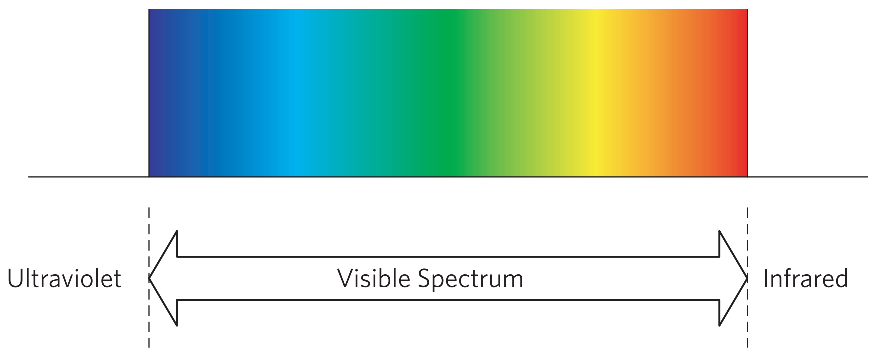
THE NATURE OF LIGHT AND COLOR

THE PHYSICS OF LIGHT

Electromagnetic radiation travels through space as electric energy and magnetic energy. At times the energy acts like a wave and at other times it acts like a particle, called a photon. As a wave, we can describe the energy by its wavelength, which is the distance from the crest of one wave to the crest of the next wave. The wavelength of electromagnetic radiation can range from miles (radio waves) to inches (microwaves in a microwave oven) to millionths of an inch (the light we see) to billionths of an inch (x-rays).

The wavelength of light is more commonly stated in nanometers (nm). One nanometer is one billionth of a meter. Visible light has wavelengths of roughly 400 nm to roughly 700 nm. This range of wavelengths is called the visible spectrum.

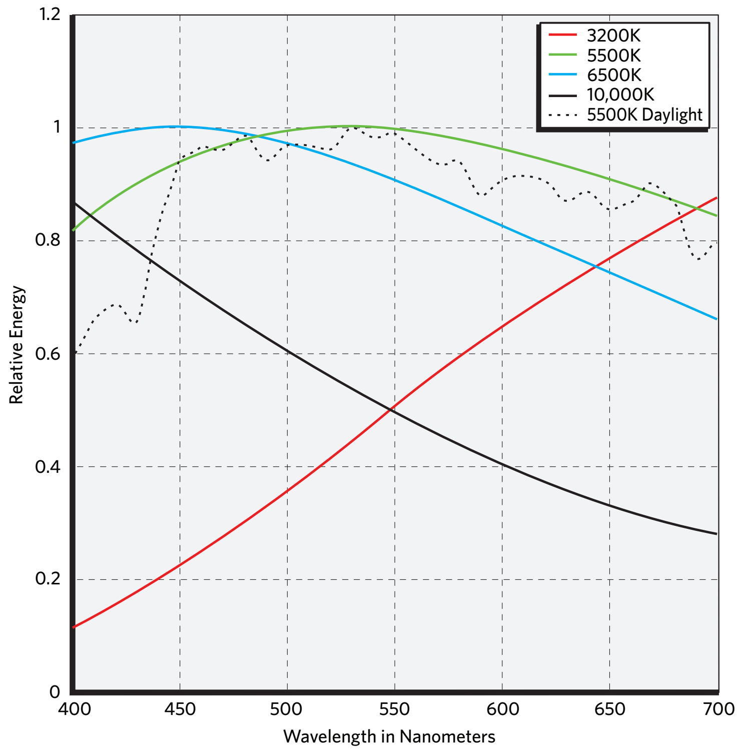


Electromagnetic radiation in the visible spectrum is typically generated by one of these sources:

- Incandescent sources. The most common incandescent source is a tungsten light.
- Non-incandescent sources such as fluorescent, metal halide, mercury vapor, neon, and HMI lights.
- The sun. (The sun is actually an incandescent source, since it produces light by incandescence. However, in the photographic community, incandescent refers to artificial sources.)

