Master of Marine Sciences – Aix Marseille Université

Marine Optics

and Biogeochemical Applications

OPB305

Special COPERNICUS program

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Course material available for download at
http://www.com.univ-mrs.fr/~petrenko/TEACHING/OPB305/Copernicus_OPB305_English

Course plan:

I Colour - Interaction of light with "transparent" materials

1. Reminder of the physics
2. Brief history and reminders about light
3. Colour of irradiance
4. Refractive index
5. Colour due to refraction
6. Colour due to reflection
7. Colour due to scattering
8. Colour due to diffraction

II Radiometry and IOPs

1. Reminders – Radiometry
2. Optical properties of water
3. IOPs

III IOPs of marine water

1. Absorption
2. Scattering
3. Studying the energy of phenomena

IV Light through the water column

1. Air/water interface
2. Fate of light in water – "Rules" for light to disappear
3. Vertical profiles – de Beer's law

V AOPs

1. AOPs in marine water
2. Gordon normalisation of Kd

VI Fate of light in water - qualitative

1. Underlying assumption of the equations
2. Radiative transfer equation
3. Numerical methods to solve the equations
4. Inverse method
5. Bio-optical modelling

VII In situ instrumentation

1. Radiometric measurements and derivation of AOPs – The Secchi disc
2. IOP and fluorometric measurements + derived products: particle sizes, …

VIII Remote sensing oceanography

1. Instrumentation
2. Water colour: Measurement types and algorithms; Coastal applications

The objective of this course is to provide high-level training in optical oceanography by providing students with the knowledge essential for the correct use of data collected in situ by optical oceanographic instruments (PAR, radiometer, biogeochemical Lagrangian floats, etc.) or provided by remote sensing measurements; by allowing them to understand the radiative transfer equation from which simpler laws for the transmission of light in water are derived, to know about optical instruments both in situ and on remote sensing satellites, and their derivative products.

Tutorials: A. Petrenko and C. Pinazo

Analysis of optical data (on PCs with Matlab)
& use of satellite images – Preparation of tutorial reports

The objective of the tutorials is to analyse in situ data sets allowing the students to put the theoretical knowledge into practice and to study physical and/or biogeochemical processes using satellite images obtained from CMEMS and others. Some data will be compared with outputs from a coupled physical-biogeochemical model. This course forms part of the Copernicus Academy training programme.

External speakers:

Dr. J. Uitz (CNRS, LOV, Villefranche sur mer): Remote sensing applications in biogeochemistry
(Primary production, Plankton functional types, physiology)

Dr. E. Martinez (IRD, LOPS, Brest): Physical-biological interactions and variability (satellite)

+ CMs by **Dr. H. Claustre** (CNRS/LOV) BGC floats (together with OPB 301)

References:

* **Light and Water - Radiative Transfer in Natural Waters**
Mobley, Academic Press 1994

and this site which is still being developed:
http://www.oceanopticsbook.info/view/introduction/overview

* **Light & Photosynthesis in Aquatic Ecosystems,** Kirk, Cambridge Univ Press, 1994

* **Remote sensing and image interpretation,** Lillesand & Kiefer, Wiley, 2000

+ other web sites mentioned in the course material

Acknowledgements:

I would like to thank the external speakers who have participated in this course over the years, as well as Curt Mobley and colleagues for their permission to use some of their figures.
I would also like to acknowledge Wikipedia from where I obtained some more general and/or historical information that is used either directly or in adapted form.

I Colour - Interaction of light with "transparent" materials

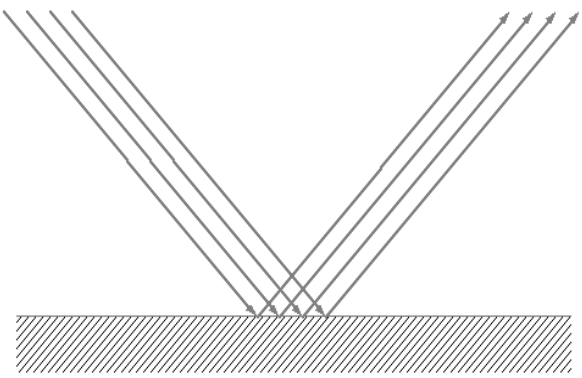
1) <u>Reminders of the physics</u>

<u>Emission:</u> a body heated to a certain temperature converts its internal energy (at the molecular level) into thermal radiation.
<u>Absorption:</u> When light hits a surface, part is transformed into internal energy (heat) and is called absorbed. This is the inverse process to emission.
<u>Transparency and opacity:</u> A medium that entirely transmits the energy contained in an incident light wave is called transparent (e.g., vacuum). To a first approximation, glass is also transparent to visible wavelengths. Conversely, a body that does not transmit any of the incoming light is called opaque.
<u>Black body:</u> By definition, a black body is an object that entirely absorbs any incoming radiation. Under these conditions, there is zero reflection and the entire energy flux emerging from the black body is due to emission (see definition of emission above).
<u>Reflection:</u> Instead of being absorbed, irradiance incident onto an object can also be directly reflected. We distinguish between two cases: a) the reflected light obeys the laws of geometrical optics and we speak of specular reflection; b) the reflection occurs in all directions and we speak of diffuse reflection.

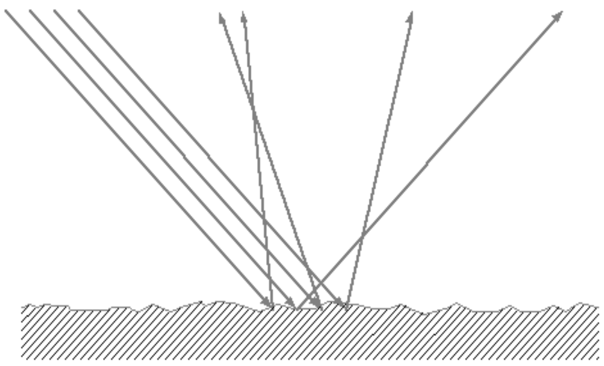
Reflection is called specular when the incident light ray gives rise to a single reflected light ray. Ideally, the energy contained in the incident ray is totally reflected as well, although, in practise, part of the energy is usually absorbed or scattered at the interface.

Diffuse reflection occurs at irregular interfaces where the incident light is reflected in a large number of directions and the incident energy is distributed among several reflected rays.

When the medium of propagation changes and part of the electromagnetic wave returns to the original medium then we have reflection. The best-known case of reflection is light reflecting off a mirror, but this also concerns X-rays (X-ray mirror) and radio waves: reflection of megahertz waves on the ionosphere, parabolic antennae, reflections on the Moon, etc.



a) specular reflection (http://commons.wikimedia.org/wiki/File:Reflexion_speculaire_fr.png)



b) diffuse reflection (http://commons.wikimedia.org/wiki/File:Reflexion_diffuse_fr.png)

Refraction: When the medium of propagation changes and the second medium is transparent to the light wave but with a refractive index different from the first medium, then the wave crosses into the second medium but changes direction, i.e., it is refracted. This concerns light (optical lens, fata morgana), waves in water, and also radio waves (refraction of HF waves in the ionosphere).
For those interested, and in particular those who have followed the course on ocean swells, there is an animation of the refraction phenomenon at http://fr.wikipedia.org/wiki/Indice_de_réfraction

Scattering: When a wave encounters an obstacle (e.g., and atom, molecule, etc.), it is scattered by it, i.e., it changes direction. We distinguish between three types: (i) Rayleigh scattering which does not change the wavelength of the scattered light (therefore called “elastic” scattering); (ii) Raman scattering which is a type of scattering where the wavelength of the scattered light is changed (inelastic scattering), and (iii) Compton scattering, the scattering of a photon (typically X- or gamma ray) by a charged particle (e.g., an electron) which typically leads to an increase in wavelength (decrease in energy) as part of the photon energy is transferred to the recoiling electron (Compton effect).

Interference: Like all waves, electromagnetic waves can interfere. In the case of radiocommunications, this causes signal interference (see signal-to-noise ratio).

Diffraction: The interference of scattered waves is called diffraction (diffraction theory; diffraction at an aperture; Young’s double-slit experiment; diffraction grating; X-ray diffraction, etc.).

2) Brief history and reminders about light

Century		Particle	Wave
XVII	**Descartes** (France 1596-1650) Treatise (1633-34) published post mortem	X	
	Huygens (Netherlands 1629-95) reflection, refraction, wave behaviour (1670) + measured $c \sim 3\times10^8 ms^{-1}$; but waves needed some medium to propagate (at the time a concept identical to acoustic waves needing a medium to propagate)-> hypothesis of a luminiferous "ether", postulated medium for the propagation of light		X in ether
	Newton (GB 1642-1727); light = small particles 1675 prism – colour dispersion; 1704 publication of "Opticks" [Theory of emission (forces) -> acceleration of light speed in water; attention this theory is false (see below: Foucault)] Planetary system + forces –> no need for an ether (E)	X	w/o E
XIX	**Young** (GB 1773-1829) interference – Young double-slits (1801)		X
	Fresnel (France 1788-1827) interference; wave length; diffraction; polarisation		X
	Foucault (France 1819-68) Theory of "undulations"; measurement of reduced light speed in water (1850)		X
	Maxwell (Scotland 1831 - 1879) Theory of electromagnetic waves (1864) but the waves may need a medium to propagate? (return to questioning the existence of an ether)		X E?
	Michelson-Morley experiment: 1881 (Michelson only) and 1887 (Michelson and Morley) questions the existence of the ether		no E
XX	**Max Planck** (Germany 1858 - 1947) 1900 quantum concept of light (discretized energy) from black-body radiation	X	
	Einstein (Germany, Switzerland, USA 1879-1955) Existence of "particles" (1905), explained by: - Photo-electric effect measured in 1895 - Theory of relativity –> no ether	X	non E
	L. de Broglie (France 1892 – 1987) All matter has wave-like properties Energy $E=h\nu=hc/\lambda$ (1924) h = 6.626 10^{-34} Js Planck's constant	x	X
	G. Lewis (USA 1875 – 1946) Particles called "**Photons**" (1926)	X	
	Bohr & Co (1920's) Quantum theory and the dual nature of light with photons ($L<\lambda$ **) and waves (** $L>\lambda$ **)**	X	

Short biographies of the aforementioned scientists (adapted from Wikipedia)

Christiaan Huygens (The Hague, 1629 -1695) was a Dutch mathematician, astronomer, and physicist. He is known for arguing the wave-like nature of light (see: wave-particle duality). In response to articles published by Isaac Newton on the nature of light in 1672, he begins to study the nature of light. In 1677, using geometrically cut crystals, he re-discovers what is now called

Snell's law of reflection and refraction ($n_i sin\theta_i = n_r sin\theta_r$) based on the wave-like nature of light. In 1678 he presents his wave theory of light which is published in 1690 in his Treatise on Light, which is regarded as the first mathematical theory of light. His theory was initially rejected in favour of Isaac Newton's corpuscular theory of light.

