INTRODUCTION

The Electromagnetic Spectrum

I. What is electromagnetic radiation and the electromagnetic spectrum?

What do light, X-rays, heat radiation, microwaves, radio waves, and gamma radiation have in common? Despite their differences, they are all the same kind of "stuff." They all travel through space and have similar electrical and magnetic effects on matter. This "stuff" is called electromagnetic radiation, because it travels (radiates) and has electrical and magnetic effects.

Electromagnetic radiation is the means for many of our interactions with the world: light allows us to see; radio waves give us TV and radio; microwaves are used in radar communications; X-rays allow glimpses of our internal organs; and gamma rays let us eavesdrop on exploding stars thousands of light-years away. Electromagnetic radiation is the messenger, or the signal from sender to receiver. The sender could be a TV station, a star, or the burner on a stove. The receiver could be a TV set, an eye, or an X-ray film. In each case, the sender gives off or reflects some kind of electromagnetic radiation.

All these different kinds of electromagnetic radiation actually differ only in a single property — their *wavelength*. When electromagnetic radiation is spread out according to its wavelength, the result is a spectrum, as seen in Fig. 1. The visible spectrum, as seen in a rainbow, is only a small part of the whole electromagnetic spectrum. The electromagnetic spectrum is divided into five major types of radiation. As shown in Fig. 1, these include radio waves (including microwaves), light (including ultraviolet, visible, and infrared), heat radiation, X-rays, gamma rays, and cosmic rays. Your eye can detect only part of the light

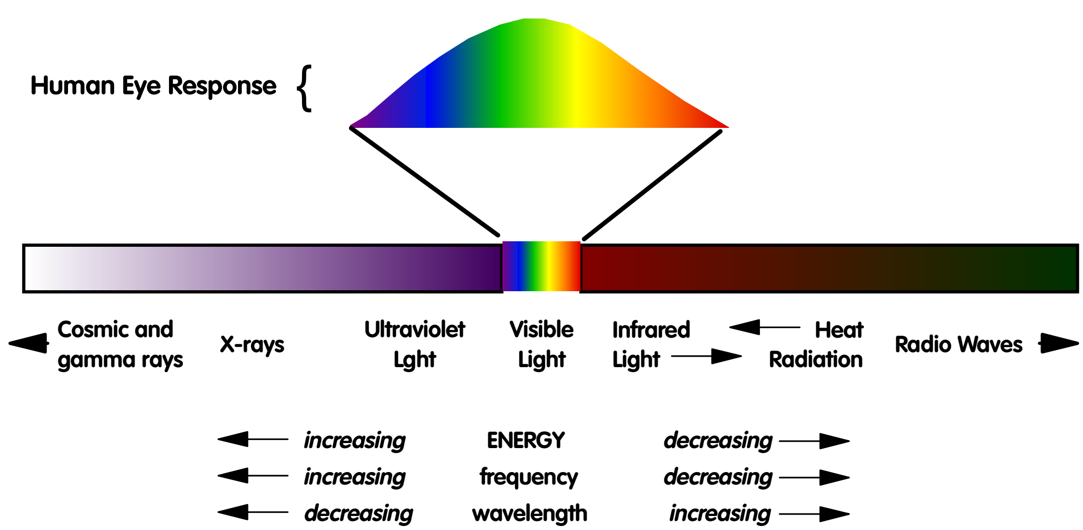

Fig. 1. The electromagnetic spectrum.

spectrum. Humans cannot sense any other part of the electromagnetic spectrum without the aid of special equipment. Other animals (such as bees) can see the ultraviolet while some (snakes) can see the infrared. In each case, the eye (or other sense organ) translates radiation (light) into information that we (or the bee looking for pollen or the snake looking for prey) can use.

Figure 1's "human eye response" is a magnified portion of the electromagnetic spectrum and represents the sensitivity of the average human eye to electromagnetic radiation. As this graph shows, the human eye is most sensitive to light in the middle part of the visible spectrum: green and yellow. This is why emergency vehicles are often painted garish yellows or green — they stand out in all weather, including fog, and at night better than the "old-fashioned" fire-truck red. The eye is much less sensitive toward the red and purple ends of visible light. The infrared and ultraviolet portions of the spectrum are invisible to humans.

Since the beginning of the modern age, mankind has expanded its ability to "see" into other parts of the electromagnetic spectrum. X-rays have proved useful for looking inside otherwise opaque objects such as the human body. Radio waves have allowed people to communicate over great distances through both voice and pictures. Today, increasingly clever uses of the spectrum allow us to see into the heart of a molecule (or person) while exploring Earth and space for the benefit of all.

