"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:
Sciencemotion

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/

Artistic Part, Chapter 1

Title of scene:
The Light

Video clip or still:
Chapter 1, Artistic Part

Author:
Stefan Heusler, Annette Lorke

Scientific keywords:
speed of light, spectrum of visible light, constants of nature

Description of scene:
The scientist Nick introduces himself to the audience. He works for Prof. Ethereal. As a practically-minded person Nick likes scientific explanations to be simple and clear. Therefore it is not always easy for him to accept the professor's mathematical theories which often seem to be far from reality.

When Prof Ethereal enters the scene, he does not introduce himself but starts directly with explaining his latest idea: His visualization of electrons, positrons, the light and the *void*. The *void* in spite of its complete nothingness still has structure. In the professor's model this structure is represented by two worlds – the normal world and the anti-world. In the normal world particles such as electrons are created and in the anti-world anti-particles such as the positrons are created. When electrons and positrons collide on the border between the two worlds, they decay into light (or photons). According to this model light neither belongs to the normal world nor the anti-world but exits on the border because light has no rest mass. Light in the void propagates always at the same speed, independent of the motion of the observer – the speed of light is a *constant of nature*.

After this introduction, Prof. Ethereal and his assistant Nick present their first experiment with a prism. Visible light is separated into its spectrum ranging from blue to red light. Prof. Ethereal explains that each colour corresponds to a wave with a fixed wavelength. Then Nick asks a very important question: "Can the light wave be overtaken?" Prof. Ethereal explains that water waves and sound waves can be overtaken once you move faster than the propagation speed of the wave. However, he claims that light waves cannot be overtaken. He does not prove his statement but points out its consequences for the relation between space and time, formulated in the theory of relativity by Albert Einstein (for further information about the theory of relativity see chapter 1f of the technical part)

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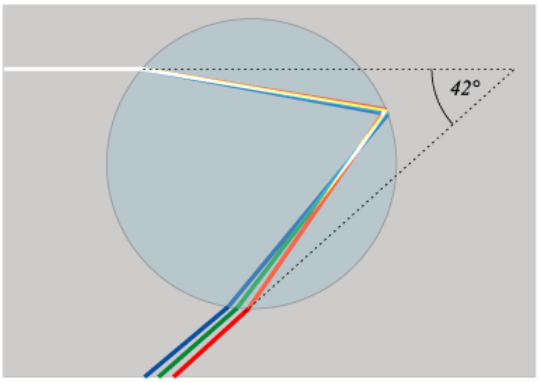
Basic level

Do you know why a rainbow occurs only when it is raining and the sun is shining at the same time? The white light from the sun consists of different colours which represent specific energies. Blue light has more energy than red light. Each raindrop works similar to a small prism when the white light is shining through. The raindrop separates the sunlight into its different colours. This happens because of a very simple principle: Light always chooses the *fastest* possible path.

When light hits the surface of water, it does not follow the straight path any more, because the speed of light in water is smaller than in air. Even more, the speed of light in water depends on the energy of the light. Therefore, the fastest possible path is different for the different colours of the sunlight. Similar to a prism, water makes the sunlight separate into its colour spectrum due to the difference of light velocity in water for the different colours.



In this picture you see the raindrop and the white light which is *refracted* at the boundary. This simply means that it does not follow the straight path any more. If the speed of light in water was the same as in air, the light would follow the straight path. But in water the velocity of light is smaller than in air and depends on the colour of the light. Blue light is faster than red light. Since the speed of blue light in water is closer to the speed of light in air, the path of blue light is closer to the straight line than the path of red light. Due to this difference, the paths of the blue and the red light separate from each other. The colours of the rainbow occur because in each single raindrop, the different colours separate in the same way. In chapter 1, Prof Ethereal and his assistant perform a similar experiment with a prism.

