Spectral Volume Rendering

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Abstract

Path tracing applications usually ignore the effects of wave optics and wavelength dependency. Depending on the scene, these effects may be more or less pronounced. The goal of this seminar is to implement spectral rendering support for volumetric path tracing in the VPT framework in order to reproduce some of the effects of wave optics.

1. Introduction

Light, is fundamentally composed of photons, which exhibit dual characteristics, behaving both as waves and particles. These photons are defined by specific wavelengths which are perceived by the human eye as distinct colors. Variations in wavelengths also lead to different behaviors among photons. Spectral rendering is a technique that considers the wavelength-specific behavior of photons, thereby enabling a more accurate and visually rich representation of scenes.

This report details the development of a spectral volume renderer, an enhancement designed for integration with the existing Volumetric Path Tracing Framework (VPT). The implementation aims to augment VPT's capabilities by incorporating a wavelength-dependent renderer, providing a more physically accurate depiction of volumetric data.

2. Foundations of Light and Color

To implement a realistic simulation of light in rendering, a basic understanding of ransformation of photon wavelengths into perceived colors is essential.

2.1. Spectrum of Light

Visible light is a segment of the broader electromagnetic spectrum. Human perception of light is limited to electromagnetic radiation with wavelengths ranging from approximately 380 nm (perceived as blue) to 700 nm (perceived as red). This range encompasses our whole visible spectrum, and radiometric measurements within this bandwidth are crucial for accurately simulating how light interacts with objects and how it is perceived as different colors.

Light sources are characterized by their Spectral Power Distribution (SPD), which describes the intensity of light they emit at different wavelengths. An example of an SPD is that of standard D65 daylight.. Figure 1 illustrates the SPD for D65 daylight, demonstrating the distribution of emitted light across the visible spectrum.

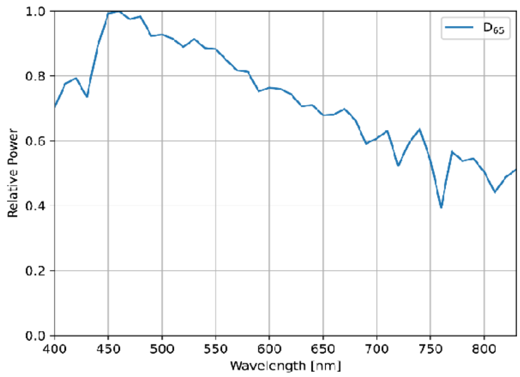

Figure 1: *D65 Daylight Spectral Power Distribution*

Similarly to light sources, the optical properties of materials are defined by spectral functions such as reflectance, absorption, and transmission. These functions describe how a material interacts with light across different wavelengths, influencing the material's appearance under various lighting conditions.

Color, as perceived by humans, is a psychological construct formed from our interpretation of light wavelengths ranging from 380 nm to 700 nm. This range represents the visible spectrum which hits our eyes' photoreceptors. These photoreceptors are specialized cells in the retina that respond to different ranges of wavelengths: photoreceptors sensitive to shorter wavelengths mainly perceive blue, those sensitive to middle wavelengths predominantly perceive green, and those sensitive to long wavelengths primarily perceive red.

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2.2. Color Spaces

Tri-stimulus response of the human eye forms the biological basis for the RGB (Red, Green, Blue) color model, which is utilized by various technologies, such as display screens. These devices use filters to compose light into red, green, and blue components. However, this model has limitations because it can only represent a subset of colors visible to the human eye, known as the RGB color space. The sRGB color space, a standard for RGB color models, also includes gamma correction to adjust for the non-linear response of human vision, allocating more bits to darker colors.

The XYZ color space was introduced by the International Commission on Illumination (CIE) as part of an effort to create a color model that more accurately reflects the full range of human color perception than the RGB model. Unlike RGB, which is based on three primary colors, XYZ is derived from a series of experiments that measured human visual response to different light wavelengths. This led to the creation of the XYZ color matching functions.

These functions are mathematical representations of the average human eye's color sensitivity across the visible spectrum and are pivotal in accurately transforming light wavelengths into perceived colors. Figure 2 illustrates these functions, which are also integral to our implementation of converting photon wavelengths to colors.

