Radiation

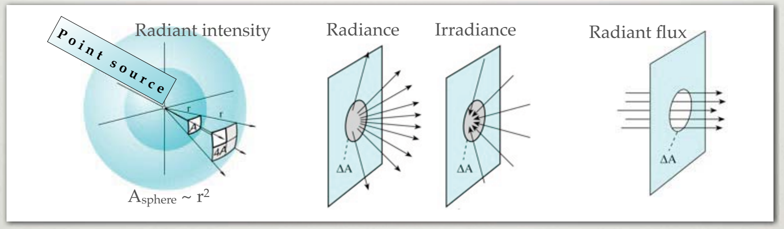
Miklós Kellermayer

Radiation is everywhere

Source → Radiation → Irradiated object

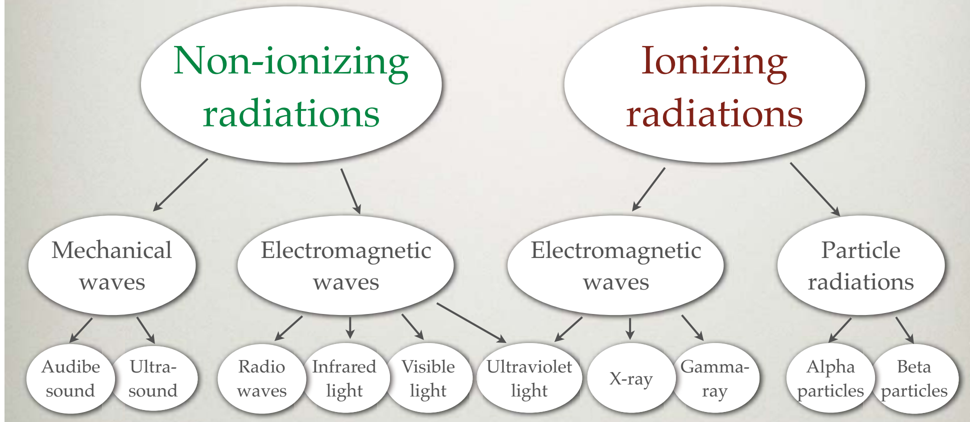
Radiation

Propagating ***energy***, in the form of waves or subatomic particles, emitted by an atom or body as it changes from a high energy state to a lower energy state.



Quantity	Symbol	SI unit	Abbr.	Notes
Radiant energy	Q	joule	J	energy
Radiant flux	Φ	watt	W	radiant energy per unit time, also called *radiant power*
Radiant intensity	I	watt per steradian	$W \cdot sr^{-1}$	power per unit solid angle
Radiance	L	watt per steradian per square metre	$W \cdot sr^{-1} \cdot m^{-2}$	power per unit solid angle per unit *projected* source area. Sometimes confusingly called "intensity".
Irradiance	E, I	watt per square metre	$W \cdot m^{-2}$	power incident on a surface. Sometimes confusingly called "intensity".

Types of radiations



Oscillation

Oscillations are sources of waves

Tacoma Bridge catastrophy

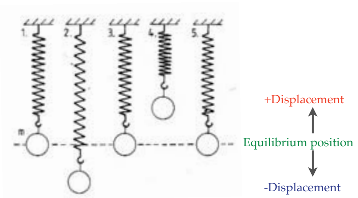
The original Tacoma Narrows Bridge was opened to traffic on July 1, 1940. It was located in Washington State, near Puget Sound. It was the third-longest suspension bridge in the United States at the time, with a length of 5939 feet including approaches. Its two supporting towers were 425 feet high. The towers were 2800 feet apart.

Strong winds caused the bridge to collapse on November 7, 1940. Initially, 35 mile per hour winds excited the bridge's transverse vibration mode, with an amplitude of 1.5 feet. This motion lasted 3 hours.The wind then increased to 42 miles per hour. In addition, a support cable at mid-span snapped, resulting in an unbalanced loading condition. The bridge response thus changed to a 0.2 Hz torsional vibration mode, with an amplitude up to 28 feet.

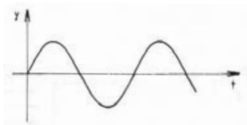
Oscillation

Movement (or change) that has a periodic component

Simple Harmonic Oscillation (SHO):
oscillation that can be described with sine function



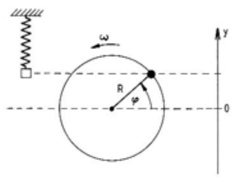
Mass on a spring



Displacement vs. time

Displacement vs. time function of SHO

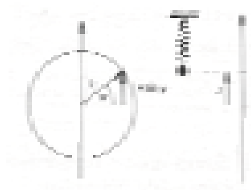
Simple harmonic oscillation and uniform cirular motion are related



$$y = R\sin\varphi$$

ϕ=phase angle at time t
y=displacement at time t

y is maximal at sinϕ=1
Maximal displacement: "amplitude(A)"