Later on, Prof. Ethereal explains that the speed of light is a *constant of nature*. What is a constant of nature? In the case of the speed of light it means that within the medium air the velocity of the light cannot change. The speed can only change when light passes from air into water. Let's consider the following model: Think of a ball which you let fall from a huge tower. The velocity of the ball increases because it gains energy due to the gravitation. The speed of the ball is not a constant of nature because it changes all the time. If you let light "fall down" from a tower, the light beam will also gain energy but its velocity exactly will remain the same all the time. The increasing energy will only change the colour of the light and not the speed.

Website about the rainbow:
http://en.wikipedia.org/wiki/Rainbow

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Advanced level

Light is a wave which cannot be overtaken in the vacuum. The speed of light in the void is always the same – it is a constant of nature. That's all you need to know in order to develop the theory of special relativity. It took so long to understand this fact because all the other waves that have been known when Einstein developed special relativity *can* be overtaken. The reason for light being so special is that light does not need a medium to exist. In contrast to sound waves or water waves, light is a wave which *can* propagate through the void.

There is a fundamental relationship between measurements and constants of nature (see also http://www.ptb.de/en/wegweiser/einheiten/_index.html). The fact that the speed of light is given by the odd number c=299,792,458 metres per second must be understood as a historical accident. Metres and seconds as units had been defined before the discovery of the constants of nature.

Today, one metre is *defined* as the distance the light covers in the vacuum in 1/299,792,458 of a *second*. The next obvious question is: What *is* a second? For the definition of a second you need an oscillator with the period T (that is with the frequency v = 1/T). Now we define the second by counting a certain number of periods of the oscillator. This is the common principle of all mechanical clocks. Instead of using a mechanical clock, we want to be more precise and choose an atomic clock. The precision of the atomic clock is based on the fact that we know both the exact energy E = h*v of a certain photon emitted by the atom caesium and the value of Planck's constant h. One second is defined by using the frequency v = 9 192 631 770 1/s of this photon which is emitted from the caesium atom, in other words the photon oscillates 9 192 631 770 times in one second.

Websites about SI unit system
http://en.wikipedia.org/wiki/SI
http://en.wikipedia.org/wiki/Second

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Scientific level

The speed of light in the void is always the same. But *speed,* that is, the ratio between propagation length and time, is a *classic* quantity. Special relativity as formulated by Einstein is a *classical* theory. By classical we mean that position and momentum variables commute (see Chapter 4 for the definition of the commutator).

The quantum description of light is more complicated. *Light* is in permanent interaction with the quantum vacuum. The coupling strength of light with electrons and positrons is described by a small number, the fine structure constant $\alpha=e^2/(2\,\epsilon_0\,h\,c)\approx 1/137$. Here, e is the charge of the electron, and ϵ_0 is the vacuum permittivity. The photon has a certain probability to create electron-positron pairs out of the quantum vacuum. This probability depends on the energy of the photon. Strictly speaking, the value of the coupling strength α depends on the energy (α= α(E), "running coupling constant"). It takes the value α ≈ 1/137 only for low energies.

In spite of the permanent interaction with the quantum vacuum, the rest mass of the photon is exactly zero and independent of the energy. If the photon had a rest mass, the world would change dramatically. Any particle which has a rest mass can in principal be slowed down to zero velocity. As a consequence the speed of light in the vacuum would not be a constant of nature, and special relativity would be wrong.

It is not certain at all that quantum corrections and the interaction with the void do not change the rest mass of a particle. For example, the carriers of weak interaction are the massive $W^{+/-}$ and Z^0 bosons, which were discovered at CERN in 1983. The electroweak interaction is described by a theory which is very similar to quantum electrodynamics. In the standard model of elementary particles, the rest mass of the photon vanishes, because it does not couple to the Higgs particle. The $W^{+/-}$ and Z^0 bosons couple to the Higgs field and therefore receive a rest mass from the vacuum energy of the Higgs field. In the next generation of particle accelerators such as the LHC at CERN it is most important to search for the Higgs field, which so far hasn't been observed directly.
(http://public.web.cern.ch/Public/Content/Chapters/AboutCERN/Achievements/Achievements-en.html)