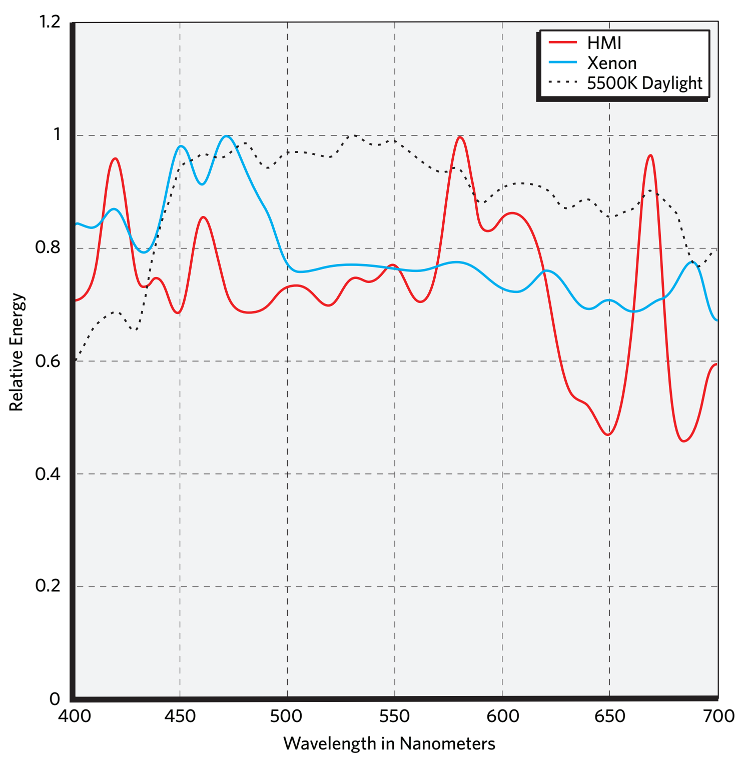
All objects emit some electromagnetic radiation. As an object is heated, it emits relatively more of the shorter wavelengths of electromagnetic radiation and relatively less of the longer wavelengths. It is this property of light that allows a light meter to measure light's color temperature. The following figure demonstrates the visible wavelengths of the relative energy emitted at each wavelength of various color temperatures and in 5500K Daylight. At 3200K there is a relatively large amount of the long wavelengths and a relatively small amount of the short wavelengths. As the color temperature increases to 5500K, 6500K, and 10000K, the relative amount of the long wavelength energy decreases and the relative amount of the short wavelength energy increases.

The 5500K Daylight curve is not as smooth as the 5500K curve because daylight is a combination of the energy emitted by the sun, energy absorbed by the earth's atmosphere, and energy scattered by particles in the earth's atmosphere.



Relative spectral energy curves for different color temperatures.

When the electrons in a molecule or a gas are excited, they rise to a higher energy level within that atom or molecule. After a period of time, the electrons return to their normal energy level and emit the difference in energy as electromagnetic radiation. The energy emitted is frequently in the visible spectrum. The figure below shows the HMI and Xenon lamp spectral curves compared to the 5500K Daylight curve.



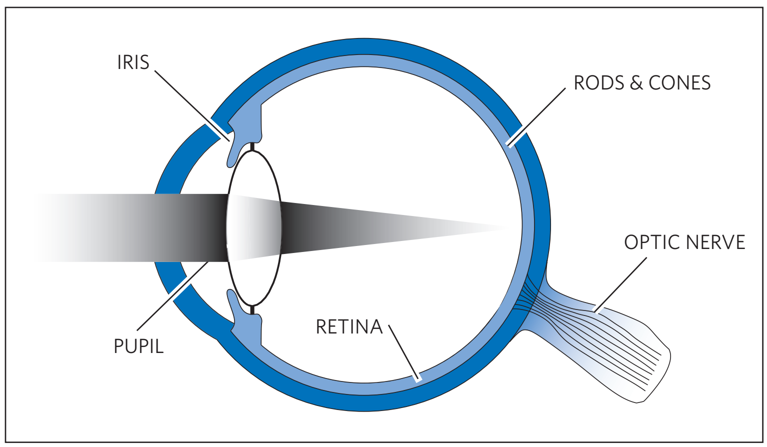
Relative spectral energy curves for the HMI and Xenon lamps compared to the 5500K Daylight curve.

