antennas and ultraviolet sensors, let us see the invisible wavelengths. As the wavelength increases, frequency decreases -- and so does the energy.

Red light, blue light, infrared light, ultraviolet light, radio waves, x-rays they all consist of moving, oscillating electric and magnetic fields. We often think of radio waves as something we *listen* to. But that's just because the radio receiver translates the radio waves into sound waves, just as a television translates radio waves into pictures. The radio waves themselves are basically the same as light.

Although these forms of radiation are all electromagnetic, they do interact with matter in quite different ways. What makes some forms of radiation dangerous, others beneficial, and the rest indifferent?

Compare the wavelength of a radio wave with that of an x-ray. The wavelength uniquely identifies the type of radiation. Radio waves are between a millimeter and hundreds of kilometers long that's why TV and radio antennas are the size they are. X-rays, by contrast, are about a billionth of a meter long. If you could magically squeeze an electromagnetic wavelength from 1 meter to 1 billionth of a meter, you would *presto-chango* have turned a radio wave into an x-ray. For visible light, the wavelength identifies the color of the light. If you could compress the wavelength of red light roughly in half, the light would turn blue.

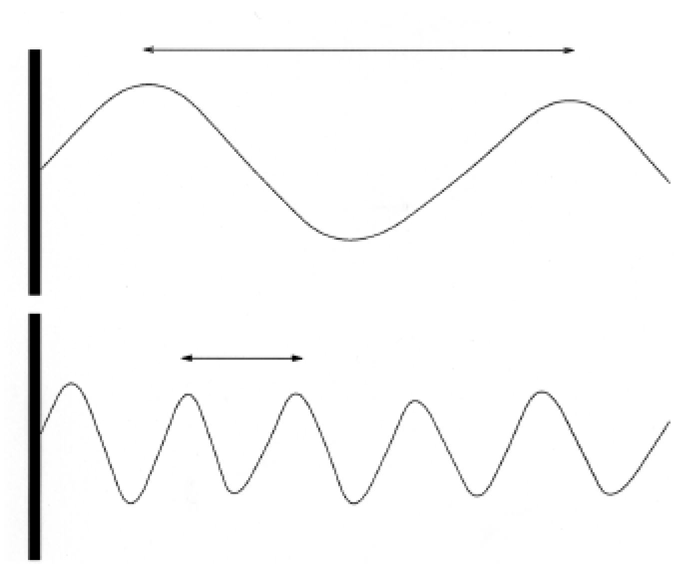
So the question really is: What makes the length of the wave so critical? How can it be responsible for the differences in the way radiation interacts with matter?

There's More to Light Than Meets the Eye

Making Waves

To understand this, think about the following experiment. Imagine you have a 3-meter (12-foot) rope and tie one end to a door knob. Now you move the other end of the rope up and down until the rope makes a wavy pattern with two peaks. Measure the distance between these peaks with your mental ruler to get a feel for the length of the wave. Think about how much energy you are expending to create this wave; that is, how fast do you get tired?

Now suppose you start to move your arm up and down so that you make five peaks, while keeping the height of the wave the same as before (see diagram). (Aren't you glad this is just a thought experiment?) How has the wavelength changed? How has the energy you put into the wave changed? Stop here and write down a physical relationship between the input energy and the wavelength. A simple phrase is fine. For example: "The wavelength ________ as the input energy ________."



Standing waves. Tie a rope to a door knob and make a wavy pattern by moving your arm up and down. Which of these two patterns require more energy on your part?
Diagram by Debra A. Fischer

Done? Good, now you're a theoretical physicist! Hopefully, you have deduced that short wavelengths require more energy than long wavelengths. To become an experimental physicist, you have to actually tie the rope to the wall and make the measurements. Try using a long Slinky. It's easier to visualize standing waves in a rope, but easier to create them in a Slinky.

The same concept applies to electromagnetic radiation. The energy put into the wave equals the energy transmitted. Unit for unit, long-wavelength radiation (such as radio waves) transmits less energy than short wavelength radiation (such as x-rays). It's a big difference. If the wavelength changes 1 billion times, then the energy changes 1 billion times.