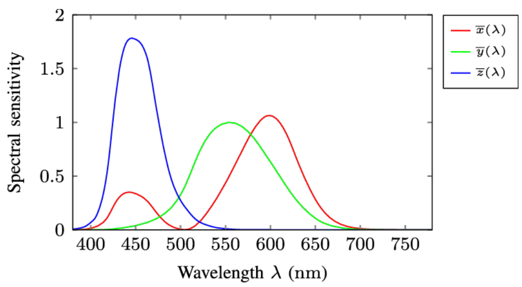

Figure 2: *CIE 1931 Color Matching Functions*

2.3. Phenomena of Light as a Spectrum

Understanding the phenomena associated with light as a spectrum is crucial, as we will simulate the following phenomena in our implementation.

Rayleigh Scattering

Rayleigh Scattering explains why the sky is blue and why sunsets often appear red. As sunlight passes through the Earth's atmosphere, light of shorter wavelengths (such as blue) scatters more widely in random directions, while longer wavelengths (such as red) scatter less and remain more concentrated in the direction of the light source. This differential scattering is due to the size of the atmospheric particles being smaller than the wavelength of visible light, affecting shorter wavelengths more significantly. During the day, the sky appears blue because blue light is scattered across the sky. At sunset, the sunlight must pass through a greater thickness of the atmosphere, scattering more blue light out of the direct path to our eyes and allowing more red light to reach us directly, hence the reddish hues.

Fluorescence

Fluorescence occurs when materials absorb light at one wavelength, usually ultraviolet, and emit light at a longer, visible wavelength. This process involves the absorption of light energy, which excites electrons to a higher energy state. When these electrons return to their original energy state, they emit photons at a longer wavelength than the light absorbed. This phenomenon is widely observed in various materials and biological entities, providing distinct visual effects that are particularly pronounced under UV light.

Metamerism

Metamerism is a phenomenon that arises from the complex interactions between the spectral properties of light and human visual perception. This effect occurs when two objects, each possessing distinct spectral reflectance characteristics, appear identical in color under certain SPD of the light source illuminating these objects. Despite their inherent differences in how they reflect light, the specific SPD can cause both objects to reflect wavelengths that are processed similarly by the human eye, resulting in the perception of the same color.

3. Implementation

This chapter details the integration of a spectral volume renderer within the VPT framework, using WebGL for rendering and Python scripts for visualizing and validating the correctness of our approach.

3.1. Path Tracing

Our renderer enhances the existing Monte-Carlo path tracing algorithm used in VPT by incorporating spectral characteristics into the simulation. Each photon in our renderer is assigned a specific wavelength,.

Building upon the Monte-Carlo path tracing foundation provided by VPT, our spectral renderer assigns each photon a wavelength attribute. This addition allows photons to exhibit wavelength-dependent behavior as they traverse the volume, such as varying degrees of absorption, reflection, and scattering, which are all defined with certain custom functions.

3.2. Wavelength Sampling Techniques

To effectively simulate the spectrum of visible light, which ranges from 380 nm to 700 nm, photons must be assigned wavelengths that reflect this range. We utilize a function named *sampleWavelength* for uniform sampling across this spectrum.

However, to mimic real-world light conditions more accurately, we consider the spectral power distribution (SPD) of natural daylight, specifically D65. *sampleWavelengthD65* employs rejection sampling to select wavelengths according to the D65 SPD, ensuring that the distribution of photon wavelengths accurately represents natural lighting conditions. Figure 3 illustrates the results of sampling the D65 spectral power distribution (SPD) using our Python script, which employs the same methodology as our renderer. The plot is generated from 10,000 samples. By comparing this figure with Figure 1, we can observe a close resemblance between the two.

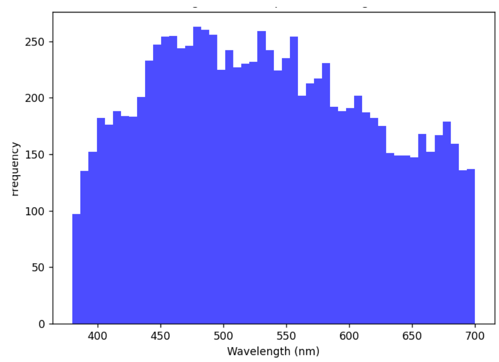

Figure 3: *D65 SPD Sampling Results from 10,000 samples*

In addition to visible light, it is crucial to consider ultraviolet (UV) photons for materials exhibiting fluorescence. These materials absorb UV light and re-emit it at longer, visible wavelengths. To simulate this, *sampleWavelengthUV* function extends the wavelength sampling below 380 nm to include UV wavelengths, crucial for rendering fluorescent effects.

