Basic Physics of Light

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Light

Light - fascinating and mysterious companion throughout human history

How our vision works?

Light and vision

We know today that light and vision are inseparable. But it was not always so.

Ancient Greeks

Today's science has its roots in ancient Greece. They have developed different theories, among them also some very interesting about vision.

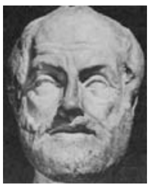
“Emission Theory”

Euclid, Ptolemy and their followers believe that vision occurs when rays emanate from the eyes and are intercepted by visual objects.

If we saw an object directly it was by 'means of rays' coming out of the eyes and again falling on the object.

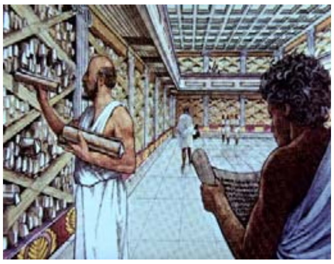
“Intro-Mission Theory”

The school of Aristotle and Galen advocated the approach which explains vision with rays coming from object and entering the eyes.



This theory seems to be closer to modern theories, but it did not provide any experimental foundation.

Egipt around AD 1000



Although the Ancient Library of Alexandria does not exist anymore there is still a lot of knowledge in Egypt in that days.

Vision and light finally together!

Alhazen (Abu-'Ali Al-Hasan ibn Al-Hasan ibn Al-Haytham) written in Arabic: أبو علي الحسن بن الحسن بن الهيثم .

In his Book of Optics (Kitab al-Manazir, lat.: De Aspectibus, 1021) Alhazen linked light and vision based on common observations such as the eye being dazzled or even injured if we look at sun.

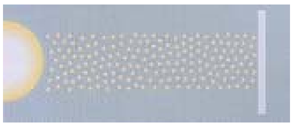
Vision is since than inseparably linked with light.

Western World in 17th century

In 17th century the question is not anymore: "How we see?" but already: "What is light?"

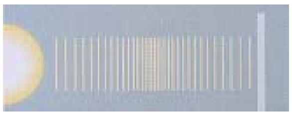
Corpuscular theory of light

Sir Isaac Newton, inspired by Gassendi's work, stated in 1675 that light is composed of "corpuscles“ (little particles) which travel in straight line with a finite velocity and possess kinetic energy.



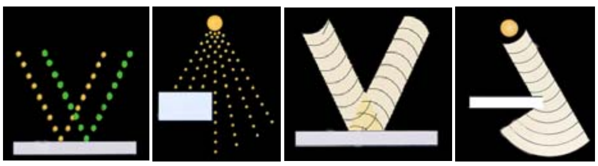
Wave theory of light

Christiaan Huygens published his wave theory of light in 1690. He proposed that light is emitted as a series of waves in a medium called the luminiferous ether. As waves are not affected by gravity, it was assumed that they slowed down upon entering a denser medium.



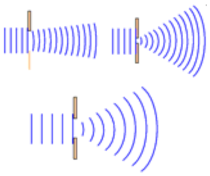
Waves or corpuscles?

Both "parties" found plenty of evidence in favor of own theory and against an opponent's theory.



If the light would consist of waves...

... it should bend around small obstacles and spread past small openings (diffract) like waves on water.



Today we know that light diffracts - that is why the edge of the razor blade on a picture looks fuzzy and not sharp.

If the light would be stream of particles...

...two "jets" of light, which cross each other, would interact with one another, like two jets of water.

On the other hand, the rotation of the Crookes radiometer was “easy” to explain with particles and “was not possible” with waves which needed “luminiferous ether” to propagate (if vacuum is supposed inside).

Who was right?

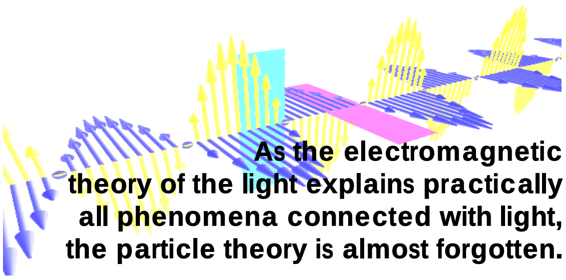
“Once and for all I want to know what I’m paying for. When the electric company tells me whether light is a wave or a particle I’ll write my check.”

We know today that non of them was exactly right or wrong but Newton's reputation helped the particle theory of light to hold sway during the 18th century.

