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Color Education and Color Synthesis in Computer Graphics

The important role that color science plays in computer-graphics image synthesis is discussed. Simulated scenes of environments with diffuse and specular reflections as well as light scattering are used as examples to demonstrate how tristimulus colorimetry and color-naming systems are used in computer graphics. These examples also illustrate the need for color-science literacy in the field of computer graphics. Color-science educational software that has been developed to meet this need and that utilizes both vector-graphic and raster-graphic devices is also described.

Introduction

Color science and computer graphics share a mutually beneficial relationship. Computer-graphics researchers use color spaces developed by color scientists in order to select colors, and employ the principles of tristimulus colorimetry to reproduce synthesized spectral energy distributions. Color scientists can use computer-graphics techniques to depict three-dimensional color spaces, and are finding computer-graphics hardware useful in exploring new color-organization schemes.

This article illustrates the commonality between these two fields from the computer-graphics point of view. Two programs that were written to teach the principles of color science to computer-graphics students are described in the first section. In the second section, color synthesis in computer graphics and its dependence on principles of color science are briefly discussed.

Using Computer Graphics to Teach Color Science

The tristimulus nature of human color vision and the abstract three-dimensional color spaces that result make computer graphics a natural vehicle for illustrating the basic principles of color science. Instructional software is easy to develop, given the geometric transforms, hidden-surface algorithms, and color displays that computer graphics provides. In addition, the interactive nature of computer graphics can make the resulting program a powerful didactic tool. Alternative views of a color space can be produced quickly, and the full three-dimensional nature of the color space can easily be explored. The programs described in this section have been used to teach the principles of color science to hundreds of computer-graphics students.

The sequence of pictures in Fig. 1 illustrates one program that is used to teach the principles of color science to computer-graphics students. This program can be used interactively to demonstrate color-space transforms, the derivation of the chromaticity diagram, the gamuts of color-reproduction devices, and the loci of various color collections. Starting in the *LMH* (low-, medium-, high-wavelength) primary system used to perform the color-matching experiments, the equal-energy spectrum locus and the cone of realizable color are shown in Fig. 1(a). By selecting the *XYZ* color space, the displayed objects can immediately be transformed into CIE *XYZ* space as shown in Fig. 1(b). The unit plane and its curve of intersection with the cone of realizable color are also shown in this figure. By switching to an orthographic projection and orbiting to obtain a view in the *Z*-axis direction, the chromaticity diagram emerges as shown in Fig. 1(c). The boundary of a particular color-television gamut, the loci of Munsell colors of constant Hue at different Values, and the equal-energy spectrum locus are shown in a chromaticity and luminance space (Yxy) in Figs. 1(d) and 1(e). Figure 1(d) is an orthographic projection looking down the Y axis while Fig. 1(e) is a perspective projection obtained by orbiting to a different viewpoint. Finally, these objects are transformed in Fig. 1(f) into the color space (RGB) of the television monitor itself.

The use of full-color-shaded computer graphics to illustrate the characteristics of a color space is shown by the picture of the Munsell color solid in Plate I. The surfaces of each polyhedral element are determined by employing a visible-surface algorithm. The chromaticity and luminance for each element was found from the Munsell renotation tables.[1] Using Lambert's Law of diffuse reflection, the lu-