When light strikes an object, the light can be transmitted, absorbed, or reflected. In many cases, all three occur. Transmission, absorption, or reflection can be determined by the wavelength of the light. For example, a piece of clear glass will transmit all the wavelengths of light striking the surface of the glass. If the glass is colored, some wavelengths are absorbed and some wavelengths are transmitted. If there are small particles in the glass, some of the wavelengths may be absorbed, some transmitted, and all reflected. In this case we would describe the glass as both colored and opaque. A piece of colored paper reflects some wavelengths, absorbs some wavelengths, and transmits no light.

If light strikes the surface of a transmitting object at an angle other than straight on, the light will be bent as it enters and exits the object. This property of light allows a lens to focus the light rays on a surface, such as the surface of the film used to photograph an object. Additionally, the short wavelengths are bent more than the long wavelengths. It is this property of light that produces a rainbow. As the light enters a water droplet, the light is bent. The light then reflects off the back of the water droplet. Then, as the light exits from the water droplet, the light rays bend again. Because the short wavelengths are bent more than the long wavelengths, the wavelengths of light are spread across the sky and we see the rainbow.

COLOR VISION

Vision starts when light from a scene enters your eye. The lens in your eye focuses the light as an image onto your retina. The human retina uses two types of cells to sense the light: rods and cones. These microscopic sensors are distributed across the retina, and each type serves a very different purpose. The rods and cones convert light into minute electrical impulses, which travel along nerve fibers to the brain. At the brain, they're translated into an impression of the shape and color of the observed object.

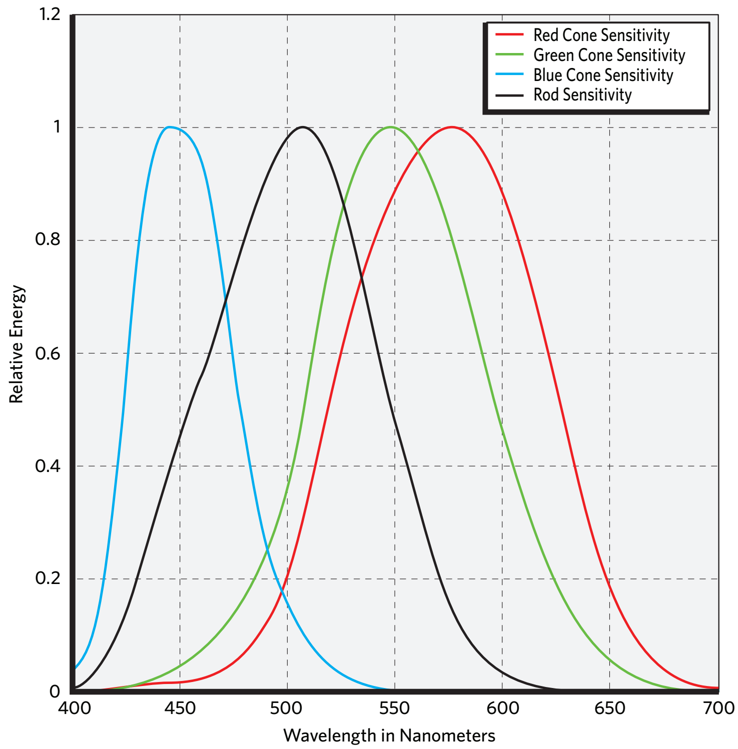


All rods have the same sensitivity to the wavelengths of light and, therefore, cannot see the color of an object. Rods see all objects as shades of gray. Because the rods are also very sensitive to light—much more sensitive to light than cones—they enable us to see in very low light levels, such as a night scene illuminated only by the stars or the moon. In bright scenes the rods are flooded with light and they cease to produce the signal that the brain uses for vision. In high brightness scenes only the cones provide useful information to the brain.