Electromagnetic theory of light

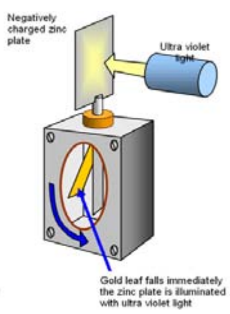
James Clerk Maxwell discovered that self-propagating electromagnetic waves would travel through space at a constant speed equal to the speed of light. From this, he concluded in 1862 that **light is a form of electromagnetic radiation**.

Electromagnetic theory of light



As the electromagnetic theory of the light explains practically all phenomena connected with light, the particle theory is almost forgotten.

Electromagnetic theory of light

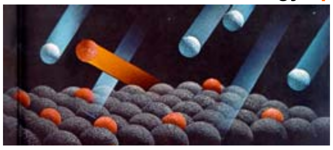


But there are some anomalies in his theory. Among them is also a **photoelectric effect**, which, according to experiments, depends also on wavelength of the light and not only on its intensity as it should be if the light would be electromagnetic radiation.

Quantum theory of light

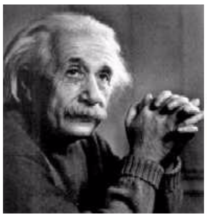
In 1900, Max Planck developed a theory that explained another anomaly: a contradiction between the wave theory of light and measurements of the electro-magnetic spectrum emitted by thermal radiators.

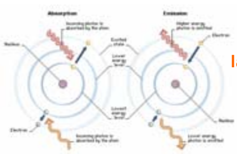
Quantum theory - black bodies emit light only as discrete packets of energy: quanta.



Finally! Particle theory revisited!

In 1905, Einstein solved photoelectric effect puzzle with help of quantum theory forming so the basis for wave–particle duality of light and qualifying for Nobel prise.

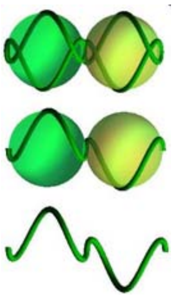




Few years latter quantum of light was named photon.

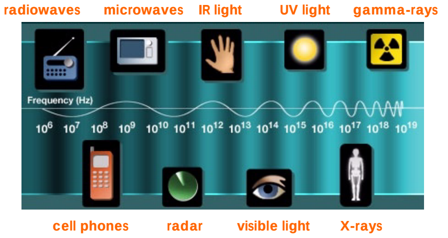
Quantum electrodynamics

Starting from Einstein we are talking about the duality of particles, where each particle has also certain wave properties. The further development of this thinking led to quantum electrodynamics.

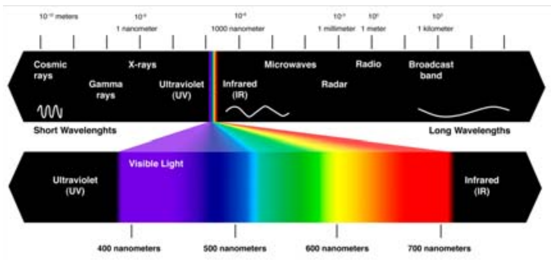


Light as part of the EM spectrum

If the light is considered as part of the electromagnetic spectrum it is located between microwaves and X-rays.

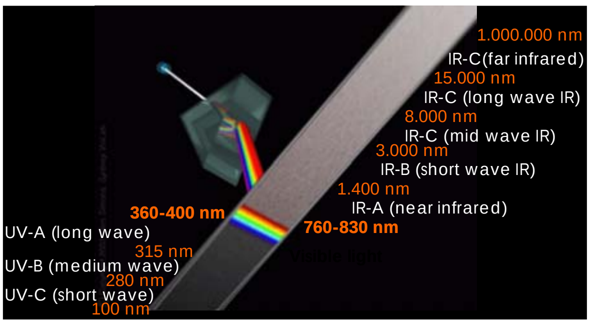


Light as part of the EM spectrum



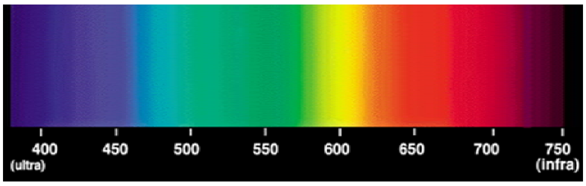
Only a small part of the light spectrum can be perceived with human eye.