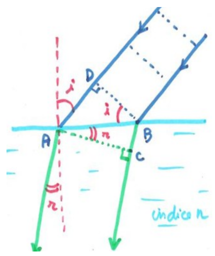
Sir Isaac Newton (1643 –1727) was an English mathematician, physicist, astronomer, theologian, and author (described in his own day as a "natural philosopher") who is widely recognised as one of the most influential scientists of all time and as a key figure in the scientific revolution. His book Philosophiæ Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy), first published in 1687, established classical mechanics. Newton also made seminal contributions to optics, and shares credit with Gottfried Wilhelm Leibniz for developing infinitesimal calculus. In 1666, he conducted his first experiments on the nature of light. By passing light through a prism he observed that the light exiting the prism was divided into a spectrum of rainbow colours. Previously, this phenomenon had been interpreted as the prism glass having some hidden intrinsic colour that the incident light caused to emerge. Newton was able to produce white light by shining the rainbow spectrum exiting the first prism through a second prism which led to his revolutionary conclusion: **colour is part of the light itself and does not originate from the glass**. Thus, white light is actually a combination of all the colours of the visible spectrum.

In 1704, he published his treatise "Opticks" in which he expounded his corpuscular theory of light, his theory of refraction and diffraction of light, and his theory on colour. He demonstrated that white light is composed of several colours and stated that it is made up of particles or corpuscles. In addition, Newton put forward his "emission theory", stating that light accelerates when it passes through an optically more dense medium (refraction). Beware, his reasoning, briefly summarised below, is actually faulty. "When a light ray passes from air into water, the tangential force remains the same; the perpendicular force at the surface is proportional to n; since $n_{air} = 1$ and $n_{water} = 4/3$, c(water) = 4/3 c(air)". Based on this reasoning the light speed would be higher in water than in air.

Thomas Young (13 June 1773-10 May 1829) was a British polymath (like Leonardo da Vinci, Gottfried Leibniz, or Francis Bacon, for example) who made notable contributions to the fields of vision, light, solid mechanics, energy, physiology, language, musical harmony, and Egyptology. Young has been described as "The Last Man Who Knew Everything". While practising medicine all his life, he is mostly known for Young's double-slit interference experiments, which helped him establish the wave theory of light (in contrast to Newton's particle theory), and for his definition of Young's modulus in materials science. Through his interest in Egyptology he "made a number of original and insightful innovations" in the decipherment of Egyptian hieroglyphs (specifically the Rosetta Stone).

Augustin Jean Fresnel (1788 -1827) was a French civil engineer and physicist whose research in optics led to the almost unanimous acceptance of the wave theory of light, excluding any remnant of Newton's corpuscular theory. He is perhaps better known for inventing the catadioptric (reflective/refractive) Fresnel lens and for pioneering the use of "stepped" lenses to extend the visibility of lighthouses, saving countless lives at sea.

Jean Bernard Léon Foucault (Paris, 1819- 1868) was a French physicist best known for his demonstration of the Foucault pendulum, a device demonstrating the effect of the Earth's rotation. He also made an early measurement of the speed of light, discovered eddy currents, and is credited with naming the gyroscope. He proposed the "undulation theory" of light; 2 light rays (1 and 2) travelling parallel to one another must remain in phase when transitioning from air to water. As the rays arrive at an oblique angle (see sketch below), ray 1 will hit the water surface before ray 2 and they will travel different distances in air and water. As the distance travelled by ray 2 through air before hitting the water is greater than the additional distance travelled by ray 1 through water, they can only remain in phase if c(water) < c(air).



a) Consider two parallel rays that are in phase: ray 2 travels the additional distance DA through air at speed c while ray 1 travels the additional distance BC through water at speed c_{H20}. For them to remain in phase we need: $DA/c=BC/c_{H2O}$ hence $c_{H2O}=c\times BC/DA$

b) Snell's law: 1 sin i = n sin r

$$\frac{DA}{AB}=n\frac{BC}{AB} \text{ hence } \frac{BC}{DA}=\frac{1}{n} \qquad c_{H2O}=\frac{c}{n}$$

He confirmed this theory experimentally in 1850 showing that light travels faster in air than in water, thereby "invalidating" Newton's corpuscular theory of light in favour of the wave theory approach. This experiment was very clever and quite challenging because it succeeded in measuring the speed of electric currents while highlighting the differences in travel time between a light beam passing through water versus a beam passing through air. The experimental setup consisted of 3m tubes. Considering that light travels a distance of 3 m in 1/100,000,000th of a second, time needed to be measured 100,000 times more precisely than during a Formula 1 race.

James Clerk Maxwell (1831 -1879, Edinburgh) was a Scottish scientist in the field of mathematical physics. His most notable achievement was to formulate the classical theory of electromagnetic radiation, bringing together for the first time electricity, magnetism, and light as different manifestations of the same phenomenon. Maxwell's equations for electromagnetism have been called the "second great unification in physics" where the first one had been realised by Isaac Newton. With the publication of "A Dynamical Theory of the Electromagnetic Field" in 1865, Maxwell demonstrated that electric and magnetic fields travel through space as waves moving at the speed of light. He proposed that light is an undulation in the same medium that is the cause of electric and magnetic phenomena. The unification of light and electrical phenomena led to his prediction of the existence of radio waves. Maxwell is also regarded as a founder of the modern field of electrical engineering.

The Michelson-Morley experiment (1881 et 1887) was an attempt to detect the existence of the luminiferous ether, a supposed medium permeating space that was thought to be the carrier of light waves. The experiment was performed by American physicists Albert A. Michelson and

Edward W. Morley and compared the speed of light in perpendicular directions in an attempt to detect the relative motion of matter through the stationary luminiferous ether ("ether wind"). The result was negative, in that Michelson and Morley found no significant difference between the speed of light in the direction of movement through the presumed ether, and the speed at right angles. This result is generally considered to be the first strong evidence against the then-prevalent ether theory and initiated a line of research that eventually led to special relativity, which rules out a stationary ether. Of this experiment, Einstein wrote, "If the Michelson–Morley experiment had not brought us into serious embarrassment, no one would have regarded the relativity theory as a (halfway) redemption." Michelson–Morley type experiments have been repeated many times with steadily increasing sensitivity and always with the same result. In 1907 Michelson received the Nobel Prize in physics.

Max Karl Ernst Ludwig Planck (1858 - 1947) was a German theoretical physicist whose discovery of energy quanta won him the Nobel Prize in Physics in 1918. While working to create an exact formulation of the second principle of thermodynamics, Planck turned his interest toward black body radiation in 1894 adopting Boltzmann's statistical methods. In what is now known as the "Planck postulate", he suggested that electromagnetic energy could be emitted only in quantized form, in other words, the energy could only be a multiple of an elementary unit: $E=h\nu$ where h was named Planck's constant (introduced already in 1899) and ν the frequency of radiation. This was the birth of quantum theory and physicists now call these quanta photons. Planck also introduced the so-called Boltzmann constant (k). It is worth noting that Einstein's hypothesis of light quanta (photons), based on Heinrich Hertz's 1887 discovery of the photoelectric effect, was initially rejected by Planck as he was unwilling to discard completely Maxwell's theory of electrodynamics.

Albert Einstein (Germany,1879-1955 USA) was a German-born theoretical physicist who developed the special theory of relativity in 1905 and the general theory of relativity in 1915, one of the two pillars of modern physics (alongside quantum mechanics). He received the 1921 Nobel Prize in Physics "for his services to theoretical physics, and especially for his discovery of the law of the photoelectric effect", a pivotal step in the development of quantum theory. He is best known to the general public for his mass–energy equivalence formula $E = mc^2$, which has been dubbed "the world's most famous equation".

Einstein revisited Planck's results to study the photoelectric effect, and concluded by stating that light behaves both as a wave and as a flow of particles. The photoelectric effect therefore provided a simple confirmation of Max Planck's quantum hypothesis. In 1926, quanta were starting to be called photons. This modern name "photon" is derived from the Greek word for light and was chosen in 1926 by chemist Gilbert N. Lewis when publishing a rather speculative theory in which photons were "uncreatable and indestructible". Although Lewis' theory was never accepted and even disproven experimentally, the new name "photon" stuck and was adopted by the scientific community.

Louis Victor de Broglie (1892-1987) was a French physicist and aristocrat who made groundbreaking contributions to quantum theory. In his 1924 PhD thesis, he postulated the wave nature of electrons and suggested that all matter has wave properties. This concept is known as the de Broglie hypothesis, an example of wave–particle duality, and forms a central part of the theory of quantum mechanics. De Broglie won the Nobel Prize for Physics in 1929, after the wave-like behaviour of matter was first experimentally demonstrated in 1927.