It is important to note that directly sampling from a single SPD corresponds to simulating just one light source. To facilitate the simulation of multiple light sources, we propose aggregating the SPDs of all relevant light sources into a composite SPD. This composite can then be sampled to reflect the combined influence of all light sources.

Importantly, when a wavelength sampled from this composite SPD directly interacts with a light source, we apply rejection sampling to this specific interaction. This method helps to prevent the overrepresentation of light's intensity that would occur if these hits were naively processed.

3.3. Gaussian Approximations of Color Matching Functions

To convert the wavelength of a photon into the XYZ color space, we utilize the CIE 1931 color matching functions. For simplicity we have chosen to approximate these functions using Gaussian functions. This approach follows the findings of Wynam et al. [WSS13], who identified optimal Gaussian approximations for $\tilde{x}$, $\tilde{y}$, and $\tilde{z}$ that closely mimic the original x, y, and z functions:

$$\begin{aligned}\tilde{x}(\lambda) = 1.065\exp\left(-\frac{1}{2}\left(\frac{\lambda-595.8}{33.33}\right)^2\right) \\ +0.366\exp\left(-\frac{1}{2}\left(\frac{\lambda-446.8}{19.44}\right)^2\right),\end{aligned} \tag{1}$$

$$\tilde{y}(\lambda) = 1.014\exp\left(-\frac{1}{2}\left(\frac{\ln(\lambda)-\ln(556.3)}{0.075}\right)^2\right), \tag{2}$$

$$\tilde{z}(\lambda) = 1.839\exp\left(-\frac{1}{2}\left(\frac{\ln(\lambda)-\ln(449.8)}{0.051}\right)^2\right). \tag{3}$$

We plotted these approximations in Python to validate their accuracy. Figure 4 depicts these approximated color matching functions.

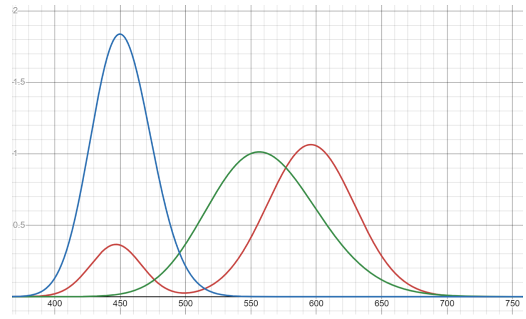

Figure 4: *Approximations of CIE 1931 Color Matching Functions*

By comparing them to the standard CIE 1931 color matching functions in Figure 2, we can observe a good resemblance.

3.4. The Color Pipeline: Wavelength to sRGB

The process of converting a photon's wavelength into a perceivable color involves several steps. Initially, we calculate the XYZ color space values corresponding to the given wavelength using the gaussian approximated CIE 1931 color matching functions. Subsequently, these XYZ values are transformed into the RGB color space through a linear matrix transformation [PJH16] .

Although the standard sRGB color space typically requires gamma correction to adjust for human visual perception, this step is not necessary in our implementation within the VPT framework. The tone mapping component of VPT effectively handles gamma correction, simplifying our color processing pipeline.

This entire pipeline has been implemented in Python and visualized to demonstrate the transformation of the entire visible spectrum. Figure 5 showcases the resulting visualizations.

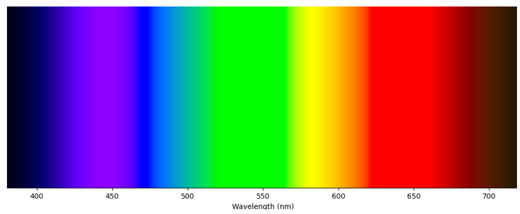

Figure 5: *Python Visualization of the Wavelength to sRGB Pipeline*

3.5. All You Need is Spectrum

The VPT framework utilizes transfer functions to map the density of a voxel to specific albedo values for RGB components. However, with the introduction of wavelength dependency, our approach to representing material color has evolved. We now define albedo using a 3D function that varies with both density and wavelength, a method that mirrors our shift from RGB colors in environment maps to SPD for light sources. For instance, a material can be configured to exhibit high albedo at longer wavelengths and low albedo at shorter wavelengths. This setup inherently produces colors with a more reddish hue, independent of the material's density.

