Light colors our world, so in the world of gemstones and minerals, it is important to standardize lighting.

Color Our World

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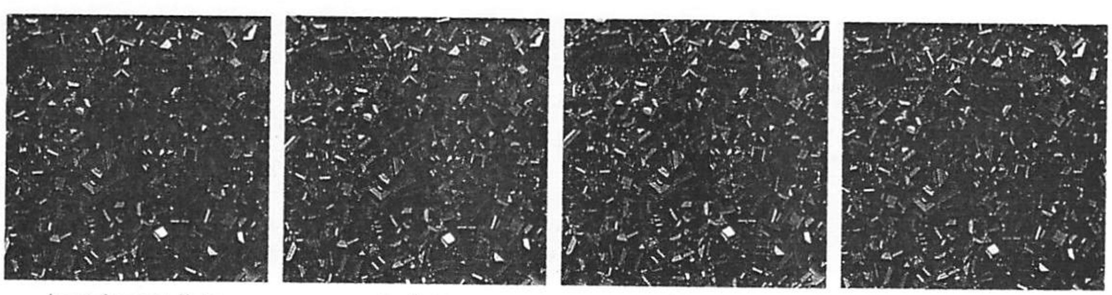
Whether you are buying or selling rough or finished colored gems indoors or out, the lighting used is an important consideration. Specifically, the light source and quality of light emitted has a profound effect — sometimes positive, sometimes negative — on the appearance of colored gems and rocks.

The same gem can appear as three different colors to the same observer under three different light sources. English poet Robert Browning remarked so in 1869: "Yes, I answered you last night, no this morning/ Sir, I say, colors seen by candlelight will not look the same by day."

Most people realize that lighting affects color. For many of us, the lesson is brought home, both literally and figuratively, when trying to match wallpaper, paint, carpet, or other home items against swatches seen under storeroom lights. Here, we will take a closer look at just how lighting affects color.

Anyone who deals with colored stones, from agates to zoisite, *must* understand the relationship between lighting and color appearance. This knowledge is essential, especially in today's market where profit margins — when going from rough to cut, when recutting to improve color, or when searching for an



incandescent light | daylight | D-65 | fluorescent light

Ruby, as seen under four different lighting scenarios.

exact match for a colored gem — are greatly affected by final color appearance.

The majority of gems and minerals owe their wide assortment of colors to a process known as selective absorption. Light rays entering a gemstone or mineral (i.e., transparent, solid, crystalline, or amorphous material) are selectively absorbed at various wavelengths by the atoms of the material. The remaining unabsorbed light rays are then transmitted and reflected through the material back toward the eye.

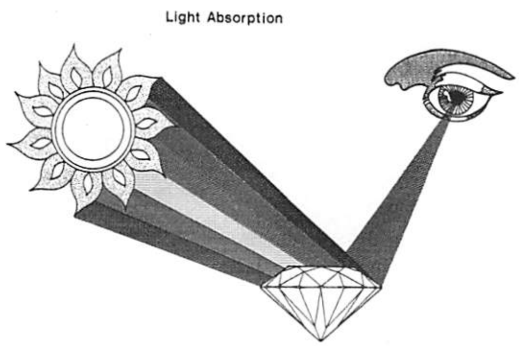
The philosopher Voltaire didn't call it selective absorption, but he accurately described it in 1734 when he wrote: "From what cause, therefore, do colours arise in Nature? It is nothing but the disposition of bodies to reflect the rays of a certain order and to absorb all the rest." In other words, the combination of all wavelengths of light not absorbed by a transparent crystalline gemstone causes the sensation of color.

The point in explaining the details of spectral power distribution, spectral absorbance or transmittance, and human spectral response is that all three are required for the physical production of color. The combination of a light source, an object, and a detector (usually the human eye), when multiplied together, provide the stimulus, or physical signal, that the brain interprets as our perception of color.

From a scientific viewpoint, what happens to light rays once they are inside the gemstone involves impurity atoms and defects. The impurity atoms and defects induce new vibration modes to the crystalline lattice, resulting in light absorption at wavelengths characteristic to the interatomic forces between the host material and the impurity atoms or defects. When such impurities or defects cause light absorption in the visible range, they are referred to as color centers.

The wavelength of any color center can be accurately specified and measured using an instrument such as a spectrophotometer. These automated optical instruments are designed to separate white light emitted from a specific light source (that is housed in the unit) into the familiar ribbon of color (Red, Orange, Yellow, Green, Blue, Violet or ROYGBV) with great accuracy and precision.

