A Physically Based Anisotropic Iridescence Model for Rendering Morpho Butterflies Photo-realistically

Iman Sadeghi∗
University of California, San Diego

Figure 1: Rendered images of Morpho butterflies from different viewing angles showing the anisotropic iridescence colors of the developed model. To watch a short video check author’s web-page.

Abstract

Rendering the brilliant iridescent colors of the Morpho butterflies has been a challenge in computer graphics. The cause of vivid blue color of the wings of these species is not as the result of the pigments of the wing. They are caused by the physical microscopic structures on the scales of the wing. These micro-structures has been studied extensively in various fields by different expertise [Yinlong Sun . 2006] [FOX, D. 1976] [VUKUSIC, P. AND SAMBLES, R,2003].

In this paper I have addressed the problem of rendering the anisotropic iridescence colors of the Morpho butterflies photo-realistically. The developed model is physically based and combines two previously presented models; Multi-layer thin film model [Yinlong Sun . 2006] and separate lamellae model [S.KINOSHITA et al. 2002]. Both of those models fail to describe the anisotropic nature of the light reflectance on these structures. The introduced model in this paper produces an anisotropic model with interpolating between those two isotropic models. The model is based on the physical properties and analytical derivations of the microscopic structures of on the scales of the wings.

Rendered images with this model match the experimental description [Fox 1976; Simon 1971] of iridescence properties of the Morpho butterflies.

Keywords: Morpho butterfly, iridescence, interference, photo-realistic rendering, physically based model

1 Introduction

∗e-mail: iman@graphics.ucsd.edu

Iridescence is an optical phenomenon characterized as the property of surfaces in which hue changes according to the angle from which the surface is viewed. Iridescent colors occur on many animals such as butterflies, beetles, birds, and fishes [Fox 1976; Simon 1971]. They also occur on soap bubbles, shells, opals and some plants [Lee 1991, 1997; Vukusic and Sambles 2003]. Ordinary colors are caused by pigments inside the material and insensitive to directions [Fox 1979; Judd and Wyszecki 1975; Verity 1980]. In contrast, iridescent colors are caused by micro-structures and therefore are sensitive to change of viewing directions. Iridescence is caused by multiple interaction of light with different micro-structures of the material in which phase shift and interference of the reflections modulates the incident light by amplifying or attenuating some frequencies more than the others.

According to studies, the physical origins for biological iridescences are light interference at multiple thin layers and also diffraction of light at gratings [Nassau 1983; Parker et al. 2001; Vukusic and Sambles 2003; Williamson and Cummins 1983]. These physical origins have been investigated by different expertise with different interests for a long time [Fox 1976; Kinoshita et al. 2002; Mason 1927; Parker 2000; Vukusic and Sambles 2003].

In the case of Morpho butterflies iridescence is caused by the sub-micron structures on the scales of the wing. These structures cause an extraordinarily uniform color reflectance along a fixed viewing direction cite3. The interaction of light with multiple layers of these microscopic structures are the main source of iridescence colors of the wings. Multi-layer nature of those structures plus their lamellar shapes with irregular heights are important aspects in producing those iridescence colors [Yinlong Sun . 2006] [S.KINOSHITA et al. 2002]. Besides, it has been shown that the presence of pigment beneath the iridescent scales greatly enhances the purity of the reflected colors by absorbing the undesirable background lights.

2 Previous Works

Any natural phenomena which relates to the interference of light and the iridescence reflectance of light has been the topic of research from different perspectives. They have been studied by
physicist, biocientist chemist and computer graphics researchers.

In the history of computer graphics, there are many studies involving or representing the structural colors. In [Fred Almgren et al 1993] developed a shading model for rendering soap film interference. They surveyed their results on the geometry of bubble clusters for rendering soap bubbles photo-realistically. In this another paper [Fred Almgren et al 1990] proposed a model on streaks of light taking into account both refraction and diffraction of light aiming at drive simulators. In [Jay S. Gondek et al 1994] developed a virtual goniophotometer by using a Monte Carlo ray tracer to cast rays into a surface for analyzing and making pictures of thin films, idealized pigmented materials, and pearlescent paints. Later on in another publications [T.Nishiya et al 1996] [A.J. Freeham et al 1999] an analytic model for rendering sunlight and sunlight considering the effects of atmosphere were developed. This paper [N. Nagata, et al 1997] proposed a method of modeling and visualizing pearls for a pearl-quality evaluation simulator, by using a physical model, called an “illuminant model,” for multi-layer film interference considering the multiple reflection in spherical bodies. Stam developed a reflection models for metallic surfaces that handle the effects of diffraction [Jos Stam 1999].