Since, from circular motion,

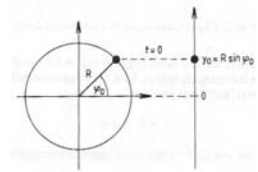
$$\varphi = \omega t$$

ω=angular velocity

we may write:

$$y = A\sin(\omega t)$$

If at the beginning of examination $\phi \neq 0$



$$y_0 = A\sin\varphi_0$$

y_0=intitial displacement
ϕ_0=initial angle (phase angle or phase shift)

$$y = A\sin(\omega t + \varphi_0)$$

Since $\omega = \frac{2\pi}{T}$

We may write

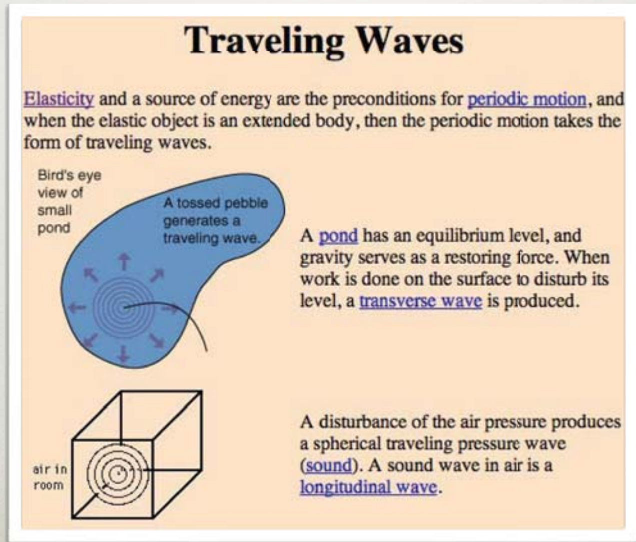
$$y = A\sin\left(\frac{2\pi}{T}t + \varphi_0\right)$$

Waves

Types of waves

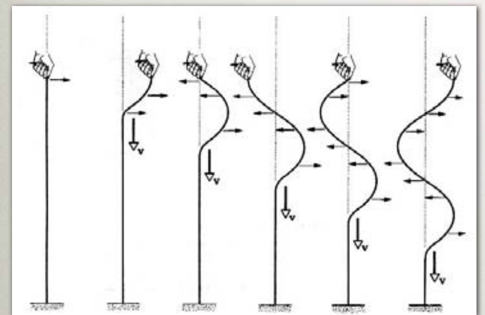
- According to source:
  1. Mechanical: elastic deformation propagating through elastic medium
  2. Electromagnetic: electric disturbance propagating through space (vacuum)
- According to propagation dimension:
  1. One-dimensional (rope)
  2. Surface waves (pond)
  3. Spatial waves (sound)
- According to relative direction of oscillation and propagation:
  1. Longitudinal
  2. Transverse

Waves

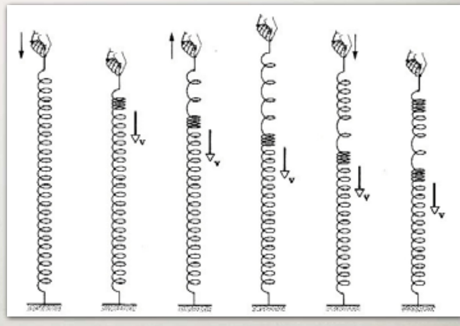


Relative propagation directions

1) **Transverse** (direction of oscillation is perpendicular to direction of propagation, e.g., light)



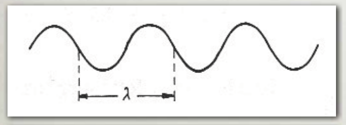
2) **Longitudinal** (direction of oscillation is parallel to direction of propagation, e.g., sound)

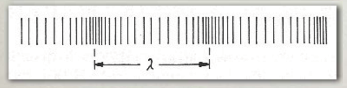


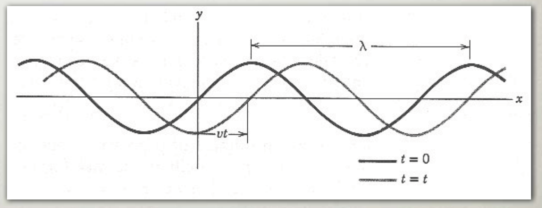
Parameters of a wave

- Harmonic waves: particles go through harmonic oscillations.
- Oscillation time (**period**): duration of a single oscillation (“T”).
- **Frequency**: inverse of period (f).
- The wave propagates with a given **velocity** (“phase velocity”, “v” or “c”)
- Distance between points of identical phase: “**wavelength**” (λ)