When a gemstone is placed in the instrument's light path, a basic measure of the absorption coefficient or relative transmittance of the stone can be plotted, wavelength by wavelength, on a graph. The result is a curved line that extends from one end of the visible spectrum to the other — from a wavelength of approximately 400 nanometers (nm) at the violet end to 700 nm at the red end.



Selective absorption of light.

THE HUMAN COLOR CODER. The various peaks and valleys seen anywhere along one of these spectral curves denote specific wavelengths (measured in nanometers, nm, or electron volts, eV) where absorption or transmittance is taking place in that particular colored stone. In part (a) of Figure 1, this spectral curve shows a relatively high percentage of transmittance in the green, yellow, orange, and red regions (between 510 and 720 nm) and low transmittance below 510 nm, resulting in a yellow colored stone.

In part (b) of Figure 1, the absorption curve of the same stone is a mirror image of the transmission curve. Here the peaks represent absorption at a specific wavelength and the valleys indicate those wavelengths, that when combined, produce the color of the material, in this case yellow.

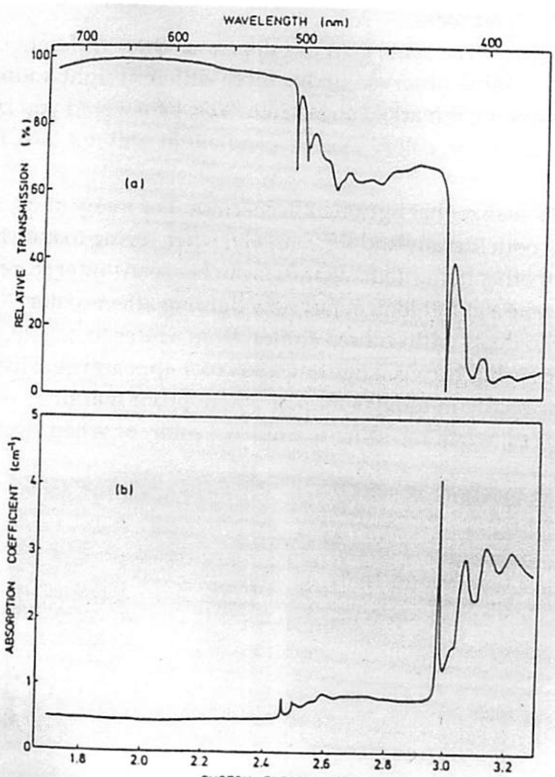


Figure 1. Absorption and transmission spectra recorded for a yellow diamond. Reprinted with permission (Collins).

When the transmitted and/or reflected colored light rays finally reach the eye of an observer, two additional factors — physiology and psychology — must be taken into account. From a physiological standpoint, the human eye is a complex detector of color that works in tandem with the nervous system and the brain to perceive color. The human eye functions similarly to a camera, with the light focused through a transparent lens onto the light sensitive back surface known as the retina (see Figure 2).

Remarkably, each of our eyes consists of approximately 137 million small light sensitive nerve endings, located at the back of the retina. It is here in the nerve fibers of the retina, through a process of converting radiant energy (light rays) into chemical energy (neurological signals) that the monumental task of vision is performed.

In cross-section the light sensitive nerve endings are shaped like rods and cones. Vision experts estimate that approximately 130 million nerve endings (rods) function to detect light and dark, permitting vision in dim light (scotopic vision). The remaining seven million nerve endings (cones) function to detect fine detail and perceive color, hue, and saturation (photopic vision).

The greatest concentration of cone-shaped nerves is found principally near the center of the retina in an area about 0.3 millimeter in diameter known as the fovea. At the fovea, the eye involuntarily focuses the image of an object that must be examined in minute detail. It is also where all critical color discrimination and color matching takes place.

When observing a faceted gemstone or an unpolished rock, for example, the most common "instrument" used for deciphering color is the human eye and brain in combination. No matter what other sophisticated instrument is used, a spectrophotometer for example, its output must eventually be correlated with the subjective properties of human vision.

Together, the eye and brain receive color signals in such a unique way that it defies any of our attempts to duplicate the process we call vision. Despite these limitations, color vision researchers have concluded that there are three types of cone-shaped optic nerve endings, each having different sensitivities to wavelengths of light (red, green, and blue). The exact details of how this works are very complex; it is enough to know that light entering the cone-shaped nerve endings allows us to perceive color through an additive mixture of red, green, and blue light.

