# SPECTRUM-BASED COLOR MODEL VERSUS PERCEPTION-BASED COLOR MODELS IN LIGHT SIMULATIONS

BY

Robert Campbell Farish Jr.

*THESIS*

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Thesis Advisor: Pushpak Karnick

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Spectrum-based Color Model versus Perception-based Color Models in Light Simulations

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APPROVED:

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|---|---|
| Dr. Dmitri Volper date<br>Graduate Program Director | Dr. Xin Li date<br>Dean of Faculty |
| Dr. Dmitri Volper date<br>Department Chair, Computer Science | Claude Comair date<br>President |

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| Pushpak Karnick date | Mark Henne date |
| Thesis Committee Chair | Thesis Committee Member |
| Gary Herron date | Dmitri Volper date |
| Thesis Committee Member | Thesis Committee Member |

# ABSTRACT

Most color models used in digital displays are based on human biological sensation of color perception. As computer graphic trends increase focus on realism, these models suffer from decreasing accuracy when simulating the physical world; when modeling the light physics involved in the color determination process, more information is required than current color models (like RGB) provide.

This paper proposes a color model which describes the color process before the perception stage and considers how photons evoke perception based on spectral composition. This research looks at how color perception-based models differ from spectrum-based models and when those differences justify the increase in computational cost and complications of a spectral model.

The proposed model utilizes a special texture-based format for storing the spectral model and implements shader-based rendering on the GPU shaders. Sample renderings show that spectrum-based data results in more realistic color output than perception-based models when the material-source interaction differs non-uniformly per wavelength. There are some scenarios where the benefit from spectral rendering is greater than others; the more the spectral data involved strays from an equally distributed wavelength function, the greater the photorealism qualities of the spectral model over the perceptual model.

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CHAPTER 1

# Introduction

Light is present throughout the universe and has guided the evolution of the biological systems of most plants and animals on this planet. Plants use light to power their growth while most higher-level species have some form of vision, in which light perception is used to judge surroundings. Humans do more than just sense that light is present, the brain and eyes process light's spectral make-up and react to it—and this judgment is known as **color**.

Optic nerves and the brain form a color-processing system that transforms photon activity into sensations[43, 85]. The brain is an integral part of the color system and creates color perceptions that are not being triggered directly by photons. The brain adds bias into color judgment and therefore when discussing color descriptions in this thesis, a distinction must be drawn between the two ways of describing color: a biological and perception-based idea of color; and a physical and spectral-based idea of color.

Research will delve into the following main areas:

- **Light Physics**

Physics laws are meant to be immutable and repeatable and, as with many other physics systems, these can be successfully simulated in computer programming. Also, quirky light phenomenon from this area provide several future-work scenarios for this thesis.

- **The Biological Visual System**

  Color is a sensation, or judgment, that happens in the brain—therefore during a discussion about light physics, talk of color is only a correlation to the human visual system. Color perception begins in the eyes, travels through nerves, and ends in the brain. The eye cells truncate photon data input and then the brain is able to tweak perceptions slightly, making this area of color study subjective.

- **Color Models**

  Humans can use color information to aid in object recognition; color adds an instant and effortless identifier[22]. Man has sought to manipulate color for aesthetic and scientific purposes and many models have been created and honed over the centuries. The technology age has given rise to more professional color models than ever as color has become a more precise part of manufacturing processes. There are several ways to categorize color experience and society has adopted standard methods for casual, professional, and scientific uses[36].

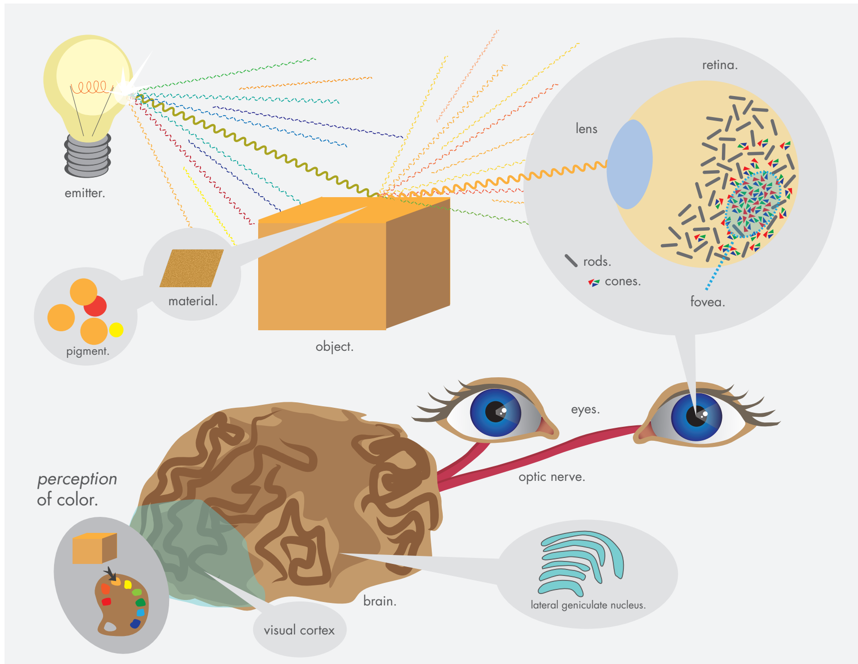



Figure 1. System of Color Perception *Graphic Source: R. Campbell Farish*

## 1. The Mechanics of Color

The flow chart in *Figure 1.* outlines the interactions involved in pyschophysical color processing. In summary, when a human being perceives a color[14, 5]:

- The process begins with an emission source that is radiating photons. This group of photons can be described by its individual strength per wavelength in a histogram format that represents the source's structure.
- In most lighting scenarios there are several emission sources at play. These may include natural light, a number of artificial emission sources, and/or some ambient light.
- Each spot in an environment will contain varying strengths of photons from

these emission sources which add together to form a spectral pattern of wavelengths at any specific point in space.

- When light encounters an obstruction, that object is made of a material, and that material typically contains a pigment. Pigment will absorb certain wavelength values and reflect back others.

- The resulting spectral histogram leaving the object is now a make-up of both the emitting light that was present to begin with and the absorption pattern of the material it hit. The object has filtered the initial light pattern into a new one, which will end up representing the color of said object.

- If someone were standing in the correct position for these resulting photons to enter the eyes, then these photons would be captured, settling within the retina on the fovea.

- The fovea is dense with specialized wavelength-sensitive cells that detect what wavelengths are present in the incoming light and turn that information into a nerve impulse pattern. The histogram details are now lost during biological absorption.

- The nerve impulses reach the brain where further color, shading, and texture processing continue in an area of the brain called the **Lateral Geniculate Nucleus** and then to the visual cortex[43, 99]. During this step the sensory input is turned into a perceptual judgment: color.

CHAPTER 2

# The Photon

**Light** is emitted from sources in an oscillating stream of discrete energy packets, called **photons**. They are universally omnipresent and adhere to their own unique physics system. The photon is the premiere member of the classification of **wave-particles**, meaning it exhibits properties of both waves and particles. It does this by operating as a point of energy with zero mass and is so unique that a photon's speed helps define how humans perceive time, space, and reality.

When illumination occurs, photons are present, being absorbed and reflected, and the ones reaching the eye provide sight. The human visual system processes photons in great numbers, not one at a time, so it's important to regard their greater behavior as a group.

Light physics often comes coupled with stories of its history. Definitive conclusions on what exactly light *is* took centuries and its history is full of theories that pushed other laws of the known universe. Theories of light began as controversial—and sometimes blasphemous—scientific ideas, but in recent centuries physicists including Newton, Einstein, Young, and Planck built on each other's work to form a complete idea of light[5].

The most controversial debate over light was whether it should be categorized as a wave or a particle. In the end, the categories were rewritten to allow for a photon to be both a wave *and* a particle.

### 1. The Wave System

To understand the debate between the categorization of a photon as a wave or a particle one should consider the wave system. In physics, waves are oscillating repeating patterns. They can be mechanical and travel through a physical medium, much like the aptly named waves in water. There also exists an **electromagnetic wave**, meaning it travels through space, regardless of a physical medium being present. All waves exhibit the characteristic of being able to affect one another's patterns, known as **interference**.

The following are some properties of waves[31]:

- **Wavelength** is the distance between two points along a wave at the same point in the sequential cycles of a wave formation. It can be thought of as the distance between two crests (or peaks) of a wave.

- **Frequency** is how many times the wave oscillates through a certain point over a change in time. The **period** of a wave describes the change in time between waves, and it is the inverse of frequency.

- **Amplitude** is the height of a wave from the origin to its crest. (Note that the total horizontal range of the entire wave is twice the amplitude.)

- **Wave propagation** describes how the wave travels, with the two main types being longitudinal waves and transverse waves.
- **Wave vector** is used to describe the propagation direction.
- **Waveform** is the shape of the wave cycle.

The behaviors of a wave include the following[31]:

- **Reflection** occurs when a wave encounters an obstruction that changes its direction.
- **Absorption** occurs when a wave is absorbed by an obstruction.
- **Interference** occurs when multiple waves encounter each other.
  - **Constructive Interference** occurs when multiple waves combine into an amplified wave.
  - **Destructive Interference** occurs when multiple waves cancel each other out.
- **Refraction** occurs when a wave enters a new medium and changes its speed.
- **Diffraction** occurs when a wave bends around an obstructing force.
- **Polarization** occurs when a wave's oscillation is restricted in range.

## 2. The Particle System

Theoretical particles are multiple small amounts of mass or energy in which their group behavior is observable on a grander scale[39]. When particles come together in a system one can ascribe additional macroscopic features such as **density** which refers to how closely together the particles are packed. These particles can group together or be broken apart and maintain a continuous momentum until some force acts upon them. Unlike waves, particle units do not phase through materials. When encountering an obstruction, particles must react by either absorption or reflection.

One single particle can have properties such as:

- **Mass or Energy** describes the make-up of the particle.
- **Velocity and Acceleration** represent the movement of the particle over a period of time.
  - **Speed** is how fast the particle is moving.
  - **Direction** represents the forward vector of the particle.
- **Momentum** is the mass or energy multiplied by the velocity of the particle.

Particle actions include:

- **Absorption** is a particle merging with obstructing matter.
- **Reflection** is a particle encountering an obstructing force that causes it to change direction.
- **Scattering** is when particles hit obstructing forces and reflect in many different directions—not unlike billiard balls on a pool table.

## 3. The Photon as a Wave-Particle

A **wave-particle** takes properties from both the behavior of waves and the behavior of particles and combines them into a new system.

*Figure 2.* illustrates Young's Double Slit Experiment, which proves that light exhibits wave properties by showing that multiple photons can create interference patterns, which is a defining characteristic of waves[5, 290]. Young's Double Slit Experiment involves splitting a beam of light into two beams of light and then observing their resulting patterns on a surface. The light can be isolated using pin holes in a board or a more modern example involves splitting a laser into two beams by shining it through three pieces of lead. The two resulting beams then interfere with one another and this is evident by the rippled effect of the beams' outer edge when it hits a surface.

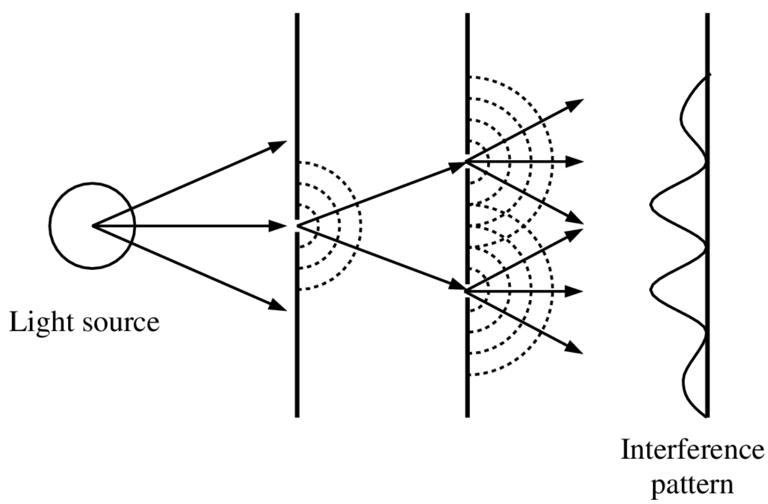



Figure 2. Illustration of Young's Double Slit Experiment. *Graphic Source: Foundations of Vision, Brian A. Wandell*

Photons also exhibit observable particle behavior; for example, shadows demonstrate the photons not phasing through materials but rather being absorbed like particles. Due to observable scenarios of light exhibiting both kinds of behavior, mainstream physics amended its previous notions. Einstein resolved the paradox surrounding the photon's classification with his famous $E = mc^2$ equation stating that matter could transmute into energy[6, 373]. This new idea was paramount in the realization of the photon as a wave and a particle; even though the photon was energy it could behave like a particle of matter in certain instances.

This addition to the theory of light was important because it explained how light is able to travel through the vacuum of space which is void of medium. Mechanical waves, like sound waves, act upon matter and therefore they cannot travel through the vacuum of space[31]. However light can travel through a medium-less void because it is essentially its own medium.

When light is emitted from a source, a chemical compound undergoes a molecular change, shooting off extra energy in the form of a photon, leading to a stream of photons—the particles of the system[38]. Photons are considered **subatomic particles**. The term 'subatomic' by definition means smaller than an atom and when visualizing a single photon interaction it is on this micro scale.

## 4. Photon Velocity

When people use the term "the speed of light" in the vernacular—the famous constant number that is so fast that nothing can reach it—what they really mean is "the speed of light in a vacuum." Contrary to popular belief, people interact with changing light speeds all the time, but it is in a vacuum where photons travel at their theoretical maximum speed of $299,792,458 m/s$[23, 8][1]. This special constant is incredibly important to the human condition; life-defining principles, like time and distance, are all based on it.

Photon speed behaves differently than the speed of objects; it exhibits **non-relative velocity**[6, 157]. An example of *relative velocity* involves a person walking from one end of a train to the other. To an observer outside the train, the velocity of this walking patron is that of his stride as well as the train's movement. Light does not work like this. Light exhibits the same speed to an observer watching the train from outside as it does to an observer inside the train car; speed can not be added to it.

## 5. Photon Energy, Frequency, and Wavelength

A photon is an energy particle—a constant amount of energy concentrated in a point and moving along an oscillating path. Planck discovered photon energy comes in discrete energy packets that cannot be broken down any further[34]. One energy packet is called a **quantum** and **quanta** is the flow of these energy units. The amount of energy per quantum differs per wavelength; the shorter the wavelength of light the more energy per quanta packet[6, 165].

Planck created an equation that relates the quantum of energy to a corresponding photon frequency. The two are related with a scalar used to assist

[1] Various laboratory experiments seem to have broken the speed of light. However, for practical purposes, light's max speed is achieved in a vacuum.

with this conversion, **Planck's Constant** (*2.1*), commonly represented as ($h$). The Planck-Relation Equation, or Planck-Einstein Equation (*2.2*), relates energy ($E$), Planck's Constant ($h$), and frequency ($\nu$)[34].

$$h = 6.626068x10^{-34}\, m^2 kg/s \tag{2.1}$$

$$E = h * \nu \tag{2.2}$$

The Planck-Relation Equation shows energy as most closely tied to a photon's frequency and these two values never change for the life of the photon. **Frequency** can be thought of as the number ($n$) of cycles ($x$) per a change in time ($\Delta t$). The unit of Hertz (Hz) is used for photon frequency, which is the number of cycles per second. The symbol **nu**, $\nu$, is typically used when describing frequency in equations.

$$\nu = \frac{n * x}{\Delta t} \tag{2.3}$$

Another important property of photons is its wavelength. **Wavelength** ($\lambda$) is the change in distance ($\Delta d$) per one cycle ($x$).

$$\lambda = \frac{\Delta d}{x} \tag{2.4}$$

The wavelength of a photon can be thought of as the consequence of the energy (or frequency) of the photon and its speed. While energy and frequency are constant for the life of the photon, a photon's speed can be variable—meaning it is possible for a photon to exhibit varying wavelengths throughout its life.

Through manipulating *Equation 2.3* and *Equation 2.4*, the wavelength multiplied by the frequency results in a scalar of change in distance over change in time (*Equation 2.5*). Change in distance over time, or speed as it is typically referred, is notated as $c$ in photon equations. If a photon's wavelength and frequency is known, how fast it is going can be determined—and vice-versa.

$$\nu * \Delta t = n * x, \qquad x = \frac{\Delta d}{\lambda}$$
$$\nu * \Delta t = n * \frac{\Delta d}{\lambda}$$
$$\nu * \lambda = n * \frac{\Delta d}{\Delta t} \tag{2.5}$$

The following equation represents the relation between light speed ($c$), frequency ($\nu$), and wavelength ($\lambda$):

$$c = \lambda * \nu, \quad \lambda = \frac{c}{\nu}, \quad \nu = \frac{c}{\lambda} \tag{2.6}$$

Substituting *Equation 2.6* into *Equation 2.2*, the Planck-Relation Equation, energy ($E$) can now also be related to wavelength ($\lambda$) and light speed ($c$).

$$E = \frac{h * c}{\lambda}, \qquad \lambda = \frac{h * c}{E} \tag{2.7}$$

Energy and Frequency as variables are really one and the same, merely different ways to describe a possible constant state of a photon. Variation in speed—and therefore wavelength—drives observable quirky light behavior in which photon wavelengths are changed or uniquely affected. An ideal scenario for observing a photon's true state—meaning unaffected wavelength—would be for light to travel through a vacuum and be observed by a static source.

## 6. Electromagnetic Wavelength Spectrum and Human Gamut

The range of all wavelength values comprises the **Electromagnetic Wavelength Spectrum**. This spectrum is of ubiquitous use in modern society; X-Rays, microwaves, radar, radio, and television are technically manipulating photons. That list contains some of the biggest life changing technological advancements in health, culture, military, and communication. Some photon wavelengths are harmful, and each section of the spectrum acts differently with varying degrees of particle and wave behavior.

Everything within the Electromagnetic Wavelength Spectrum in *Figure 3.* is considered a photon, but **visible light** refers to photons humans can detect. The **Visible Light Spectrum (VLS)** is a subset of wavelengths that excite cell reactions in humans and lies roughly in the middle of the electromagnetic spectrum with a relatively small span of $380nm$ to $780nm$[7, 3]. *Figure 3.* illustrates how narrow the VLS is compared to the whole range of photon activity.

The VLS is based on the biological sensitivity of human beings which varies from person to person, and is therefore a subjective range. The leading data comes from a small percentage of participants compared to the 6 billion currently on the planet; very few people—if any outside of a research setting—know their own VLS range. Technically, there is individuality to this range, however human beings are similar enough to operate on a global color system.

Not surprisingly, the uniqueness of each human being's biology gives rise to an individuality component to color perception that has made definite figures on the

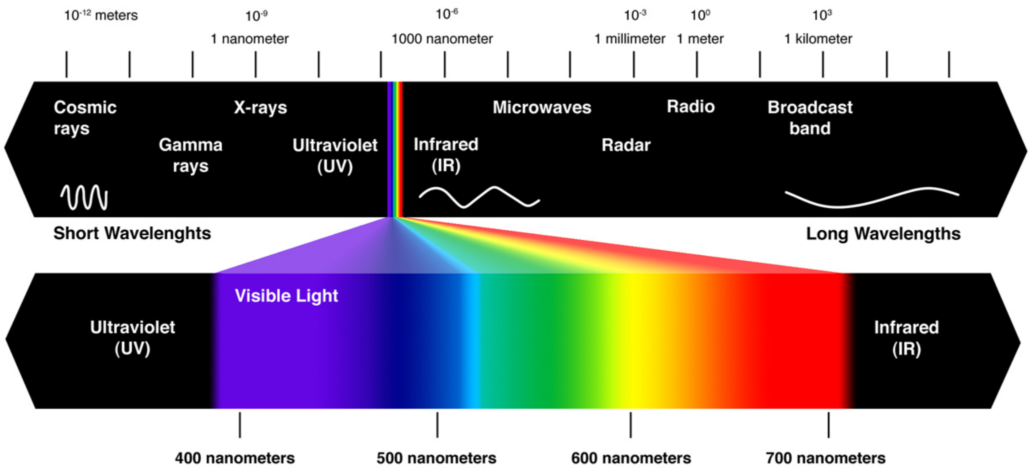



Figure 3. Electromagnetic Spectrum. *Graphic source: Comp Sci Division UC Berkeley.*

VLS elusive at times. A search for VLS data results in wildly conflicting reports on what the total range is, as well as how it breaks up into subsequent color ranges[2]. Blurred numerical boundaries around color ranges are to be expected in such a fluid subject, however there are reports that put entirely opposite color sensations in the same boundary. For instance, *Figure 3.* shows yellow for the color at $600nm$, while *Figure 4.* lists it as orange. It seems that there is more at play here.

*What are the practical values for the VLS?* Or, at least, *what are the average or most common VLS boundaries?* The authority on all matters of **colorimetry**—the science and technology behind defining color quantifiably—is the **International Commission on Illumination (CIE)**[36]. The CIE lists the total VLS wavelength range as, $380nm - 780nm$, and because it is the authority on color science, this range is the best place to start for defining standard VLS boundaries.

[2] For example, *Color Gamut Mapping* lists the VLS range as $400nm$ to $700nm$[30, 22]

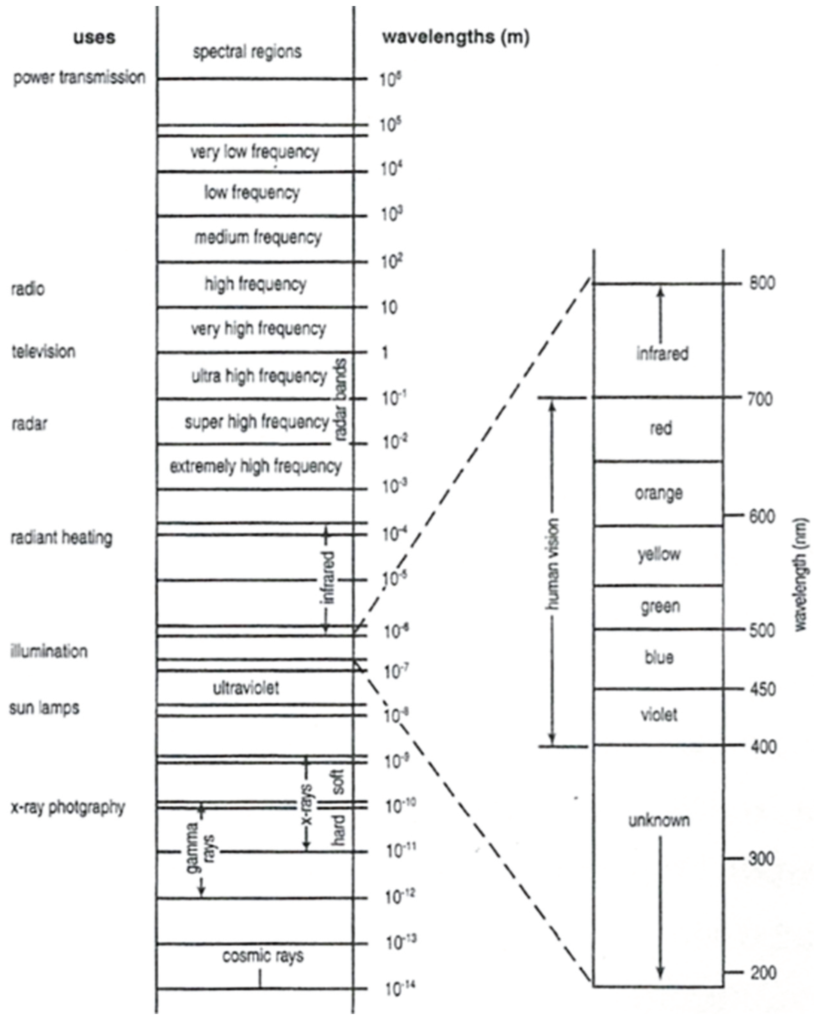



Figure 4. Electromagnetic Spectrum. *Graphic source: Beauty of Light, 1988 Ben Bova.*

| Color | Wavelength Range | Frequency Range |
|---|---|---|
| violet | $\approx 380 - 450$ nm | $\approx 668 - 789$ THz |
| blue | $\approx 450 - 475$ nm | $\approx 631 - 668$ THz |
| cyan | $\approx 476 - 495$ nm | $\approx 606 - 630$ THz |
| green | $\approx 495 - 570$ nm | $\approx 526 - 606$ THz |
| yellow | $\approx 570 - 590$ nm | $\approx 508 - 526$ THz |
| orange | $\approx 590 - 620$ nm | $\approx 484 - 508$ THz |
| red | $\approx 620 - 750$ nm | $\approx 400 - 484$ THz |

Figure 5. Visible Light Spectrum

What the CIE does *not* list is a definitive breakdown of wavelength range per corresponding color perception. *Figure 5.* is merely inferred by the colored graphs from the CIE. This chart represents an estimated range for what color perception relates to which area of the gamut, and is merely meant to aid in discussion. There is most likely no definitive hue list, because the hue delineations of the VLS are not mathematically important and are just verbal labels for general wavelength behavior and thus not absolute. The concept of color during discussion of light physics is merely a correlation to color perception because color is a biological sensation. Therefore any verbal descriptor for color during a physics conversation is going to be subjective.

CHAPTER 3

# Photons in a Group

When there are no visible light photons present in an environment, everything will appear to an observer as total darkness. Light photons come from a source, also called an **illuminant** or **emitter**, and when these emission sources undergo a change in energy they release their excess as a stream of photons[35, 53]. Once there is a source adding photons into the area, there is the presence of light, or **illumination**. Photons stream forth in huge numbers, interfering with each other, and making it onto the viewer's eye cells as a packet of light[43, 85].

The photon wavelength range makes up one very important and unique part of color perception, but the amount of light and its make-up are responsible for the variety of colors we experience. The human brain has created an expansive coded system and instantly reads the physical properties of light and turns it into millions of possible experiences.

### 1. Photon Density and Intensity

When photons become more densely packed together their energy and **intensity** increases. This results in color sensations one might declare as *brighter, lighter,* or *stronger*. There are two different scales on which to discuss intensity:

- The **radiometric** measurement corresponds to the physical energy intensity per wavelength. This refers to the number of photons present creating more or less intensity[23, 29].
- The **photometric** measurement corresponds to the eye's perceived intensity, or rather the inherent brightness a color judgment has to a viewer[23, 49].

Photon strength has a value in both the radiometric and photometric scales, and there are conversion functions between these two models as well[1]. Radiometric measurements represent hard numbers in physics and are not subjective.

The amount of light a source emits on a radiometric scale is **radiant flux**, or radiant power[7, 6]. This variable directly relates to how dark or light one perceives a particular color. When viewing the same object in a room with less or more photons present that reach the eye, that object will appear dimmer or brighter. The unit for radiant flux is **watt** and the range starts at zero and goes theoretically to infinity. The system of lightbulbs operates on this scale and most people are somewhat familiar with bulb wattage—a typical household bulb is in the range of 60-150 watts, for example.

[1] This thesis is mainly interested in the radiometric scale not the photometric scale. If the subject was on color to grayscale conversion, photometric values would be integral.

When light from a source sprays out in all directions, the density of the resulting photon power decreases as distance from the source increases. Close to the light bulb the photons are all just beginning their journey and huddled around a point; they are the closest they will ever get to each other at the moment of their emission and then begin to fan away from one another. If a book is held close to a sole light source, like a lamp, a white page will encounter many photons still present in that environment with close proximity to the source. Now take the book to the other side of the room and the page is dark and hard to read. This is because from farther away, the photons from the lamp have spread out too much and there are fewer of them to reflect off the page back to the eye.

## 2. Spectral Power Distribution

Photons with wavelengths within the VLS combine in different ways to create the variation of perceived colors humans experience. Humans detect photons as a flowing group—or "packet"—when perceived by the brain as color[43, 419]. The color sensation formed from this packet can be described as different patterns of photon strength per wavelength.

A **rainbow**—be it in the sky, on a compact disc, or refracted from a prism—is a great example of light's visible spectrum make-up in daily life. During rainbow phenomena, some refracting medium is causing the forward direction of photons to spread away from each other based on their different wavelengths. From a beam of source light (white light if it contains all the wavelengths), comes a band of the wavelengths contained within it[6, 100].

Rainbow phenomena only displays the photon types present in the source light being fanned out; for example, if the light has no long waves then the rainbow would have no red. The rainbow's overall appearance displays that of which the emission source is made up; wavelength bands that have a higher power will display a hue component that is stronger in intensity. A rainbow is essentially a chart of these intensity strengths, which is the *spectral distribution* of the light packet's make-up. The power of photons at each wavelength makes up a **Spectral Power Distribution (SPD)**[23, 89]. *Figure 6.* shows an SPD as a graph of the photon strength at each narrow wavelength band of the Visible Light Spectrum. The various possible shapes of SPDs correlate to the array of colors that humans perceive.

