# Refraction of Light



**Scientific subject and topic:**
Physics / Light

**Movie / Year:**
QED - Matter, Light and the Void / 2005

**Movie producer:**
Hans-Bernd Dreis, Stefan Heusler

**Director:**
Stefan Heusler

**Cast:**
Prof. Ethereal and his colleague Nick

**Websites of movie:**
Filmography links and data courtesy of Sciencemotion
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:**
Filmography links and data courtesy of Sciencemotion
http://www.sciencemotion.de/files/english_trailer.mpg

**DVD:**
Order the DVD for EUR 20.00 plus shipping charge here
http://www.sciencemotion.de/en/orderdvd.html

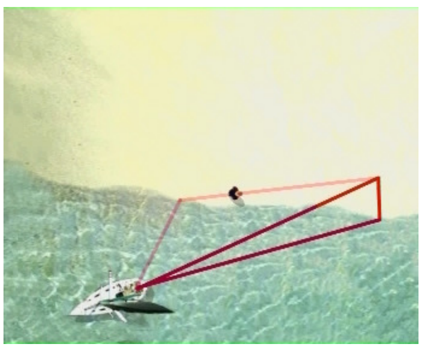
**Title of scene:**
Refraction of light

**Video clip or still:**
Chapter 1b, Technical Part

**Author:**
Stefan Heusler, Annette Lorke

**Scientific keywords:**
law of refraction, Fermat's principle, total reflection of light

**Description of scene:**
A red laser beam is passing from air into water. On the border between air and water the beam is refracted. We explain the law of refraction and Fermat's principle by using a simple metaphor:



A man is standing on a beach. He wants to reach his boat which lies at anchor in the shallow water the *fastest* possible way. As running along the beach is faster than swimming in the water, the man should stay longer on the beach and swim a shorter distance through the water. Thus, the shortest path (the straight line) is not the fastest path. Fermat's principle states that light always chooses the fastest possible way. Since light is faster in air than in water, it is refracted on the border.
Finally, total reflection, which is important for technical applications, is explained.

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**Movie clip:** Chapter 1b, Technical Part
**Director:** Stefan Heusler
**Film Studio:** Science*e*motion, [www.sciencemotion.de](http://www.sciencemotion.de)

**Basic level**

If you want to perform a little experiment, go into the kitchen and fill a glass with water. Look through the glass of water and watch, for example, one of the chairs in your kitchen. You will see the chair distorted while looking through the glass. Can you think of the reason for this observation?

Every object that you can see with your eyes reflects light. While you are looking at the chair through the glass of water the light that is reflected from the chair is going through the air and your glass of water before reaching your eye. On the boundary between the air and the glass of water the light is refracted which means that it does not go the straight path any more. A very simple and fundamental law of physics sums up this behaviour of the light: *Light does not go the shortest, but the fastest possible way*. It is the speed of light that determines the path. If the speed of light is not the same in two different substances (here: air and water), there is a difference between the *shortest* and the *fastest* way. Light is faster in air than in water. This is the reason why light is refracted when passing from air into water.

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**Advanced level**

The speed of light is smaller in water than in air. This experimental observation leads to the phenomenon of the *refraction* of light. One very simple and fundamental principle can be used to explain all different kinds of refraction, through water, prisms, lenses …. It is the so-called Fermat's principle: "Light always chooses the fastest possible path".

Fermat's principle explains the reason why light doesn't run along a straight line representing the shortest way between air and water. Since the propagation speed of light is different in air and in water, the straight line is not the fastest path. This is illustrated by the man running a longer distance on the beach and swimming a shorter distance in the water to reach his boat the fastest possible way.

Now, let's have a closer look at the experiment with the laser beam shown in the video clip to understand how total reflection occurs. Let α be the incident angle in the air, β the refraction angle in the water, $v_{Air}$ the velocity of the light in the air and $v_{Water}$ the velocity of the light in the water. The relation between the ratio of velocities $v_{Air}/v_{Water}$ and the ratio of angles α, β can be derived by using Fermat's principle and is described by Snellius' law of refraction:

$$\frac{\mathrm{Sin}[\alpha]}{\mathrm{Sin}[\beta]} = \frac{v_{Air}}{v_{Water}}$$

The angle is larger in that medium in which the velocity of light is faster.

