A phenomenological representation of iridescent colors in butterfly wings

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ABSTRACT

The representation of the color of butterflies has always been a challenge to artists, whatever the medium involved. These colors are highly complex to reproduce, even with the use of computer generated images. This article introduces a new algorithm developed to simulate and generate the iridescent colors that are found on the wings of particular butterflies. The model presented here is based on the scientific description of the butterfly *Morpho menelaus*. Wing color is determined by interference, diffraction, absorption and reflection of light on microscopic wing's structures. The color varies depending on a combination of the following parameters: view angle, incidence and characteristics of the light source, and surrounding medium. This algorithm which tends to real-time imaging required by computer graphics artists still renders images with a fairly high degree of accuracy.

Keywords

Interference, Natural phenomena, Butterfly wing, BRDF, ray-tracing.

1. INTRODUCTION

The simulation of natural phenomena has always been a source of excitement for researchers. Such interest is directly linked to the need of a better understanding of our environment and of the way we perceive it.

The representation of the color of butterflies has always been a challenge to artists, whatever the medium involved. Even using computer generated images, theses colors are highly complex to reproduce. They are specific to each species and are due to combinations of several optical phenomena such as: pigment absorption, diffraction, interferences [Vuk99, Vuk00, Ben01, Ber99, Dai95] …

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Figure 1. Scales (x100) ***(thanks to [Ber99])***

The article presents a new algorithm developed to simulate and generate the iridescent colors of a particular butterfly: *Morpho menelaus*. The model presented here is based on the scientific description of this species. The main source for the physiological and optical data is the works of Serge Berthier [Ber99] who has carried out an exhaustive study of the microscopic wing's structure. His study demonstrates that the color varies depending on a combination of various parameters: view angle (fig. 9), incidence and characteristics of the light source and the surrounding medium: air, alcohol, water… (fig. 10).

Some algorithms [Bri90, Hir00] have already been published on the representation of iridescent colors of butterfly wings. Unfortunately, even though these models are accurate, their calculating speed is too slow for real-time imaging required by computer graphics artists.

In this article, the properties of the *Morpho menelaus* wings will be described. Then, a description of the interference lighting phenomenon will be introduced. Finally, after developing a basic model, we will present all the successive improvements proposed in order to produce images in quasi-real-time.

2. MICROSCOPIC STRUCTURE AND OPTICAL PROPERTIES OF THE *MORPHO MENELAUS* WINGS

Description of the microscopic structure. The colors of the *Morpho menelaus* wings will vary depending on two parameters: the incidence of the light source (fig 9) and the view angle. A collimated light source generates the well-known beautiful iridescent colors.

An observation of the wing surface at a microscopic level shows that the wing is covered with two distinctive layers of chitinous scales, the length of these scales being approximately 100 micrometers (fig 1). The lower scales - named ground scales - are pigmented and show a dark brown hue. The upper scales - named glass scales - are transparent and thus can generate refraction, diffraction and interference. Each glass scale is composed of "mullions" [Ben01] 1 micrometer apart from one another (fig. 2.left). Each of these "mullions" is a multi-layer structure, composed of a series of air and chitin layers (fig. 2.right).

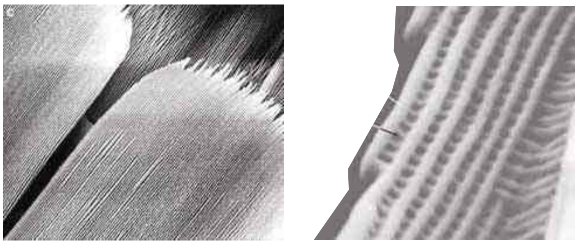

Figure 2. (left) Structure of the scales (x1000), (right) Structure of the “mullions” (x50000) *(thanks to [Ber99])*

Iridescence and interference. Iridescence is known as the “change in hue of the color of an object as the observer changes viewing position”. Iridescent color itself is due to the interference of light, which comes from multiple reflections within the physical structure of a material. In general interference can occur when light rays from one source (such as a laser or lamp) reaches some point in space by different routes.