Now you can see why x-rays are generally more dangerous than radio waves. X-rays pack more punch. Not only that, but their small wavelength allows them to penetrate deep into the human body, right into our cells.

For the same reasons, ultraviolet radiation is more dangerous than visible light.

The different types of radiation can also be defined by their frequency. The frequency is just the number of waves that go by each second. If you stretched the wavelength, fewer waves would go by every second, so the frequency would go down. In the rope experiment, the frequency was the number of times your arm went up and down each second. To make a shorter wavelength, you had to move your arm with a greater frequency.

X-rays have a smaller wavelength than radio waves; therefore, they have a greater frequency. This is what the frequencies on your radio dial mean. If you could somehow tune your radio receiver to 1 trillion megahertz, you could pick up x-rays. At 600 million megahertz, the receiver would detect light. In reality, though, no single receiver could detect all frequencies of electromagnetic radiation; the energies span too wide a range.

A radio antenna is one of the many contraptions that can detect or create electromagnetic radiation. The antenna does its thing because electrons inside the antenna accelerate up and down (assuming the antenna is vertical). This up-down motion occurs at a certain rate say, 1 million times per second, the frequency of a 1-megahertz AM (medium-wave) radio station. If the antenna is transmitting, the up-down motion of the electrons produces an electromagnetic wave with the same frequency. The energy carried by this wave comes from the energy used to push the electrons up and down; this energy, in turn, comes from the electric current from the radio transmitter. To increase the transmission frequency, you'd have to increase the frequency of the up-down motion, and, everything else being equal, this would take more energy. Your electric bill would go up.

Faster Than a Speeding Bullet

Whether they are the visible light from the head lamp of an oncoming train or the microwaves warming your leftover supper, electromagnetic waves share a special property: If you multiply the wavelength by the frequency, you always get the same number.

Can you guess what that number might be? Like all great scientists, find a way to cheat, uh, I mean cleverly deduce the answer. A standard trick that scientists use is to look at the measurement units of the quantities being multiplied. Wavelengths are distances, usually measured in meters. Frequencies are numbers of waves per second. Therefore, wavelength times frequency must have units of "meters per second." That, of course, is the measurement unit of speed. The magnitude of this speed is the speed of light: 300 million meters (186,000 miles) per second. In the 19th century, scientists noticed that the speed of light equals the speed of an electromagnetic wave. This was evidence that light is a form of electromagnetic wave.

From this relationship of wavelength, frequency, and speed, you can calculate the wavelength for a particular frequency, or vice-versa. Just divide the frequency into the speed to get the wavelength. For instance, an FM radio station at 106 megahertz (106 million waves per second) broadcasts a wavelength of about 3 meters (9 feet). An AM (medium-wave) station at 1,000 kilohertz (1,000 thousand waves per second) broadcasts a wavelength of about 300 meters (1,000 feet). This is why AM stations, unlike FM ones, fade out when you drive under a bridge: The AM wave is too big to fit under the bridge.

Comparing the speed of light to the speed of an electromagnetic wave is one of the many ways that scientists have tried to unlock the secrets of radiation. Whenever we talk about radiation, we are like children with an early birthday present. We can pick it up and shake it. We try to guess what it is. But we are not allowed to open it. After all, you can't lay radiation on a laboratory bench and dissect it. In the 19th century, scientists shook the mysterious box of electromagnetic radiation -- "light," as its most familiar wavelengths are known -- and found that it was a wave.

Later, scientists shook the box a different way and found something else. Their experiments indicated that, in fact, electromagnetic radiation is a particle, like a minuscule grain of sand. They gave this particle a name: *photon.*