If we were to plot the spectral response of these red, green, and blue receptors on a graph by wavelength, they would appear much like Figure 3, referred to as the standard observer curves for normal human vision. This set of spectral response curves provides the experimental definition of the 1931 CIE 2° standard observer as proposed by the Commission Internationale de l'Eclairage (CIE). Using these three curves, we can calculate an average spectral response curve for the human eye (see Figure 4), which shows that the human eye is most sensitive to wavelengths in the green spectral region (at approximately 550 nm) with decreasing color sensitivity toward the violet and red wavelengths respectively.

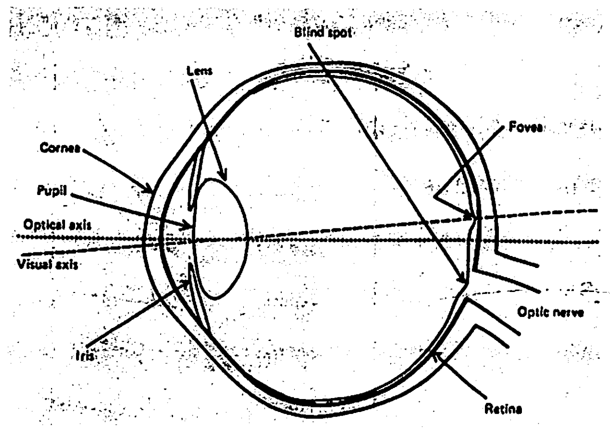


Figure 2. A cross section of the human eye.

NATURAL LIGHT. Light sources, on the other hand, are classified into two basic types, *natural* and *artificial.* When you observe a colored stone outdoors, you are using natural light coming directly from the sun (sunlight) and reflected off the sky (sky-light). The combination of sunlight and sky-light is referred to as natural daylight, or simply daylight. In general, the color of daylight is considered to be white, yet taken separately sunlight is yellowish, while the color of sky-light is bluish.

On the subject of diamonds, Jean Baptiste Tavernier wrote in 1676, "... whereas we in Europe make use of day-light to examine the rough stones, the Indians do that in the night-time, setting up a lamp with a large wick in a hole which they make in a wall, by the light of which they judge . . . ."

Later, and for so long now that it has become a tradition, the "standard" light source for looking at color in diamonds has been north daylight. In the colored stone business, various other phases of natural light are preferred (e.g., sunlight for rubies, sky-light for sapphires, a balance of sunlight and sky-light for emeralds).

However, gem merchants have noted that north daylight, sunlight, sky-light, and balanced daylight appear different in many of the world's gem trading centers, including Antwerp, Bangkok, Geneva, Hong Kong, London, New York, and Tokyo. Studies conducted by color scientists confirm these observations and indicate that the strength and color composition of natural light is variable at different times of the day and is also subject to changing weather conditions, atmospheric pollution, and geographic factors such as latitude.

In order to understand how these phases of natural light relate to each other and to other types of daylight (i.e., sunrise, noon sunlight, a cloudy day, clear blue sky-light, etc.), it is necessary to look at a color temperature chart representing all the phases of natural light (see Figure 5). In an attempt to organize the color of various lights, color scientists have devised a numerical scale, referred to as the color temperature scale.

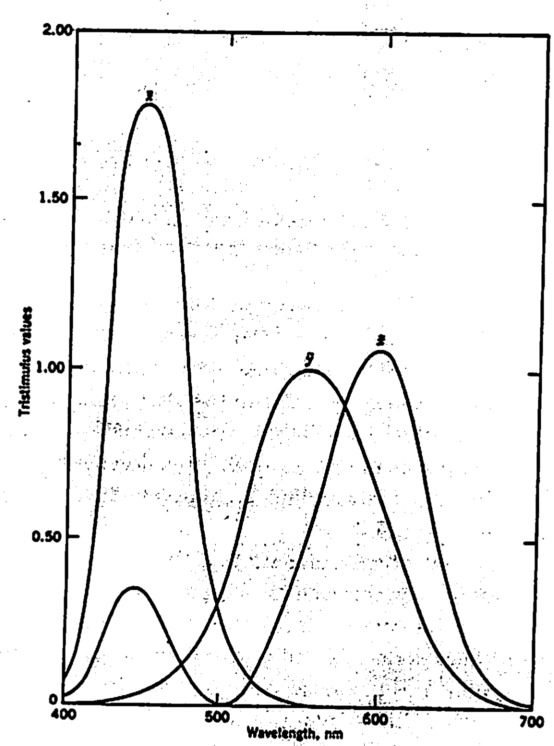


Figure 3. The standard observer curves for normal human vision are derived from the eyes' response to blue, green, and red wavelengths of light. Reprinted with permission (*Principles of Color Technology*).

