COMPUTER AIDED COLOR APPEARANCE DESIGN

Gary W. Meyer
Department of Computer and Information Science
University of Oregon
Eugene, OR 97405
USA
gary@cs.uoregon.edu

ABSTRACT

Recent developments in the field of computer graphics will provide color scientists with a new set of design tools. Real-time shading will make it possible to interactively evaluate surfaces that exhibit complex variation in the direction and color of reflected light. New software simulation techniques will facilitate the prediction of these important surface reflection properties. Together these tools for synthesizing and evaluating color appearance define a new methodology called computer aided color appearance design. This paper reviews the important computer graphics advances in real-time shading and surface reflection modeling that have made this novel approach to color appearance design possible.

Keywords: *computer graphics, color, image synthesis, reflection modeling*

1. INTRODUCTION

The first commercially successful application of computer graphics was in the area of computer aided design. In the 1960's the automotive companies (primarily General Motors) and the aircraft firms (primarily Lockheed) took the lead and, together with computer manufacturers (primarily IBM), created the first computer aided design systems [1]. Using the interactive power of computer graphics, a mechanical design was created at the cathode ray tube instead of at the drafting board. This innovation made it possible to consider more alternatives, to numerically analyze the strength and heat resistance of component parts, and to refine the design before the first prototype was actually constructed. In addition, a description of the design could be stored in a database and could be shared by other engineers who were working on the project. When fabrication of the design was required, the database could be used to produce a program for a numerically controlled machine.

Even though computer graphics hardware has changed dramatically in the last forty years, computer aided design continues to use the power of interactive computer graphics primarily to depict the geometry but *not* the color appearance of a design. This is in spite of the fact that computer graphics systems now involve digital control of each spot on a color television monitor. While static color pictures have been synthesized of complex surface reflection phenomena such as brushed metal, cloth, and metallic automotive paint, the real time generation of such pictures has, up until very recently, been impossible. This was because of the limited surface reflection model, called the Phong model, which was available on most computer graphic workstations.

Progress in computer graphics will soon make it possible for computer aided design to include color appearance. A complete specification of color appearance must include both the spectral and the spatial distribution of the light reflected from a surface [2]. The most general way of modeling this distribution is the bidirectional reflection distribution function (BRDF). Recent developments in graphics hardware and software have made it possible to display, in real-time, a surface that has an arbitrary BRDF. This important advance allows a color scientist to critically evaluate the color appearance of a computer generated object. In addition, computer graphic algorithms for modeling surface reflection have also improved dramatically in the last few years. These breakthroughs make it possible to generate a BRDF for a surface by knowing a few key parameters of the surface or by actually constructing a model of the surface and simulating how light reflects from it. The combination of real-time BRDF based rendering and powerful tools for BRDF synthesis will revolutionize the way in which color engineers create new surface coatings.

This paper will review the developments that have taken place in the field of computer graphics to make computer aided color appearance design an important new technique for the coming decade. To begin, the first three decades of real-time color raster graphic hardware evolution will be overviewed. This will establish the ultimate potential and current limitations of today's computer graphic workstations. Next, the recent innovations in real-time shading, that make it

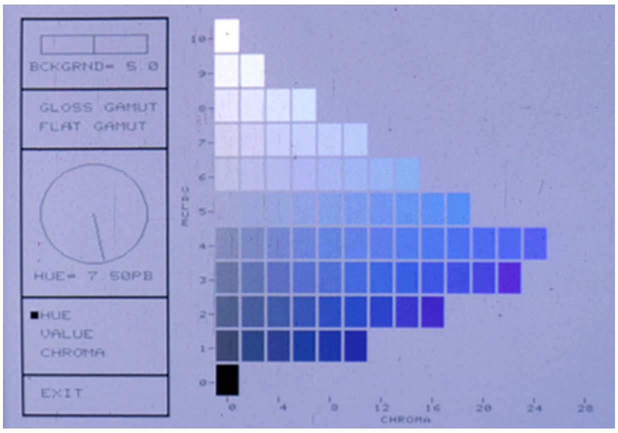

Figure 1: Page from the Munsell Book of Color displayed on a 1970's frame buffer (from [3]).

possible to display a surface with an arbitrary BRDF, will be discussed. Here it will be seen that clever utilization of graphics hardware is at last making it possible to move beyond the Phong reflection model. Finally, computer graphic algorithms for modeling surface reflection will be covered. A review will be done of how increasingly detailed surface models are being constructed and how these models are being subjected to ever more powerful light reflection simulations.

