A Comparison of Color Computation in RGB versus in spectral Space.

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Abstract

The RGB color space is an obvious choice for color computation and is today used in almost all image generation software. Colors are often selected interactively on an RGB monitor, and the result is also displayed on the monitor. But the current trend towards photorealism in Computer Graphics emphasize the use of measured material and light source properties. This paper shows that the computational error that wasn't visible with the old ad hoc way of chosing surface colors and properties, is definitely a problem when physical data is used in an illumination model. The proposed solution involves doing the illumination calculations in spectral space wavelength for wavelength instead of in RGB−space. The reader should be aware that this problem is NOT restricted to illumination models, but is an unavoidable defect caused by doing physical calculations in a perceptual computational space such as RGB. Thus the problem should be a fertile area for research not only in computer graphics, but also in printing technology.

1. Introduction

Illumination calculations are often done within the RGB−model, this paper shows why this is wrong and illustrates the visible effects of the errors with an experiment.

Many illumination models are subsets of an illumination model of the form:

$$\text{I} = \text{ambient light} + \text{diffuse reflection} + \text{specular reflection} + \text{transmitted light}$$

To simplify the discussion only the first term will be considered hereafter.

$$I(\lambda) \quad = \quad K_a(\lambda)\, I_a(\lambda)$$

Illumination models such as Phong [Phon 75] are often expressed without explicit reference to the wavelength of the light used. The implicit assumption is that the illumination calculation is repeated for each and every wavelength. But the general interpretation is to repeat the color computation using red, green, and blue ad hoc color values for materials. For further reading see also [Gour 1], [Blin 77], [Kay 79], [Whit 80], [Cook 82], [Hall 83] or [Neum 89]. These references show a shift in research from solving hidden surface problems to creating realistic appearances to simulating the behaviour that creates the appearance.

2. Color computations with illumination models

We need to separate color computations that only changes the *representation* of the color, not its appearance, from those calculations that change the *color* appearance.

The former introduces computational errors in some transforms, although most transformations, such as RGB → XYZ, are linear and invertible. The latter group can be divided into perceptually based calculations, such as an artists view of color mixture, and physically based calculations, such as an illumination model.

The process of simulating a lamps reflection on a surface can thus be divided into one physical and one (or more) perceptual computations. The light starting from the lamp can be defined by its spectral distribution, and the surface by its spectral reflectance distribution [Judd 75], [Purd 70]. The illumination model uses these properties to calculate the resulting reflected spectrum. This spectrum may then be transformed into its perceptual equivalent, which then can be converted to RGB for monitor viewing, or CMYK for printing.

Thus the sequence in reality is light bouncing around in a physical reality and then seen (transformed into a perceptual domain) by a pair of eyes. But until recently the goal has been to produce images that *looked* "good", **not** to simulate reality. The recent trend towards ever increasingly realistic images has begun to require physically correct simulation. One problem is to keep the separation of the color computations mentioned above clear in mind. One major error, one so common as to form the de facto standard way of handling illumination computations is described in the next paragraph.

3. Computation in RGB

A commonly accepted fact is that one can use three primary colors to describe a certain set of colors. The most common color model is RGB.

Three primary colors, R, G and B with three dominant wave lengths in the low, middle and high part of spectrum lead naturally to repetition of the illumination calculation three times, one for each primary.

$$I_R = K_{a,R} \cdot I_{a,R} \qquad I_G = K_{a,G} \cdot I_{a,G} \qquad I_B = K_{a,B} \cdot I_{a,B}$$

Until recent trends towards physically based calculations, the parameters of the illumination model were set by the programmer/application user. If one wanted a red object, one adjusted $K_{a,R} \sim 1$, $K_{a,G} \sim 0$, $K_{a,B} \sim 0$ until the image "looked right".

We can depict the situation like this:

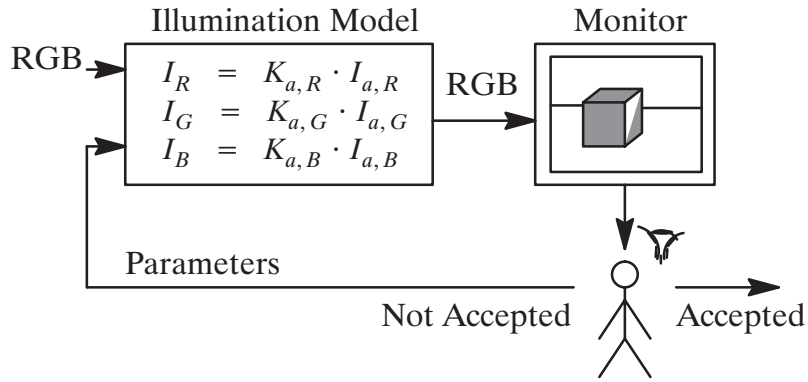

Figure 1. Data flow with feedback loop with user in traditional rendering setup.

This feedback loop will quickly adjust for errors done in the illumination calculation! This is one explanation why RGB has successfully been used in computer graphics illumination calculations until recently.

The next figure shows what happens when the user no longer interactively sets the RGB coordinates used to describe the colors fed into the illumination model, but rather tries to take physical spectrum of colored materials into RGB.

