Propagation and interactions of light I.

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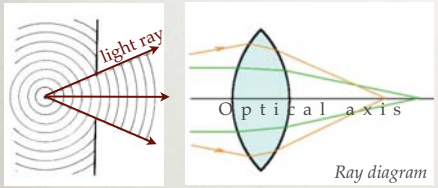
Propagation and interactions of light I.

- Geometric optics, wave optics
- Reflection, refraction, refractometry
- Total internat reflection, endoscopy
- Diffraction on optical grating
- Optical imaging, lens equation
- Light microscope

Geometric optics and wave optics

Geometric optics

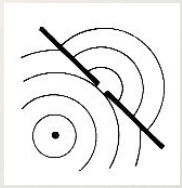
If light propagates through a slit much larger than its wavelength, then the spreading of the wavefront (phase) may be simplified into a line ("light ray").



- Optical (light) ray ("light beam"): abstraction, mathematical line.
- Arrows represent the direction of energy propagation.
- Optical axis: line connecting the midpoint of optical components (e.g., lenses).
- Principle of reversibility: the direction of energy propagation (arrows) may be reversed.

Wave optics

If light propagates through a slit comparable or smaller than its wavelength, then its wave properties ust be taken into account.



Important parameters of the propagating wave:

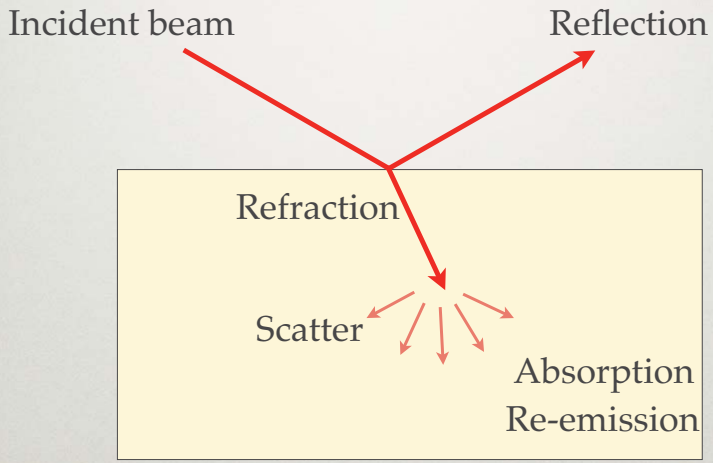
- **Period** (T)
- **Frequency** (f=1/T)
- **Velocity** (v, c)
- **Wavelength** (λ): distance covered in a period:

$$\lambda = cT = \frac{c}{f}$$

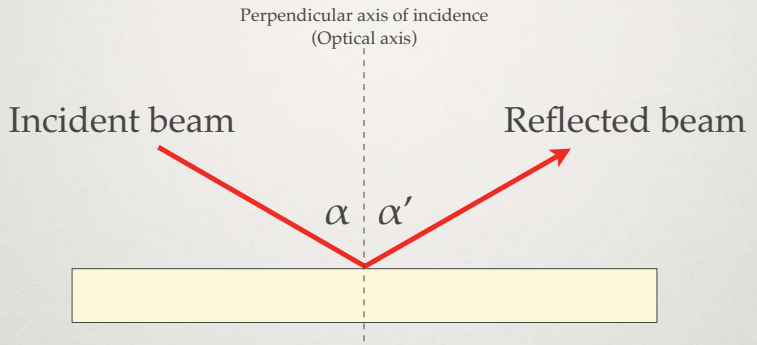
Speed of propagation of light in ***vacuum***: c=2,99792458 x 10^8 ms^{-1}
In optically denser media the speed of propagation is reduced (c_1).
This may be expressed with the ***absolute refractive index*** (n_1):