2. COLOR RASTER GRAPHICS HISTORY

Color computer graphics first became available in the 1970's. These raster graphic systems were constructed from separate minicomputers, digital frame buffers, and color television monitors. Each of these components was purchased from a separate manufacturer, and the integration of the system was the responsibility of the buyer. Besides the basic read/write pixel operation, the frame buffers had limited graphic hardware capabilities (usually just text generation), and the entire system was only able to display static two dimensional color computer graphic images. Nevertheless, digital control of a color television monitor was possible, and the colorimetric capability of this hardware configuration was explored [3]. Figure 1 shows a computer graphic reproduction of the Munsell Book of Color that was created during this period of time.

The 1980's saw the integration of the minicomputer, digital frame buffer, and color television into what became known as the computer graphic workstation. Specialized computer graphic hardware was added to these machines [1] in order to provide real-time graphics capability. At the level of workstation that was typically purchased for use by a design engineer in a large company, the machine had 8 bits of color per pixel and was able to interactively display the outline of polygons. These wireline graphics workstations could draw pictures of complex three dimensional objects and the user could translate, rotate, and scale the object in real time. A color solid drawn using a color gamut visualization program [4] written in the 1980's is shown in Figure 2.

The personal computer became the dominant graphics platform of the 1990's. By swapping out the graphics card in these machines, users could dramatically increase the graphics capability of their computers. By the end of the decade, graphics cards costing hundreds of dollars were providing performance equivalent to that found in 1980's workstations costing thousands of times more. These graphics cards could easily render, at interactive rates, many thousands of fully shaded hidden surface removed polygons. Significant amounts of texture mapping memory were also available on many graphics cards before the year 2000 arrived. An example of a three dimensional color solid produced using a 1990's color gamut visualization program [5] is shown in Figure 3.

The graphics hardware development that will dominate the first decade of the new millennium and that has significant implications for computer aided color appearance design, is the introduction of real-time shading. No longer will the user be restricted to the use of the Phong model for local illumination calculations. Any parameterized reflection model can be employed including a full BRDF. Even programmable shaders, commonly found only in high-end software rendering packages, will be available. This new graphics hardware will make it possible to carefully control

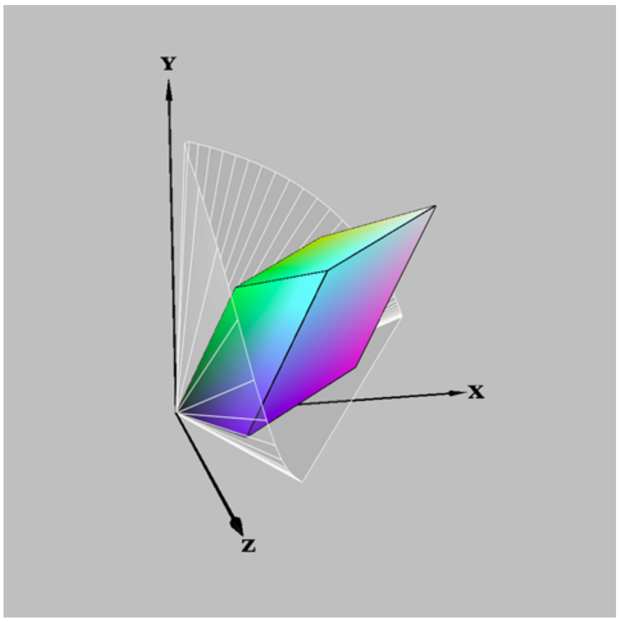

Figure 2: Color monitor in CIE XYZ space created using a 1980's computer graphics workstation [4].

