Color in the Non-biological World

Edward J. Olsen

This discussion should begin by saying what light really is; but this is not possible, since light is essentially more primitive than any of the terms that might be used in an effort to explain it. —SIR CHARLES DARWIN

This view of the physicist grandson of the author of *Origin of Species* fairly well sums up the current state of understanding of the phenomenon of light. For at least 2,500 years Western man has wrestled with the question of what light "really is."

In the Classical World several fanciful views were held. One explanation regarded light as a stream of minute, invisible particles fired like projectiles from any light source. Isaac Newton, twenty-one centuries later, came to the same conclusion. He developed the idea and expanded it into a physical theory of the mechanics of motion of the particles, and it came to be called the *corpuscular theory of light*.

During his own time, however, and in the following two centuries, an impressive body of experimental data accumulated indicating that light could *only* be explained as a wave-like phenomenon which is propagated away from a source much like ripples on the surface of a pond into which a pebble has been dropped. The hypothetical medium through which it was propagated was called the *ether*. The *wave theory of light* became extremely successful in predicting its behavior under all known conditions, and the corpuscular theory gradually dropped into disuse—until the early part of this century. It was then that certain experimental results arose which could only be explained when light was treated, again, as having the properties of particles (that is, corpuscles).

Thus arose a good deal of consternation in the world of physics over this puzzling dual behavior of light. Was it made up of waves or of particles?

The puzzle was compounded by other new experiments which suggested that this kind of dual behavior is not restricted to light. There are, for example, very minute particles called electrons. These are definitely particles. In all normal experiments electrons behave like tiny, electrically charged particles. If, however, they are accelerated to very high velocities, they exhibit wave like characteristics. Upon slowing down, they cease acting like waves and once again act like particles. Now what do you make of that?

If you are not a physicist you must remain baffled. If you are a physicist you must become mentally ambidexterous: when it is necessary to treat light as a wave, you do so; when it is necessary to treat it as a stream of particles, you do that. At the present time then you cannot ask what light "really is." This essential duality of light (and matter) is today the major metaphysical frontier in the natural sciences.

In our exhibit Color in Nature it is more convenient to treat light as waves. Waves have three basic properties. *Wavelength* is the measure of the length of a wave from the top of one wave crest to the top of the next crest. *Frequency* is a measure of the number of crests that appear to pass a given point in one second of time. Thus, if 60 crests pass in one second, the frequency is called 60 cycles per second, or 60 Hertz (abbreviated, 60 Hz.). The cycle-per-second unit was named "Hertz" to honor a 19th century German physicist. *Amplitude* measures the height of the crests and is a measure of the energetic power of the wave. It is possible to have two waves of the same wavelength and frequency, but very different amplitudes.

When white light shines through a prism or reflects off a finely ruled grating, it is broken up into the visible *spectrum* of colors: red, orange, yellow, green, blue, violet. The wavelengths range from 27-millionths of an inch at the red end to 15-millionths of an inch at the violet end; the corresponding frequencies are from 430 trillion Hz. to 770 trillion Hz., respectively. This is the range of frequencies visible to the human eye. Some animals—bees, for example—are capable of seeing beyond the violet into the ultraviolet.

Beyond the ultraviolet, at ever-decreasing wavelengths, the spectrum continues through X-rays, gamma rays, and finally cosmic rays, which are of extremely short wavelengths, trillionths of an inch, and hence very high frequencies. Beyond the red end of the visible spectrum, at ever-increasing wavelengths, are the infra-red, which we cannot see but can sense as heat waves, radar waves, television waves, and ultimately radio waves, with wavelengths that range over ten miles long and hence have extremely low frequencies, under 10,000 Hz.

This whole expanse, from gamma waves to radio waves, is called the electromagnetic spectrum, so called because a ray of any of these waves has associated with it an electrical field and a magnetic field.

In the natural world we are deluged with the visible colors. When sunlight impinges upon our atmosphere it is refracted (scattered) by the atoms of the air as well as by suspended water droplets and very fine dust. Because blue light is more strongly scattered than other wavelengths of the color spectrum, the sky apears blue; some of the blue wavelengths in the sunlight are bent downward toward the earth's surface. The other colors are less affected and generally pass on through our atmosphere. This effect is strongest at right angles to the sun; when the sun is low, the sky goes from whitish to pale blue around the horizon to deeper blue, almost violet, overhead.

The blue of the sea is the blue of a cloudless sky reflected in the water. When the sun is covered by clouds, the sea appears greenish due to the microscopic plants, phytoplankton, that float just under the surface. These faint greens are swamped out by the blue on sunny days. On very cloudy days even the greens cannot be seen and the water appears gray, even black, due to the weak light.

During a rain the air is filled with droplets of water, and because it is necessarily always cloudy during storms, the sky is dark. If, however, there should be a break in the clouds and the sunlight streams through, we may obtain one of Nature's most spectacular color displays—a rainbow. A water droplet at a certain angle between the sun's rays and your eye can act like a prism and break up the sunlight into the spectrum of colors. All the raindrops in the air which are located at the proper angle act cooperatively, each contributing its small share, producing the strong and bright spectrum which we observe.

