A Spectral Database for
Realistic Image Synthesis

Gary W. Meyer and Richard E. Hale

Department of Computer and Information Science
University of Oregon

* 35 mm slides for the color illustrations labelled Slide 1 to Slide 7 are available from Gary Meyer at a cost of $0.75 each.

A Spectral Database for Realistic Image Synthesis

Gary W. Meyer
Richard E. Hale

Department of Computer and Information Science
University of Oregon
Eugene, Oregon   97403

Abstract

A database for storing and searching spectral curves is presented. The database gives the user of a synthetic imaging system a means to select spectral reflectance, emittance, transmittance, and absorptance curves for use in the realistic image synthesis process. This provides an alternative to the usual RGB and HSV interfaces that are typically used for image color selection and specification. The design of the database, the method for adding curves to it, and the techniques available for searching it are discussed.

Introduction

It is now widely realized that the correct approach to realistic image synthesis involves an accurate simulation of the physical world. For illumination modeling this means that electromagnetic energy must be treated in a way that correctly predicts its interactions with surfaces and that light must be handled in an energy conservative manner (Goral, et. al., 1984; Cohen and Greenberg, 1985; Kajiya, 1986; Rushmeier and Torrance, 1987). To simulate the movement of an object, equations of motion must be written that take into account the mass of the object and the forces acting upon it (Wilhelms and Barsky, 1985; Isaacs and Cohen, 1987; Platt and Barr, 1988). To make a photorealistic image, the optics of a camera must be modeled

1

including imaging artifacts such as motion blur and depth of field (Potmesil and Chakravarty, 1982; Potmesil and Chakravarty, 1983).

In the case of color, this emphasis on correctly simulating the physical world leads to the conclusion that light must be modelled on a wavelength by wavelength basis (Cook and Torrance, 1982; Hall and Greenberg, 1983; Meyer, 1988). This means that the user of such a rendering system must assign spectral energy distributions to light sources, spectral reflectances to opaque surfaces, and spectral transmittances to transparent objects. To convert the spectral energy distributions that result from the simulation to tristimulus values, the absorptances of a color camera or the human eye must be specified. This necessitates a database of such spectral curves and a means for easily selecting them.

While numerous techniques have been developed to facilitate the selection of color in terms of red, green, and blue tristimulus values or hue, saturation, and brightness color coordinates (Joblove and Greenberg, 1978; Meyer and Greenberg, 1987; Schwarz, Cowan, and Beatty, 1987; Smith, 1979; Taylor, Murch, and McManus, 1989), only very simple systems exist to help select color in terms of wavelength composition (Meyer and Greenberg, 1986). This paper describes a database system that has been developed to help the user of a synthetic imaging system select spectral reflectance, emittance, transmittance, or absorptance distributions. This system allows the user to search for spectral distributions with specific properties, examine those distributions and the colors that they produce, and

2

add new distributions to the database from measured and published curves.

Database Design

For the database, it was decided to use a relational model to reduce the amount of data duplication required. After reviewing several options, including writing a database from scratch in C++, it was decided to use Oracle for Macintosh, a commercially available relational database. Features in its favor included availability on many different platforms, and the ability to call the high level SQL (Structured Query Language) routines from C. This allowed more flexibility in the original design, including the option to pick curves that fall into an arbitrary user-defined class of curves. Also, the networking capability of Oracle will make it possible to place the database on a network file server, with the ability to access it from networked Unix workstations and Macintoshes. The fact that Oracle runs on the Macintosh made it possible for us to take advantage of this machine's graphical user interface in the design of our database access program.

A spectral curve can represent either a reflectance, an emittance, an absorptance, or a transmittance. Each curve that is stored in the database is placed into one of these four categories.

> **reflectance** The amount of light reflected at each wavelength. It has values between 0.0 and 1.0. Example reflectances in the database include those for paints, metals, soils and vegetation, and human skin.

emittance The amount of light emitted at each wavelength. It has values between 0.0 and some maximum emittance. Example emittances in the database include those for the CIE standard sources, blackbody radiators, fluorescent lighting fixtures, and light emitting diodes.

absorptance The amount of light absorbed at each wavelength. It has values between 0.0 and 1.0. Example absorptances in the database include those for the fundamental spectral sensitivities, color camera taking sensitivities, and film dye spectral sensitivities.

transmittance The amount of light transmitted at each wavelength. It has values between 0.0 and 1.0. Example transmittances in the database include those for theater lighting gels, Kodak Wratten filters, color film dyes, and Rayleigh scattering in the atmosphere.

