Exhibition of Experiments about Light *

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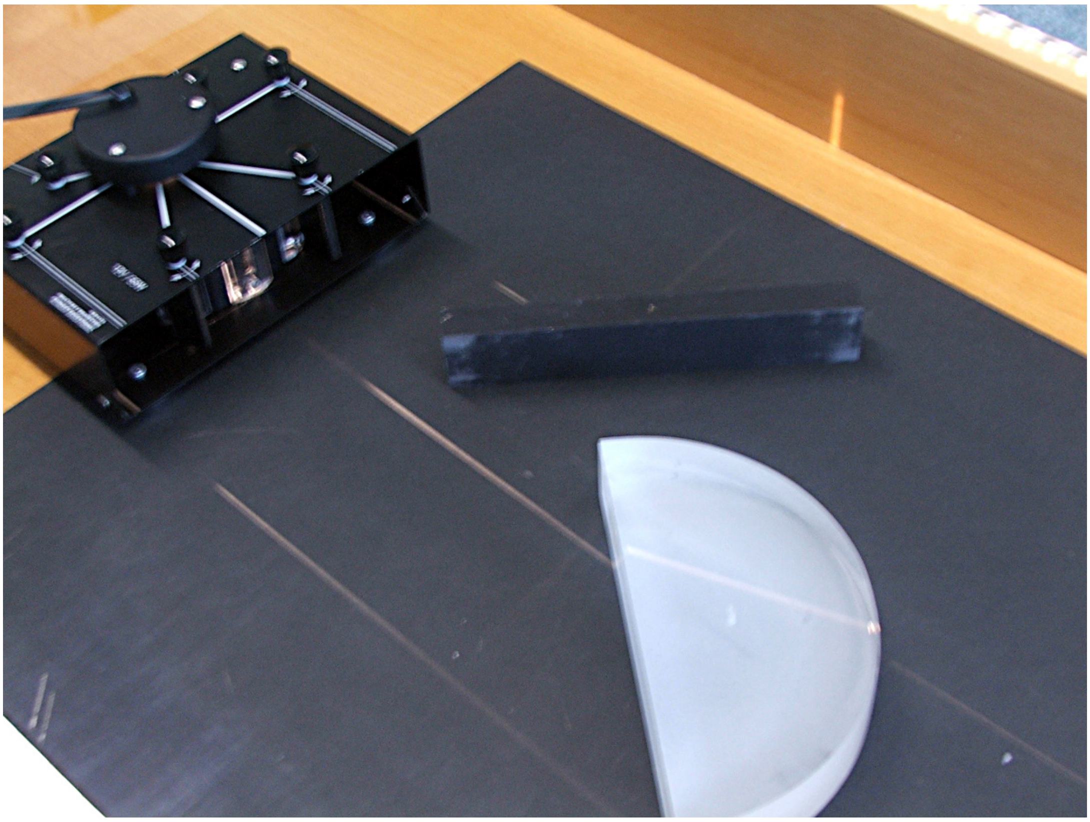
Light is a phenomenon that has attracted the attention of many scientists throughout history. The physical explanation of light gave rise to two main rival theories, source of very heated debates among the scientific community. Those two rival theories were only reconciled in 1905 after Einstein's explanation of the photoelectric effect, which is one of the events commemorated during **2005 - International year of Physics**.

The experiments in this exhibition follow the evolution of the theories of light from Newton (XVII century) to Einstein (XX century).

1 Light reflection and refraction



When we place a barrier with a slit in front of a light source, only the light rays in the lines that go through the source and the slit can go through the barrier. That way we can produce a thin light beam. That fact is an argument in favor of the **corpuscular theory of light**, which asserts that light is composed of small particles ejected in straight lines from the source.

Light is reflected in a plane mirror with the incident and reflected rays making the same angle with the surface of the mirror. That's what we would expect from a system of small particles hitting a rigid surface.