Specifically, rendering Morpho butterflies has been tackled by different physically based models. Such as modeling the wings with multi-layer thin film models [Yinlong Sun , 2006] [J.Gonzato et al. 2003] or with some variation of a multi-layer thin film as in [K.Ishiguro et al. 1985] or with totally different models as presented in [S.KINOSHITA et al. 2002] which modes the structures by simple separate lamellar micro-structures. We will discuss these models more in depth later in this paper.

4 Developed Model

The model presented in this paper is very similar to the model in [S.Iwasawa et al. 2004]. There are some differences which I will explain later in in section 6.2. In that paper they have considered two perpendicular directions on the wings of butterflies. One along the direction of the ridges and one perpendicular to the other one. If the light intersect with the wings perpendicular to the direction of ridges the appropriate model would be Separate Lamellae described in [S.KINOSHITA et al. 2002]. In contrast, if the light intersect with the wing along the ridges the appropriate model would be the multi-layer thin film described in [Yinlong Sun , 2006] [J.Gonzato et al. 2003]. At the end we interpolate between the results of these two models for any given direction to approximately simulate the anisotropic iridescence appearance of the butterfly wings.

4.1 Theoretical Background

4.1.1 Multi-layer Thin Film Model

The multi-layer thin film has been used extensively for simulating the appearance of Morpho butterflies [Yinlong Sun , 2006] [J.Gonzato et al. 2003] [S.Iwasawa et al. 2004]. I chose the paper by Y.Sun [Yinlong Sun , 2006] as my reference for this model which was itself a paper about rendering Morpho butterflies. Obviously this model fails to explain the anisotropic property of the light reflectance on the wings. It simply assumes that the wings have a multi-layer thin film structure in any given direction. The motivation for choosing this model is that many studies with electron microscopy have showed that the main reason for iridescence reflectance of the light in many different species of insects is the light interference at multiple thin layers [Anderson and Richards 1942; Ghiradella 1991; Tabata et al. 1996; Vukusic et al. 2001b].

The author of [Yinlong Sun, 2006] has derived an analytical solution for the problem and then introduced an approximation which almost matches the exact analytical curve for higher performance. [Yinlong Sun , 2006]

The model consists of $N$ parallel thin films separated by another medium (in our case the air), and has $2N$ interfaces between these

3 Iridescence in Morpho Butterflies

The wings of male Morpho butterflies demonstrate iridescent colors which varies from cyan to blue and violet, with increase of the lighting or viewing angle [Fox 1976; Simon 1971]. Also, under some conditions the iridescence of a Morpho butterfly disappears for example by increasing the viewing angle [Fox 1976; Vukusic et al. 2001a].

According to studies by electron microscopes the ridges extend into the air in multiple layers and film thickness and air thickness are almost the same about 90 nm [Nassau 1983]. The refractive index of the solid material of the wings is 1.56 [Vukusic et al. 1999]. When the light interacts with the ridges, multiple rays reflect from the film surfaces. These rays interfere with each other and make the iridescence color which is amplified in some wave lengths and attenuated in some other wave lengths. The number of layers for the Morpho butterfly is around 10 in average.

The studies with an electron microscope [Vukusic and Sambles 2003] show that the spatial distribution of lamellar ridges are to be periodic. The laminage of the ridge can be simulated as a perfectly periodic multi-layer plus some random fluctuations in the layer thicknesses. These random factors will make the interference spectra broader and result in less saturated colors.

This simple model also applies to many other iridescent animals such as ground beetles [Yinlong Sun , 2006] [Fox 1976; Simon 1971].
layers. All of the film layers have exactly the same physical properties like index of refraction, width etc. Also, the model assumes that the absorption of light is zero at each interface. In this model Y.Sun mathematically justifies that it is sufficient to consider only the rays that have exactly one reflection and ignore the ones with multiple reflections.