In essence, color temperature is a theoretical scale that assigns a light source of a particular color a temperature expressed in absolute Kelvin (K) temperature units. A blackbody radiator is a surface that absorbs completely all the radiation striking it, so the light it emits depends only on its temperature and not upon the material of which it is constructed. Therefore, it is used as the standard reference for relating color to temperature. The temperature of a blackbody is usually expressed on the absolute or Kelvin scale, also represented on a chromaticity diagram (as in Figure 6), which shows color change along a curved line with increasing temperature (i.e. Plankian locus).

Very simply, red colored lights (objects heated to "red" heat) exhibit a color temperature in the approximate range 1000-1500 K, orange 1500-2500 K, yellow 2500-4000 K, white 4000-8000 K and blue 8000 K and above. Thus, each phase of natural light can be expressed in terms of a color temperature. Sunrise and sunset are typically thought of as having a color temperature of approximately 1800-2000 K, average sunlight at noon is 5000-5200 K and a clear blue sky-light is associated with 13,000 K and above.

As shown on the left side of Figure 5,

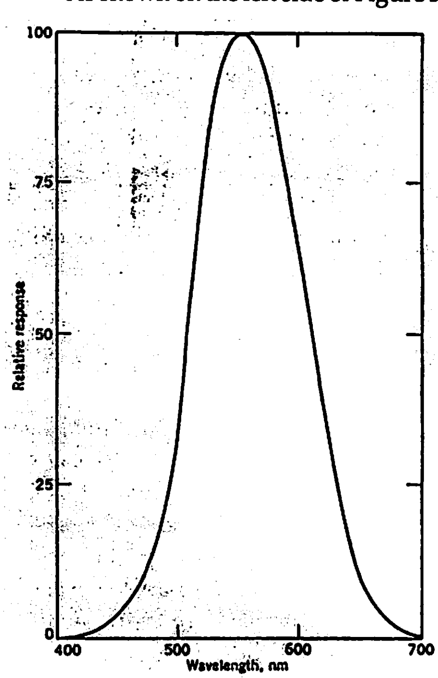


Figure 4. Curve shows the relative spectral response of the human eye to various wavelengths of light. Reprinted with permission (*Principles of Color Technology*).