Several pieces of information are stored with each spectral curve. Each curve is identified as belonging to one of the four broad categories mentioned above. Each of these categories is further subdivided into subcategories that more precisely describe what type of curve this is. Example reflectances, emittances, absorptances, and transmittances mentioned above are all subcategories in the database. Basic colorimetric information is also stored with each each of the curves. In the case of reflectances, emittances, and absorptances, the CIE chromaticity and luminance are computed and stored. Initially this is done with respect to CIE standard source C for

4

the reflectances and transmittances. It is possible, however, to designate one of the emittances in the database as the light source to use when performing this calculation for new database entries.

Database Construction and Searching

Curves are input into the database by freehand sketching or by scanning and tracing an existing curve from the literature (Moon, 1941, 1942; McCamy, Marcus, and Davidson, 1976; Wyszecki and Stiles, 1982). In the latter case, a program has been written which allows the individual to use a black and white scan of a spectral curve as a tracing template. Once the diagram has been digitized it is input into the tracing program where the mouse is used to follow the curve outline. Before tracing can begin, the user must locate the axes of the graph and the range of values over which the abscissa and ordinate can vary. Auto tracing techniques were evaluated for this task but they were abandoned because it was not possible to easily handle cases involving grid lines and more than one curve in a diagram. Once the tracing is complete a text file is output containing the value of the curve at five nanometer increments.

To input a curve into the spectral database, the **New** menu button is selected. The user is then prompted to specify either a template or a blank curve. A file produced by the tracing program (or by any text editing program) must be selected if a template is desired. Otherwise, the user is given a blank curve to modify. Certain of the information that is stored for each curve (chromaticity, luminance, etc.) is automatically calculated and some of it (category, color name,

5

etc.) must be input manually. Once the user is satisfied with the definition of the curve the **Save** menu button is chosen.

There are several ways in which the database can be searched and curves can be selected. The most straightforward is to peruse the entire list of curves and make a choice from it. Another search technique is to look for a key or keys that match a particular string or pattern. The most general approach is to make use of the structured query language (SQL) that Oracle provides. SQL makes it possible to look for curves that have specific parameters or that have values that fall within a certain range. For example, as shown in Figure 1, all curves that have chromaticity coordinates within a certain region of the chromaticity diagram can be located. Or a curve can be identified that has a specific category or subcategory. Figure 1 shows the result of searching for all curves that have the skin subcategory.

Once a curve of interest has been identified, the user can open it and display the information that is stored with it. For example, Slide 1 shows the spectral reflectance curve for dark Caucasian skin and the chromaticity for this curve on a chromaticity diagram. The patch in the upper left hand corner of the spectral plot in Slide 1 displays the color of this reflectance when illuminated with CIE standard source C. Clicking on the color patch activates a color selection palette program and shows the position of the color within a standard color solid. Modifications can be made to the reflectance curve, and, as these alterations occur, the color swatch and chromaticity diagram are immediately updated to reflect the changes that have been made. A

6

Search String: WHERE SUB_CATEGORY='skin'

Sample Search Strings:
WHERE SUB_CATEGORY = 'brick'
WHERE SOURCE like '*KRINOV*'
WHERE CIE_X > 0.5 AND CIE_Y > 0.5

[Ok]   [Cancel]

cauc1
cauc2
cauc3
hindu
japanese
mulatto

[Open]