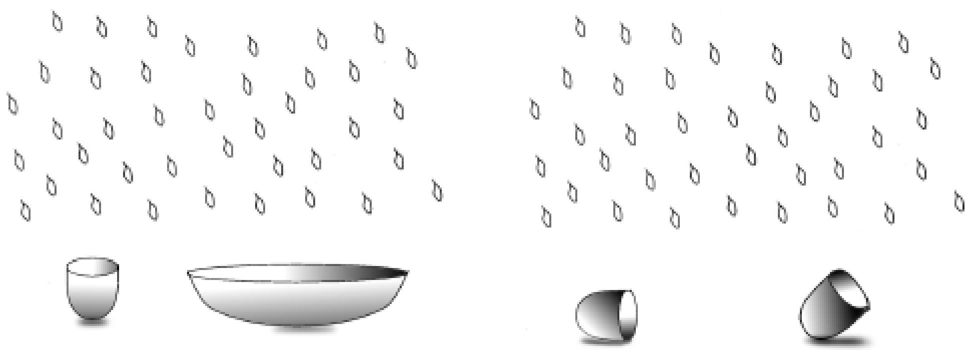
This means that light comes in little chunks. It's not a continuous wave, but more like a series of waves. Each of the chunks, the photons, has an energy that depends on its wavelength (or, equivalently, frequency). A radio-wave photon has a billionth the energy of an x-ray photon. If you want to send a certain amount of energy, you could send one x-ray photon, or you could send a billion radio photons.

In Flux

The electromagnetic radiation that streams out of the Sun is a hailstorm of photons. The x-rays are like bowling-ball-size hailstones: potent, but thankfully rare. The radio photons are like the very smallest hailstones: puny, and also relatively uncommon. Visible-light photons are like your average-size hailstones: neither especially strong nor especially weak, and by far the most common.

The photons that fall upon the Earth provide the energy that keeps plants alive, powers our weather systems, and warms our skin on a sunny day. To collect the photon hailstones, you might imagine setting out a sort of bucket. A solar panel is an example of a photon bucket. So is a telescope. The rate at which these buckets collect energy is called the *flux.* Flux is measured as the energy per second that falls on a unit area, such as a square centimeter.

What happens when you tilt a bucket? How does this affect the number of photons or hailstones you catch? Try this with a readily available photon bucket: your hand. On a sunny day, hold your hand palm up. Wait a few seconds until you notice the warmth of the Sun. Then slowly rotate your hand so that your palm tilts away from the incoming light and your thumb points toward the sky. You should notice less heat on your palm. This is because flux of solar energy onto your palm has decreased. The flux that photon buckets intercept depends on the angle between the incoming photons and the opening of the bucket (see diagram).



Rain gauge. If photons of light are like raindrops, then telescopes are like buckets. The rate of rainfall onto a unit area is called the *flux* of rain. If two buckets, large and small, are sitting flat on the ground, the *flux* into both is the same. The large one traps more flux, and therefore more water left). If you tilt a bucket, it'll gather less rain; the flux into the bucket, relative to the area of the bucket, will decrease (right). The same ideas apply to telescopes and other light buckets. To gather the most light, you want as big a collecting area as possible, and you want to orient the area so that it isn't tilted with respect to the light source. Diagrams by Debra A. Fischer

A house plant that is starved for sunlight will turn the flat surface of its leaves toward a nearby window. The plant is reorienting its photon buckets to collect the greatest amount of flux. With time, the plant will develop a contorted shape as it grows toward the window, a process known as *phototropism.* Another way to demonstrate the concept of flux in the classroom is to use solar cells. Put a light bulb in a circuit powered by a solar cell. As you rotate the cell, watch the intensity of the bulb change.

This business of tilting photon buckets explains why we have seasons. The angle between sunlight and the surface of the Earth, and therefore the flux of the sunlight, is smaller in winter than in summer [see "To Every Season There Is a Reason," *The Universe in the Classroom,* Winter/Spring 1995].

These, then, are the three major principles that teachers can convey to students: Light is the same basic type of wave as radio, x-rays, and so on; it comes in little packets whose energy depends on wavelength; and collecting lots of these packets provides the energy to drive photosynthesis, climate, solar panels, and so on.

There's More to Light Than Meets the Eye

Humpty-Dumpty White Light

It is difficult to do experiments with K12 students which demonstrate that light involves electric and magnetic fields. Most experiments with electromagnetic radiation study the different wavelengths of visible light. Visible light ranges from 400 nanometers (400 billionths of a meter, corresponding to violet light) to 700 nanometer (red light). The classic demonstration is to make a rainbow, or spectrum, out of white light (see activity). The Exploratorium's *Science Snackbook* has other demonstrations that involve mixing colors of light.