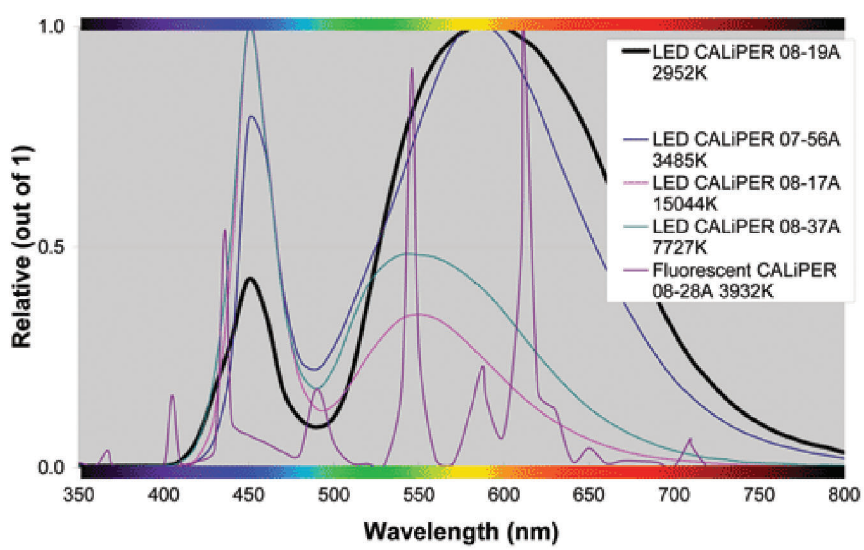



Figure 6. A sample SPD (Spectral Power Distribution). *Graphic source: Department of Energy.*

The equal-energy spectrum—sometimes referred to as *broad spectrum* or *full* *spectrum*—refers to SPD patterns that are evenly distributed across the entire VLS range[23, 119]. Equal-energy spectrums are theoretical and practical SPDs will be slightly skewed towards a subset of the domain; meaning there will be a higher intensity concentrated around at least one area of the spectrum—and even some wavelengths with no photons. SPDs can also be banded or have strong emissions from only one or several areas along the gamut. The term *pure light* is sometimes used for SPDs with only a single narrow band of wavelength strength[36].

CHAPTER 4

# Light Phenomenon

## 1. Photon Emission

Visible light emission comes from several general types of sources, each with varying SPD patterns. A molecular excitement causes a change in the energy of the emission source and the extra energy releases in the form of a stream of photons[6].

The CIE understood that the light sources illuminating materials would influence resulting color perception and the burgeoning color science field could benefit from universal guidelines. Therefore, they developed a list of spectral behavior of common light sources—the **standard illuminants**[36, 37-46]. This list is always in flux, with standards dying out and new ones being added due to changes in lighting technology.

*Figure 7.* shows the first three standard illuminants created by the CIE in 1931, which are: A (incandescent light), B (direct sunlight), and C (average daylight). When describing sunlight, Standard illuminants B and C are out dated in favor of a new class, D standard illuminants[36, 38]. Standard illuminant E is the equal-distribution spectrum; it is of theoretical interest and sometimes used to represent

**ambient light**, low level base light that comes from reflections rather than directly from sources.

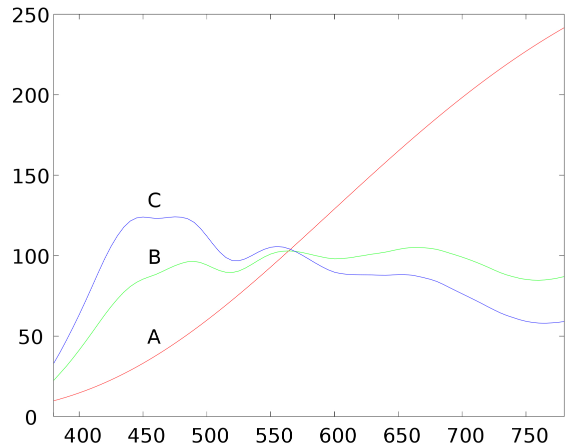



Figure 7. SPD of standard illuminants A, B, and C.

**1.1. Standard Illuminant A.** A tungsten filament lamp with a color temperature of 2856$k$, often referred to as an "incandescent" source, is denoted as standard illuminant A[22, 18]. As illustrated in *Figure 8.*, there are variants of this source type with temperatures associated that change the graph slightly. Their strength increases towards the long wavelengths of the VLS creating an overall warm color output that is favorable against the skin[6, 247]. There are many varieties in use—however they are losing ground to more efficient illumination methods[33, 105].

The term "incandescence" stands for emitting indoor light, and Edison, who is credited for the propagation of electrical lighting, coined this term for his electric bulb. Edison was not the first to pioneer all the methods used, but he was the one that combined and perfected them—and more importantly ushered them into the world[6, 240]. This source works by running electricity through a filament in a vacuum and

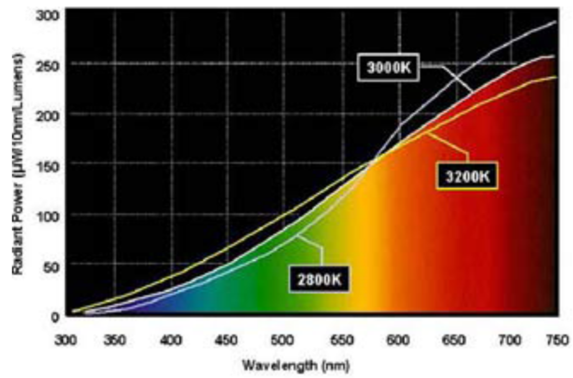



Figure 8. Sample SPD of incandescent source. *Graphic source: GE.*

the spectral output is dependent on the type of filament. The original bulbs designed by Edison used carbonized bamboo[33, 102]. It was the breakthrough in the filament design that allowed Edison to gain the edge on the electric illumination industry.

**1.2. Standard Illuminant D and Natural Light.** D illuminants represent sunlight and are further categorized with temperature values that denote their output pattern, as in *Figure 9.* Varieties in sunlight SPDs correlate to where the sun is relative to the viewer and the strength of Rayleigh Scattering Effect[43, 48].

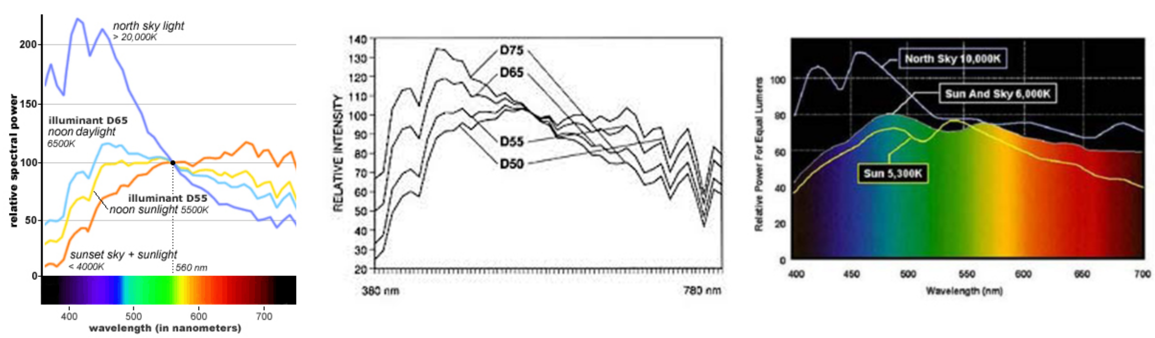



Figure 9. Sample SPD of sunlight. *Graphic source: GE [8].*

**Natural** light comes from the sun, which sits $93,000,000$ miles away from earth, and during the day it takes around 500 seconds to reach humans on the surface[29]. The emitted photons leaving the sun encounter very little in the vacuum of space until they enter earth's **atmosphere**. Atmosphere is a gaseous medium made up of varying densities of molecules, all invisible to humans only because photons bend around and through them. The atmosphere is crucial to life and contains a majority Nitrogen ($\approx 78\%$), then Oxygen ($\approx 20\%$) and the remainder is made of **aerosols**, which are other airborne particles[6, 33].

The sun emits the entire range of electromagnetic wavelengths, which can be predicted using black-body radiation curves[35, 54]. Within the human gamut the sun's spectrum is well distributed. However encountering atmosphere turns it into an entirely different source. Atmosphere has interesting effects on the spectral distribution of sunlight and is responsible for the unique daytime lighting conditions humans experience.

*Figure 10.* illustrates that the distance between the sun to a point on Earth varies, which directly relates to how much of the sun's photons are passing through the atmosphere. When the sun is near the horizon with respect to point P, then the atmospheric filtering amount is a lot greater than when the sun is directly above P. The longer this distance of atmosphere interaction, the more pronounced the filtering effects. This distance is affected by the placement of the earth in its yearly orbit around the sun, as well as location on the surface, and varies with the time every day as the earth rotates.

Consider the perceived color of the sky; when looking up while outdoors, one is

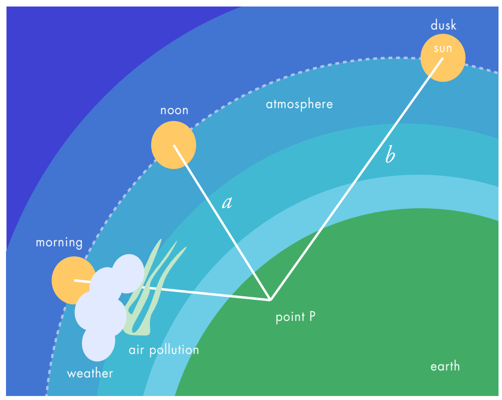



Figure 10. Factors effecting sunlight at point P. *Source: R. C. Farish*

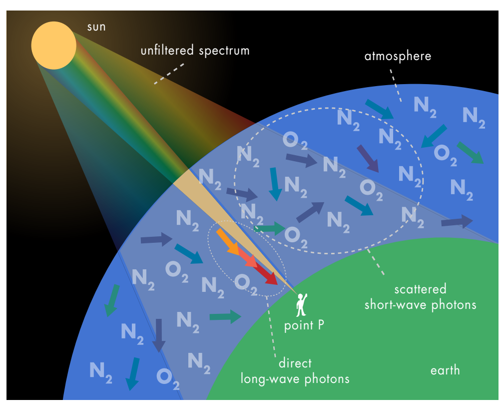



Figure 11. Rayleigh Scattering Effect . *Source: R. C. Farish*

actually looking *towards* the vacuum of space—a place mostly void of photons—and to see a color above, there must be photons that are present and heading towards the eye. What is making the sky appear blue is caused by a phenomenon known as the **Rayleigh Scattering Effect**[43, 48]. As illustrated in *Figure 11.*, when photons of shorter wavelengths (blue hues) encounter very small molecules like the oxygen or nitrogen in the atmosphere, they will scatter more, causing them to spread out into the sky; and photons of longer wavelengths (red hues) maintain a straighter trajectory—which is why the Sun appears warm in color[22, 16].

Rayleigh Scattering Effect results in varied sunlight patterns throughout the day. Mid-day, when the sun is directly overhead, photons from the sun travel the shortest amount through the atmosphere to the average viewer on earth; less photons means less wavelength-dependent scattering resulting in a broader spectrum. Sunrise and sunset exacerbates the Rayleigh Scattering Effect as photons have to travel through more of the atmosphere which means more filtering of blue waves[22, 17,82].

Weather also affects the sky's appearance and sunlight's SPD[19, 148]. Rises in humidity—the number of water molecules in the air—means larger molecules in the atmosphere, and that means Rayleigh Scattering Effect is spreading wavelengths more evenly. Water droplets affect the color in various ways dependent on: size, location in atmosphere, and their state—whether they are liquid or frozen.

Aerosols are particles in the air, such as: dust, smoke, pollen, and bacteria; they cause Rayleigh Scattering to affect the sky in unique ways[26, 50]. These aerosols are air pollutants, however they can create unique lighting conditions for Earth's skies[3].

The SPD of outdoor **shaded light** would be missing the direct light from the sun which contains more red wavelengths. Instead outdoor shade is made from outdoor ambient light, which is the blue scattered light that colors the sky.

The moon itself is not its own emitter and **moonlight** is reflected from the sun. Moonlight is not usually strong enough to activate cones, only rods, and therefore objects viewed in such conditions appear in a desaturated grayscale palette—and there are perceptual phenomenon that amend how scenes are viewed in moonlight[10]. Moonlight follows the same Rayleigh Scattering Effect as sunlight because it is traveling though earth's atmosphere. An example SPD of moonlight is illustrated in *Figure 12.*

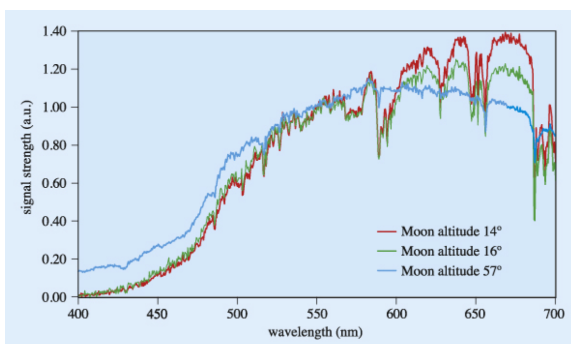
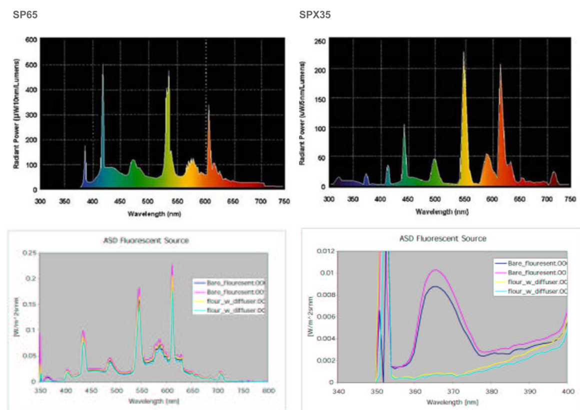



Figure 12. Sample SPD of moonlight. *Graphic source: Ciocca and Wang[10].*

**1.3. Standard Illuminant F and Other Sources.** Fluorescent lights are denoted as standard illuminants F and consist of 12 unique SPDs[35, 55]. The subcategories are: ( F1 - F6 ) *standard*; ( F7 - F9 ) *broadband*—for fluorescent technology attempting a fuller spectrum output; and ( F10 - F12 ) *narrowband*—which output three strong bands correlating to the tristimulus values. The emission spectrum is different from the more constantly sloping incandescent graph and features spikes of intensity at different wavelengths. *Figure 13.* shows examples of fluorescent light SPDs.




Fluorescent source with and with out diffuser

Fluorescent source with diffuser absorbing emission line.

Figure 13. Sample SPDs of fluorescent sources. *Graphic source: GE and Ientilucci, 2000.*

Fluorescent lights are more powerful and efficient than incandescent bulbs. They create light in a two-step process of exciting mercury vapor in a tube which emits ultraviolet light which is outside of the VLS. These ultraviolet waves than go on to excite a phosphor coating on the circumference of the tube from which the actual visible light is then emitted[43, 166].

High-Energy fluorescent bulbs are becoming increasingly popular and may shape the look of the future, or could simply be the trend of the day. These are wrapped to form a traditional bulb shape, and there are several varieties on the market that produce a fuller emission range than previous fluorescent bulbs[7].

A flame illumination source is the ancients' way of illuminating the dark, and was man's dominant nocturnal partner for centuries. Spectral distributions are based off the atomic chemistry of the materials involved and flames are actually a large umbrella of kinds of light emitters. For more information on flame SPDs see *Flame Emission Spectroscopy: Fundamentals and Applications*[45].

Neon is a glowing gas. It fills chambers that can be molded into shapes which has given rise to the popular "open" sign or similar neon display. Unlike another tubular gas light, fluorescents, there is no phosphor coating and the light emitted comes directly from the excited gas, including neon for which this method is named. *Figure 14.* shows the emission spectrum for neon and some other gases used in similar lighting, and displays spectral information in what is referred to as "line" form.

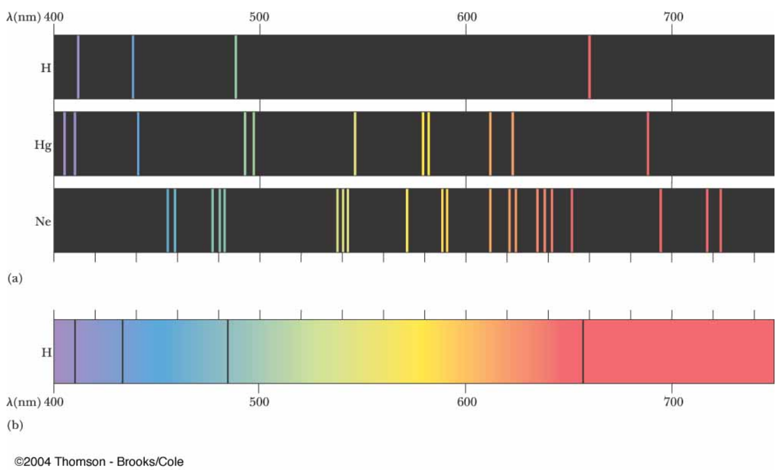



Figure 14. spectral distribution of neon and other gas emitters. *Graphic Source: Physics for Scientists and Engineers (6th ed.) by Serway and Jewett (Thomson Brooks/Cole, 2004)*

## 2. Photon Absorption and Reflection

Absorption and reflection of photons occurs when they encounter an object made of a material and this material consequently has a pigment[1]. Pigment is made up of molecules, and these molecules absorb photons of certain wavelengths and reflect others[42, 271]. The light that bounces off an object is from the emission source that hit the object minus whatever was absorbed by the object, and this light is what hits the eyes and gives that object a color[14, 5].

When photons encounter a molecule they can affect the electron's orbit. The varieties of these interactions determine which photons are absorbed and which ones are reflected back. Molecules that are large and more complicated tend to have narrower bands of reflection and therefore evoke more vibrant colors. In the end the color of something is related to its chemical make-up. The modern manufacturing industry divides colorants into two main categories: absorption colorants (dyes); and effect pigments (metallic and pearlescent)[22, 1].

## 3. Refraction

**Refraction** is the bending of light's propagation direction by a new medium. Every medium has a scalar at which it slows down light, but it also does so slightly differently per wavelength as well[6, 128]. This change in speed also results in changing the light's propagation direction.

[1] It is possible that a material has no absorbing pigment and the photons pass directly through, or that the photons must travel through layers into the object before encountering pigment molecules.

| Medium | Refraction Index | Speed of Light |
|---|---|---|
| Vacuum | 1.0 | $\approx 299,800km/s$ |
| Air | $\approx 1.0003$ | $\approx 299,700km/s$ |
| Ice | $\approx 1.31$ | $\approx 228,800km/s$ |
| Ethyl alcohol | $\approx 1.362$ | $\approx 220,100km/s$ |
| Crown glass | $\approx 1.5 - 1.62$ | $\approx 190,000km/s$ |
| Flint glass | $\approx 1.57 - 1.75$ | $\approx 180,000km/s$ |
| Polystyrene | $\approx 1.59$ | $\approx 188,500km/s$ |
| Diamond | $\approx 2.417$ | $\approx 124,000km/s$ |

Figure 15. Light Speed and Refraction in Various Mediums

To keep track of how much the light is slowed down per medium there is a special predetermined coefficient, a **Refraction Index**. The maximum speed photons exhibit is while in a vacuum—or medium-less space—which has a refraction index of 1.0. All other mediums cause light to decrease speed, although the factor that represents the amount at which they do so actually increases from 1.0, as illustrated in *Figure 15.*[23].

The decrease in speed of the photon causes its direction to bend towards the normal of the surface it's intersecting; the surface normal and the refraction index determine what the new forward velocity of the light will be. The classic example of refraction is seen in *Figure 16.* which illustrates a straw entering into water. The line of the straw is broken into an obvious bend at the water's surface[26, 78]. The amount of this bend is the **angle of refraction** and is mathematically defined through **Snell's Law**.

The formula for refraction, or Snell's Law (*Equation 4.1*), is as follows where $Idx_{leave}$ and $Idx_{enter}$ relate to the refraction index of the two mediums, $V_{enter}$ and $V_{leave}$ are their velocities, and $\theta_{leave}$ is angle of light in the first incoming medium and

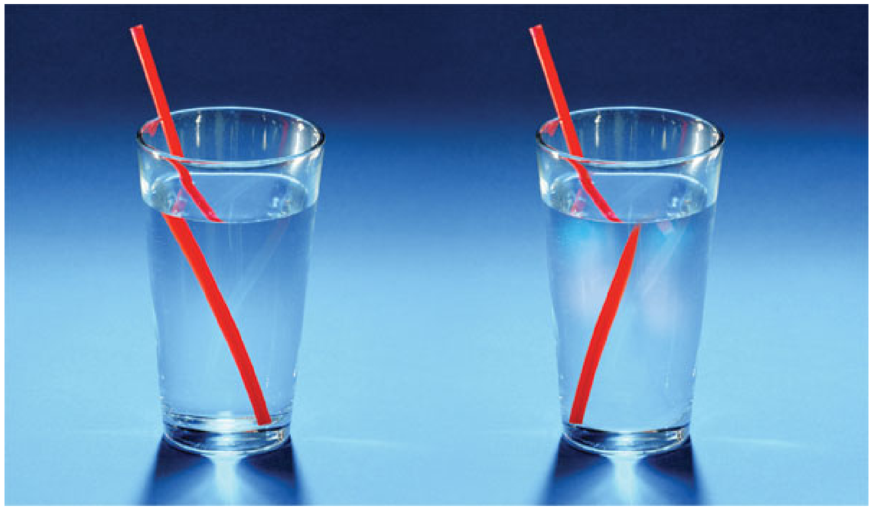


Figure 16. Refraction example. *Graphic source: Optics: Farewell to Flatland, by Ortwin Hess.*

$\theta_{enter}$ is angle of light after it has entered the second medium[23, 196].

$$\frac{\sin\theta_{enter}}{\sin\theta_{leave}} = \frac{V_{enter}}{V_{leave}} = \frac{Idx_{leave}}{Idx_{enter}} \tag{4.1}$$

The refraction index is not constant for all wavelength values of light, which results in a phenomenon called **dispersion**[22, 26]. Slightly different refraction indices per wavelength means photons begin to spread, or fan, in the new medium. Short waves, attributed to blue, have lower refraction indices than long waves, attributed to red. Not only is refraction wavelength specific, but mediums are also unique on how much they vary per wavelength; some mediums may have a narrow range of refraction indices for the VLS, while others have a large range[5, 95].

CHAPTER 5

# Sensing Light

Color is a psychophysical perception, a biological sensation that has been activated by light that is then perceived by the brain[43]. The notion of light now enters the biological realm where the study of color theory takes root. Light physics is now subject to the biased human brain and formulas are secondary to the will of the visual processing system. However, optical judgments are consistent and highly observable and the way man reacts to light and forms the notion of "color" comes from human genetics.

Vision most likely arose from photo-reactive cells in earth's oldest ancestors. A clue to what would become the building blocks of the complicated visual process is found where life began—in the ocean. The emergence of a specialized cell that could react in some way to photon presence became the very first step in 'sight,' giving the organism some clue about its photon environment[6, 42]. There are many ways organisms react to photon presence: color changing skin, movement based on light like some algae, and compound eyes. Over time sensory cells became denser and localized; a lens formed to focus light; more complicated nerve cells developed; and the brain became better at judging spectral make-up.

**Eyes** are concentrated sensory inputs that lead to a perception of the world in front of a viewer—vision. Humans are trichromatic, within the eye there are three different types of wavelength sensitive cells with which to sense color. These three cells, along with one other special eye cell, send signals to the brain where the grander idea of color and vision take place. The eyes are merely data ports, it is the brain that gathers together a unified judgment of one's surroundings.

### 1. The Human Visual System (HVS)

Humans' best biological system for inputting information is vision. The old adage "a picture is worth a thousand words" is an accurate sentiment, however the factor is a bit off; humans receive information visually ten times faster than audibly or any other way[6, 5]. Vision becomes a paramount tool in modern society's communication; color assists in instant and abstract classifications and communications—like in the traffic light system. Not only do humans color-code things on an organizational level, but people recognize things based on color. If someone picked up a blue banana they would be wary that it was indeed a banana, or at least be wary about its freshness.

A person's visual system, **the Human Visual System (HVS)**, is highly sensitive to light[16]. Within the eyes, photons land on a grid of cells sensitive to light waves, which transform photon energy into nerve pulse output; this is the **biological response** component to the system. The nerve pulses are then decoded by the brain which combines it into a greater field of vision; this is the **perceptual filtering** component. It is the brain that renders a final psychophysical color sensation along with other complex visual judgments.

Some humans have vision that differs greatly from average. The most common of these chromaticity abnormalities is **color-blindness** where a set of hues are indistinguishable from each other, such as a diminished ability to perceive red and green. Tetra-chromacy is having four cell receptors in the eye for color—instead of the more common three, which boosts visual acuity of red hues. Reports vary on the number of people with tetra-chromacy but the trait seems to be more likely in females[20].

## 2. HVS: Biological Response

When photons enter the eye, they are focused by a lens, filtered slightly by layers of cellular tissue, and then hit the **retina**, as illustrated in *Figure 17.* The retina is packed with two basic kinds of light sensitive cells: **rods**, which react to the amount of total light sensed; and **cones**, which react based on the wavelength of the light. Rods relate only to intensity while cones determine hue[16, 1].

The cellular makeup of the retina varies throughout and contains one very sensitive spot specifically for color and detail judgments called the **fovea**. The center of the fovea contains only cones, with rods becoming mixed in around the periphery, and the outside of the fovea is almost completely rods[16, 113]. Viewer move their eyes through a scene targeting areas of interest within their fovea. The distance

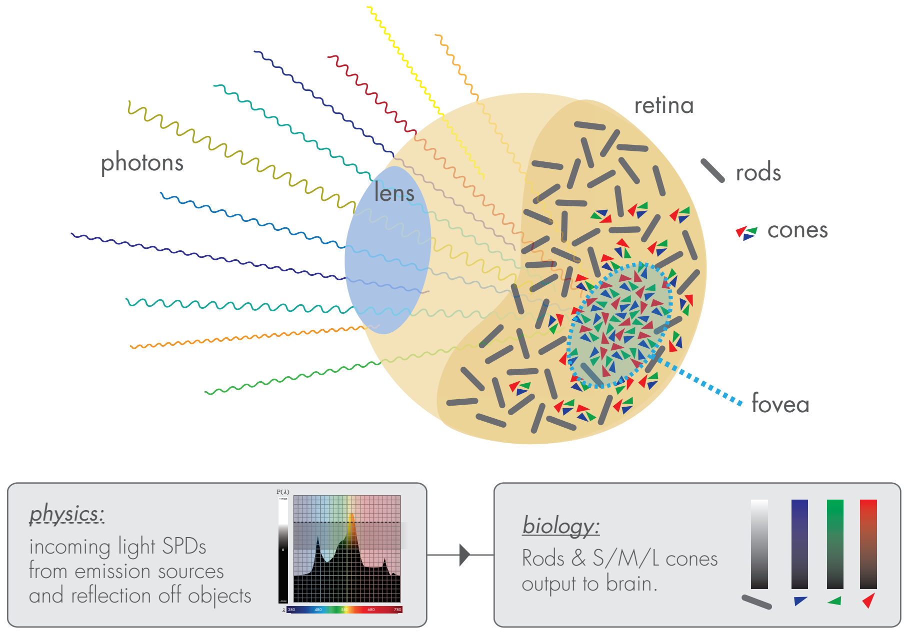



Figure 17. Diagram of human eye. *Graphic Source: R. Campbell Farish*

away from the fovea is measured in degrees, with zero indicating the center and most cone-dense part (see *Figure 18.*)[36, 27].

During **scotopic**—or dim light vision—rods are the active visual cells; they also complete peripheral vision—the edges of the visual field[16, 53]. Rods convey no hue information to the brain, which is why dark scenes are gray and drab. **Rhodopsin** is the receptor protein that reacts to photon energy and puts out neurological pulses[16, 95]. This pigment is most sensitive to blue-green wavelengths and barely sensitive to red wavelengths at all[43, 101][1].

Cones are packed closely together and become incredibly dense in the very

[1] An example of using this phenomenon to one's benefit is seen in ship navigation design where the instruments give off a red light. The captain can see at night whilst acclimated to the dark where only the rods are at work, then when he glances at the instrument panel there are only red lights present and those do not disturb the rods, allowing the captain to stay sensitive to dim lighting conditions.

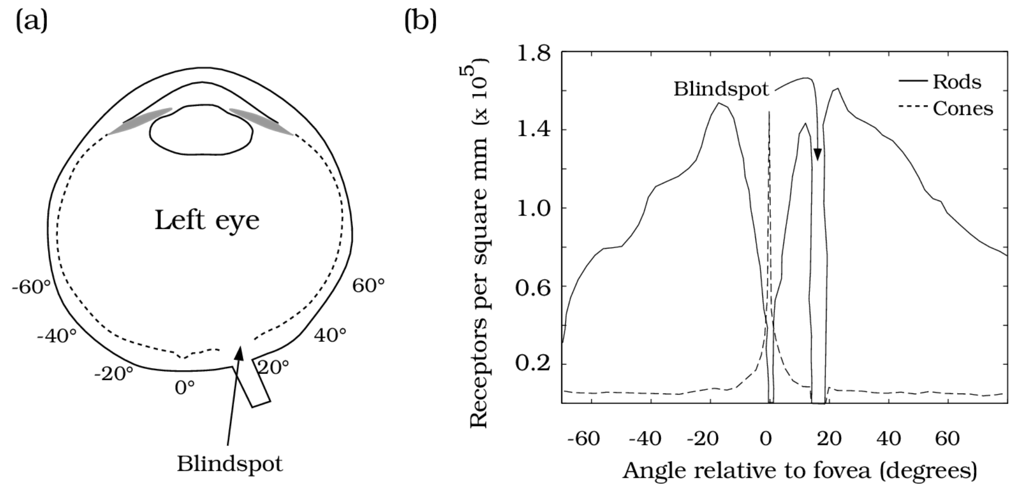



Figure 18. Cross section of the eye illustrating degree from fovea and cone/rod distribution. *Graphic Source: Foundations of Vision, Brian A. Wandell*

center of the fovea. Cones, the hue sensors, need stronger illumination than rods. **Photopic**, or bright light vision, activates cones instead of rods. Color sensations only arise when a space is adequately lit, and even then only in the center of a viewer's gaze[43].