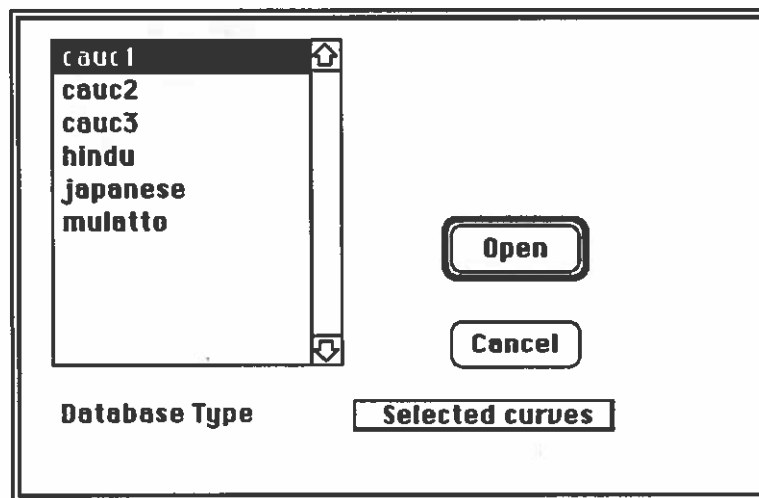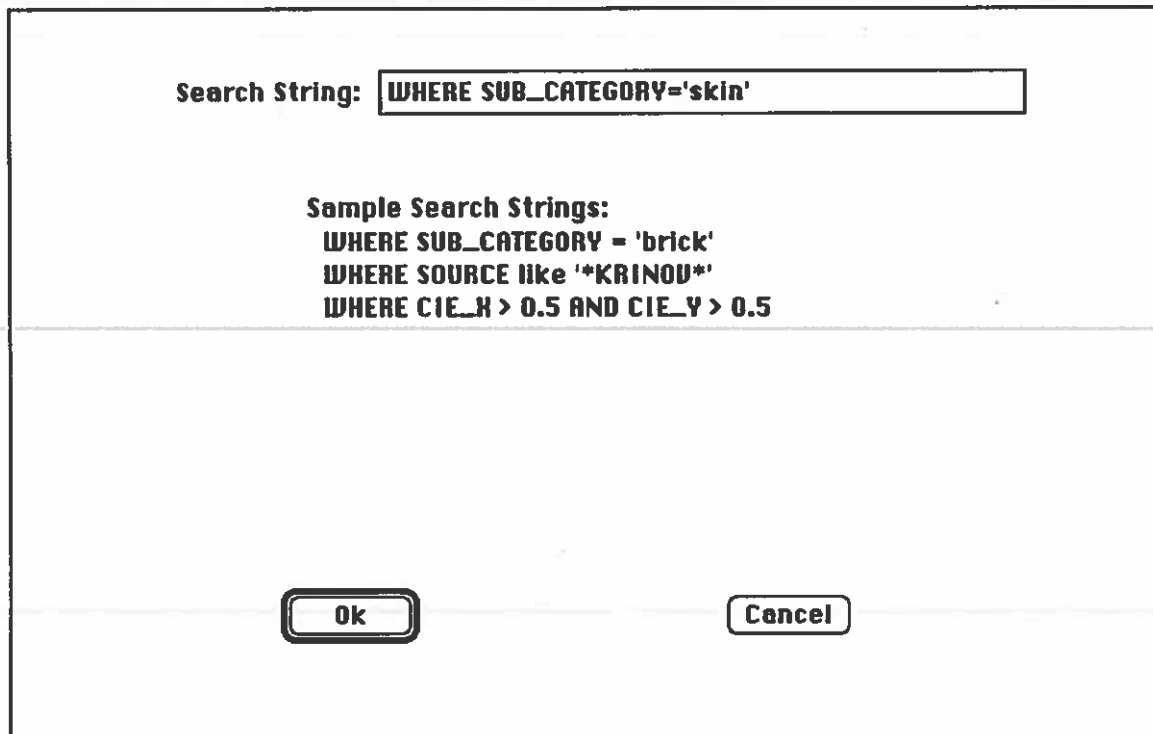[Cancel]

Database Type   Selected curves

Figure 1. Use of Structured Query Language to search the database for all curves having subcategory of skin (top) and resulting list of curves (bottom).

7

rendering program is available to examine the reflectance when it is applied to a three dimensional surface. Slide 1 shows two spheres that have been created using different shading parameters to show how the color looks under strictly diffuse and under diffuse plus specular illumination.

Analytically Defined Functions

In addition to storing measured spectral reflectance, emittance, absorptance, and transmittance curves, the database can also compute certain analytically defined spectral curves. The dialog boxes that are used to set the parameters for some of these functions are shown in Figure 2.

blackbody radiation The spectral emittance curve for blackbody radiation can be computed at any given temperature in degrees Kelvin. This allows the user of the database, for example, to examine the color of different white point settings for a color television monitor.

Rayleigh scattering The simple inverse quadratic power law relationship that governs the scattering of light in the atmosphere can be used to compute the color of the sky (Klassen, 1987). An example of the use of this color in the production of a synthetic image is given in Slide 2.

8

Black Body

$$E(\lambda)=\frac{2\pi C_1}{\lambda^5(e^{C_2/\lambda T}-1)}$$

$$C_1=0.59544 \times 10^8 \; \frac{W\mu m^4}{m^2}$$

$$C_2=14.388 \; \mu mK$$

⦿ T=2856K
◯ T=5400K
◯ T=6500K
◯ T=9600K
◯ Other: T= [2856.000] K

[OK]
[Cancel]

Rayleigh Scatter

$$E(\lambda)=\frac{1}{\lambda^4}$$

[OK]
[Cancel]

Single layer interference

$$I(\lambda)=\left[A_0(\lambda)\cos\left(\frac{2\pi tn}{\lambda}\right)\right]^2$$

Thickness: [425.000] nm.
Index of refraction: [1.50000]

[OK]
[Cancel]

Multi-layer interference

$$I(\lambda)=\frac{1}{2}A_0(\lambda)\left(\frac{\sin 2\pi(l+1)t\lambda}{\sin 2\pi t\lambda}\right)^2$$

