Simulating Iridescence in Computer Graphics using the wave theory

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Abstract

Iridescence is a natural phenomenon which is caused by the wave nature of light. In this report we will be looking at modeling light as a wave to generate interference in light waves, which can then be taken further to create the iridescent effect of the Morpho butterfly.

Keywords: wave theory, iridescence, interference, spectra, morpho butterfly

1. Introduction

The Morpho butterfly is among the most beautiful of creatures in the world due to the metallic, blue, green shimmering colour of its wings. The wings shimmer in this way because the wings surface is iridescent; it is coated with thousands very small scales that reflect incident light repeatedly at successive layers. This leads to interference that relies both on the wavelength of light and the angle from the viewer. From [5] we know that a butterfly wing's scale is made of multiple layers and interference occurs at each of these layers and light reflected from each layer will have phases thus giving it the beautiful shimmer. Figure 1a shows a cross section of one of the scales showing it multi-layer structure. As we will see the challenge of creating a model for the complete multi-level butterfly wing is far to big for the scope of this project so we will be looking at the i interference of light and how representing light as waves, as opposed to the more commonly used particle representation, can give us these results.

Figure 1
Picture of Blue Morpho butterfly (*Morpho menelaus*) showing the spectacular iridescence created by the wings. Image from [10]

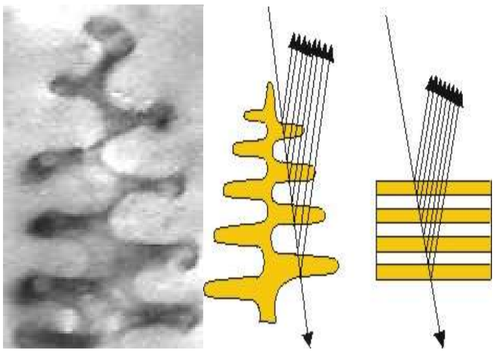

Figure 2
left: cross section of the Morpho butterfly scale showing the multi level structure.
right: diagram to show how a the multi level structure would reflect the light from all the levels. Image from [5]

2. Related Work

The main two pieces of work have looked at light modeled as a wave in computer graphics are [1] in which light has been modeled as waves to try and explore new ways to create three dimensional imagery. In [2] Ian Stephenson looks at modeling light as waves to create a virtual pinhole camera. Some other interesting resources that does not relate to computer graphics but talk more in general about natural structural colour and iridescence in butterfly wings are [ ] and [ ].

3 Light and Colour

2.1 The Nature of Light

Some background on light waves from [3] and [3]:

Light is electromagnetic radiation in range of wavelengths than the human eye can detect. According to the wave-particle duality principle of quantum theory light has characteristics of both particles and waves. For our purposes we are not interested in lights particle properties therefore will only be looking at light as a wave. Figure 2 shows the standard variables that can be used to describe waves the amplitude of a wave is the measure of the magnitude of the maximum displacement in the medium during one wave cycle.

The crest is the highest point of a wave, while the trough is the lowest point. The wavelength ( ) is the distance between two crests or two troughs that are beside each other. For electromagnetic radiation, it is usually measured in meters (m) and in the case of light nanometers (nm).

The period is the name given to the time taken to complete one entire oscillation of a wave and is usually measured in seconds (s), and the frequency is the number of periods per unit time. Frequency is measured in Hertz (Hz).

3. Pigmental and structural colour

There are two primary methods that create colour on surfaces, the main method is what we see everyday on surfaces and is coloration created due to the presence of chemical pigments that absorb different wavelengths of light and transmit or reflect others. Different pigments have different colours and that is the reason surfaces have different colours. Iridescent colour is not produced with chemical pigments but as a result of the way in which interference occurs due to multiple reflections in the actual physical structure of the material, for this reason it is sometimes called structural colour. Structural colour and pigmental colour can add together normally if on the same surface.