Cones respond based on the incoming photon's wavelength and come in three types[43, 103][2]:

- **S-Cones**, responding to short wavelengths (blue hues);
- **M-Cones**, responding to medium wavelengths (green hues); and
- **L-Cones**, responding to long wavelengths (red hues).

In cones, instead of Rhodopsin, three other light-sensitive pigments are responsible for cell reaction. They are **Photopsins** labeled I, II, and III corresponding

[2]as mentioned earlier some people may have 4 cone types.

to the S-Cones, M-Cones, and L-Cones respectively[1, 83]. Each of these compounds has a different pattern of photon wavelength sensitivity, as illustrated in *Figure 19.*[43, 103]. All three cones are each stimulated slightly by any photons with a wavelength in the VLS; their sensitivities overlap and it is impossible to stimulate just one at a time.

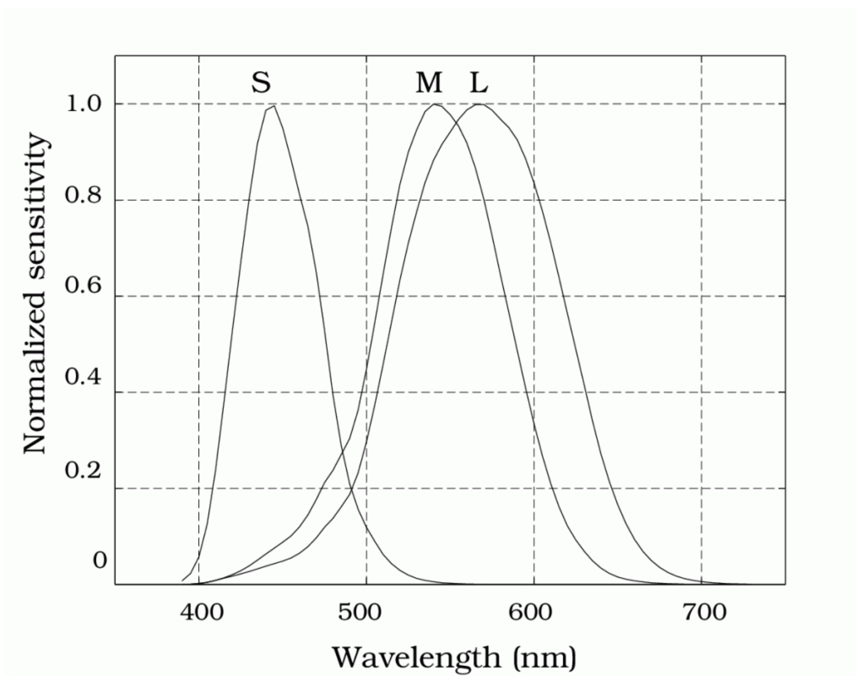



Figure 19. Normalized Cone Sensitivity. *Graphic source: Stockman and Macleod, 1993.*

Photons travel faster than the eye and brain can react to them; multiple photons hit color cells in the eye before they are able to distinguish them as individual sensations. This phenomena allows for quickly moving images to become an animation, and is known as **persistence of vision**. Persistence of vision is around one twenty-fourth of a second and effected by three main factors: phenomenological persistence, neural persistence, and informational persistence[11].

There is also a blind spot in the eye where the optic nerve attaches to the retina where there are no light sensing cells at all, instead the brain is responsible for filling in this gap[1, 24].

### 3. HVS: Perceptual Filtering

Neurological output from the retina eventually reaches an image processor in the brain, the **Lateral Geniculate Nucleus (LGN)**[1, 300]. Researchers think the LGN takes in nerve pulse data from the eye and decides what precise color judgment to make, which then goes to the visual cortex which processes vision as a whole. The LGN likely performs many duties for the visual cortex such as: recognizing patterns and textures, and performing edge detection[3].

The brain is also responsible for completing the visual field which humans experience; based on the cellular excitement of the eye a perception of forward surroundings is sensed. Visually, humans scan across their possible field of view and focus on details of interest, centering important light data within the color-detail rich fovea. During these scans the brain is remembering previous scan information, which aids in the visual field appearing in color rather than an obvious radial gradation of hue into grayscale[4]. This biological property allows viewers to skip over areas of constant color, or little detail, and achieve higher visual acuity on areas important to them by using their most capable cells.

[3]For more information on the eye, LGN, the brain, and their roles in color processing, see sources such as *Light Vision Color*[43].

[4]An optical trick helps illustrate this point: take an object of unknown color and slowly bring it into field of view from behind. It may seem surprising how far from the periphery and into the center of view the object has to be to correctly guess its color.

An object's perceived color at any given time is dependent on the light in the environment. Different source SPDs will cause the same material to reflect unique SPDs and the perception of its color may change. For the sake of practicality, object colors need to be described as they appear most commonly to a viewer. This mirrors the brain's color constancy which is the tendency for viewers to interpret an object's color as static even when under different lighting scenarios[43, 282].

## 4. Metamerism

Humans exhibit the psychophysical phenomenon of **metamerism:** multiple spectral power distributions (SPDs) producing the same color perception—as illustrated in *Figure 20.*[13, 37]. A singular color perception is a **metamer** and the complete set of metamers encompasses all unique color judgments perceivable[19, 71].

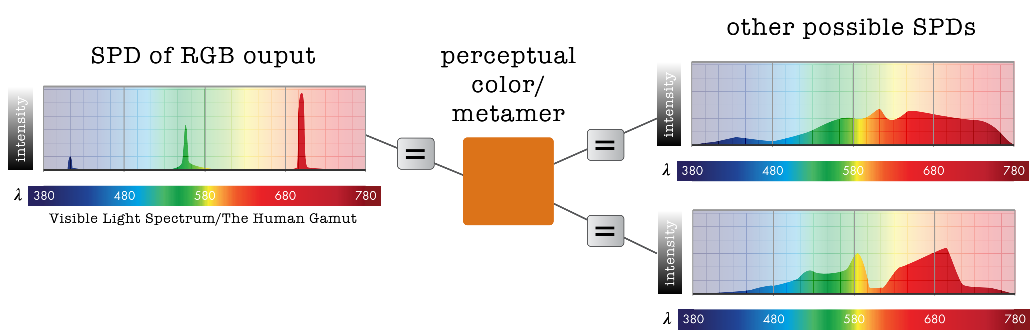



Figure 20. Different SPD patterns can equal an identical perceptual color. *Graphic Source: R. Campbell Farish*

Photons hitting the retina could be made of any combination of wavelengths within the VLS. However, the eye's nerve output can only be from at most four types of cells, the rods and the three types of cones (and only cones excite color judgments). Human biology has condensed photon data slightly when turning it into metameric data, illustrated in *Figure 17.*

The set of all SPDs is mapped onto a set of finite color perceptions, which is one-way; color perceptions provide only an estimate of spectral data. The mapping happens initially in the eye with a simple formula: any quantities of light that excite receptor cells to the same degree reach the brain appearing as the same color. The brain is then free to perform further transformations on the color before making a final perceptual output.

## 5. The Three Components of Color

*Figure 21.* and *Figure 22.* represent the three basic qualities of color judgment resulting from light's SPD. The three ways in which metamers differ are[43, 209]:

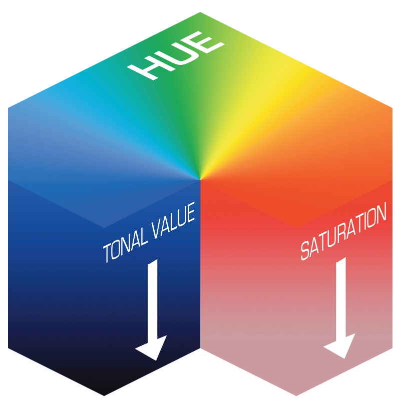



Figure 21. The three components of color: hue, tonal value, and saturation. *Graphic Source: R. Campbell Farish*


Figure 22. Illustrates relationship between hue, saturation, and tone. *Graphic Source: R. Campbell Farish*

- **Hue** is the dominant wavelength of the SPD[13, 86]. Hues come in varieties such as: violet, blue, cyan, green, yellow, orange, red, magenta, purple, and shades in between[5]. Hues leaning towards yellow-red are often referred to as warm, while hues leaning towards blue-green are referred to as cool[14].

- **Saturation** is the degree of wavelength dominance[14, 14]. A high saturation value means the light has a very narrow range of photon strength and the resulting color perception is vibrant. The term **pure color** is used to describe color sensations very high in saturation; "pure" referring to the number of different wavelengths present being as low as possible. **Dull** means low in saturation, or **desaturated**, and these colors appear washed out. Achromatic grays have a minimum saturation value.

[5]These hues are found around the edge of the human gamut including the *line of purples* (see *Section 4.3: The Chromaticity (xyY) Diagram)*

- **Tone** describes the overall intensity; how dark or light. This component is a percentage scaler from minimum (black for all colors) to maximum, the lightest the hue can be—or lack thereof depending on saturation. Tonal luminance is sometimes separated from the other two variables—hue and saturation—which combine to become known as **chromaticity**[14, 257].

### 6. Spectral and Non-Spectral Colors

The term *spectral colors* is used to define color judgments that are evoked from a single narrow band of the VLS[4]. These could be categorized as: Blue, Cyan, Green, Yellow, Orange, and Red—as well as all hues interpolated between a neighboring hue[6].

Humans have visual perceptions in addition to spectral colors, referred to as *non-spectral* or *extra-spectral*. For example, a rainbow represents an incomplete range of color perceptions, it is merely displaying the VLS; the full color palette is in the mind. Anything made from more than one wavelength of light is considered non-spectral, but some of the main visual sensations are[7]:

- **Magenta** and **Purple** are sensations made from photons from both ends of the spectrum, a mixture of blue correlated wavelengths and red ones. Magenta tends to have a brighter connotation and lean towards a red perception, while purple leans more towards a blue perception and has a dimmer connotation.

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[6] Violet and Red have only one spectral neighbor with which to interpolate between and still be considered spectral.

[7] Labeling color perceptions with verbal terms is subjective, as discussed in *Section 2: Verbal Descriptors.*

- **Gray**, when viewed under **photopic vision** (well lit conditions), is representative of a reasonably equal distribution along the SPD, enough to excite each cone equally. Grays—meaning anything along the gradient from black to white—contain no specific hue and they have a minimum saturation value.

- **White** is the sensation of a maximum tone; photons are exciting all three retinal cone types enough that they are firing off nerve impulses at maximum capacity. This means there are a high number of photons present. White also has no specific hue value, but its tone is at maximum. Its saturation is at minimum because the definition of saturation is a narrow bandwidth, and white requires a broad power distribution within the human gamut. When one says an object is "white" they mean "a very light hue-less gray." White happens whenever there are enough photons to excite cones to their limit, and this can be caused by a variety of SPDs so long as they are powerful enough. If a white SPD pattern was reduced to a human's comfortable intensity range then one could better determine whether or not it was gray, or had a dominant hue.

- **Black** pushes the idea of what it means to be extra-spectral because it is theoretically not made of any photons at all, but it is certainly not a color perception along the spectral locus so it is technically extra-spectral. A black sensation occurs when no photons are exciting any cell receptors. This could be because there is no light in the area, or because whatever object appearing black is absorbing the light that is present. Black only has a tone component, and that tone is zero. The hue and saturation could be any value because black does not have a specific hue or saturation. When one says an object is "black" they really mean "close to theoretical black;" most objects are going to reflect back a little bit of light. Actual total black is very hard to achieve, only a few materials are said to absorb all light.

- **Brown.** This can refer to many color sensations, but is usually a darker and/or desaturated yellow or orange[4, 43]. Browns have a less equal distribution of wavelengths than gray skewing towards the red-yellow spectrum.

### 7. Additional Aspects of Color Judgment

The eye adjusts its sensitivity to light using the **pupillary light reflex (PLR)**, and this process can take up to 30 minutes. The *Purkinje effect* states that as intensity levels change, perceived color intensity and contrast with neighboring colors can change for certain hues; the *Bezold-Brucke shift* can change hue perception in high or low lighting situations[43, 151]. The fact that eyes adapt to intensity levels makes color experience something that is constantly in flux—and unique per individual at any given time.

Radiometric is the measurement of physical light intensity, but **photometric** is the scale of perceived light intensity. Certain hues appear innately brighter to the viewer than other hues of the same radiometric power; this is known as the *Helmholtz-Kohlrausch effect*[13, 123]. **Luminance** is the photometric measurement for this perceived intensity, and *Figure 23.* illustrates the luminance values of several hues.

Blues have the lowest luminance while yellows have the highest values. Luminance becomes especially important when grayscale comes into play.

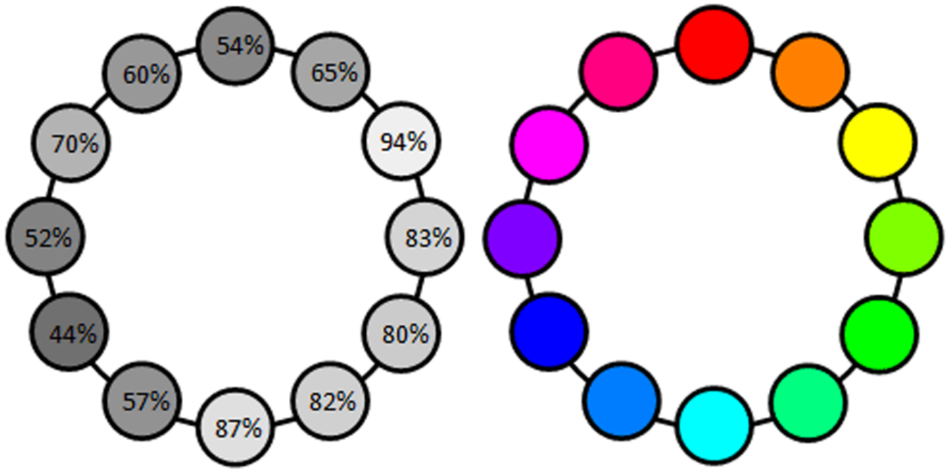



Figure 23. Color luminance values (perceived brightness) and the colors from which they resulted. *Graphic Source: WorkWithColor.com*

Humans cannot see infinite color variations. The number of distinct color perceptions is in the debated range of $2,400,000$ to around $10,000,000$—or even above[44]. All reported ranges reflect the fact that the number of color perceptions humans can see is finite, and it is in the millions[43, 16].

**Color constancy**, or **chromatic adaptation**, is the tendency to think something is the same color under varying lighting conditions[4, 44]. This helps humans identify objects illuminated by different source SPDs and not think of the object itself as changing colors. This a perceptual phenomenon that occurs in the brain and essentially means observers can judge colors against each other. So even in a scenario where the environment is bathed in a dominant hue, a person could still pick out a desired object by its color.

The distribution of colors within the visual field can affect each other's resulting color judgment[14]. For example, *Figure 24.* illustrates one such instance in which the same gray value displays different hue leanings. In the visual field dominated by blue and green the achromatic gray areas take on a warm tint. In the image dominated by red and yellow the gray areas take on a cool tint. For further information on color perception phenomenon, see resources like *Color Appearance Models*[13].

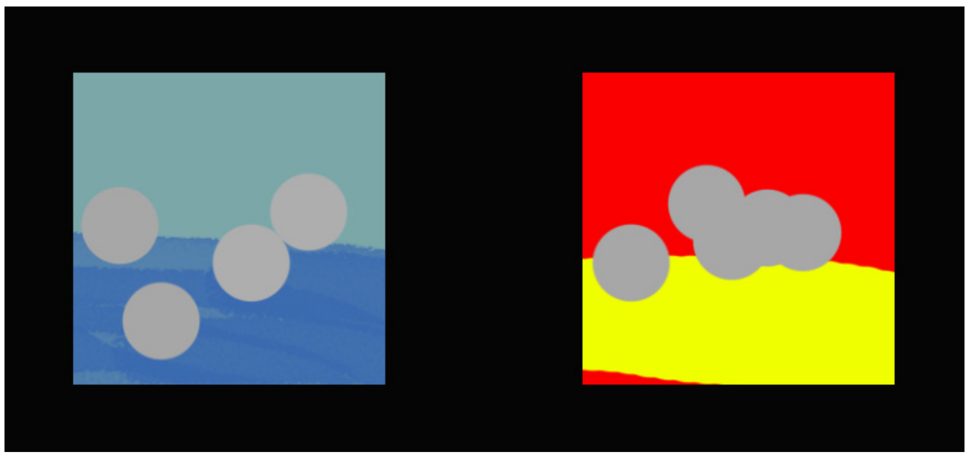


Figure 24. Example of Perceptual Color Equalization. Even though the gray is all the same value, it appears warmer on the left and cooler on the right. *Graphic Source: R. Campbell Farish*

CHAPTER 6

# Light and Color Quantified

## 1. Man Defines Color

The sense of color is part of the human condition that current generations share with earth's earliest people[22, 2]. Color gives an instantaneous clue about an object beyond just its shape and man has turned color into something greater: a symbol. Color has a longstanding tradition of representing more than just a psychophysical response, and over time society has created a multitude of color uses, and with it many unique models used to describe color perception.

Colors can alert a viewer to an idea or message not being spoken or written. A direct example of this is any color coding system used to organize information, but it is also used in more subtle ways in our advertising and manufacturing industries. Different color palettes evoke different correlated mental schema. Colors have played their role in societal realms as well, albeit a more capricious one. At times a color could represent holiness and proper morals and then later the exact opposite could be true of the same hue[32].

Some of the earliest quantification of color judgment happened through the dye houses of ancient civilizations. Combining a plethora of pigments with binding mordants, they made dyes and paints. The dye houses worked with crushed stones or, more often, organic material to create their array of colors. Different dye houses had different techniques but some popular dye sources used were: *woad, indigo, lapis lazuli, mollusks, azurite, soapberry and soapwart whitening, malachite, verdigris, buckthorn berries, nettle leaves, leek juice, and weld*. Some mordants used to turn these dyes into usable pigments: *tartar, alum, vinegar, urine, and lime*. Early man used these as the building blocks of the first *color model*, a system in which to define, and thereby reproduce, color perceptions[32].

Colors "mystical and mysterious" properties impacted the dye industry as well, and before the 15th century not a single color recipe mixed dyes[32, 72]. Mixing dyes was seen as an affront to the gods, a sort of magic or witchcraft. The stigma surrounding light and color eventually faded and the conversation changed from faith to physics. Color manipulation became a science in and of itself and demanded systems in which to operate. Color discussions now form the range of technical to casual, and therefore a myriad of color descriptions have been born, each with its own balance of complexity and usability.

## 2. Verbal Descriptors

Society has adopted a casual way of defining color experience by communicating about color through vague verbal terms[13, 86]. Color is **pyscho-physical**, meaning the human visual system can be mapped to reasonably predict color sensation based on the physical system of light[43].

Most people only interact with color in a basic verbal way, adding color labels to nouns to describe them and more effectively communicate what is being referenced. "Pass the *blue* mug" would certainly aid the deliverer of the mug in choosing the correct one—and saying "blue" is certainly a more practical way of describing the color sensation excited by the mug than somehow defining its SPD. Therefore people *describe* color instead of *define* it.

Even though color is a nuanced system, man still speaks of it in vague terms; a person's color descriptor vocabulary is limited compared to the millions of colors distinguishable; it would be impractical to have a unique name for every slight color difference experienced. Instead people break up the color experience into sub-experiences and speak of 'light' and 'dark', 'dull' and 'bright' alongside the hue they perceive—which even then can be a mix of hues[14]. Even though this system is not concrete, society manages to communicate about color. Man's color nomenclature is not absolute, it is a communication tool.

While verbal descriptors of color are an easily usable method for color categorization, they are imprecise[30, 13]. Each person's color descriptors are slightly different and may not even be in the same language. The hues that fall into the category 'red' may be slightly different from person to person. Further specialized names like 'crimson' will evoke a smaller set of color judgment but there is still no one true 'crimson.' Then there are terms, like 'pink' for instance, that can encompass a huge range of—arguably very different—color perceptions from magenta to light red.

With verbal descriptors the level of precision suffers; as a species, man can agree at least that 'red' is not 'blue,' but language becomes problematic when decreasing the set of colors being defined.

## 3. Color *Models*, Color *Spaces*, and Color *Profiles*

Man often wants to perform a repeatable or predictable task involving color and therefore color perception needs to be mapped to a quantifiable scale. **Color models** assign numerical values to colors with a system optimized for the particular manipulation use needed[13]. There is no one color model that serves every purpose; sometimes a quick estimate of color is sufficient, and other times we need to render the exact shade and hue across multiple objects like in the manufacturing industry.

Due to having multiple tailored models, a typical user's experience with color involves many conversions—often losing or skewing data slightly. For instance a user that takes a digital photo and then views it on a screen as well as prints it has interacted with several color conversions. Display screens operate on one model while printed pieces operate on another, and within those uses are a wide range of technologies for home and professional purposes[23]. The result is a lot of conversion between color models.

Color models are **device independent**, meaning they operate on a theoretical scale without referencing a specific piece of technology; and **color space** is an actualized and fine-tuned version of a color model that works with a particular color output device[30]. A color space is typically **device dependent**—meaning it is calibrated to a specific machine—but can be device independent as well. There is also a **color profile**, which is very similar to a color space, but is *always* device dependent[15].

Take for example a group of monitors from brand X. The entire set runs on RGB as the color model. Each monitor can then have a different color space corresponding to RGB, like sRGB for example. Finally, they may have an even further specialized color profile. This profile could relate to exact materials used to make the monitor, or from users creating their own color profile to combat their own unique lighting scenario under which the monitor is being viewed.

## 4. Color Systems

**4.1. The Standard Colorimetric Observer.** In the 1920s attempts were made to standardize color with the goal of developing a universal scale that would tie together the physics and perception discussions. The process began with two scientists named Guild and Wright who independently performed similar tests on several human subjects[36, 9]. They would show the subject an area of monochromatic light and then allow the subject to control dials of other light sources to match it. However there were some monochromatic wavelength values that could not be matched. To compensate for this they added to the base stimuli being matched, in order to gain visual symmetry between the two colors.

The compilation of data from Guild and Wright led to the **1931 Standard Colorimetric Observer**, which describes the average human perceptions in regards to color[36, 224]. The data they compiled led to the **LMS Color Model** which stands for Long, Medium, and Short cones. By astutely looking to biology for inspiration, this model relates the amount each cone receptor is stimulated to photon wavelength. LMS is rarely used however, because of its undesirable negative ranges. LMS gave rise to its sibling color model, the XYZ color model, based off the same data.

The 1931 standard observer has a foveal field of observation of 2 degrees; however, in 1964 a standard colorimetric observer with a foveal field of 10 degrees was compiled as well[36, 225]. Color perceptions change depending on their location from the fovea, due to cones gradually decreasing towards the visual periphery. *Rod-intrusion* occurs with the larger 10 degree foveal field and can interfere with color results.

**4.2. The XYZ Color Model.** This color model was created by the International Commission on Illumination (CIE) with the goal of removing values and equalizing the integrals of stimulations. The result was the **CIE XYZ Color Model**, a system based upon the biological cone stimulation data that defines color perception with three numbers—the XYZ values referred to as the **tristimulus values**[36, 30].

$$\phi(\lambda) = R(\lambda)S(\lambda) \tag{6.1}$$

$$X = k\int_{380nm}^{780nm} \phi(\lambda)\overline{x}(\lambda)d\lambda \tag{6.2}$$

$$Y = k\int_{380nm}^{780nm} \phi(\lambda)\overline{y}(\lambda)d\lambda \tag{6.3}$$

$$Z = k\int_{380nm}^{780nm} \phi(\lambda)\overline{z}(\lambda)d\lambda \tag{6.4}$$

$$k = \frac{100}{\int_{\lambda} S(\lambda)\overline{y}(\lambda)d\lambda} \tag{6.5}$$

*Equation 6.2*, *Equation 6.3*, and *Equation 6.4* provide the formula for computing the XYZ values. They take the integral of a graph relating to stimulation along the gamut of each type of color cell; the X roughly related to red, the Y roughly related to green, and the Z roughly related to blue. In this formula, the strength per wavelength interval of a packet of light, $\phi(\lambda)$, is multiplied with a corresponding value from the functions $\overline{x}(\lambda)$, $\overline{y}(\lambda)$, or $\overline{z}(\lambda)$—these standard observer functions are displayed as a look-up table in *Figure 29.*[36, 6]. The three integrals are a representation of the cumulative stimulation of each cone.

Cone stimulation—and thereby color judgment—is excited by light headed into the eye. This light can come directly from an emitting source, such as a monitor, or from a material that has reflected a source. This source and material interaction is illustrated in *Equation 6.1*[36, 33]. In this equation: the light entering the eye to be judged is referred to as $\phi(\lambda)$; the emission function, $S(\lambda)$, represents an intensity formula; the reflection function, $R(\lambda)$, represents the amount of relative reflectance-to-absorbance per wavelength; and the lambda, $\lambda$, refers to a wavelength interval in between the two bounds.

*Equation 6.5* describes the formula for a scaler for the XYZ values after their integral summations[36, 33]. For a full spectrum source, or when dealing directly with a source, the k-value is merely divided by the integral of the Y standard observer function—because the Y-value is related to luminance. Otherwise the bottom half of the k-value is the source SPD applied to the Y-integral. This serves to normalize the

XYZ values. The top half of the equation is whatever scale in which XYZ will be. In *Equation 6.5* it is 100, therefore a Y-value of 100 would represent full luminance.

**4.3. The Chromaticity (xyY) Diagram.** Describing a color range in two-dimensions makes it easier to relate to visually, hence the **CIE-1976 U.C.S. Chromaticity Diagram** was derived from the XYZ model. By dividing color into intensity and **chromaticity**—which is hue and saturation combined into one value—the two-dimensional ranges of hue and saturation can be plotted on an xy-plane; the intensity then serves as an overall scaler. *Figure 25.* represents the human gamut of chromaticity perceptions.

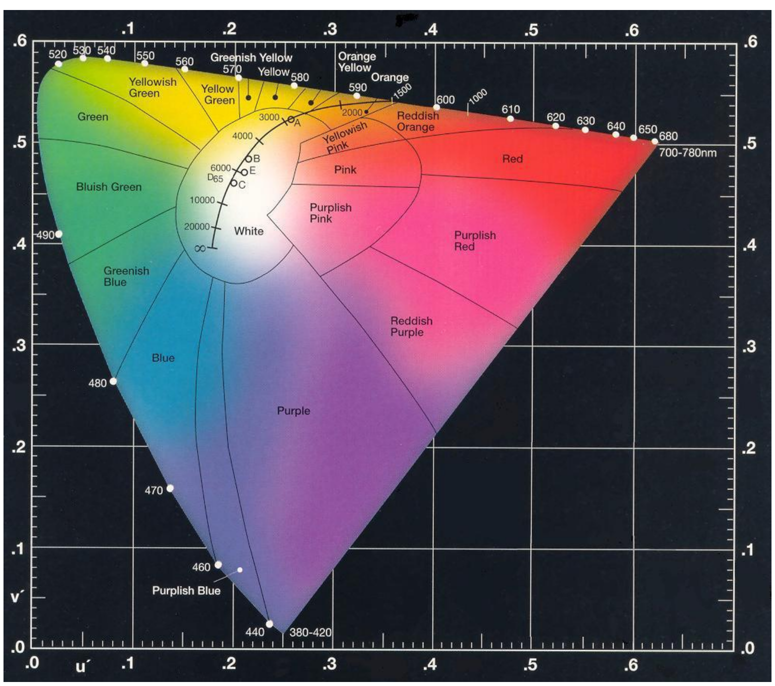



Figure 25. CIE-1976 U.C.S. Chromaticity Diagram

The **chromaticity coordinates** are calculated from XYZ values by normalizing the X-value and Y-value[36, 33]. The normalized Z-value can be inferred from the other two normalized values and therefore is not necessary in this model. *Equation 6.6* displays the formulas for XYZ to xy conversion.

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \tag{6.6}$$

On the chromaticity diagram, visible light wavelength values run along the curved top perimeter, called the *spectrum locus*[23, 99]. The flat portion of the perimeter, sometimes called the "line of purples", connects both wavelength extremes[19, 81]. This line allows for the inclusion of the human extra-spectral perception of magenta in ranges from violet to red. Colors along the entire perimeter of the graph display all the gradations of hues of maximum saturation.

A popular use for the chromaticity diagram is for comparing color-manipulating technologies' outputs against each other. Color spaces are plotted on the diagram with points where each of their singular components is outputting at maximum, and the interior of the resulting shape represent their chromaticity capabilities. Because the chromaticity diagram is not a simple polygon, it cannot be perfectly mapped using only a small number of points. The area outside of the plotted shape represents lost colors that a technology simply cannot output.[1]. These lost colors include those from the shape's perimeter to the locus, which are hues at maximum saturation.

**4.4. The RGB Color Model. RGB** is a popular color model commonly associated with display technology that defines color information with three

[1]Note that while these values are related to the actual output of the technology and absorption of the eye cells, the brain is free to interpret and enhance or change colors as it sees fit. So it is possible that under the right circumstances a color outside of this triangle could be *perceived* by the viewer.

components, corresponding to the color perceptions **red**, **green**, and **blue**[4, 109]. This model relies on the condition that three color emitters are positioned very close together in order to hit the same group of cells. Then, by changing the intensity of each color component between zero and its maximum, humans are able to perceive those three emitters as a range of possible colors.