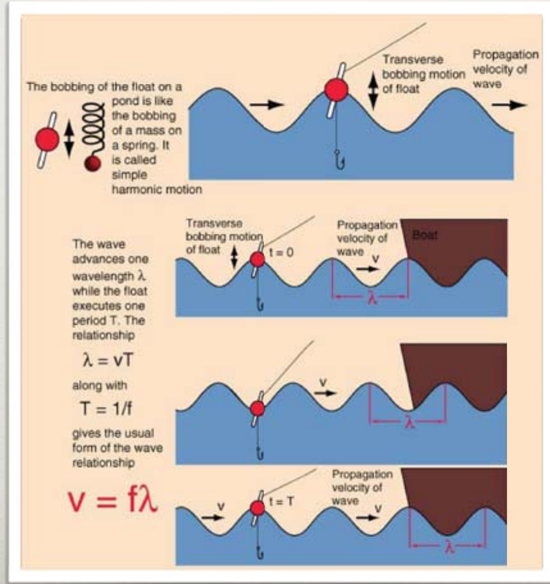
$$\lambda = cT = \frac{c}{f}$$







Traveling wave relationships



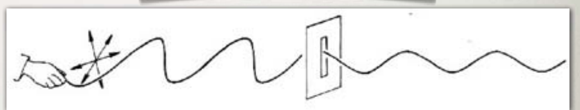
Polarization

Polarization:
oscillation is oriented in some preferred direction

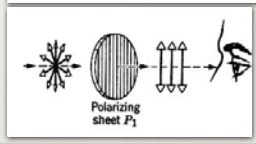
Birefringence is related to polarization:
anisotropic propagation velocity

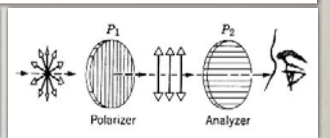
Only **transverse** waves can be polarized.

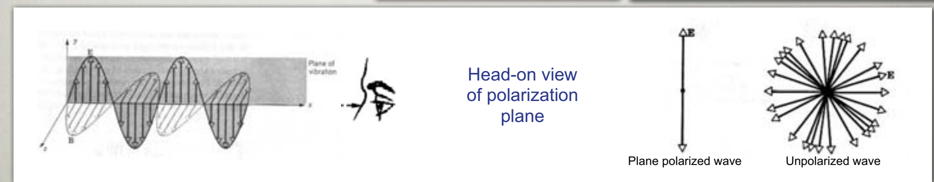
Polarization of mechanical waves:



Polarization of electromagnetic waves (light):

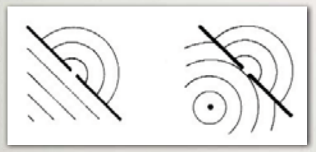




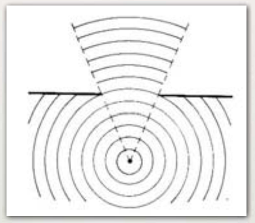


Diffraction

Huygens-Fresnel principle:
every point of a wavefront is the source of further waves



Slit smaller than λ



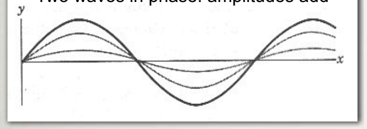
Slit greater than λ

Slit comparable to λ

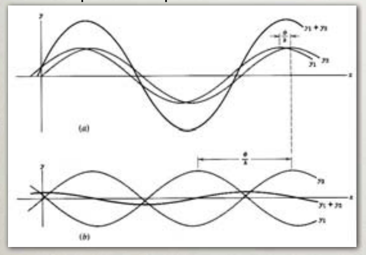
Interference of waves

Principle of superposition!

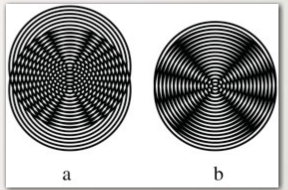
Two waves in phase: amplitudes add

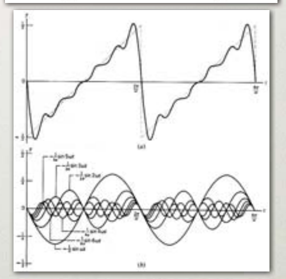


Two identical waves slightly out of phase: amplitude doubles



Two identical waves with phase slightly different from π: wavelength doubles



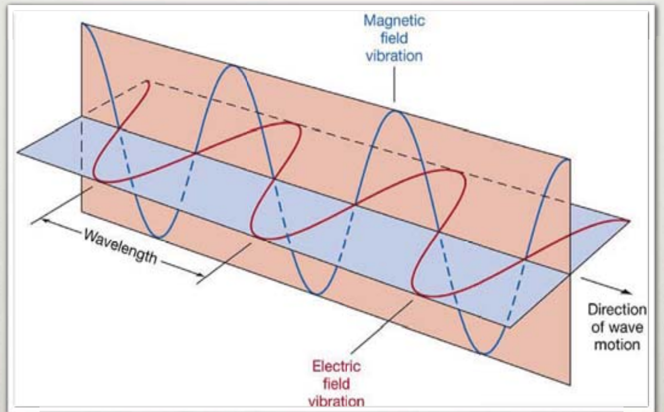


Decomposition of complex function into component sinusoidal waves (Fourier's principle)

