Optics 4 : The interaction of light with matter

Scattering. When light strikes or passes through a material the electric field may set the electric charges of the material in motion. These moving charges act as a new source to re-emit light and the light is said to be scattered. When the particles are small and randomly distributed the intensity of the scattered light is proportional to the square of the volume of the particles and to $1/\lambda^4$. Short wavelengths (blue) are therefore scattered more than long wavelengths. Scattering from the rarified upper atmosphere is responsible for the colour of the sky (Rayleigh scattering) and the blue colour of fresh tobacco smoke is also due to this type of scattering.

When tobacco smoke is blown out, the particles have become larger by aggregation and hydration. Their diameter is of the same order as the wavelength of light and they scatter by Mie scattering which is independent of wavelength – thus exhaled smoke is white. Similarly clouds are made of relatively large particles and scatter white light.

Reflection. Metals are good conductors of electricity and the surfaces are rich in free electrons. The electrons respond so well to the electric field of a light wave that the oscillations exactly cancel the incident field and metals are therefore opaque. The oscillating electrons efficiently re-radiate (scatter) light that adds constructively in only one direction to create the reflected beam.

Refraction. Materials such as glass have charges that respond less well to the electric field of an incident light beam. Some light is reflected, but much of the light penetrates the material. Inside such a material the light is scattered by encounters with electric charges and the scattered light mixes with the transmitted incident wave. Molecular responses are not immediate and the time-lag produces a phase shift that *apparently* slows the light down. Usually we say that the *phase velocity* of light in a medium is slowed compared to the speed of light in a vacuum. In practice (even though strictly incorrect) we can just think of the speed of light as reduced in a medium. The ratio of the speed of light in a vacuum, c, to phase velocity in the medium, v, is called the refractive index of the medium n.

$$n = c/\mathrm{v}$$

Medium	Refractive index n
Air	1.00029
Ice	1.31
Water	1.33
Tupentine	1.47
Glass	1.51 – 1.72
Polystyrene	1.59
Diamond	2.42
Gallium Phosphide	3.50

Since the frequency must be constant across a boundary this means that the effective wavelength of light, λ_e, in the medium is also different.

$$\lambda_e = \lambda/n$$

Absorption. If the light has a frequency that is close to a molecular resonant frequency it may be absorbed by the material. Usually the energy will then be degraded to heat but some of it may be re-emitted by fluorescence by suitable materials.

Polarization. Finally, scattering, reflection or refraction through some materials may polarize light. Some materials, called dichroic, can polarize light by preferential absorption.

Summary – when light strikes a material:

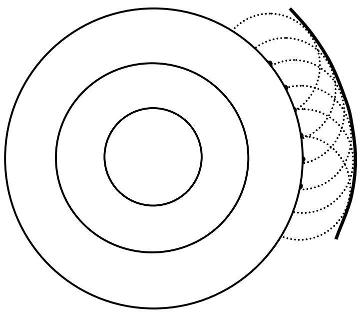
- It can be scattered.
- It can be reflected.
- It can be transmitted with an effectively reduced speed (refracted).
- It can be absorbed.
- In addition to all the above it may become polarized.

Huygens Wave theory

The mathematical treatment of waves is difficult. Fortunately, Huygens principle (1690) is a simple scattering theory that can be used to understand many optical phenomena.

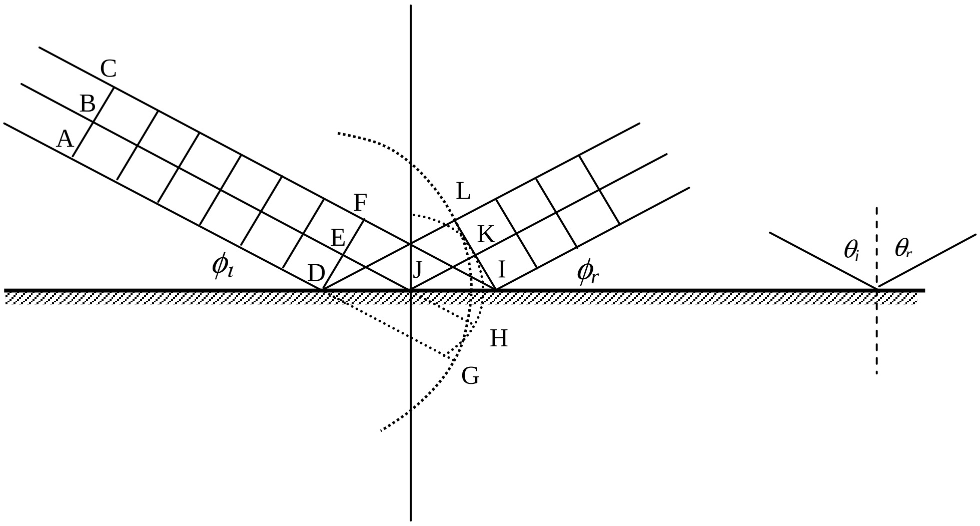
- any point on a wavefront behaves as a new source, from which secondary waves *(wavelets)* spread out in a *forward* direction only with the same frequency and speed as the primary wave. The neglect of backwaves is reasonable since points from which wavelets arise are not independent sources, but are set in motion as a result of a wavefront from the original source.