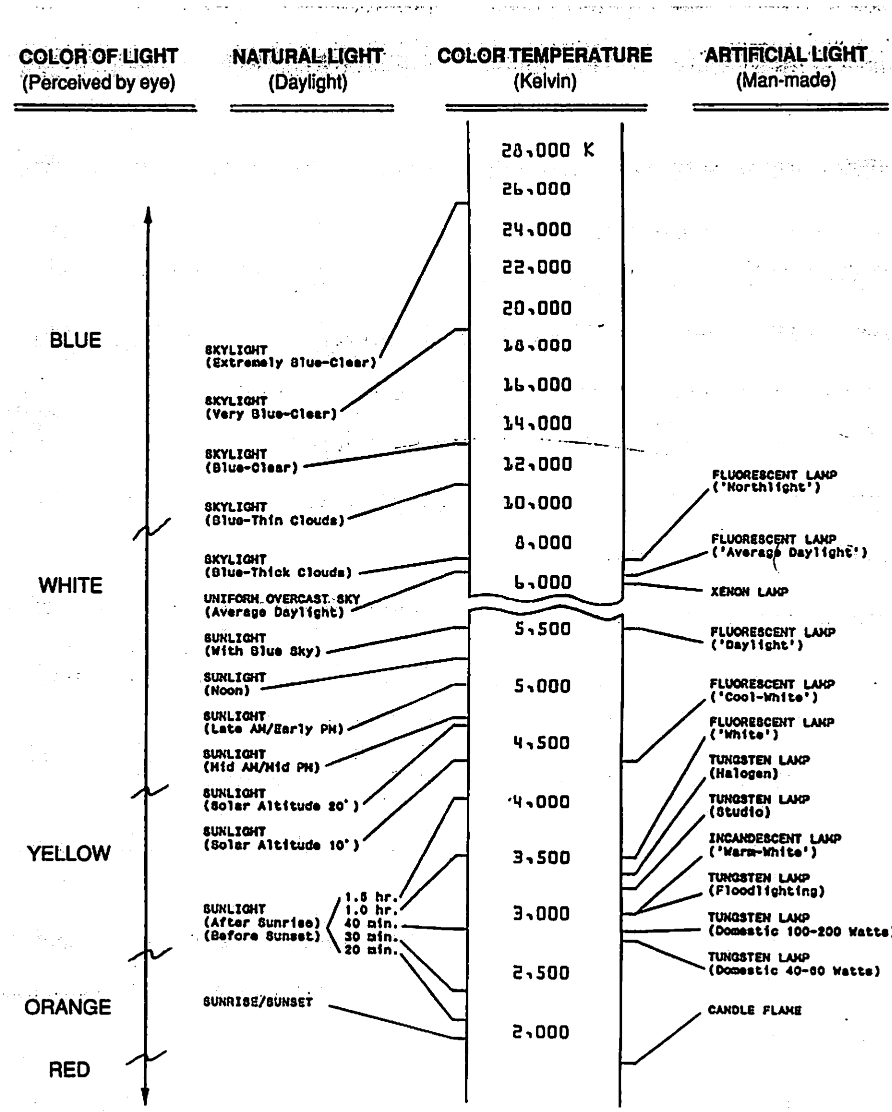


Figure 5. A color temperature scale shows the relative position of various phases of natural and artificial light in relation to Kelvin scale of temperature.

sunlight displays a certain color order as the day brightens after sunrise (red, orange, yellow, and white), which changes in reverse color order in the afternoon. The color of sky-light is also variable — deep blue in remote areas vs. yellowish in major metropolitan areas due to dust and pollution.

All phases of natural light can be shown on this chart and expressed with a color temperature. Of equal importance is the spectral power distribution of a light source, represented by a curved line showing light output versus wavelength, shown in Figure 7, for various daylight conditions (sunlight and north sky-light).

According to color scientists, average north daylight (i.e., facing north, away from the sun toward blue sky, in a location above the equator) is equivalent to approximately 7500+ K in color temperature. Such light is reflected off particles in the atmosphere that are so tiny they diffuse the shortest (blue) wavelengths, making the "north" light appear slightly bluish in color. When measured and plotted on a graph showing relative spectral power distribution of light output, north daylight has a higher emission of wavelengths in the blue (400-500 nm) spectral region (curve B of Figure 7).

Average sunlight, on the other hand, has a color temperature approximately equivalent to 5000 K, toward yellow on the color temperature scale. When plotted on a graph showing relative

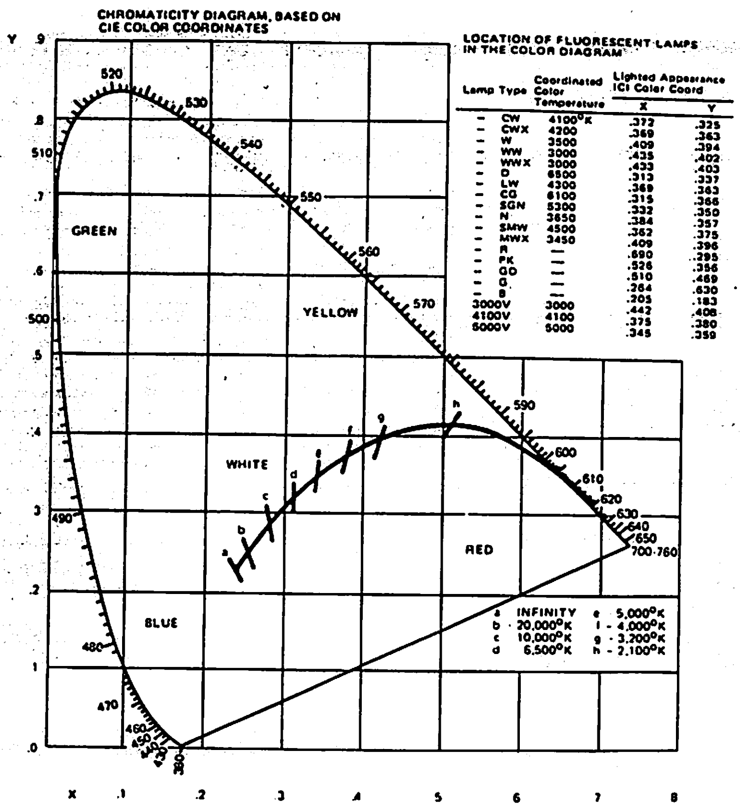


Figure 6. Chromaticity diagram (CIE 1931) shows location of various colored lights as temperature Kelvin (K) is raised from 2100 K to infinity. Reprinted with permission (*Measuring Colour*).