Niels Henrik David Bohr (1885-1962, Copenhagen) was a Danish physicist who made foundational contributions to understanding atomic structure and quantum theory, for which he received the Nobel Prize in Physics in 1922.

He conceived the principle of complementarity: that items could be separately analysed in terms of contradictory properties, like behaving as a wave or a stream of particles. The notion of complementarity dominated Bohr's thinking in both science and philosophy.

In October 1927, he met Albert Einstein for the first time at the fifth Solvay Conference. Both maintained frequent exchanges until 1935. Einstein preferred the determinism of classical physics over the probabilistic new quantum physics to which he himself had contributed, while Bohr firmly believed that it was an accomplished theory. These so-called Bohr-Einstein debates are one of the sources of his Philosophical Writings, published in four volumes (1963 and 1998).

Bohr & Co: Bohr (Denmark), L. de Broglie (France), Erwin Schrödinger and Wolfgang Pauli (Austria), Werner Heisenberg (Germany), Paul Dirac (England). To establish quantum theory, they worked on the intrinsic nature of atomic physics facing many paradoxes before coming to understand that the materialist view does not work on the subatomic scale. In a sense, on this scale, matter does not exist with certainty but “tends to exist", introducing the concept of probabilities. In addition, they also showed that, at the subatomic scale, reality does not exist independently of the observer (e.g., Heisenberg’s uncertainty or Schrödinger's cat).

3) Light

There are two main types of waves in physics: the mechanical wave and the electromagnetic (EM) wave. A mechanical wave is the displacement of a mechanical disturbance (jolt, vibration, etc.) in matter. Electromagnetic waves can move in a vacuum or in matter. All waves transport energy; however, the fundamental difference between electromagnetic and mechanical waves is the type of displacement adopted by this energy. Mechanical waves set their medium in motion (waves stir the liquid, earthquakes shake the ground) and energy is transmitted by this movement. This is not the case with electromagnetic waves: they do not interact mechanically with their environment. **An electromagnetic wave is the propagation of a signal, corresponding to variations in electric and magnetic field amplitudes which are both linked and oscillating together.**

Light, as any moving object, can be considered either as a wave or as a stream of particles (called photons in this case). However, modern physics considers that each of these photons can itself be considered a wave (this is called wave-particle duality in quantum mechanics).

Propagation: In a homogeneous and isotropic medium, the electromagnetic wave propagates in a straight line. There may be changes of direction, for example, when encountering an obstacle (scattering); during a change of medium (reflection and refraction), or during changes in the properties of the (thus heterogeneous) medium (refraction).

Electromagnetic waves

The electromagnetic wave is a model used to represent EM radiation. In fact, we need to distinguish between:
- electromagnetic radiation, which is the phenomenon we study here, and
- the electromagnetic wave, which is one of the representations, or models, of the phenomenon.

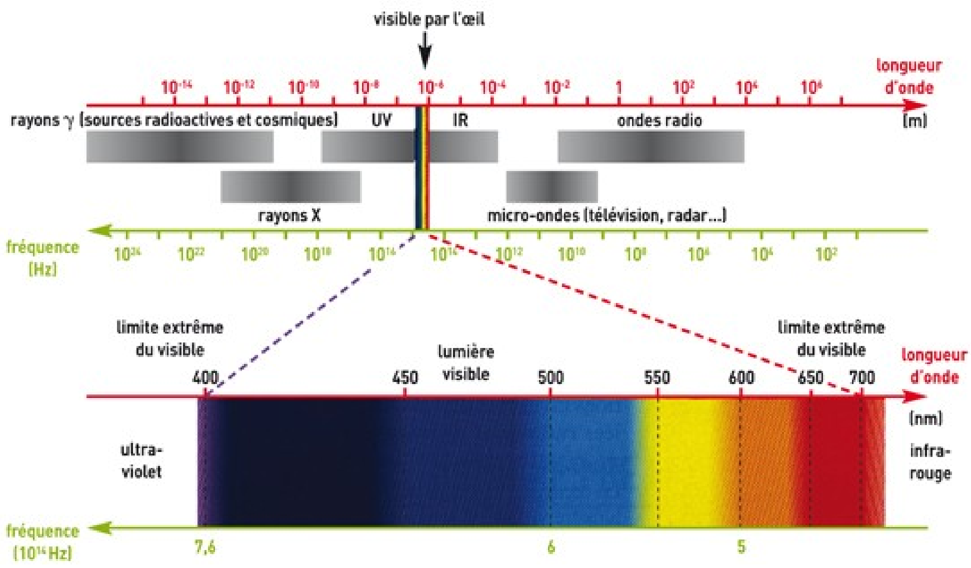
The electromagnetic wave represents two things (e.g., it is like looking at the shadow of a cylinder: if it is the shadow of its cross-section we see a disc, if it is the shadow of its side we see a rectangle):

a) the macroscopic variation of the electric (**E**) and the magnetic (**H**) field vectors;

b) the wave function of a photon, i.e., the squared norm of the wave gives the probability of the photon being present.

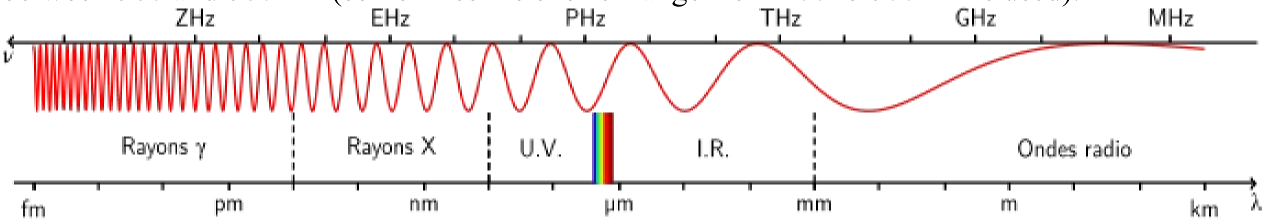
Each photon "carries" a determined quantity of energy, equal to $E = h\nu$, where h is Planck's constant and ν the frequency of the light. We can thus calculate the photon flux through a surface. Directed energy flows in physics (the transfer of energy per unit area per unit of time) are usually denoted with the so-called **Poynting vector**, written as **S**, **R**, **N**, or **P**. For electromagnetic waves it is $\mathbf{S}=\mathbf{E}\times\mathbf{H}$. Its SI unit is Watts per square meter (W/m^2). It is named after its discoverer John Henry Poynting (GB 1852-1914) who first derived it in 1884.

Depending on the wavelength (frequency), the terminology differs:



(http://www.educonline.net/spip/spip.php?article269)

A light wave is an electromagnetic wave whose wavelength is part of the visible spectrum, i.e., between 380 and 780 nm (sometimes the shorter range from 400 to 700 nm is used).



Frequency: 10^{21} zettahertz ZHz; 10^{18} exahertz EHz; 10^{15} petahertz PHz; 10^{12} terahertz THz ; 10^{9} gigahertz GHz; 10^{6} megahertz MHz

Wavelength: 10^{-6} micrometre µm; 10^{-9} nanometre nm; 10^{-12} picometre pm; 10^{-15} femtometre fm

Supplement on microwaves (invisible but well known):

Microwaves have wavelengths in the range of approximately 30cm (1 GHz) to 1mm (300 GHz), between infrared and radio broadcast waves. The term microwave comes from the fact that these waves have a shorter wavelength than those of the VHF band, used by radars during WWII.

Different uses:

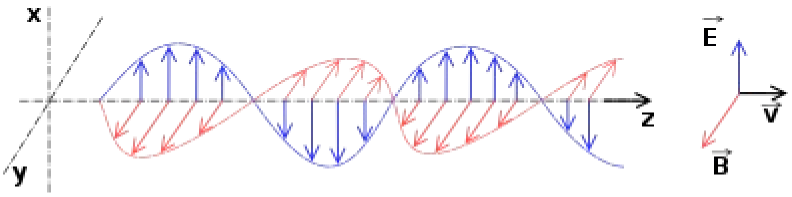
- satellite transmissions because this frequency easily crosses the Earth's atmosphere and with less interference for the highest wavelengths (e.g., GPS);
- radars to measure distance, speed, and other characteristics of distant objects;
- wireless transmission for local networks such as Wi-Fi, Bluetooth (2.4 and 1.9 GHz);
- cable TV and coaxial cable Internet access;
- local wireless video transmitters (baby monitors, watching TV in the bedroom without having a wired antenna, etc.);
- mobile telephony (0.8, 1.8, and 2.6 GHz);
- microwave ovens use a magnetron as a microwave generator at an approximate frequency of 2.4 gigahertz in order to heat food (since the 1980s);
- ultra-short magnetic pulse, which is used in cancer treatment;

Quiz: Can we calculate the speed of light from microwaves? (see Le Monde August 2015 "Micro-ondes, vitesse de la lumière et chocolat fondu", + article by J.-M. Courty in "Pour la science", 2011).

Plane wave

Most light waves can be approximated as a plane wave. Like all propagating electromagnetic waves, it consists of electric (**E**) and magnetic (**B**) fields that are both perpendicular to the direction of propagation (**z** or **v**). The vector of propagation is usually named **k** and defined below

The triple (**k**,**E**,**B**) is a set of orthogonal vectors (in the image below this corresponds to the x-, y-, and z-axes):



(https://en.wikipedia.org/wiki/Electromagnetic_radiation)

The wave vector **k** has the norm $\frac{2\pi}{\lambda}$, with λ being the wavelength.