- the surface which touches, or envelops, all of these wavelets at a particular instant forms a new wavefront.



Huygen's theory assumes that the effect of the wavelets is limited to that part which touches the new wavefront. This assumption was later shown to be a reasonable consequence of *interference* between wavelets (Fresnel 1800's) – they cancel each other out.

Huygens Construction for Reflection



ABC is a plane wave (ie light from a distant source) incident on a plane reflecting surface (eg a flat mirror) at angle θ_i to the normal. The associated rays are AD, BE and CF.

Points on the wavefront do not arrive at the mirror at the same time. The wavefront arrives at point D arrives first, followed by point J and then point I. Huygens theory considers each of these points D, J, I, and those in between, as secondary sources for new wavelets. By the time the wavefront reaches I on the mirror surface the wavelet generated at point J has reached K and the wavelet from D has reached L.

Combination of these Huygens wavelets, (and those from all points between D and I) give the new , flat wave front IKL which is tangent to all of the wavelets. In the absence of a mirror the wavefront would reach IHG which could also be constructed from the Huygens wavelets.

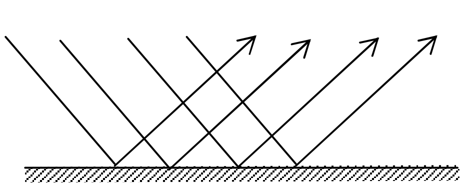
In other words symmetry of the figure shows that DG makes the same angle with the mirror as DL and hence that *the angle of incidence and reflection are equal*. This is the **Law of Reflection**.

For the tangent of wavefront LG to be common with a tangent of the wavefront KH and the point I where a wavelet is just being emitted, the length DL must be equal to the length FI.

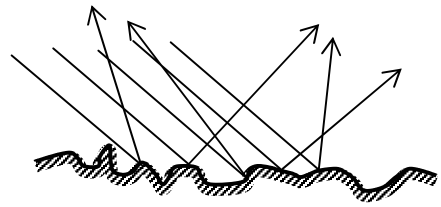
$$\mathrm{DL}\sin(\phi_r) = \mathrm{FI}\sin(\phi_i)$$

Hence $\phi_r = \phi_i$ and therefore $\theta_r = \theta_i$.

For surfaces that are smooth in comparison with λ the wavefronts are highly correlated over a wide distance and the reflection is said to be specular. For surfaces that are rough in comparison with λ, the reflected rays are randomized giving a diffuse reflection.



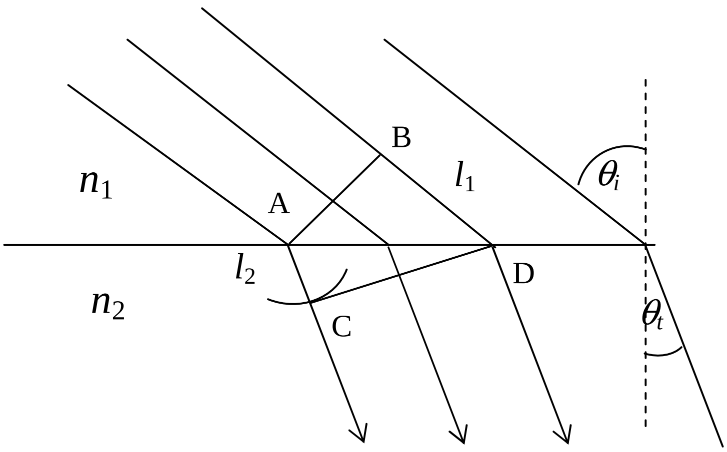
Specular Reflection



Diffuse Reflection

Huygens Construction for Refraction

For refraction the figure below shows a plane wavefront AB passing from a medium with refractive index n_1 into a second medium with refractive index n_2. The effective speed of light in each medium is given by : $\mathrm{v}_1 = c/n_1$ and $\mathrm{v}_2 = c/n_2$