There are three types of cones: one has the greatest sensitivity to the long wavelengths of visible light; one has the greatest sensitivity to the middle wavelengths of visible light; and one has the greatest sensitivity to the short wavelengths of visible light.

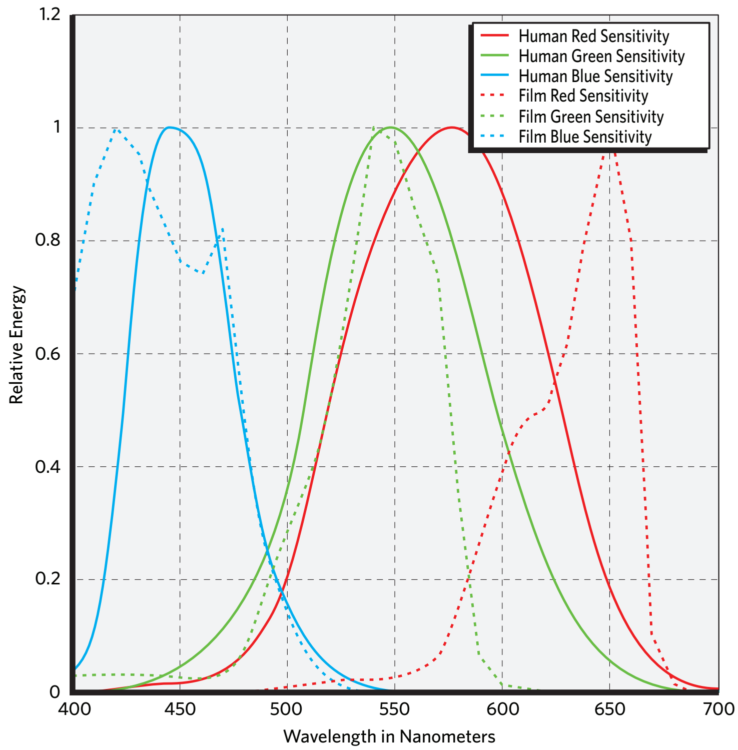
We perceive brightness based on the total level of the signal coming from all the cones. We perceive color based on the relative signal levels coming from the three types of cones. When the cones sensitive to the long wavelengths are predominantly stimulated, we see red; when the cones sensitive to the middle wavelengths are predominantly stimulated, we see green; and when the cones sensitive to the short wavelengths are predominantly stimulated, we see blue. Because there are only three types of cones, all vision is based on these three color perceptions. Therefore, most colors are described as light or dark and a combination of two colors, for example, red and blue (a reddish-blue or a bluish-red). Because of the processing of the signals from the cones in the brain, we cannot see a greenish-red or a reddish-green. The combination of red and green gives the sensation of yellow. Therefore, the object appears as greenish-yellow or yellowish-green. These sensations are the result of different amounts of signals from the red and green sensitive cones. When those signals are exactly the same, we see yellow with no red and no green.

The figure below shows the sensitivity of the rods and the three types of cones to the wavelengths of visible light.



Spectral sensitivities of the human rods and red, green, and blue sensitive cones

Film spectral sensitivities are similar to the sensitivities of the cones. The following figure compares the cone and film spectral sensitivities. There are a number of reasons for the differences in the film and cone spectral sensitivities. The large overlap of the red and green cone sensitivities requires a considerable amount of image processing in the brain in order to produce the sensations of redness and greenness. Film is not capable of that much image processing. Scanned film could be processed much as the brain processes the cone signals, but the image processing increases the graininess, or noise, in the resulting image. Also, because images are typically viewed in lower lighting conditions than those present during photography, the color must be boosted in order for the projected motion picture images to appear natural. By shifting the spectral sensitivities in the film, it is easier to chemically or digitally boost the color in the resulting film image.