Speed

The speed of light in a vacuum, c, is a constant in physics. According to the special theory of relativity, this is the maximum speed* allowed for information to travel or for a physical object to move. This quantity was estimated based on the interferometric experiments by Michelson and Morley and had been predicted as a physical constant by Albert Einstein in 1905. The speed of light is thus an *exact* and universal constant as it does not depend on any *measurement* (which would by definition be imprecise and susceptible to change due to technological advancements that lead to increase accuracies).

c = 299,792,458 m/s   or, approximately: $\mathbf{c = 3\times10^8}$ **m/s**

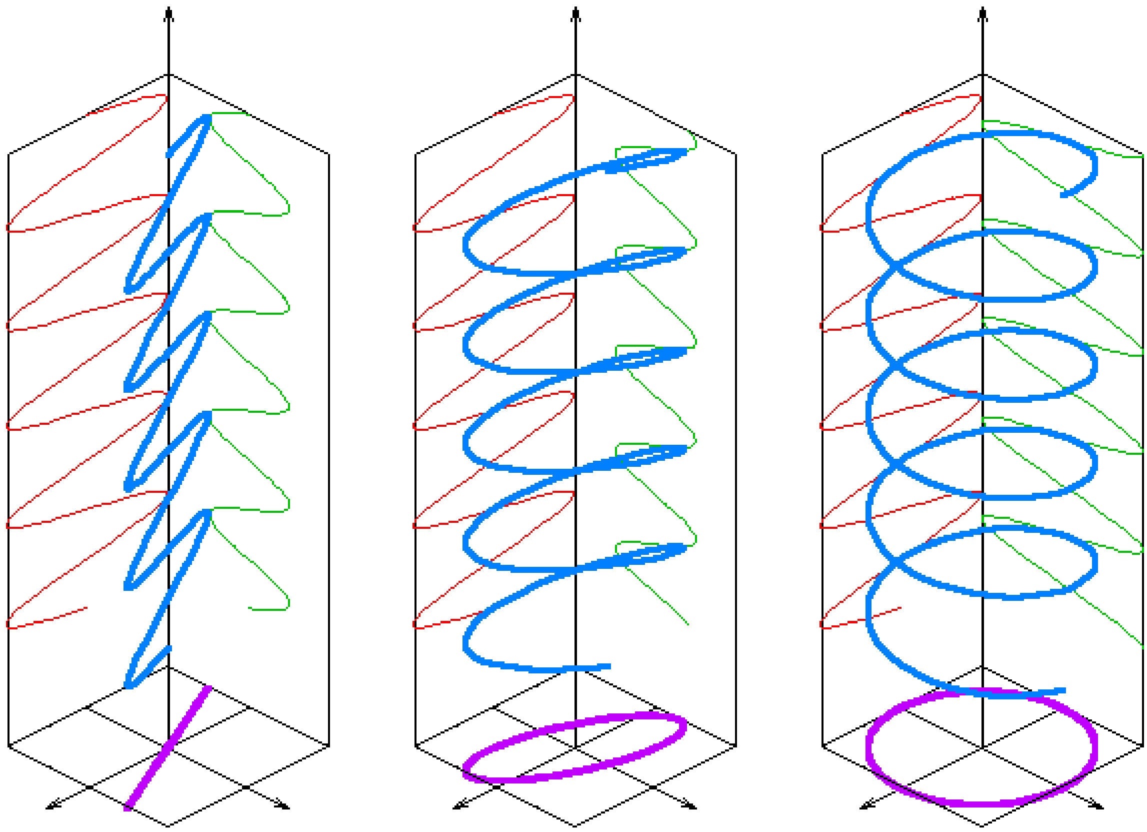
*** Note on FTL (Faster Than Light):** this is not just a real-time strategy video game; it is not possible to accelerate and exceed the speed of light but it would theoretically be possible to have a speed higher than c if it always remained higher than c (tachyons; http://en.wikipedia.org/wiki/Faster-than-light).

Polarization (Wikipedia)

Polarization characterizes the orientation of the electric field in the plane orthogonal to the direction of propagation.

We will omit the magnetic field henceforth as it can be determined from the electric field. We therefore consider only the electric field, **E**, *perpendicular to the direction of propagation*.

The oscillating electric field vector can trace an ellipse which can become a circle or flatten into a line. These different behaviours define the **state of polarization** of the light wave: one speaks of *elliptical, circular,* or *linear polarization*. Since the wave *propagates,* the ellipse described by the electric field vector, **E**, is actually a helix (see figures below for a 3D representation).



Linear *Elliptic* *Circular*

This phenomenon can be explained from the equation describing the propagation of a light wave. By breaking down the electric field vector into its two orthogonal components (shown in green and red above), we see that they are both sinusoids. When the two components oscillate in phase, the light has a linear polarization. If they oscillate out of phase (i.e., one is lagging behind the other), then we obtain an elliptical polarization. In the particular case where this phase shift is 90° and both components have the same amplitude, the polarization is circular.

Mono- and polychromatic light - coherence
Light consists of electromagnetic waves. Generally, a wave is characterised by its wavelength and phase. The wavelength determines the colour of the light. Hence, light that consists only of waves of the same wavelength is called monochromatic.
If, in addition, all waves are in phase, the light is called coherent which is what happens in a laser. The above definitions of polarization are in fact only strictly valid for monochromatic and coherent light. For all other cases the definition differs slightly.

Incoherent light
Natural light consists of various light waves, short (10^{-8} s) pulses of light that each have a random amplitude, frequency, and polarization. Natural light is thus incoherent and unpolarized.

Colour - Definition

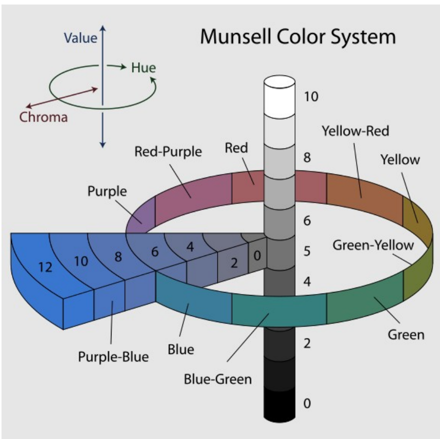
colour	wavelength (nm)	frequency (THz 10^{12} Hertz)
red	~ 625-740	~ 480-405
orange	~ 590-625	~ 510-480
yellow	~ 565-590	~ 530-510
green	~ 520-565	~ 580-530
cyan	~ 500-520	~ 600-580
blue	~ 446-500	~ 690-600
violet	~ 380-446	~ 790-690

Colours are defined based on their three characteristics **hue, brightness, and saturation**.

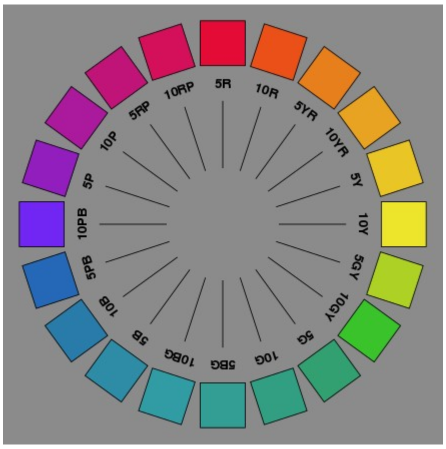
1. **Hue** refers to the frequency (or frequencies) generating the colour.
2. **Brightness (**also called **value** or **lightness)** is the luminous amplitude for the colour (number of photons of a particular colour received by the eye). The closer the colour is to black, the lower this number.
3. **Saturation** (or **chroma**) is the vibrancy (purity) of a colour; in contrast, desaturation refers to the degree of mixing of a colour with a grey of the same brightness.

Grey refers to intermediate colours between white and black. Each shade of grey can be considered a colourless hue; black and white are extreme greys. Black is a grey of zero brightness and corresponds to the total absence of light (no light is received by the eye). White is a grey of maximal brightness and can be considered as the ensemble/combination of all colours.

Since light is characterised by 3 parameters it needs to be represented on a 3D graph. The Munsell Colour System (using the so-called HSV or HSL colour space: hue, saturation, value or lightness) corresponds to a cylindrical coordinate system (r, θ, z) where r corresponds to saturation, S, θ to hue, H, and z to brightness or value V.

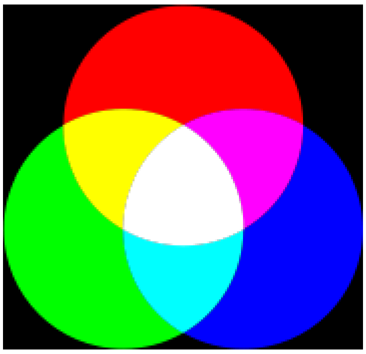


Munsell Colour System, showing: a circle of hues at value 5 chroma 6; the neutral values from 0 to 10; and the chromas of purple-blue (5PB) at value 5.



The Munsell colour system (https://en.wikipedia.org/wiki/Munsell_color_system).

Additive mixing



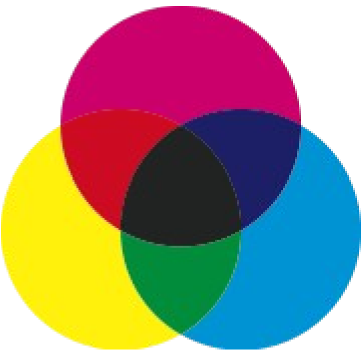
Additive colour, or additive mixing, is a property of a colour model that predicts the appearance of colours made by coincident component lights, i.e. the perceived colour can be predicted by summing the numeric representations of the component colours. The full gamut of colour available in any additive colour system is defined by all the possible combinations of all the possible luminosities of each so-called primary colour in that system.

The most commonly used primary colours are those that, in theory, when fully saturated, cause the maximal stimulus in the three types of retinal photoreceptors in a normal human eye (i.e., an eye not suffering from colour blindness or other dyschromatopsia).

In the most commonly used RGB system, the **three primary colours are red, green, and blue**.

The three secondary colours in the additive system are cyan (from mixing green and blue, complementary colour to red), magenta (mixing red and blue, complementary to green), and yellow (mixing green and red, complementary to blue) which are primary colours in the so-called subtractive colour system (e.g., the CMYK system used in printers – cyan, magenta, yellow, black).