The word *iridescence* is itself defined as the change in hue of the colour of an object as the observer changes viewing position. Examples of iridescent colour include soapy bubbles or a thin layer of oil on water; the colours on these surfaces seem to shift and change as we look at it from different angles. Iridescent colours are among the most spectacular and purest and cannot be matched by even the brightest pigmental colours in their depth and intensity.

4 Interference In Light

4.1 Interference and Thomas Young

Looking the at interference and the Thomas young Double Slit Experiment will give us some background into how real light works and will give us a good idea as to what we should be expecting from our results. Interference occurs in waves when two or more waves of the same wavelength coming from the same source

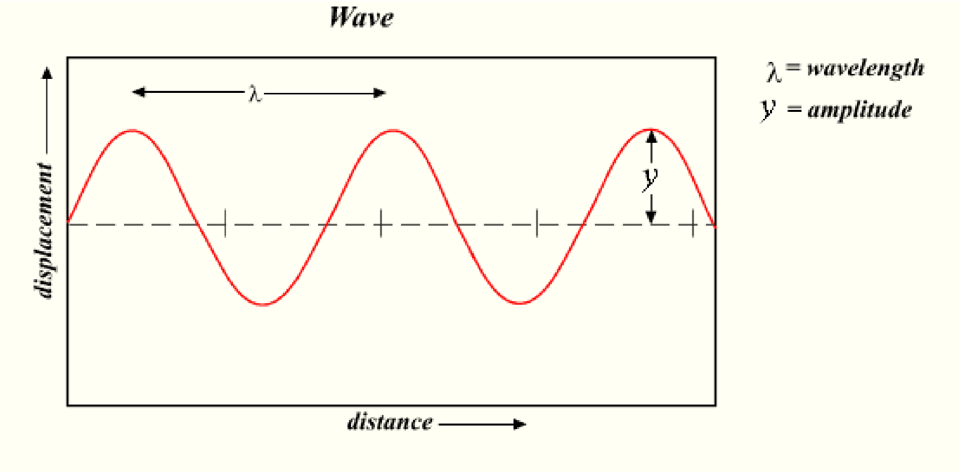

figure 3:
The amplitude and wavelength of a wave Image taken from [10]

superimpose. In other words are added or subtracted from each other based on their amplitude.

If two waves are moving with the same phase (in phase), that is the crests and troughs of one wave coincides with the crests and troughs of another then the resultant wave would have double the amplitude of the individual waves and this is known as constructive interference. If the two waves are out of phase, which is when the crest of one wave coincides with the trough of another then the two waves will cancel each other out. This is shown in Figure 3.

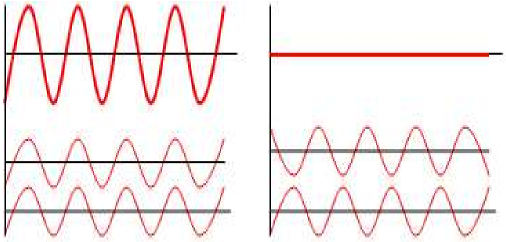

Figure 3:
left: shows constructive interference between two waves
right: shows destructive interference between 2 waves. Image from [10]

In 1803 Thomas Young devised a simple method to see if light had characteristics of waves like interference. In his experiment sunlight would pass through one single slit and then through 2 thin vertical slits and then ends up and is viewed on a screen. When either of the slits is covered a single peak is seen on the screen from the light coming from the other slit. However when both slits are open instead of the sum of the two singular peaks that would be expected if light were wade of particles a pattern of light and dark bands are seen on the screen, as shown in figure 4.

This pattern is explained by interference of the light waves as they recombine after passing through the slits, similar to the way water waves will recombine to create peaks and swells. In the brighter bands there is constructive interference, and the dark bands are a result of destructive interference.