Three color emission sources are chosen to most efficiently activate each separate cone cell type, the wavelengths used to determine the CIE standard observer were $348nm$, $546nm$ and $700nm$[36, 29]. RGB takes advantage of the biological system and metamerism; in a sense, RGB mimics SML cones. As previously discussed, the human visual system operates in terms of cell stimulation, not directly off of light's spectral distribution. This fortuitous quirk of the visual system allows man to create color outputting technology that utilizes only three dominate wavelength outputs; otherwise, display technology would have to produce any conceivable pattern of visual wave output for the viewer to register a salient portion of the color gamut.

As discussed in the previous section, the maximum output value of the three source colors become points on the chromaticity diagram, and the interior of the triangle made from the lines between them represents the color output subset that can be derived from those three colors[23, 98]. Their strengths relative to one another determine hue and saturation properties, and the overall total strength determines tone. For example, 100% red, 50% green, and 0% blue will produce a lighter orange than the same pattern scaled by half (50% red, 25% green, and 0% blue). All three values at zero represent black, and all three values at their maximum represent white.

RGB is a *color model*, so the specific wavelengths of the red, green, and blue are theoretical. On a basic level, the color model of RGB is a succinct enough way to manipulate color. However, in practice, the *model* form of RGB is too vague. When performing real-world actions in RGB, a user is actually operating under a color space, or color profile, of RGB. The screen manufacturing industry deals with cost and performance factors when choosing what materials to use to induce these three colors and therefore there are a range of RGB-based color experiences[15].

*Color spaces* tend to be used when manipulating RGB values, like when doing photo editing. *Color profiles* are finely tuned color spaces that are usually per monitor[15]. Advanced computer users have most likely performed a monitor calibration before, in which the system will ask the viewers to make choices about what looks good to them and then a custom color profile will be made for the monitors to use during output display[2].

**4.5. Other Color Models.** For the purposes of this research, the XYZ and RGB color models are an integral part, but there are many ways that color is defined. Each model typically comes tailored with a use for whatever color manipulation is at work.

4.5.1. *CMY and CMYK.* CMY is the inverse counterpart to the RGB model, using amounts of **cyan**, **magenta**, and **yellow** to describe color[14, 46]. Both color models operate on the same color wheel, however RGB is used to describe an output source's photon emission and CMY describes how pigment molecules absorb photons.

[2]See *Section 6: XYZ to RGB Shader Algorithm.* for more information on specific color spaces and their varying triangles of gamut coverage.

Display technology operates on RGB and printing technology operates on CMY. This model is based off the idea that when pigments overlap in various amounts the way they absorb and reflect light will be combined. For instance, if cyan is placed on top of yellow, those colors result in a green.

When added together, the cyan, magenta, and yellow colors *should* produce a dark gray, because the combination of all of these in equal wavelengths would absorb all the wavelengths of light and therefore not reflect any back. However, in practice, ink mixing does not behave as well as light mixing and a component was added to the printing process called the *key* value, which is loosely related to black and improves the richness of color output[4, 116]. This is why the CMYK space is more common when discussing printing rather than just CMY. This makes CMYK a special case and there are even printers that expand the number of inks used beyond four[30, 39].

Like RGB, this model has a limited output triangle compared to the human gamut[14, 50]. It is also subject to the fact that the illuminating source pattern makes a big difference on what the resulting color perception a viewer will receive from a printed piece. This is different than RGB which is operating as its own light source. Printed CMY(K) is absorbing light from the illumination source and not illuminating itself, therefore the spectrum of the emission source must be considered.

In summation, CMY is a color model, and CMYK is a color space, and each individual printer will have its own color profile, and there is a huge range of printing done in the modern world from home to professional use[15]. Like the RGB model, CMYK is a popular color model in several industries. The same issues with RGB production, like cost and quality, also result in the tiered color model-space-profile hierarchy for this model.

4.5.2. *CIELAB Color.* The 1976 CIE L*a*b.(CIELAB) color model uses the same principles as the CIE XYZ model but seeks to create a more uniformly distributed color space in terms of perception—meaning the change in values along the spectrum represent equal color differences to the viewer[36, 59]. L*a*b. Color is merely another color space used to quantify metamers. The acronym in this case is L: Lightness; a: the red-green color axis; b: the blue-yellow color axis[22, 141]. L*a*b. is a popular device-independent color space because it is a complete—meaning it covers the entire gamut—and the perceptual uniformity makes it user-friendly.

4.5.3. *HSV, or HSL. Figure 26.* illustrates this model, which describes light based on the three basic ways it varies: **H**ue, **S**aturation and **V**alue or **L**uminance—the terms HSV and HSL are both commons names for this model[14, 45][3]. The division of color into these three main components is also the basis of the perceptually equal *Munsell system*[13, 99].

Hues along the spectral locus and the line of purples are defined in this model by using a measure of degree from 0 to 360; the hue value indicates a spot somewhere on the circumference of this hue circle and represents the dominant wavelength of the perceived color in question[27, 21]. The saturation component is a value that describes how close the color is to a fully saturated hue—the circumference of the color-circle—or how close the color is to gray, the center of the circle. Values in

[3] The term *chroma* or *brightness* are often substituted for *saturation* as well. The terms *tone* or *lightness* are sometimes used to describe value. All of these terms are referring to color based on its three basic parts.

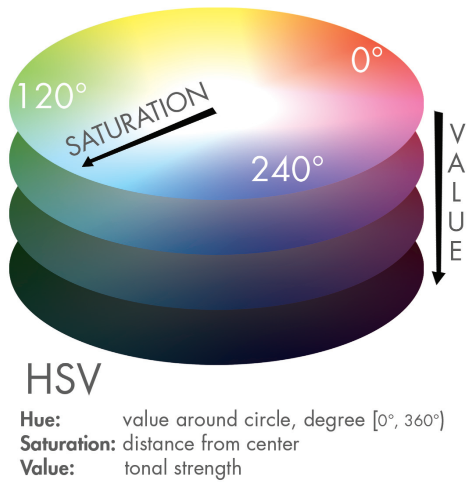



Figure 26. HSV color model. *Graphic Source: R. Campbell Farish*

between these two extremes interpolate for a more or less intense color. The final component, value, is another single number that represents how light or dark the color is—its tonal value.

## 5. Light and Color Operations

Consider a far away billboard with a checkerboard pattern of two colors—*blue* and *red*. Imagine at this distance the squares are too small to make out individually, and the entire board is perceived as one solid color—*magenta*. The eye's cell grid has a finite density, at great distances the cell resolution is not sharp enough to detect the colors from the squares individually[16]. They land on the same cell, combining into one packet. Both *blue* and *red* photons land on the same receptor area, and the eye receives a "mixture" of their individual color perceptions. Walk closer to the board and photons from these same checker boxes hit a larger area of cone cells, increasing visual acuity, and eventually the previous singular color judgment breaks into a checkerboard of two separate color entities—this is illustrated in *Figure 27.*

When light is traveling very closely together, so that photons hit eye cells together in a "group" it can also be described with a SPD, just like when sources emit light. Color mixing operations can be described by combining SPDs in different ways. When two sources emit into the same environment then their wavelength strengths add together. And when two materials merge they also blend their absorption SPDs. However, with materials there is more at play, such as different pigment molecule sizes that require a weighted average of absorption patterns.

There are two basic categories that practical color mixing fall into:

- the *additive* mixing of emitted light sources; or
- the *subtractive* mixing of two pigments.

The moment a packet of photons hits cone cells is a major junction of change: on one side is the physical real world—in which the "color" is energy waves; on the other side is the metamerism-based perception world—in which the "color" is an idea. When discussing the notion of material color mixing there are two basic sides of the issue:

- *physical side*: mixing together of photons of various wavelengths (SPDs), more photo-realistic;
- *perceptual side*: mixing together of color sensations (metamers), more subjective;

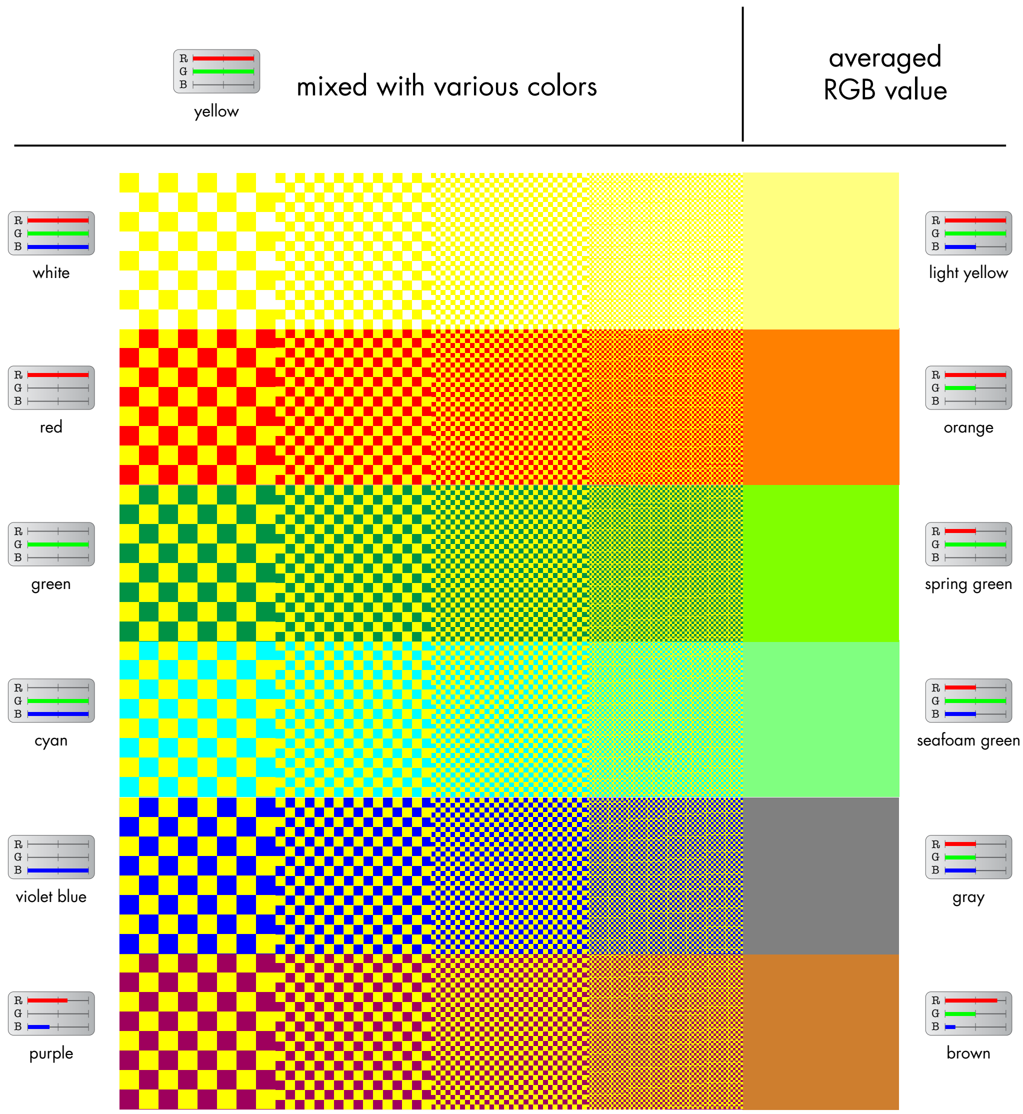



Figure 27. When viewed on a monitor, the last two columns appear be more similar than when viewed on a print-out (squinting helps to compare colors). This is because displays operate on the output of emitted light, in which additive properties are straightforward, while printed pieces are less predictable due to pigment mixing. *Graphic Source: R. Campbell Farish*

The best way to determine how color interacts between sources and objects is to know its spectral data. As long as the color issue in question involves a static color perception then metamers and SPD data behave equally well; if the intended output is purple, both methods can result in the same purple. Once a color operation is attempted on an object the metamer's lost information makes it harder to predict a precise and unique outcome, and the two methods may result in slightly different resulting colors.

### 6. Grassman's Law of Additive Light Mixing

Additive light in the physical realm is simply the summation of the sources' strengths per wave interval. H. G. Grassman formulated basic empirical laws of additive color mixing and their modern equivalents are as follows[36, 27]:

1. To specify a color match, three independent variables are necessary and sufficient.

2. For an additive mixture of color stimuli, only their tristimulus values are relevant, not their spectral compositions.

3. In additive mixtures of color stimuli, if one or more components of the mixture are gradually changed, the resulting tristimulus values are changed gradually.

Most models perform additive color mixing in a straightforward manner, like XYZ or RGB, because they are based *directly* on cone stimulation. Tristimulus values can be added or averaged and produce true results—as stated in the second empirical law. Other models like HSV are trickier when it comes to additive operations. The saturation and value component can be averaged together but the angle of the hue circle becomes a bit more problematic because one could travel clockwise or counter-clockwise[4].

## 7. The "Subtractive" Mixing of Materials

For centuries man has mixed physical colors for production reasons, necessitating standards to handle the process of subtractive color modeling. Red, yellow, and blue (RYB) make up the "standard artist palette" of pigment colors used in subtractive mixing—this has more to do with the availability of pigments throughout history than it does with those three colors covering a wide gamut[18, 74][5]. RYB are sometimes referred to as "primary colors", however the problem with this definition is that it creates the notion that with three pigments one can create all color judgments—which is just not true. The human chromaticity gamut's odd shape makes it hard to plot with a handful of points—see *Section 4.3: The Chromaticity (xyY) Diagram.*

Using two metameric values in color operations creates a paradox: how can two *perceptions* combine? In the physical world an object does not have a color until a source acts upon it, so when assigning an object a color value it describes how the object is *most likely* to appear under most illumination circumstances. Metameric values estimate color's spectral contents creating many

[4] Typically the average between the two values of the smallest angular difference is chosen.
[5] In RYB, red takes the place of magenta and blue takes the place of cyan.

possible interpolations between two color values, using two spectral definitions would be more precise.

Spectral models may be superior for subtractive color operations, man has not always had access to this data and has needed to utilize more practical color perception based models. One such model is CMY—see *Section 4.5.1: CMY and CMYK.*—which provides darker hues the more of each color is combined. Each color component creates theoretical black in this model versus in a additive model which would create theoretical white. The relationships between colors around the human gamut are still the same as with an additive system but the primary hues have been shifted.

CHAPTER 7

# Designing a Spectral Model for Storing Color Data

Color-emission technology is inspired by the psychophysical sensation of color and many of the popular color models used to program display output follow this metamerism-based approach to color description. However, when using metameric data in lifelike simulation programing, the spectral data of sources and materials must be *estimated*. As hardware becomes capable of more processing more computations in real-time, the case for such an estimation weakens. Using spectral data in graphics rendering is already happening but there are reasons beyond computing power as to why it has not become mainstream. This approach offers a real-time solution that is flexible and aims to combat some of the issues with spectral color models.

When the topic of color involves a static source—e.g., color matching—metameric color models and a spectral one provide identical outputs—and the metameric approach even out performs the spectral approach by being more concise. However when the topic involves color operations such as sources illuminating objects and metamer data is used, this data represents a truncated version of the actual physics involved.

An expansion of color data means more operations to achieve color output and the benefits that come with this computational tax should be weighed. There are even instances when a spectral model and metameric one would produce the same results in a dynamic color scenario. If an application requires more control over color operations, then a spectral model would be superior to a metameric one as it is simply more detailed.

The spectral model proposed in this paper describes SPDs discretely by storing intensity values for intervals in some discernible wavelength range of the electromagnetic spectrum, presumably the human gamut. When using these SPDs in color operations, actions are performed per element—which represent wavelength intervals—and are converted to a metameric model right before render-target output. In the proposed algorithm, to keep the code flexible, the SPD values are transformed first into XYZ values—a theoretical and complete color model—and then are transformed into a specific RGB color space.

Color operations are usually done per pixel at the shader level, so the solution described in this paper for simulating spectral color is optimized for the GPU. The main code is encapsulated into a shader program that allows for easy addition into existing projects. This spectrum-based color rendering process is certainly more laborious than using simple RGB values for color operations. The shader aspect addresses this by allowing for use on a per object basis, and only when the computer's extra processing time is worth it. A programmer can choose to only add it to certain objects in the scene that require emphasis on the photo-realism of the color output.

As is with many shaders, the input must be formatted properly, therefore there are steps in the algorithm outside the shader as well.

### 1. SPD Structure

A discrete SPD is a two-dimensional graph of points—an array of positive values. *Figure 28.* illustrates a sample SPD as a bar graph, which points out that SPDs can be discontinuous and some can be difficult to describe with functions. A vector data structure serving as a look up table for the SPD data works with its discontinuous nature.

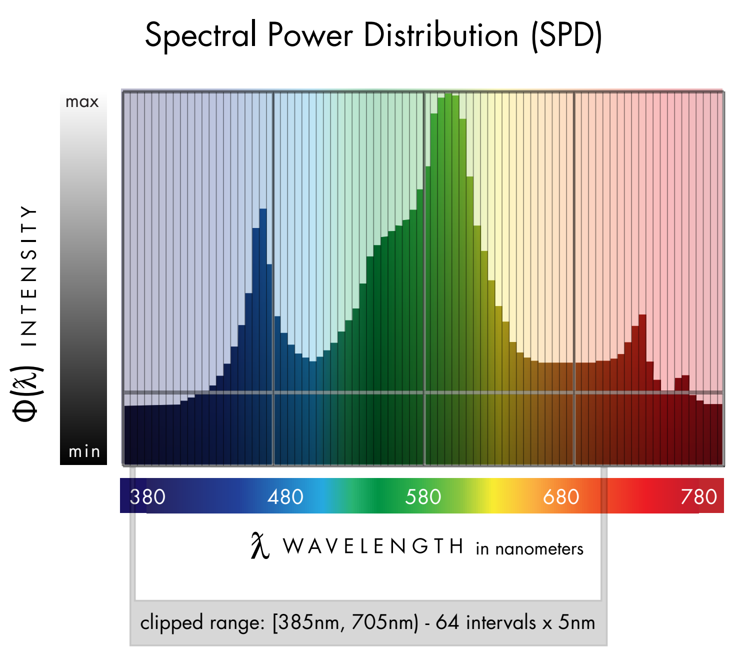



Figure 28. A sample SPD. *Graphic Source: R. Campbell Farish*

In this proposed model, each element of the array represents an interval in the electromagnetic wavelength spectrum. The total range of these intervals, the X-range, should cover the salient portion of the human gamut. There should also be enough intervals along this X-range to describe a pattern of light in a sufficiently detailed manner, referred to as $N_{interval}$.

In order to stress the compatibility with older hardware and put an emphasis on real-time rendering the SPD structure discussed in this section uses textures that are of dimension equal to a power of 2 as well as describes the values in an incoming texture channel using integer in the range (0,255). This is an implementation choice and the algorithm with various sizes spectrum ranges with various levels of details all behave in the same theoretical way. However the more detail involved the more accurate the simulated calculations would presumably be. The levels of detail chosen for this demo study all produced dramatic enough visual results to deem them acceptable.

Many graphic engines use metameric models requiring three data numbers for storage and operations[1]. However, in the spectral case, this becomes a set of $N_{interval}$ numbers. The smaller the interval's wavelength span, the more elements are needed to cover the visible spectrum; and the more elements, the longer it takes to process an array. For practical purposes of users and developers, the number and size of the interval requires a balance between performance and results.

*The 1931 CIE Standard Observer look-up table* used in converting SPDs to XYZ, included in *Figure 29.*, is broken up into wavelength intervals of $5nm$ which they recommend as an acceptable level of detail[36, 30]. At $5nm$ intervals, covering a range of $400nm$ necessitates an 80 element array.

[1]See *Section 4: Color Systems.*

| wavelength λ | x(λ) | y(λ) | z(λ) | x(λ)/1.7826 | y(λ)/1.7826 | z(λ)/1.7826 | R | G | B |
|---|---|---|---|---|---|---|---|---|---|
| 380 | 0.0014 | 0.0000 | 0.0065 | 0.0008 | 0.0000 | 0.0036 | 0 | 0 | 1 |
| 385 | 0.0022 | 0.0001 | 0.0105 | 0.0012 | 0.0001 | 0.0059 | 0 | 0 | 2 |
| 390 | 0.0042 | 0.0001 | 0.0201 | 0.0024 | 0.0001 | 0.0113 | 1 | 0 | 3 |
| 395 | 0.0076 | 0.0002 | 0.0362 | 0.0043 | 0.0001 | 0.0203 | 1 | 0 | 5 |
| 400 | 0.0143 | 0.0004 | 0.0679 | 0.0080 | 0.0002 | 0.0381 | 2 | 0 | 10 |
| 405 | 0.0232 | 0.0006 | 0.1102 | 0.0130 | 0.0003 | 0.0618 | 3 | 0 | 16 |
| 410 | 0.0435 | 0.0012 | 0.2074 | 0.0244 | 0.0007 | 0.1163 | 6 | 0 | 30 |
| 415 | 0.0776 | 0.0022 | 0.3713 | 0.0435 | 0.0012 | 0.2083 | 11 | 0 | 53 |
| 420 | 0.1344 | 0.0040 | 0.6456 | 0.0754 | 0.0022 | 0.3622 | 19 | 1 | 92 |
| 425 | 0.2148 | 0.0073 | 1.0391 | 0.1205 | 0.0041 | 0.5829 | 31 | 1 | 149 |
| 430 | 0.2839 | 0.0116 | 1.3856 | 0.1593 | 0.0065 | 0.7773 | 41 | 2 | 198 |
| 435 | 0.3285 | 0.0168 | 1.6230 | 0.1843 | 0.0094 | 0.9105 | 47 | 2 | 232 |
| 440 | 0.3483 | 0.0230 | 1.7471 | 0.1954 | 0.0129 | 0.9801 | 50 | 3 | 250 |
| 445 | 0.3481 | 0.0298 | 1.7826 | 0.1953 | 0.0167 | 1.0000 | 50 | 4 | 255 |
| 450 | 0.3362 | 0.0380 | 1.7721 | 0.1886 | 0.0213 | 0.9941 | 48 | 5 | 253 |
| 455 | 0.3187 | 0.0480 | 1.7441 | 0.1788 | 0.0269 | 0.9784 | 46 | 7 | 249 |
| 460 | 0.2908 | 0.0600 | 1.6692 | 0.1631 | 0.0337 | 0.9364 | 42 | 9 | 239 |
| 465 | 0.2511 | 0.0739 | 1.5281 | 0.1409 | 0.0415 | 0.8572 | 36 | 11 | 219 |
| 470 | 0.1954 | 0.0910 | 1.2876 | 0.1096 | 0.0510 | 0.7223 | 28 | 13 | 184 |
| 475 | 0.1421 | 0.1126 | 1.0419 | 0.0797 | 0.0632 | 0.5845 | 20 | 16 | 149 |
| 480 | 0.0956 | 0.1390 | 0.8130 | 0.0536 | 0.0780 | 0.4561 | 14 | 20 | 116 |
| 485 | 0.0580 | 0.1693 | 0.6162 | 0.0325 | 0.0950 | 0.3457 | 8 | 24 | 88 |
| 490 | 0.0320 | 0.2080 | 0.4652 | 0.0180 | 0.1167 | 0.2610 | 5 | 30 | 67 |
| 495 | 0.0147 | 0.2586 | 0.3533 | 0.0082 | 0.1451 | 0.1982 | 2 | 37 | 51 |
| 500 | 0.0049 | 0.3230 | 0.2720 | 0.0027 | 0.1812 | 0.1526 | 1 | 46 | 39 |
| 505 | 0.0024 | 0.4073 | 0.2123 | 0.0013 | 0.2285 | 0.1191 | 0 | 58 | 30 |
| 510 | 0.0093 | 0.5030 | 0.1582 | 0.0052 | 0.2822 | 0.0887 | 1 | 72 | 23 |
| 515 | 0.0291 | 0.6082 | 0.1117 | 0.0163 | 0.3412 | 0.0627 | 4 | 87 | 16 |
| 520 | 0.0633 | 0.7100 | 0.0782 | 0.0355 | 0.3983 | 0.0439 | 9 | 102 | 11 |
| 525 | 0.1096 | 0.7932 | 0.0573 | 0.0615 | 0.4450 | 0.0321 | 16 | 113 | 8 |
| 530 | 0.1655 | 0.8620 | 0.0422 | 0.0928 | 0.4836 | 0.0237 | 24 | 123 | 6 |
| 535 | 0.2257 | 0.9149 | 0.0298 | 0.1266 | 0.5132 | 0.0167 | 32 | 131 | 4 |
| 540 | 0.2904 | 0.9540 | 0.0203 | 0.1629 | 0.5352 | 0.0114 | 42 | 136 | 3 |
| 545 | 0.3597 | 0.9803 | 0.0134 | 0.2018 | 0.5499 | 0.0075 | 51 | 140 | 2 |
| 550 | 0.4334 | 0.9950 | 0.0087 | 0.2431 | 0.5582 | 0.0049 | 62 | 142 | 1 |
| 555 | 0.5121 | 1.0002 | 0.0057 | 0.2873 | 0.5611 | 0.0032 | 73 | 143 | 1 |
| 560 | 0.5945 | 0.9950 | 0.0039 | 0.3335 | 0.5582 | 0.0022 | 85 | 142 | 1 |
| 565 | 0.6784 | 0.9786 | 0.0027 | 0.3806 | 0.5490 | 0.0015 | 97 | 140 | 0 |
| 570 | 0.7621 | 0.9520 | 0.0021 | 0.4275 | 0.5341 | 0.0012 | 109 | 136 | 0 |
| 575 | 0.8425 | 0.9154 | 0.0018 | 0.4726 | 0.5135 | 0.0010 | 121 | 131 | 0 |
| 580 | 0.9163 | 0.8700 | 0.0017 | 0.5140 | 0.4881 | 0.0010 | 131 | 124 | 0 |
| 585 | 0.9786 | 0.8163 | 0.0014 | 0.5490 | 0.4579 | 0.0008 | 140 | 117 | 0 |
| 590 | 1.0263 | 0.7570 | 0.0011 | 0.5757 | 0.4247 | 0.0006 | 147 | 108 | 0 |
| 595 | 1.0657 | 0.6949 | 0.0010 | 0.5978 | 0.3898 | 0.0006 | 152 | 99 | 0 |
| 600 | 1.0622 | 0.6310 | 0.0008 | 0.5959 | 0.3540 | 0.0004 | 152 | 90 | 0 |
| 605 | 1.0456 | 0.5668 | 0.0006 | 0.5866 | 0.3180 | 0.0003 | 150 | 81 | 0 |
| 610 | 1.0026 | 0.5030 | 0.0003 | 0.5624 | 0.2822 | 0.0002 | 143 | 72 | 0 |
| 615 | 0.9384 | 0.4412 | 0.0002 | 0.5264 | 0.2475 | 0.0001 | 134 | 63 | 0 |
| 620 | 0.8544 | 0.3810 | 0.0002 | 0.4793 | 0.2137 | 0.0001 | 122 | 55 | 0 |
| 625 | 0.7514 | 0.3210 | 0.0001 | 0.4215 | 0.1801 | 0.0001 | 107 | 46 | 0 |
| 630 | 0.6424 | 0.2650 | 0.0000 | 0.3604 | 0.1487 | 0.0000 | 92 | 38 | 0 |
| 635 | 0.5419 | 0.2170 | 0.0000 | 0.3040 | 0.1217 | 0.0000 | 78 | 31 | 0 |
| 640 | 0.4479 | 0.1750 | 0.0000 | 0.2513 | 0.0982 | 0.0000 | 64 | 25 | 0 |
| 645 | 0.3608 | 0.1382 | 0.0000 | 0.2024 | 0.0775 | 0.0000 | 52 | 20 | 0 |
| 650 | 0.2835 | 0.1070 | 0.0000 | 0.1590 | 0.0600 | 0.0000 | 41 | 15 | 0 |
| 655 | 0.2187 | 0.0816 | 0.0000 | 0.1227 | 0.0458 | 0.0000 | 31 | 12 | 0 |
| 660 | 0.1649 | 0.0610 | 0.0000 | 0.0925 | 0.0342 | 0.0000 | 24 | 9 | 0 |
| 665 | 0.1212 | 0.0446 | 0.0000 | 0.0680 | 0.0250 | 0.0000 | 17 | 6 | 0 |
| 670 | 0.0874 | 0.0320 | 0.0000 | 0.0490 | 0.0180 | 0.0000 | 13 | 5 | 0 |
| 675 | 0.0636 | 0.0232 | 0.0000 | 0.0357 | 0.0130 | 0.0000 | 9 | 3 | 0 |
| 680 | 0.0468 | 0.0170 | 0.0000 | 0.0263 | 0.0095 | 0.0000 | 7 | 2 | 0 |
| 685 | 0.0329 | 0.0119 | 0.0000 | 0.0185 | 0.0067 | 0.0000 | 5 | 2 | 0 |
| 690 | 0.0227 | 0.0082 | 0.0000 | 0.0127 | 0.0046 | 0.0000 | 3 | 1 | 0 |
| 695 | 0.0158 | 0.0057 | 0.0000 | 0.0089 | 0.0032 | 0.0000 | 2 | 1 | 0 |
| 700 | 0.0114 | 0.0041 | 0.0000 | 0.0064 | 0.0023 | 0.0000 | 2 | 1 | 0 |
| 705 | 0.0081 | 0.0029 | 0.0000 | 0.0045 | 0.0016 | 0.0000 | 1 | 0 | 0 |
| 710 | 0.0058 | 0.0021 | 0.0000 | 0.0033 | 0.0012 | 0.0000 | 1 | 0 | 0 |
| 715 | 0.0041 | 0.0015 | 0.0000 | 0.0023 | 0.0008 | 0.0000 | 1 | 0 | 0 |
| 720 | 0.0029 | 0.0010 | 0.0000 | 0.0016 | 0.0006 | 0.0000 | 0 | 0 | 0 |
| 725 | 0.0020 | 0.0007 | 0.0000 | 0.0011 | 0.0004 | 0.0000 | 0 | 0 | 0 |
| 730 | 0.0014 | 0.0005 | 0.0000 | 0.0008 | 0.0003 | 0.0000 | 0 | 0 | 0 |
| 735 | 0.0010 | 0.0004 | 0.0000 | 0.0006 | 0.0002 | 0.0000 | 0 | 0 | 0 |
| 740 | 0.0007 | 0.0003 | 0.0000 | 0.0004 | 0.0002 | 0.0000 | 0 | 0 | 0 |
| 745 | 0.0005 | 0.0002 | 0.0000 | 0.0003 | 0.0001 | 0.0000 | 0 | 0 | 0 |
| 750 | 0.0003 | 0.0001 | 0.0000 | 0.0002 | 0.0001 | 0.0000 | 0 | 0 | 0 |
| 755 | 0.0002 | 0.0001 | 0.0000 | 0.0001 | 0.0001 | 0.0000 | 0 | 0 | 0 |
| 760 | 0.0002 | 0.0001 | 0.0000 | 0.0001 | 0.0001 | 0.0000 | 0 | 0 | 0 |
| 765 | 0.0001 | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 | 0 | 0 | 0 |
| 770 | 0.0001 | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 | 0 | 0 | 0 |
| 775 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0 | 0 | 0 |
| 780 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0 | 0 | 0 |

Figure 29. 1931 CIE standard observer with 2 degree foveal field x(), y() and z() functions, and their translation into RGB values in the range [0,255] for storage on a texture. Highlighted portion represents unused values in the 64x5nm demo range. *Graphic Source: R. Campbell Farish*

In the demo example used for compiling sample results from spectral rendering, the RGB entries are mapped to a integer range of 0 to 255—which is the case for 8-bit color—. After mapping, several intervals near the borders of the range have all three of their function output values clamped to zero, making them insignificant[9]. Removing those entries would leave 68 intervals where at least one of the values is not zero[2].