In the time Δt taken for light to travel the length $l_1 = \mathrm{v}_1 \Delta t$ from B to D the secondary wavelet (shown) from A has expanded to C; a length $l_2 = \mathrm{v}_2 \Delta t$. Note that angle BAD is θ_i and angle ADC is θ_t and that AD is a common hypotenuse to the triangles ADB and ADC. Then $AD\sin(\theta_i) = l_1$ and $AD\sin(\theta_t) = l_2$ giving

$$\frac{\sin(\theta_i)}{\sin(\theta_t)} = \frac{l_1}{l_2} = \frac{\mathrm{v}_1}{\mathrm{v}_2} = \frac{n_2}{n_1}$$

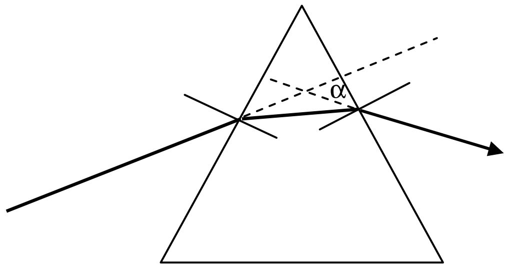
Re-arranging and putting $n_1 = n_i$ and $n_2 = n_t$ for the incident and transmitted medium gives an easily remembered form of Snells law of refraction.

$$n_i \sin(\theta_i) = n_t \sin(\theta_t)$$

Note that light is refracted *towards* the normal when passing from a lower to higher refractive index and *away* from the normal when passing from a higher to lower refractive index.

Refraction of Light by a Prism

Consider what happens when a ray of light passes through a triangular prism.



Light is refracted at both surfaces of the prism and deviates away from the path it would otherwise have taken. The angular deviation α depends on the refractive index of the glass

Dispersion

As Newton knew, white light is just a mixture of coloured light that can be separated by a prism. But how does a prism do this? As we have seen, colours correspond to light of different frequencies and light is bent by a prism according to the refractive index of glass. In fact, in most materials light of short wavelength travels more slowly than light of long wavelength. In other words the refractive index varies as the wavelength changes. This is called dispersion. Thus the angular deviation of light passing through a prism varies with frequency and the constituent colours can be separated.

Dispersion of Crown Glass

Wavelength λ/nm	Refractive Index n
728	1.5346
668	1.5363
505	1.5442
471	1.5462
414	1.5537
389	1.5577

Absorption

When light travels in a substance, part of the light is absorbed. Substances such as air, water and glass are transparent because very little light is absorbed, and therefore most is transmitted. Light that is absorbed is converted into heat. A fuller understanding of absorption is possible using quantum theory.

General and Specific Absorption

- general absorption - all wavelengths are absorbed more or less equally
- selective absorption - some wavelengths absorbed much more than others

A matt black substance shows general absorption, while coloured dyes show specific absorption.

Filters and Tints

The property of absorption is used when making tinted spectacles or contact lenses. Selective absorption is a useful property for lenses designed to cut out harmful radiation such as goggles for welding, or for use on sunbeds etc.

Attenuation coefficient

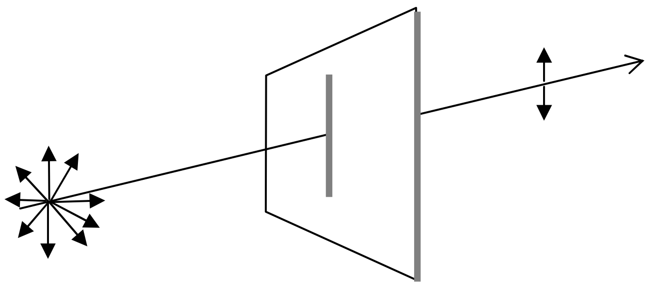
The amount of light that is absorbed by a material, at a given frequency, depends on the absorption, or attenuation, coefficient α. For an incident irradiance $I_0 = I(0)$ at the surface the irradiance at a depth y in the material is

$$I(y) = I_0 e^{-\alpha y}$$

Opaque materials have a high α while for transparent materials α is small.

Polarization

Light from a heated object is unpolarized: it has a random mixture of all polarizations. Some plastics that have been strained in manufacture consist of very well aligned molecules. Light passed through these materials will become polarized just as a cord passing through a slot would only transmit transverse waves aligned with the slot. In the diagram below filled arrows represent the E-vector of a narrow light beam – only vertically polarized light can pass through the slot that represents aligned molecules.

