"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:
Science*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:
Special relativity

Video clip or still:
Chapter 1f, Technical Part

Author:
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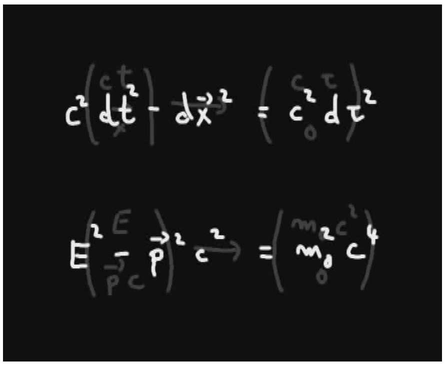
Scientific keywords:
spacetime, relativity, time dilation

Description of scene:



What is a distance? The geometry in a flat, three-dimensional *space* has been known since Euclid. However, the time component is completely ignored in Euclidian geometry. It was Einstein who understood that the speed of light in the vacuum is a constant of nature. Using this fundamental idea, he was able to derive a formula for distances in *spacetime* including the time component. Applying this spacetime geometry, he could prove the relation between rest mass and energy. In this scene, we explain these important equations of special relativity.

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Basic level

Imagine you have a younger sister, which is exactly 2 years younger than you. If you were 15 years old, your sister would be 13 years old. If you were 17, your sister would be 15. Although your age and your sister's age change all the time, the *difference* between your age and your sister's age stays the same. The difference is independent of the ongoing time. By the way: This is only true as long as neither your sister nor you travel at an extremely high speed, but we don't care about this detail at the moment.

It was a considerable scientific step forward to discover that some things in nature do *not change* while time is advancing. These things are called *constants of nature*. If you measure your weight every day, it will change from time to time. Obviously, this is not a constant of nature. Your age will change from year to year. Obviously, this is not a constant of nature. Even the age difference between you and your sister is not a constant of nature. At first sight you might say that this age difference does not change and therefore it is a constant. But there is more to a constant of nature than meets the eye. What was the age difference 1000 years ago? It did not exist since you and your sister had not been born yet. However, the constants of nature existed 1000 years ago. They haven't been changing until today for at least 13 billion years.

Light travels very fast, about 300 000 kilometres per second in the vacuum. Light in the vacuum cannot be overtaken. Albert Einstein discovered that the speed of light c in the vacuum is a *constant of nature*. Since this *velocity* is fixed, space and time are *relative* meaning they depend on the ratio between your velocity v and the speed of light c which is v/c. Since the speed of light is extremely fast, your velocity is very small compared to it. Therefore, in daily life, you do not feel that space and time are relative because the dependence on the ratio v/c is just too small (almost zero) to be noticed. But there are exceptions: The ratio between a satellite's velocity and the speed of light does matter if you want to describe the satellite's motion around the earth. You need Einstein's theory of special relativity to calculate the satellite's orbit.

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Advanced level

If you switch on the GPS navigation system in a car, your position and motion is tracked by satellites. On each satellite, a very precise atomic clock initiates the emission of radio impulses in regular intervals which are received by control stations on earth. Today, 24 American satellites orbit the earth (the corresponding European programme is called Galileo, see http://en.wikipedia.org/wiki/Galileo_positioning_system). The orbits of the satellites are chosen in such a way that from almost any place on earth, signals from at least 4 satellites can be received. This system, first introduced for military purposes by the US army, could not have been invented without the knowledge of the spacetime geometry proposed by Einstein (both special and general relativity). If we assumed that time is absolute and the space is flat (Euclidian geometry), the position calculated by the satellite would be wrong. The error would increase every day by a few kilometres. Millions of users of the navigation systems depend both on special and general relativity.

Basically, two effects play a role:

1. **Time dilation:**
The satellites move at a height of 20000 km above the earth's surface at a speed of about w = 4 km/s (corresponding to 14400 km per hour, thus orbiting the earth twice a day). If 1 second has passed on the satellite more than 1 second has passed on the earth. To calculate this time dilation, take the following formula:

$$\frac{1\,s}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{1\,s}{\sqrt{1-\left(\frac{4}{300000}\right)^2}} = 1\,s + 8.9 * 10^{-11}\,s$$

In the additional time caused by the time dilation, the radio wave travels the additional distance of about 2.7 cm. If we ignored this time dilation, the error in calculating the position would steadily increase with 2.7 cm per second (roughly 2.3 km per day). For simplifying matters we have ignored in our estimation the fact that in reality the position is determined by at least three satellites.