The additive mixing of colours is achieved by adding the wavelengths of the component colours. E.g., if the green and red pixel components in a computer monitor light up, the colours emitted by the individual colour pixels overlap due to the poor resolution of the human eye, and we see a yellow colour.



Subtractive Colour System

In colour printing, painting, and the manufacture of stained glass, colour cannot be generated by adding primary colours through mixing of light, but one uses pigment colours.
All opaque bodies, when illuminated, reflect some or all of the light they receive and absorb the rest. We can therefore obtain any colour of the spectrum by using pigments that absorb (subtract) a certain colour or colours and reflect the rest.

The more pigments that are mixed together the darker the resulting colour. For example yellow and magenta give orange-red.

In this case we speak of subtractive mixing and the primary colours are usually called **fundamental colours** to differentiate them from the primary colours of the additive system. They correspond to the secondary colours of the additive system: **cyan**, **magenta**, and **yellow** which form the CMY system.

In theory, and if we have a perfect set of pigments, the use of the three fundamental colours allows to obtain:

- blue by mixing cyan and magenta;
- green by mixing cyan and yellow;
- red by mixing magenta and yellow.

In practise, subtractive mixing using common dyes does not make it possible to obtain all of the colours visible to the human eye. When we mix two differently coloured materials, we may obtain the desired hue but loose brightness. If we try to compensate for the loss in brightness by adding white, we desaturate our hue, which means that for some colours we may not be able to simultaneously obtain the desired levels of brightness and saturation.

The colour resulting from the subtractive mixing of colours can be calculated by removing certain wavelengths from the incident light spectrum. For example, grass or leaves on a tree appear green to us because they absorb everything but green, i.e., they absorb the purple and ultraviolet parts of the spectrum which they use for photosynthesis.

3) Incandescence – the emission of light from a hot body

*** Planck's law** describes the spectral density of electromagnetic radiation emitted by a black body in thermal equilibrium at a given temperature, T, when there is no net flow of matter or energy between the body and its environment. The formula is complicated.

When the radiation propagates in a medium of refractive index 1, e.g., in a vacuum or - to a first approximation - in air, Planck's law can be simplified to:

$$L_\lambda = \frac{1}{\pi}\frac{c_1\lambda^{-5}}{\exp\left(\frac{c_2}{\lambda T}\right) - 1}$$

where c1 and c2 are constants, λ the wavelength
T the temperature of the surface of the black body in kelvin

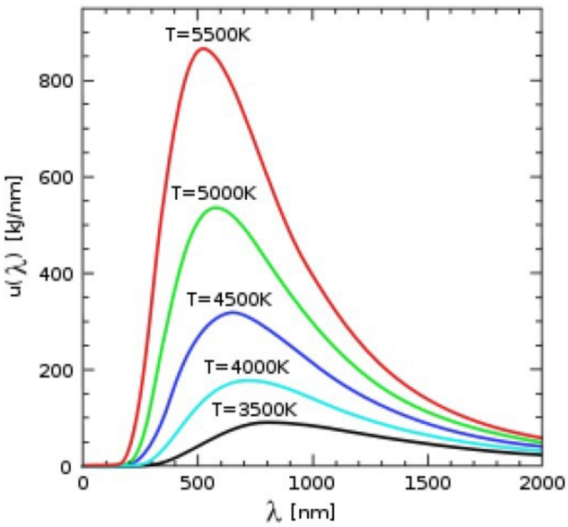
[Reminder: The **kelvin** (symbol **K**, from Lord Kelvin) is the SI unit of thermodynamic temperature.]

Unlike degrees Celsius, the kelvin is the absolute temperature which was introduced based on the third law of thermodynamics. A temperature of 0 K corresponds to -273.15°C which is absolute zero (the triple point for water is at +0.01°C).

Since it is not a relative measure, the kelvin is never preceded by the word "degree" or the symbol "°", unlike Celsius or Fahrenheit: 2°C or 2°F.

Quiz: what does the temperature "Fahrenheit 451" correspond to?

[See novel by Ray Bradbury, 1953].



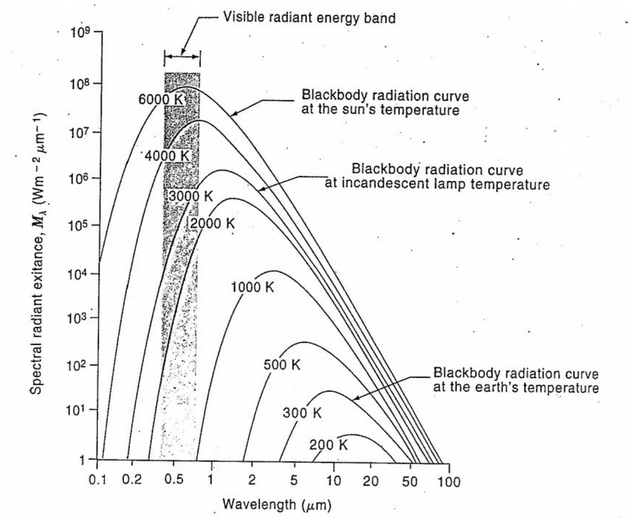
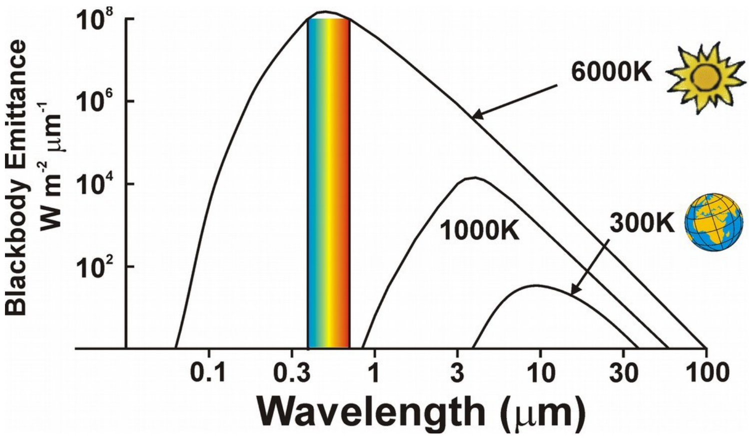


Figure 1.4 Spectral distribution of energy radiated from blackbodies of various temperatures. (Note that spectral radiant exitance M_λ is the energy emitted per unit wavelength interval. Total radiant exitance M is given by the area under the spectral radiant exitance curves.)

Black body radiation
(Source: Wikipedia)

"Remote sensing and image interpretation"
Lillesand and Kiefer; ed. Wiley, 2000, 4th Ed

As a simplified drawing:



* The **Stefan-Boltzmann law** describes the power radiated from a black body in terms of its temperature. Specifically, it states that the total energy radiated per unit surface area of a black body across all wavelengths per unit time, *M*, is directly proportional to the fourth power of the black body's thermodynamic temperature *T*:

$$M = \sigma T^4$$

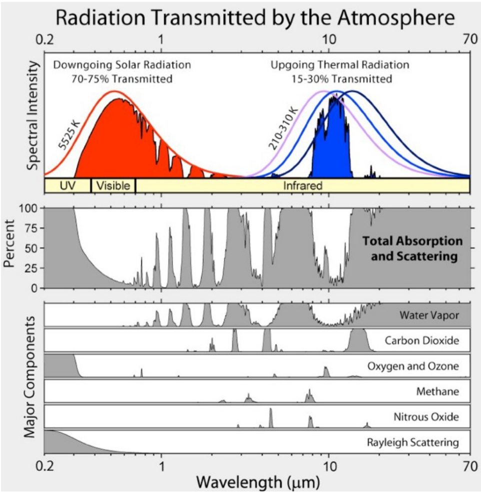
where σ is the Stefan- Boltzmann constant (also Stefan's constant)
$\sigma = 5.6697\,10^{-8}$ [W/m^2/K^4]
and *T* the temperature in kelvin

*** Wien's law** states that the peak emission in the Planck black body emission spectrum occurs at a wavelength that is inversely proportional to temperature:

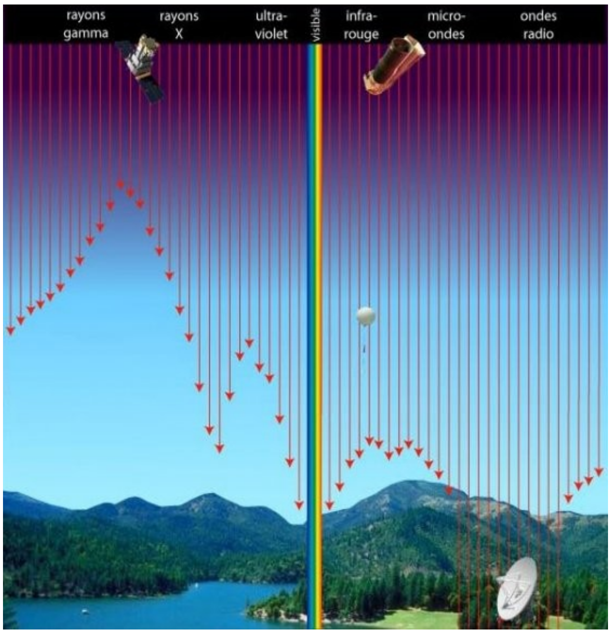
$\lambda_{max} = a/T$ in [μm] with $a = 2898\,\mu m\,K$
and T the temperature in Kelvin

What crosses our atmosphere:

(http://www.educonline.net/spip/spip.php?article269)



Courtesy Roelofs, Utrecht summer school, 2012.



The red curve shows that about 73-75% of the solar radiation incident at the top of the atmosphere is able to cross the atmosphere and reach the Earth's surface. The rest is absorbed (e.g., by water vapour, CO_2, O_2, ozone, methane, nitrous oxide N_2O) or scattered (e.g., Rayleigh scattering).