In most cases, the glass scales remain transparent and the wing appears the color of the ground scales: the pigmented chitin brown. If the parameters allow an interference effect, light will be refracted and reflected on each air-chitin layer. The combination of all these reflected/refracted light rays produce the special iridescent blue color.

Influence of the surrounding medium. In addition to the two main parameters (viewpoint and light position), a third one is to be taken into consideration: the refractive index of the surrounding medium (fig 10). If the refractive index of the chosen medium is close to the refractive index of chitin - the major component of any insect exoskeleton - interference will not occur and the butterfly wing will appear the color of the ground scales (fig 10).

Diffraction. Apart from these interference effects, the microscopic structure of wings allows the generation of diffraction effects. In our case, the effects have little influence on the resulting color. Thus, the development of our model will focus only on interference.

3. INTERFERENCE COLORS

Before entering the description of our model, a few basic elements of optics should be reviewed.

Reflection and transmission between media

Let us consider an interface - air-water or air-chitin for instance fig. 3 - an electromagnetic wave, when reaching this interface, will generate two new waves: a reflected wave (E_r), and a refracted wave (E_t). The relation between the incidence angle θ_i, the reflection angle θ_r and the refraction angle θ_t, is determined by the Snell-Descartes law: $\theta_r = \theta_i$ and $n_i.sin\theta_i = \tilde{n}.sin\theta_t$, where n_i and $\tilde{n}$ are the refraction indexes of the two media.

The amplitudes of the reflected wave (E_{rp}, E_{rs}) and the transmitted wave (E_{tp}, E_{ts}) are calculated by the following formulae:

$$E_{tp} = t_p * E_p \qquad E_{ts} = t_s * E_s \qquad \text{and}$$

$$E_{rp} = r_p * E_p \qquad E_{rs} = r_s * E_s$$

where t_p, t_s (resp. r_p, r_s) are the transmission (resp. reflection) coefficients. These coefficients are given by the Fresnel law :

$$r_p = \frac{n_i \cos\theta_t - \tilde{n}\cos\theta_i}{n_i \cos\theta_t + \tilde{n}\cos\theta_i}$$

$$r_s = \frac{n_i \cos\theta_i - \tilde{n}\cos\theta_t}{n_i \cos\theta_i + \tilde{n}\cos\theta_t}$$

$$t_p = \frac{2n_i \cos\theta_i}{n_i \cos\theta_t + \tilde{n}\cos\theta_i}$$

$$t_s = \frac{2n_i \cos\theta_i}{n_i \cos\theta_i + \tilde{n}\cos\theta_t}$$

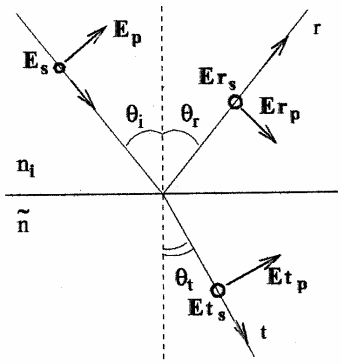

Figure 3. Reflection and transmission on an interface.

A quick overview of the existing models

The iridescent color is the result of all the reflections and transmissions occurring at each air-chitin interface. The glass scale having multiple layer structure (fig. 4), this modeling implies a recursive calculation of each ray decomposition leading us into a combinatorial explosion. This method of calculating the resulting color has been implemented by Hirayama [Hir00].

This model, despite its high accuracy, is not satisfactory regarding our real-time imaging criterion.

A model has been presented by S. Bennett et A. Amezcua [Ben01], specifically designed for *Morpho menelaus.* The glass scale being composed of 8 to 12 layers *(N),* this model determines the amplitude of the outgoing ray *I as a* function of the entering ray 10 and its angle of incidence 6. The colorimetric space used is the electromagnetic spectrum model decomposed into 95 wavelengths. The following formula is used for each wavelength:

$$I(\lambda,\theta) = \frac{1}{2} I_0(\lambda) \left(\frac{\sin\left(\frac{2\pi N(\delta\cos(\theta) + d\sqrt{n_f^2 - \sin^2\theta}}{\lambda} \right)}{\sin\left(\frac{2\pi(\delta\cos(\theta) + d\sqrt{n_f^2 - \sin^2\theta}}{\lambda} \right)} \right)^2 \qquad (1)$$

where δ is the distance between two layers, *d* the thickness of each layer and *N* the number of layers.