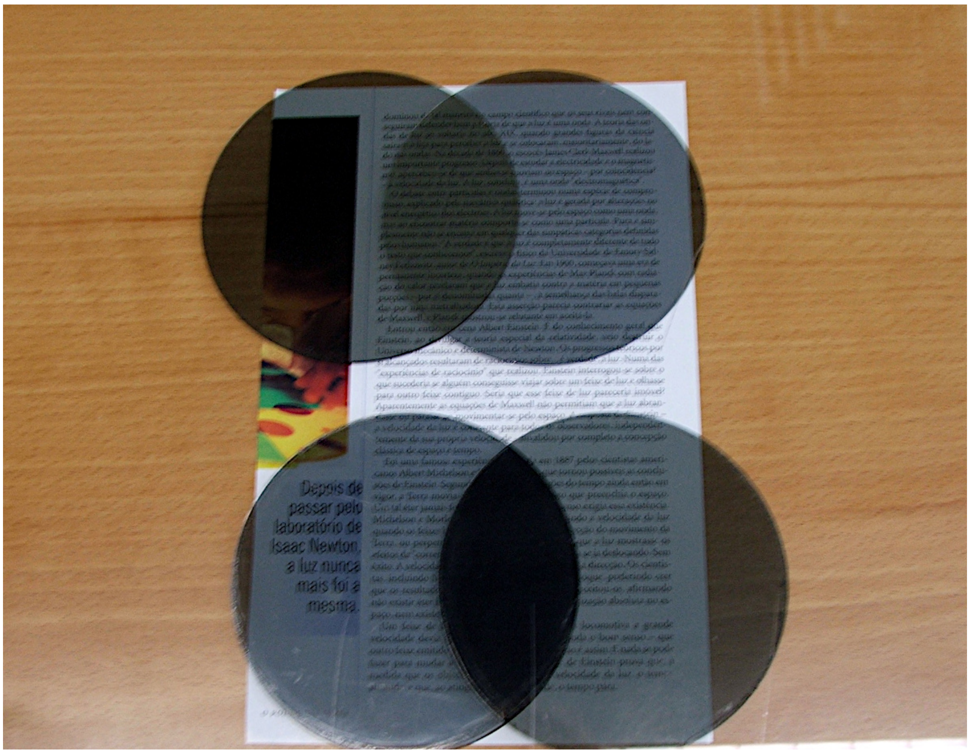
Light **refraction** is the passage of a ray of light from one medium to a different one. In that case, the angles of the incident ray and the refracted one with the surface dividing the two media are not the same. The relation between those two angles depends on the two media. The corpuscular theory of light explains that difference by assuming that the speed of light is different in the two media.

The **wave theory** of light can also explain how beams of light are formed as well and the equality of the incidence and reflection angle and the difference between the angles of the incident and refracted rays. However, its arguments for those phenomena are not as straight forward as in the corpuscular theory.

In the case of refraction there is an important difference between the predictions of the two theories. When light passes from air to water, the refracted ray comes closer to the perpendicular to the boundary surface. According to the corpuscular theory that approximation is due to a higher speed of light in water as compared to air. In the wave theory it is concluded that the speed of light is lower in water than in air.

In Newton's and Huygen's time (XVII century) the speed of light could not be measured with enough accuracy to determine which theory was right, so the stronger reputation of Newton prevailed and the corpuscular theory was preferred over the wave theory. Nowadays we know that light moves slower in water than in air as predicted by the wave theory.

2 Polarization of light



The polarization of light is another prove of its wave nature. Some crystals have the property of **polarizing** light: only a part of the light, oscillating in a given plane, can pass through them. Light coming out of a polarizing filter oscillates in a single plane.

If we place a second polarizing filter after the first one and if the polarization planes of the two filters are perpendicular, no light will come out of the two filters. Light is also polarized when reflected on a surface. If we look at the light reflected on a surface through a polarizing filter, rotating the filter will make the reflection disappear when the polarization plane of the filter is perpendicular to the plane of the surface.

Liquid crystal have the property of polarizing light when there is an electric current through them. That property is used to construct the LCD (Liquid Crystal Display) in a calculator or cellular phone.

The polarization of light can be easily explained assuming that light is a **transversal wave** (namely, it oscillates in a plane perpendicular to the direction of propagation). But at the time of Newton and Huygens that argument was in fact used against the wave theory of light. According to Huygens light waves would be oscillations of a hypothetical medium called **ether** in the same way that sound waves are oscillations of the air. But waves propagating in an elastic medium, such as sound, must always be **longitudinal waves** (the medium particles oscillate in the same direction as the wave propagates). Thus, Newton concluded, Huygen's wave theory of light cannot be valid.

3 Diffraction of light

Two experiments used by Fresnel as strong arguments in favor of the wave theory of light (by the end of the XVIII century and beginning of the XIX century) were the **interference** when light goes through two slits and the **diffraction** of light.