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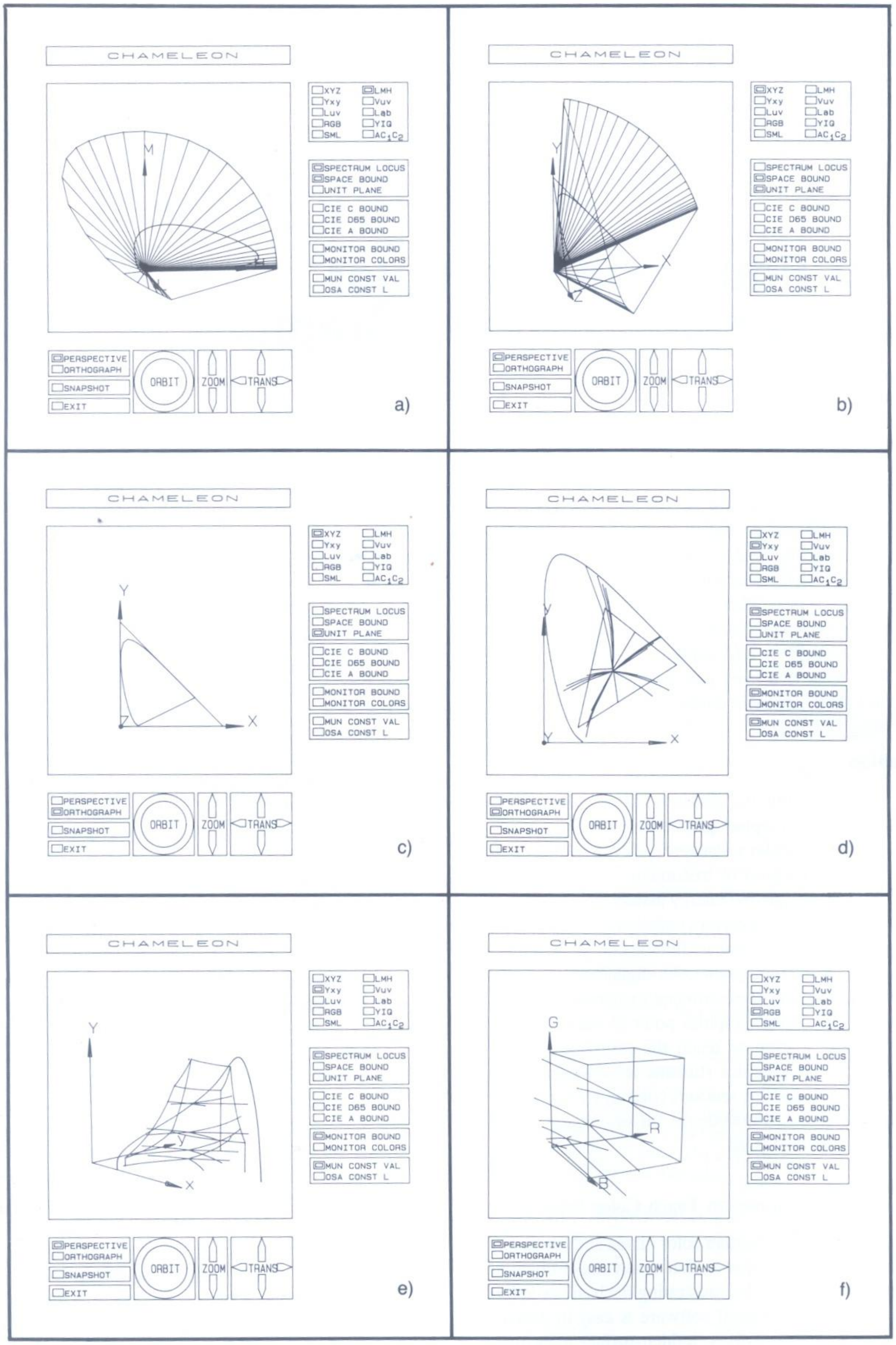

FIG. 1. Examples from the color-science instructional program. Alternative color spaces are listed in the upper-right c
of each example, and objects that can be displayed are enumerated below this.

ninance was adjusted based on the cosine of the angle between each polygon's surface normal and a vector from the polygon to the light source. The CIE-*XYZ* to monitor-*RGB* transformation.[2,3] was used to determine the signals necessary to drive the display. The relation between the Munsell color solid and the *RGB* monitor gamut can be seen by examining Fig. 1(f) and Plate I. The "spiders" of constant Munsell Hue and Value that are centered on the diagonal of the cube in Fig. 1(f) become horizontal cross sections in Plate I(a) and are easily recognizable in the top view given in Plate I(b).

Using Color Science for Computer-Graphics Color Synthesis

To simulate the color of synthetic scenes it is necessary to predict the spectral energy distribution that reaches each point of the picture plane, to compute CIE *XYZ* tristimulus values for each of these spectral energy distributions, and to transform these device-independent color specifications into the color coordinates necessary to drive a particular color-reproduction device. The magnitude and shape of the spectral energy distribution at the picture plane is dependent upon the path the light has taken through the simulated environment, as well as the interactions that it has had with the material in the environment, all on a wavelength basis. Each interaction of light with a material can be categorized as being either a reflection (either diffuse or specular), a transmission, an absorption, or a scattering. In addition, the material itself may emit light. The following three examples illustrate some methods currently used in computer graphics to model each of these types of interaction as well as the propagation of light through the environment.