2. Light and color

As shown in Fig. 1, each type of electromagnetic radiation has its own wavelength. But what length of what wave? Electromagnetic radiation moves through space (not just "outer space," but the atmosphere, buildings, lenses, etc.) as a wave, as wavelike changes in electrical and magnetic properties, similar to waves on the surface of water. The wavelength of electromagnetic radiation is the distance from the peak of a wave to the next peak, as shown in Fig. 2.

Electromagnetic waves can also be described by their frequency — that is, how many times a wave "waves" in a unit of time. For instance, imagine yourself as a ticket taker at a sports arena. Say 65 people pass your booth in 10 minutes. So, 6.5 people pass you per minute — the frequency of people passing is 6.5 people per minute. The frequency of an electromagnetic wave is exactly the same thing: the number of whole waves (or cycles) that pass by a point in some amount of time. Television and radio waves are usually described by their frequency; your favorite TV show might be on channel 8 in the VHF (very-high-frequency) band, or you might program your car's stereo to 92.8 Megahertz (millions of

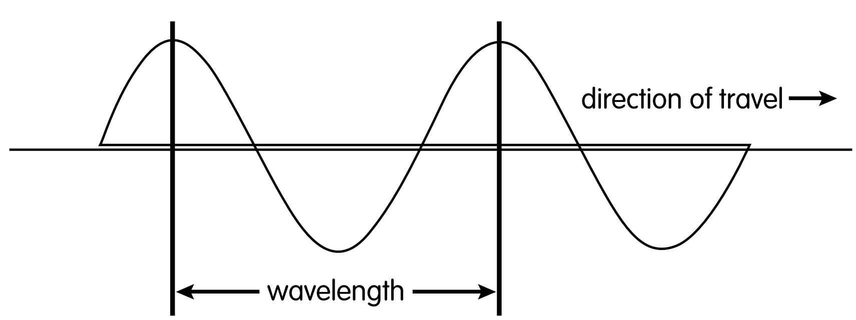

Fig. 2. The wavelength of electromagnetic radiation.

cycles per second) on the FM (frequency modulation) dial. Notice on the legend under Fig. 1 that energy and frequency increase together toward the left side of the figure, whereas the wavelength increases toward the right side of the page. That is because the wavelength and frequency are related to each other:

$$\text{wavelength} \times \text{frequency} = \text{the speed of light}$$

or

$$\lambda \times f = c$$

In this equation, the Greek letter "lambda" (λ) is used as shorthand for the wavelength and the fancy "f" (f) is used to represent the frequency; "c" is the speed of light (186,000 miles per second or 300 million meters per second). Since the speed of light is constant, the wavelength and frequency are limited; if one is big the other has to be small. That is why large (high) frequencies correspond to small wavelengths and large wavelengths correspond to small (low) frequencies. This same relationship (also known as "the wave equation") applies to all waves, including electromagnetic waves, waves on a rope (here the speed of light is replaced by the speed of the wave in the rope), or any other kind of wave. It's a universal relationship.

In some cases, especially when light interacts with atoms, it behaves more like particles than like waves. These particles are called photons. Each photon of light represents a distinct bit of energy; the greater the frequency of the light, the greater the energy. Using the same notation as above,

$$\text{Energy} = h \times f = h \times (c \div \lambda)$$

where "h" is a number called Planck's Constant. (Planck was a German physicist who studied the electromagnetic spectrum, and how light interacts with matter.) Consider how factors are related in this equation; if the frequency is doubled, so is the energy. If the frequency is decreased by half (50%), energy is decreased by half. The second relationship comes from the wave equation, already discussed; it has simply been rearranged by dividing each side by the wavelength, so that

$$f = c \div \lambda$$

Look what happens to energy if the wavelength is doubled: the energy is halved. If the wavelength is halved, then the energy is doubled. In this way, energy is inversely proportional to wavelength. The bigger (longer) the wavelength, the less the energy associated with that part of the electromagnetic spectrum. The shorter the wavelength, the greater the energy. Referring again to Fig. 1, one can see that when we say a light is of a certain color, we are really saying that the energy it radiates is of a certain frequency, or wavelength, which our eyes interpret as useful information.