This look-up array is going to be stored as texture (more on that below) and therefore matching array length to a power of two would be an efficient fit to keep it compatible with older hardware, such as $64 = 2^6$[2, 157]. Raising the threshold of what is considered significant data—once converted to an 8-bit integer scale—from any total greater than 0 for the three numbers, to any total greater than 1 provides exactly 64 intervals. Those insignificant intervals do not outweigh the benefit of storing the SPD information in a tidy fashion. Therefore, the demo implementation of the proposed spectral model will describe 64 intervals of 5nm a piece, representing from $385nm$ to $705nm$ along the electromagnetic spectrum.

The value of each element of the spectral array represents relative intensity per wavelength interval, it is the Y-axis of the SPD. SPDs are going to need to be stored on textures—for demo purposes, mapped to the range of 0 to 255. The SPD patterns need to cover a global minimum and maximum intensity scenario. No light, or total darkness, is represented by 0 and subsequently a value of 0 in an interval means there is no photon activity. However, the maximum value is not as easy to determine.

[2]Converting the function values into monochromatic values involves dividing the values by the max value the chart exhibits which is 1.7826, and then multiplying them by 255. This is needed because there are some values in the functions over 1.0.

In principle there is no maximum intensity for light, sources can be very powerful[7, 9]. However there is a limit to the intensity strength that the eye can handle. Once the eye's sensory cells are maxed out, any intensity beyond that is meaningless—and actually dangerous. The eye's relative intensity levels are also always in flux[16]. The best way to handle color intensity within the texture is therefore on a relative scale of minimum to maximum.

In this model, there is source intensity value, which is additional to the relative intensity value that is stored on the SPD texture. This source intensity value can be thought of as the physical intensity factor applied to an emission source's SPD pattern to represent a change in overall intensity. Providing this factor is helpful when describing the intensity change of sources and during object shading techniques.

In all scenarios, scaling a SPD by a factor will yield identical results to using a metameric model like XYZ; this is stated by *Grassman's Law*[3]. Increasing light's intensity per wavelength either by scaling it by a factor or by adding sources both follow the law that spectral and metameric perception results are equivalent. This law allows color operations after color source/object interaction is performed to be computed in metameric form in the interest of saving computations.

To further understand the way this proposed method operates, consider a source emitting an equal distribution at full intensity; its SPD would be an array of maximum values—imagine it as a bar graph creating a solid rectangle block. If viewers were to input this maximum scenario SPD they would perceive white[4]. Now

[3]See *Section 6: Grassman's Law of Additive Light Mixing.*
[4]Note this is not the only SPD that would cause the viewer to perceive white.

consider a source that does not have an equal distribution, it begins to erode away from the top of this block of maximum values in the previous SPD. The source then encounters a material which absorbs wavelengths at different levels, decreasing the bar graph values even further. Eventually a resulting SPD enters viewers eyes and transform into metameric color perceptions.

In this model there are two basic types of SPD patterns:

1. **Emission patterns for sources** that give off light, herein referred to as **ESPDs**. ESPDs represent the relative wavelength strength per interval pattern of a light source. A value of 0 means that there is no photon strength in that wavelength interval, and a value of 1 means that the source is at its relative maximum in that interval.

2. **Reflection patterns for objects** that absorb some light and reflect back the rest, herein referred to as **RSPDs**. RSPDs represent how an object's material interacts with light ultimately giving the object a perceived color. Per element of a RSPD: a value of 0 means that no photons are reflected, but instead are *all absorbed*, and a value of 1 means none of the photons are absorbed and they are *all reflected*.

The distinction between types of SPDs is important when performing operations as they interact differently. ESPDs can be scaled element-wise by a factor and two ESPDs can add together using an element wise addition of values. RSPDs cannot be scaled by a factor because their patterns are unchanging for a material of a static color; while a light can vary in its strength, a material's absorption and reflection pattern is relative and stays constant in this model. The only operation a RSPD can perform is to act upon an ESPD to simulate an object reflecting photons back at the viewer. The ESPD multiplies its values element by element with those in an RSPD to result in a SPD representing the light entering the observer's eye.

### 2. SPD Shader Input Texture

The GPU reads textures quickly and a texture is essentially a look-up function, which is the same data format the proposed model uses for spectral rendering[2]. This model needs to input: the standard observer function data, in the form of look-up tables of constants used to turn SPDs into XYZ values; ESPD patterns; and RSPD patterns. All of this data can be represented as predetermined constant arrays and thus can be mapped onto one of the color channels of a texture graphic.

*Figure 30.* displays how the demo code implements the storing of SPD data on a texture that is 64 pixels square, as previously mentioned 64 is a number chosen for its convenient mapping of CIE standard observer function data. The pixel column of the SPD texture represents the wavelength range. The rows then function as various SPD entries.

The very first row of this texture contains the 1931 CIE standard observer functions x(), y(), and z()—*Figure 29.*—in the Red, Green, and Blue channels, respectively. These function values, used in SPD conversion, are converted to the range of minimum and maximum values per channel of an RGB color texture. The other rows of the texture represent source emission patterns (ESPDs) in the

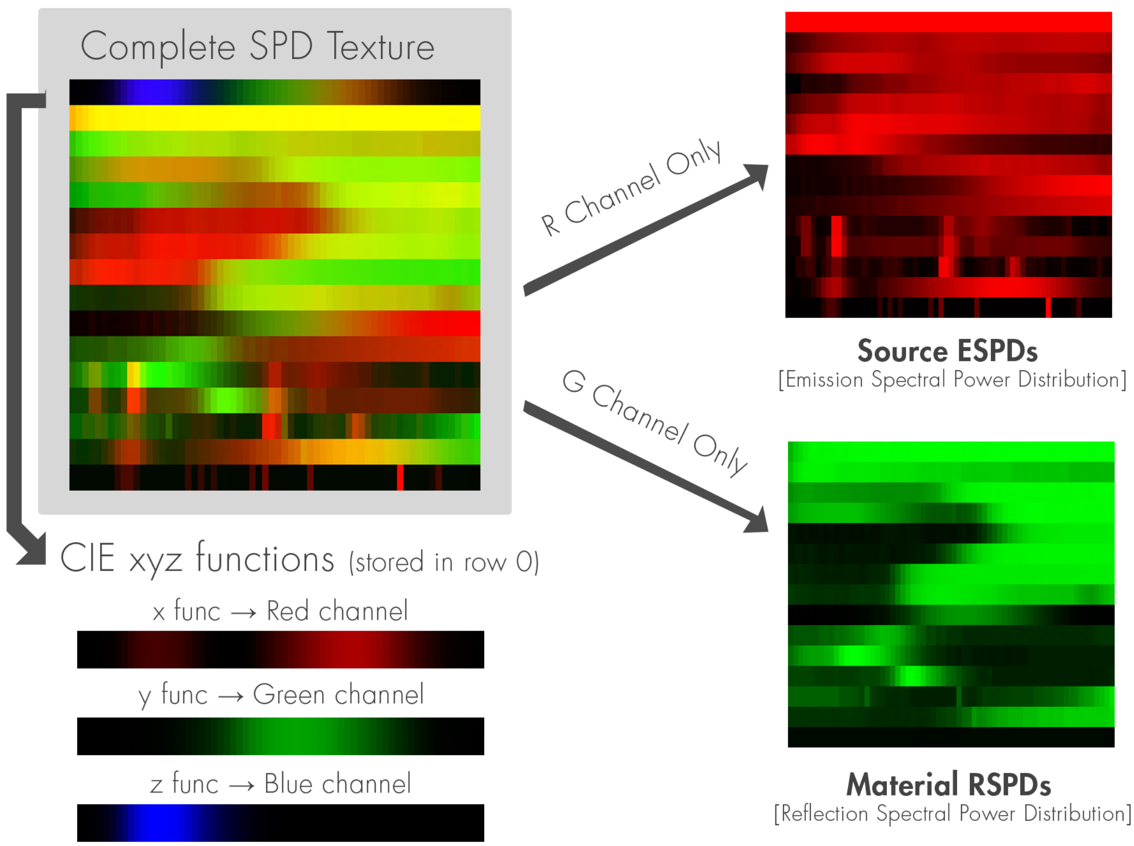



Figure 30. An example texture storing SPD data to be inputted into the shader. *Graphic Source: R. Campbell Farish*

Red Channel and material reflection patterns (RSPDs) in the Green Channel. The programmer needs only to know the row in the texture of the RSP they are interested in.

The demo texture is an example of the kind of texture that could be used. Many improvements can be made such as: increasing pixel size thereby allowing more wavelength acuity; dividing the image into more rows; and adding information to the Blue channel. One texture can hold a lot of SPD data, and consequently objects in the code then merely hold onto a look-up key value. The trade off for reducing the object's color data size is the main engine requires adding a texture to the GPU's memory.

### 3. SPD Rendering Shader Input Variables

This algorithm for SPD rendering is flexible and encapsulated. Like most rendering processes with a shader component, there are options to set before rendering and important calculations are performed in the shader. Variables needed as input to the shader are:

- **The SPD texture**. The SPD input texture contains all the hard spectral data used to run the algorithm[5]. This file is created with an image editing software that allows assignment of RGB values to individual pixels.

[5] In addition, perhaps the artist is choosing from different "palettes" as well, aka SPD textures compiled into groups for specific uses, in which case the correct desired texture would need to be inputed.

- **Keys to sources' ESPD and objects' RSPD**. Instead of having a tristimulus color value, objects have a key that points to the row in the SPD texture pattern containing its RSPD. Each light would also have a key pointing to the row with its ESPD.

- **Lighting information**. This can be any data used to determine lighting effects. The aforementioned source's strength variable is an example of this kind of data[6]. This includes other properties such as: distance, falloff rate, direction, etc.

- **XYZ to RGB conversion matrix.** The standard observer data produces results in the XYZ color model, but screens work on the concrete color *spaces/profiles*, not with theoretical color *models*. The final step of the algorithm is conversion into RGB values tailored to the working color space/profile of the display. A custom or default conversion matrix can be used.

- **Other color correction variables**. Continued calibration, such as gamma correction, is common among display output and the results of the XYZ to RGB conversion can be tweaked as well. Such correction is not always necessary, can be more taxing on the hardware, and is a fine-tuning step.

## 4. SPD Rendering Shader Overview

*Figure 31.* highlights the basic steps. To describe the algorithm in brief:

[6]However it could also default to one and assume a maximum strength for all sources.

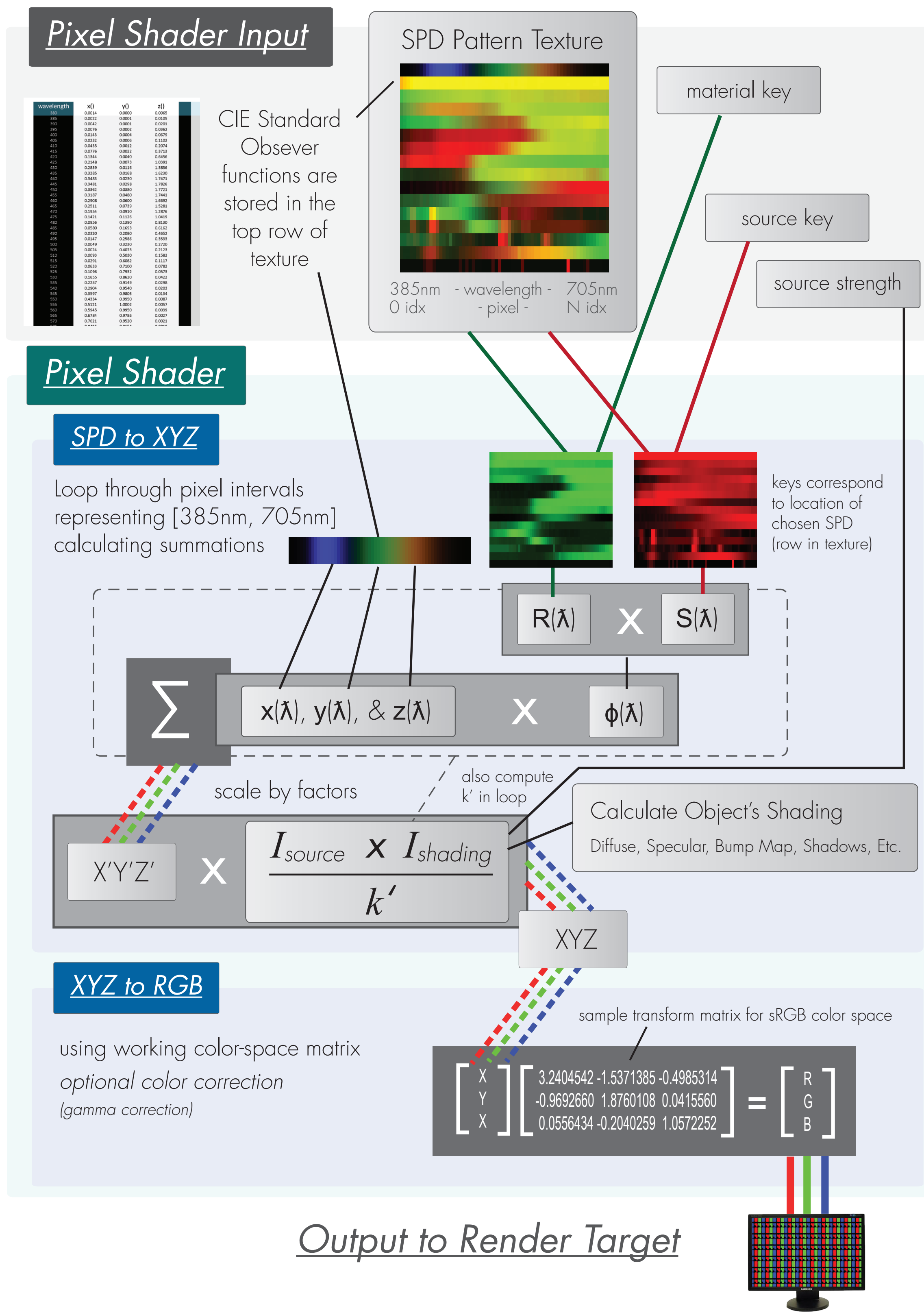



Figure 31. Flow chart of spectral rendering algorithm in pixel shader. *Graphic Source: R. Campbell Farish*

- Compute the SPD of light coming towards the viewer, $\phi(\lambda)$, at the current pixel, based on ESPDs, $S(\lambda)$, and RSPDs, $R(\lambda)$, involved, as in *Equation 7.1*.
- Use the resulting SPD when converting to XYZ using *Equation 7.2*, *Equation 7.3*, and *Equation 7.4*.
- Convert XYZ to RGB for output, including any color calibration.

$$\phi(\lambda) = R(\lambda)S(\lambda) \tag{7.1}$$

$$X = k \sum_{0}^{N_{interval}} \phi(\lambda)\overline{x}(\lambda)d\lambda \tag{7.2}$$

$$Y = k \sum_{0}^{N_{interval}} \phi(\lambda)\overline{y}(\lambda)d\lambda \tag{7.3}$$

$$Z = k \sum_{0}^{N_{interval}} \phi(\lambda)\overline{z}(\lambda)d\lambda \tag{7.4}$$

$$k = \frac{1.0}{\sum_{0}^{N_{interval}} S(\lambda)\overline{y}(\lambda)d\lambda} \tag{7.5}$$

The *Equation 6.2*, *Equation 6.3*, *Equation 6.4*, and *Equation 6.5*, are conversion formulas into the metameric CIE XYZ color model and created directly from collected spectral data. The *Equation 7.2*, *Equation 7.3*, *Equation 7.4*, *Equation 7.5* are the discrete summation versions of these equations, and the ones used in practice[36, 32].

### 5. SPD to XYZ Shader Algorithm

The SPD to XYZ algorithm begins with a for-loop that computes the three separate summations for X, Y, and Z. This loop goes from zero to the maximum number of wavelength intervals, $N_{interval}$—the demo code has 64; each step in the loop represents a slice of the Visible Light Spectrum—in the demo code this range is from $385nm$ to $705nm$.

Before the loop, the inputed row values determine where on the SPD texture to find the ESPD and RSPD being referenced[7]. At each iteration of the loop, the algorithm has access to an ESPD, a RSPD, and CIE XYZ functions—these must all match up in number of elements as the loop treats one interval at time.

*Equation 7.1* determines the light headed towards the viewer to become color judgment, referred to as $\phi(\lambda)$—or herein referred to as viewer SPD (VSPD). The VSPD is the product of the relative spectral emission power, $S(\lambda)$ (ESPD), to the relative reflectance power, $R(\lambda)$ (RSPD).

After $\phi(\lambda)$ is calculated in the loop for one interval, it is multiplied by the CIE standard observer function values from $\overline{x}(\lambda), \overline{y}(\lambda)$, and $\overline{z}(\lambda)$ respectively. The result is added to the container holding the current summation total and at the end of the loop there are three values: X', Y', and Z'—following *Equation 7.6*, *Equation 7.7*, and *Equation 7.8*.

$$X' = \sum_{0}^{N_{interval}} \phi(\lambda)\overline{x}(\lambda)d\lambda \tag{7.6}$$

$$Y' = \sum_{0}^{N_{interval}} \phi(\lambda)\overline{y}(\lambda)d\lambda \tag{7.7}$$

[7]In most circumstances, and such is the case with the demo, determining the row and therefore the corresponding SPD can be done before the loop. However, if one wanted to map a texture onto an object that served as a look-up table for RSPDs then one would determine the ESPD and RSPD involved at the beginning of the loop.

$$Z' = \sum_{0}^{N_{interval}} \phi(\lambda)\overline{z}(\lambda)d\lambda \tag{7.8}$$

A $k'$ scaler is also being calculated during this loop. The formula for $k$, *Equation 6.5*, which has a discrete version, *Equation 7.5*, represents the maximum luminance present with regards to the current source's strength. It is used to normalize the X'Y'Z' values after their summations are complete[8]. *Equation 7.9* illustrates that during actual calculations a summation is computed and then serves as a dividing factor.

$$k = \frac{1.0}{\sum_{0}^{N_{interval}} S(\lambda)\overline{y}(\lambda)d\lambda}, \qquad k = \frac{1.0}{k'} \tag{7.9}$$

When a source illuminates an object there are several lighting factors involved. These can be object-shading related factors, $I_{shading}$, and can be represented as a total amount of light from a source based on whatever lighting effects are at play, such as: diffuse lighting, specular lighting, bump mapping, or shadow mapping. Sources also have a source strength factor, $I_{source}$, which has no upper theoretical limit. In this model, values can go beyond their perceptual limit for intensity and are simply clamped at output.

The source's intensity variable adds a real value into a formula of percentage indices. Patterns can be scaled, but what makes this scaling unique is the hard maximum that is defined by the output—values automatically clamped to the maximum output power of the screen. The technical artist behind the spectral

[8] To conversion into RGB values—which will be in the range [0.0, 1.0].—the XYZ values should ideally be in the range [0.0, 1.0]. That is why instead of 100 as a numerator in *Equation 6.5*, *Equation 7.5* has 1.0.

model then determines SPD patterns and light intensities that create a desired effect. For instance there are many ways one could create white: take any SPD pattern that provides non-zero results for each tristimulus, turn up the source intensity, and eventually the color perception will reach white.

*Grassman's Law* allows the scaling of SPD patterns or their metamer equivalents, both will produce the exact same results with no loss of information. Scaling XYZ values requires less computations than a spectral array, so that is the preferred method. The lighting and $k'$ factors are combined, as in *Equation 7.10*, and used to scale each component of the previously computed X'Y'Z' values resulting in the XYZ values that will be converted to RGB for output. If there were multiple sources, each would have a resulting X'Y'Z' and their own scaling factors. They would then result in their own unique XYZ values, all of which would be added together before converting to RGB for final output.

$$\left(\frac{I_{source} * I_{shading}}{k'}\right)\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{7.10}$$

XYZ is a color model, it is theoretical and abstract, but is a great landing point for this algorithm. Once the data is in this XYZ form, conversion algorithms can turn it into whatever color space is needed for final display. The algorithm always produces identical values up to this point, because those values are theoretical. Once XYZ is converted into a device dependent space, like a RGB color space, then this algorithm has been calibrated to that specific machine or use.

## 6. XYZ to RGB Shader Algorithm

A conversion matrix is used to transform XYZ into RGB, and this matrix is unique for all the various RGB color spaces and profiles[9]. Each RGB space covers a slightly different area of the chromaticity diagram—see *Figure 32.* This is because each space represents its tristimulus components with slightly different wavelength outputs[41].

The three wavelength components used to describe RGB along with a *white point* are used to calculate the conversion matrix from the XYZ model, which is used as an intermediary model, to the real-world outputting model. A **white reference point** is an interior point within a model's chromaticity range triangle that the model considers to be white—meaning an equally distributed spectrum[15]. The white point serves to try and correct RGB emission sources that greatly favor one area of the spectrum due to issues involving manufacturing processes. This system of defining a special point allows for the flexibility of technology to define white independently for their applications.

As the name implies, the white reference point can greatly effect the spaces' rendering of white and using an incorrect point can greatly skew predicted hue outcomes. Recommended white points are defined for the **standard illuminants** and display technologies. The standard illuminant D65's white point is considered to be the base white point for sRGB, which is the common color space for most

[9]The algorithm could convert output to any color model which has a XYZ conversion formula, however RGB is the applicable model for screen output —see *Section 3: Color Models, Color Spaces, and Color Profiles.*

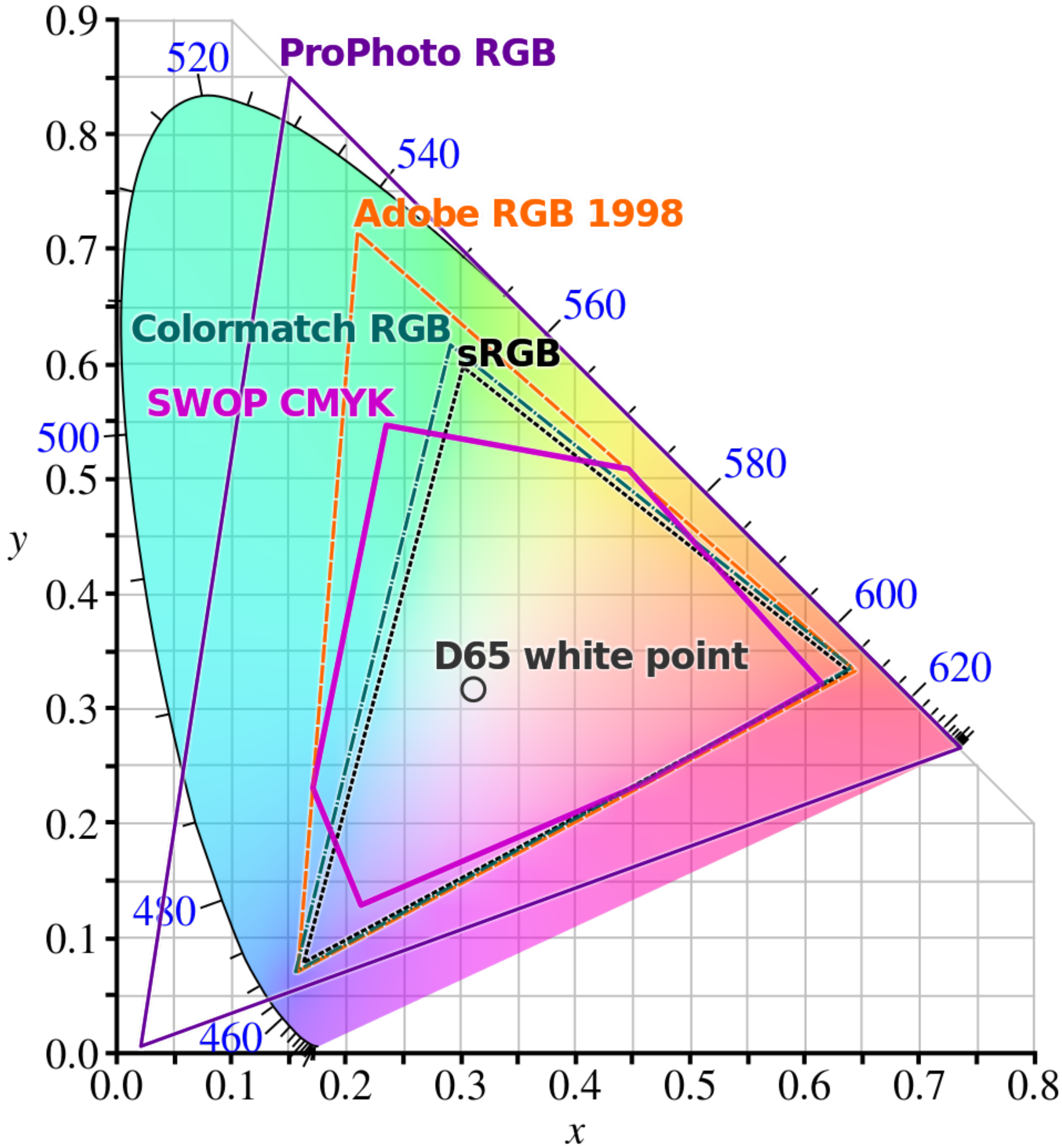



Figure 32. Example of various color spaces graphed on the CIE xyY chromaticity chart. *Source: Blatner and Fraser's "Real World Photoshop CS*

screens—although theoretically any white point can be used[9, 280].

The resulting RGB values can now be displayed directly to the render target desired—presumably the screen—or other color correction can be applied. Gamma correction is a popular such technique that seeks to spread out the intensity levels of colors more evenly, however it can be another costly computational step. Like all rendering options, pros and cons must be weighed per project.

| RGB color space | XYZ to RGB matrix |
|---|---|
| sRGB (D50) | $\begin{bmatrix} 2.754840 & -1.306783 & -0.4238215 \\ -0.993467 & 1.922852 & 0.042594 \\ 0.077074 & -0.282603 & 1.464398 \end{bmatrix}$ |
| sRGB (D65) | $\begin{bmatrix} 3.240970 & -1.537383 & -0.498611 \\ -0.969245 & 1.875968 & 0.041555 \\ 0.055630 & -0.203977 & 1.056972 \end{bmatrix}$ |
| sRGB (E) | $\begin{bmatrix} 2.689989 & -1.276020 & -0.413845 \\ -1.022095 & 1.978261 & 0.043821 \\ 0.061203 & -0.224411 & 1.162860 \end{bmatrix}$ |
| CIE RGB (E) | $\begin{bmatrix} 2.370674 & -0.900041 & -0.470634 \\ -0.513885 & 1.425304 & 0.088581 \\ 0.005298 & -0.014695 & 1.009397 \end{bmatrix}$ |
| Adobe RGB (D65) | $\begin{bmatrix} 2.041369 & -0.564946 & -0.344694 \\ -0.969266 & 1.876011 & 0.041446 \\ 0.013447 & -0.118390 & 1.015410 \end{bmatrix}$ |
| Apple (D50) | $\begin{bmatrix} 2.951537 & -1.289412 & -0.473845 \\ -1.085109 & 1.990857 & 0.037203 \\ 0.085493 & -0.269496 & 1.091298 \end{bmatrix}$ |
| NTSC (C) | $\begin{bmatrix} 1.909996 & -0.532454 & -0.288209 \\ -0.984666 & 1.999171 & -0.028308 \\ 0.058306 & -0.118378 & 0.897554 \end{bmatrix}$ |
| PAL/SECAM RGB (D65) | $\begin{bmatrix} 3.062897 & -1.393179 & -0.475752 \\ -0.969266 & 1.876011 & 0.041556 \\ 0.067876 & -0.228855 & 1.069349 \end{bmatrix}$ |

Figure 33. XYZ to RGB conversion matrices for several applicable RGB color spaces. This data comes from data gathered from Susstrunk, Buckley and Swen[41] and from an technical color source on the web from Bruce Lindbloom[25].