Thickness: [510.000] nm.
Number of layers [6]

[OK]
[Cancel]

Figure 3.   Dialog boxes used to set parameters for various types of analytically defined spectral curves.

interference phenomena   The colors produced by single and multiple thin film interference effects can be investigated (Smits and Meyer, 1990).   The thickness of the film and the number of film layers can be specified, and the resulting spectral reflectance computed.   As can be seen in Slide 3, the sinusoidal shape of the reflectances for single film interference makes them spectral in nature, but they also have tails that give them a more pastel color.   The "Newton's colors" depicted in Slide 3 are used in Slide 4 to produce an image of an oil slick on wet pavement.   On the other hand, for multiple thin film interference, the reflectance curve has a sharper peak and is therefore much closer to being a spectral color.   Slide 5 shows the spectral reflectances that result due to multiple thin film interference on the surface of the Morpho butterfly.   Slide 6 shows how these colors vary with surface orientation giving a metallic appearance, and Slide 7 shows the colors on the surface of the butterfly itself.

pigment mixing   Colors produced by mixing together standard pigments can be investigated.   Pigment curves that are included as reflectances in the database can be selected, the proportion of each that is desired can be specified, and pigment mixing theory applied to produce the resulting color (Kubelka and Munk, 1931; Kubelka, 1948).   For example, paint mixing on an artist's palette can be simulated by using the standard artist's pigments.

10

Curves produced from their analytical definition are treated the same as new curves that are read in from the curve scanning program. As such, they can be added to the database provided that the user supplies necessary information regarding category, subcategory, and other descriptive data. Emittance curves defined in this way can also become the light source that is used to determine the color of reflectances and transmittances. For example, the user can experiment with the color produced by shining the light from a series of blackbody radiators of different color temperature on a single reflectance patch. Additional analytically defined spectral functions will be added to the database in the future. These might include such things as the laws governing refraction (Thomas, 1986; Musgrave, 1989) and diffraction effects (Nakamae, et. al., 1990).

Conclusions

A database for accessing spectral reflectance, emittance, transmittance, and absorptance curves has been developed. This database allows the user of a synthetic imaging system to select reflectances for opaque surfaces, emittances for light sources, and transmittances for transparent materials. The standard CIE XYZ matching functions can be used as absorptances to convert spectral energy distributions to tristimulus values. The absorptances of specific imaging systems such as color television and film can also be explored. Tools are provided to assist the user in inputing new curves into the database and in searching the database for a particular curve. The database currently contains some 500 spectral

curves taken from the literature and four different types of analytically defined curves. Work continues on expanding the database to contain additional curves and analytical functions.

Acknowledgements

References

Cohen, M., and Greenberg, D. P., (1985), "The Hemi-Cube: A Radiosity Solution for Complex Environments," *Computer Graphics, 19*, 31-40.

Cook, R. L., and Torrance, K. E., (1982), "A Reflectance Model for Computer Graphics," *ACM Transactions on Graphics,1*, 7-24.

Goral, C. M., Torrance, K. E., Greenberg, D. P., and Battaile, B., (1984), "Modeling the Interaction of Light Between Diffuse Surfaces," *Computer Graphics, 18*, 213-222.

Hall, Roy A. and Greenberg, Donald P., (1983), "A testbed for realistic image synthesis," *IEEE Comput. Graphics Appl., 3*, 10-20.

Isaacs, Paul M. and Cohen, Michael F., (1987), "Controlling Dynamic Simulation with Kinematic Constraints, Behavior Functions, and Inverse Dynamics," *Computer Graphics, 21*, 215-224.

Joblove, G. H. and Greenberg, D. P., (1978), "Color spaces for computer graphics," *Computer Graphics, 12*, 20-25.

Kajiya, J. T. (1986), "The Rendering Equation," *Computer Graphics, 20*, 143-150.

Klassen, R. Victor, (1987), "Modeling the Effect of the Atmosphere on Light," *ACM Transactions on Graphics, 6*, 215-237.

Kubelka, P. and Munk, F., (1931), "Ein Beitrag zur Optik der Farbanstriche," *Z. tech. Physik.*, *12*, 593.

Kubelka, P., (1948), "New Contributions to the Optics of Intensely Light-scattering Materials, Part I," *J. Optical Society of America*, *38*, 448.

McCamy, C. S., Marcus, H., and Davidson, J. G., (1976), "A color-rendition chart," *J. Appl. Photogr. Eng.*, *2*, 95-99.

Meyer, Gary W. (1988), "Wavelength Selection for Synthetic Image Generation," *Computer Vision, Graphics, and Image Processing*, *41*, 57-79.