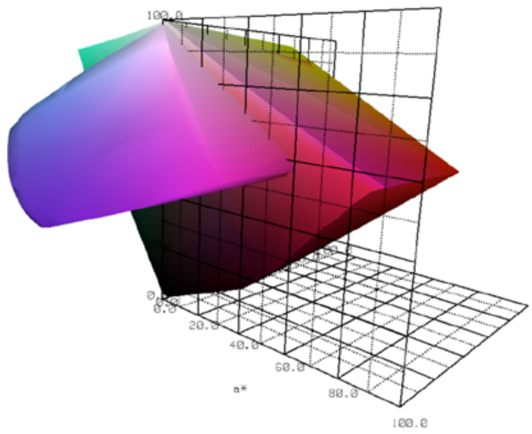

Figure 3: Monitor gamut in CIE Lab space cut away to reveal printer gamut. Produced using 1990's computer graphic hardware and software visualization tools (from [5]).

both the color and the spatial distribution of the reflected light from a surface. This will facilitate the real-time display of novel surface finishes and will play an important role in making computer aided color appearance design a reality.

3. REAL-TIME SHADING

Real-time shading makes use of multipass rendering to implement sophisticated reflection models on hardware that does not natively support these techniques. This approach takes advantage of alpha blending operations that have become common on most graphics cards. The alpha blending technique was originally developed to permit the compositing together of two graphic images [6]. In the context of multipass rendering, alpha blending makes it possible to decompose the evaluation of a single complex shading equation at each pixel into a sequence of additions and multiplications of simpler individual terms. In a double buffered system, one image is displayed while the next image in the real-time sequence is formed using the multipass technique. When the new picture is ready, the buffers are swapped and the just computed image becomes the displayed image while the previously displayed image is recomputed.

One approach to real-time shading is to decompose a multi-variable reflection model into the product of individual bi-variate functions. A two dimensional hardware texture map can then be used as a sampled version of each bi-variate function. Texture mapping then becomes the evaluation of a bi-variate function instead of the usual indexing into a surface texture pattern such as marble or wood grain. The sampled value of the bi-variate function serves as one term in the sequence of alpha blending operations described in the preceeding paragraph. Heidrich and Seidel [7] show how parameterized reflection models can be handled in this manner. The use of singular value and normalized decomposition to reduce a four dimensional BRDF into the product of a pair of two dimensional functions is covered in [8]. This permits real-time rendering of surfaces with arbitrary BRDF's illuminated by point light sources.

Figure 4: BRDF for metallic paint generated using a virtual goniospectrophotometer (from [17]).

Mirror and glossy reflections can be added to real-time shading through the use of environment mapping techniques. An environment map records the total reflected light for each possible surface orientation. If the object to be rendered is replaced by a sphere that has the same BRDF, then the sphere will reflect the surrounding scene and the environment map for the object will be the orthographic projection of the sphere from the desired point of view. Multipass methods can be used at render time to create a complex BRDF from separate environment maps that record, for example, the diffuse, mirror, and Fresnel portions of the surface reflection. Cabral et al. [9] show how to create an environment map for a particular point of view by warping together environment maps from surrounding viewpoints. A novel parabolic parameterization given in [7] can be used to create a single mirror environment map that is valid from all points of view. Techniques for makeing environment maps for arbitrary glossy BRDF's are given in [10].

Real-time implementations of programmable shaders have also been developed. A programmable shader provides the ultimate flexibility in reflection modeling. Instead of using a single parameterized reflection model or BRDF, the user is allowed to combine shading techniques by writing a program that is executed each time a shading calculation needs to be performed. A specialized language is often provided to compose these shading programs. The first real-time version of a shading language was created by Olano and Lastra [11]. The RenderMan Shading Language [12, 13] was implemented on the special purpose PixelFlow hardware system. Recently another real-time version of RenderMan was developed for widely available graphics hardware [14]. This research employed multipass techniques to make RenderMan work in real-time on top of OpenGL.

Computer-aided color appearance design will be feasible because of the development of real-time shading. Just as aircraft and automobile designers have been able to use interactive computer graphics to inspect the geometric aspects of a new mechanical design, it will now be possible for color scientists to evaluate the appearance attributes of a proposed new surface finish. In many cases it will be possible to change the appearance properties of the surface in real time using reflectance models and BRDF's not commonly available on today's computer graphic computers. In other situations it will be necessary to generate a new BRDF offline using complex surface reflection modeling software. The important factor is, however, the speed and thoroughness with which the new appearance attributes can be evaluated due to real-time shading. This makes it possible to try many different surface coating formulations before it is necessary to manufacture the material.