Experiments with ultraviolet and infrared light reinforce the idea that electromagnetic radiation extends beyond the visible wavelength range. Experiments with ultraviolet light, in particular, are visually impressive. For advanced students, these experiments can show how light reveals the structure of atoms.

Fluorescence with ultraviolet light

Light just beyond the violet edge of the visible spectrum is called *ultraviolet* light. As anyone who has been sunburned knows, ultraviolet photons carry *more* energy than the visible variety. You should protect your eyes by wearing UV-absorbing goggles. Another safe alternative is a light-viewing box, available from scientific supply houses or easy to build yourself. In such a box, the UV light is directed away from the eyes toward the black interior of the box, where it is absorbed and safely emitted at longer wavelengths.

The best UV light sources produce both long-wavelength (300-400 nanometer "black light") and short-wavelength (less than 300 nanometer) light. Fluorescent minerals or dyes, which absorb the UV light and emit it as visible light, create a spectacular demonstration. If you switch the UV light from long-wavelength to short-wavelength, you will see a difference in the color (wavelength) of the emitted light. The phenomenon of fluorescence involves the structure of atoms (see Inside an Atom).

Blocking UV light

Visible light penetrates glass. We can see it! But UV light does not. Put a fluorescent mineral inside a light box containing a UV source. Then cover the mineral with a glass jar. Is the rock still fluorescent? How quickly does the fluorescence turn off? Does it make a difference if the UV light is long-wavelength or short-wavelength? Other materials, such as a plastic cup or UV-absorbing goggles, can also be tested to see whether they block UV light.

Infrared light

Light just beyond the red edge of the visible spectrum is called *infrared* light. Its photons carry less energy than those of visible light. Our hands are better detectors of IR light than our eyes. Things that emit in the IR feel warm: fire, electric heaters, Sun-baked pavement.

The ASP's Project ASTRO activities handbook, *The Universe at Your Fingertips,* describes an experiment to test whether there is light below the red edge of the visible range. This experiment involves three thermometers, which measure the temperature of the air where the experiment is being done. Break sunlight into a spectrum using a prism and place the thermometers at three points in the spectrum: one in the violet range, one in the yellow range, and one just barely beyond the red end. What do the thermometers read?

In the Dark

It is easy to have misconceptions about a topic as abstract, yet misleadingly common sensical, as light. Drawing out these misconceptions is an important first step to rebuilding students' knowledge. Students commonly have trouble understanding that the visible window is just one small part of a continuum of electromagnetic radiation (see Dreams of Fields). The reasons may include:

- X-rays and ultraviolet radiation are hazardous. Visible and infrared are life-saving. So how can they all be the same type of radiation?
- We see visible light. Therefore, it must be different from the other radiation we can't see.

Another source of confusion is the different results students get when mixing colors of light, as opposed to mixing colors of pigments. Mixing red, green, and blue light makes white light because these are the wavelengths that comprise white light. By contrast, mixing red, green, and blue paints creates black ‹ the absence of light and color. This happens because the red paint absorbs all colors except red light; the green and blue pigments absorb the red. Only when we confront our misconceptions can we can begin to replace them with facts.

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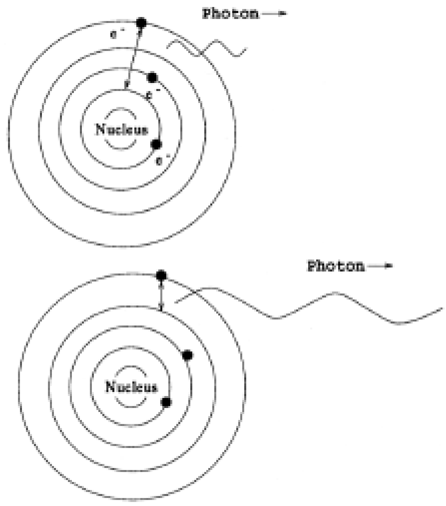
Inside an Atom

Light lets us peek inside the atom -- if we know how to look. According to the simple Bohr model, an atom consists of a nucleus around which electrons buzz in orbits. Each electron orbit represents a discrete energy level; the lowest energy levels are those closest to the nucleus. It takes energy to move up to a higher level.