3. Where does electromagnetic radiation come from?

Electromagnetic radiation is one of nature's ways of moving energy from one place to another. In physics language, this is called energy transfer. For instance, think about a neon lamp, such as a store sign. High-voltage electricity flows through the neon gas in the lamp, and some of the electrical energy gets captured by neon atoms. The captured energy is stored in the atoms' electrons, by moving them away from the atoms' nuclei. The electrons can then move back to their usual places in the neon atoms by releasing some energy as a photon of

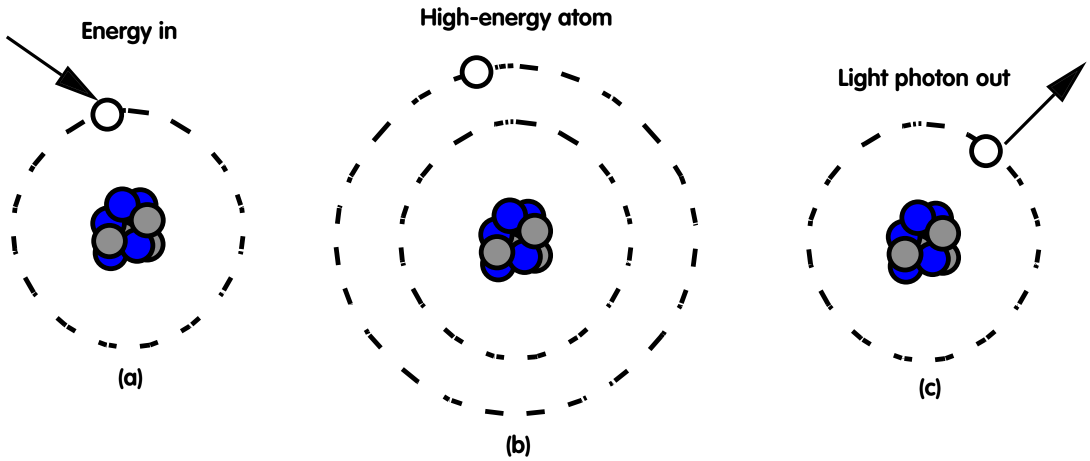

Fig. 3. Emission of light (a photon) by an atom. Moving from left to right, **(a)** energy is given to an electron in a neon atom (small circle) — the nucleus is composed of protons (black) and neutrons (gray); **(b)** the electron jumps to the higher energy shell due to its newfound energy; however, this situation is unstable and the electron falls back to its original energy shell; and **(c)** in so doing, it gives off the energy given it originally by emitting a photon. The photon's energy is equal to the difference in energy between the original electron shell and the shell to which the electron had been temporarily "promoted."

light. This light is the orange-red glow of the neon lamp. This process is shown in Fig. 3. Because the electrons in neon atoms (and all other kinds of atoms) are arranged in a very precise and orderly fashion, neon atoms can only give off certain energies (or frequencies or colors) of light as the electrons move back to their original locations. The energy difference between where the electron starts and finishes is the energy that will be given to the photon of light.

Most atoms absorb energy and reemit photons almost instantaneously; the amount of time required to move between electron shells in an atom has never been measured, except in the sense of ". . . the time was less than X to go from one shell to the other." Some atoms, however, save the energy for long times, and so give off photons long after the energy source has gone. This delayed emission of light is *phosphorescence*; you've all seen phosphorescence as "glow in the dark" stickers, T-shirts, Frisbees, etc.

Materials can also emit light of different energies (or wavelengths) than they absorb. This effect is *fluorescence*. Most often, the emitted light has a lower energy (longer wavelength) than the absorbed light. So, most often any fluorescence we can see is produced by light with higher energies (shorter wavelengths) than visible light. This shorter-wavelength light is ultraviolet, the kind that causes sunburn. Fluorescent lamps produce ultraviolet light first to make their light. Inside a fluorescent lamp tube, there is a mix of gases with a little bit of mercury. When high-voltage electricity passes through the gas, its atoms absorb some of the electrical energy and their electrons get elevated, just like in a neon lamp (see Fig. 3). The gas in a fluorescent lamp radiates ultraviolet light as its electrons return to their home positions. The ultraviolet light is then absorbed by a thin coating on the inside of the lamp tube (this coating looks white when the lamp is off); electrons in this coating are pushed to high-energy positions. The coating then fluoresces — emits visible light — as its electrons return to their homes.

