"QED – Matter, Light and the Void"

Scientific subject and topic:
Physical properties of light

Title / year:
"QED – Matter, Light and the Void" (2005)

Movie producer:
Scienc*e*motion

Director:
Stefan Heusler

Website of movie:
http://www.sciencemotion.de/

Description of movie:
In the first part of the DVD, the properties of light are shown in a puppet animation movie (30 Min.). Prof. Ethereal and his colleague Nick perform experiments about the physical properties of light and try to explain their results by using models. Not all of their explanations are complete, and not all of their ideas lead to correct conclusions. But their discussions and experiments impart methods of scientific research in a humorous way: A scientist should not be satisfied with just one theory and a corresponding experiment but should try to refine his methods of understanding nature, in this case with the final goal to comprehend the fascinating properties of light better and better.

In the second part of the movie, all the models and experiments are explained on a scientific level using mathematical formulas. In this part, facts of modern research are presented, culminating finally in the theory of quantum electrodynamics (QED). The level of the scenes (about 30) varies between high-school and university level, depending on the difficulty of the specific topic related to the question "What is light?"

Link to Trailer Site:
http://www.sciencemotion.de/

Buy DVD:
Order the DVD for EUR 20.00 plus shipping charge on the website
http://www.sciencemotion.de/

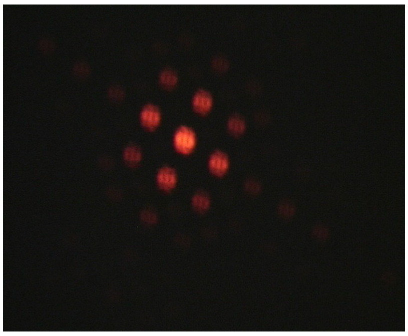
Title of scene:
Interference of light

Video clip or still:
Chapter 1d, Technical Part

Author:
Stefan Heusler, Annette Lorke

Scientific keywords:
interference, superposition, Fermat's principle, double slit experiment

Description of scene:



Usually if you point a red laser beam towards a dark wall you see one red light spot on the wall. In our little experiment the laser beam has to shine through the pores of a silk stocking we have put in front of the laser. Instead of one spot a regular lattice of spots appears on the wall. For explaining this regular lattice we use a simple wave model and calculate the relation between the spots' distance on the wall and the pores' distance in the silk stocking.

To simplify matters we assume that one light wave is emitted from each pore of the silk stocking. The waves from each pore interfere with each other. If the phase difference between the light rays equals the multiple of the wavelength, constructive interference enhances the light waves. If the phase difference between the light rays equals half the wavelength, destructive interference annihilates the light waves.

Author: Stefan Heusler, Annette Lorke
E-mail: sciencemotion@web.de

Movie: QED – Matter, Light and the Void
Movie clip: Chapter 1d, Technical Part
Director: Stefan Heusler
Film Studio: Scienc*e*motion, www.sciencemotion.de

Basic level

If you throw a stone into the water, you can observe a circular wave on the water surface. What will happen if you throw two stones from two different positions into the water? Two different circular waves will emerge and they will *interfere* if they meet each other. This means that you have to add the two waves. If you call “zero” the height of the water surface, then the height of the first circular wave is sometimes above zero, sometimes below zero. The same is true for the second circular wave.

Consider one fixed point on the water surface. If you add both waves at this point and at the moment when the height of both waves is above zero, then the resulting height will be even bigger than zero. This is called “constructive interference”. If you add both waves at this point in a moment when both waves are below zero, then the resulting height will be even much lower than zero. This is also called “constructive interference” because both waves enhance each other! Only if one wave is above zero, and the other is below zero, the two waves add up to a result close to zero. This is called “destructive interference” because both waves annihilate each other.

Interference is the most important property for all kinds of waves, such as sound waves, water waves, light waves.... Find more examples!

Try out this: Take two stones and throw them into the water. You can compare the result of your experiment with some computer simulations if you like, e.g.:

http://www.schulphysik.de/java/physlet/applets/optik2.html?Intensity=on&wavelength=3
http://www.schulphysik.de/ntnujava/doubleSlit/doubleSlit.html

Author: Stefan Heusler, Annette Lorke
E-mail: sciencemotion@web.de

Movie: QED – Matter, Light and the Void
Movie clip: Chapter 1d, Technical Part
Director: Stefan Heusler
Film Studio: Science*e*motion, www.sciencemotion.de

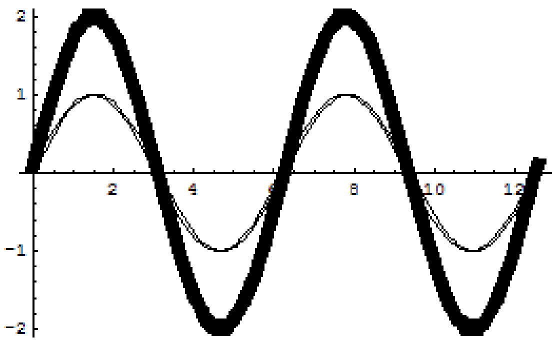
Advanced level

The superposition principle of waves means that two waves have to be added if they meet each other. The resulting wave depends on the phase difference φ between both waves.