If the light is monochromatic (one wavelength) then constructive interference will make the intensity brighter, and destructive interference will make the intensity darker, but when composite light like white light (the visible spectrum) is used then all of the bright and dark spots from the separate wavelengths will compose together to create a colour based on the phase of all the wavelengths from the spectrum.

4.2 Diffraction

Diffraction is the bending and spreading of waves when they meet an obstruction. It can occur with any type of wave, including sound waves, water waves, and electromagnetic waves such as light. Diffraction also occurs when any group of waves of a finite size is propagating; for example, a narrow beam of light waves from a laser must, because of diffraction of the beam, eventually diverge into a wider beam at a sufficient distance from the laser. As a simple example of diffraction, if you speak into one end of a cardboard tube, the sound waves emerging from the other end spread out in all directions, rather than propagating in a straight line like a stream of water from a garden hose. To simulate diffraction we will need to look at Huygens principle. Huygens' principle simply states that a large hole can be approximated with many small slits, each of which generates waves as a point source. A point source generates waves that emerge traveling spherically outward, like the waves caused by dropping stones in a pond.

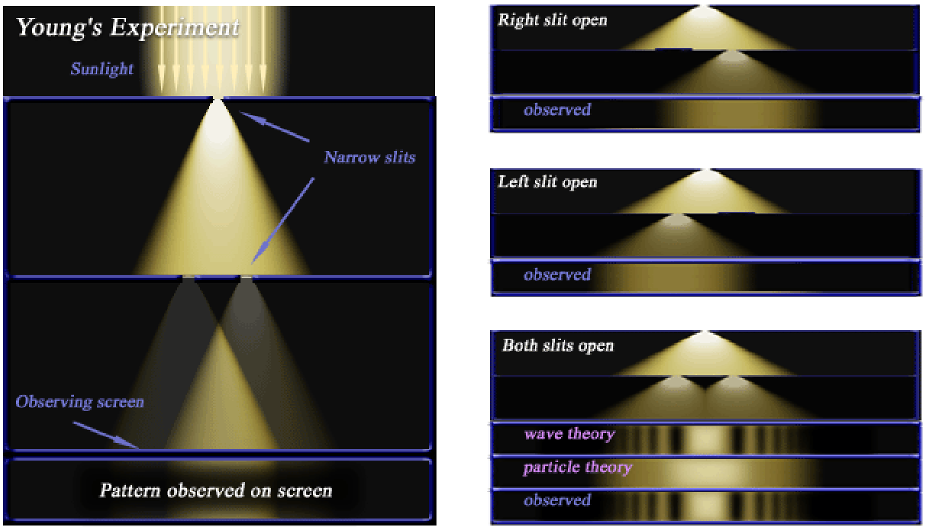

Figure 4

Diagram showing Thomas Young's double slit experiment in the bottom right image we can see that the light o the screen appears as bands of dark and light colour. Diagram from [10]

4.3 Iridescence in Thin Film

From [9].The occurrence and distribution of iridescent colours and the various theories regarding their manifestation in the natural world were for a long time discussed by scientists. Even Sir Isaac Newton in his book Opticks, published in1704, put forward a reason for the iridescent nature of the colour from the feathers of peacock tails. The credit for formulating the principle of iridescence goes to Robert Boyle who was a contemporary of Isaac Newton. One hundred years later Thomas Young explained in detail interference with his "Double Slit" experiment, this explained how iridescence was possible.

According to Young's definition very thin plates or film, like that of oil on water or the skin of soapy bubbles will reflect some of the incoming light from their shiny top surface As a result of the light waves journey through the film and its reflection from the bottom surface it could have a different phase to the light reflected from the upper reflective surface. The light that is not reflected will continue through the film and be reflected by the lower surface. The light that enters the film will be bent from its original path based on the film's refractive index. (In physics air has a refractive index of 1 which is the norm, anything denser than air will have a higher refractive index). The refractive index or density of a material describes how much light is bent, and slowed down, as it passes through the material. So as the light enters the film the movement of the light is slowed down and the waves become smaller. After the light hits the lower surface it is reflected and travels back up to the upper layer at the slowed-down pace. The light will be transmitted through the upper layer and rejoin the light reflected at the upper layer only it will have a different phase due to the transmission it has gone through, this is shown in Figure 5.