Sunrises and sunsets usually present the most memorable displays of color in the sky—red, yellow, orange, pink, blue-greens, and greens. These colors become prominent because the sun's rays are passing through more of the earth's atmosphere when the sun is close to the horizon. So, before it reaches your eye most of the blue end of the spectrum has been removed by scattering downward and upward. In addition, because of daytime winds and animal and human activities during the daylight hours, many particles of dust have been lofted into the air. These aid in scattering the blue wavelengths out of the sunlight making it appear redder. The more such dust in the air, the more spectacular the sunset. This is why sunsets are often redder in populous areas, around cities, where there are a great many more dust and smoke particles in the air than in isolated places. It is also the reason that sunrises are usually less spectacular than sunsets; animal and human activities are much diminished during the dark hours of the night, so there is less dust in the air at sunrise. Also, the dust from the previous day has settled during the night and night breezes are commonly less gusty, raising less dust. This again is different in populous areas. In large cities it is common to burn trash during the nighttime hours, giving the air an abundant supply of fine particles that scatter the morning's rays, producing redder sunrises than might otherwise be the case.

Most of us are not accustomed to thinking of color in the space away from our earth. It is there, albeit it is not especially spectacular. The planet Mars is a definite rusty red color; Venus is snow white; Mercury and our moon are gray; the planet Neptune is pale green; and Jupiter has a huge, bright red spot in its upper atmosphere that revolves around the giant planet. Beyond our solar system the stars themselves show a range of colors—some red, some yellow, some brilliant white.

Photos: At left—North American Nebula in Cygnus; from Hale Observatories, Pasadena, California; copyright by California Institute of Technology and Carnegie Institute of Technology. At right, from top to bottom—*Novacekite*, a uranium mineral; *Smithsonite*, a zinc mineral, which comes in several different colors; and *Cuprite*, a copper mineral.

The color of any mineral is purely an accidental feature of it. This is in contrast to plants and animals where coloration usually plays a significant role in several aspects of survival. For a given mineral, whether it has one color or another is purely immaterial and irrelevant from the mineral's point of view, if an inanimate object can be thought of as having a point of view.

The origin of colors in most minerals is only poorly understood. It is not uncommon for a specific mineral to show a wide variety of colors in its different occurrences in nature. The common mineral fluorite, for example, has been found in twelve different colors. In some instances fluorite will show a color change within a single crystal—a matter of an inch or less. There is no clear explanation of the wide variety of colors in this mineral.

Occasionally, however, color can be related to the chemical composition of a mineral. Manganese minerals are often red; cobalt minerals often pink; copper minerals often green, and so forth. It is, unfortunately, not always that simple. Some copper minerals are blue; some manganese minerals black; some cobalt minerals silver colored. There are no perfect rules in this regard.

A minor impurity can sometimes cause a mineral color to change. The mineral called *microcline* is normally creamy white. With a small impurity of lead (about 0.03 percent), it is a startling blue-green color that is attractive enough to create a demand for the mineral as a semi-precious gemstone —called *Amazonstone.* The mineral *sphalerite,* a compound of zinc and sulfur, in its pure form is pale amber in color. A few tenths of a percent of iron impurity cause it to darken to a shiny black, called *blackjack* by miners.

The chemical addition of oxygen to a mineral always alters the color and properties. Minerals that contain small amounts of iron become pink or reddish-brown by oxidation. In the extreme case, a mineral can be completely converted by this process to a new mineral with a very different appearance. The mineral *galena,* for example, is a lustrous metallic gray. It is a combination of equal parts of lead and sulfur. When it is oxidized with four parts oxygen, it becomes the mineral called *anglesite,* which is clear, transparent, and colorless—very different from galena in appearance.

Heating a mineral in air can sometimes cause mild oxidation to take place. This principle has been used for centuries in the gem industry. When gem quality green *beryl* is mined, it is routinely heated in air for a period of days. This sometimes converts it to a medium-blue color, and it is then called *aquamarine,* which is a good deal more valuable than green beryl. Similarly, colorless to pale pink *spodumene* can be converted to the deep rose-colored gem *kunzite,* and gray *zoisite* to a deep blue gem called *tanzanite.*

It has long been known that exposure to radioactivity and X-rays can change the color of a mineral. Quartz becomes smoky, white topaz becomes brown, white fluorite becomes purple. Such radioactively induced changes are not always permanent, however. Once the mineral is removed from its radioactive surroundings it will often gradually revert to its original color.

In some rare instances a mineral will change its color when the atoms that compose it are geometrically rearranged. The best examples of this phenomenon are the minerals composed of simple carbon. When the carbon atoms are arranged in stacks of planar sheets, the mineral is black and shiny, almost metallic in appearance. It is called *graphite.* When the same carbon atoms are relinked into a three-dimensional network, the mineral is transparent, clear, and brilliant—*diamond.*

Probably the questions that are most often asked a mineralogist by the public pertain to why minerals exhibit the often striking colors they do. These are, regrettably, just the questions that cannot be answered. One can occasionally produce a weak reply, knowing that the "answer" is really no answer at all. A great deal is known about the properties of mineral structures—their physical and electrical properties, geometrical properies, etc. Unfortunately, these are not the aspects about which most people are curious.

One could say that if so little is known about coloration in minerals, perhaps the mineralogist ought to devote some effort to a study of it. Mineralogy, like most of the geological sciences, depends heavily for its advances in understanding upon advances in the disciplines of physics and chemistry. Mineral color is the result of the interaction of light upon solid matter—the chemical compounds we call minerals. Search for a real understanding of color production in these solids leads us immediately back to the question of the nature of light itself. And that, as we have seen, leads right back to the dual nature of light as a form of electromagnetic radiation—one of the major unresolved questions of the physical universe today.

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