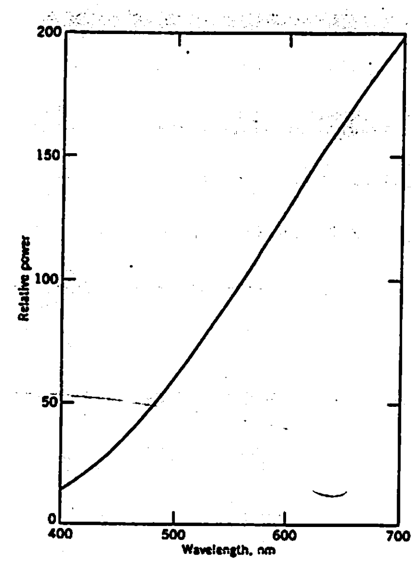


Figure 8. Relative spectral power distribution of a tungsten incandescent light source with a correlated color temperature of 2854 K. Reprinted with permission (*Principles of Color Technology*).

spectral power distribution (curve A of Figure 7), sunlight shows a lower output of light in the blue region and a higher output in the yellow, resulting in a decidedly yellowish color appearance as compared to north daylight.

Using an instrument known as a spectroradiometer to measure light output, different phases of daylight can be expressed with a curved line, showing the distribution of wavelengths versus power output and how this relates to color, from bluish to yellowish tints. Color scientists agree that white light is best represented within a narrow range of color temperatures (5000-6500 K). The spectral power distribution curve of average daylight would thus fall somewhere between the two curves in Figure 7.

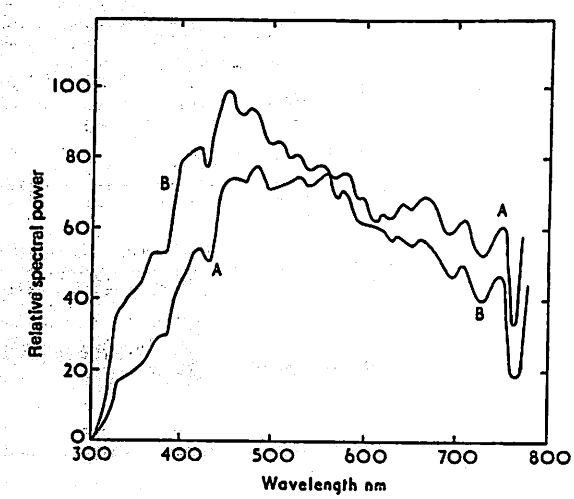


Figure 7. Relative spectral power distribution of two different phases of daylight (a) sunlight and (b) north daylight. Reprinted with permission (*Measuring Colour*).

The conditions necessary to achieve the so-called *pure* white light of average daylight require sunlight and sky-light to be mixed together. When sunlight and sky-light are mixed and filtered through a cloud or a uniform (moderately) overcast sky, light is reflected and refracted many times so that the dispersed wavelengths combine to form white light.

When inside an office or a jewelry store, various degrees of this natural white light enter through the windows, allowing a variety of viewing conditions — some days leaning toward bluish and on others a more yellowish light. In addition to the weather, geographic location, and the time of day, factors such as colored reflections from nearby buildings, surrounding walls, and dirty windows can also influence lighting where you buy and sell polished and rough colored stones.

It is important to reiterate that the color of natural light is quite variable, as the color temperature chart shows. Reproducing all these changes and fluctuations of natural light is virtually impossible with one single man-made light source. The best that can be done currently is to reproduce the characteristics of natural light at certain times of the day with several artificial light sources.

ARTIFICIAL LIGHT. Essentially two types of artificial light sources are used today for viewing colored gems, incandescent and fluorescent. Incandescence refers to light given off when a solid material is heated to a high temperature. The most familiar incan-

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descent light is the 40-150 watt (ordinary household) tungsten filament lamp.

As seen on the color temperature chart (right side of Figure 5), the color of such a lamp is decidedly yellowish, yet it can vary somewhat depending on the type of lamp and the wattage. The spectral power distribution curve of a tungsten filament lamp with a color temperature of 2854 K confirms this, showing that the light emitted is predominantly toward the yellow, orange, and red end of the spectrum (see Figure 8).

In the gem industry, the tungsten lamps that represent another type of incandescent light source are widely used, especially in jewelry stores. These lamps usually have a color temperature in the range 3200-3400 K. However, the color of any tungsten lamp can be made to appear "whiter" like that of average daylight (6500 K) or north sky-light (7500 K) by placing a suitable blue color filter in front of the lamp or a blue-colored reflecting surface along the sides. These serve to reduce the amount of long-wavelength light available,

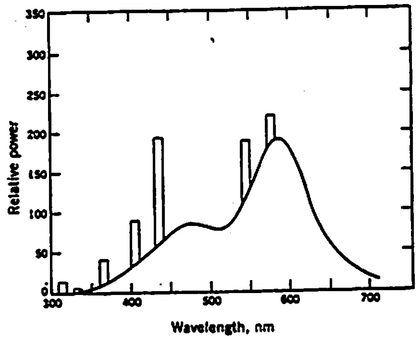

Figure 9. Relative spectral power distribution of a cool white fluorescent light source. Bright line emission is characteristic of mercury in the blue spectral region. Reprinted with permission (*Principles of Color Technology*).

thereby shifting the balance toward the shorter wavelengths.