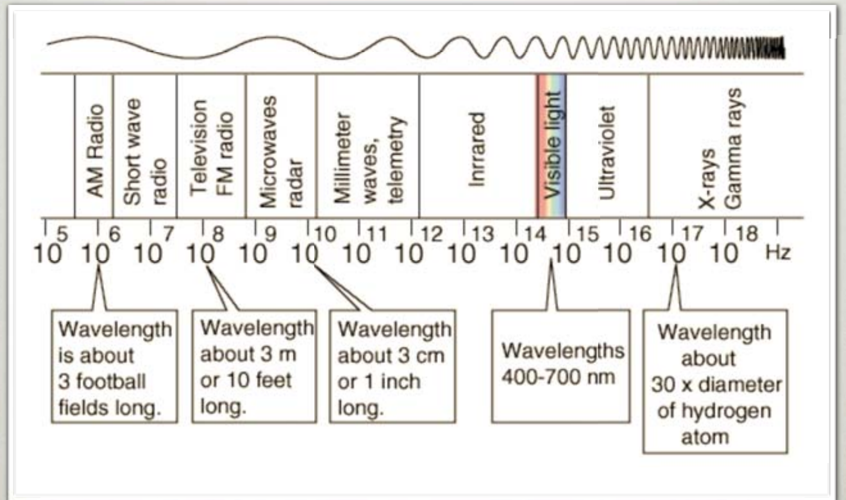
Electromagnetic waves

The electromagnetic wave

Electromagnetic disturbance propagating in space
No elastic medium is required.

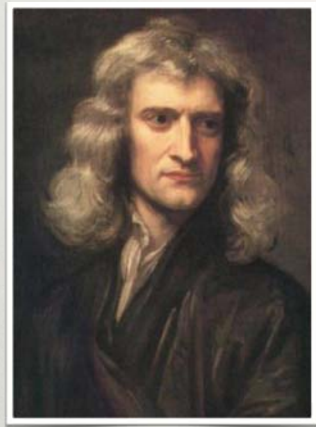


The electromagnetic spectrum



Dual nature of light

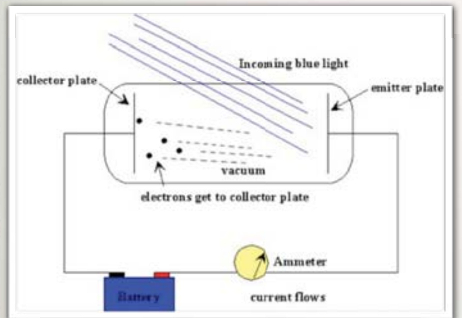
Light: Particle versus wave?

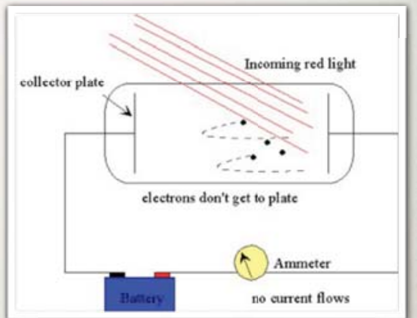


Sir Isaac Newton
1643-1727

Christiaan Huygens
1629-1695

Photoelectric effect The experiment

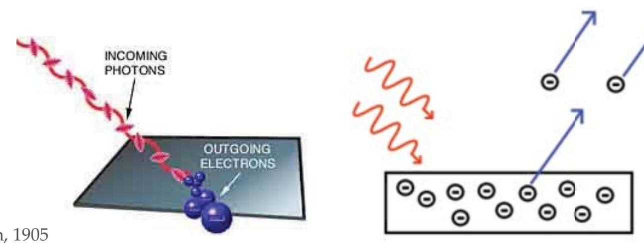




Wilhelm Hallwachs, 1888
Philipp Lenard, 1902

- Electron emission: instantaneous upon illumination
- Electron emission in BLUE light
- NO electron emission in RED light
- Photoelectric current: depends on light intensity
- Photoelectric current: does NOT depend on light color

Photoelectric effect The explanation



Einstein, 1905

$$E_{kin} = hf - W_{ex}$$

E_{kin} = kinetic energy of escaped electron
h = Planck's constant ($6.62 \cdot 10^{-34}$ Js)
f = frequency of light
hf = light energy = light quantum, ***"photon"***
W_{ex} = work necessary for the escape of the electron from the atom