Light as part of the EM spectrum



Light as part of the EM spectrum

The part of the EM spectrum between approximately 380 nm to 780 nm can be perceived by the human visual system and is called visible light.

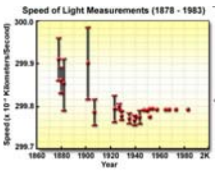


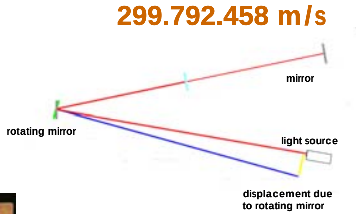
Phenomena connected with light

Whatever light is (waves or particles) when it travels through the space some interesting phenomena can be observed such as: refraction, specular and total internal reflection, dispersion, absorption, scattering, interference, diffraction and polarization.

Speed of light

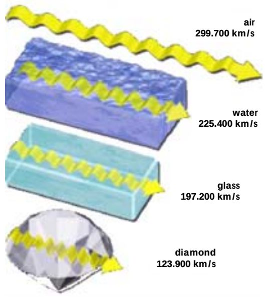
The speed of light in vacuum is 299.792.458 m/s





Rotating mirror device used by Leon Foucault for measuring the speed of light in 1862. Result: 298.000 km/s.

Speed of light



The speed of a light is dependent upon the properties of the medium.

The relationship between the speed of light in vacuum and in medium gives the refractive index.

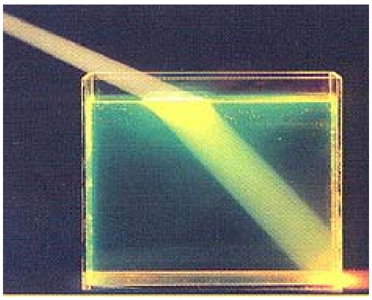
Refractive index

$$n = \frac{c}{v}$$

c ... speed of light in vacuum
v ... speed of light in medium

Air	1,0003
Water	1,33
Glycerin	1,47
Oil	1,515
Glass	1,52
Quartz	1,66
Zirconium silicate	1,92
Diamond	2,42
Lead sulfide	3,91

Refraction of light

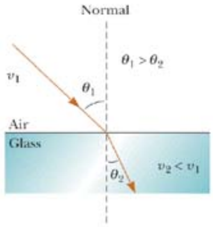


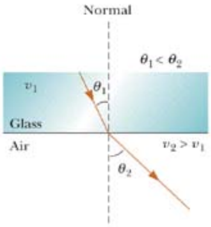
Refraction is the bending of light as it travels through the boundary of two mediums. How much the light bends depends on the refractive indices of the two mediums.

Refraction of light

$$n_1 \cdot \sin\theta_1 = n_2 \cdot \sin\theta_2$$

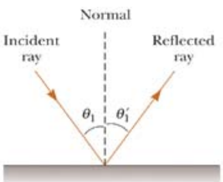
n **... refractive index**





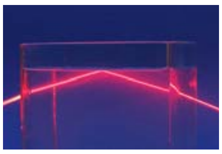
Specular reflection of light

Specular Reflection is the mirror-like reflection of light from a surface of the medium with a higher optical density (with higher refractive index).

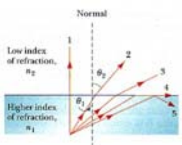


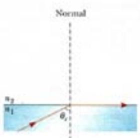
The angle of incidence equals the angle of reflection.

Total internal reflection of light



If light travels from medium with higher refractive index to one with lower one it will be partially refracted at boundary surface and partially reflected.

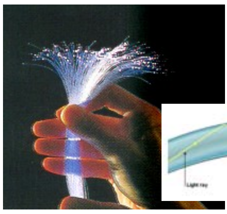


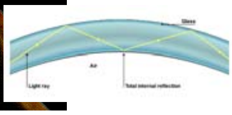


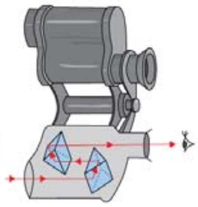
If the angle of incidence is greater than the critical angle the light will be totally reflected back.

Total internal reflection of light

Total internal reflection is used in many fields of technology to reflect light (almost) without losses.