4. BRDF SYNTHESIS

Modeling a surface and computing the BRDF for that surface is an important part of the computer aided color appearance design process. However, it is most often accomplished using a stand alone software simulation program and is almost never done in real-time. There is, of course, a vast color science literature concerning the computation of reflectance for a surface coating. For example, given the constitute pigments of a paint, much research has been done on how to determine the color of the resulting paint mixture. In this paper we concentrate on work that has been accomplished in the field of computer graphics to synthesize a BRDF when given either a model of the surface microstructure or a few key parameters, such as rms roughness, for the surface.

The most general approach to synthesizing a BRDF is to create a "virtual goniospectrophotometer." In this method an explicit model of surface and subsurface microstructures is created. Many light rays are cast at the surface model from a particular direction and geometric optics is used to determine how the light rays behave both above and below the surface. A data structure is employed to capture the light rays that are reflected and scattered from the surface. A new ray direction is then selected and the process is repeated. In the end the data structure contains the BRDF. Cabral et al. [15] were the first to develop the method, and Westin et al. [16] elaborated the approach to generate BRDF's for complex surfaces. Extensions to handle wavelength, interference, and subsurface structures were added in [17, 18, 19] (see Figure 4). Nagata et al. [20] have used the method to make pictures of pearls and Heidrich et al. [21] have recently shown how to efficiently handle indirect, scattered light as part of the BRDF synthesis.

Figure 5: Synthetic scene for which colors were mixed from pigments by using the Kubelka Munk method (from [22]).

Another popular technique for creating a BRDF does not attempt to explicitly model all of the surface and subsurface microstructures. Instead, the surface is typically modeled as set of layers, and bulk absorption and scattering properties are assigned to each layer. One dimensional linear transport theory is then used to compute the radiation exchange between the layers, and the overall reflectance properties of the surface are determined. Kubelka-Munk is the typical example of this approach and it was introduced to computer graphics by Haase and Meyer [22] (see Figure 5). Hanrahan and Krueger [23] were the first to construct a model of a surface from layers and to solve for the reflectance using linear transport theory. Dorsey and Hanrahan [24] showed how a layered model and the Kubelka-Munk approach could be used to create the apperance of metallic patinas. Later, the same researcher [25] employed scattering functions and Monte Carlo ray tracing to simulate subsurface scattering in stone. Recently Pharr and Hanrahan [26] have solved non-linear scattering equations using a Monte Carlo approach.

The traditional approach to generating a BRDF in computer graphics is the use of a parameterized model. Rather than create surface microstructure or solve a radiation exchange equation, a previously derived reflection model is utilized. The model may be