The derived analytic formula for this simplified model is described as:

\[ I_{out} = I_{in}r[1 - (1 - r^2)e^{-i\sigma_a}] \frac{1 - (1 - r^2)^2e^{-i\sigma_b}N}{1 - (1 - r^2)^2e^{-i\sigma_b}} \] (1)

where \( N \) is the number of thin film layers, \( r \) is the Fresnel term and \( I_{in} \) and \( I_{out} \) are the incoming intensity and outgoing intensity of light respectively. Besides, \( \sigma_a \) and \( \sigma_b \) are defined as:

\[ \sigma_a = \frac{4\pi}{\lambda}n_{film}d_{film}\cos\theta' \] (2)

\[ \sigma_b = \frac{4\pi}{\lambda}(n_{film}d_{film}\cos\theta' + d_{air}\cos\theta) = \sigma_a + \frac{4\pi}{\lambda}d_{air}\cos\theta \] (3)

where \( \theta \) is the viewing angle and \( \theta' \) is the refracted direction of ray after first interaction with the thin layers.

This model is able to described some observed properties of the biological iridescence. For example it shows that when the viewing angle is zero the reflectance is dominated by a single peak around \( \lambda = 460.8 \text{ nm} \) which corresponds to cyan color. Also, it can describe the movement of the reflectance peak toward the short-wavelengths when the viewing angle increase which matches the color change in wings of Morpho from cyan to blue and violet when the \( \theta \) increases. [Fox 1976; Simon 1971]. When the viewing angle goes toward the \( \pi/2 \) the peak goes out side of the visible spectrum and the iridescent colors disappear.

For more information and details about this model refer to [Yinlong Sun . 2006]. Note that this model naturally assumes that light is always incident to the surface from all directions and therefore is light direction independent.

4.1.2 Separate Lamellae Model

This model is fully described in [S. KINOSHITA et al. 2002] where the authors state that the extraordinarily uniform color of the wings of Morpho butterflies cannot be explained using a simple multi-layer interference model. They had performed microscopic, optical and theoretical investigations on the wings of four Morpho species and have found that separate lamellar structure with irregular heights is extremely important. By introducing a very simple model, they have shown that the combined action of interference and diffraction is essential for the structural color and it matches the experimental results very well.

Similar to the multi-layer thin film model the separate lamellae model does not consider the anisotropic nature of the wings and basically provides a two dimensional reflectance model for these structures. This model assumes that the wing surface is composed of periodical tree-like structures. The derived analytical model of iridescence function of Morpho wings has the following assumptions:

1) the lamellae has finite length and separated by air layer with each adjacent lamellar
2) each tree is elevated randomly in vertical direction and the amount of elevation is not correlated with its neighbors.

In this model authors have assumed a beam of light is incident on \( N \) separate lamellae having a finite width in one direction and an infinite length in the other. Further, each cuticle layer is assumed to be infinitely thin, and the incident and diffracted light is not subjected to reflection nor refraction while passing through the other layers. In their simplified model they do not take into account the multiple reflection of light between the cuticle layers. However, at the end they show that this simple model matches with the measured data very closely.

According to this model the intensity of the diffracted light toward the viewing angle \( \phi \) given a light direction \( \theta \) is expressed as:

\[ I_{\phi} = I_0 \frac{N}{2\pi^2} \frac{\sin^2(\pi dvM/\lambda) \cos^2(\pi au/\lambda)}{\sin^2(\pi dv/\lambda)} \frac{\sin^2(\pi dvM/\lambda)}{\pi^2} \cos^2\theta \] (4)
where $\phi$ is the outgoing light direction and $\theta$ is the incoming light direction and $\lambda$ is the wavelength. $M$ is the number of layers stacked on top of each other and $N$ is the number of lamellar structure incident to a beam of light. $d$ and $a$ are the distance between two layers and width of a lamellar structure respectively. $u$ and $v$ are defined according to the following formulas:

$$u = \sin \theta + \sin \phi$$

$$v = \cos \theta + \cos \phi$$

For more information and details about this model refer to [S.KINOSHITA et al. 2002]. Note that this formula is defined for a two dimensional model and is both view direction dependent and light direction dependent.

4.1.3 Interpolating Between Two Models

I used a simple interpolation scheme for interpolating between the two models. The formula is

$$L_1 \cos(\omega) + L_2 \sin(\omega) \rho \cos(\phi)$$

and is different from the formula used in [S.Iwasawa et al. 2004] which is $(L_1 + L_2 + (L_1 - L_2)\cos2\omega)/2$. But according to my implementation this will not affect the simulation results dramatically. Image to the left of Figure 7 shows how these two different models are blended together to result in an anisotropic reflectance function.