The blue curve (much lower absolute intensity than the incoming solar radiation but normalised to have the same height as the red curve) shows that only about 15 to 30% of the Earth's thermal radiation can cross the atmosphere and leave our planet (without being absorbed or scattered).

4) Refractive index

The refractive index of a medium at a given wavelength gives the factor by which the phase speed of light is reduced in that medium.

A medium is characterized by its refractive index m = *c*/*v*, where *c* is the speed of light in vacuum and *v* its speed in the medium considered.

This index is a complex number m = n-ik.

It is related to the dielectric permittivity, ε, to the magnetic permeability, μ, and to the electrical conductivity σ.

$$m^2=(n^2-k^2)-i2nk=\mu\varepsilon c^2-i2\pi\mu\sigma c^2/v$$

Since the complex part is usually very small, it is neglected and we only use the real part n.

The real part n

The refractive index, n, generally depends on the wavelength of the light. The primary effect is refraction with the angle of refraction depending on the colour of the light. This explains how dispersive prisms can break up light into its spectral components (as illustrated on the cover of the Pink Floyd album "The Dark Side of the Moon") or how suspended rain drops can create rainbows. This phenomenon is also responsible for chromatic aberrations in optical instruments. The variation in the refractive index of a transparent medium across the visible spectrum is called dispersion.

The refractive index of a medium also depends on other parameters such as temperature, T, pressure, p, salinity, S, or density, etc. In general, if T decreases n increases; if S increases n increases; if p increases n increases; if density increases n increases. The refractive index in air is equal to 1.0002926 under normal conditions of temperature and pressure, but it varies for different air densities, i.e., between different layers of air (in general, temperature is the primary source of variation) which explains the phenomenon of fata morganas.

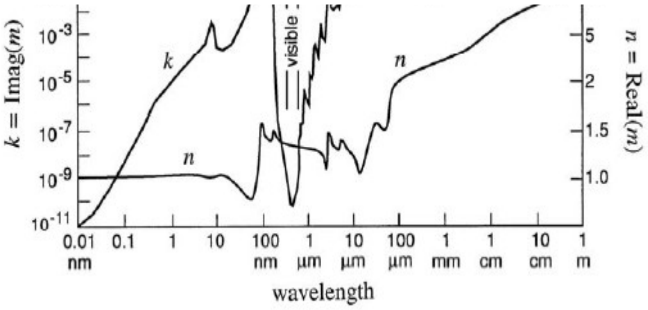
The refractive index also depends on the polarizability (the ability of electric charges to align in an applied electric field).

The complex part

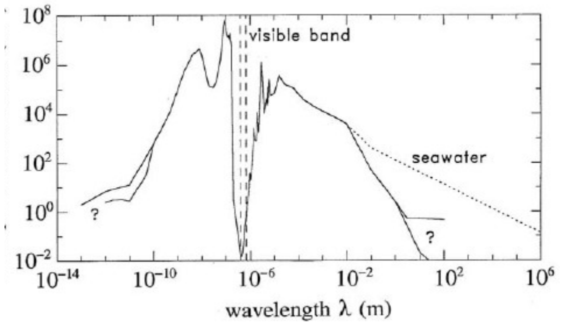
The imaginary part of the refractive index is called the extinction coefficient. It should be noted that in the case where one uses a temporal dependence of $e^{i\omega t}$ instead of $e^{-i\omega t}$, the complex index takes the form $n - ik$ instead of $n + ik$.

Since $nk=\pi\mu\sigma c^2/v$ and by employing the general equation for *m*, we obtain:
$k(\lambda)=\lambda a(\lambda)/(4\pi)$ [Kerber, 1969], where λ is again the wavelength of light.

k depends on λ and on the absorption coefficient of the medium for that wavelength.



3.3. The optical constants of pure water. The left axis gives the imaginar of *m*, and the right axis gives the real part of *m*, where *m* is the comple x of refraction [redrawn from Zoloratev and Demin (1977) wit



. Spectral absorption coefficient of pure water (solid line) and of pur er (dotted line) as a function of wavelength. [drawn from data compile and Querry (1973), Jackson (1975), Smith and Baker (1981), an ev and Demin (1977)]

Source: "Light & Water: Radiative transfer in natural waters", Mobley, 1994, Academic Press

<u>Values</u>

n_{air} = 1.0002926 so we usually use: n =1
n_{H2O} = nw = 1.329128 or nw = 1.33 for λ = 700 nm and nw = 1.34 for λ = 400 nm
$n_{salt\ water}$ = 1.33 to 1.367
living phytoplankton: (1.01 to 1.09) × nw
inorganic particles: (1.15 to 1.2) × nw

<u>Annex</u>

The so-called "left-handed" or "negative-index (meta)materials" (Theory by Victor Veselago, 1967) require a permeability and permittivity that are both negative. For a long time, it was difficult to achieve this double-negative condition, although media with a negative permittivity had been known for a long time (e.g., plasmas). In 2006, John Pendry proposed an approach using periodic metal structures formed of cut concentric rings, called split-ring resonators (SRR) and continuous metal wires.

The creation of these materials could have remained an experimental curiosity, had it not been for Pendry's proposal to use these exotic materials to produce a super lens whose resolution would no longer be limited by the classical laws of optics. In the same year, Pendry and Leonhardt proposed a theoretical approach to create an invisibility cloak using these metamaterials. Several teams have since demonstrated that these theoretical predictions could indeed be realized by producing prototypes of super lenses and microwave invisibility cloaks.

see https://en.wikipedia.org/wiki/Metamaterial

In electromagnetism, the term metamaterial designates an artificial composite material that exhibits electromagnetic properties that are not found in naturally occurring materials.

5) Colour by refraction

a) Reminder on refraction

In wave physics (especially in optics, acoustics, and seismology), refraction describes the phenomenon by which a wave is "bent" as its speed changes between two media. Refraction generally occurs at the interface between two media or during a change in density (or impedance) of the medium.

We can represent such a wave by two approaches:

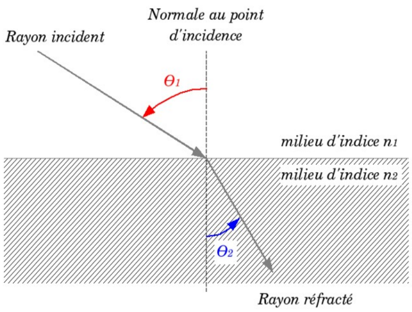
- by its wave front: this is the line described by a wave in water (wave optics and seismology);
- by a ray: it is the direction of propagation of the wave, perpendicular to the wave front (geometric optics).

While both models are equivalent for describing refraction, the first model is usually preferred to *explain* the phenomenon and the second is used to *quantify* it.

Refraction was first mentioned by *Ibn Sahl* (ca. 940-1000).
It is usually called Snell's law:

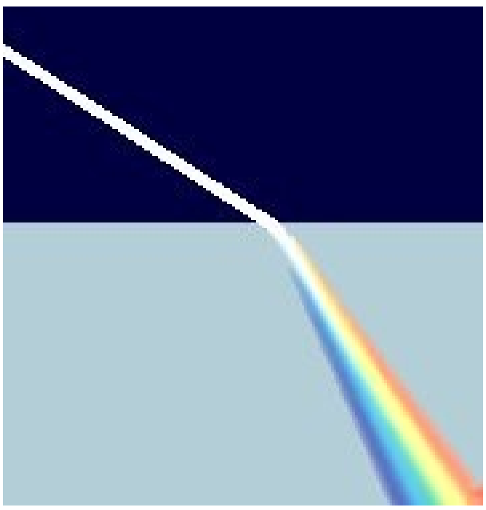
$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2).$$

(Snell 1621)

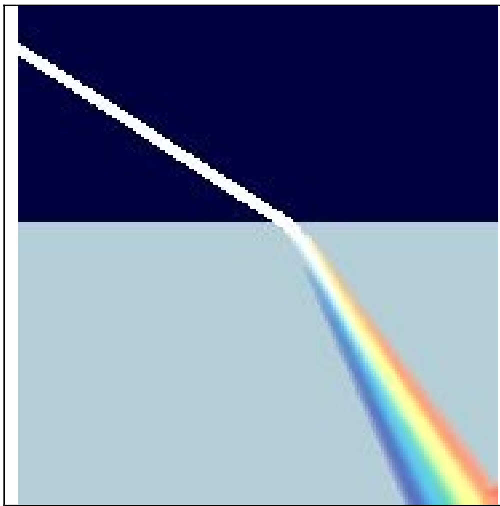
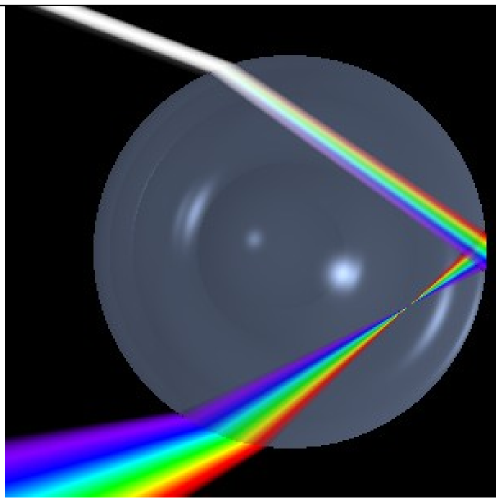
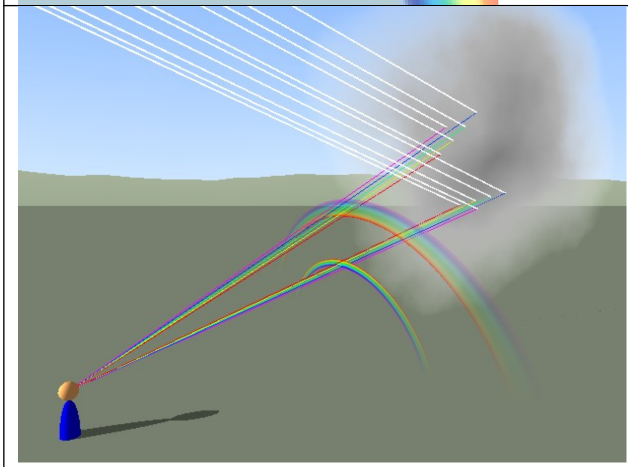


b) **Colours due to refraction**

Polychromatic light is characterised by its spectrum, i.e., the distribution of intensities across its wavelengths. For visible light, we perceive the different wavelengths as colours. In general, light waves are polychromatic, i.e., they contains several wavelengths. As such, sunlight contains almost all visible colours. Refraction allows us to separate and visualise these constituent wavelengths.