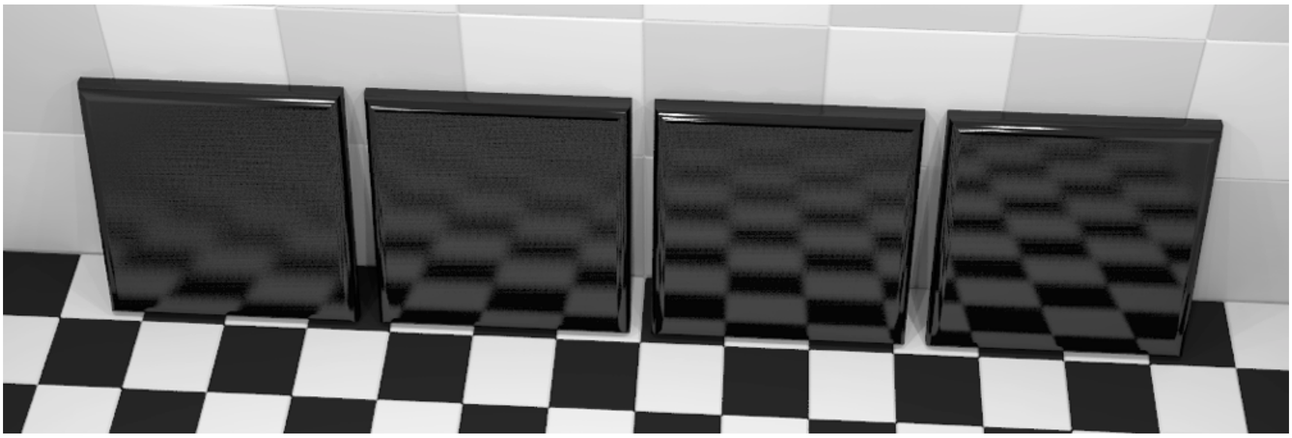

Figure 6: Tiles with ASTM standard gloss of 20, 40, 60, and 80 (left to right) [34].

specialized for one type of surface and may have parameters for surface features such as roughness and color. The model could be efficient enough to be incorporated into a real-time shader. Early computer graphic reflection models are those developed by Phong [27] and Blinn [28]. More sophisticated reflection models followed including those that account for Fresnel reflection [29] and directional diffuse reflection [30]. An efficient model that was fit to measured data and that handles anisotropic reflection was developed by Ward [31]. Recently Stam [32] has invented a model that includes diffraction effects and Ashikhmin et al. [33] have produced a model that takes a 2D microfacet orientation distribution as input. Finally, gloss measurements have been incorporated as a reflection model parameter [34] (see Figure 6).

5. CONCLUSIONS

Recent advances in computer graphic hardware and software will soon expand the range of possible computer aided design techniques. Rather than being limited to geometric design problems as has been the case since computer aided design was first developed by the automobile and aircraft industries, color appearance problems will now be solvable using computer graphic workstations. The principle reason that this will become possible is the development of real-time shading techniques. These new shading methods will permit the color scientist to evaluate the appearance of new color coatings and surface finishes as they observe a computer generated picture of an object that has been assigned these surface reflectance properties. In addition, new BRDF synthesis techniques are being developed both inside and outside of the field of computer graphics. These simulation programs make it possible to predict the reflectance properties for new paint formulations and surface coatings. The combination of advanced reflectance prediction techniques and real-time shading methodologies will make computer aided color appearance design an important new tool for color engineers.

6. ACKNOWLEDGEMENTS

This work was partially funded by the National Institute of Standards and Technology.

7. REFERENCES

[1] Carl Machover. Four decades of computer graphics. *IEEE Computer Graphics and Applications*, 14:14–19, November 1994.

[2] Richard S. Hunter and Richard W. Harold, editors. *The Measurement of Appearance*. John Wiley & Sons, second edition, 1987.

[3] G. W. Meyer and D. P. Greenberg. Perceptual color spaces for computer graphics. *Computer Graphics*, 14(3):254–261, July 1980.

[4] Gary W. Meyer, Linda S. Peting, and Ferenc Rakoczi. A color gamut visualization tool. In *Proceedings of the First IS&T/SID Color Imaging Conference*, pages 197–201, November 1993.

[5] Gary W. Meyer and Chad A. Robertson. A data flow approach to color gamut visualization. In *Proceedings of the Fifth IS&T/SID Color Imaging Conference*, pages 209–214, November 1997.

[6] T. Porter and T. Duff. Compositing digital images. *Computer Graphics*, 18(3):253–259, July 1984.

[7] Wolfgang Heidrich and Hans-Peter Seidel. Realistic, hardware-accelerated shading and lighting. *Computer Graphics*, 33(Annual Conference Series):171–178, 1999.

[8] Jan Kautz and Michael D. McCool. Interactive rendering with arbitrary brdfs using separable approximations. In *Tenth Eurographics Workshop on Rendering*, pages 281–292, June 1999.

[9] Brian Cabral, Marc Olano, and Philip Nemec. Reflection space image based rendering. *Computer Graphics*, 33(Annual Conference Series):165–170, 1999.

[10] Jan Kautz and Michael D. McCool. Approximation of glossy reflection with prefiltered environment maps. In *Proceedings of Graphics Interface '00*, 2000.

[11] Marc Olano and Anselmo Lastra. A shading language on graphics hardware: The PixelFlow shading system. *Computer Graphics*, 32(Annual Conference Series):159–168, August 1998.