CHAPTER 8

# Spectrum-Based Model Versus Metamerism-Based Model

The algorithm for spectral rendering has been demonstrated through a sample program comparing its color output against a metamerism-based method. Results show that because metamers lack data structure complexity, they can inaccurately predict a simulation mimicking color's physical behavior, which the spectrum-based model predicts with more precision. When the SPD patterns of sources and materials exhibit extreme variations in their wavelength patterns the difference is more apparent between spectral and metameric color system output.

The metameric model is simulating the biology of man, which is why it performs adequately when representing static color judgments, which are biological perceptions. For this reason, light sources may also be added together in both models to produce the same results. However, identical color results will not always result from source and material interaction between a spectral and metameric model. The spectrum-based model is based on physics and represents real world data without the bias of the human perception. *Figure 34.* is a screenshot of a sample program which features a split screen that independently renders the left side of the screen using a metamerism-based method (XYZ) and the right side with a spectrum-based method. Comparing these two sides is a great way to identify when a spectral model is useful. Within this program the user can explore a range of options for source emission and material absorption SPDs.

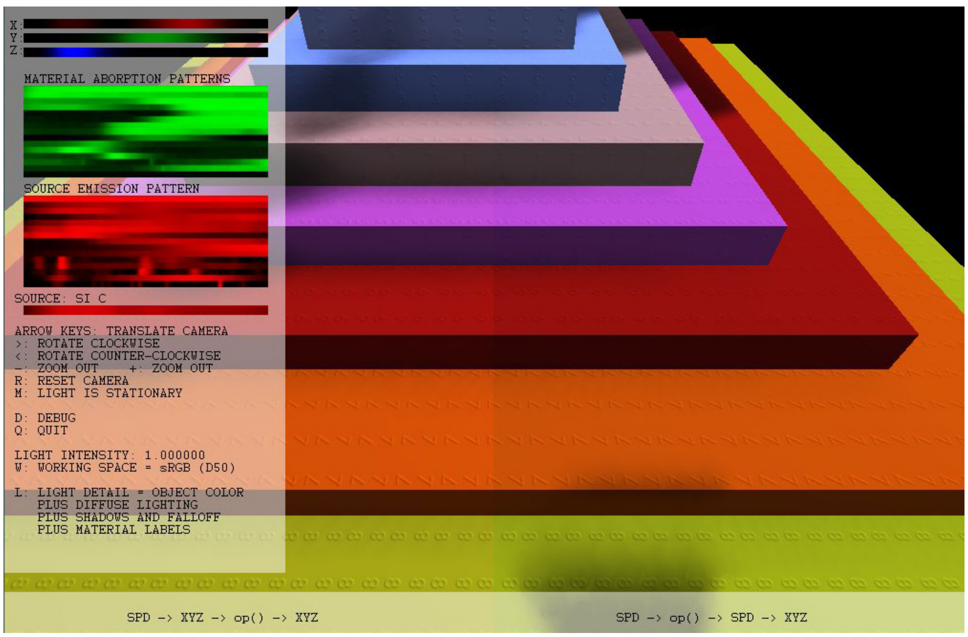



Figure 34. Screen-shot of a program which renders the left half using a metameric process, and the right half using a spectral process. *Graphic Source: R. Campbell Farish*

To keep the results balanced between the two rendering methods, the metamerism-based rendering assigns colors to objects and lights based on the same SPDs used by the spectrum-based rendering. Both sides of the screen have almost identical rendering algorithms; they only vary in whether or not source and material interaction is done on a per wavelength basis. During metamerism-based rendering:

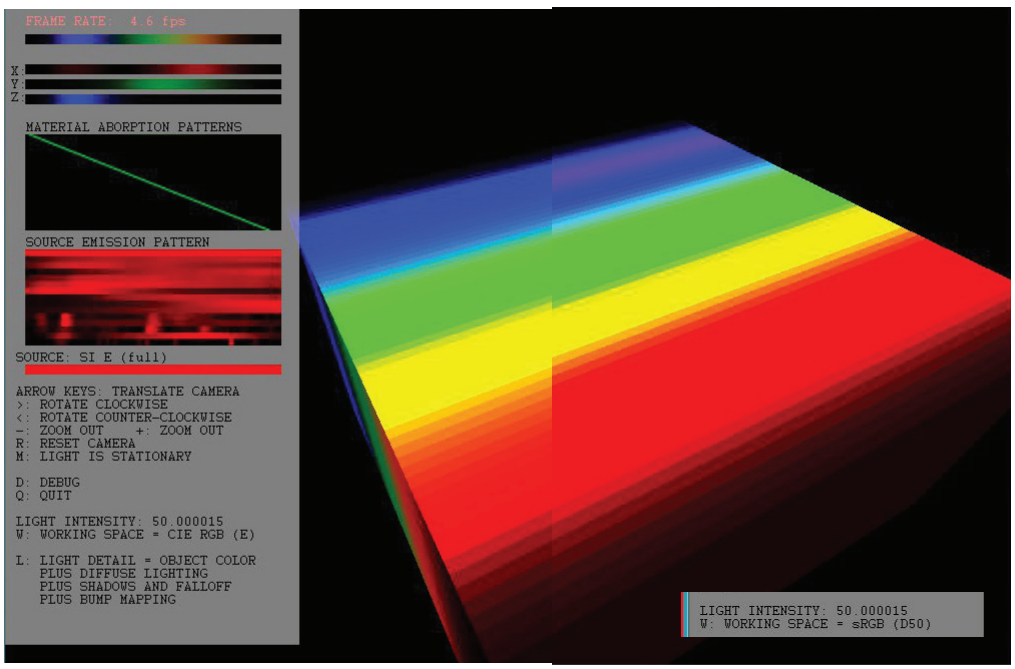
SPD data is being transformed into XYZ data[1]; which is then used in source/material operations; and which is then outputted in RGB. During spectral rendering: SPD data is used in all source/material operations; which is then transformed into XYZ data; and which is then outputted in RGB.

## 1. Empirical Results

*Figure 35.* displays a hypothetical cube made up of slices—like a loaf of bread—each with their own material that corresponds to a row in the SPD input texture. This helps to display how changes in absorption SPDs effect the spectral versus metameric exploration. This sample program displays how changes in SPD patterns affect output in a user-friendly manner by looking at how the input RSPD gradient changes. For example, in *Figure 35.* the cube is showing the effect of shifting a singular strength wavelength band across the spectrum.

*Figure 35.* also illustrates the difference between transformation from XYZ into various RGB color spaces. The split-screen compares the CIE RGB theoretical color space and the sRGB space—which is the space most typical for monitors[30, 83]. Each of these spaces can also have a variable white reference point, however some have standard recommendations. For example, the CIE RGB space, which is theoretical, also uses a theoretical white point of standard illuminant E[36, 66]. sRGB is the most widely used space of RGB, and has a range of standard white points with

[1]Conversion of ESPD patterns into XYZ values is computed by imagining a full and equally distributed reflective surface, meaning where the reflectance factor is always 1. Conversion of RSPD patterns into XYZ values is computed by imagining a fully equal light source, where the emission factor is always 1.




source: standard illuminant E
working space: CIE RGB (E)

source: standard illuminant E
working space: sRGB (D50)

Figure 35. Screenshot displaying per interval SPD results under full illumination, but outputted to RGB using different color working-space matrices. *Graphic Source: R. Campbell Farish*

| Standard illuminants | |
|---|---|
| standard illuminant A | incandescent |
| standard illuminant B | sunlight (outdated) |
| standard illuminant C | sunlight (outdated) |
| standard illuminant D | sunlight |
| standard illuminant F | florescent |

Figure 36. Summary of standard illuminants.

those from standard illuminants D50 and D65 being the most commonly used[9, 292].

*Figure 37.* and *Figure 38.* display this per interval SPD material texture under a range of standard illuminants[2]. When objects are illuminated by a source of equal spectrum (standard illuminant E) the two rendering methods produce identical results. As the source spectrum become more varied and unique in their strengths along the wavelength range, there are more varied color outputs between the two methods. Spectral data is expressing a uniqueness on a per wavelength basis and for materials lit by a theoretically equal source, the per-wave descriptor is not necessary, only a single variable is needed to express this. In equal-spectrum lighting scenarios, there is no relevant source-material interaction taking place in order to justify the extra computations of using spectral rendering.

*Figure 37.* and *Figure 38.* represent a light intensity of 50 in this model: $I_{source} = 50$. Because the material RSPDs only reflect back one small range the source intensity must be increased in order to brighten the results. This is illustrated in the top image of *Figure 39.*

Some singular wavelength intervals require a higher intensity strength for a viewer to clearly recognize its chromatic value. Therefore to explore results with a

[2]see *Section 1: Photon Emission.*

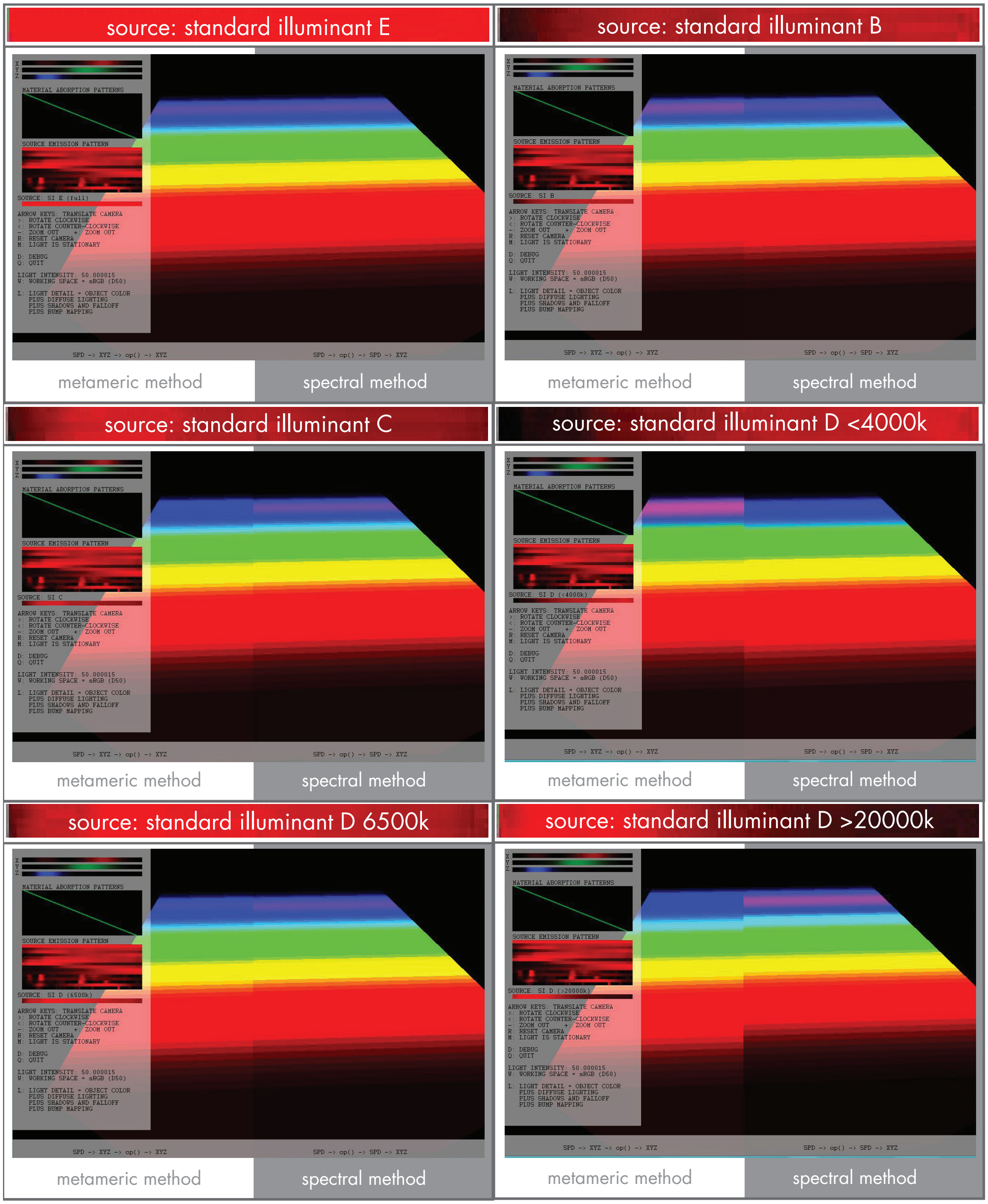



Figure 37. Renderings of material SPDs of a singular wavelength at full intensity under various illumination sources. *Graphic Source: R. Campbell Farish*

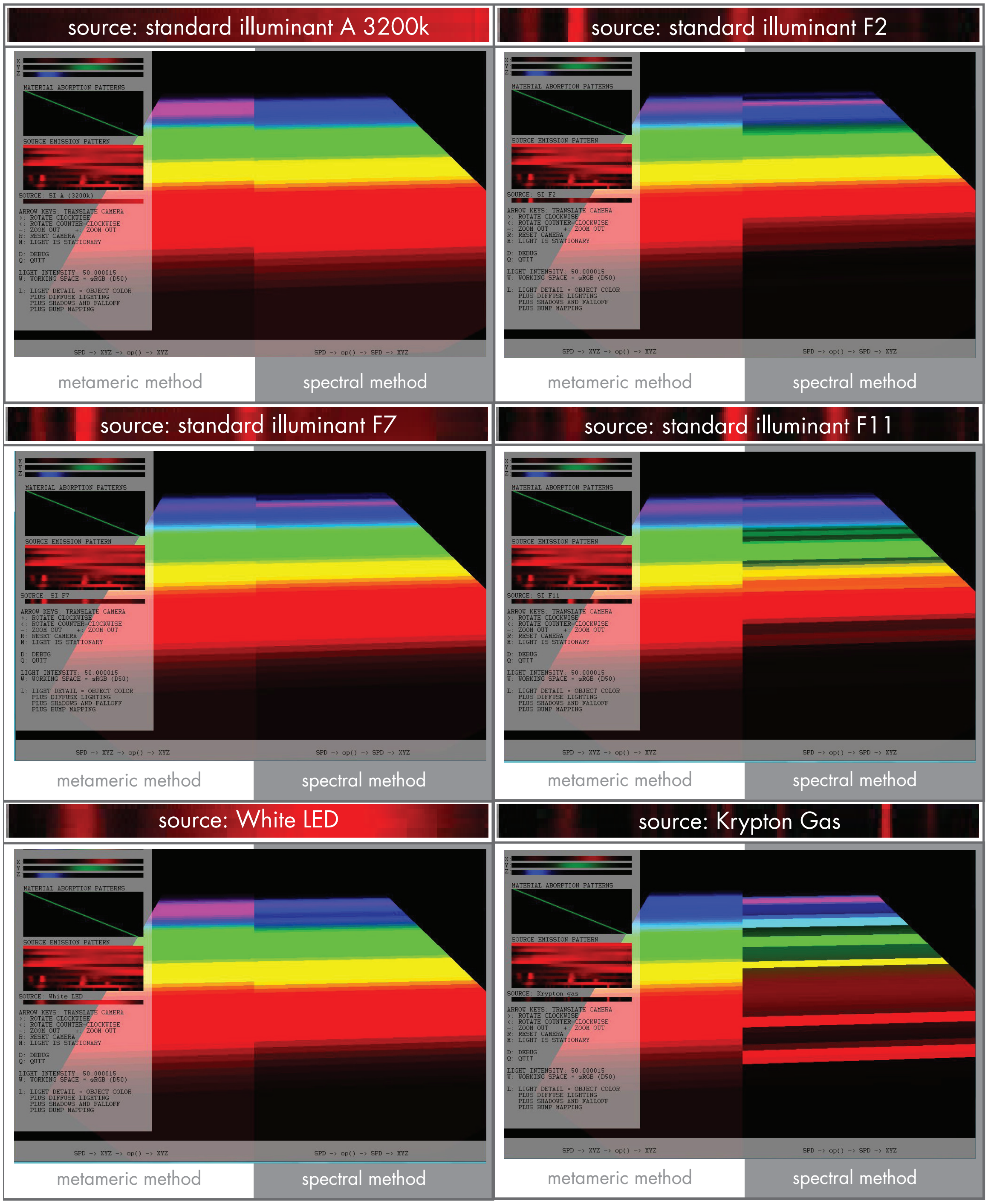
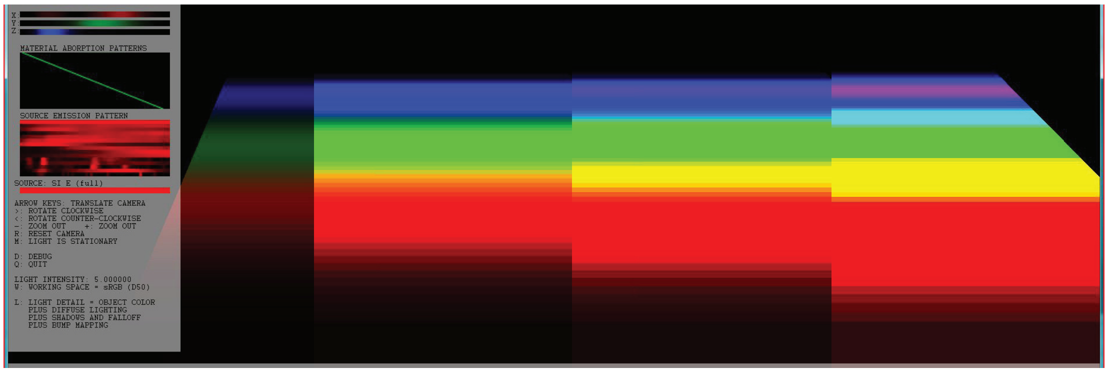
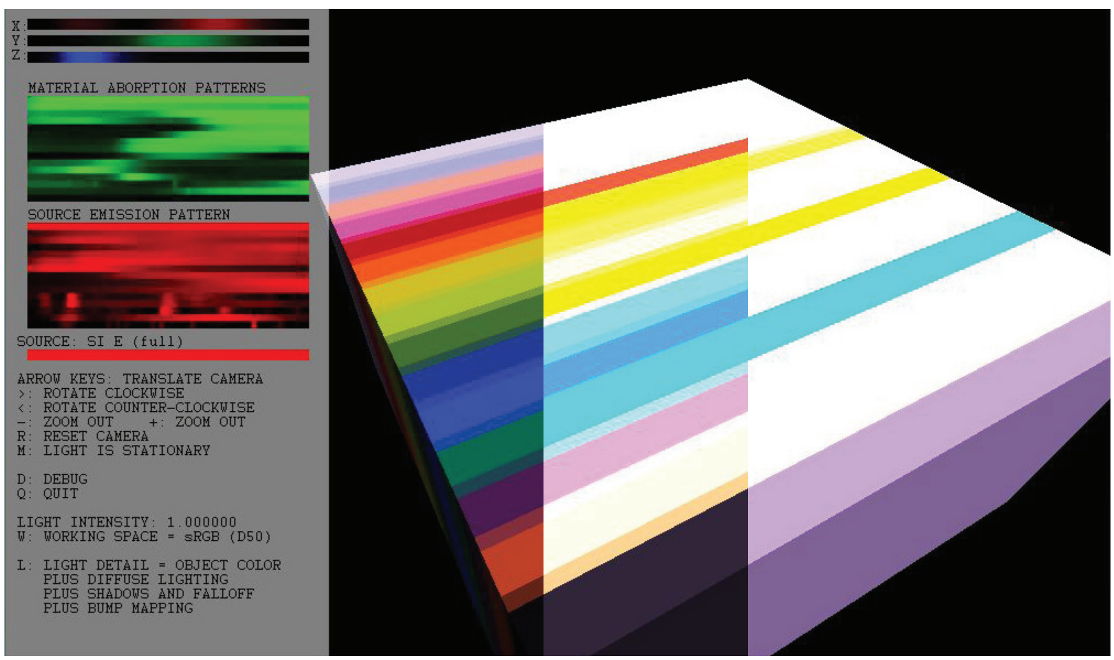



Figure 38. Renderings of material SPDs of a singular wavelength at full intensity under various illumination sources. *Graphic Source: R. Campbell Farish*




source strength increase of standard illuminant E
(theorhetical single wavelength reflection texture)




source strength increase of standard illuminant E
(crayon texture)

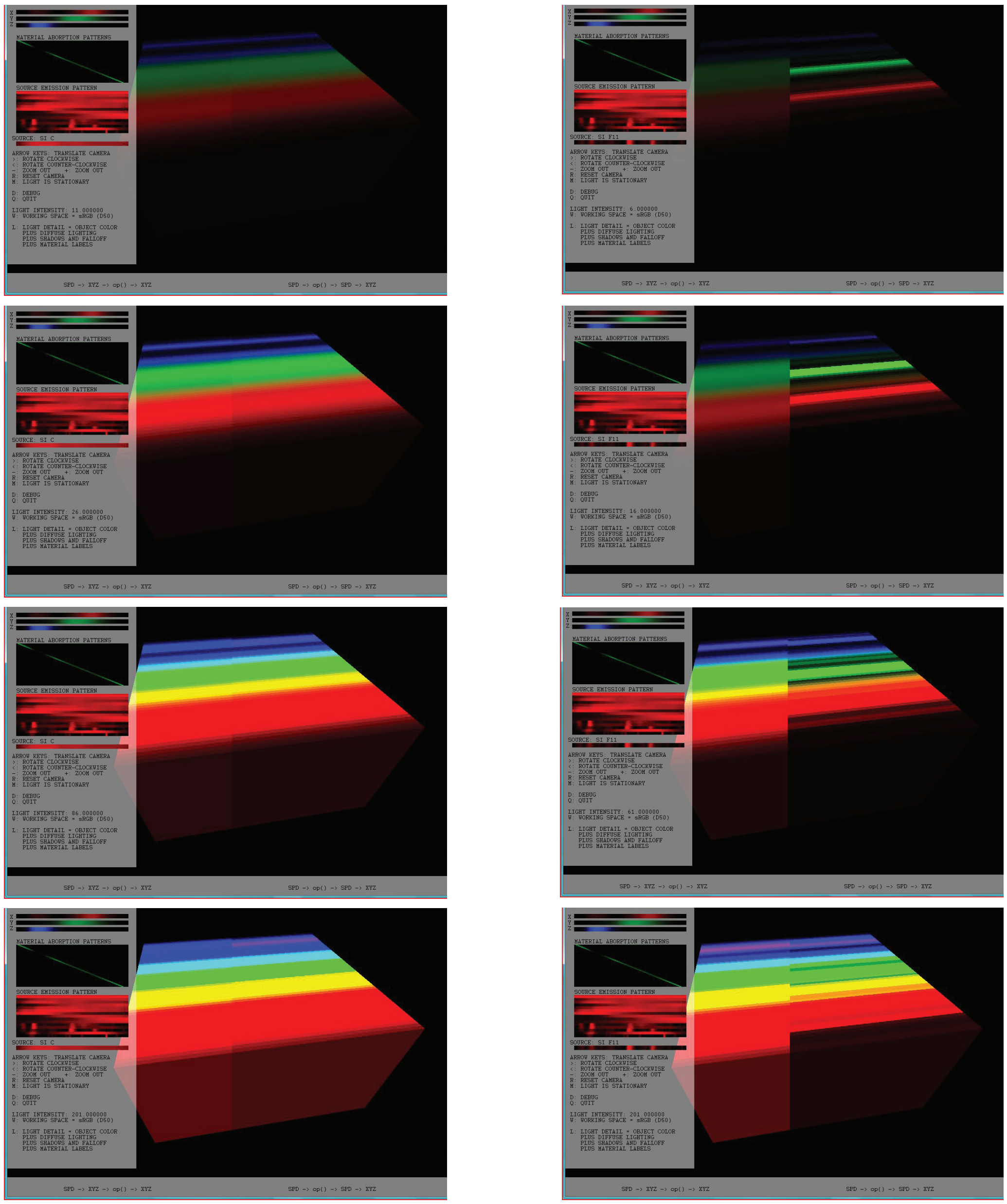
Figure 39. Screenshots displaying the results of an increase of source strength. *Graphic Source: R. Campbell Farish*

more evenly distributed intensity output a slightly different input SPD was used for *Figure 40.* In this input SPD file the pattern for reflectance is weighted so that intervals that need more intensity to strongly display their hue have a higher reflectance value.

The most drastic comparison results come from banded source ESPDs such as the fluorescent category and gas-based light emitters, such as Krypton. In these scenarios, the metameric half exhibits output similar to blurring the spectral results. This brilliantly illustrates the concept of a spectrum-based method capturing sharp details, and a metamerism-based method being more of an estimate when source-material interaction is involved.

The degree of banding in sources and their overall strength play a role. If banding sources have wavelength activity near what corresponds with humans cone cell stimulation, there is a larger chance for it to be sufficient to represent a full gamut. In fact, three banded sources outputting a wide array of color perceptions is the basis of screen outputs. The left column of *Figure 40.* illustrates how the F11 illuminant begins to render more and more of the gamut with increased emission strength.

Most materials are not going to feature just one interval of photon reflectivity and *Figure 41.* features a sample empirical material SPD texture pattern. The main purpose of this texture is to feature spots of varying strengths and weakness along the spectrum, much like an actual RSPD might have. *Figure 41.* illustrates that source strength and illuminant type still create very different color results, not only when compared to one another, but also between metameric and spectral rendering



source strength increase of standard illuminant C

source strength increase of standard illuminant F11

Figure 40. Screenshots of increasing the source strength of illuminants C and F11. *Graphic Source: R. Campbell Farish*

methods.

While banded SPD patterns can produce drastic results, other instances can also cause a metameric method to fail in correctly capturing the true colors in a physics simulation. For example, in the screenshot displaying standard illuminant D $> 20000k$ in *Figure 41.*, the metamer-based model renders resulting red hues more strongly red than the spectrum-based side. In this scenario, the illuminating source has very little red photon strength and such a red material should skew cooler in hue and darker in tone, which the spectral method represents very well. In the same figure we see the illuminant A $2800k$ fail to produce as strong of purples and blues on the spectral side versus on the metameric side. Once again the spectral side captures a more correct color output—considering the source has much less blue power.

*Figure 42.* and *Figure 43.* show this sample SPD texture under various illumination sources. They confirm the previous results: the more constant and equally distributed the source SPD is, the more similar the results from the two methods are. Sources including fluorescents, various gases, and even the White LED source really display the difference between methods.