Photon:

- travels with the speed of light (c) in vacuum
- does not exist at rest, has momentum
- has no rest mass

Light is at once wave and particle

Wave ⟷ **Particle**

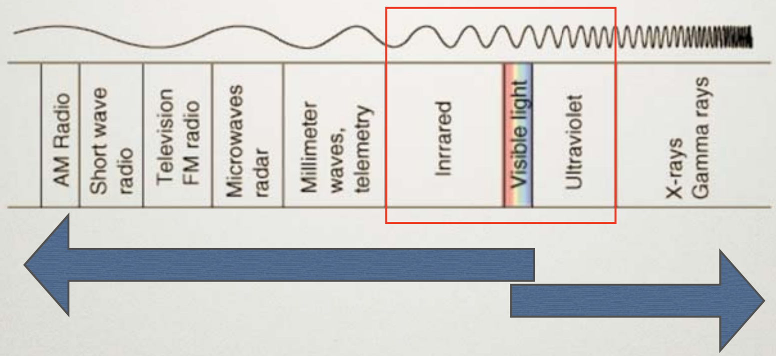
During propagation

Manifestations:
Diffraction
Interference
Polarization

During interactions

Manifestations:
Photoelectric effect
Refraction
Excitation
Ionization

Light is a special range of the EM spectrum



Long wavelengths: wave nature dominates

Short wavelengths: particle nature dominates

The Electron Volt:
Convenient photon energy unit

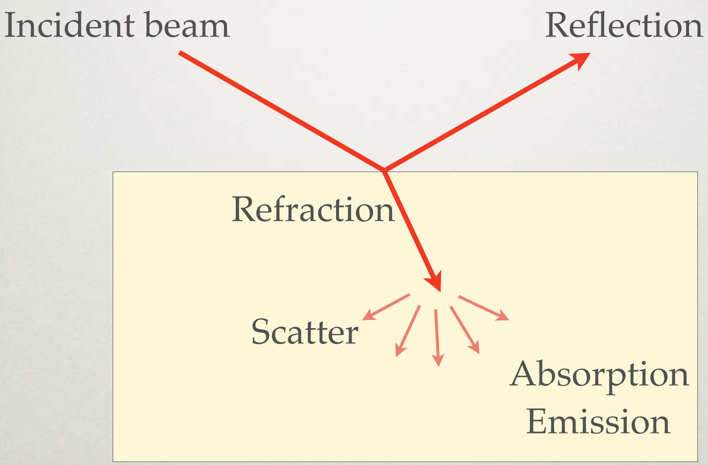
Energy gained by a single unbound electron when it accelerates through an electrostatic potential difference of one volt.

$$1\ \text{eV} = q \cdot V = 1.6 \cdot 10^{-19}\ \text{CV} = 1.6 \cdot 10^{-19}\ \text{J}$$

- 1 TeV: about the energy of motion of a flying mosquito.
- 210 MeV: average energy released in fission of one ^{239}Pu atom.
- 200 MeV: total energy released in nuclear fission of one ^{235}U atom.
- 17.6 MeV: total energy released in fusion of deuterium and tritium to form ^{4}He.
- 13.6 eV: energy required to ionize atomic hydrogen. Molecular bond energies are on the order of an eV per molecule.
- 2.5 eV: energy of blue-green photon (500 nm).
- 1/40 eV: the thermal energy at room temperature.