For our laser beam experiment this means:

$$v_{Air} > v_{Water} \rightarrow \alpha > \beta$$

The path of light is reversible. If the time to go from A to B is minimal, this is also true for the reversed path from B to A.
Now, imagine the light ray is passing from the water into the air. To understand total reflection, we use the fact that the angle β is smaller than α. If we increase β, α also increases because of Snellius' law. However, Snellius' law only is valid as long as the light passes from one medium into another. Snellius' law can only be applied as long as α is smaller than 90°. For α = 90°, β reaches a value smaller than 90° which is called the "critical angle".
In our experiment we go on increasing β beyond this critical angle. In doing so we cannot employ Snellius' law anymore to describe which path the light beam takes because the light only runs along a path in one medium. Which path does the light choose now? Within the water the light's path is a straight line. On the border the light is reflected according to the reflection law "incident angle = reflection angle". This is the so-called *total reflection* of light.

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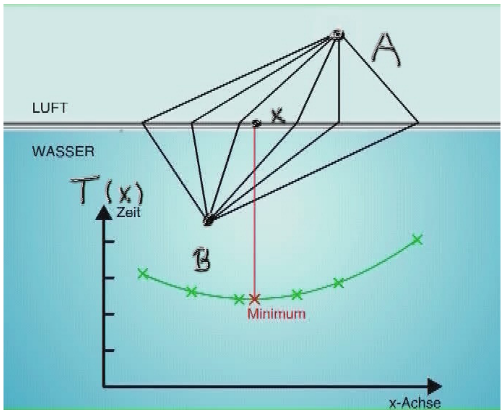
**Scientific level**

If the light hits the boundary between two media with the refraction indices $n_1$ and $n_2$, some part of the light is reflected and the remaining part is refracted. The reflection follows the law "incident angle = reflected angle", since the path of light must be reversible.

The speed of light in a medium is given by v = c/n with c being the speed of light in the vacuum (c ≈ 299,792 km/s). With Fermat's principle, Snellius' law for the refracted light can easily be derived by minimizing the function T[x]. In the movie, the function T[x] is defined as the time the light needs to go from A to B through the point x on the boundary.




The minimum dT[x]/dx = 0 corresponds to Snellius' law:

$$\frac{\mathrm{Sin}[\alpha]}{\mathrm{Sin}[\beta]} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

Fermat's principle cannot only be applied to the refraction of light in the medium water but to all kinds of media such as optical lenses. However, the refraction index n strongly depends on the light's wavelength λ. In liquid water and in glass, the refraction index of blue light is larger than the refraction index of red light, $n(\lambda_{blue}) > n(\lambda_{red})$. In other words, blue light in glass propagates slower than red light in glass. For this reason a prism splits white light into the colours' of the rainbow.

The path of refracted light must also be reversible. In contrast to the reflection law the symmetry between the ingoing and outgoing light ray is broken because the angles β and α are different. If the light passes from the optically dense region into the optically less dense region, it can be totally reflected if the incident angle β is larger than the critical angle:

$$\beta > \beta_{cr.} = \mathrm{ArcSin}\left[\frac{n_1}{n_2}\right]$$

In technical applications total reflection is used for data transmission using fibre optic cables. On account of the total reflection the frequency and amplitude modulated carrier frequency is transmitted over large distances without any loss. The carrier frequency in common fibre optic cables is in the GHz-region (Microwaves). More bits per second can be transmitted for higher carrier frequencies.
The generalization of Fermat's principle in quantum mechanics is discussed in chapter 1d (interference).

**Websites about refraction:**
http://en.wikipedia.org/wiki/Refraction
http://en.wikipedia.org/wiki/Refraction_index
http://en.wikipedia.org/wiki/Fibre_optic_cable