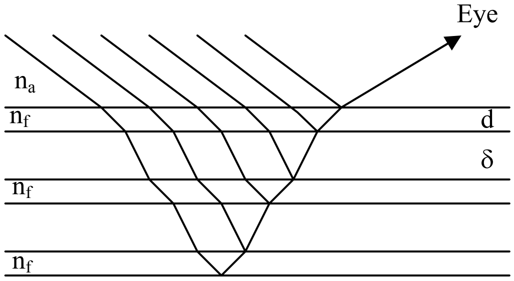

Figure 4. Reflection and transmission through a multiple-layer.

This model, close to real-time imaging, and reasonably accurate, is still limited in some aspects. The choice of a single BRDF[1] is a limit for the potential user: only one degree of freedom is available (the position of light OR viewer). Furthermore, this model is devoted to and applicable to the representation of the iridescence of the *Morpho Menelaus* butterfly species seen in its environment (air with refraction index equal to 1).

Our approach will tend to offer to the user a more open model with more degrees of freedom. This permits to extend the potential application of this model to other effects generated by butterflies even in other media (moisture in the air, wet wings…).

In the following section, our basic model will be presented, followed by phenomenological modifications. Finally, a few computational aspects will be introduced.

4. OUR MODEL

We have chosen a more global approach of the phenomenon, in order to obtain a more versatile model. Keeping in mind our different criteria (reasonable accuracy, and a close to real-time

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[1] Bidirectional Reflectance Distribution Function

imaging ...), we have developed a model which proposes more degrees of freedom and more parameters for the user. Furthermore, the flexibility of this model makes it easy to be modified for the rendering of other iridescent color phenomena.

A single-layer model

We have chosen a single-layer model with two incident rays (fig 5) described by Yinlong Sun [Sun00]. The ray (2) enters the structure, is reflected and then interferes with the ray (I). The resulting interference is only visible if the viewer eye is in the axis of the ray (0).

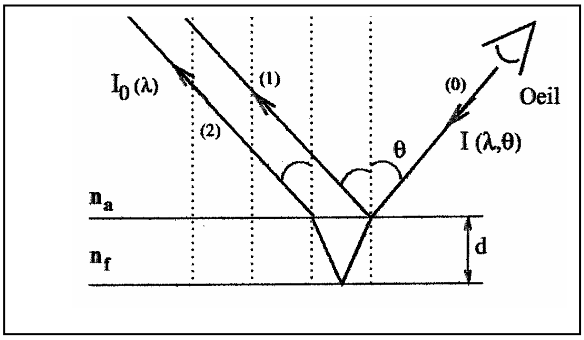

Figure 5. Simple-layer model

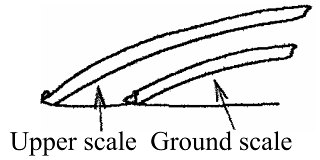

Figure 6. Scale orientation on a wing

Interference is the result of the difference of phase between the two incident rays and is equal to :

$$\delta(\lambda,\theta)=\frac{4\pi d}{\lambda}\sqrt{n_f^2-n_a^2\sin^2\theta}+\pi \quad (2)$$

The illumination of the reflected ray (0) is equal to :

$$I(\lambda,\theta)=I_0(\lambda)\cos^2(\delta(\lambda,\theta)) \quad (3)$$

The main advantage of this model compared to the actual physical phenomenon is its reasonable computational cost, its easy implementation and its flexibility. Yet, its simplicity is a limit to the rendering of a structure as complex as a *Morpho menelaus* wing. A phenomenological approach will now be used to enhance our model and render the wing color as realistically as possible.