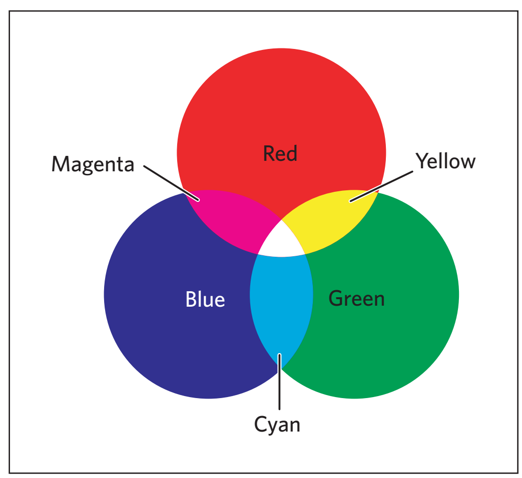
Spectral sensitivities of the human cones and red, green, and blue sensitive layers of color film.

THE REPRODUCTION OF COLOR

There are two basic systems of producing color: the additive color system and the subtractive color system.

Additive Colors

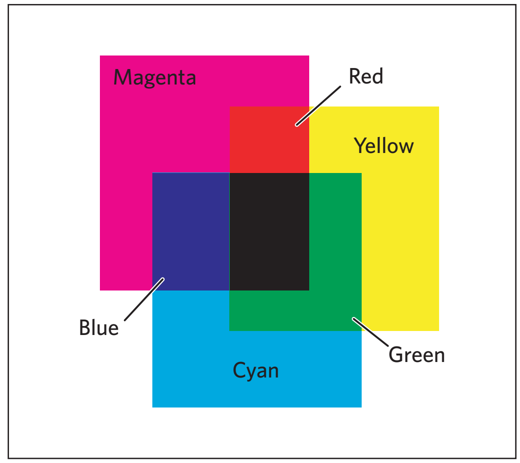
The additive color system reproduces colors by adding colored lights—its primary colors are red, green, and blue (RGB). If none of these colors are present, black results. If all the colors appear at their maximum intensities, the color produced is white. All the colors that can be produced by a three-color additive system are combinations of these three primary colors. When mixed together in various proportions, the additive color primaries of red, green, and blue give us the range of colors that we see. Two common additive systems are a television and a digital projector.



In the areas where two primary colors overlap, a secondary color appears. When overlapped, green and blue create cyan. Blue and red produce magenta. Red and green produce yellow. When added in equal proportions, red, green, and blue result in white light. The absence of all three colors results in black. Mixing varying proportions or intensities of two or three additive primaries creates intermediate colors.

Subtractive Colors

The subtractive color system reproduces colors by subtracting some wavelengths of light from white. The three subtractive color primaries are cyan, magenta, and yellow (CMY). If none of these colors is present, the color produced is white because nothing has been subtracted from the white light. If all the colors are present at their maximum amounts, the color produced is black because all of the light has been subtracted from the white light. All the colors that can be produced by a three-color subtractive system are combinations of these three primary colors.

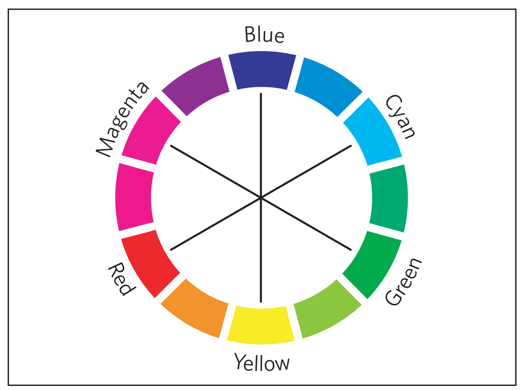


The subtractive system is associated with systems that depend on chemicals for their color, such as ink or dyes on paper and dyes on a clear film base (slide films, negative films, and motion picture print films). The colors that we do see in the subtractive system are the result of the wavelengths that are reflected or transmitted—not absorbed. The cyan absorbs red and reflects or transmits green and blue, the magenta absorbs green and reflects or transmits red and blue, and the yellow absorbs blue and reflects or transmits red and green.

