STUDENT: Rainbows-- while we may not notice them, there are rainbows all around us as we go about our daily lives. They are hidden in the reflection of soap bubbles, the shine on a CD, and even in oily puddles on the street. In this video, we'll explore the phenomenon of light wave interference and how it creates the colors we see on the surfaces of thin films.

Since soap and oil are usually colorless, why do they have iridescence? Let's start with the laws of light reflection and refraction, then peruse through some visual simulations of these fundamental principles.

When waves travel through space and hit an interface or a surface, some of the wave reflects off the surface and the rest refracts, continuing through the new medium at a different angle. When the refracted wave hits another surface, part of it reflects back out of the medium and combines with the first wave or interferes with the first wave.

Since the first and second reflected waves travel different paths, the second wave acquires a phase shift in comparison to the first wave. When it adds to the first wave, this phase shift may cause the two waves to completely cancel each other out, resulting in destructive interference. Or if the phases are perfectly aligned, the resultant wave has twice the amplitude, resulting in constructive interference.

Notice that the resultant wave has destructive interference when the phase shift is about 180 degrees or pi radians. And it reaches the maximum amplitude, having constructive interference, when the phase shift is a multiple of 2 pi radians.

For light traveling from one medium or material to another medium, for example, from air to water, Snell's law of refraction, given by this equation here, states that the angle at which light travels through the two different mediums is proportional to the velocities of light through the two mediums, V1 and V2, which is inversely proportional to the refractive indices, N2 and N1. This equation can be simplified to N1 sine theta 1 equals N2 sine theta 2.

Snell's law can be rearranged to represent N1, the refractive index of the first medium, in terms of the incident light angles of the two materials and the refractive index of the thin film. This trick will be useful in some of our later calculations.

Remember how waves with shifted phases interfere? In this case, the phase shift is a difference in path length that the first reflected wave and the second travel. Geometrically, the path difference between the wave reflected off the top surface and the wave reflected off the bottom surface of a thin film is given by this equation here, where AB, BC, and AD refer to the line segments in this diagram. Using some trigonometry, the line segment lengths can be calculated in terms of the refractive indices and the refracted light angles.

Now, using Snell floor to substitute for N1, the path difference between the two reflected waves can be expressed in terms of the thin film medium only, only depending on N2 and theta 2. That means for constructive interference between the two waves, the phase shifts has to be 0 and the path difference has to be an integer multiple of the incident lights wavelength, lambda.

When the medium a wave is traveling into has a refractive index that is greater than the index for the medium that the wave is coming from, that is, N2 is greater than N1, there is one extra caveat. The reflected wave has a 180-degree phase shift. In that case, the condition for constructive interference is that the path difference must be a half integer multiple of the incident light's wavelength. For a typical thin film, which has a higher refractive index than its surroundings, which is usually air, this is a condition for constructive interference between waves reflected off the top and bottom surfaces of the film.

This simulation shows a wave traveling through air, then reflecting off the top and bottom surfaces of a thin film. The bold reflected waves represents the summation of the waves reflected off the top and the bottom on the film, and should grow largest when there is constructive interference and the two waves' phases align line.

I can change four different parameters in this situation-- the thickness of the film, D, the refractive index of the film, the angle of the incident light hitting the surface of a film, and finally, the wavelength of the light hitting the film. Changing all of these parameters changes the resultant wave that reflects back out of the film.

You might be wondering why changing the wavelength makes the wave different colors. That's because the visible light spectrum can be represented by waves of different wavelengths ranging from three 80 nanometers to 750 nanometers. The human eye has light receptors, or cones, that actually only perceive three colors from the visible spectrum-- red, green, and blue. The entire visible spectrum people see is really a superposition of the waves of these three colors, which mix in different ratios to provide all the other colors of the rainbow.

The light that humans see making rainbow swirly patterns on the surface of soap bubbles or in the oil sheen on water has a minimum wavelength of 380 nanometers and a maximum wavelength of 750. Red has a wavelength of about 700 nanometers, green 546, and blue 436.

The strength of each of these colors, or the intensity, that people perceive is proportional to the square of the wave's amplitude. Since the amplitude represents the energy, E, of a wave, intensity is also a representation of the wave's energy density. The more intense a wave, the larger amplitude it has, and the more its color dominates our perception.

The total color that we see reflected off a point on the film surface is a combination of these three waves proportional to their intensities. For example, for a film thickness of 200 nanometers with refractive index 1.5 and incident angle 45, we can see that there is more blue in this color than green or red. If we try changing the film thickness to, let's say, 400 nanometers, the refractive index to 2, and keep the incident light angle at 45, we can see that green would be the dominating color.

For thin films which have a greater refractive index than the air, we can show the color reflected off a thin film as a function of the film's thickness. Likewise, we can see how the reflective wavelength colors vary with the incident light wave angle. Here are two plots Mathematica has generated for a thin film with refractive index 1.5, first with a constant incident angle of 45 degrees and second with a constant thickness of 200 nanometers. Notice that with varying thicknesses, the color shifts alternate between reddish, greenish, and bluish colors, while for varying angle, the spectrum is a more gradual gradient.

Let's envision a flat thin film of oil floating on a perfectly flat surface of water. The refractive indices of oil, water, and air are respectively about 1.5, 1.33, and 1. As light reflects off the top of the oil, there is a 180-degree phase shift since the refractive index of oil is greater than the refractive index of air. But there isn't a phase shift when the wave reflects off the bottom interface between the oil and the water because water's refractive index is less than oil's.

This interactive graphic shows how an oil firm with varying thicknesses reflects light of a point source at varying heights above the oil's surface. We can increase the height of the light to get this iridescence pattern. Or we can increase the film's thickness. We can see that with increasing the light height, there is a wider range of incident light angles, whereas when we move the film thickness, there is a wider range of colors that are produced on the surface of the film.

In reality, the surface of a puddle really isn't completely flat. This interactive graphic shows thin film interference of oil on rippling water. Again, if we increase the thickness of the oil film, there is a wider range of colors. We can also change the x, y, and z positions of the light and see how the iridescence pattern changes.

For a spherical soap bubble, the refractive index of so varies with the recipe, but it's always greater than the refractive index of air. That means that there is also a phase shift of 180 degrees when light hits the outer surface of the bubble, but not when it reflects off the inner surface.

This simulation shows the effect of multiple point source lights on a soap bubble. Note that in real life, light sources around a syllable usually aren't just point sources and the bubble isn't an even thickness throughout, as is assumed in this simulation. Hence, the color patterns that we see on surfaces of soap bundles are usually far more complex than what we see in the simulation.

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