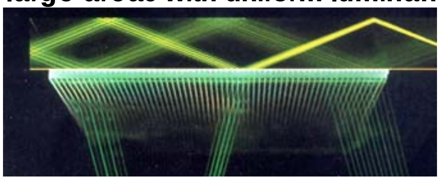






Total internal reflection of light

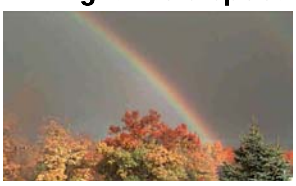
We use total internal reflection also in lighting to produce luminaires with large areas with uniform luminance.



Example of ELDACON technology (Siteco)

Dispersion of light

A wavelength-dependent refractive index causes different colors (wavelengths) to refract at different angles, splitting white light into a spectrum.



Absorption of light

When light propagates through the medium, part of its energy gets "lost".

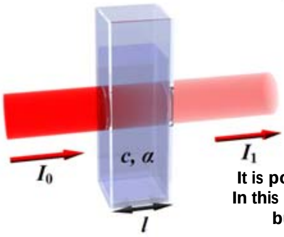
The light is absorbed by medium.

The energy is transformed to other forms like:

- heat,
- radiation with another wavelength,
- electrical energy or
- chemical energy.

Absorption of light

When light propagates through a homogeneous medium its intensity decreases exponentially:



$$I = I_0 \cdot e^{-\alpha \cdot l}$$

I_0 ... initial intensity,
α ... absorption coefficient ($f(\lambda)$),
l ... distance the light travels through the medium.

It is possible that α has negative value. In this case the light is amplified (laser), but we need to supply the energy.

Scattering of light

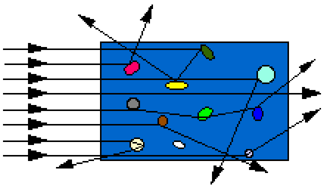
Scattering is process where light is forced to deviate from a straight trajectory by one or more localized non-uniformities in the medium through which they pass.

Example: water drops in fog scatters light.

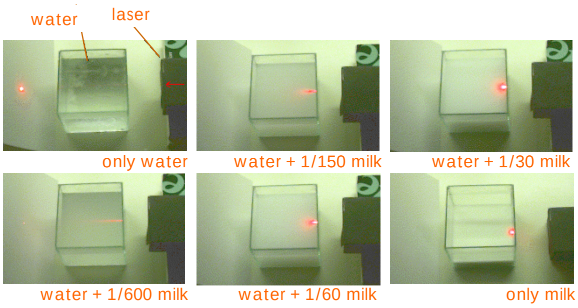
Scattering of light

The scattering occurs when light is propagating through inhomogeneous medium.

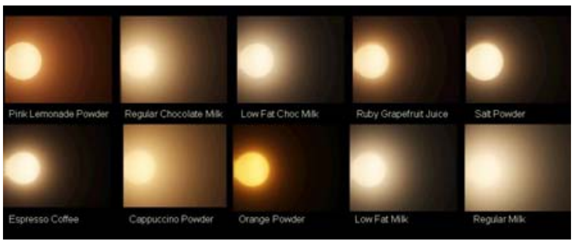
As the light deviates from a straight trajectory we can not see objects through such medium.



Scattering of light

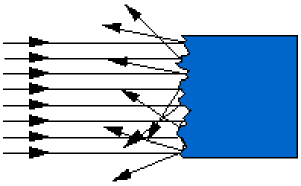


Scattering of light



Diffuse reflection

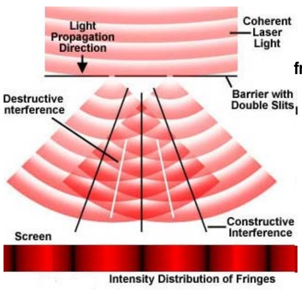
Diffuse reflection is a reflection from a rough or matte surface which creates a beam of scattered light with no directional dependence.

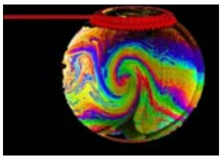


We can not see reflected image on such surface.

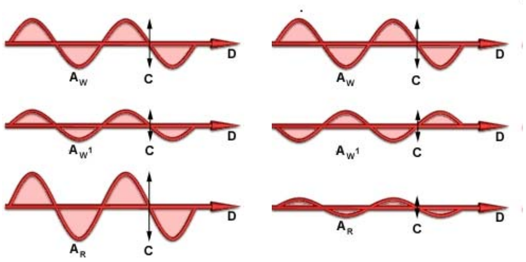
Interference of light

Interference is the addition of two correlated or coherent waves (of light) that results in a new wave pattern. Coherent waves come from the same source or have the same or nearly the same frequency.