$$n_1 = \frac{c}{c_1}$$

Interaction of light with matter

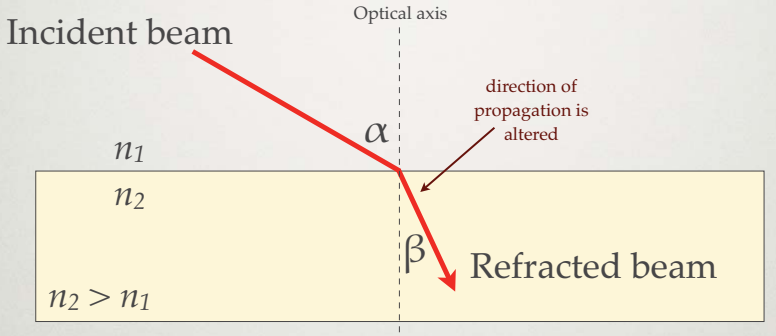


Reflection



- α = angle of incidence; α' = angle of reflection.
- Incident beam, reflected beam and optical axis are in the same plane.
- Incident and reflected angles are identical ($\alpha=\alpha'$).

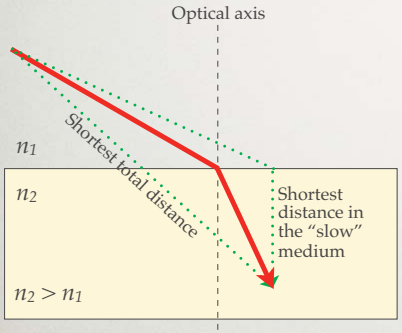
Refraction



- α = angle of incidence; β = angle of refraction.
- Incident and refracted beams and axis of incidence are in the same plane.
- Snell's law:

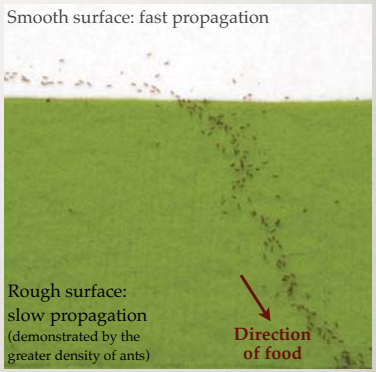
$$\frac{\sin\alpha}{\sin\beta} = \frac{c_1}{c_2} = \frac{n_2}{n_1}$$

Explanation of refraction:
Fermat's principle of least times



Light "chooses" the path that can be covered in the least time (i.e., fastest).

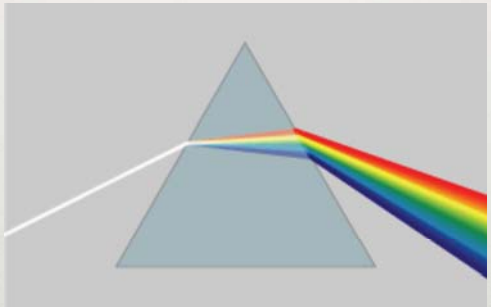
Fermat's principle is at work in other places, too!



Path "selection" by ants (*Wasmannia auropunctata*) at the boundary of media with different "resistances".

Dispersion

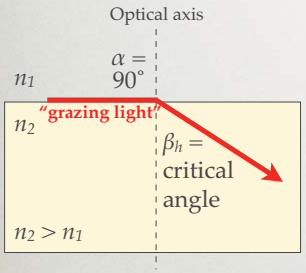
Index of refraction depends on wavelength!



- The smaller the wavelength - the greater the refractive index.
- A prism decomposes white light according to wavelength (physical color).

Analytical application of refraction: Refractometry

Boundary condition of refraction



Since $\sin(90^\circ) = 1$, according to Snell's law:

$$n_1 = n_2 \sin \beta_h$$

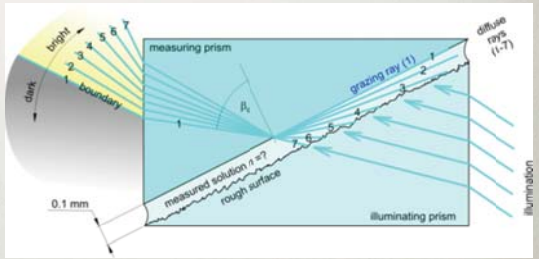
Thus, in case we know n_2, by measuring β_h the refractive index of the incident medium (n_1) may be obtained.