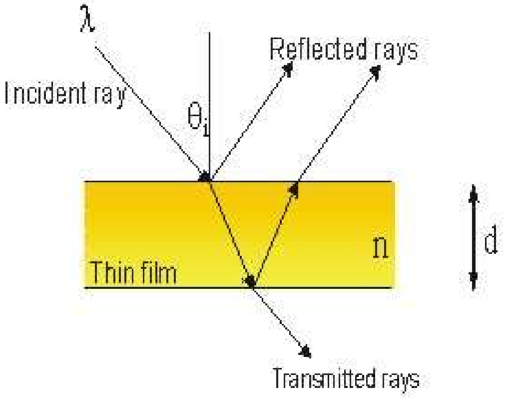

Figure 5
Diagram from [5] representation of iridescence in a thin film. The diagram shows that the incident ray is reflected by both the upper and lower surface therefore the 2 reflected rays will have a different phase.

How much out of phase depends on two factors, how thick the film is and also the angle that
the light strikes the surface. If the phase difference of the upper and lower surface reflected beams are equal to or a multiple of one, then constructive interference will occur and that that particular wavelength or colour will be reinforced. If the phase of the waves differ by half a wavelength, or an odd multiple of half wavelengths, then destructive interference will occur as the waves are said to be completely out of phase. In this case some other wavelength whose wavelengths coincide would be visible.

If a full spectrum of colours in the form of white light enters the film then according the film thickness and refractive index only one colour from that spectrum will meet those conditions for constructive interference and that is the colour that will be seen. So when light is directed at the thin film, only one colour will be strongly reflected at a certain angle. For example lets assume that a green ray, after having traveled through the film and back, has a phase difference of two full wavelengths when it rejoins the green light reflected at the upper surface. It is now in phase with this green light. The green color is therefore reinforced and because the wavelengths of the other colors are different, they are by necessity out of phase and are therefore either eliminated or appear not as strong. However, if the phase difference between the two green light rays were one and a half wavelengths, they would neutralize each other and become invisible. In that case, some other color whose wavelengths coincide would appear.

On the other hand, for monochromatic light, if constructive interference happens then the colour will be brighter and if destructive interference happens then the colour will be black. Therefore you would get bright and dark bands of light.

The colour will be purest and constructive or destructive interference will be strongest if the waves reflected from each surface have the same amplitude.

5 Method

5.1 Wave Representation

For our simulation we will be using the idea that light is a wave because that is the only way that we can get a realistic model for light will allow for interference, which is the basis for iridescence. In our research we have looked at the Morpho butterfly and how its wings are iridescent also we have gone into how iridescence works based on Thomas Young’s discovery that constructive and destructive interference occurs in light waves. To create a full iridescence model based on the thin film example described in figure 5 is too big a task for the scope of this project, instead we decided to create a simple realistic model similar to Thomas Young's Double slit experiment to show the interference of light. We then took this model and created a program that created an image based on some of the theories and methods explained above and also some of the theories and methods in [2] and [3].

For our simulation we have created a simple scene which involves a light source which is where the waves will be created, also we have a line of holes which the light waves will go through and hit a screen that will pick up the colour, and any interference will be shown on this screen. Figure 6 shows this situation. In our program we implemented an object loader to load in .obj files exported from a 3D package so that we can easily and intuitively set up our scene. We load in two objects one that represents the holes and another that represents the screen.