Reflectance Spectroscopy

The ALTA Reflectance Spectrometer measures how much light, of different colors or wavelengths, reflects off objects. This kind of measurement is *reflectance spectroscopy,* and is a basic technique in most environmental studies of the Earth and studies of the planets. In reflection spectroscopy, the light does not originate on the object you are sensing; it comes from somewhere else. For instance, Mars is visible in the sky because light from the Sun reflects off it to Earth and our eyes. Measurement of the light that objects emit themselves is called *emission spectroscopy,* which the ALTA cannot do. Stars can be studied by emission spectroscopy, because they give off light of their own. Emission spectroscopy of heat radiation is sometimes used in environmental studies. Measurement of light that passes through objects is called *absorption spectroscopy,* which the ALTA cannot do well. Absorption spectroscopy is used to study relatively transparent things, like the Earth's atmosphere. Our knowledge of ozone abundances and holes in the Earth's upper atmosphere comes from absorption spectroscopy.

1. What happens when light hits an object?

When light hits an object, some of it reflects off and into our eyes or the ALTA spectrometer. But not all the light will reflect off — some of it may be absorbed by the object, and some of it may be transmitted through it (Fig. 4). These three processes should account for all the light:

All light = reflected light + absorbed light + transmitted light.

This equation is part of the Conservation of Energy principle of physics, which says that energy cannot be created or destroyed (remember that light is a form of energy). The ALTA Reflectance Spectrometer can only measure how much light is reflected from an object.

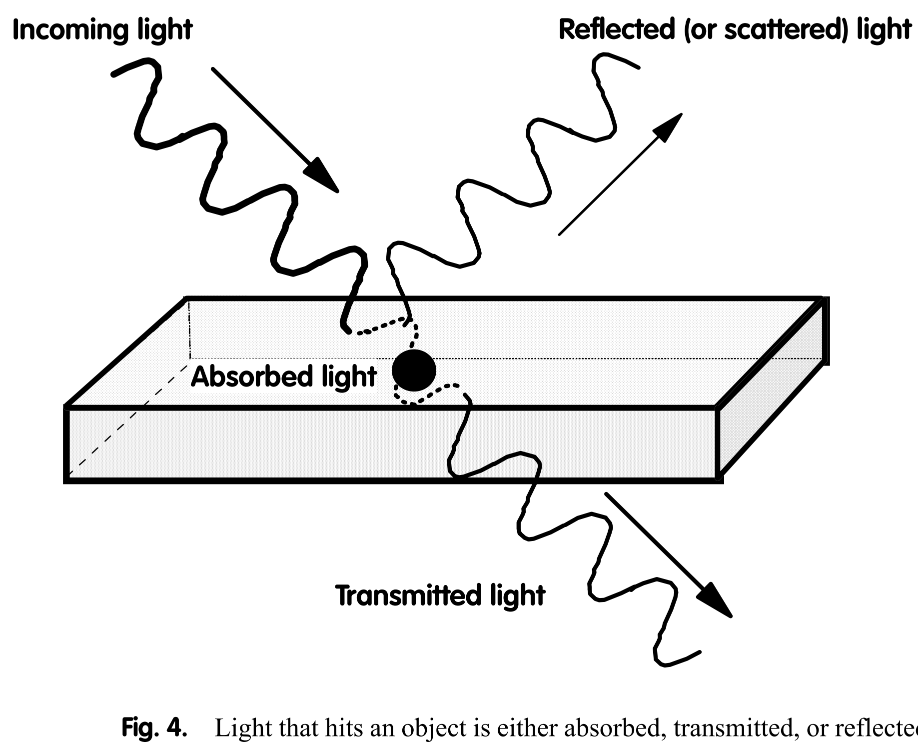

Fig. 4. Light that hits an object is either absorbed, transmitted, or reflected.

2. Reflectance spectroscopy

What actually happens to light when it interacts with objects is complicated — the stuff of advanced physics classes. It is enough to know that objects can absorb or reflect different wavelengths of light to different degrees, and that different objects absorb or reflect light differently. Most of the solid objects you'll look at with reflection spectroscopy don't transmit very much light through them, so the equation above becomes even simpler:

All light = reflected light + absorbed light

All the light that isn't absorbed by the object must reflect (or scatter) off it. So, the way light is *absorbed* by an object usually dictates what its reflected light looks like. For instance, if an object absorbs no light, whatever hits the object reflects (or scatters) off. Our eyes see objects like this as white (Fig. 5). On the other hand, if all the light that hits an object is absorbed, there is no light left over to reflect off and come to our eyes or the ALTA spectrometer (Fig. 6). An object like this appears black.