2. Gravitation:
The gravitational potential 20000 km above the earth's surface is much weaker than the gravitational potential on the earth itself. Imagine falling down to the earth's surface starting at the height of 20000 km. How much energy would you gain on account of the gravitational potential? According to Newton, the potential energy V(R) at a distance R from the earth's centre is given by:

$$V(R) = G\frac{M}{R}$$

G is Newton's gravitational constant and M is the mass of the earth.
The radio waves emitted by the satellite also gain energy through the gravitational potential while travelling towards the earth.
We define r ≈ 6400 km as the average radius of the earth and s ≈ 20000 km as the distance between the satellite and the earth's surface. Then r + s ≈ 26400 km is the

average distance between the satellite and the earth's centre. By applying the relation between light energy and light frequency E = h*v (h is Planck's constant) and the relation between mass and energy $E = m*c^2$, we find the frequency increase for a photon which is travelling towards the earth's surface by:

$$\frac{\Delta E}{E} = \frac{\Delta v}{v} = \frac{V(r+s) - V(r)}{c^2}$$

The earth's mass is about $6*10^{24}$ kg, and the gravitational constant has been measured as $G = 6.67*10^{-11}$ Nm^2/kg^2. With these numbers, we find the following formula for the frequency increase Δv on account of the gain of gravitational energy:

$$\frac{\Delta E}{E} = \frac{\Delta v}{v} = 5 * 10^{-10}$$

For non-military purposes, the basic signal frequency transmitted by the satellites is 1.575 GHz ($1.575*10^9$ oscillations per second). On account of the gravitational potential this frequency becomes larger by about 0.79 Hz when the radio waves travel towards the earth.

Combining the effect of time dilation and gravitation, we obtain a total frequency shift by calculating (w = 4 km/s is the satellite's velocity):

$$\frac{\Delta v}{v} = \frac{V(s+h) - V(s)}{c^2} + \left(\sqrt{1 - \left(\frac{w}{c}\right)^2} - 1\right) =$$

$$\frac{\Delta V}{c^2} - \frac{1}{2}\left(\frac{w}{c}\right)^2 + o\left[\left(\frac{w}{c}\right)^4\right] = 5 * 10^{-10} - 0.9 * 10^{-10} = 4.1 * 10^{-10}$$

Note that the radio waves gain energy because of the gravitational potential while travelling towards the earth. Therefore their frequency becomes larger. But the effect of the gravitational potential is a little compensated by time dilation. Time dilation implies that the radio frequency becomes smaller on earth. In total, the emitted radio signal of 1.575 GHz increases by about 0.65 Hz when measured on earth.

Websites about special relativity: http://en.wikipedia.org/wiki/Special_Relativity

Relativity and GPS: http://en.wikipedia.org/wiki/GPS#GPS_and_relativity

The article by Neil Ashby about GPS and relativity is also recommendable.
http://relativity.livingreviews.org/Articles/lrr-2003-1/

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Scientific level

Special relativity is a fantastic example for impeding prejudices in the history of science. Einstein had to ignore two paradigms – or call it prejudices – to find special relativity:

A. The first prejudice: Time is absolute.

B. The second prejudice: Electromagnetic waves cannot propagate through the vacuum. They need a medium, the so-called “ether”, to propagate.

A. About 5 years before Einstein, the Dutch physicist Lorentz wrote down the equations which transform one coordinate system into another coordinate system moving at a relative speed v (the so-called Lorentz transformations). However, he wouldn’t even have dreamt about the possibility of time being relative and thus failed to find the correct interpretation of his transformations.

B. In the 19th century, electromagnetism was studied by using the paradigm of the existence of “ether”. Similar to sound and water waves, it was assumed that electromagnetic waves also propagated through a substance.

Einstein ignored both prejudices while thinking about light. He claimed that time was relative and that light waves could also propagate through the void. Moreover, he declared that light waves in the vacuum propagated always at the same speed.
If you have two coordinate systems moving in x-direction with a relative velocity v, the light, starting at the position x = x’ = 0 at the time t = t’ = 0, reaches the position x (x’) after the time t (t’):

$$x^2 - c^2 t^2 = x'^2 - c^2 t'^2$$

Since c is constant, we find as the solution for the transformation between (c t, x) and (c t’, x’) the Lorentz transformations:

$$x' = \frac{x + v\,t}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \qquad t' = \frac{t + \frac{v}{c^2}\,x}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

In the differential form, we can easily derive the formula for the relativistic addition of velocities:

$$\frac{dx'}{dt'} = \frac{dx + v\,dt}{dt + \frac{v}{c^2}\,dx} = \frac{\frac{dx}{dt} + v}{1 + \frac{v}{c^2}\frac{dx}{dt}}$$

Here, w’ = dx’/dt’ is the velocity observed in the primed coordinate system, and w = dx/dt is the velocity in the non-primed system. This formula shows that c is the maximal possible speed: If we choose the speed of light as the velocity w in the non-primed system, w = c, we will find the velocity w’ in the primed system which moves at the speed v relative to the non-primed system as:

$$w' = \frac{c + v}{1 + \frac{c\,v}{c^2}} = c$$

Because of w = w’ = c, the Lorentz-transformations imply that the speed of light c is the same in both systems of reference, independent of the relative velocity v.