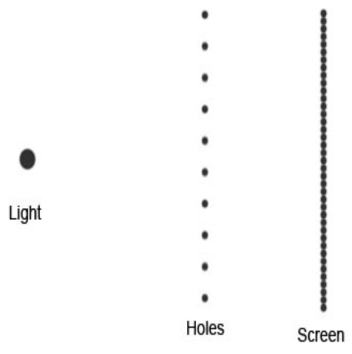

Figure 6:
Diagram showing the scene for our simulation. There are significantly more points on the screen as there are holes.

5.2 Simulating the waves

The screen will be made up of lots of different points, and the idea is to calculate the colour value for each of these points based on the light coming in through all the holes. The points on the screen should vary in colour because the phase of light will be different at all the holes and this is because the initial phase (phase shift) of the light waves will be different since all the holes are different distances apart. The initial phase of the wave is calculated by taking the total distance the wave travels and dividing it by the wavelength of the wave. This initial phase tells us how many times the wave oscillates for the distance it has covered but we are not interested in how many whole oscillations we get but the fraction that is left over, because this gives us how far into the next oscillation we are. As we have scene in section 4.1 it is important to calculate the phase of light at that point and because we are not taking time into consideration for our simulation the initial phase will be sufficient To calculate this we use the following equation:

$$\Phi = (d \ / \quad) - \text{floor} \ (d \ / \quad)$$

Where Φ is the phase shift, is the wavelength, d is the distance and floor returns the largest integral value less than or equal to what it is given.

So for each point on the screen we need loop through the holes and find the distance from the light to the point on the screen via the hole, and this is illustrated in figure 7. Let's say that each of these distances is a wave we need to calculate the phase shift for each of these waves. The phase shift for each of the points is going to be different because all the distances are going to be different.

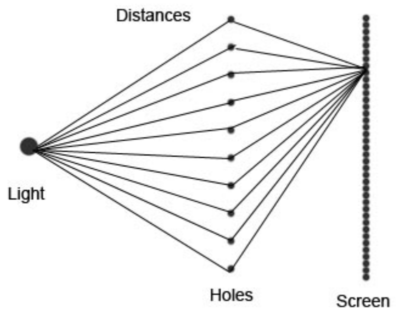

Figure 7:
This diagram shows the process of how we loop through all the holes and find the distances from the light to the point on the screen, and then we can use them along with the wavelength to find the initial phase for each..

Once we have all the phase shifts we can then use them to calculate the x and y values for the amplitude of the wave at each hole by using trigonometry, these equations are:

$$x = \sin (2 \quad + \Phi)$$

$$y = \cos (2 \quad + \Phi)$$

This equations will gives us a vector that represents the amplitude of the wave at that hole. If we then take all the amplitudes vectors for all the holes we can add them all up and that will give us a vector that represents the amplitude of the wave at the point on the screen so we are in other words superimposing all the waves from the different holes together to get the wave at the point on the screen after interference has been taken into account. If we then take the magnitude of this vector we will then have a phase or intensity value for that wavelength. This is how we simulate diffraction using Huygens construction like in [2] and [3].

We can then, for any given wavelength in the visible spectrum calculate the intensity for every point on the screen and this will give us the screens colour values for that colour. In other words we have the amount of colour we are receiving from a given wavelength of light, an example wavelength could be 550nm which would give a green colour.

We started out by doing tests for just red light which has a frequency of about 650nm so we got the intensity for each point on the screen for this wavelength and plotted it on a graph to see what the data looked. This was helpful because at first we approximated our screen with only one hundred points and on the graph was not smooth enough so we then increased the number of points on the screen until the graph was sufficiently smooth enough, and found that 1000 points is enough to get descent enough results without slowing things down at all. Ideally we would like to take a lot more samples to get perfect accuracy.

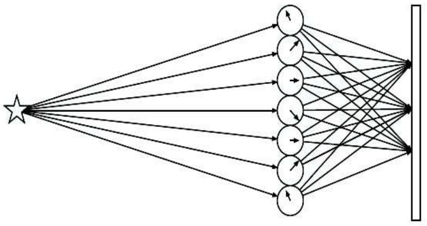

Figure 8: For
For a wavelength in the visible spectrum the amplitude is calculated for the waves at every hole this is shown by the arrows at the holes. If we up all the amplitudes we get an intensity value for that point on the screen. Image from [2].