Meyer, Gary W., and Greenberg, Donald P., (1986), "Color Education and Color Synthesis in Computer Graphics." *Color Research and Application*, *11*, S39-S44.

Meyer, Gary W., and Greenberg, Donald P., (1987), "Perceptual Color Spaces for Computer Graphics." in *Color and the Computer*, ed. by H. John Durrett. Academic Press, Boston.

Moon, Parry, (1941), "Colors of ceramic tiles," *Opt. Soc. Am.*, *31*, 482-487.

Moon, Parry, (1941), "Optical reflection factors of acoustical materials," *Opt. Soc. Am.*, *31*, 317-324.

Moon, Parry, (1941), "Wall materials and lighting," *Opt. Soc. Am.*, *31*, 723-729.

Moon, Parry, (1942), "Colors of furniture" *Opt. Soc. Am.*, *32*, 293-298.

Moon, Parry, (1942), "Reflection factors of floor materials," *Opt. Soc. Am.*, *32*, 238-242.

Moon, Parry, (1942), "Reflection factors of some materials used in school rooms," *Opt. Soc. Am.*, *32*, 243-246.

Musgrave, F. Kenton, (1989), "Prisms and Rainbows: A Dispersion Model for Computer Graphics," *Graphics Interface '89*, 227-234.

Nakamae, Eihachiro, Kaneda, Kazufumi, Okamoto, Takashi, and Nishita, Tomoyuki, (1990), "A Lighting Model Aiming at Drive Simulators," *Computer Graphics, 24,* 395-404.

Platt, John, and Barr, Alan, (1988), "Constraint Methods for Flexible Objects," *Computer Graphics, 22,* 279-288.

Potmesil, M. and Chakravarty, I., (1982), "Synthetic Image Generation with a Lens and Aperture Camera Model," *ACM TOG, 1,* 85-108.

Potmesil, M. and Chakravarty, I., (1983), "Modeling Motion Blur in Computer-Generated Images," *Computer Graphics, 17,* 389-399.

Rushmeier, H. E., and Torrance, K. E., (1987), "The Zonal Method for Calculating Light Intensities in the Presence of a Participating Medium," *Computer Graphics, 21,* 293-302.

Schwarz, M. W., Cowan, W. B., and Beatty, J. C. (1987), "An experimental comparison of RGB, YIQ, LAB, HSV, and opponent colour models," *ACM Trans. Gr., 6,* 123-158.

Smith, A. R., (1979), "Colour gamut transform pairs," *Comput. Gr. 13,* 12-19.

Smits, Brian E. and Meyer, Gary W., (1990), "Newton's Colors: Simulating Interference Phenomena in Realistic Image Synthesis," *Proceedings of the Eurographics Workshop on Photosimulaton, Realism and Physics in Computer Graphics,* 185-194.

Taylor, Joann M., Murch, Gerald M., and McManus, Paul A., "TekHVC: A Uniform Perceptual Color System for Display Users," *Proceedings of the SID, 30,* 15-21.

Thomas, Spencer W., (1986), "Dispersive Refraction in Ray Tracing," *Visual Computer, 2,* 3-8.

Wilhelms, Jane and Barsky, Brian, (1988) "Using Dynamic Analysis to Animate Articulated Bodies Such As Humans and Robots," *Proceedings of Graphics Interface.*