Depending on the type of incandescent lamp and the blue (daylight) filter it is matched with or reflecting material used, a range of color temperatures from 4500-7500+ K can be simulated and a new spectral power distribution is thus created with more output in the blue wavelength region.

Of greater importance to the gem and jewelry industry are the many types of fluorescent lamps, which represent more phases of daylight and are more economical to use. Most fluorescent lamps are low pressure mercury lamps, shaped like 12", 15", 24", and 48" tubes coated on the inside with luminescent powders called phosphors. The phosphors absorb the ultraviolet light from the mercury vapor and re-emit it as visible light.

For many years commercial lighting manufacturers have been experimenting with different phosphors to produce various types of fluorescent lights (referred to as *bright line* or *emission* spectral curves) with different spectral power distribution curves (Figure 9) and various color temperatures (right side of Figure 5).

The most popular fluorescent light sources are the "warm-white" lamps with color temperatures in the range 2900-3000 K, the "cool-white" lamps at approximately 4100-4300 K, and the (artificial) "daylight" lamps with color temperatures ranging from 5500-6500 K. In addition to these popular fluorescent lamps, others with color temperatures such as 3500 K, 4050 K, 5000 K, and 7500

K are available from lighting manufacturers.

As foretold at the outset of our discussion, the combination of a light source, an object, and a detector (usually the human eye), when multiplied together, provide the stimulus, or physical signal, that the brain interprets as our perception of color. This relationship can be graphically expressed in the equation shown in Figure 10, which shows that if any one of these three curves is changed or altered, the result will be a change in the perceived color.

Using this equation of color, we can now simplify the problem of finding the effect lighting has on color. In our case, we will consider the color appearance of a single object (polished gemstone) observed by a single person, when illuminated by more than one source of light.

THE LIGHT SOURCES we will consider are those most often used in the gem and jewelry industry; average natural daylight (6500 K), artificial daylight with a color temperature of 6500 K, cool white fluorescent light (4100 K) and tungsten incandescent light (2900 K). Toward making these distinctions useful in a practical setting, the author has developed a color card that permits gemologists to instantly identify the color temperature and light source being used (see box, "Communicating Color").

If we look at a ruby, for example, under these four different light sources we can clearly see the effect that lighting has on color. Both of the daylight light sources produce a natural looking color that is neither too red nor too dark, showing the so-called "true" color of the ruby. However, under the incandescent lamp the ruby appears redder and more saturate in color, while the cool white fluorescent lamp gives the ruby a bluish and darker color appearance to the eye.

Considering the lights we have chosen, the incandescent lamp is stronger in the red wavelengths than daylight (thereby enhancing the red hue and saturation of the ruby) and the fluorescent lamp is stronger in the blue wavelengths than daylight due to bright line emissions (thereby shifting the gem's hue toward bluish and increasing

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its darkness).

The explanation for this lies in the formula for color as outlined in Figure 10. The absorbance or transmittance curve for ruby is now substituted in place of the spectral reflectance curve, while the spectral response curve of the human eye remains the same in the color equation. Yet when either one of the spectral power distribution curves — natural daylight (Figure 7), tungsten incandescent light (Figure 8) or cool white fluorescent light (Figure 9) — are substituted for the spectral power distribution curve in Figure 10, the resultant color stimulus (combined wavelengths reaching the eye) is shifted, giving the object a different color appearance.

A similar process occurs with the gem material alexandrite. When it is observed by a single observer under an incandescent light source, the stone exhibits a purplish red color. Under an artificial daylight source the stone exhibits a bluish green color.

Once this equation for color is visualized, it is easy to understand why different lights can affect the color of a polished gem or rough stone. In many cases when there is a color disagreement between two people, it can be traced back to the light source (provided the spectral response of the two observers is not widely divergent; i.e., neither is color blind).