When two waves emitted from two point sources are combined they produce an **interference pattern**: there are localized regions where the resulting wave has maximum and minimum values. In the case of light, those interference patterns are observed as bright and dark regions.

Diffraction is the tendency of waves to "go around" obstacles. At the boundary between light and shadow projected by an object one can observe interference patterns which are the result of the diffraction of light.

Those two phenomena, interference and diffraction, are a signature of the oscillatory nature of waves and would not occur in the case of beams of particles. Therefore, interference and diffraction of light are proofs of its wave nature.

4 Michelson interferometer

By the end of the XIX century Maxwell's contributions to the theory of electromagnetism established the wave nature of light as an **electromagnetic wave**. Namely, a combination of time-varying electric and magnetic fields that can prevail even in the absence of any charges or electric currents.

One of the biggest successes of Maxwell's electromagnetic theory was that it could correctly predict the speed of light, from the values of the electric and magnetic constants, in very good agreement with the value measured experimentally for the speed of light.

But since the values of the electric and magnetic fields are different when measured in a moving reference frame, the speed of light could not be the same in all reference frames. It also seems evident that if we move with respect to the medium where a wave is propagating, we will measure a different speed for that wave; thus the speed at which a wave propagates is different in different frames.

Most XIX century physicists believed there was an absolute space (the hypothetical ether) where Maxwell's equations would be valid. The speed of light derived from those equations would be the speed of light with respect to that absolute space. Measuring the speed of light in different reference frames would then allow us to determine the **absolute speed** of those frames.

Many experiments were conducted using light from the stars and light from sources on Earth. All of those experiments always failed in detecting any differences in the speed of light; it seemed impossible to detect any differences when the source and/or the observer were in motion. After each new failed experiment a new amendment would be introduced into the theory of ether to account for that failure, such as the principle of ether dragging by sources or observers. Ether dragging didn't seem to follow any simple rules but it rather appear as an artifice that could adjust any possible result.

An active research activity in that area led Michelson to conceive several experimental devices to detect minute differences in the speed of light in a moving reference frame. The evolution of those devices culminated in an interferometer known as Michelson interferometer, where any effect of ether dragging could clearly be eliminated.

A Michelson interferometer splits a light ray into two perpendicular beams as the ray passes through a semitransparent mirror that reflects half of the light and lets the other half pass through. The two beams, emitted from the same source, are then reflected back to the beam splitter, where they interfere with each other creating an interference pattern that is projected into a screen.

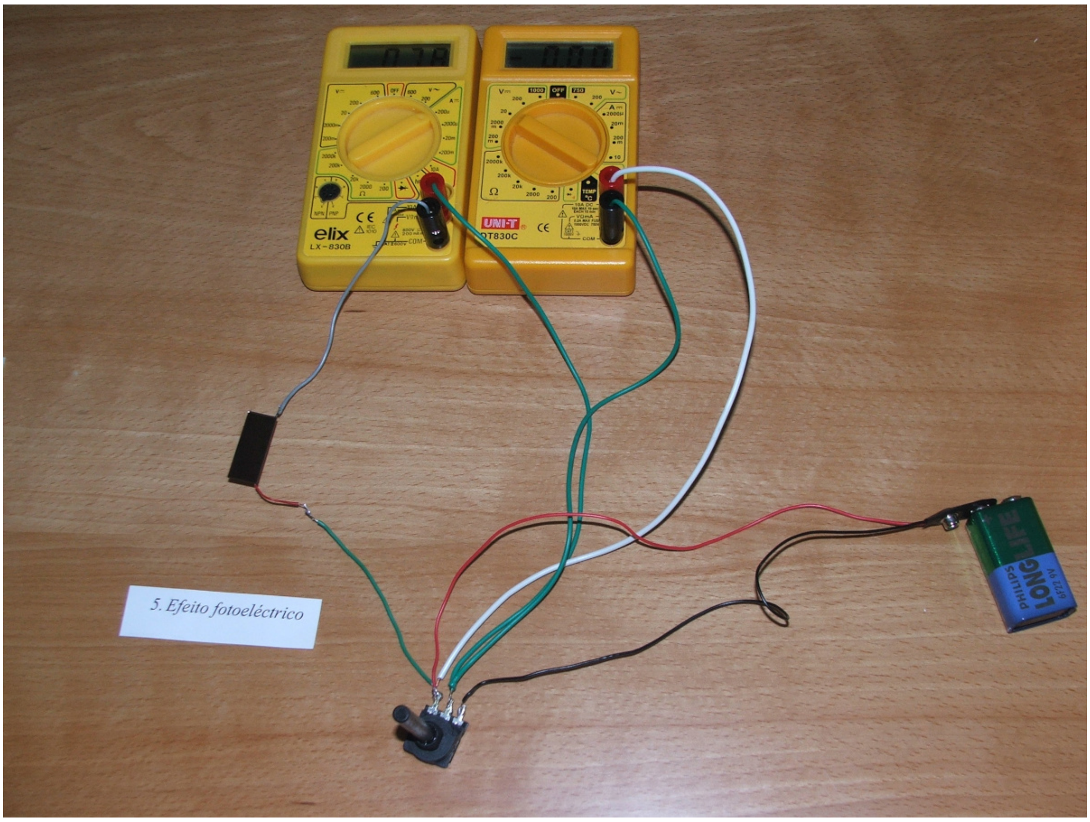
The distances traveled by the two beams (optical paths) can be adjusted with high precision. A slight variation on the time taken by the two beams to travel those paths can be observed as a shift of the fringes in the interference pattern. If the speed of light were different in different directions (due to the motion of the Earth), as the interferometer were rotate the interference pattern should move.