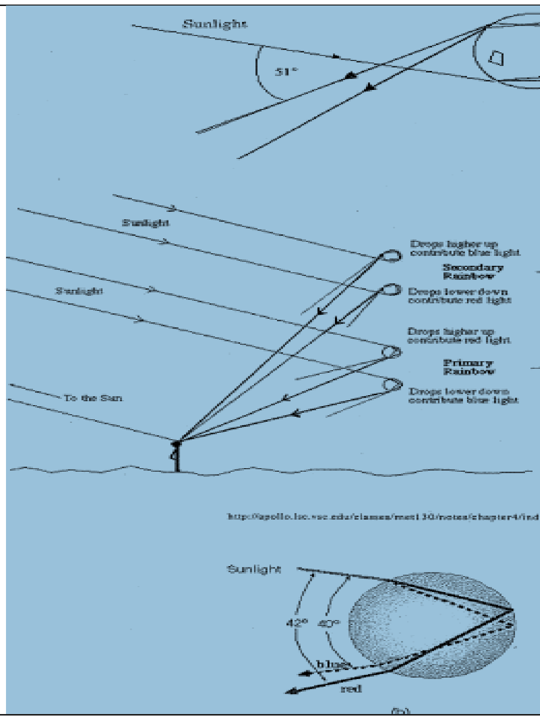
An everyday example is the rainbow. Rainbows result from the scattering of sunlight by water droplets suspended in the air. In order to see a rainbow you must always face away from the sun, as can be easily verified.

	
 Source: Wikipedia – Rainbow	 <u>Primary rainbow:</u> refraction when entering the drop followed by a single reflection inside the drop <u>Secondary rainbow:</u> refraction followed by 2 reflections inside the drop

Note: while the primary rainbow shows the red colour at the top and violet at the bottom, this colour order is reversed in the secondary rainbow.

There are also many types of halos, all formed by the interaction between sunlight (direct or reflected by the moon) and ice crystals suspended in the air or present in clouds visible in the upper troposphere, between 5 and 10km altitude. The shape and particular orientation of the crystals, as well as the angle of incidence of the light are responsible for the particular type of halo observed.

E.g., "the 22° halo" is circle offset by 22° from the light source consisting of white with a red inner fringe; "the 46° halo" is a circle offset by 46° from the source.



6) Colour due to reflection

The Fresnel coefficients are important for describing the phenomena of reflection and refraction of electromagnetic waves at the interface between two media with differing refractive indices. If we know the amplitude of the incident wave, the Fresnel coefficients can be used to calculate the amplitudes of the reflected and transmitted (refracted) waves.

In a simplified approach, one introduces the coefficients of reflection, *r*, and transmission, *t*, of the electric field as:

$$r = \frac{E_r}{E_i} \quad et \quad t = \frac{E_t}{E_i}$$

where E_i, E_r, and E_t are the electric field amplitudes of the incident, reflected, and transmitted (refracted) rays, respectively.

The Fresnel coefficients are a little more complicated as they depend on the polarization of the incident light. One usually considers two cases: 1) a transverse electric (TE) mode: no electric field in the direction of propagation, i.e., the electric field is polarised in a plane perpendicular to to the plane of incidence and the associated magnetic field is parallel to the plane of incidence; 2) transverse magnetic (TM) mode: no magnetic field in the direction of propagation, i.e., the magnetic field is polarized perpendicular to the plane of incidence while the electric field is parallel to the plane of incidence.

$$r_{TE}=\frac{n_1 cos\theta_1 - n_2 cos\theta_2}{n_1 cos\theta_1 + n_2 cos\theta_2} \text{ and } t_{TE}=\frac{2 n_1 cos\theta_1}{n_1 cos\theta_1 + n_2 cos\theta_2}$$

Note that $r_{TE}=t_{TE}-1$ (and not $r_{TE}+t_{TE}=1$).

For more details, see https://en.wikipedia.org/wiki/Fresnel_equations or other textbooks on optics.

A) case of a polished flat surface

If the light is incident at an angle of 90° on the polished flat surface ($\theta_1=\theta_2=0$) :

$$r_{TE}=\frac{n_1-n_2}{n_1+n_2} \text{ and } t_{TE}=\frac{2n_1}{n_1+n_2}$$

AN n1 = 1, n2 = n(glass) = 1.5; r_{TE} = -0.5/2.5 = -0.2

The eye is sensitive to the signal intensity, i.e., to r_{TE}^2 .

Glass has a reflectivity of 3 to 4% which may seem small but can create non-negligible effects (reflections on a picture frame or on eyeglasses, etc.).

AN2 n1 = 1, n2 = n(H2O) = 1.33; $\theta_1=\theta_2=0$ r_{TE} = -0.33/2.33 = -0.14

L'œil est sensible à l'intensité du signal, soit au carré de r_{TE} .

If you look at water from directly above, it has a reflectivity of 2% which is again small but non-negligible (e.g., for remote sensing applications). Usually, and although we often look at an interface at an angle, we obtain the same result if we use $\theta_1=\theta_2$

E.g.: $\theta_1=\theta_2=60°;cos(\theta_1)=0.5 r_{TE}=\frac{0.5-1.33*0.5}{0.5+1.33*0.5}=\frac{-0.33}{2.33}$

B) Thin films or small obstacles

When light hits an obstacle we can observe interference effects. If the incident light is monochromatic, destructive interferences cause the light to vanish (light waves cancel out) while positive interferences will intensify the light. If the incident light is polychromatic, we can see different colours (e.g., iridescence of soap bubbles, oil films, butterfly wings, etc.). These phenomena are exploited in semiconductors (electronic microchips).

In the animal kingdom (iridescence is rather rare among plants), it is the particular nature of the molecules (i.e., metallic), but also their arrangement in regular nanostructures which is responsible for creating the colours and iridescent reflections off the wings of butterflies, the scales of fish, or from mother-of-pearl shells. Among birds, it is the fine network of barbs in their plumage that causes this phenomenon. Researchers have been trying to manufacture products based on this bio-optical phenomenon.


Blue Morpho


Soap bubbles


Ammonite

A simple but precise description can be found in “The strange theory of Light and Matter” by Richard Feynman*.

*US 1918-1988 one of the most influential physicists of the second half of the 20th century, notably because of his work on relativistic quantum electrodynamics, quarks, and superfluid helium. Together with Sin-Itiro Tomonaga and Julian Schwinger, he was awarded the 1965 Nobel Prize in physics for the work on quantum electrodynamics.
The Feynman diagram is a tool he invented in the late 1940s to perform scattering calculations in quantum field theory.

7) Colour due to scattering

A) Reminder on scattering - Colours

Scattering is the phenomenon by which a beam of radiation (light, acoustic, neutron, X-rays, etc.) is forced to deviate from a straight trajectory by localized non-uniformities (including particles and radiation) in the medium through which it passes. The polarization of the incident radiation is generally modified in this process.

Scattering can take place when encountering an "obstacle" (e.g., a particle), an interface (between two media), or while crossing a medium (e.g., the case of a prism breaking up light into its spectrum or rainbows are both examples of a diffuse transmission or refraction).

This process is most often "elastic", i.e., the frequency of the incident beam of radiation remains unchanged.

Brief History: Tyndall (Irish scientist 1820-1893) carried out an experiment to demonstrate the scattering of light incident on solid particles whose size was smaller or comparable to the wavelengths of the incident light. This effect can be observed in colloidal systems, suspensions, or emulsions. The phenomenon is also easily observed when light passes through zones that are laden with solid or liquid particles (e.g., dust). Using his observations, Tyndall was able to explain the blue colour of the sky before Rayleigh could provide the underlying theory (1871) and also other “Tyndall effects” (e.g., rays of the sun seen in the mist).

Scattering is also responsible for the blue eye colour in newborns. The iris is made up of crystalline regions, air vesicles, and areas with pigments (e.g., melatonin). At birth, the pigments of Caucasian babies tend not to be active and scattering (in particular blue-grey) dominates compared to absorption. As the baby grows older, coloured pigments are activated and absorption becomes the main responsible factor determining eye colour.

(Wikipedia) Some bird plumages are blue or green due to scattering (different from a colour due to pigmentation or iridescence). The rays incident to the feathers encounter very small and disperse air vesicles and microgranules of melanin (black). These microgranules scatter the shorter (blue) wavelengths and allow longer (red) wavelengths to pass through (warming the bird). The combination of the different types of pigmentation and these optical phenomena produce the wide variety of colours observed among birds. Breeders often make their selection decisions in order to obtain a plumage of a particular shade or colour.