The problem of the orientation of scales

The scales are not parallel to the plane of the wing (fig. 6). They are slanted at 10.5° ([Ber99] page 85). This angle introduces an asymmetry in colors (i.e, the color will vary depending on the orientation of the light source: Base/Apex or Apex/Base)

In order to solve this problem an angle of 10.5° must be added to the normal of the 3D modeled scale plane,

Distortion of the resulting color

When the reflection spectrum of a real wing is compared to the spectrum of a wing generated by our model, a noticeable difference appears, due to the approximation of the single-layer model. This difference is also due to the successive conversions between the RGB and spectral colorimetric spaces (chap 4.5.1) (the butterfly wing is calculated in the spectral space, whereas all the 3D scene is classically encoded in RGB). Objects and light sources colors are also encoded in RGB in order to use classical rendering algorithms.

The reflection spectrum of a real wing for various orientations of light source can be seen in figure 7.left. The reflection spectrum of our computer generated wing for the same orientations is presented in figure 7.middle.

A discrepancy between the two figures can be observed. The computer generated curves are *70nm* higher than the reference curves. After an empirical study, our choice has been to include a corrective *70nm* deviation into our formula (fig. 7.right). The formula becomes:

$$\delta(\lambda,\theta)=\frac{4\pi d}{\lambda-70nm}\sqrt{n_f^2-n_a^2\sin^2\theta}+\pi \quad (4)$$

The illumination of the reflected ray (0) is equal to :

$$I(\lambda,\theta)=I_0(\lambda)\cos^2(\delta(\lambda,\theta)) \quad (5)$$

A second peak appears around the *300nm* in the corrected spectrum. But even though this peak is within the visible spectrum, it does not need to be suppressed as the corresponding colors will have little visible effects after the Spectral-RGB conversion.

Asymmetric reflections

Figure 9 represents the various colors of the wing depending on the incidence angle of the collimated light source. The visible asymmetry of color is mainly due to the *10.5°* slant of the scales.

Under certain orientations of light, the "mullions" covering the glass scales annihilate the light reflection. After numerous tests, the following hypothesis is made: if a light ray intersects a scale in the direction of the "mullions", the reflection is automatically generated. If the light ray intersects the scale in the direction that is perpendicular to "mullions", only a diffraction phenomenon appears. This diffraction is the cause of the annihilation of the reflection.

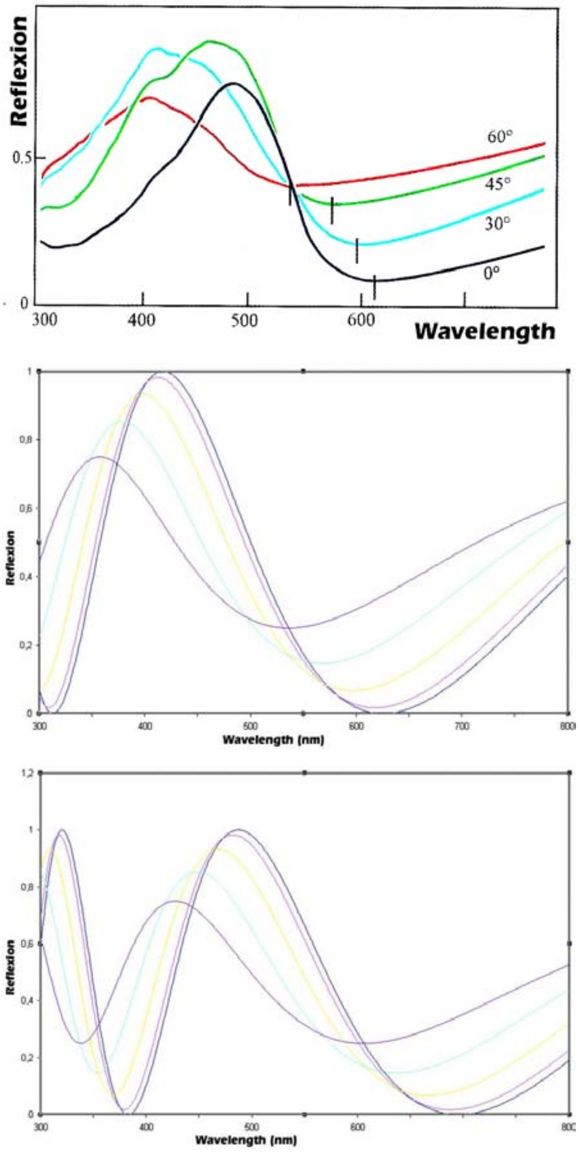

Figure 7. (top) real reflection factors [Ber99], (middle) Simulated spectrum, (bottom) Corrected spectrum