Modeling the color of the twilight sky is an example in which only a single material (air) is involved, the material itself does not emit light, and scattering and transmission are the predominant physical mechanisms. Adams, Plass, and Kattawar[4] have produced a model of the twilight sky that accounts for Rayleigh scattering due to air molecules, Mie scattering due to aerosols, and absorption due to ozone. They provide chromaticity coordinates for the resulting spectral energy distributions as a function of angular position above the horizon. The data were used to produce the picture of the twilight sky shown in Plate II.

Ray tracing is a global-illumination model frequently employed in computer graphics.[5] This approach does not maintain the conservation of energy but is capable of handling specular reflections. A ray is traced from the viewing position through each point in the picture plane. When the ray strikes a surface in the environment, reflected and transmitted rays are spawned. After all ray paths have terminated, the intensity to be displayed at the picture plane is found by accumulating the intensity contribution from each surface-intersection point. Spectral energy distributions are found by repeating this final step for individual wavelengths of light.[6] An image produced using the ray-tracing method is shown in Plate III.

The interactions of light with a material can be further demonstrated by modeling the color of an environment in which all of the light reflections and emissions are considered to be perfectly diffuse. The energy that leaves each surface is called its radiosity, and is the sum of the incident light that is reflected by the surface and the light that the surface itself emits. The incident light includes a fraction of the light leaving each of the other surfaces in the environment. This fraction is a function of the relative orientation, area, and distance between the neighboring surface and the surface under consideration. An energy balance for the entire scene leads to a set of simultaneous linear equations that can be solved to determine the radiosity leaving each surface. Spectral energy distributions can be found by repeating this analysis for individual wavelengths of light, although usually several discrete wavelength bands suffice. This technique, which is known as the radiosity method, accurately models interreflection effects that are wavelength dependent[7] and shadows that include penumbras.[8,9] In addition, the results are viewpoint independent. Plate IV shows a picture produced by using the radiosity method.

In order to use either the ray-tracing or radiosity methods for image synthesis, spectral reflectances and emittances must be assigned to all of the surfaces in the environment. A modeling program that has been developed to accomplish this has access to a library of over 475 reflectances and emittances. These curves are taken from several sources[10–17] and are arranged into the categories shown in Table I. In addition to a plot of each curve, the user of the modeling program can interrogate the database for the Munsell notation, the ISCC-NBS color name, or the CIE chromaticity and luminance of each distribution. As an aid in visualizing the color produced by each curve, a picture on a color-television monitor of a cylinder rendered using a particular reflectance or emittance can also be requested. The spectral reflectances and emittances that have been assigned to the environment of Plate IV are shown in Fig. 2.

TABLE I. Categories of spectral reflectances and emittances available in the modelling program.

Reflectances		Emittances
Acoustical plaster	Rock	Blackbody
Asphalt floor tiles	Sheet metal	Fluorescent
Asphalt wall tiles	Shingles	CIE standard
Bare areas and soil	Skin	LED
Brick	Tile, wall board	
Carpets	Upholstery materials	
Chalkboards	Vegetative formation	
Enamel paint	Wall boards	
Enameled steel	Wall linoleums	
Floor tiles	Wall tiles	
Linoleum desk tops	Water surfaces, snow	
Linoleums	Window shades	
Macbeth chart	Wood desk tops	
Paints	Wood, cork, rubber	
Plaster, cast tiles		

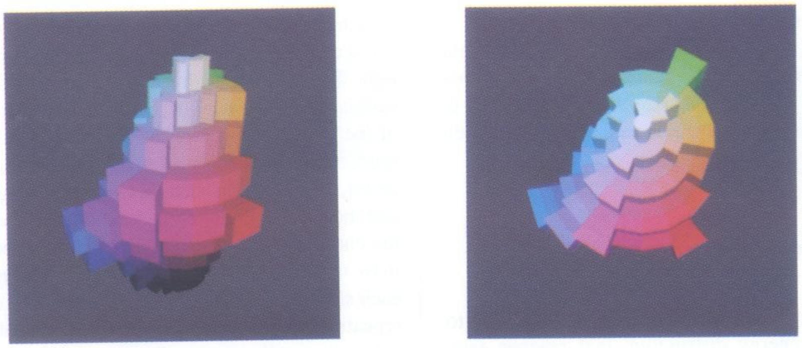

PLATE I. Raster-graphics image of the Munsell color solid.
a, Side view; b, Top view.