But what if only some colors are absorbed? Say a piece of fruit absorbs all the purple, blue, green, yellow, and orange light that hits it, and doesn't absorb all the red light that hits it. What color will this fruit appear to your eye (or to the ALTA spectrometer)? Since only part of the red light is absorbed, the rest must be reflected from the fruit. So the eye responds to the only light it receives, the red light, and you will see the fruit as red (Fig. 7). With your knowledge of color (reflection spectra) of many fruits, you can decide that this fruit is not an orange, a grapefruit, a pear, a peach, a banana, or a grape. You might need more clues (like its shape) to tell if the fruit is an apple or a tomato.

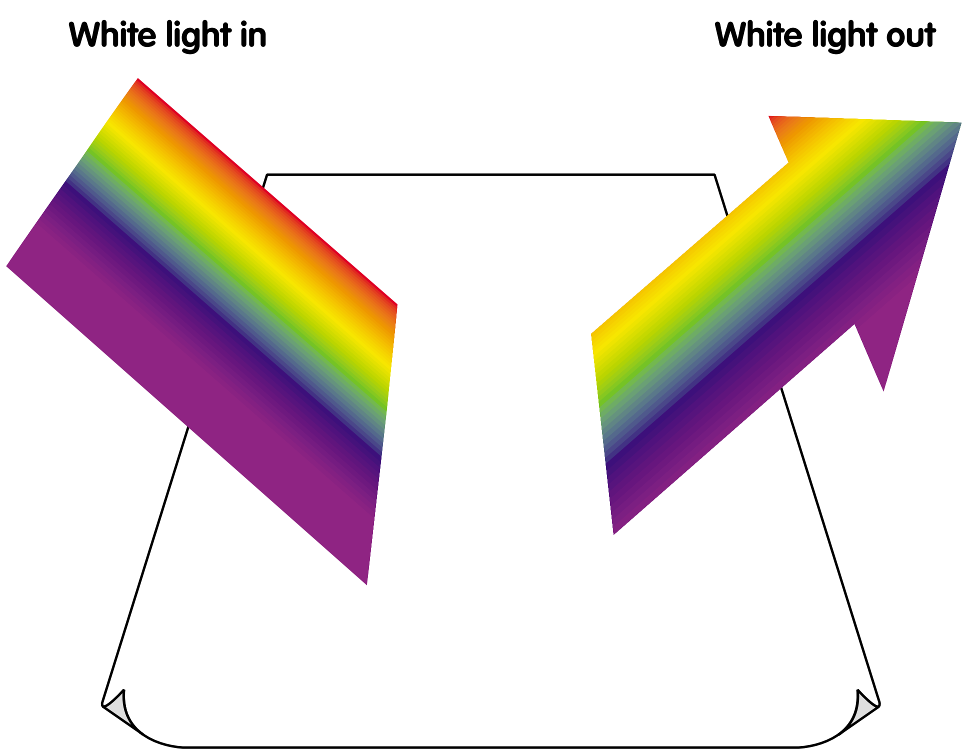

Fig. 5. If no light is absorbed by an object, it appears as white.