Refractometry

Refractive index of dilute solutions (n_1) depends on solute concentration (c):

$$n_1 = n_0 + k \cdot c$$

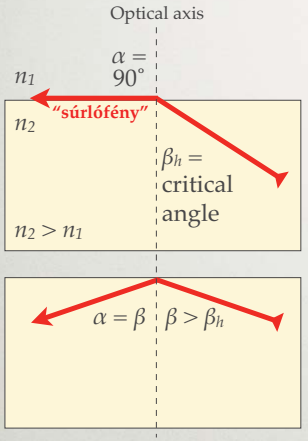
n_1 = refractive index of solvent, k = constant



Conditions of applicability:

- Liquid sample
- Sample is transparent
- Refractive index of sample is smaller than that of the measuring prism.

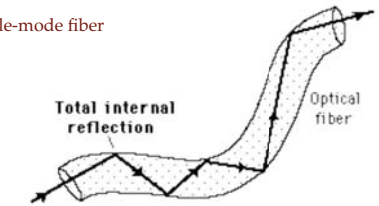
Total internal reflection

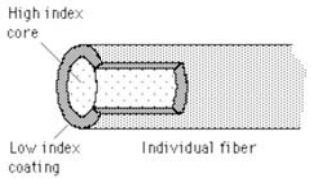


Total reflection within the optical medium of greater refractive index ("total ***internal*** reflection", TIR)

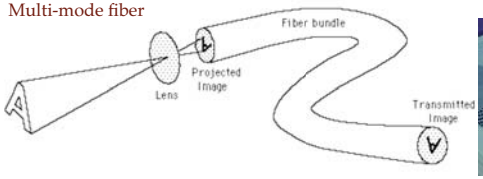
Biomedical Application of TIR: optical fibers

Single-mode fiber





Multi-mode fiber



If the arrangement of fibers is maintained within the bundle, then the image is faithfully transmitted.

Medical fiber optics: endoscopes

TYPES

- **Arthroscopy:** diagnostic and therapeutic examination of joints (arthroscopic surgery)
- **Bronchoscopy:** examination of the trachea and bronchi
- **Colonoscopy:** examination of the colon
- **Colposcopy:** examination of the vagina and cervix
- **Cystoscopy:** examination of urinary bladder, urethra uterus, prostate. Through urethra.
- **ERCP (endoscopic retrograde cholangio-pancreatography):** delivery of X-ray contrast agent, via endoscope, into biliary tract and pancreatic duct.
- **EGD (Esophago-gastroduodenoscopy):** examination of upper GI tract (gastroscopy).
- **Laparoscopy:** examination of abdominal organs (stomach, liver, female gonads) through abdominal wall.
- **Laryngoscopy:** examination of the larynx.
- **Proctoscopy:** examination of the rectum sigmoidal colon (sigmoidoscopy, proctosigmoidoscopy)
- **Thoracoscopy:** examination of pleura, mediastinum and pericardium via chest wall.

OBJECTIVES

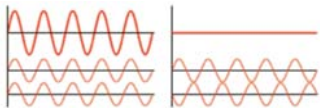
- **Diagnostics:** visual inspection, biopsy, contrast agent delivery
- **Therapy:** surgery, cauterization, removal of foreign objects

Wave optics: light diffraction on a grating

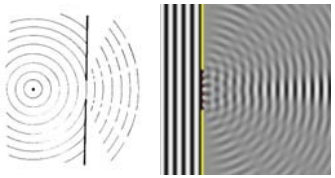
Interference occurs: its basis is the principle of superposition