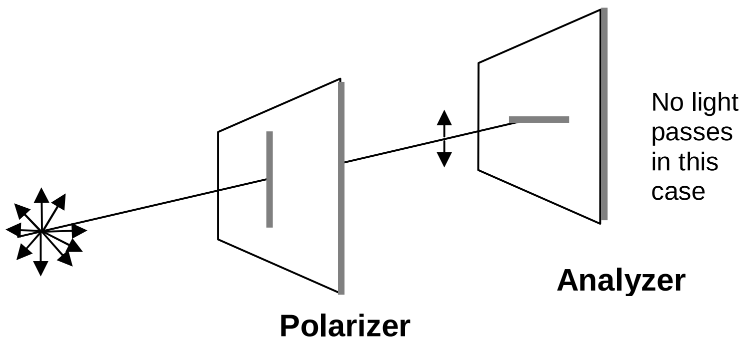


Light may also become partially polarized by specular reflection from a surface. The angle of incidence for which this is a maximum is given by the polarization angle or Brewsters angle θ_p

$$\mathrm{Tan}\left(\theta_p\right)=\frac{n_t}{n_i} \quad .$$

Light from the sky is also polarized by Rayleigh scattering – bees use this for navigation.

If, a second slot or polarizer is placed beyond the first, and the angle of this slot is altered, then all of the vibration will pass through the second slot only when it is parallel to the first. None will pass through when it is perpendicular to the first.



The second slot can be thought of as an *analyser*, since if the orientation of the second slot is known it can be used to discover, or analyse the direction of polarization of the first.

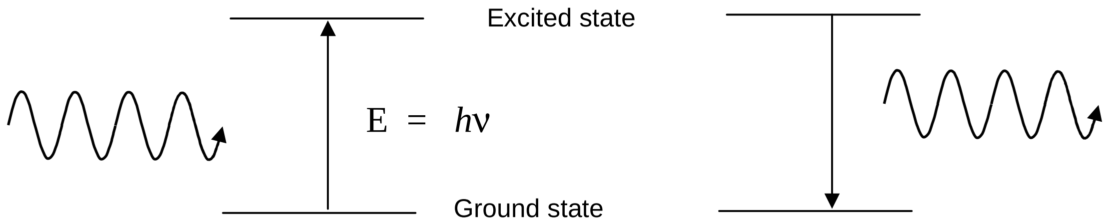
Polarization and vision

Polarizers are used for a number of purposes in ophthalmology, for example:

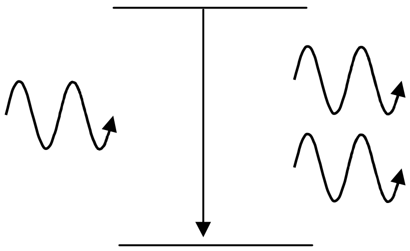
- as sunglasses - polarizing filters can be used to reduce the visibility of polarized reflections from surfaces.
- in order to dissociate the two eyes.
- for demonstrating Haidinger's brushes.

Lasers

We have seen that light can be absorbed by molecules by one of their resonant frequencies. Excited molecules can also emit light at that frequency.

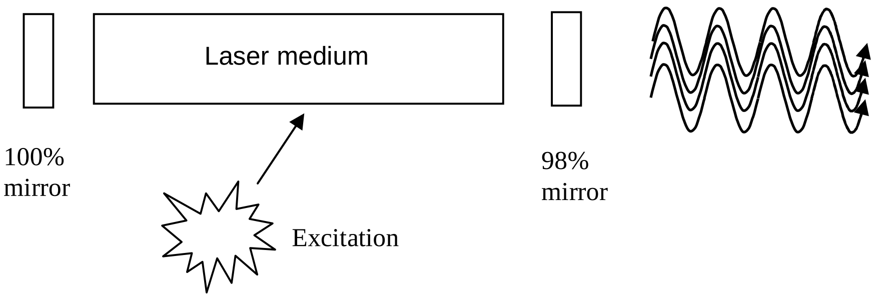


But an already excited state can also be stimulated to emit a photon by another photon



The resulting two photons are **in phase** (coherent). If there are many excited atoms a single photon can lead to a cascade of photons. The Laser (Light Amplification by Stimulated Emission of Radiation) exploits this property to produce light that is of a very narrow frequency, coherent, collimated (directional) and frequently polarized.

Typically, a medium (eg He/Ne, Ar+, ruby) is placed in a cavity between two mirrors. The medium is excited in a suitable way (electrical discharge, light flash, chemical reaction etc) to create a **population inversion** – that is an excess of excited atoms or molecules. Needless to say, the energy level diagram is usually a bit more complicated that the above but the principle is the same.



Perhaps a single photon is emitted spontaneously, but as it moves down the tube it stimulates other excited atoms to release their energy. The photons are reflected back many times between the mirrors snowballing in numbers each time. If one of the mirrors is made to be only 98% reflective some of the radiation leaks out and can be utilised. Continuous excitation to replenish the excited atoms allows lasers to operate continuously.

The high power, pure light that lasers produce have a huge number of uses – including the welding of detached retinas.

- Never look directly into a laser beam.