Wyszecki, Gunter and Stiles, W. S., (1982), *Color Science: Concepts and Methods, Quantitative Data and Formulae*, 2nd Ed., Wiley, New York.
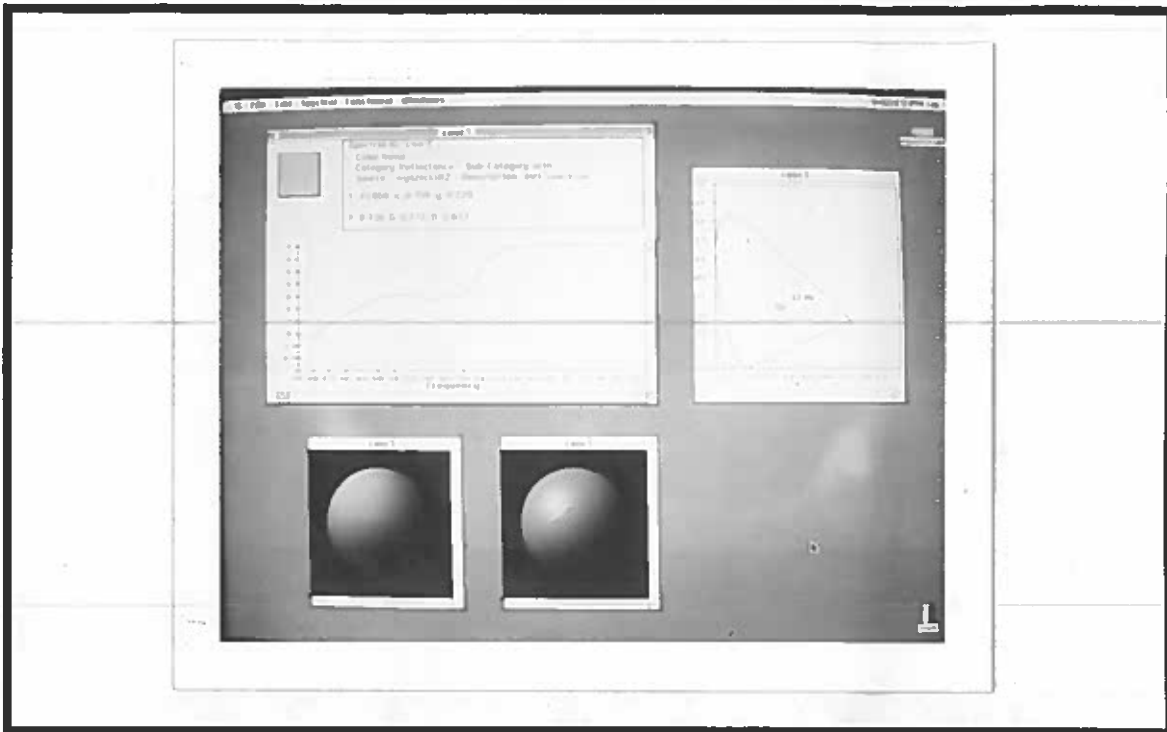
Slide 1: Spectral reflectance of human skin, the color that is produced when this reflectance is illuminated by CIE standard source C, and how the color appears when rendered with both diffuse and specular reflection.