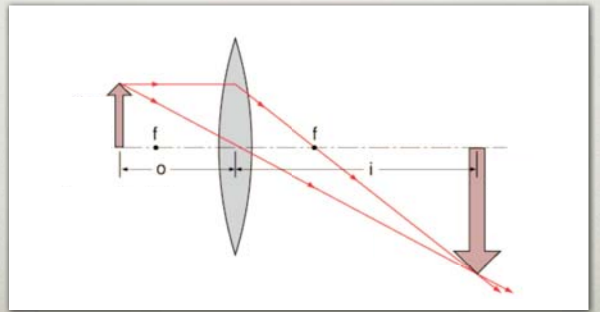
Interaction of light with matter

Types of interaction of light with matter

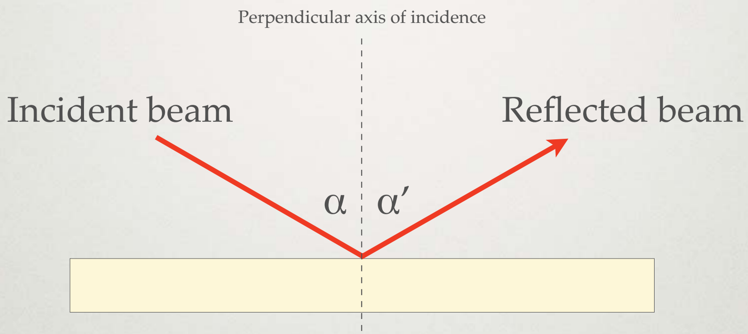


Geometric optics

- The optical ray or beam
- Ray optic diagram
- Principle of reversibility

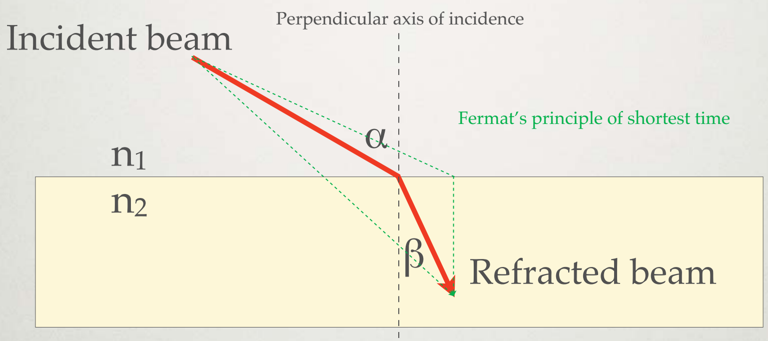


Reflection



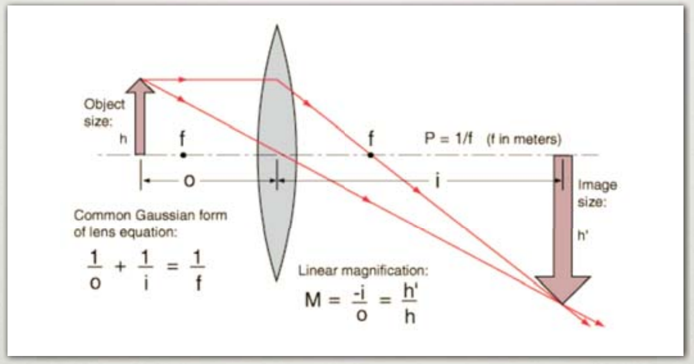
- Incident and reflected beams and axis of incidence are in the same plane.
- Incident and reflected angles are identical (α=α′)

Refraction



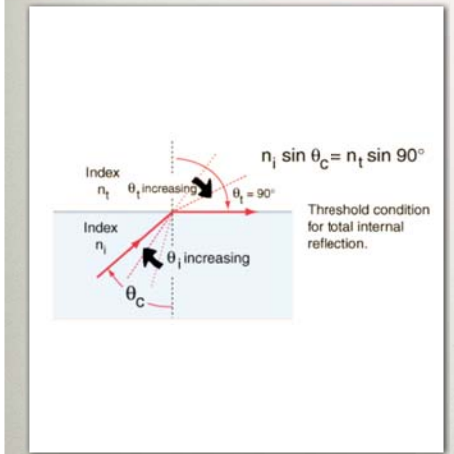
- Incident and refracted beams and axis of incidence are in the same plane.
- Snell's law: $$\frac{\sin\alpha}{\sin\beta} = \frac{c_1}{c_2} = \frac{n_2}{n_1}$$

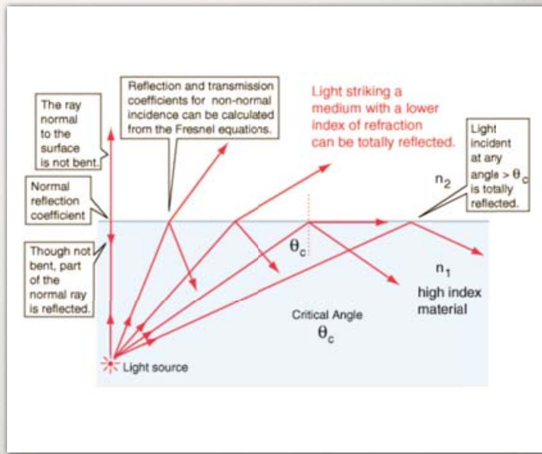
Image formation by convex lens



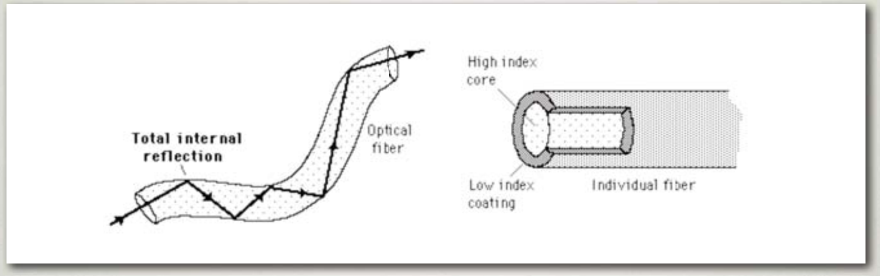
Refractive power (diopter, m^{-1}): $D = \frac{1}{f}$