A photon of light provides the energy that an electron needs to climb up a level. If the photon comes close enough to an atom, it can be absorbed by the atom, pushing the electron up (see diagram below). Depending on how much energy the photon contains, the electron might move up one, two, a few, or many energy levels. If the energy is great enough, the electron may go flying out of the atom altogether.

Atoms are good at absorbing energy, but not so good at holding on to it. Within a few billionths of a second, the electron comes bumping back down to a lower level. Each bump is a step from a higher energy orbit to a lower energy one. At each step, the atom must spit out a photon whose energy equals the energy difference between the two levels.

The key thing is that the atom does not have to release a single photon of light. It can, and often does, release light in a whole series of steps. In this case, the total energy from all the steps must equal the energy of the initially absorbed light. Because there are several outgoing photons, each individual photon is lower in energy -- therefore, longer in wavelength -- than the incoming photon. That's how atoms can turn ultraviolet light into visible light.



Emission from an atom. The Bohr model of the atom gives a rough idea of what happens when an atom absorbs or emits light. The atom looks like a miniature solar system: a nucleus surrounded by electrons in various orbits. In the top case, a photon of short-wavelength light is absorbed by the atom, causing one of its electrons to jump farther away from the nucleus. If this electron falls back down to its original position, it emits a photon of the exact same wavelength. In the bottom case, the electron does not fall to its original position, but rather to an intermediate position. In this case, it emits a photon of lesser energy (longer wavelength). Diagram by Debra A. Fischer.

Dreams of Fields

Opposites attract; like repels. What would pop songs and love sonnets do without the metaphors of magnets? Most of us have played with fridge magnets or compasses; we have seen magnetic poles with the same polarity repel each other and magnetic poles with opposite polarity attract each other. It all depends on the invisible magnetic fields.

Although the concept of a field is abstract, it is easy to envision when you try to push two like magnetic poles together. The magnetic fields penetrate space. They contain energy -- the ability to do work. Slide two magnets with the same polarity toward each other on the surface of a table until they are uncomfortably intimate. If you let go of the magnets, they will scoot away from each other. The energy in the magnetic field is doing work on the magnets.

An analogous situation exists for electric charges. Similar charges repel; opposite charges attract. As with magnetic poles, electric charges are accompanied by electric fields that penetrate space. A negatively charged electron is pulled by the electric field of a positive charge and repelled by the field of a negative charge. Electric fields become even more interesting when they penetrate materials, such as metal wires. There they exert a force that causes the electrons to move through the wire -- the phenomenon of electricity.

But that's not all. Perhaps the most amazing property of electric and magnetic fields is the way they interact with each other. If you take a magnet and plunge it through a loop of wire, an electric field is created. We know an electric field is created because it forces the electrons in the wire to move; we can measure the resulting current. In fact, this is the principle used by electric generators in power stations.

Likewise, moving charges create a magnetic field. To observe this, build a simple circuit with a piece of wire and a battery. Connect one end of the wire to the positive terminal of a 9-volt battery and the other to the negative terminal. Place a compass next to the loop of wire and watch the compass needle move as you connect and disconnect the wire from one of the battery terminals. An important ingredient in both of these experiments is the variation of the fields. Static, unchanging magnetic fields don't spawn electric fields, and steady electric fields don't create magnetic fields.

Once created by a moving magnet or changing electric current, a field can break free of its source. It departs and sails through space like a thought without a thinker. And that is what we call *light.* Light and other forms of electromagnetic radiation contain both electric and magnetic fields that oscillate in strength. A change in the electric field creates a magnetic field. In return, the oscillating magnetic field creates an electric field. The two fields become entwined in a cyclical dance, each one pushing and then being pulled by the other.