In general there is a lot of variation in color output that is dependent upon illumination sources, no matter which method is being used. In *Figure 44.*, White LED illumination, for instance, is quite orange, especially when compared to standard illuminant D $> 20000k$ which is quite blue. In conclusion, not only does emission spectrum have a lot to do with a material's perceived color output, but as the SPD of that source strays from an equal distribution, the benefit from using spectral rendering

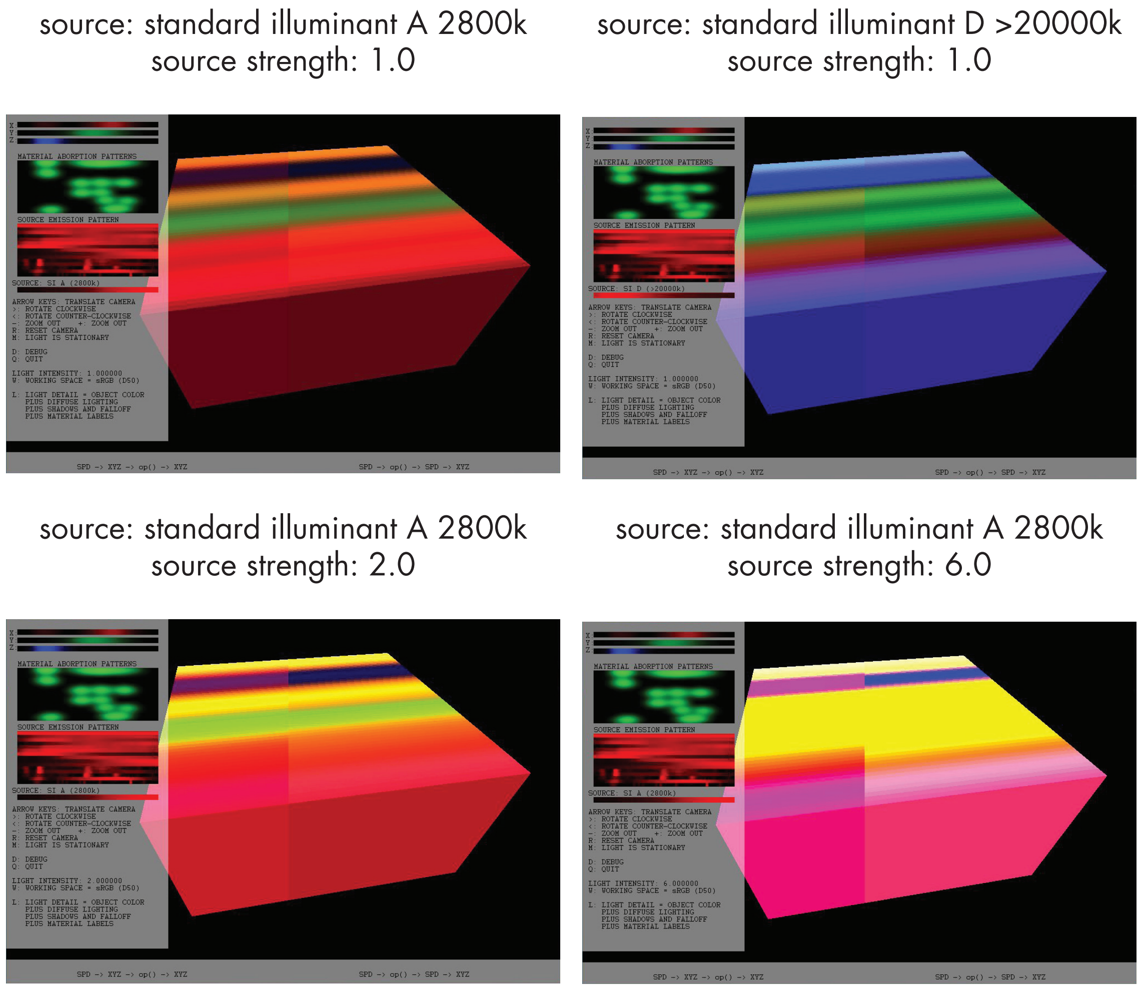



Figure 41. Screenshots of a sample texture of varying strengths and under different illuminants. *Graphic Source: R. Campbell Farish*

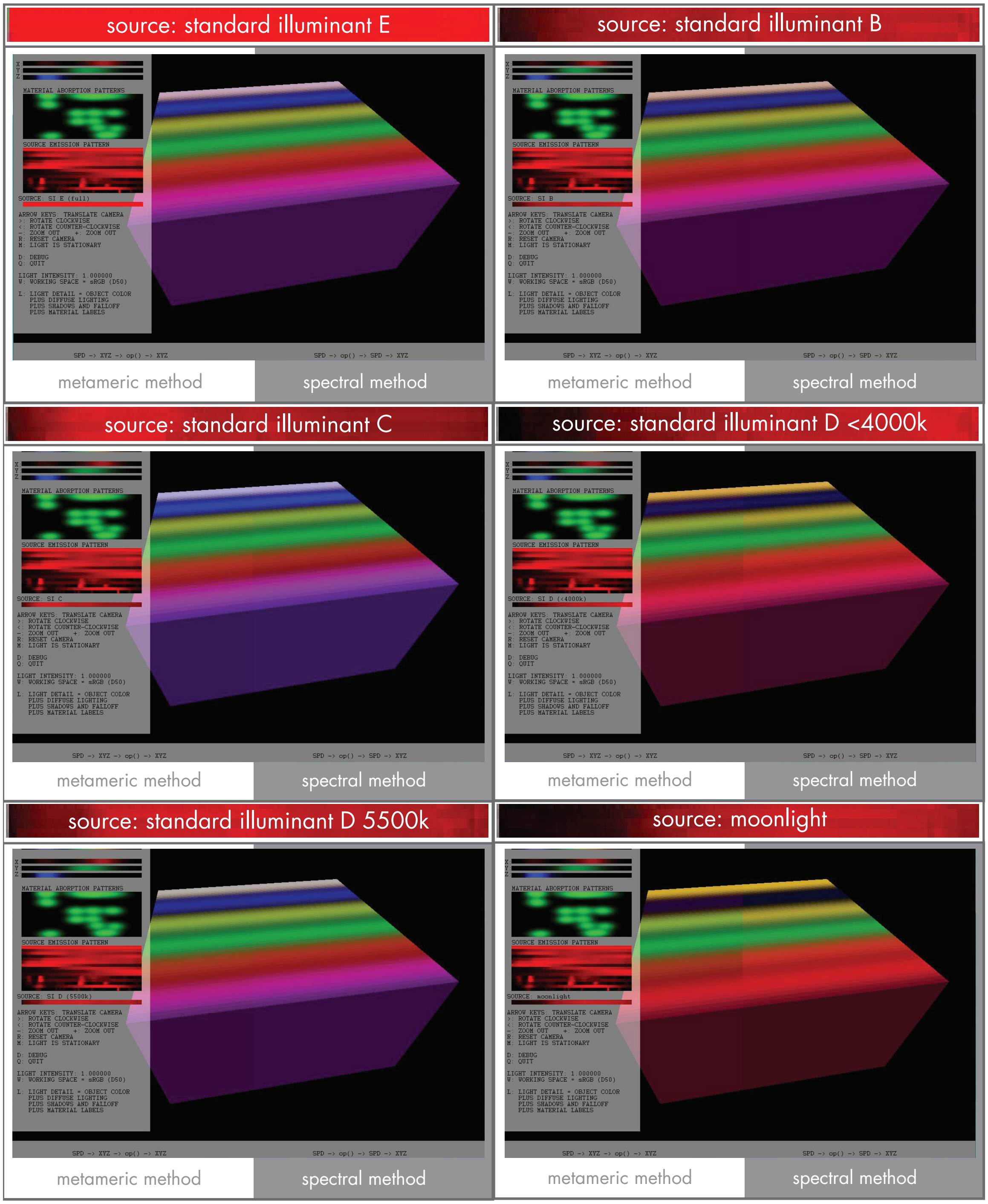



Figure 42. Screenshots of a sample texture under different illuminants. *Graphic Source: R. Campbell Farish*

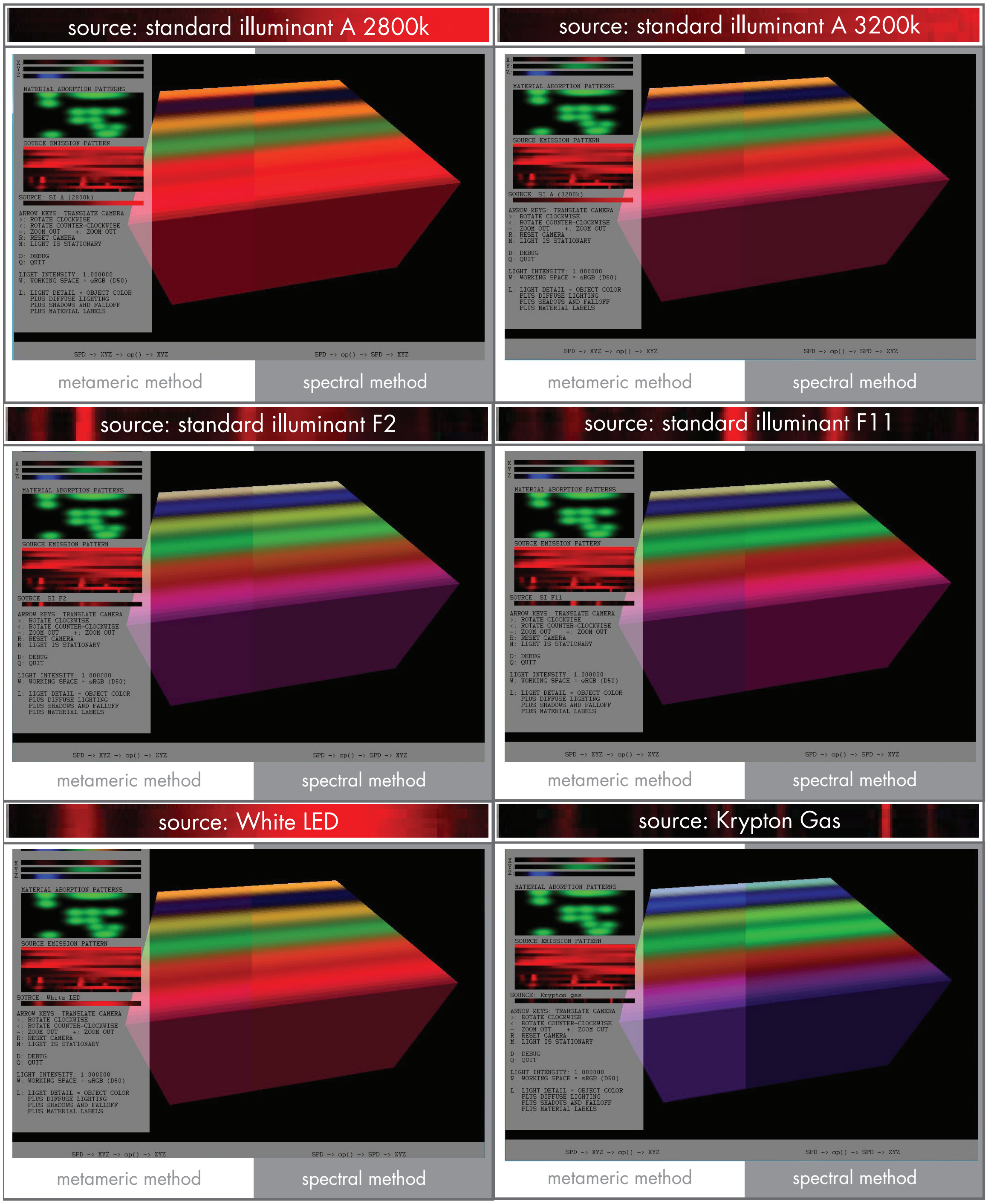



Figure 43. Screenshots of a sample texture under different illuminants. *Graphic Source: R. Campbell Farish*

increases as well.

## 2. Case Study: Spectrum-Based Rendering Using the Spectral Data from Crayons

The main intention of gaining greater control over color by utilizing a spectral method is to mimic real-world physics, therefore consider some example collected spectral data.

In most simulated environments an object or material is assigned a constant metamer value. Such a procedure goes against the logic of what a physics simulation is attempting to reproduce—this paper has reiterated many times that materials output a range of color perceptions based upon their illuminating source. A material's color output is dynamic, not static. However, programmers must be able to assign some definitive data to the object they are trying to mimic and the work-around has been to use RGB values. The purpose of the proposed spectral method is to do away with the notion of assigning metamer values to objects and assign them RSPDs instead—however this comes with complications.

Data on light source SPD is much more straightforward and standard than reflection data; spectral information for emitters is readily available and plentiful. Spectral measurements of common reflectance data is harder to find, perhaps because of the many permutations of materials. Also there is an added step in measuring reflectance, while emission SPDs are measured directly from their output, reflectance RSPDs would have to be calculated while illuminated by a source with a *completely*

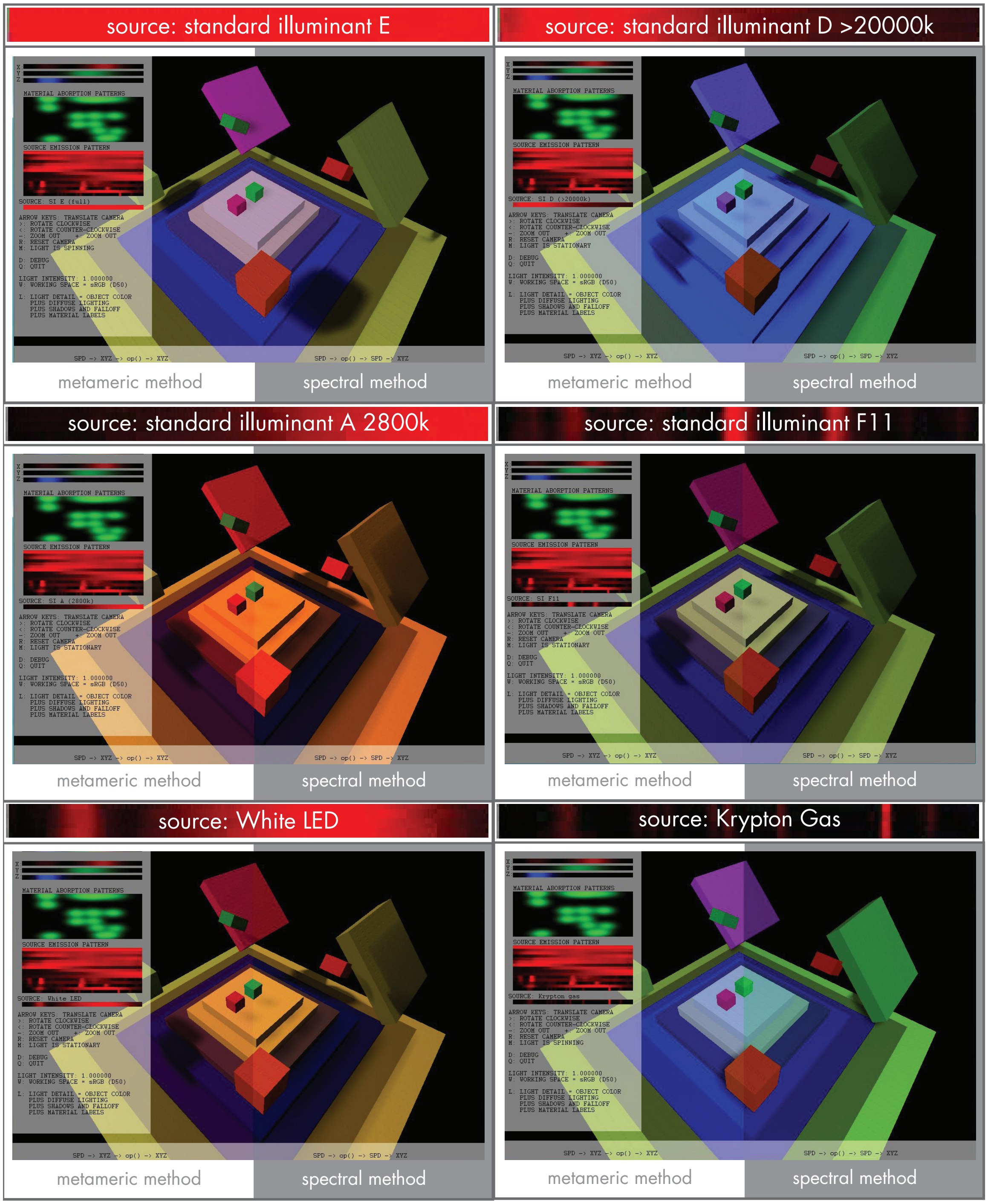



Figure 44. Screenshots of a sample texture under different illuminants. *Graphic Source: R. Campbell Farish*

equal spectrum.

*Figure 45.* illustrates an estimation of source ESPDs based on a variety of reported emitters referenced throughout this document[3]. These serve as the real world examples of light emission—note they are also the same set of sources from the previous example. In order to create this ESPD data, spectral graphs have been truncated into the proper range (385nm - 705nm) and scaled to fit on a square texture of 64 pixels. Then these spectral graphs are placed on a linear gradient from black to white. Finally to create a row of values representing a SPD the first background value (from black to white) that is above the highest point in each column of the graph is chosen to represent the intensity value.

Reflection SPDs that a programmer might need for a simulation, like concrete or grass, have a more complicated calculation process involved than the spectrum of an incandescent bulb. Therefore RSPD data is simply more difficult for the average person to locate and lacks the user-friendly system of illuminations standards. However data does exist such as, *Figure 47.*, calculated by photographer Mark Meyer, which displays calculations for spectral reflectance of a box of crayons. This is incredibly intriguing sample data as it fits the bill of real-world spectral sample data that displays color variations.

From the various reported crayon SPDs several were chosen and illustrated in *Figure 48.* and converted into RSPD texture data for the algorithm[4]. *Figure 50.* and

[3] *Figure 46.* lists the illumination source SPDs, in order, used in the sample program to compile test results for comparison of the methods.

[4] *Figure 49.* lists the material RSPDs, in row order, used in the sample program to compile test results for comparison of the methods.

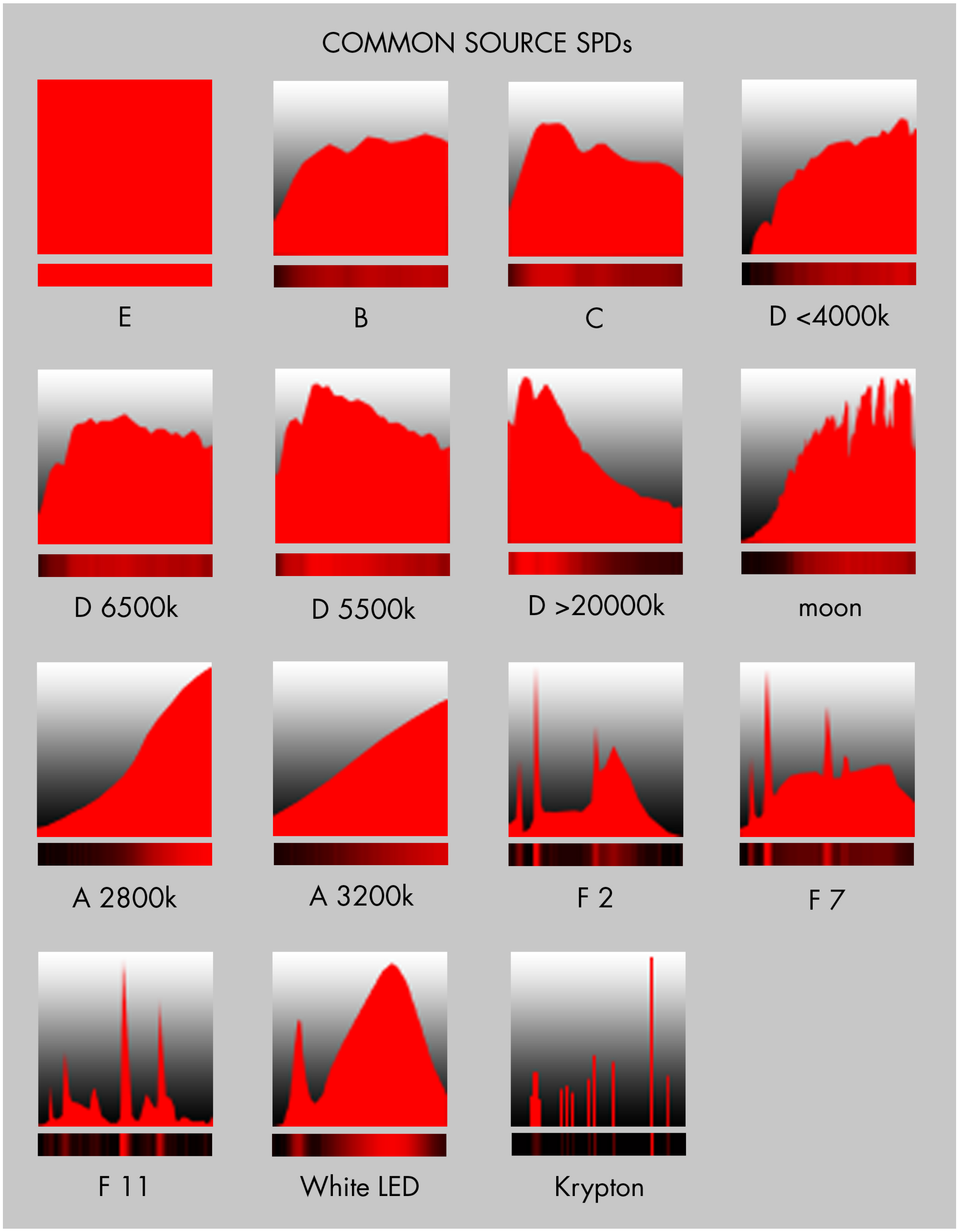



Figure 45. Estimation of reported ESPDs of standard illuminants and popular light sources, and how they translate into textures for algorithm. *Graphic Source: R. Campbell Farish*

| |
|---|
| Standard Illuminant E |
| Standard Illuminant B |
| Standard Illuminant C |
| Standard Illuminant D $< 4000k$ |
| Standard Illuminant D $5500k$ |
| Standard Illuminant D $6500k$ |
| Standard Illuminant D $> 20000k$ |
| moonlight |
| Standard Illuminant A $2800k$ |
| Standard Illuminant A $3200k$ |
| Standard Illuminant F2 |
| Standard Illuminant F7 |
| Standard Illuminant F11 |
| White LED |
| Krypton gas |

Figure 46. Source SPDs used in sample program.

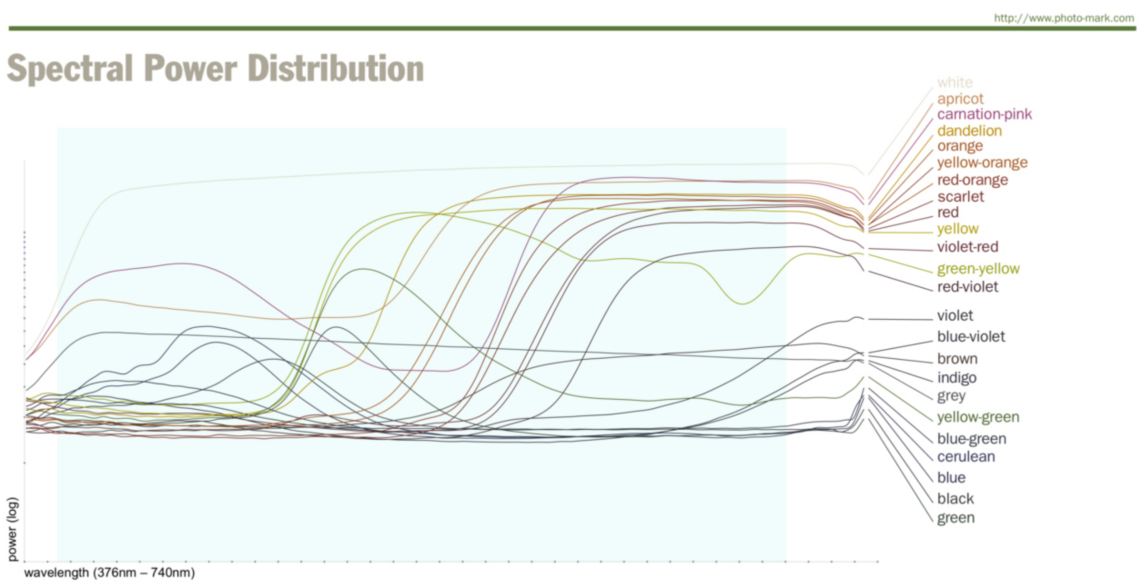



Figure 47. Reported reflectance SPD values of colored crayons *source: Mark Meyer Photography, www.photo-mark.com*

*Figure 51.* show the results rendering in the form of the gradient cube, while *Figure 52.* and *Figure 53.* display the results rendered as a scene of objects with additional lighting effects.

The crayon rendering example confirms the results from empirical data; the more source patterns (ESPDs) diverge from equal or smooth distribution the more differences are apparent. The more the material patterns (RSPDs) diverge from equal or smooth distribution the more the two methods produce noticeably different color results. The crayon RSPDs cover more of the spectrum than the empirical example with only one wavelength band. The more that a reflection SPD is distributed across the spectrum the less banded and more general it is, which creates less of a difference between methods—the same is true for ESPDs. When RSPDs or ESPDs are banded or heavily biased they become especially unique in their wavelength composition, therefore a spectral method is going to produce results that are more closely related to the physical world, which may be different from the metameric model's estimation.

The overall color output of the scene varies greatly based on illumination source and the metamerism-based model does capture the overall effect of objects under specific illumination sources; the spectral model however is more correct. The ESPD patterns that cause the greatest difference in color output are D $> 20000k$, A $3200k$, and F2—the first two of which greatly skew to one end of the spectrum and F2 is the most severely banded of the fluorescent examples. Surprisingly the illumination from Krypton gas provides pretty similar results between the two methods despite how banded it is, and this is most likely due to its bands lining up with intervals of

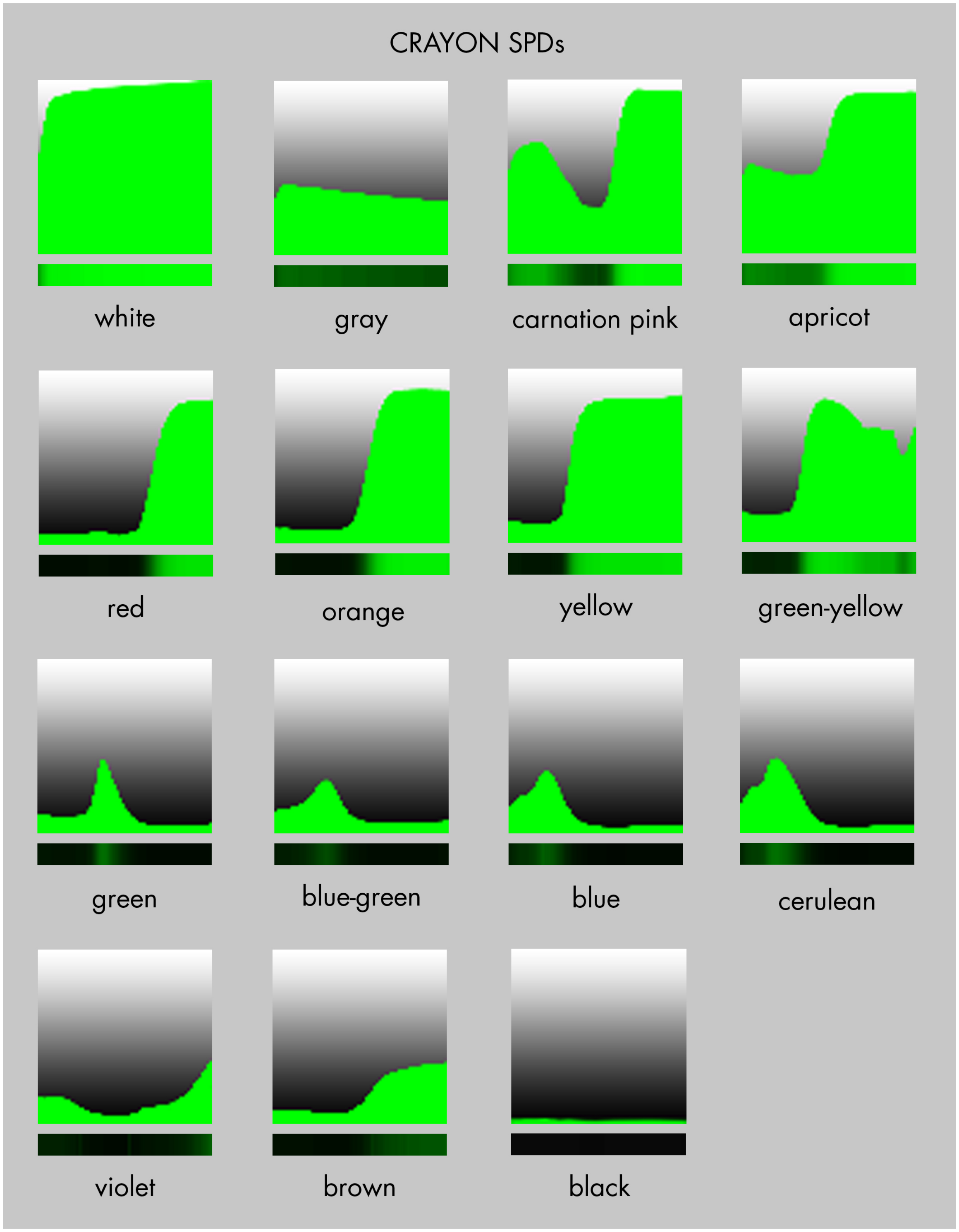



Figure 48. Spectral reflectance values of colored crayons converted into textures for algorithm. *Graphic Source: R. Campbell Farish*

| |
|---|
| White |
| Gray |
| Apricot |
| Carnation Pink |
| Red |
| Orange |
| Yellow |
| Green-Yellow |
| Green |
| Blue-Green |
| Blue |
| Cerulean |
| Violet |
| Brown |
| Black |

Figure 49. Material RSPDs used in sample program.

high tristimulus excitement.

*Figure 54.* is another example of how the RGB working color space matrix can influence color output. The white crayon—the top flat cube in the figure—ranges from yellowish, to orangish, to greenish depending on the working space. This is due to the fact that using an incompatible matrix to render a scene will produce these tinged results. Notice this matrix keeps a pretty consistent amount of difference between spectral and metameric outputs; colors that are more different than one another tend to continue to be more different, even through changes in working space. For instance, the gray flat cube stays similar between methods while the apricot one below it consistently produces different results.