Additionally, we have implemented control over the scattering direction of photons through the anisotropy parameter. This parameter is defined by a 2D function that relates wavelength to anisotropy in Henyey-Greenstein scattering. For example, by assigning a high anisotropy value to longer wavelengths, photons at these wavelengths are made to scatter predominantly in the same direction. Conversely, assigning a low anisotropy value to shorter wavelengths causes these photons to scatter more diffusely. This entire configuration is for instance designed to emulate the Rayleigh scattering observed in the Earth's atmosphere.

4. Results

In this chapter we present the visual results of the implemented spectral renderer in VPT framework as well as its performance metrics.

4.1. Visualizing Phenomena of Light as a Spectrum

In this section, we demonstrate the successful implementation of our spectral renderer by visualizing the three phenomena discussed in the second chapter.

Rayleigh Scattering

Our first simulation depicts Rayleigh Scattering. To achieve this, we adjusted our methods to control the scattering of different wavelengths effectively. We opted not to use the SPD of a D65 daylight source for the light source simulation, as it already represents sunlight after atmospheric interaction, rather than the sun itself. Instead, we simulated sunlight more directly by uniformly sampling all wavelengths, which mimics the sun's nearly uniform emission across the visible spectrum.

We set the albedo for all wavelengths at 0.8, ensuring that most wavelengths predominantly scatter rather than absorb. The anisotropy settings were adjusted to vary with wavelength; the shortest visible wavelengths were set to an anisotropy of zero, increasing to one for the longest wavelengths. This gradation in anisotropy helps to simulate the characteristic blue of the sky and the redish colors directly behind the sun (light source).

Figure 6 illustrate the effects of Rayleigh Scattering under these settings. The light does not appear completely white, as the SPD is sampled uniformly.

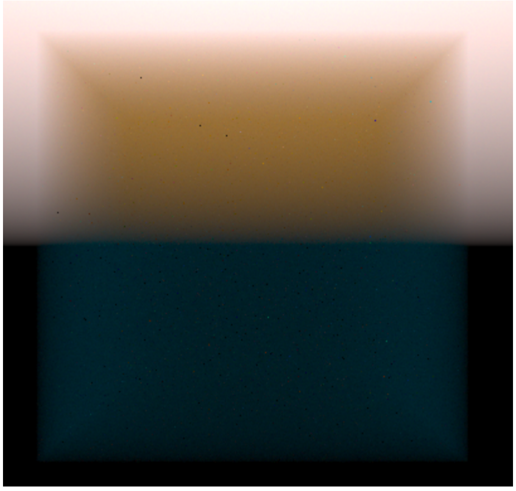

Figure 6: *Rayleigh Scattering Effect*

Flouroscence

Next we depict flouroscence. We achieved this by making the light source's SPD only emit low wavelengths, more specifically from 275 nm to 450 nm, which encompasses UV lights as well as blue and purple visible light. We than transformed UV wavelengths (lower than 380 nm) into longer wavelengths using gaussian distribution with peak at 550 nm. This gives effect of the material being different color than the light, as it is emitting it's own light. The fact that the light only contains blue and purple wavlengths and material is seen as greenish, while if it didn't flouroscence it would have to be the of similiar hue that the light source is, but it is not, proofs that the flouroscence effect is working. Figure 7 illustrates a florouscent frog.

Figure 7: *Florouscent Frog*

Metamerism

The final phenoma we want to present in the VPT framework is metamerism. We achieved this on a very simplified example. One material scatters only low end of the spectrum, while the other scatters low and also high end. If we sample light with D65 distribution, which contains all visible wavelength, the two materials will scatter and absorb different wavelengths, thus appearing different color. However if we sample only one half of the D65 SPD, the two materials will scatter almost the same wavelengths, thus appearing the same color under that lighting. Figure 8 shows two cubes being different color under D65 SPD lighting while Figure 9 shows them being the same color, as we only light the lower half of the D65 SPD.