Incredibly, no energy is lost in this process. In a vacuum, an electromagnetic wave would travel forever without losing any energy. It disappears only when it is absorbed by matter -- for instance, a hand that intercepts sunlight and becomes warm. This process of transporting energy is called *radiation.*

There's More to Light Than Meets the Eye

Classroom Activity: Making a Rainbow

This activity was developed by Philip Sadler as part of Project STAR, funded by the NSF.
It was first published as: Philip M. Sadler. Projecting Spectra for Classroom Investigations. The Physics Teacher, 29(7), 1991, pp. 423-427.

When white light from the Sun or a light bulb passes through a prism, the light splits into its component wavelengths. Collectively, these components of light are called a spectrum. It's what you see when there's a rainbow, in which case the droplets of water in the air act as the prism.

Materials:

- Transmission-diffraction grating (4-inch square sheet, available from scientific supply houses)
- Overhead projector or slide projector
- Two large books or magazines
- White wall or screen to project the rainbow on
- Ruler
- Red, blue, green colored filters - if possible, cut 1x4-inch pieces of the filters for each student

Part I

Demonstrate that white light is a mixture of many wavelengths of light. You can take this opportunity to follow a systematic, scientific method. One such method is: Ask a question, make a hypothesis, design and carry out an experiment, and check your results against the original hypothesis.

Part II

Investigate the properties of filters. Our eyes see all wavelengths of light in the visible window. Color filters create an even smaller sub-window inside the visible window. A red filter, for example, lets through red wavelengths of light, but blocks out the green and blue wavelengths. Many students have the misconception that filters somehow dye the light a certain color. Before starting this experiment, have the students look through the filters at an ordinary white light, such as light from the Sun or an incandescent bulb. (Filters are not perfect. They let through all of their own color, as well as some of the neighboring colors in the spectrum.)

Procedure:

To create an intense rainbow in the classroom, use an overhead projector. On the flat table of the projector, position two large books so that all the light is blocked except a narrow slit in the middle. This slit of light should shine toward the bottom of the projecting lens. Tape the diffraction grating over the lens where the image exits toward the screen or the wall. To fine-tune the width and position of the rainbow, adjust the width of the light slit by moving the books together or apart. You may need to angle the projector slightly to get the image to appear straight ahead on a screen.

The Project ASTRO activities handbook, *The Universe at Your Fingertips*, describes another method for making a bright rainbow in a classroom: Put a slide with a narrow slit in a slide projector, focus to a white vertical line, and position a diffraction grating over the lens.

Activity #1

1. The question: In what order will the colors in the rainbow (or visible spectrum) appear?
2. For the students: Make a hypothesis. What colors will appear and in what order? (redorangeyellowgreen-blueindigoviolet)
3. Create the rainbow. Younger students can draw the rainbow and make up a mnemonic for remembering the order of the colors (such as, ROY G. BIV).
4. Check the results against the hypothesis.

Activity #2

1. The question: What colors of the rainbow will be visible with the various filters?
2. For the students: Make a hypothesis.
3. Create a rainbow on the screen or wall. Look at the rainbow through the filters. Filter sheets can be positioned in front of the diffraction grating, or students can look through their individual filters at the rainbow. Which colors can be seen through each filter? Which filters are truest, letting through the fewest number of wavelengths?
4. Check the results against the hypothesis.

For older students

Have students measure the position of the different colors on the screen. A good way to do this is to tape a ruler onto the wall or screen so that it crosses the colors of the rainbow.

- Are all color bands the same thickness?
- Now, check the positions of the colors by looking at them through the color filters. If the filter were merely coloring the light, wouldn't it change the blue light into red light? Instead, the blue light is clearly blocked out.

Why do we get so many different wavelengths of light from the Sun? Why does sunlight seem nearly white, rather than a single pure color? The reason is that photons escaping from the Sun are absorbed, re-emitted, and bounced around millions of times. The light that ultimately escapes from the Sun spans an enormous range of energies.

But guess where most of the energy is? In the visible window! So it's no surprise that our eyes see the wavelengths that they do. It may seem annoying that we can only see light from one small part of the spectrum, but biologists say our brains are busy enough already. They'd be fried if had to sort out all those other wavelengths. Many students think of invisible light as a different phenomenon from visible light. It isn't; the various forms of electromagnetic radiation differ only in wavelength. Our eyes are insensitive to other wavelengths because of evolution.