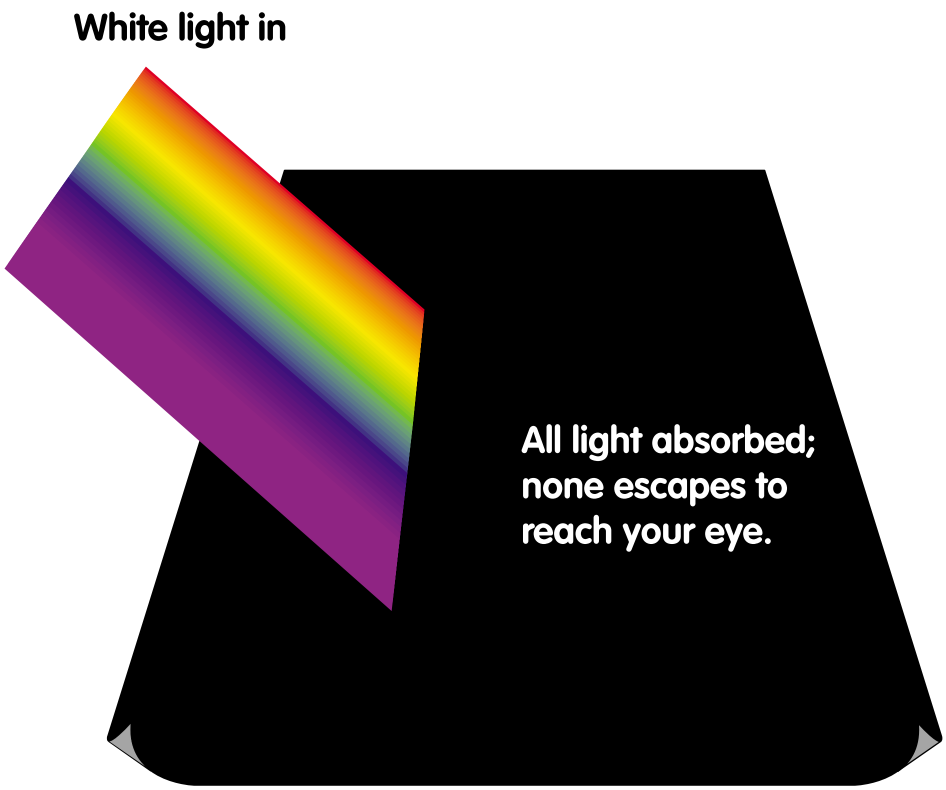

Fig. 6. When all visible light is absorbed by an object, it appears black.

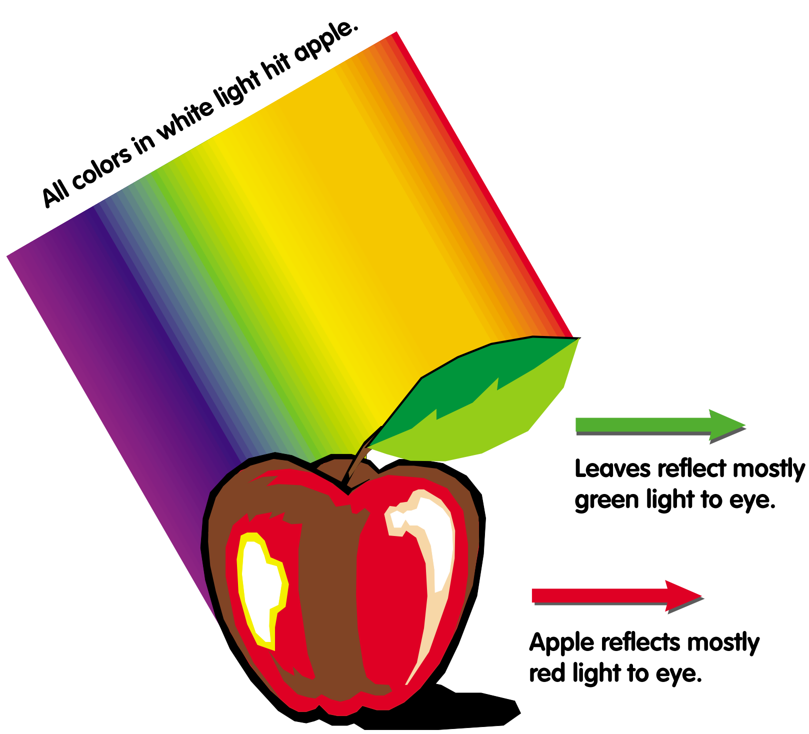

Fig. 7. An apple appears red, and its leaf green, depending on which colors are reflected back to the eye.

For another example, look at the green leaf on the apple. Because you see it as being green, you know that the leaf must be reflecting green light to your eyes. Also, the leaf is *not* reflecting much light in blue, yellow, orange, or red. So what wavelengths of light is the leaf absorbing? The leaf absorbs wavelengths that correspond to blue, yellow, orange, and red. In a green leaf, the chemical chlorophyll is the culprit that absorbs the light and then converts its energy into food for the plant. Surprisingly, the green color of leaves is not really from the chlorophyll — it is from the light that the chlorophyll doesn't absorb.

These differences in absorption and reflectance of different colors of light give us important clues to understanding and interpreting the world around us. Reflection spectroscopy does the same — although it does it better in some ways than our eyes can. With reflection spectrometer instruments (like the ALTA), we can sense many distinct wavelengths of light, while our eyes are sensitive to only three. With a reflection spectrometer, we can also measure and quantify how much light is reflected from an object. The numbers we can measure (the reflectances) hold clues to the nature of the objects we measure, whether they are in the laboratory (as with the ALTA), on the Earth's surface below a satellite, or on the surface of Mars.