Waves in phase ($\phi=0$): amplification

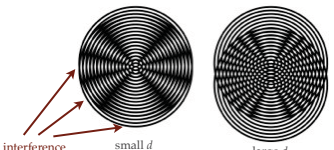
If $\phi=\pi$: cancellation



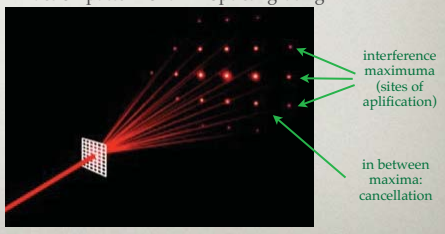
Slit comparable to wavelength
(=pointlike slits separated by distance d, where $d\sim\lambda$)



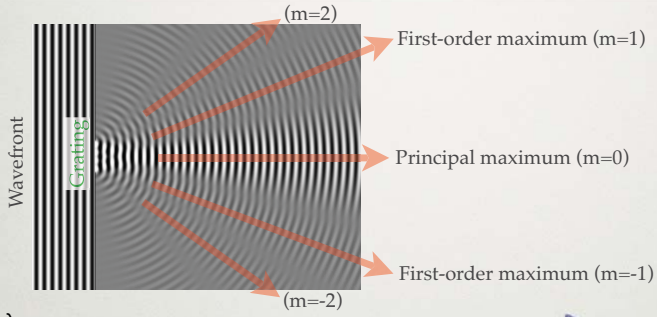
Interference pattern depends on distance (d) separating the pointlike slits



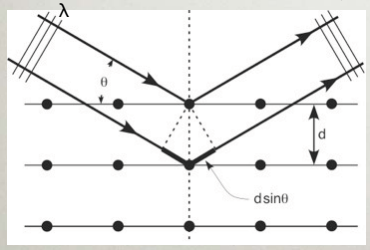
Diffraction pattern of a 2D optical grating



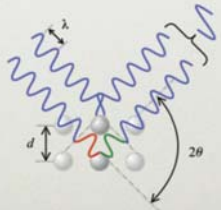
The diffraction pattern carries information about structure



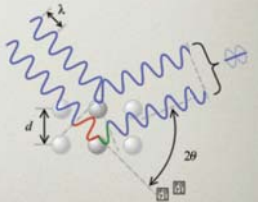
Information about the structure of the grating (lattice constant, d)



Condition of constructive interference: $2d\sin\theta = n\lambda$



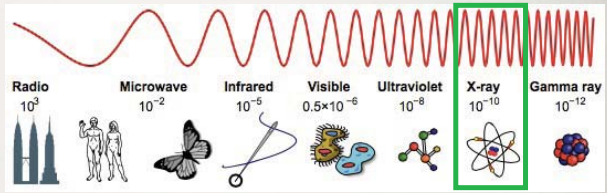
Constructive interference (amplification)

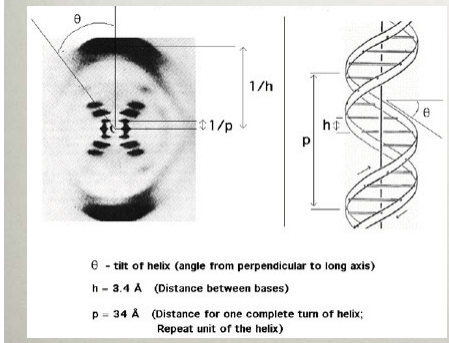


Destructive interference (cancellation)

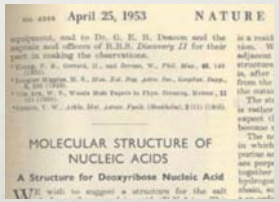
Application of diffraction

If the wavelength of the radiation matches atomic dimensions, then molecular structure may be revealed!