An empirical and corrective term K_{ψ} must be included in eq. 4 in order to decrease progressively the reflection factor of the wing. This term is preponderant if the incidence of light is perpendicular to the direction of the scales (equal to the direction of the "mullions"). K_{ψ} is defined by the following formulae:

$$K_{\psi} = \cos(2\pi \cos(\psi)) \qquad (6)$$

where ψ is the angle between the incident light ray and the scale direction.

The design of the algorithm

Ray-tracing algorithm

Images are generated by a classical ray-tracing algorithm. The specificity of our method is to mix two colorimetric spaces. The global scene is encoded in RGB color space. When an RGB-encoded ray hits a scale, its color is automatically translated into the spectral space. The transformations of this ray are treated in the spectral space. The outgoing ray is then re-encoded into RGB space. This particular color encoding has the advantage of permitting to link our model to other renderers.

The RGB-to-spectral translation uses the Glassner [Gla88] algorithm. The spectral-to-RGB translation uses the Roy Hall [Hal89] algorithm.

The use of a BRDF

The illumination computation uses very precise spectrum (from 380nm to 780nm every l nm). This is highly time consuming due to the 400 samples that have to be computed for each intersection between a ray and a scale. Consequently, we have chosen to pre-compute a BRDF [Sch94]. In order make it more flexible, we have implemented a two dimensional BRDF. It stores all the generated colors for all view angles and all incidences of the light source in order to retrieve instantaneously generated color in function of light source and viewpoint position.

In order to sample the scale upper half-space, a tessellated hemisphere named "N' is used. The normal of a face of the hemisphere represents the direction of the light source (fig. 8). The second parameter is the view angle. To take this parameter into account, a new hemisphere "B" is attributed to each face of "N'. Each RGB value resulting from

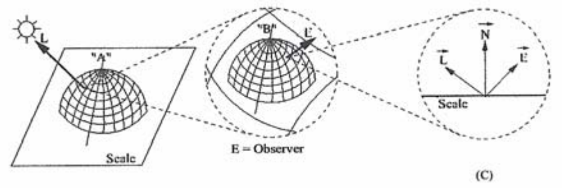

Figure 8. structure of the BRDF.

the combination of these parameters is stored on the corresponding face of "B". In figure 8.(C), L represents the direction of the light source and E the view angle.

During the rendering, when a ray hits a scale, in given conditions (L and E), the interference color is directly determined from the BRDF values by a by-linear interpolation.

Scales are distributed on the whole butterfly wing. This potential distribution does not re-call into question the use of only one BRDF. The BRDF is only use when a ray hits a scale.

5. CONCLUSION

Results

Figure 9 represents computer graphics images for various sources of light. The rendering of colors is quite accurate, if we compare the fig 9.left to fig 9.right. Yet, a more realistic effect could be reached by using a more sophisticated 3D model using Mandal model [Man00]. Figure 10 represents the wing in different media (n=1 and n=1.362). These images can be compared with real photographs proposed on figure 10.

As an experiment, measures have been carried out during the generation of 600 by 600 pixels images. The computer is a Pentium III 600 Mhz. Our Monte-Carlo ray-tracer casts 10 rays per pixel in order to limit aliasing. The BRDF uses 6,250,000 values to store the different colors. The computation duration of one image is 34 seconds, including the pre-computing process of the BRDF which takes 19 seconds. Once the BRDF is pre-computed, the computing of any new image only takes 15 seconds.

Real-time imaging is not reached yet, mostly because of the conception of the kernel of the ray-tracer used in this experiment.