B) Types of scattering

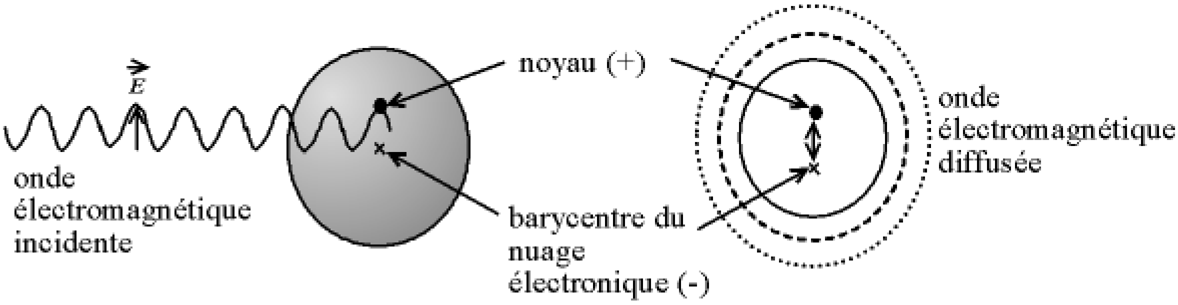
i) Rayleigh scattering (1871) d (particle) << λ (energy)

Intensity is proportional to $1/\lambda^4$, i.e., stronger for smaller λ

History (inspired by Wikipedia) : John William Strutt Rayleigh (1842 – 1919) was a British scientist who made extensive contributions to both theoretical and experimental physics. Among many honours, he received the 1904 Nobel Prize in Physics "for his investigations of the densities of the most important gases and for his discovery of argon in connection with these studies." Rayleigh provided the first theoretical treatment of the elastic scattering of light by particles much smaller than the light's wavelength, a phenomenon now known as "Rayleigh scattering". His name is attached to a range of phenomena including "Rayleigh waves" in seismology, in fluid dynamics there is the Rayleigh number (associated with natural convection), Rayleigh flow, the Rayleigh–Taylor instability, and Rayleigh's criterion for the stability of Taylor–Couette flow. He also formulated the circulation theory of aerodynamic lift. In optics, Rayleigh proposed a well known criterion for angular resolution. His derivation of the Rayleigh–Jeans law for classical black-body radiation later played an important role in the birth of quantum mechanics (see Ultraviolet catastrophe).

Rayleigh scattering is the scattering of electromagnetic waves, notably light, by atoms. One speaks of elastic scattering as the photons do not change energy (the wavelength remains the same).

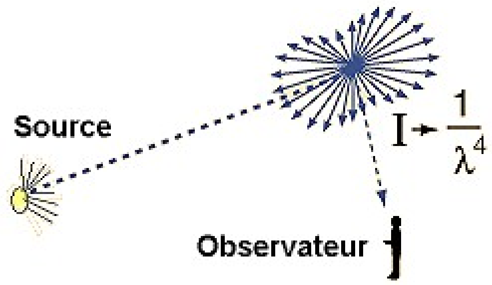
An electromagnetic wave can be described as an oscillating electric field coupled to a magnetic field oscillating at the same frequency. This electric field will deform the electron cloud surrounding the atomic nucleus, the barycentre of negative charges thus oscillates with respect to the nucleus (positive charge). This effectively creates a dipole that radiates out energy and it is this induced radiation which constitutes the Rayleigh scattering.



Rayleigh scattering: the atom, excited by the incident light, re-emits a light wave

The dipolar molecules are much smaller than the wavelength of the incident light and the scattered energy is:

$$Is(r,\psi,\lambda)=I_0\frac{(9\pi^2V^2)}{(2r^2\lambda^4)}\left(\frac{(m^2-1)}{(m^2+2)}\right)^2(1+cos^2\psi)$$



where:
- λ is the wavelength of the incident light
- m the relative refractive index with m = n particle/n ambient environment
- V is the particle volume
- R is the distance from the centre of the particle to the orserver

ψ is the angle between the direction of propagation and the direction to the observer.

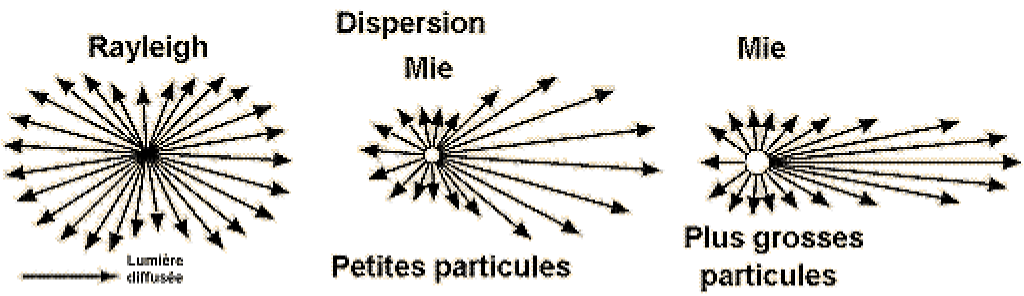
The intensity is strongly dependent on the wavelength and the viewing angle in the above formula. This explains why the sky is blue in broad daylight (scattering dominates) and why the sun appears red when it is close to the horizon. During sunsets/-rises the path of light through the atmosphere is longer than when the sun is above and there is complete scattering (and absorption) of the short wavelengths which only leaves the longer wavelengths (red and orange colours).

Rayleigh scattering is the primary cause of "blurring" in photographs or the grey-blue colour in photographs taken of an air plane, for example. This effect can be reduced by using a filter that removes short wavelengths (called UV filter).

<u>ii) Mie scattering</u> d (particle) and λ (energy) are of the same order of magnitude

e.g., water vapour, dust

For particle sizes of the order of or larger than the wavelength of the light, Mie scattering dominates. Mie scattering scatters most of the energy into the forward direction, creating emission lobes akin to those of an antenna. The larger the particle the more energy is scattered into an ever narrower forward direction.



Mie scattering does not necessarily depend on the wavelength of the incident light as was the case with Rayleigh scattering. However, it mostly affects the longer wavelengths and is non-negligible with respect to Rayleigh scattering when the sky is hazy or overcast.

<u>iii) Non-selective scattering</u> d (particle) >> λ (energy)
e.g. water drops (5-100 μm)

This type of scattering is roughly the same for the visible and near and medium IR wavelengths which is why it is called "non-selective" and it does not depend on the wavelength. As a result, mists and clouds appear white.

<u>7) Colour due to diffraction</u>

Diffraction is the result of interfering scattered waves once they have encountered an obstacle that is not completely transparent to them. The phenomenon can be interpreted as the scattering of a single wave by various particles or objects.

Note: For historical reasons, a distinction is made between diffraction and interference; however, both behaviours are due to the wave character of a phenomenon and usually always occur together, which is why it has been suggested to just use a single term. Indeed there can be no diffraction without interference. However, the converse is not true, there can be interference without diffraction in some cases.

Diffraction is observed with light and also with sound, water waves, neutrons, X-rays (an electro-magnetic wave like light), or matter. It is due to the wave character of a phenomenon.

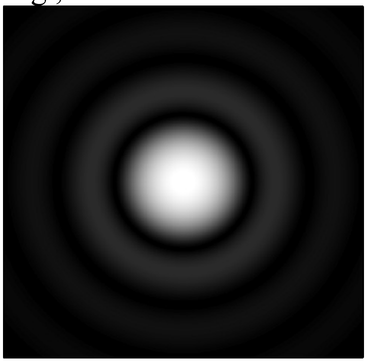
The greater the wavelength in relation to an obstacle, the easier it will be for this wave to go around, i.e., to envelop the obstacle. Diffraction is observed when the obstacle is of a size comparable to the wavelength.

If the observer is close to the object, they observe Fresnel diffraction. If they are far away, they observe Fraunhofer diffraction.

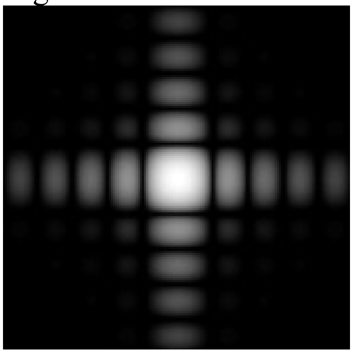
<u>History</u> (Wikipedia): Joseph von Fraunhofer (1787 -1826) was a German physicist and optical lens manufacturer. He made optical glass and achromatic telescope objective lenses, invented the

spectroscope, and developed diffraction grating. In 1814, he discovered and studied the dark absorption lines in the spectrum of the sun now known as Fraunhofer lines.

E.g., Fraunhofer diffraction of a monochromatic light source



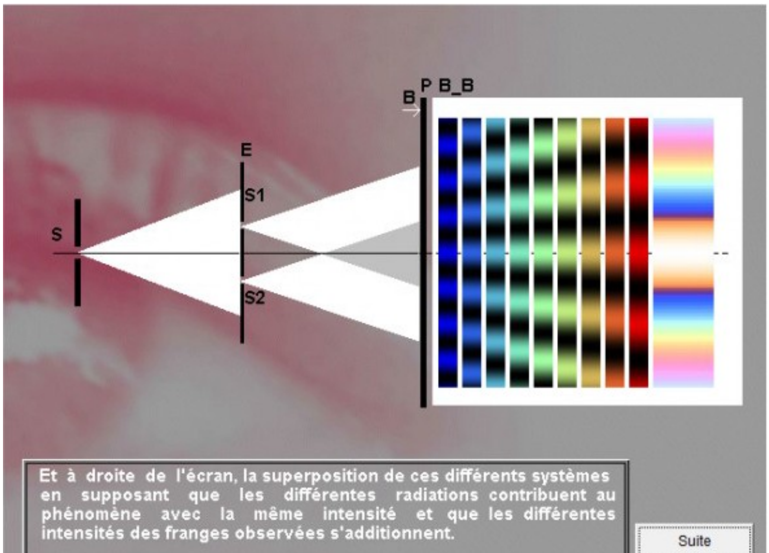
Diffraction by a round aperture



Diffraction by a square aperture

For polychromatic light, we observe diffraction spectra (colours of the visible spectrum).

http://d.ruze.free.fr/phcours2013/trois/diffraction_interferences.html



http://static.intellego.fr/uploads/1/5/1543 lumiere polychromatique.png