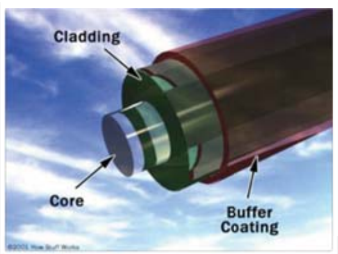
Total internal reflection





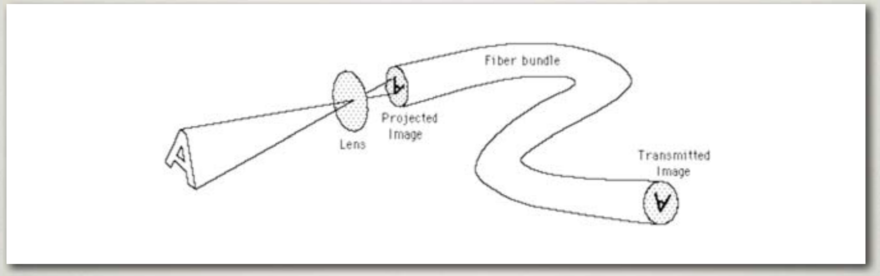
Application of TIR: optical fibers

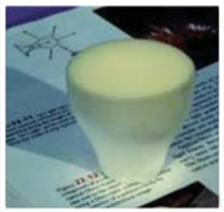




- **Core** - glass core in which light propagates.
- **Cladding** - Outer optical material, which reflects light back into core. Its refractive index is smaller than that of the core.
- **Buffer coating** - Plastic covering for protection from damage and vapor condensation.
- **Optical fiber bundle:** bundle containing hundreds of optical fibers in parallel.

Transmitting image in optical fiber





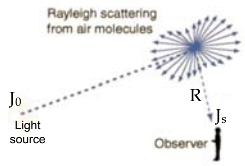
- **If the arrangement of fibers is maintained within the bundle, then the image is faithfully transmitted.**

Medical fiber optics: endoscopes

- **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

Light scattering



$$J_s = J_0 \frac{8\pi^4 N\alpha^2}{\lambda^4 R^2}\left(1+\cos^2\Theta\right)$$

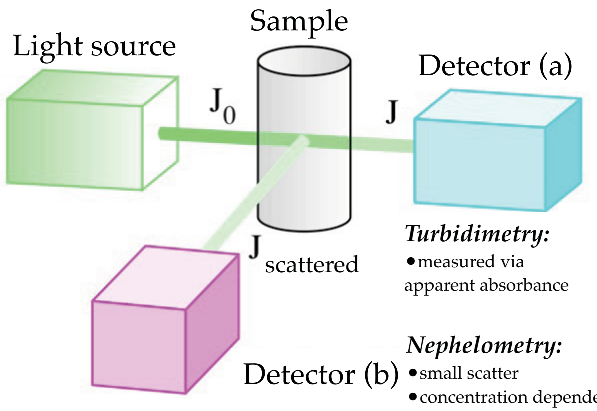
- Elastic collision: photon energy (wavelength) does not change
- Emission by resonating dipoles

J_s=intensity of scattered light
J_0=intensity of incident light
N=number of scattering particles
α=polarizability (dipole moment per electric field)
λ=wavelength of light
R=distance between scatterer and observer
Θ=angle of scattered light

Strong wavelength dependence -> enhancement of short wavelengths -> blue sky

Particle size greater than wavelength -> even reduction at all visible wavelengths -> gray clouds

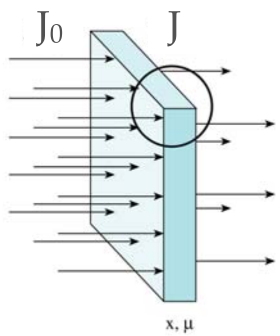
Medical applications of light scattering



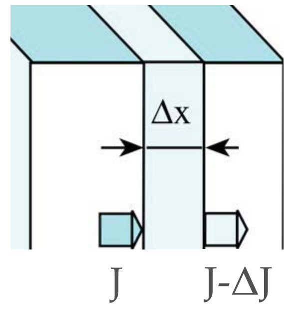
Turbidimetry:
- measured via apparent absorbance

Nephelometry:
- small scatter
- concentration dependence
- concentration measurement of immune complexes