5 Implementation

5.1 Rendering

For using both described models one has to calculate the spectral reflectance of light on each point on the wings of the butterfly. In current implementation of reflectance intensities are calculated in the range of 380nm to 740nm range, every 5nm apart. In order to calculate the intensity of incidence light, I used CIE standard illumination D65 in all the incoming directions (Simulation of outdoor environment during the day). Then the spectral intensities are converted to their corresponding XYZ values using CIE1931 matching curves and at the end XYZ values are converted to the RGB using standard NTSC conversion matrix. Note that here it is not necessary to have a rendering engine which supports full spectrum rendering. One only needs to convert the incident light from RGB to full spectrum and after calculating the reflected light spectrum convert it to RGB. However, I have ignored the first part for incident light and always assumed that the incident light is standard D65.

5.1.1 Multi-layer Thin Film

For simulating the multi-layer thin film properties of the wings I used the approximation of equation 8 derived in [Yinlong Sun . 2006] since it is simpler and closely matches the exact curves. The approximation formula is stated as:

$$I_{out} = I_{in} C_{interf} \rho |\cos(\sigma_b)|^m$$

if $\cos(\sigma_b) > 0$ and $0$ Otherwise where $\sigma_b$ is defined as before:

$$\sigma_b = \frac{4\pi}{\lambda} (\eta_{film} d_{film} \cos \theta' + d_{air} \cos \theta)$$

Refer to [Yinlong Sun . 2006] for more explanations of this approximation equation.

In order to simulate the multi-layer thin film appearance I had to calculate the equation 8 for all diffract wavelengths near the visible spectrum and cumulate the results and convert them to XYZ. And at the end convert the resulted XYZ value to RGB triplet and display them. Figure 7 shows a butterfly rendered solely with the multi-layer thin film model.

5.1.2 Separate Lamellae

As I mentioned in section 4.1.2 the proposed reflectance model is both view direction dependent and light direction dependent. But in order to interpolate between two diffract reflectance function they should have the same dimensionality. Therefore, I had to either make the multi-layer thin film model light direction dependent or make the separate lamellae model light direction independent. I chose the latter approach by integrating the equation 4 over all the incoming directions for the light.
In other words for any given view direction $\phi$ I have to calculate the following integral:

$$I_\phi = \frac{N}{2\pi^2} \int_{\theta = -\pi/2}^{\pi/2} I_{\theta} \sin^2(\pi d M / \lambda) \sin^2(\pi d u / \lambda) \frac{(u/\lambda)^2 - \cos^2 \theta d\theta}{\sin^2(\pi d u / \lambda)} \cos^2(\pi d v / \lambda) \sin(\pi d v / \lambda) (10)$$

However, integration the equation 4 analytically is very difficult and because of complex nested $\sin$ functions even commercial mathematical softwares refused to find the analytic solution to the integral. I solved this integral numerically by sampling the light direction in every degree. Note that this integral should be evaluated for all diffract wave-lengths as well. Therefore, this step is computationally expensive and solving the integration analytically would speed up this step dramatically. Image to the right of figure 7 shows a butterfly rendered solely with the separate lamellae model.

5.2 Modeling

All the models used in this paper are modeled by the author using Maya. The Modeling process was based on a photograph of the a Morpho butterfly taken from the Society of Structural Color’s webpage (http://mph.fbs.osaka-u.ac.jp/ssc/). The model also includes bump-maps, iridescence-maps, direction-maps and texture-bitmaps for the back of wings (see figure 6). All the texture-maps are also generated from the base photograph. Bump-maps are used to perturb the normals and were essential in giving the butterfly a photorealistic look. Iridescence-maps are used to determine the material of the surface and determine whether the iridescence shader should be used or not. Direction-maps will provide the direction of ridges on the wings and are essential for the anisotropic simulation of the wings. Figure 6 shows the model and all these texture-maps together.

6 Results and Discussion

6.1 Rendered Images

Figures 1 8 and 9 show some rendered images of the Morpho butterfly from different viewing directions. The shading model is independent of the direction of the light and assumes the light reaches the surface from all the direction by the spectrum distribution according to standard CIE D65. Figure 8 (right) best shows the anisotropic behavior of the model where the direction of the ridges change between the regions of the wing. The sophisticated geometry model, bump-mapping and iridescence-mapping and direction-mapping (see figure 6) have added a lot to the realism of the results. Figure 1 shows some snapshots of a movie which is available on the author’s web-page. (http://graphics.ucsd.edu/imam) This movie perfectly shows the behavior of the developed iridescence shading model.

6.2 Contributions

The rendering model developed in this paper is very similar to the paper [S.Iwasawa et al. 2004]. Still there are some differences that I want to emphasis on.