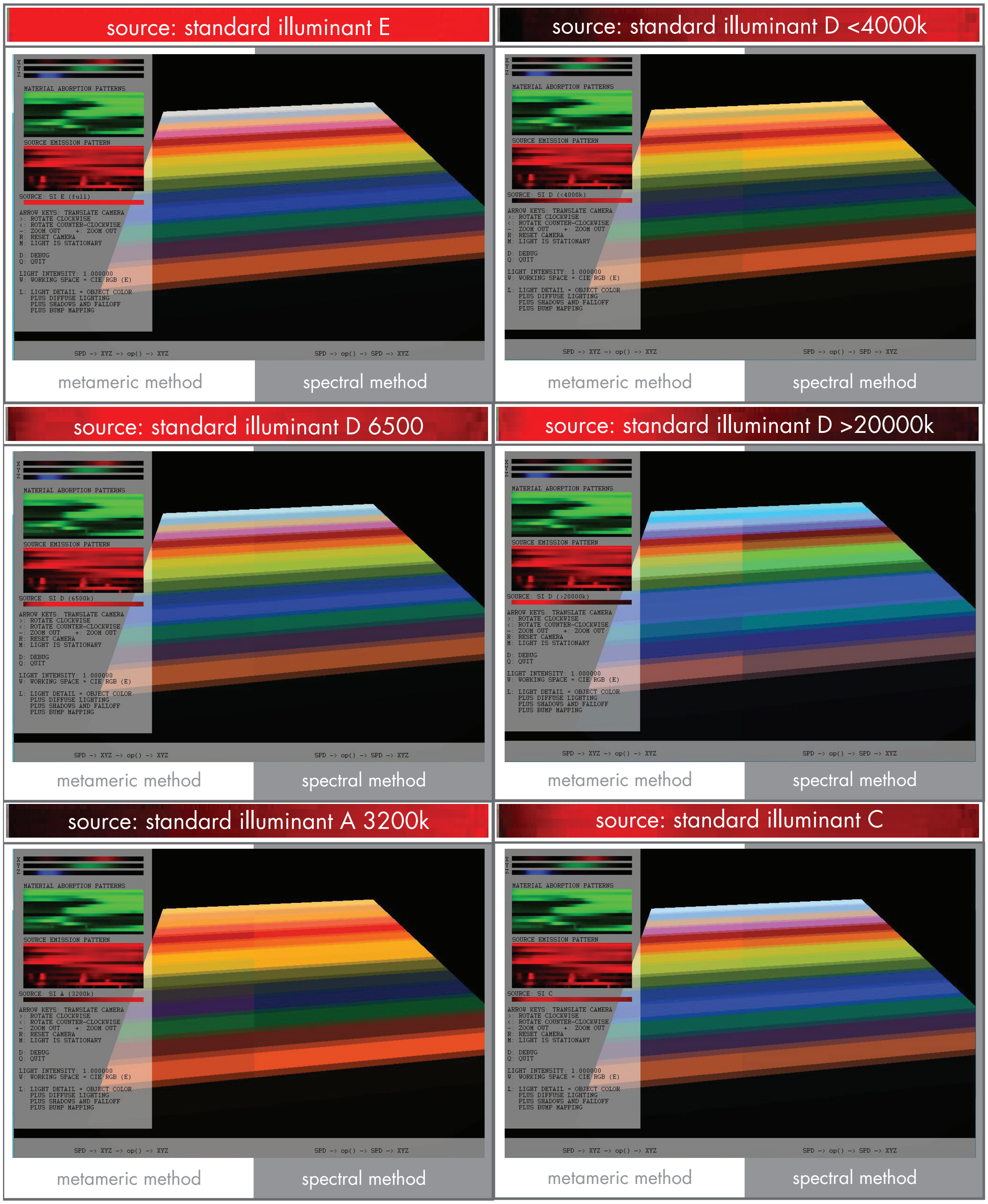



Figure 50. Screenshot of crayons under various illumination. *Graphic Source: R. Campbell Farish*

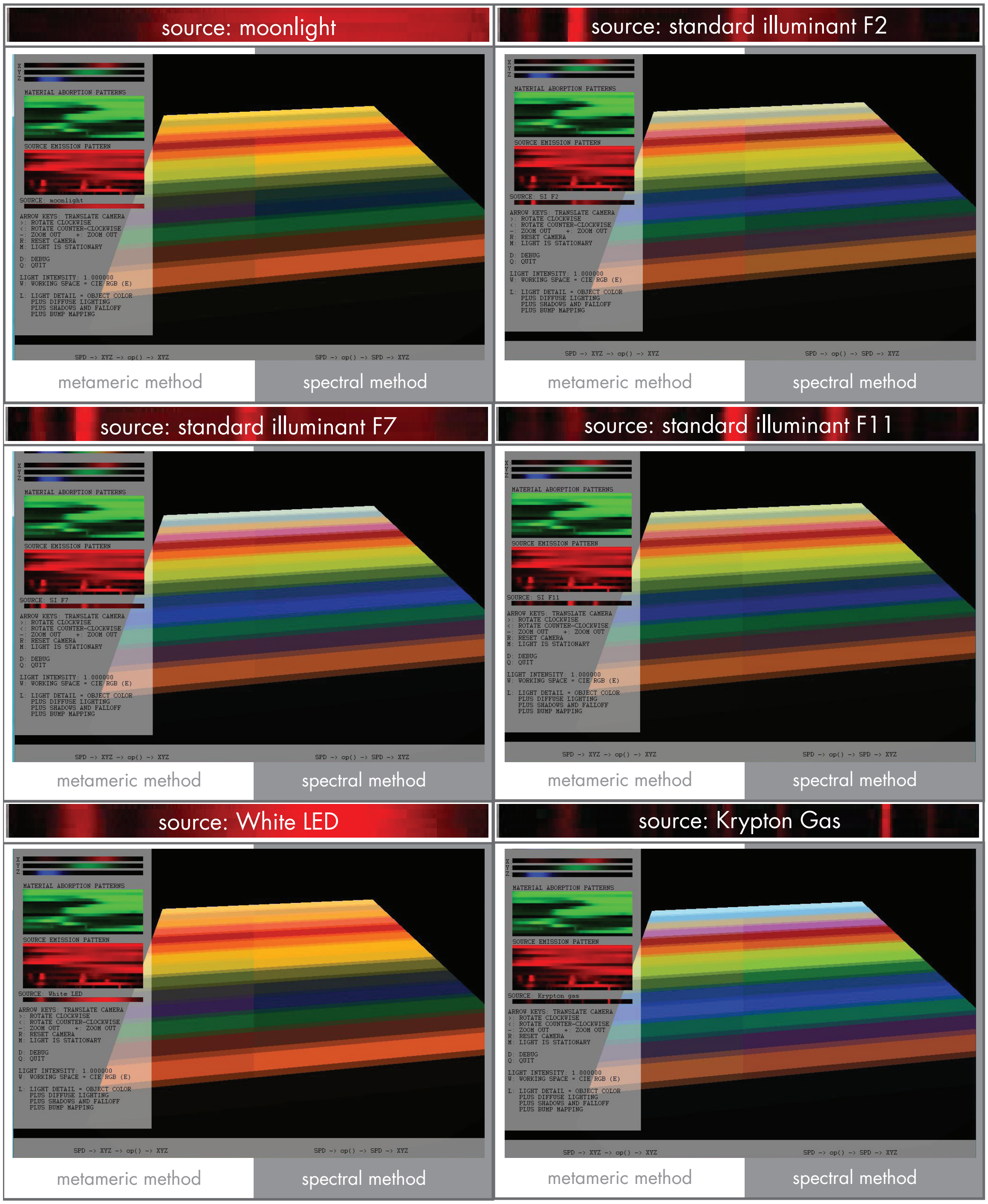



Figure 51. Screenshot of crayons under various illumination. *Graphic Source: R. Campbell Farish*

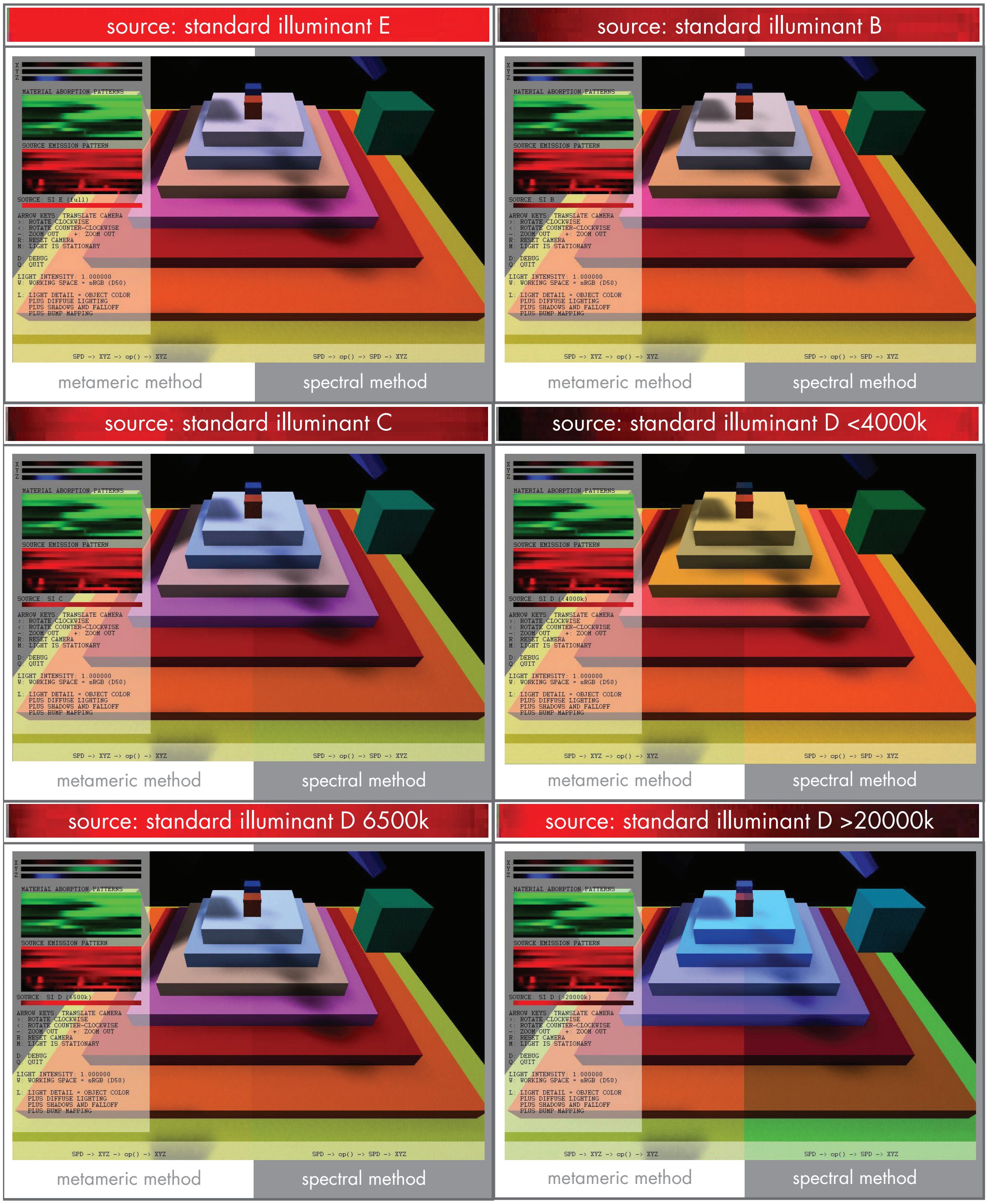



Figure 52. Screenshot of crayons under various illumination. *Graphic Source: R. Campbell Farish*

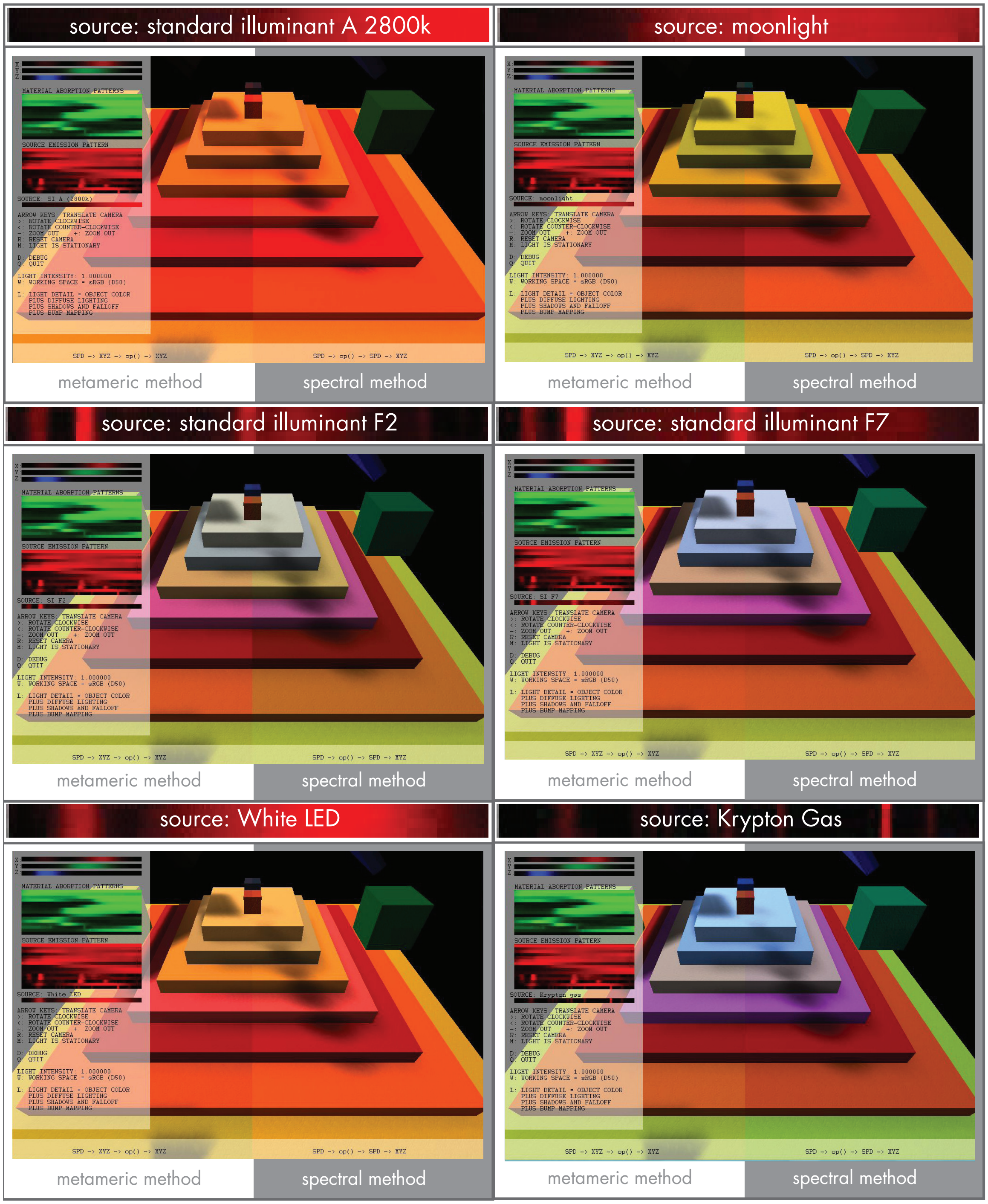



Figure 53. Screenshot of crayons under various illumination. *Graphic Source: R. Campbell Farish*

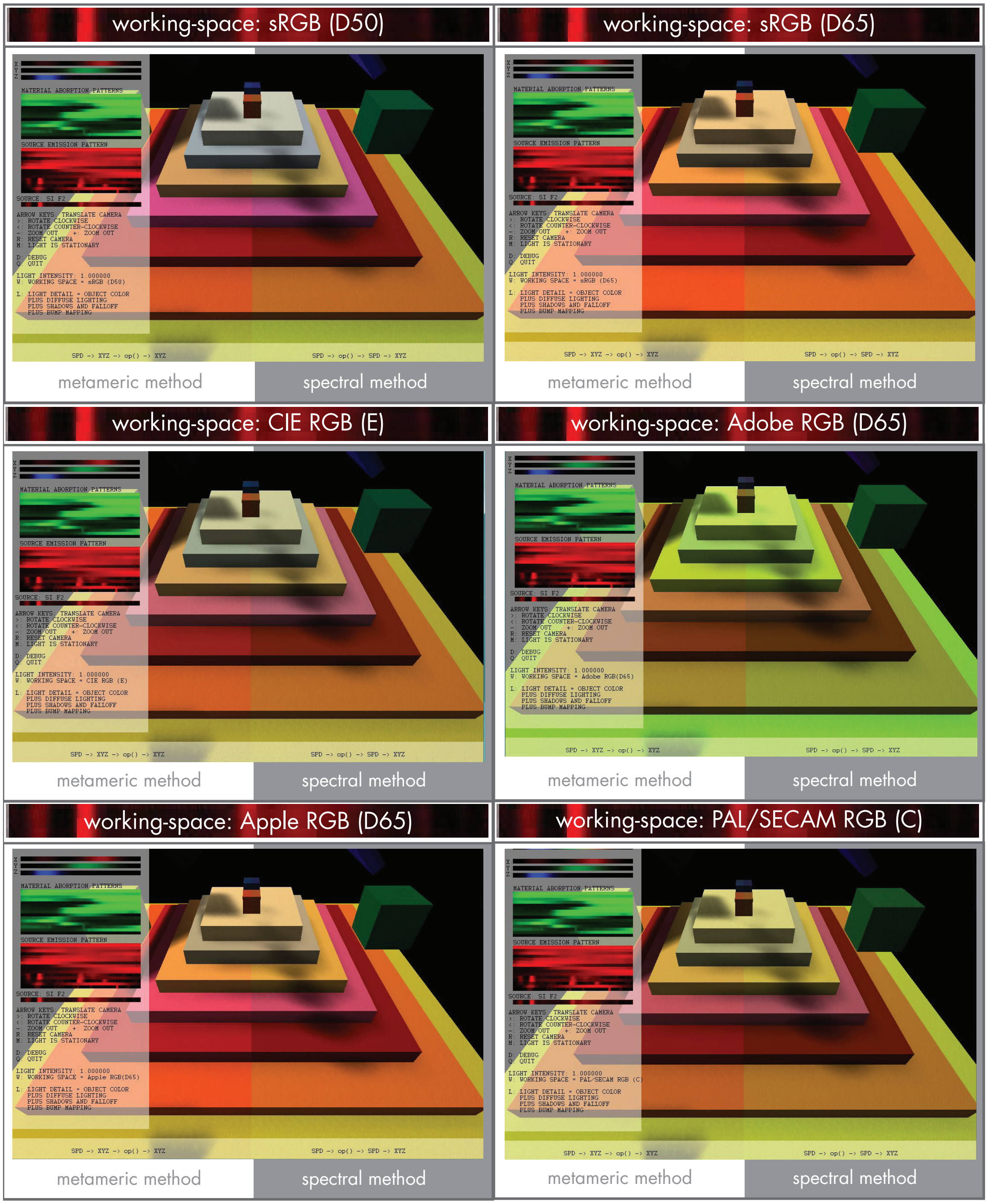



Figure 54. Screenshots of crayons rendering with various color working-space matrices. *Graphic Source: R. Campbell Farish*

## 3. Merits of Spectral Rendering

Both methods can simulate source and material color interaction, but a spectrum-based method is simply more accurate in terms of the physical world being simulated. Both methods are useful for rendering a scene that is bathed in a light source of a dominate hue, however the subtle addition to realism in color interaction may help aid the viewer in convincing immersion. A spectral method is capable of producing precise calculations that a metameric model cannot. A metameric model is estimating spectral data and therefore may produce physically based results as well, but also may not.

Imagine that one wanted to render a gradient between two colored materials—for example paints with similar pigment size. During interpolation there are several possible paths between colors when color is described as a metamer—there are also several different metameric models of which to use for interpolation. One could use weighted RGB values, or determine how HSV model's values should progress from one color to the other; both methods would be estimations of gradation. When using RSPD values however a straightforward linear average of the two per wavelength interval, could be used to produce an effect with one true output.

This spectral algorithm takes place in the shader which allows for the use of spectral rendering on only applicable objects. An environment where the light source is static would be a perfect place *not* to use spectral rendering as it would serve little purpose; color values could be pre-computed. The best use of this model is a scenario where light changes drastically, for instance outdoors. Sunlight is a singular strong light source that exhibits varying ESPD patterns depending on time of day, weather, season, dust, etc. Outdoor scenes can look very different and realistic rendering would enhance a simulation's feeling of immersion.

Materials of desaturated colors, like grays and browns, may also see a benefit from a spectral model. Desaturated colors begin to excite cones equally which can occur with a variety of SPDs. A highly saturated color is, by definition, a more specific area of the spectrum and therefore there is a smaller number of SPD permutations that can excite colors high in saturation versus desaturated colors. It is also within the ranges of these desaturated colors that slight changes in dominant hue may be more apparent; there are many shades of brown and gray. Because of this, an outdoor scene could see a benefit from the spectral model because nature features lots of grays and browns, as well as greens—the hue in which humans perceive the most variety. Outdoor scenes also features a dynamic light source: sunlight. The outdoors exhibits a range of subtle color changes and when color precision is important a spectral model is superior to a metameric one.

An instance where spectral rendering would not be as useful is when an object is likely to stay under a constant illumination pattern. In order for real-time spectral rendering to be useful the lighting must change, otherwise a programmer could pre-compute color values—still based on their spectrum—but not in real-time. For example imagine a game with indoor and outdoor spaces. The objects in the indoor spaces are more likely to be lit by one constant light source scenario than the outdoor objects which exhibit a range of source SPDs because sunlight is so varied. This makes scenarios like an indoor scene perhaps less of a candidate for spectral real-time rendering.

In a game scenario an object that is moving through different lighting conditions is a perfect candidate for spectral rendering. One such object that is almost guaranteed to encounter different illumination patterns is the avatar which is likely to move through different spaces in the simulation. Therefore character rendering would be a good place to use a spectral model.

## 4. Issues Involving Spectral Rendering

The biggest problem surrounding spectral rendering would be creating the standardized database upon which for it to run. A database of *emission* data would not be that difficult—as a matter of fact one already exists: the standard illuminants. However, the number of permutations of dyes, pigments, and materials make reflection patterns elusive. For instance, a plastic object comes in various colors, and one must contend with the overall attributes of the material but also the various pigments used to create the colors. In order for this new spectral method to really become standard, RSPDs must be collected, generalized, and otherwise turned useful.

The second largest problem involving spectral rendering is the increase in computations when performing operations. The computational time is increased by a factor of the number of wavelength intervals used in the spectral model. For example, what would take 3 calculations in a metameric model—one for each component—would be scaled by the number of intervals—64 for the sample program's texture. This means what would take 3 calculations now takes 192 calculations.

Such a jump in calculations per pixel per frame is considerable, however a more physically accurate answer can be obtained. The assumption of the future of computing has to be that computational power will continue to grow and the increase in computations from a spectral method will be a minuscule task for hardware. Until the time comes where such a computational jump is of no importance, it is up to the programmer and designer to weigh the benefits of spectral color output to processing cost.

An issue that involves both spectral and metameric rendering is choosing the perfect XYZ-to-RGB matrix. If this were to be applied to an actual application one would need the closest matrix to the final output conditions with very little conversion in between. For instance, the screen shots in this document are merely illustrative examples as they have gone through several conversions of color spaces on their way to the eyes of the current viewer reading this document.

In order to obtain mainstream use of a spectral model, spectral patterns would have to make sense to the user. An object's RSPD is determined by its chemical make-up, but asking designers to operate on such a scale could be confusing and too abstract. A system which broke up materials into their main compositions and then further subdivided them into other pigment options would be a good place to start. For instance, an artist using this model could choose to assign "wood" to an object and then pick from various wood types and stains; or an artist could assign a vinyl material to an object and then choose from a palate of standard dye SPDs.

Using this model with texturing is not as straight forward as with the RGB system in popular use today. It would be impractical to store a SPD for every pixel in a texture, however one could store a key used to access SPDs for each pixel in a texture. This involves not only the texture full of keys but the SPD input texture that would be organized by these said keys. It should be noted that one could easily add an intensity texture map to an object that is meant to be of the same material. For instance if one wanted to simulate a weave texture one could create a single channel bitmap representing the luminance differences of the texture and apply those during the spectral rendering process to the intensity of the light source.

## 5. Related Work

Many others have explored the world of simulating spectral data via the computer and attempting to form a more correct code for color.

Some earlier work in the field of digital color was done at Cornell University, which has an excellent reputation in the field of computer graphics. In 1980, Meyer and Greenberg began to think about the control over color representation in their paper *Perceptual Color Spaces for Computer Graphics*[28]. They were pushing for a uniform scale, specifically using the Munsell System.

This tradition at Cornell continued with future generations attempting to increase realism in digital rendering when they published their paper *A Framework for Realistic Image Synthesis*[17], 17 years later. Their scope was beyond color perception and spectral data but they took it into account in various ways in their lighting models. They even measured the spectral distribution of several sources.

The study of photography has been of interest for longer than display screens and when film and photography tools became commonly digital, mathematical color manipulation increased in popularity. Color editing and manipulation of images became as simple as the click of a button. And just as color systems have always been designed around their specific uses, color standards began to expand for digital use. However soon the limitations of metameric models for digital simulations became apparent, and papers like *Spectral-Based Illumination Estimation and Color Correction*[24] in 1998 began to look towards light's spectral make-up to address and fix some of these color ambiguities. However, at this time, research was focused on still images without caring about rendering time, the idea of real-time spectral processing would take many leaps in computing power before it would become feasible.

G.M. Johnson and M.D. Fairchild have done much research into simulating spectral color in computers and their 1999 paper, *Full-Spectral Color Calculations in Realistic Image Synthesis*[21], discusses the issues surrounding spectral versus metameric color operations. They even outline a process for coding such a simulation. But while they bring up the issue of run-time with spectral computations, their answer does not directly address it.

The Department of Computer Science at Purdue University has also shown interest in spectral rendering of color. In 2001, *A Spectrally Based Framework for Realistic Image Synthesis*[40] was published. Outlining a rendering pipeline similar to this paper that considers spectral data—but it does not mention a real-time approach.

An interesting sub-field of study has been turning RGB into spectral data. If spectral data becomes the future, such a thing would certainly be useful. These studies are mostly for use in the manufacturing of camera technology, such as the case of a 1994 paper, *Natural Metamers*[12]. Popular names in the field such as Glassner, Sun, and Shirley have all attempted such algorithms.

As computer power increases, advances in color have been possible as well. *Modeling Wavelength-Dependent BRDFs as Factored Tensors for Real-time Spectral Rendering*[37] is a fairly recent study that tries to achieve better color correctness and does so with an emphasis on real-time rendering. While its algorithm is different from the one proposed in this paper, it also uses a texture channel to input the CIE XYZ functions. BRDF stands for *bidirectional reflectance distribution function* and is used to calculate photon direction in light simulations. The paper's addition of "Wavelength-Dependent" to the BRDF is interesting because it is another example of looking at light's spectral make-up in simulation programming.

*Standard RGB Color Spaces*[41] provides hard data on RGB primaries for several color spaces. It also outlines a similar system of color transformations that happen from source space, to an intermediary model, and then to an output space. That pipeline is similar to this spectral algorithm, however that paper was assuming source input from a camera rather than color input from a computer simulation. In this algorithm the spectral data turns into the intermediary XYZ model which can then be calibrated for whatever output model is necessary—most likely a color space of RGB.

# 6. Further Study

Because a spectral model is more physically based and therefore more photorealistic, almost any color operations would benefit from computations using spectral data. Color science is a broad field and there are many lighting phenomena involving color that one could simulate. Light phenomena such as dispersion are inherently based on wavelength values of light, therefore a spectral model would provide more accurate calculations of those simulations. Rayleigh Scattering, the basis phenomenon behind the color perception of daytime sky and sunsets, is driven by unique wavelength behavior and would benefit from rendering with spectral accuracy.

Applying this model to more complicated lighting environments would be an excellent way to further determine how applicable and useful this change in color defining method would be to the future of gaming. More data needs to be compiled and formatted to create a meaningful photorealistic scene, but the results would certainly make a strong case either for the future of spectral rendering or for the tristimulus metamerism based approach currently in wide use.

Many objects are made of multiple materials and extending the proposed spectral model to handle such behavior would be very useful. To simulate this one could provide a texture look-up map attached to the object like a bitmap. This look-up texture could serve as a key to a row in a the SPD input texture where the spectral data for that material would actually reside.

Another interesting extension of a spectral system is photoluminescence. This is when light reflected back to the viewer from an object is different than the source in some way—meaning either in strength of current wavelengths or includes other wavelengths than the source emitter provides. To simulate this scenario an SPD assigned to an object could serve as an activation map for a second SPD on the actual color outputted. Therefore one could describe the pattern of photons needed to activate photoluminescence as well as the resulting emission pattern.

Functions could be applied to the SPD patterns to simulate color changing materials. This would be helpful for demonstrating things such as a decaying plant or skin while blushing.

Using a spectral model provides the flexibility to explore ranges outside the human gamut. Photon activity exists beyond what humans detect and the model could easily be adapted to cover any range of the electromagnetic spectrum. For example this model could be used to render what an animal sees based on their biological color system, all it would take is an edited wavelength sensitivity range and updated observer stimulation data for that species.

## 7. Broader Impact

For the real-time simulation industry, realism is paramount. And the current state of color technology in the digital age is an ever-changing and improving process. Hardware, however, fails to reach its potential without software that utilizes it well. The needs of programmers and artists have grown far beyond the days when 8-bit games were played on CRTs. As displays move closer to their asymptote of perfection, attention must be paid to the color models in the code and to their flexibility and whether the desired outputs are appropriate.

A spectral model would more accurately predict color perception under any circumstance, though currently it does so at what is considered a substantial cost. However as time goes on and technology improves, that cost becomes less substantial. If this spectral system were to be eventually adopted—because it is more complete—then optimized hardware would arise to handle its calculations, much in the way a GPU is optimized to handle rendering.

Adopting a spectral method would mean a shift in the way that programmers and artists interact with colors. It should be noted that the most common digital color model, RGB, is not the most user-friendly either; programmers and artists have to learn color model relationships. The main difference between metameric and spectral color conventions is that artists would start thinking of the materials or pigments responsible for a range of color outputs—independent of their illumination. Instead of one color perception relating to one value to the artist, one set of values now relates to a range of color possible perceptions depending on the lighting environment.

To make such a model more user friendly, a database of ESPDs and RSPDs would be ideal. Artists would then choose an "azure painted wood" as a box's texture and would not need to know much more about the technicalities of its SPD. Artists would also populate the world with "60 watt bulb from Brand X" as opposed to assigning lights a color value. The technology exists to calculate SPDs, i.e. a spectrometer, however a standardized system devised to categorize and catalogue all this information is needed before spectral rendering becomes the norm.

While the future of graphics can not be predicted, logic follows that the simplified description that metamers provide color operations will seem insufficient. And science will give rise to a more detailed spectral model. Hopefully this paper aids in the discussion of spectral rendering producing superior results and inspires further study.

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