Future works

We are currently working on the development of our model into an OpenGL software. It permits to take advantage of the material accelerations supplied by graphic cards. They can rapidly compute the projection of the scene objects on the image buffer. For each pixel, our software retrieves the information on the incidence of light and the view angle and applies the corresponding color stored in the BRDF.

When the OpenGL software permits us a real-time rendering of interference colors, the flexibility of our 2-layer model, will allow us to focus on the representation of other iridescent colors present in the Nature.

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Figure 9: Real photographs [Ber99] and computer generated images of wings for various sources of light.

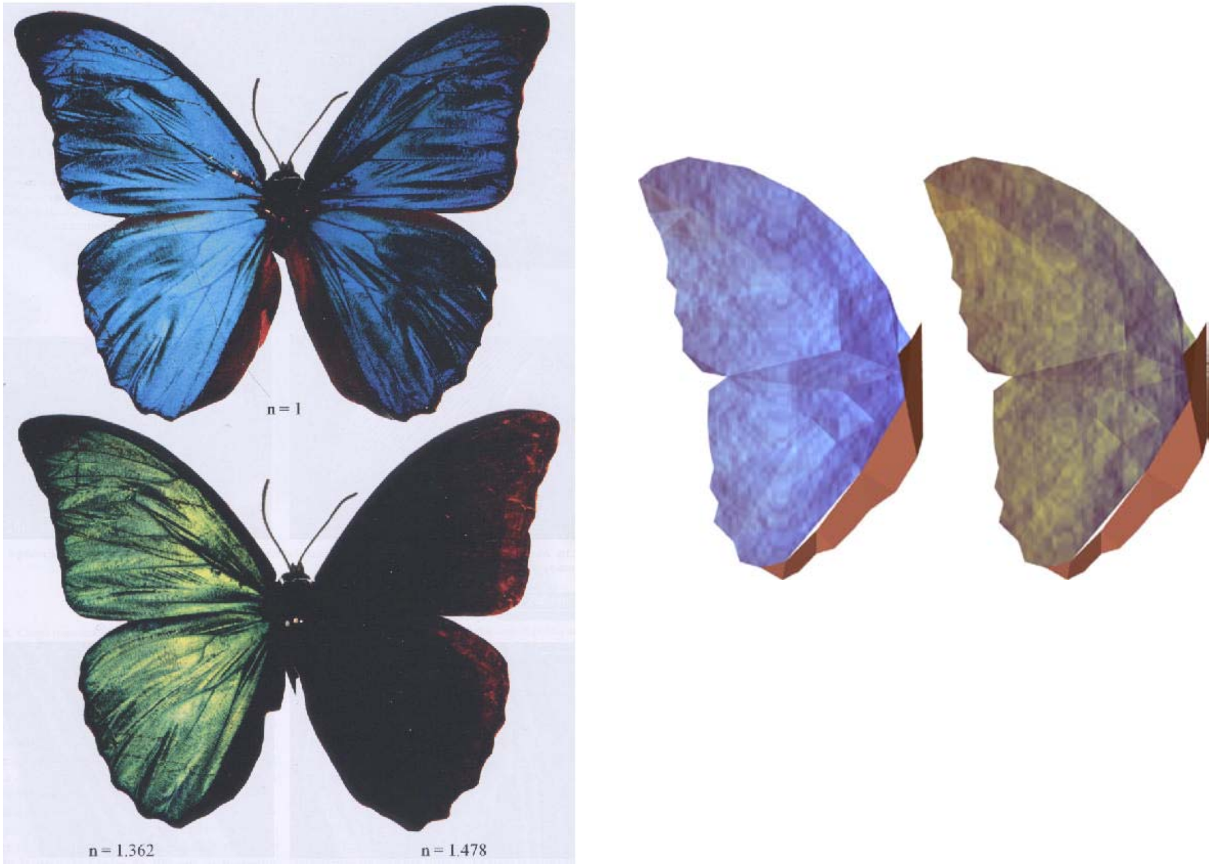

Figure 10: Real photographs [Ber99] and computer generated images of wings in the air (n=1), and in a liquid (n=1.362).