First major difference is that for the multi-layer model they used a more sophisticated model called "Inclined and Curved Multi-layer model" introduced in [K.Ishiguro et al. 1985] by K.Ishiguro. The reason being that in reality the cuticle layers are not perfectly parallel to the wing’s surface but they are slightly curved irregularly and inclined upward from the inside to the outside of the wing. Note that this model, like the regular multi-layer thin film model, is light direction independent. For more details and exact derivations refer to [S.Iwasawa et al. 2004] and [K.Ishiguro et al. 1985].

Secondly it in [S.Iwasawa et al. 2004] they combined have separate lamellae model and curved and inclined multi-layer model (which are both light direction dependent). So their resulted model would be dependent on both the position of the light and the viewing angle. In this paper, as described in section 5.1.2 I have made the separate lamellae model light direction independent by taking the integral over all incident directions. Hence, there is a major difference between the two models in dependency on the light direction.

One other difference is the interpolation scheme which is different in my implementation and the one described in [S.Iwasawa et al. 2004] . However, according to my implementation this difference does not affect the final images noticeably. One other minor difference is that in [S.Iwasawa et al. 2004] authors have assumed that the direction of the ridges are simply toward the outside of the body of the butterfly. In contract, I have considered diffract direction of ridges in different areas of the wing by using direction-maps which has added to the photo-realism of the results.

7 Conclusion

I have developed an iridescent anisotropic shading model for rendering Morpho butterflies photo-realisticly. Rendered images match the experimental descriptions of the iridescent properties of Morpho butterfly [Fox 1976; Vukusic et al. 2001a; Simon 1971].
The developed anisotropic model is archived by combining two
diffract isotropic models and applying them in two different direc-
tions. These directions presents the orientation of the underlying
microscopic structures.

For the future work I will compare my rendered images with the ap-
pearance of a real butterfly. Also, I plan to come up with an analytic
solution for the integration in the separate lamellae model which is
currently calculated numerically and is very slow and computa-
tionally expensive. Also, one can consider the shape of the lamellae
on the wing and the fact that at the top they are narrower than at their
bottom. This may lead to a new and more accurate model.

References

SHUN IWASAWA, NAOHiro SHIChIJO, YOICHIro KAWAGUCHI
2004. VRenDing Methods for Models With Complicated Micro
Structures

YINLONG SUN 2006. Rendering Biological Iridescences with
RGB-Based Renderers

SHUICHI KINOSHITA, SHINYA YOSHIOKA, YASUHIRO FUJI,
NAOKO OKAMOTO 2002. Photophysics of Structural
Color in the Morpho Butterflies

J.-C. GONZATO, B. PONT 2003. A phenomenological representa-
tion of iridescent colors in butterfly wings

ISHIGURO, K., IKEDA, H., YOKOTA, E. 1985. Nature of
Multilayer Film. Optical Thin Film. Optical Technique Series

University of California Press, Berkeley, CA

SIMON, H. 1971. The Splendor of Iridescence of Structural Col-
ors in the Animal World. Dodd, Mead Company, New York, NY.

LEE, D. W. 1991. Ultrastructural basis and function of iridescent


VUKUSIC, P. AND SAMBLES, R. 2003. Photonic structure in

York, NY.

JUDD, D. B. AND WYSZECKI, G. 1975. Color in Business,

FOX, D. L 1979. Biochromy: Natural Coloration of Living

TABATA, H., KUMAZAWA, K., FUNAKAWA, M., TAKI-

VUKUSIC, P., SAMBLES, R., LAWRENCE, C., AND
WAKELEY, G. 2001b. Sculpted-multilayer optical effects in two

NASSAU, K. 1983. The Physics and Chemistry of Color: The

VUKUSIC, P., SAMBLES, J. R., LAWRENCE, C. R., AND
WOOTTON, R. J. 1999. Quantified interference and diffrac-
B266, 14031411.
Figure 7: Anisotropic properties of the iridescence shading model. (left) The result of separate lamellae model is colored red and the multi-layer thin film results are colored green for illustration of the interpolation behavior. The amount of contribution of each model depends on the viewing angle and the direction of ridges on the wing. (center) Butterfly is rendered using only the multi-layer thin film. (right) Butterfly is rendered using only the separate lamellae model. Final image would be the combination of these two models.


Figure 8: Rendered images of a Morpho butterfly from two diffract viewing angles: When the viewing angle is zero the iridescence reflectance function is at its peak with a cyan color.

Figure 9: Rendered images of a Morpho butterfly: Iridescence colors disappear when the viewing angle goes toward $\pi/2$. 