Once we were happy with the accuracy we plotted graphs for two other colours blue and green which have wavelengths of roughly 470nm and 550nm respectively, the reason we did this was to test to see if our program simulated properly as we would expect there to be a different graph for each different wavelength. The graphs for the red, green and blue wavelengths are shown in figure 9.

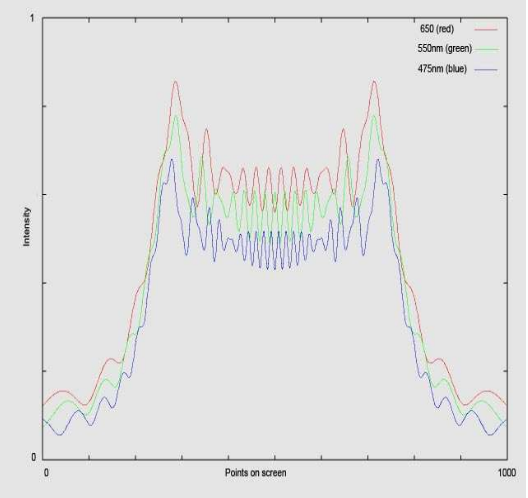

Figure 9:
The intensity curves for the wavelengths of values

650nm, 550nm and 470nm for every point on the screen.

Figure 10 is the rendered image for just the red (650nm) wavelength of light and it is shows the bands of red and black that we have been expecting to see and clearly see the interference. In our scene we modeled the screen as a line of points and to create an image a line would not be very interesting so we just extended the line so that we get horizontal bands. We can then move on to create an intensity for all the wavelengths for each point (we did not plot for all wavelengths but took 10nm intervals starting from 380nm to 780nm so we had 41 colour values for each point.) on the screen to give us a spectra for every point on the screen. So we can now plot spectra for any point on the screen.

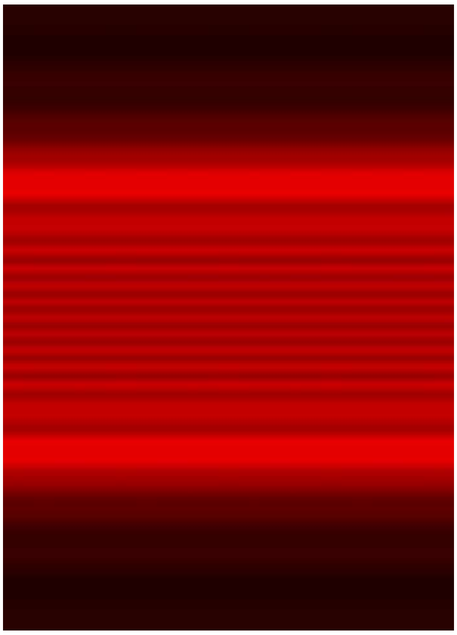

Figure 10:
Rendered image of red interference for the 650nm wavelength

5.3 Spectra and Colour Space

What we have now is spectra for every point on the screen, which means we have a amplitude foe each of the 41 wavelengths of light that we calculated for, and computers and monitors do not work in spectral colour they normal work with other colour spaces like CYMK (cyan, magenta, yellow, black) or RGB, (red, green, blue) for example. What we need is a way of converting our spectra for each point on the screen to an RGB value that we can use to create an image with. One way of doing this would be to just take an average of the amplitudes of the wavelengths ranging from 380nm to 500nm and call that the blue value, average from 500 to 600 and call that the green value and 600 to 780 and call that the red. This way would probably be simplest but not so accurate. A better way would be to convert from spectral colour space to XYZ space then from XYZ to RGB to do this we must quickly look at the device independent colour space XYZ.