Let's consider a simple mathematical model of interference: We add to two sinus-waves with the phase difference φ:

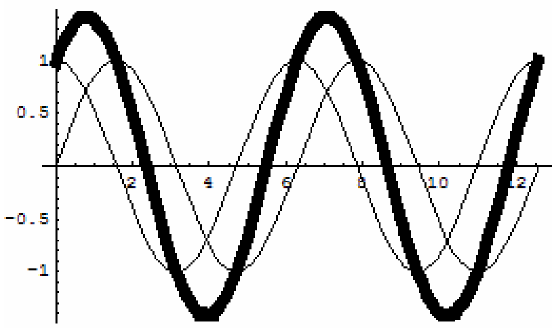
$$F[x, \varphi] = \mathrm{Sin}[x] + \mathrm{Sin}[x + \varphi]$$

In this model, two waves with the wavelength 2π interfere with the phase difference φ. Let's have a look at the resulting wave for different values of the phase difference. If φ is very small compared to the wavelength, both waves enhance each other. The result is an even larger wave with almost doubled amplitude. This is the case of constructive interference:



The thick line in the illustration is the interference wave F[x, φ] of the two sinus-waves for the phase difference φ=0.01.

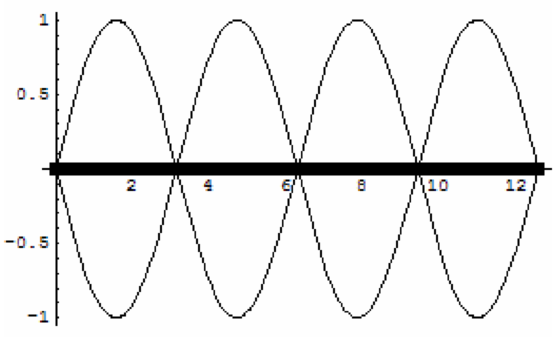
If the phase difference is about a quarter of the wavelength (in our model, λ = 2π, φ = λ/4 = π/2), the resulting superposition looks like this:



The amplitude of F[x, φ=π/2] is:

$$2\,\mathrm{Sin}[\mathrm{Pi}/4] = \sqrt{2}$$

The case of destructive interference occurs for a phase difference given by half the wavelength (in our model $\varphi = 2\pi / 2 = \pi$)



The amplitude of $F[x, \varphi=\pi]$ is zero. Furthermore, the function is zero at any point x.

$F[x,\ \varphi = \pi] = 0$

The two waves annihilate each other.

For any kind of waves and any kind of superposition, the model which we have introduced is sufficient. All you need to do is to observe the following generalizations:

1) Instead of the wavelength 2π, any other wavelength λ is possible.
2) Instead of the amplitude 1, any other amplitude is possible.
3) Instead of two waves, any number of waves is possible.
4) In each wave, the phase shift and the wavelength may be different.

The general principle – the so-called superposition principle - is the summation of all waves with the phase shift φ. Note that the superposition principle is based on a fundamental assumption: *Waves do not interact with each other*. Each single wave does not change its form if other waves are present. The waves are just added up. You can check the validity of this assumption for sound waves in a simple experiment. Play some music with a CD player and sing the melody. You cannot change the sound waves coming from the CD. Your voice is just added to the sound of music.

However the superposition principle is only a very good approximation to describe the behaviour of waves. In most cases, this approximation is completely justified and the interaction effects between the waves can be neglected.

For light waves, we discuss deviations from the superposition principle in chapter 5a of the DVD. These deviations were unknown in Maxwell's time and were discovered in the 20th century.