Light absorption



$J<J_0$

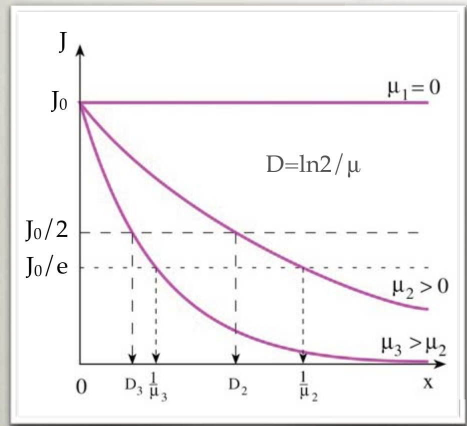


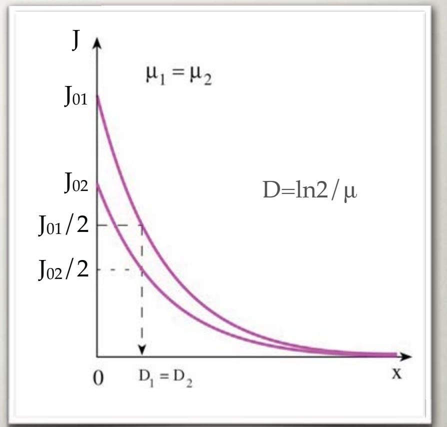
$\Delta J = -\mu \Delta x J$

$J = J_0 e^{-\mu x}$

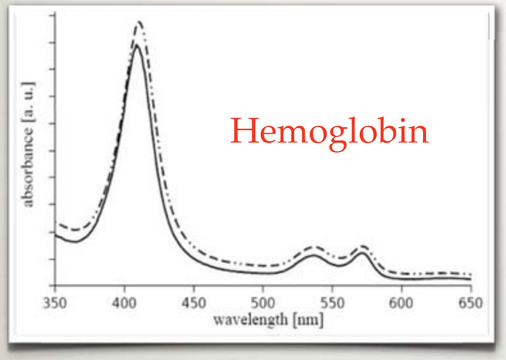
Light absorption

$$J = J_0 e^{-\mu x}$$





Light absorption



$$J = J_0 e^{-\mu x}$$

$$\lg \frac{J_0}{J} = \mu x \lg e$$

$$\lg \frac{J_0}{J} \approx \mu$$

absorbance, optical density

$$\lg \frac{J_0}{J} = \varepsilon_\lambda c x$$

Lambert-Beer's Law

ε_λ = molar extinction coefficient

c = concentration

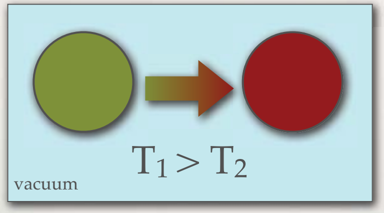
Generation of light

Generation of light

- Black body radiation (thermal radiation)
- Luminescence

Thermal radiation

Electromagnetic radiation emitted from all matter due to its possessing thermal energy



Heat exchange, temperature equilibration

Light emitted by hight-temperture object

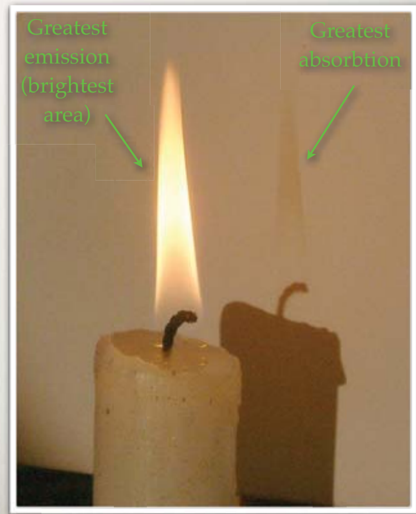
Kirchoff's law

Ratio of spectral emissive power and absorptivity is constant.

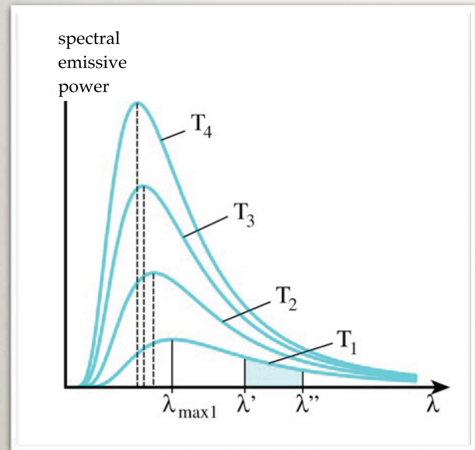
$$\frac{M_{\lambda i}}{\alpha_{\lambda i}} = \frac{M_{\lambda j}}{\alpha_{\lambda j}}$$

For a black body (BB):

$$\alpha_{\lambda BB} = 1$$



Black-body radiation



Stefan-Boltzmann law:

$$M_{BB}(T) = \sigma T^4$$

Wien's displacement law:

$$\lambda_{max} T = const$$

Planck:

$$E = hf$$

Application of thermal radiation

Thermography, infradiagnostics