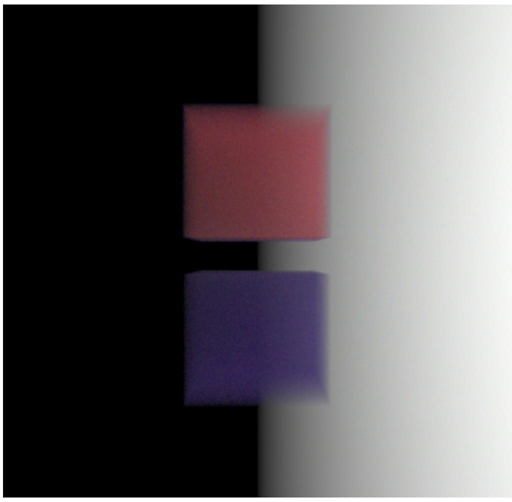

Figure 8: *Two Cubes Appearing Different Color in D65 Lighting*

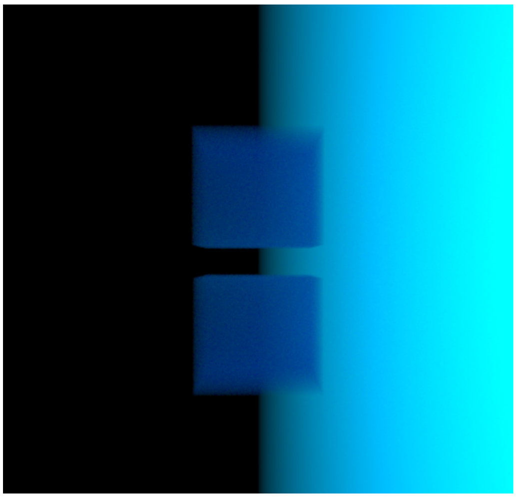

Figure 9: *Two Cubes Appearing Same Color in Certain Lighting*

5. Conclusion

This report has detailed our exploration of spectral rendering, focusing on how light's spectrum interacts with materials and how it is perceived as colors by the human eye. Our journey began with a foundational understanding of the physics of light, purpose of and transformations in color spaces and examination of the VPT framework.

We demonstrated our renderer's capabilities through the visualization of various phenomena: Rayleigh scattering, which elucidates why the sky appears blue; fluorescence, which reveals vivid colors in materials under specific lighting conditions; and metamerism, which changes our perceptions of color under varying light sources. These examples underscore the accuracy of our spectral volume renderer.

Looking ahead, there are several possibilities for enhancing our implementation. Adding support for multiple light sources with a combined SPD would allow for more dynamic and realistic lighting simulations. Further, the current static coding of material behaviors—such as fluorescence, variable albedos based on wavelength and density, and the SPDs themselves—could be made dynamic through user interface enhancements. Enabling users to adjust these parameters interactively based on their needs would significantly enlarge the applicability of all wave optics effects.

References

[PJH16] PHARR M., JAKOB W., HUMPHREYS G.: *Physically Based Rendering: From Theory to Implementation*, 3rd ed. Morgan Kaufmann, 2016. Purchase a printed copy: https://www.pbr-book.org/. URL: https://www.pbr-book.org/. 3

[WSS13] WYMAN C., SLOAN P.-P., SHIRLEY P.: Simple analytic approximations to the cie xyz color matching functions. *Journal of Computer Graphics Techniques 2*, 2 (2013). URL: http://jcgt.org. 3

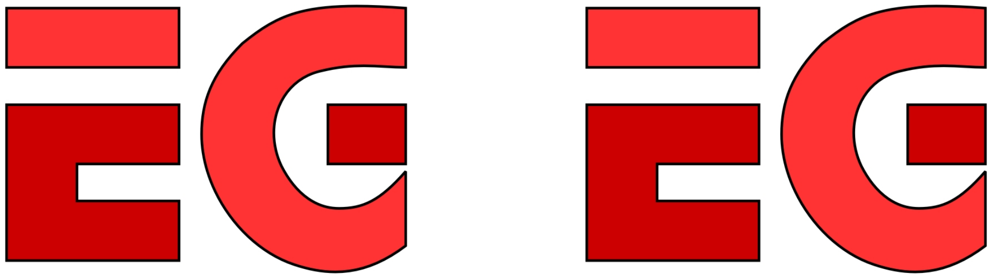

Figure 10: *For publications with color tables (i.e., publications not offering color throughout the paper) please* ***observe****: for the printed version – and ONLY for the printed version – color figures have to be placed in the last page.*
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