The complimentary colors are the colors that are absorbed by the subtractive primaries. Cyan's complement is red; magenta's complement is green; and yellow's compliment is blue. It is the light that is reflected or transmitted that we see. So a combination of a magenta and a yellow filter looks red because magenta absorbs the green and yellow absorbs the blue. Only the red is left, which we see.

The Color Wheel

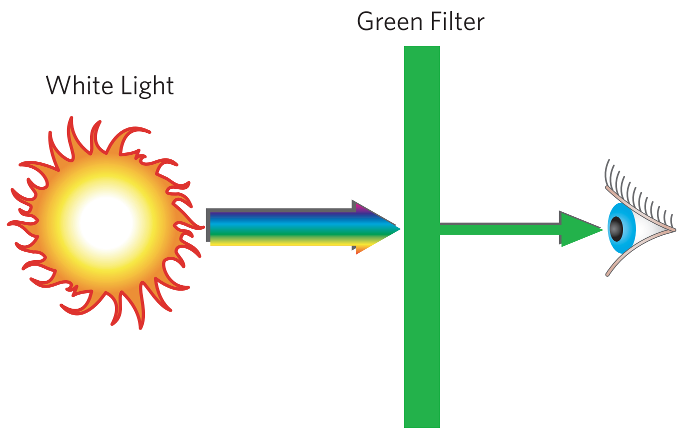
On a color wheel, complimentary colors are placed opposite one another. By combining these complimentary colors in varying degrees, you can create an infinite number of intermediate hues.



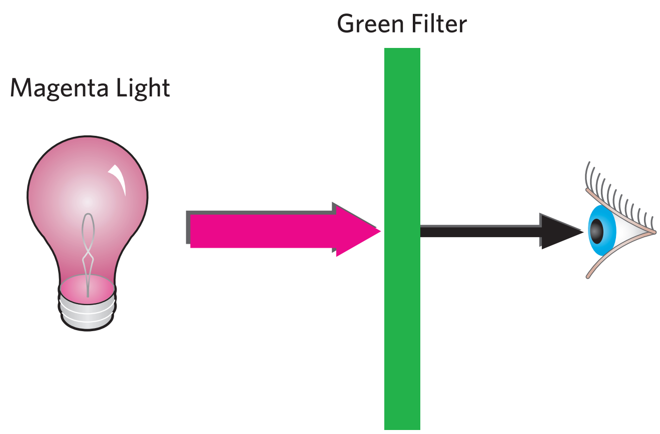
Red's complement is cyan. To render an image less red, you can add more cyan. To make an image more red, you can subtract cyan (or add more red).

LIGHT SOURCES AND COLOR

Objects that transmit light, such as stained glass or projected motion picture film, let certain wavelengths pass while absorbing others. The wavelengths that pass through are the ones that you see; they determine the color of the object. For example, a piece of green glass (or a green filter) absorbs most light from the blue and red ends of the spectrum while transmitting green wavelengths.



A magenta source yields different results. Through a green filter, most of the magenta light is absorbed and the filter appears black. An object's color rendition is the product of its actual color and the available light source.



By adjusting a filter's intensity, we control the amount of light passing through it. An intense green filter absorbs practically all magenta light. As intensity diminishes, more magenta light passes through. Filtration is used to control the color of light during exposure and projection of film.

COLOR TEMPERATURE

Color temperature, expressed in degrees Kelvin, can be measured with a color temperature meter. To compensate for different color temperatures, film is color-balanced during manufacture. When exposed in tungsten light or daylight, respective films reproduce color correctly.

Daylight film is used when the primary source of illumination is skylight, daylight or HMI light, which approximates daylight. Tungsten film is used to capture scenes in which the primary light source is tungsten. Because daylight has a relatively flat spectral curve, which means roughly equal energy at all wavelengths, the red, green, and blue sensitivities of a daylight film are roughly equal. Because tungsten light's spectral curve shows that much more red energy is emitted than blue light, tungsten film is balanced so that the blue sensitivity is correspondingly higher than the red sensitivity.