Slide 2: Blue sky color selected by using the analytical expression for Rayleigh scattering.
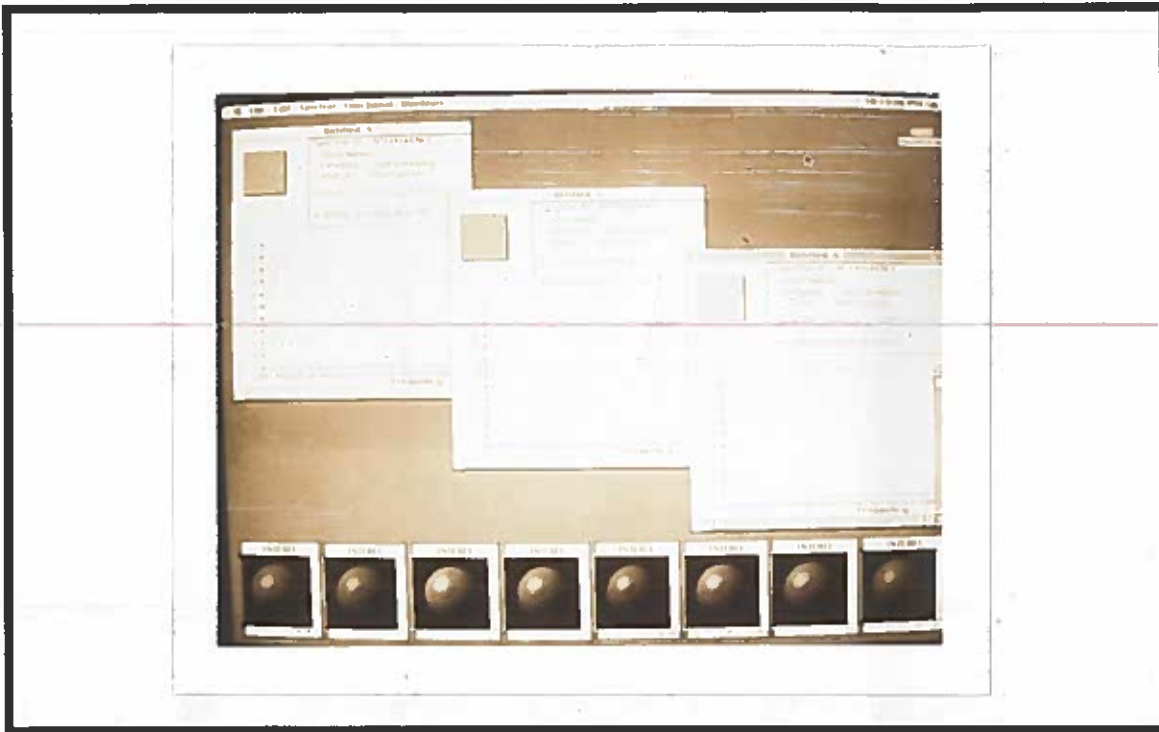
Slide 3: Spectral reflectance curves for three different single film interference thicknesses and the Newton's colors produced by a sequence of different film thicknesses.
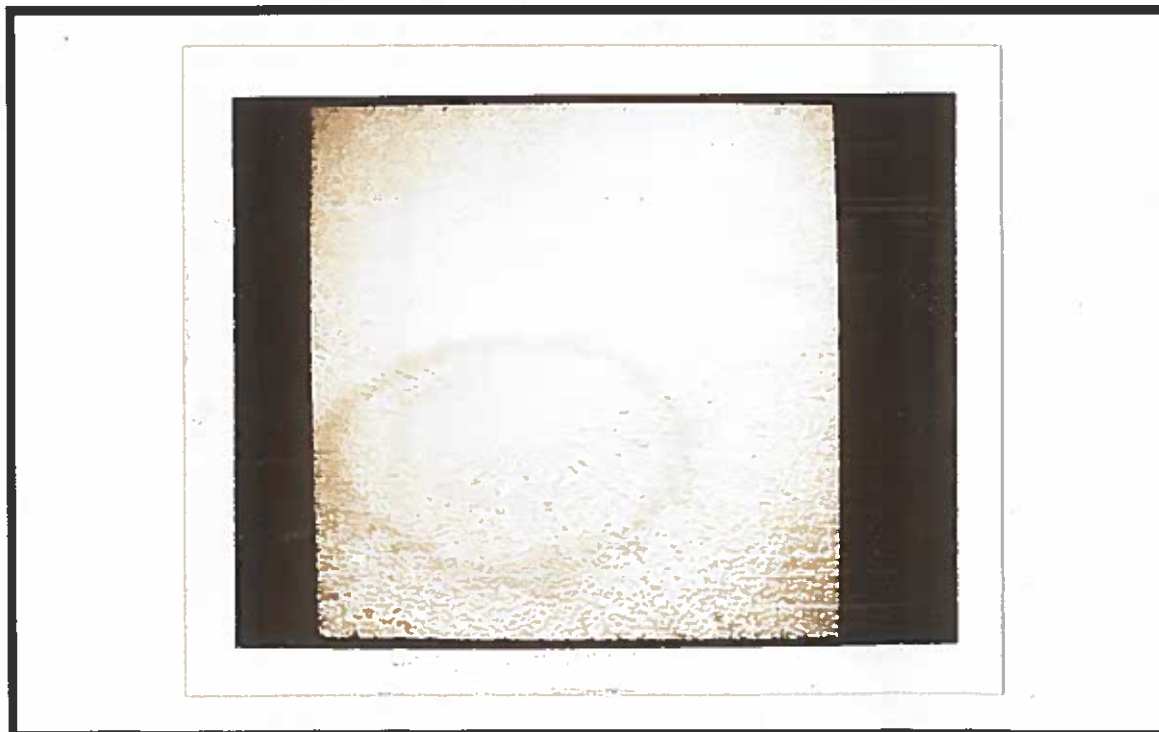

Slide 4: Simulation of an oil film on wet pavement showing the Newton's color sequence from Slide 3 (from Smits and Meyer, 1990).