Interference of light

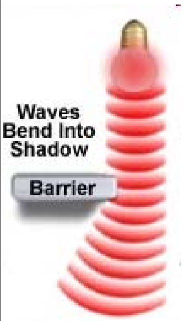


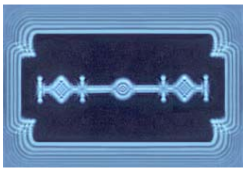
Constructive interference

Destructive interference

Diffraction of light

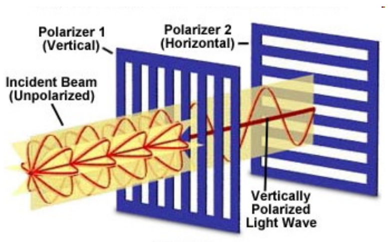
Diffraction is bending of waves around small obstacles and the spreading out of waves past small openings.





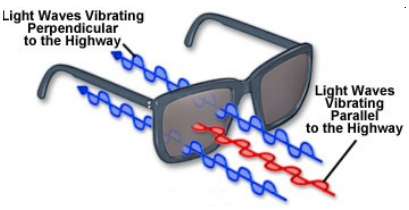
Polarization of light

When light is passing through the substance or is reflected from it, it can become polarized.



Polarized light oscillates in one direction only.

Polarization of light



Light reflected from the road is polarized in the horizontal plane (parallel to the road), so it does not pass through the vertically polarizing sunglasses and thus the glare is reduced.

Physical measurement of light

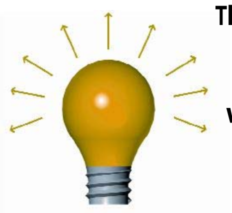
In physics, radiometry is the field that studies the measurement of electromagnetic radiation, including visible light.

Physical measurement of light

Four main radiometric quantities are:

- radiant flux,
- radiant intensity,
- irradiance,
- radiance.

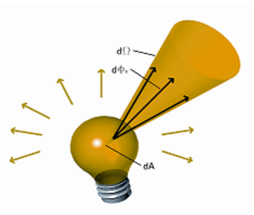
Energy and power emitted by source



The total energy emitted by a source is called radiant energy (J) and when observed per unit time, it is called radiant power or radiant flux (Φ_e).

Φ_e watt (W)

Radiant intensity



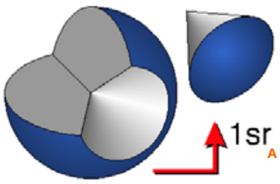
The radiant flux emitted in a given direction is called **radiant intensity (I_e)**. The direction is represented by a solid angle.

$$I_e = \frac{\phi_e}{\omega}$$

I_e watt per steradian (W/sr)

Solid angle

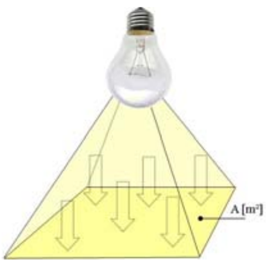
$$\omega = \frac{A}{r^2}$$



A **solid angle (ω)** is equal to the area of the segment of unit sphere. In case of non-unit sphere, the area should be divided by square of radius. The unit of solid angle can be called **steradian (sr)**.

A solid angle equals the area of a segment of unit sphere in the same way a planar angle equals the length of an arc of unit circle.

Irradiance



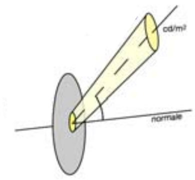
Irradiance (E_e) is radiant flux per unit area received by real or imaginary surface.

$$E_e = \frac{\phi_e}{A}$$

E_e watt per square meter (W/m^2)

Radiance

Radiance (L_e) is a radiant flux per unit projected area leaving a surface in a given direction (defined by solid angle)



$$L_e = \frac{I_e}{A \cdot \cos\theta}$$

L_e watt per steradian per square metre (W/sr m^2)

At the end

- Light is an electromagnetic radiation which exists in tiny "packets" called photons and exhibits properties of both waves and particles.
- Visible light includes wavelengths from about 380 nm to about 780 nm (depending on the individual).
- In physics radiometry is used to measure electromagnetic radiations.

... and now:

Questions?