Filters can be placed over a camera lens or light source to adjust the color balance of light reaching the film. Thus, films can be used in light sources other than those for which they were intended. Each filter has predetermined transmission characteristics that pass certain wavelengths and block others. Film data sheets specify starting filter recommendations for most common light sources. An on-site test should be performed to verify results.

Color balance is more critical in color reversal films. Filters are used to make even small shifts in color. Color negative films are made into positive prints or transferred to a variety of electronic outputs. Adjustments, therefore, can be made during the printing phase or by a colorist in a postproduction facility.

The brain can adjust the level of the signal coming from the cones based on the intensity of the light falling on the cones. When the intensity is low, the brain increases the signal level; when the intensity is high, the brain decreases the signal level. In this way a white object appears white in daylight and in tungsten light. The brain continuously adjusts the color balance of each scene so that it appears correct even in varying light.

Limits to Color Temperature Measurement

Color temperature (Kelvin) refers only to the visual appearance of a light source—not its photographic effect. For example, some light sources emit strongly in the ultraviolet region of the spectrum; the color temperature of such a source does not measure this portion of the emission because the eye is not sensitive to radiation below 400 nm. Since a film is usually sensitive to ultraviolet radiation, a scene can appear too blue unless the ultraviolet light is filtered out. Different light sources may have the same color temperature, but the photographic results obtained with each may be quite different.

Color temperature does not take into account the spectral distribution of a light source. Unless the light source has a continuous spectral distribution, its effective color temperature alone may not be reliable as a means of selecting a suitable correction filter. For example, fluorescent lamps do not have the continuous smooth spectral-distribution curve that is characteristic of a tungsten-filament source.

Correlated Color (CC) Temperature refers to non-incandescent sources such as fluorescent, metal halide, mercury vapor, neon, and HMI lights. A correlated color temperature rating approximates the nearest true incandescent source.

When using a color temperature meter, you may use a swatch book of color correction gels to determine the correct gel needed for your film stock balance.

In a green vs. magenta reading (using the CC mode), the color temperature meter may detect a large amount of green and display 30M. The meter has calculated that a strong magenta correction is needed. You may try a full minus green gel from a swatch book in front of the meter receptor, then take a new reading. This magenta gel will absorb the green spike present in certain types of non-incandescent sources, such as fluorescent and sodium vapor.

To determine a red vs. blue reading, use the color temperature mode. If the source reads 5500K, and you're trying to match a tungsten-balanced film, try placing an 85 gel in front of the receptor. Ideally, the meter will read 3200K. If the meter reading is slightly off, try mixing gels of varying density.

Color Temperature for Various Light Sources

Artificial Light	
Match Flame	1,700K
Candle Flame	1,850K
40-Watt Incandescent Tungsten Lamp	2,650K
75-Watt Incandescent Tungsten Lamp	2,820K
100-Watt Incandescent Tungsten Lamp	2,900K
3200 K Tungsten Lamp	3,200K
Photoflood and Reflector Flood Lamp	3,400K
Daylight Blue Photoflood Lamp	4,800K
Xenon Arc Lamp	6,420K
Daylight	
Sunlight: Sunrise or Sunset	2,000K
Sunlight: One Hour After Sunrise	3,500K
Sunlight: Early Morning	4,300K
Sunlight: Late Afternoon	4,300K
Average Summer Sunlight at Noon (Washington, DC)	5,400K
Direct Midsummer Sunlight	5,800K
Overcast Sky	6,000K
Average Summer Sunlight (plus blue skylight)	6,500K
Light Summer Shade	7,100K
Average Summer Shade	8,000K
Summer Skylight will vary from	9,500 to 30,000K

Note: Do not confuse sunlight with daylight. Sunlight is only the light of the sun. Daylight is a combination of sunlight plus skylight.

"Film has the depth to create the magic I was looking for. I wanted a full spectrum of colors to create the vivid world that represented Angelina's [Looking for Angelina] imagination, and her immigrant history, which is often seen in black and white and sepia tones."

—Sergio Navarretta, Cinematographer