Color Temperature

By Gergely Vass

What is white? At first glance, this question seems rather easy to answer.

None of us would have any problem pointing at something that is considered to be white. However, coming up with a proper technical definition is hard. Even looking at Wikipedia would not help us: "White is the combination of all the colors of the visible light spectrum." In fact, combining all spectral colors equally will not necessarily produce white. Furthermore, it is possible to create white by combining only three (or even two) spectral colors. As always, we need to be careful with such sources of information.

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It's hard to determine what is white, so we face problems when trying to reproduce images on computer displays.

So, what is white then? In the case of paints or pigments, the answer is simple: A white surface reflects (almost) all incident light. Can we come up with the same sort of definition for light sources? The answer is no; there is no universal white color.

On a sunny day, inside an artificially lit room, or under the cloudy sky, the stimulus—the physical rays of light—we consider white is very different. Technically speaking, there is no unique physical or perceptual definition of "white."

Human perception and many digital imaging devices adapt to the current white—essentially the color of the dominant light source—so we may not even have to care about it. We face problems, however, when trying to reproduce images on computer displays. Sending equal red, green, and blue components to monitors may result in a color that looks tinted, and we typically get different colors for different monitors. It should not be a surprise that one of the most important steps in the calibration of monitors or projectors is the setting of the "white point."

But why would we bother calibrating our monitors? If our work only involves character rigging, scripting, or subdivision modeling, we do not necessarily have to do this. However, making critical decisions regarding the lighting of our virtual scene or picking textures or material colors is only possible using a calibrated display device. This is particularly important for architectural or design visualization: We do not want our clients to look at false colors when presenting the rendered images of their future product or building.

Photo by Tim Easterday.

Digital cameras may get confused what white is, if there is a mix of incandescent, halogen, and natural lighting.

Even if there is no universal stimulus that appears white, we should at least be able to describe it quantitatively. Without this, color calibration would be impossible. The most complete description of a light source—and its color—is the spectral power distribution (SPD), a curve indicating the exact "composition" of spectral colors. The SPD is a function of wavelength, so we need at least 30 samples (numerical values) to store it digitally. But do we really need all this data to describe a specific color? Not necessarily. While there are commonly used standards describing the SPD of the illumination (for instance, the CIE D65 standard illuminant, which corresponds roughly to a midday sun), we often use a single number to describe white: the color temperature.

To understand this number, let's take a look at the sources of illumination. Most natural and man-made light sources have some heated object at their core as the primary source of illumination. Just think of a candle, lightbulbs, or the sun itself. This kind of illumination is called incandescence. Why is this important? As we will read later in this article, the color—and the complete SPD, too—of a perfect "hot" light source can be described by a single number. It is true that most natural illuminants, like the sun or fire, are not perfect in the sense that other physical/chemical/electrical effects alter the SPD. Also, the much more efficient compact fluorescent lights, LEDs, or gas discharge lamps work differently, but manufacturers do try to match their color to incandescent sources to make it look and feel more natural. Even though a given light source may not fall on the "black body locus," one can still project its chromaticity onto this curve in order to have a single number that describes how yellow or blue it is.

In the 19th century, physicists studied electromagnetism and thermodynamics very actively. With quantum mechanics not invented yet, researchers tried to explain the results of all experiments using the classical theories of the Newtonian mechanics—something that eventually turned out to be impossible. One, if not *the*, most important experiment was the heating of objects and measuring the emitted electromagnetic radiation.

Photo by Greg Smith.

The temperature of hot lava may be estimated by measuring its color.

To describe this thermal radiation, the concept of black body was introduced in 1860 by Gustav Kirchhoff: an object that absorbs all light—that is, all electromagnetic radiation—that falls on it, thus nothing is reflected from the surface. Unfortunately, if we simply paint an object black, it will not necessarily be a "black body." There is a great chance (it is certain) that the object still will be visible using an infrared camera.

The spectrum of the detected black-body radiation depends solely on the temperature of the object. While it is impossible to construct perfect black-body radiators, due to unavoidable electric and chemical reactions altering the spectrum, we can always find the nearest one that matches the chromaticity in question. For incandescent lights, this match is going to be almost perfect. And why is this important for us? The concept of black-body radiation allows us to describe white color with a single temperature value: the correlated color temperature.

The temperature of 6500 degrees K (Kelvin) correlates with the average daylight; regular lightbulbs boast approximately 3000 K degrees and appear more yellow compared to daylight. The "coldest"—1700 K to 1800 K (2600 to 2800 degrees Fahrenheit, or 1400 to 1500 degrees Celsius)—visible incandescent light source is the flame of a candle, turning into orange and red. We can see that there is a great range of stimulus our eyes can adapt to, resulting in the same "white" sensation.

The curious reader may now wonder: How should we interpret, for instance, the color temperature of 310 K? That happens to be the temperature of our own body (36 C, 97 F). Well, we can compute the electromagnetic radiation emitted by ourselves, but the resulting spectrum will not fall into the visible range of wavelengths. However, it should be clear: All objects above absolute zero Kelvin do emit electromagnetic waves. Speaking of absolute zero Kelvin (-273 C, or -460 F), objects at that temperature do not emit radiation, and it is not possible to make any object colder than that.

The sensors of thermal- and some night-vision cameras, and even some animals, can detect portions of the invisible radiations emitted by objects below 1700 K. Such special devices are often seen in Hollywood movies, used for surveillance and for military personnel to "see in the dark," but there are much more humane applications. A good example is veterinary. Horses have evolved with an ingrained tendency to mask pain to protect themselves in the wild. This makes the veterinarian's task of detecting, diagnosing, and treating a problem with a horse extremely challenging. With thermal cameras, it is very easy to "see" inflammations, and there is no need to even touch the animal. This is essentially measuring temperature by looking at color. Is that possible only in the infrared range of electromagnetic spectrum? No. Another practical application related to black-body radiation is measuring the temperature of hot lava. By simply observing the color of the molten stone, even from safe distance, the temperature can be easily estimated.

Describing the emission of heated objects—using the formula of Max Planck—is handy for us to describe the white color, but in the early 20th century, it gave birth to quantum mechanics, as well. In Planck's formula—which was fitted to experimental results and not derived theoretically—a universal constant popped up that seemed to suggest electromagnetic energy could be emitted only in small pockets, in quantized form. Note that this time, photons were not known yet. Planck did not really think much about this, but rather, took it as purely a formal assumption. He strove hard to keep his theory on the solid ground of classical physics and rejected for many years the revolutionary idea of photons, which seemed to contradict contemporary wave theories of light.

It was a couple years later that Albert Einstein laid the foundation for the photon theory, and eventually managed to reconcile mechanics with electromagnetism. And it all started by observing heated black bodies. ⁂

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