17
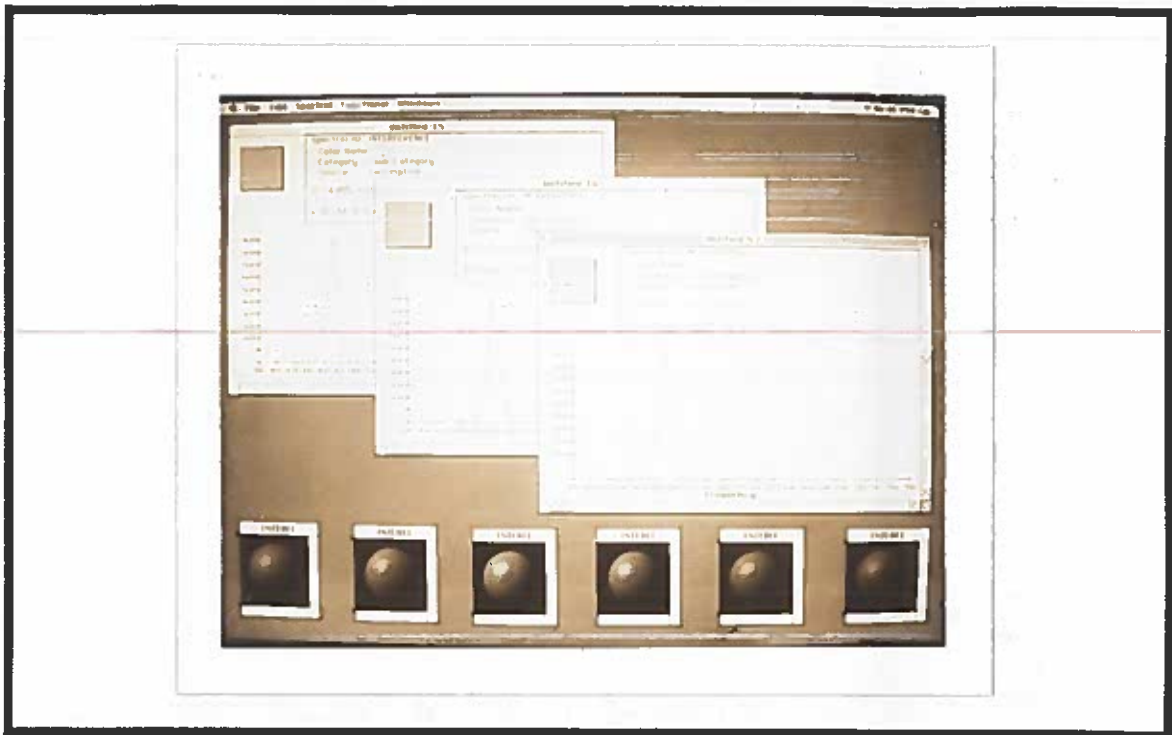
Slide 5:   Spectral reflectance curves for three different film thicknesses in twelve layer multiple film interference.   Color sequence that occurs when viewing Morpho butterfly wing at various angles.

Slide 6:   Color sequence from Slide 5 used to show metallic color appearance that results due to color variation with viewing angle.
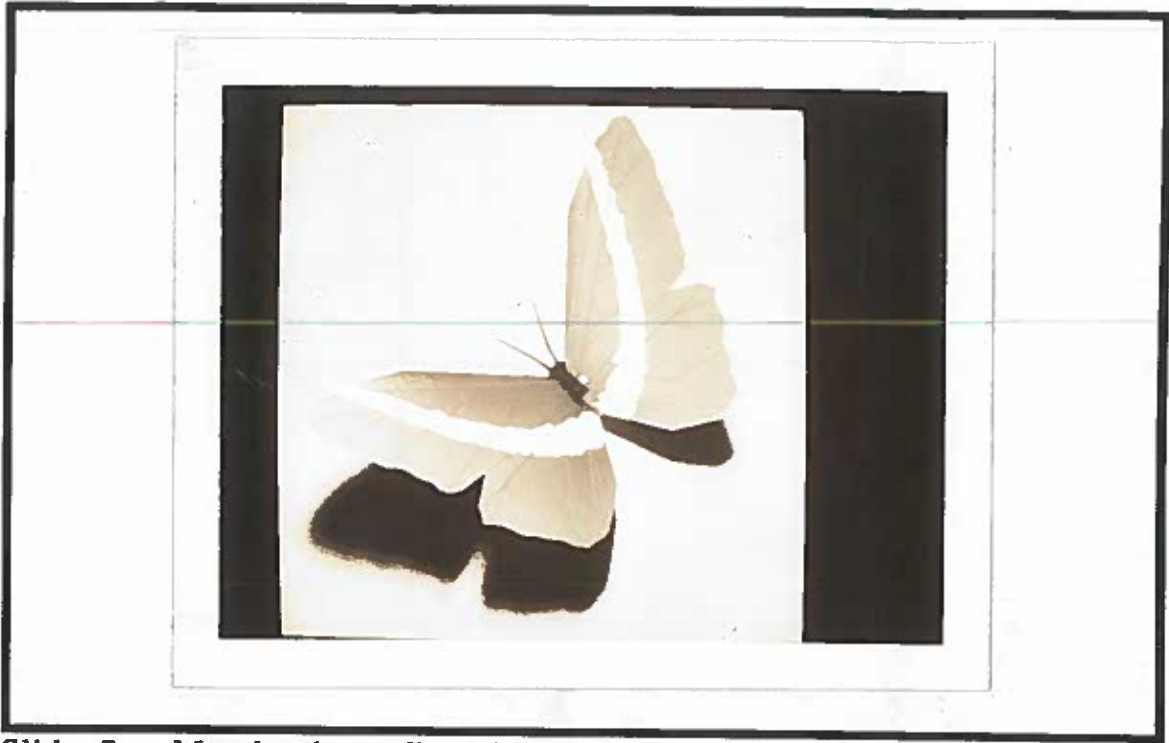
Slide 7: Morpho butterfly with wing color due to multiple thin film interference.

19