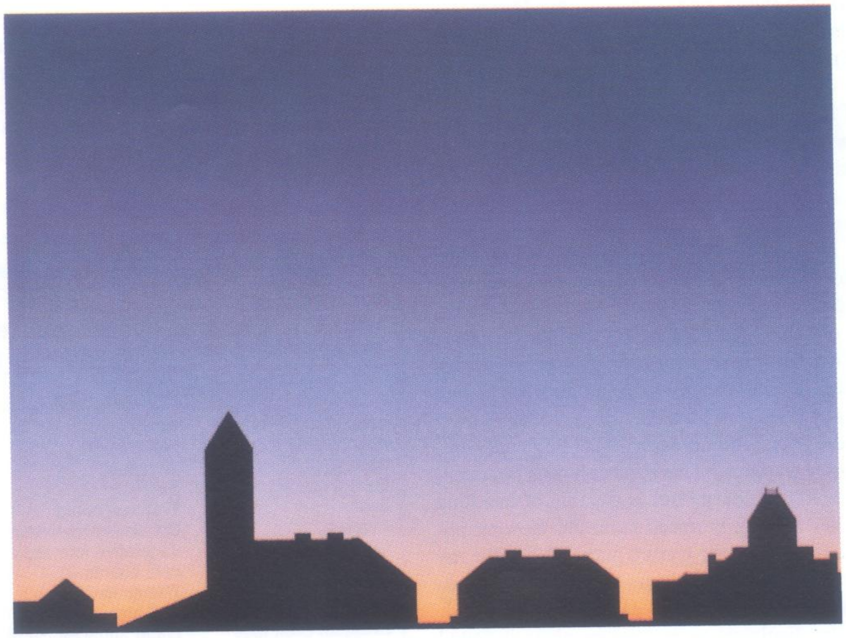

PLATE II. Synthesis of the colors of the twilight sky.

PLATE III. An image created by using ray tracing.

PLATE IV. Image produced by using the radiosity method.

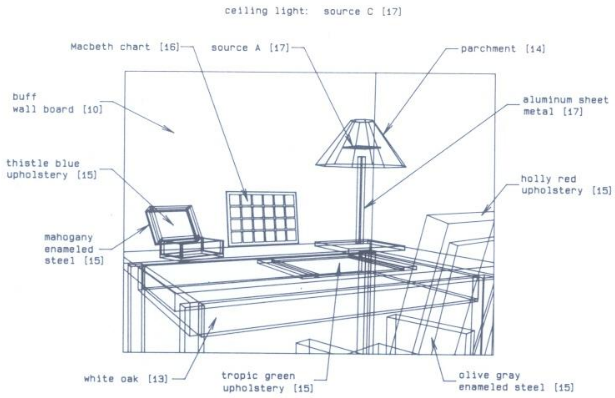

FIG. 2. Spectral reflectances and emittances used to produce Plate IV (reference numbers are given in brackets).

Conclusions

The relationship between the fields of computer graphics and color science will continue to grow beyond the examples given in this article. Color-science research that goes beyond classic colorimetry and into such areas as chromatic adaptation and opponent-color models will be of use to workers in the field of computer graphics. Some of the sophisticated illumination models being developed in computer graphics can help color scientists address color-reproduction problems that are related to an object's overall appearance.[18] Each discipline can clearly benefit from the other's research and from a closer working relationship.

Acknowledgments

The computer-generated images and some of the other software described in this article would not have been possible without the assistance of many people. The scan-line hidden-surface algorithm was written by Wayne Robertz. The modeler is the work of Eric Haines, Roy Hall, Gary Hooper, John Sisson, Chan Verbeck, and Hank Weghorst. The radiosity software was developed by Phil Brock, Michael Cohen, and Dave Immel. Rikk Carey synthesized the image in Plate III and Ted Crane provided overall system support. All of the work was performed at the Cornell University Program of Computer Graphics, under partial funding by the National Science Foundation, grant DCR–8203979, "Interactive Computer Graphics Input and Display Techniques."

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