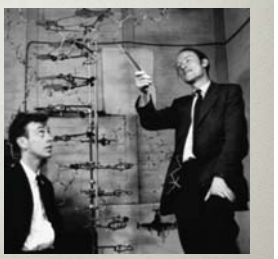




Determination of DNA structure by using X-ray diffraction (crystallography)

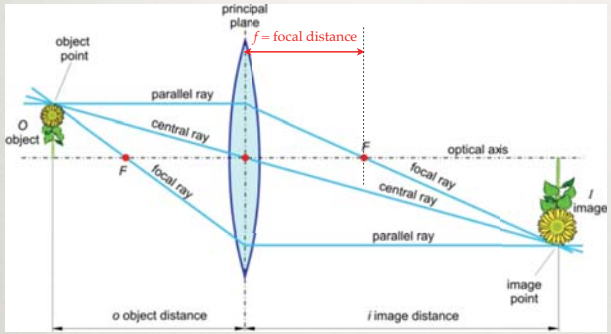


J.D. Watson and F. Crick, 1953



Optical imaging

Image formation may be achieved by using a curved refractile surface



- Real image: may be projected onto a surface
- Virtual image: may be mapped by using an accessory lens
- Magnification > 1, if the object is within $2f$ distance

Magnification

$$N = \frac{K}{T} = \frac{k}{t}$$

Lens equation

$$D = \frac{1}{f} = \frac{1}{t} + \frac{1}{k}$$

D=optical power (diopter, m^{-1})

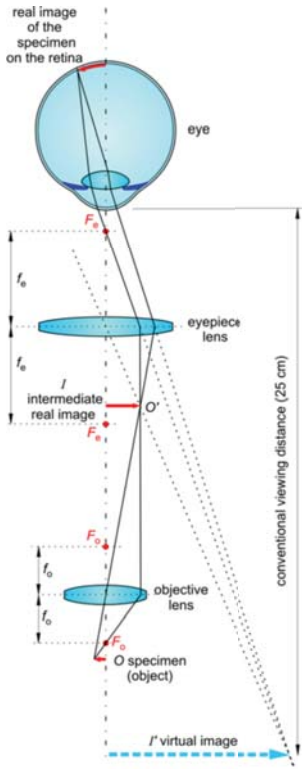
Optical power of refractile surface

$$D = \frac{n - n'}{r}$$

n-n'=difference between the refractive indeces of optical media
r=radius of curvature of refractile surface

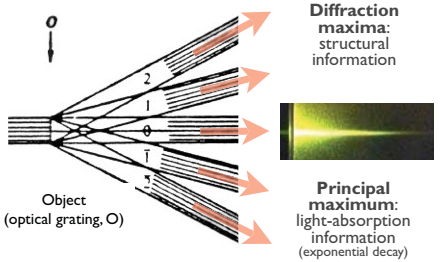
Image formation in the compound microscope

- Magnified, up-side-down, virtual image
- Condition of the formation of projected image: an accessory lens (eye lens) needs to be positioned in the optical path.
- Projection screen: retina



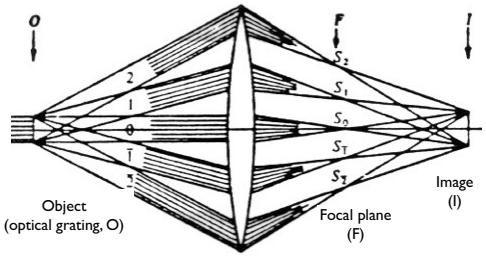
Resolving power of the light microscope is limited by wave optics

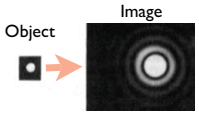
Diffraction-limited imaging: its condition is the collection of at least the first diffraction maximum



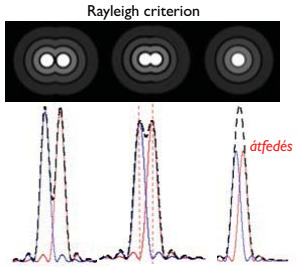
Diffraction maxima: structural information

Principal maximum: light-absorption information
(exponential decay)





Because of diffraction: the image of a point object is a disk (Airy disk)



Smallest resolved distance (Abbé-equation):

$$d = \frac{0.61\lambda}{n \sin\alpha}$$

λ = wavelength
n = refractive index of immersion medium
α = angle between optical axis and the bounding light ray