So in order to describe any colored object accurately (gem, mineral, etc.), you must learn to standardize the conditions of illumination and observation, leaving only the object itself as the variable influencing color perception. As demonstrated with the ruby, variable lighting can alter the perceived color of an object by an amount proportional to the wavelength present in the light source. ◆

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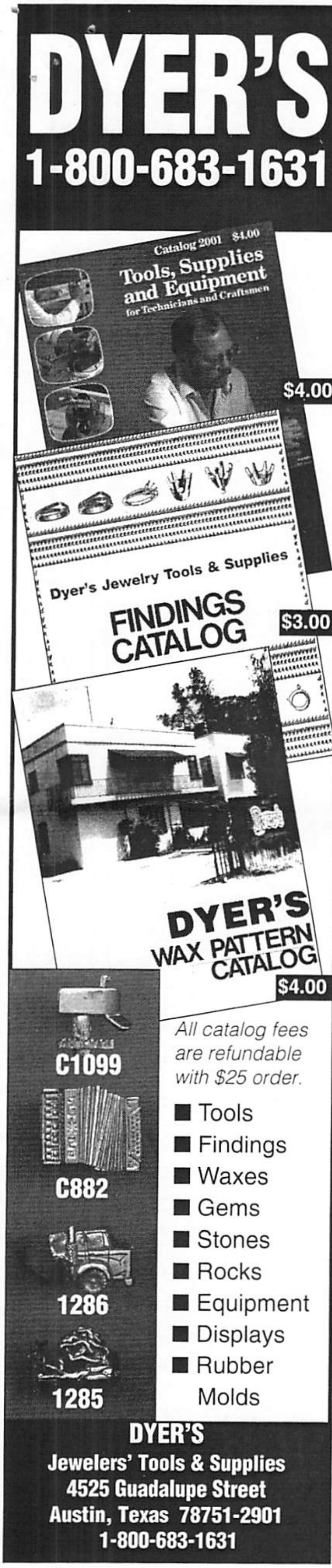

Communicating Color

On my wish list for the industry, I would like to see the day when two individuals discussing the color of a gemstone over the phone (Brisbane to Tokyo or Geneva to New York) could say to one another, "I am sitting now under a 6500 K light source . . . and the color appears to my eye to be . . ."

Toward that end, I have designed a color card that allows gemologists, gem merchants, and jewelers to instantly identify the color temperature of the light source being used. The card is small enough to be held in your hand and when slipped into its thin case, it can be stored in a shirt pocket. On the card are three strips of blue-green color labeled A, B, and C that match or mismatch under certain light sources.

T. Linton and G. Brown of the Gemological Association of Australia (GAA) evaluated the color card in two stages. First, 10 undergraduate students with no previous gemological or gem industry experience were given a card, and after reading the instructions, were asked to use the card to determine the color temperature of three light sources — a warm white 2900 K, a cool white 4200 K, and a daylight fluorescent lamp of 6500 K. Each student correctly identified the color temperature of the three light sources, without difficulty.

Next, six gemologists, one of them moderately blue-green color blind, were asked to describe the colors on the card and of the surrounding white card, when it was viewed under seven light sources of increasing color temperature. The gemologists reported that the white card changed with increasing color temperature from yellowish orange to cream, to off-white, white, then bluish white. Color blindness seemed to have little influence in this color matching experiment.

The color card can be used to interpolate temperatures of light sources other than those of 2900, 4300, and 6500 K to which the color chips were designed to respond.

Address comments or questions to me, Stephen Hofer, P.O. Box 583, Canton, CT 06019.

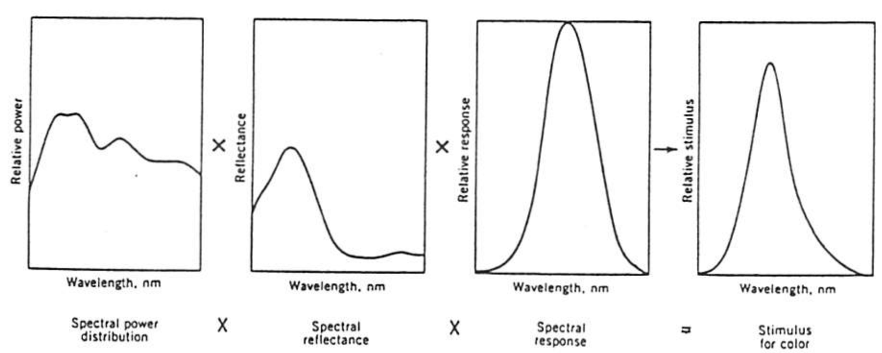

Figure 10. A graphic equation explaining the physical production of color. The wavelengths of light (stimulus) that the brain interprets as color are produced by combining the spectral power distribution curve of the light source, the spectral absorption, transmittance or reflectance curve of the object and the spectral response curve of the detector (in this case the human eye). Reprinted with permission (*Principles of Color Technology*).