Finally, here are some examples of computer simulations for interference based on the superposition principle:
http://www.schulphysik.de/java/physlet/applets/optik2.html?Intensity=on&wavelength=3
http://www.schulphysik.de/ntnujava/doubleSlit/doubleSlit.html)

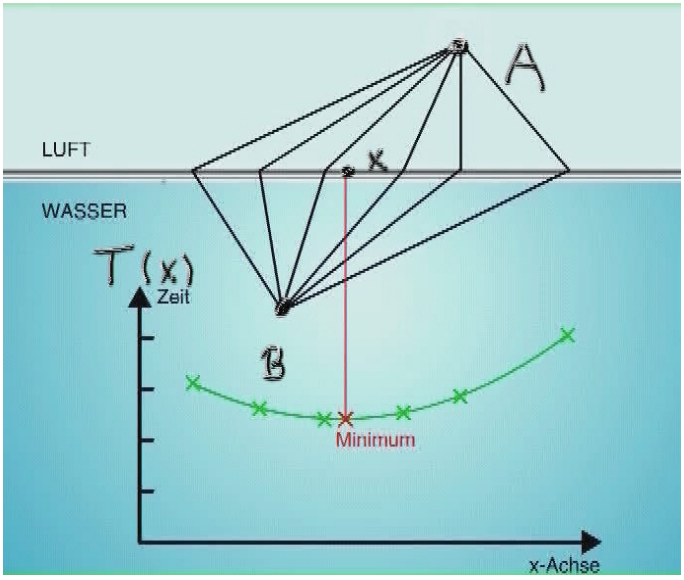
Author: Stefan Heusler, Annette Lorke
E-mail: sciencemotion@web.de

Movie: QED – Matter, Light and the Void
Movie clip: Chapter 1d, Technical Part
Director: Stefan Heusler
Film Studio: Sciencemotion, www.sciencemotion.de

Scientific level

Interference is one of the profoundest and most fascinating properties of matter and radiation. Recall Fermat's principle: *Light always chooses the fastest possible way.* This principle is based on the particle picture of light which allows the assumption that photons choose a certain path, (see also Chapter 1b). One obvious question comes to mind:

Imagine a light ray starting at point A. How can the light ray know which is the fastest possible path to go to point B? At point A, the light is in the air. Who tells the light that very soon it will hit the water surface and the straight line is not the fastest possible way?



Sometimes, pupils ask this question when Fermat's principle is explained by using the analogy of the man who wants to reach his boat in the water the fastest possible way. In contrast to the man who knows in advance the position of his boat in the water, the light ray starting at A doesn't know anything about its path in advance.

Fermat's principle does not explain how the light is able to know the fastest possible way. Fermat's explanation was developed for classical physics. For quantum physics it was Feynman who gave the correct generalisation of Fermat's principle:

The light wave starting at point A chooses not one path, but all possible paths to go from A to B. On each of these infinitely many paths, a wave with a phase depending on the length of the path emerges. At (any) point B, all the waves emerging from all possible paths starting at A interfere.

Actually, even before Feynman, this kind of wave-like description of light was known. However, what is new in Feynman's approach is the fact that one *single* photon interferes with *itself.* Moreover, the resulting wave at point B is interpreted by Feynman as a quantum mechanical wave function. Its absolute value gives the probability to find the photon at point B.

Let's call $T_{A\to B}(x)$ the time the single photon with the angular velocity ω needs for the path from A to B hitting the water surface at x, as shown in the figure. The superposition of all paths hitting the air/water boundary at any point x is given by:

$$P_{A\to B}[\omega] = \int_{-\infty}^{+\infty} \mathrm{Sin}[\omega\, T_{A\to B}[x]]\, dx$$

This integral can be evaluated using a saddle point approximation if all the path lengths are much larger compared to the wavelength, in other words, T[x] is much larger than 1/ω for any x. In this case, the largest contributions come from those paths nearby the *classical path* defined by the solution of the equation:

$$\frac{d\, T_{A\to B}[x]}{d\, x} = 0$$

The stationary solution of this equation is nothing but the classical Snellius' law of refraction. Actually, for a single photon, it is not clear at all that it will follow this fastest possible path. In quantum mechanics, only the *probability* $|P_{A\to B}[\omega]|^2$ for the observation of the photon at point B can be given. In a light beam with millions upon millions of photons, almost all photons will choose the classical path because the superposition of all paths which deviate from the classical solution shows rapid oscillations in the phase differences and is annihilated. However, a detector which is placed into the water at some point far away from the classical solution could in principle detect photons which deviate from the classical path. Even if one has to wait a very long time for such an event to come, the probability is not zero. Such events occur more often if the wavelength is of the order of the distance between A and B, in other words, T[x] has the same order of magnitude as 1/ ω.

For more details and the relation between these arguments and the double slit experiment, we highly recommend the book of R. Feynman, "QED: The strange theory of Light and Matter". In vector diagrams Feynman visualizes the annihilation of the superposition of non-stationary paths.

Website about interference:
http://en.wikipedia.org/wiki/Superposition_principle