[12] Pat Hanrahan and Jim Lawson. A language for shading and lighting calculations. *Computer Graphics*, 24(4):289–298, August 1990.

[13] Steve Upstill, editor. *The RenderMan Companion*. Addison-Wesley, 1990.

[14] Mark S. Peercy, Marc Olano, John Airey, and P. Jeffrey Ungar. Interactive multi-pass programmable shading. *Computer Graphics*, 34(Annual Conference Series), July 2000.

[15] Brian Cabral, Nelson Max, and Rebecca Springmeyer. Bidirectional reflection functions from surface bump maps. *Computer Graphics*, 21(4):273–281, July 1987.

[16] Stephen H. Westin, James R. Arvo, and Kenneth E. Torrance. Predicting reflectance functions from complex surfaces. *Computer Graphics*, 26(2):255–264, July 1992.

[17] Jay S. Gondek, Gary W. Meyer, and Jonathan G. Newman. Wavelength dependent reflectance functions. *Computer Graphics*, 28(Annual Conference Series):213–220, July 1994.

[18] Morgan T. Schramm, Jay S. Gondek, and Gary W. Meyer. Light scattering simulations using complex subsurface models. In *Proceedings of Graphics Interface '97*, pages 56–67, 1997.

[19] Morgan T. Schramm and Gary W. Meyer. Computer graphic simulation of light reflection from paper. In *Proceedings of IS&T's 1998 PICS Conference*, pages 412–423, 1998.

[20] Noriko Nagata, Toshimasa Dobashi, Yoshitsugu Manabe, and Teruo Usami. Modeling and visualization for a pearl-quality evaluation simulator. *IEEE Transactions on Visualization and Computer Graphics*, 3(4):307–315, 1997.

[21] Wolfgang Heidrich, Katja Daubert, Jan Kautz, and Hans-Peter Seidel. Illuminating micro geometry based on precomputed visibility. *Computer Graphics*, 34(Annual Conference Series), July 2000.

[22] Chet S. Haase and Gary W. Meyer. Modeling pigmented materials for realistic image synthesis. *ACM Transactions on Graphics*, 11(4):305–335, 1992.

[23] Pat Hanrahan and Wolfgang Krueger. Reflection from layered surfaces due to subsurface scattering. *Computer Graphics*, 27(Annual Conference Series):165–174, 1993.

[24] Julie Dorsey and Pat Hanrahan. Modeling and rendering of metallic patinas. *Computer Graphics*, 30(Annual Conference Series):387–396, 1996.

[25] Julie Dorsey, Alan Edelman, Henrik Wann Jensen, Justin Legakis, and Hans Køhling Pedersen. Modeling and rendering of weathered stone. *Computer Graphics*, 33(Annual Conference Series):225–234, 1999.

[26] Matt Pharr and Par Hanrahan. Monte carlo evaluation of non-linear scattering equations for subsurface reflection. *Computer Graphics*, 34(Annual Conference Series), July 2000.

[27] Bui-Tuong Phong. Illumination for computer generated images. *Communications of the ACM*, 18(6):311–317, 1975.

[28] James F. Blinn. Models of light reflection for computer synthesized pictures. *Computer Graphics*, 11(2):192–198, July 1977.

[29] R. L. Cook and K. E. Torrance. A reflectance model for computer graphics. *Computer Graphics*, 15(3):307–316, August 1981.

[30] Xiao D. He, Kenneth E. Torrance, François X. Sillion, and Donald P. Greenberg. A comprehensive physical model for light reflection. *Computer Graphics*, 25(4):175–186, July 1991.

[31] Gregory J. Ward. Measuring and modeling anisotropic reflection. *Computer Graphics*, 26(2):265–272, July 1992.

[32] Jos Stam. Diffraction shaders. *Computer Graphics*, 33(Annual Conference Series):101–110, 1999.

[33] Michael Ashikhmin, Simon Premoze, and Peter Shirley. A microfacet-based brdf generator. *Computer Graphics*, 34(Annual Conference Series), July 2000.

[34] Harold B. Westlund. Appearance based rendering. Master's thesis, University of Oregon, 2000.