Michelson and Morley conducted that experiment failing to observe any effect of the motion of Earth on the speed of light. What they observed was that the speed of light was the same in all directions. Lorentz explained that result assuming a contraction of the ether in the direction of the motion of the Earth. But he did not propose any cause or mechanism for that contraction.

In 1905 Einstein publishes his **theory of relativity**, according to which the speed of light should be the same in any reference frame. One of the consequences of that postulate is that time and distance are no longer absolute quantities, as our common sense tells us, but can take different values for different observers. There is no absolute space or ether.

Accepting only two simple principles, the laws of physics are the same for any observer and the speed of light is constant, Einstein derives the same equations obtained by Lorentz. But instead of resulting from a contraction of the ether, those equations are prove of a contraction of distance and a dilation of time which are real relativistic effects, with many consequences that have already been observed in experiments.

5 The photoelectric effect



Maxwell's theory of light, in which light is just an electromagnetic wave, opened up the possibility of producing other types of electromagnetic waves using electric circuits. The first person to succeed in that effort was Hertz, by the end of the XIX century. Ironically, while conducting the experiment that proved the existence of electromagnetic waves, leading to the end of the corpuscular theory of light, he accidentally discovered the effect that would later be used to revive that theory: while conducting his electromagnetic wave experiments, he noticed that light from a spark in a circuit could induce an electric current in another remote circuit used to detect the electromagnetic waves produced by the first.

A few years later when the electron was discovered by Thomson, it became clear that the effect observed by Hertz, dubbed as **photoelectric effect**, was due to some electrons being ejected from a metal when a light ray reaches its surface. The electromagnetic energy transported by light is absorbed by the electrons in the metal, allowing them to get free from the binding in the metal. The problem that nobody was able to explain by the beginning of the XX century was why the energy of the electrons ejected by photoelectric effect does not increase when the intensity of the incident light increases, but it does increase as the frequency of that light increases. In fact, for each metal there is a minimum frequency of light under which there is no photoelectric effect.

The energy of the electrons ejected by photoelectric effect can be measured if we connect an external voltage source to the photoelectric cell and adjust the source's voltage (opposed to the cell's voltage) until the current in the circuit vanishes.

In 1905, when there was no doubt about the wave theory of light, Einstein published a paper where he perfectly explained the photoelectric effect by assuming that light is composed of particles —**photons**— with energy directly proportional to the frequency of the light. In the theory of photons, the energy transported by light cannot be increased continuously but rather in discrete amounts, corresponding to 1 photon, 2 photons, 3 photons and so on. That theory also explained the success of Planck's hypothesis (1900) to explain the black-body radiation spectrum, under the assumption that the energy radiated by a black body could only take discrete values —**quanta**— of energy.

The work of Planck and Einstein would give rise to **quantum physics**, in which all physical objects are entities which are both particles and waves (wave-particle duality). Energy is transported from one place to another as waves, but that energy is emitted and absorbed in discrete amounts, as particles. Light, as well as any type of matter, is both a wave and a particle. That's the reality at the sub-microscopic level, but at the macroscopic level of our daily experience there seems to be a clear distinction among waves and particles.