[6] Device independent colour models are used to describe how a particular colour will be seen by humans. The most important device-independent color model, to which all others can be related, was developed by the International Commission on Illumination (CIE, in French) and is called "CIE XYZ" or simply "XYZ". The X value is the sum of a weighted power distribution over the whole visible spectrum from the standardized spectral weighting curves or table as in figure 11. So are Y and Z, each with their own different weights. So the entire visible spectrum intensities that we have obtained for each point on the screen can be compressed down to just three floating-point numbers. The weights were derived from color matching experiments done on human subjects in the 1920s and CIE XYZ has been an International Standard since 1931. Once we have the XYZ values we can simply convert them to RGB using a matrix transformation that has already been calculated for us from [ ] and create an image.

Wavelength	Weighting
380	0.001400

390	0.004200
400	0.014300
410	0.043500
420	0.134400
430	0.283900
440	0.348300
450	0.336200
460	0.290800
470	0.195400
480	0.095600
. . .	. . .

Figure 11:
Weighting conversion table example for changing spectral to X colour space

6 Results

Figure 12 shows the resulting image from our simulation and clearly we can see that the colours in the image do vary as a result of simulating the interference. However the colours are a little unsaturated and not as bright as we have seen in the butterfly. This could be because of some of the filtering that is going on in the program as no gamma correction has been taken into account. It is not a big problem in our case as we are only looking at interference of light waves and iridescence. Figure 13 shows a render that has fixed this by increasing the number of holes, and in this image we see some of the colour patterns that we would normally expect to see on a thin layer of oil on water etc. But the only problem is that in some bits it gets over exposed. A real fix would be to try and set some kind of multi layered model where the colours will become enhanced.

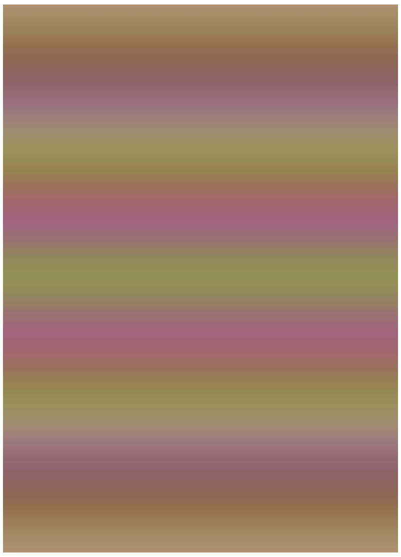

Figure 12:
Image created from our simulation showing different bands of colour as a result of interference.

We then went on to do a test to see if are model was iridescent so we changed the angle of the line of holes by about 45 degrees and the resulting images had different colours these comparisons are shown in figure 14, we then went on to create a sequence of images to show the smooth transition of colours as the angle changes

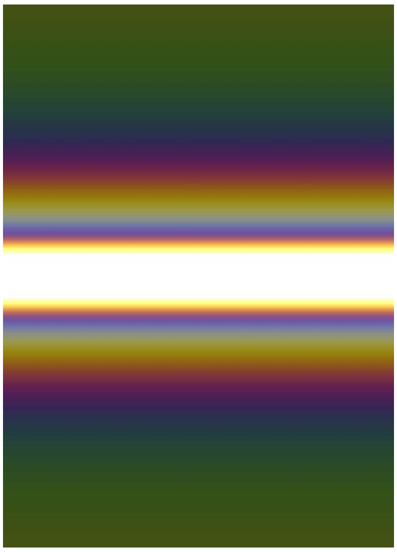

Figure 13:
Simply increasing the number of holes will give us more saturated colours and a brighter image.

7 Future Work

Currently we have just looked at created images based on two dimensions coordinates of points on a line that we call a screen. But we could expand the program to allow for three dimensional models as well and load in three dimensional models from a modeling package. We have also only looked at a model for iridescence and it would be interesting to further adapt this model to allow for multi layer interference. Or even to adapt it into a photonic structure like those explained in [11].