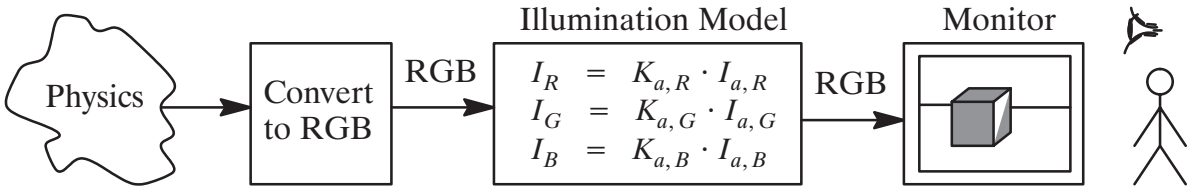

Figure 2. Data flow where RGB conversion is done first.

Note that there is no feedback and thus no self-adjusting correction for errors done in the illumination calculations!

4. Computation using spectra

Spectral computation of the illumination model is done by repeating the calculation through the visible range.

$$I(\lambda) \quad = \quad K_a(\lambda) \cdot I_a(\lambda),\ \lambda\epsilon\ [380, 780]\ nm$$

When all calculations are done and the results are to be displayed, this resulting spectrum I(λ) can be transformed into an RGB coordinate.

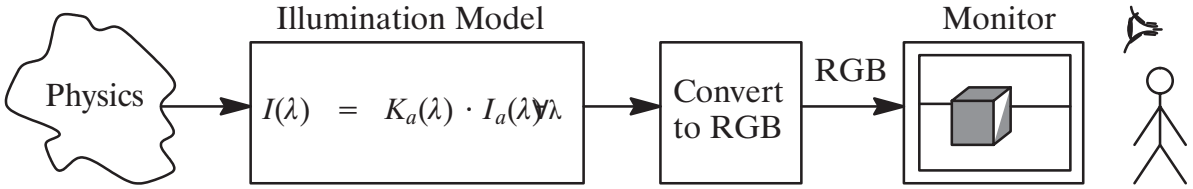

Figure 3. Correct data flow where RGB conversion is done last.

Note that there is no feedback loop.

5. Analysis of the computational flow

The question to analyze, is if the final RGB result will differ when the illumination calculations are performed in RGB or spectral space.

With spectra

$$I(\lambda) \quad = \quad K_a(\lambda) \cdot I_a(\lambda)$$

$$I_R \quad = \quad \int_{380}^{780} I(\lambda) \cdot r(\lambda) \cdot d\lambda \quad = \quad \int_{380}^{780} K_a(\lambda) \cdot I_a(\lambda) \cdot r(\lambda)\, d\lambda$$

With RGB

$$I_{a,_R} \quad = \quad \int_{380}^{780} I_a(\lambda) \cdot R(\lambda)\, d\lambda \qquad K_{a,_R} \quad = \quad \int_{380}^{780} K_a(\lambda) \cdot R(\lambda)\, d\lambda$$

$$I'_R \quad = \quad I_{a,_R} \cdot K_{a,_R} \quad = \quad \int_{380}^{780} I_a(\lambda) \cdot R(\lambda)\, d\lambda \cdot \int_{380}^{780} K_a(\lambda) \cdot R(\lambda)\, d\lambda$$

Comparing I_R with I'_R gives:

$$I_R \quad = \quad \int_{380}^{780} K_a(\lambda) \cdot I_a(\lambda) \cdot r(\lambda)\, d\lambda \quad \neq \quad \int_{380}^{780} I_a(\lambda) \cdot r(\lambda)\, d\lambda \cdot \int_{380}^{780} K_a(\lambda) \cdot r(\lambda)\, d\lambda \quad = \quad I'_R$$

The conclusion is that the result **will** differ. As shown by the experiment this difference is perceptually quite visible in some cases. Therefore one must make all illumination calculations with a spectral sample and convert to RGB as late as possible in the data flow.

6. The experiment

The experiment was designed to show four partitions of color on a computer monitor, these partitions showing illumination computations in RGB and spectral space for one and two reflections against a surface. These partitions were photographed but not included in this short paper. The differences was not only visible for most materials tested, but in some cases severe.

The equipment used was a Sparc station−1 with a color monitor SUN: Model GDM−1604−40. The monitor was photographed in a dark room with a Canon EOS600 camera with Kodachrome 64 at 1/2 second with a 300 mm telezoom objective from approximately 3 meters.

The spectral data for the standard CIE illuminant D6500 originates from [Judd 75] table 2.1 pp. 108−109, normalized to 1.00 at 560nm. The material data used are from The Macbeth ColorChecker chart [McCA 76]. These data can also be found in [Hall 89].

7. Results and suggestions

For some surface colors there are severe distorsions while for some others the effect is barely visible. Macbeth6 shows a very subtle effect, Macbeth16 has a quite visible effect in the second order reflection, Macbet19 is severely distorted, and lastly Macbeth20 is drawn to red, (all illuminated by the D6500 daylight source). Let's take Macbeth19 illuminated by D6500 as an extreme example:

First make the reflections entirely in spectral space and convert the results to RGB last:

Lighsource	Material	1:st refl.	2:nd refl.
(251,252,252)	(255,220,207)	(225,227,224)	(201,205,200)

And then make the reflections in RGB space by converting spectra to RGB first:

(251,252,252)	(255,220,207)	(252,217,204)	(253,188,166)

As you can see the difference in the first order reflection is quite big, (225,227,224) versus (252,217,204)! For most saturated colors close to the primaries there is much smaller differences.

Do not expect correct results when giving perceptually based data to a physically based calculation, as when doing an illumination calculation with RGB data!

The solution is to do all illumination calculations on spectral data, and only convert to RGB, XYZ, CMYK or any other perceptual domain as the very last step.

This will demand new methods, and further research is needed to investigate ways to reduce the calculations necessary. Research is also needed to develop similar methods to replace the CMYK calculations done for printing.

8. References

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