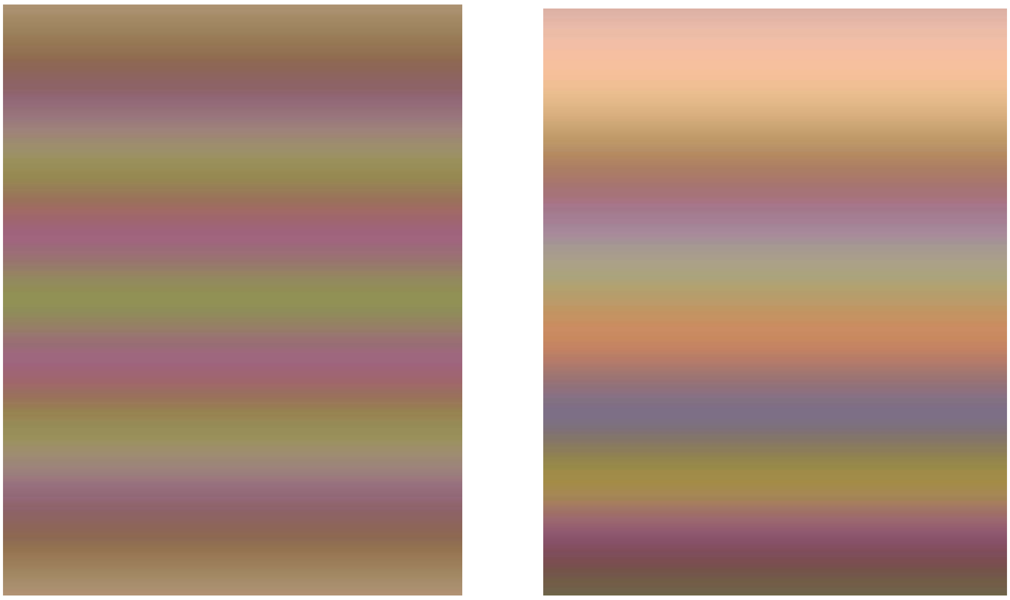

Figure 14:
A side by side comparison of the different angles for the line of holes. The image on the left is when the holes are parallel to the screen and the image to the right is when the line of holes are rotated about 45 degrees.

8 Conclusion

Iridescence is a beautiful phenomena that occurs in nature as a result of the way light waves are reflected in a surfaces material. In this paper we have successfully created a model that shows interference of light wave which intern leads to iridescence. The effect we are getting is like that seen on a thin layer of oil on water, we would need to improve the model with multiple layers of interference to get better effects like those seen in the Morpho butterfly.

<u>Recourses:</u>

[1] Hans P Moravec. 3D Computer graphics and the wave theory, Pages 289-286, SIGGRAPH, 1982

[2] Ian Stephensen, A Real Virtual Pinhole, SIGGRAPH, 2005

[3] Peter Comninos, Mathematical and Computer Programming Techniques for Computer Graphics, Pages 317 – 324, 2006

[5] Dr. Pete Vukusic and Prof. J. Roy Sambles, Iridescence in butterfly wings http://newton.ex.ac.uk/research/emag/butterflies/iridesc-text.htm [accessed January 2006]

[6] http://www.libpng.org/pub/png/spec/1.2/PNG-ColorAppendix.html [accessed march 2006]

[7] http://en.wikipedia.org/wiki/Morpho_butterfly [accessed march 2006]

[8] http://en.wikipedia.org/wiki/Interference. [accessed march 2006]

[9] http://buginabox.com/buginabox/scienofir.html [accessesed march 2006]

[10] wikipedia.com, used for general information and some diagrams. [accessed march 2006]

Further reading

[11] Photonic Structures in Biology
Dr. Pete Vukusic and Prof. J. Roy Sambles
Thin Film Photonics School of Physics, Exeter University