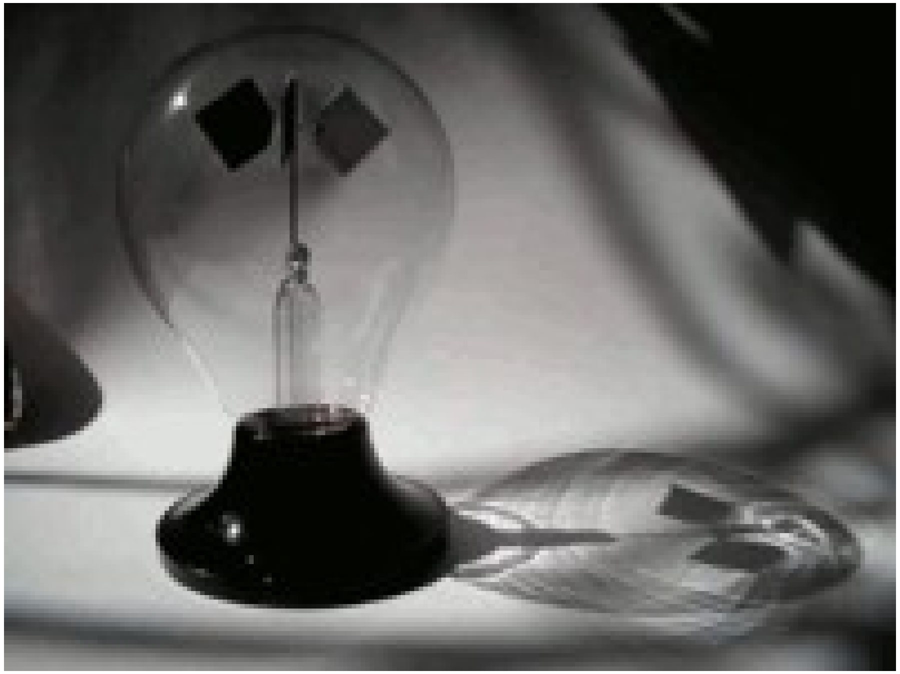
Nature of Light

Nature of Light: particles?

Crookes radiometer (erroneous explanation in terms of particles)



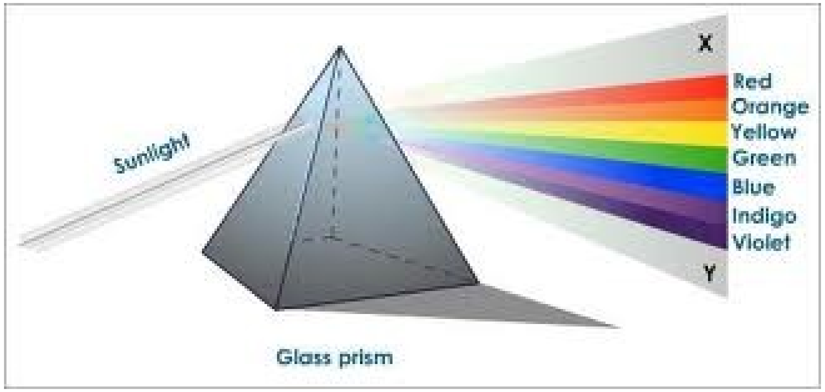
Pierre Gassendi

Isaac Newton
(Hyphotesis of Light, *Opticks)*

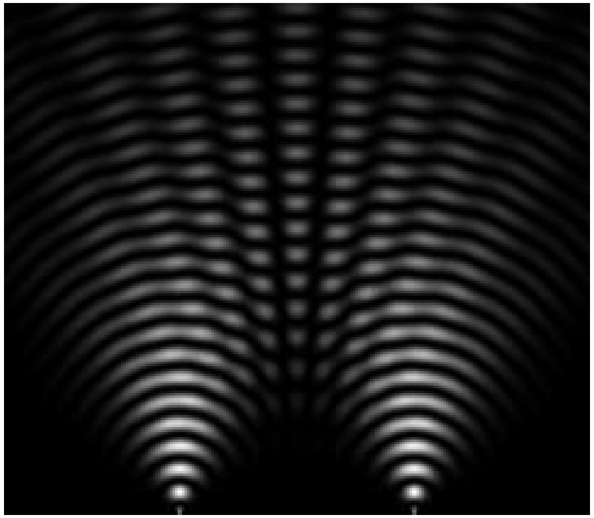
Images: Wikimedia Commons

Nature of Light: waves?

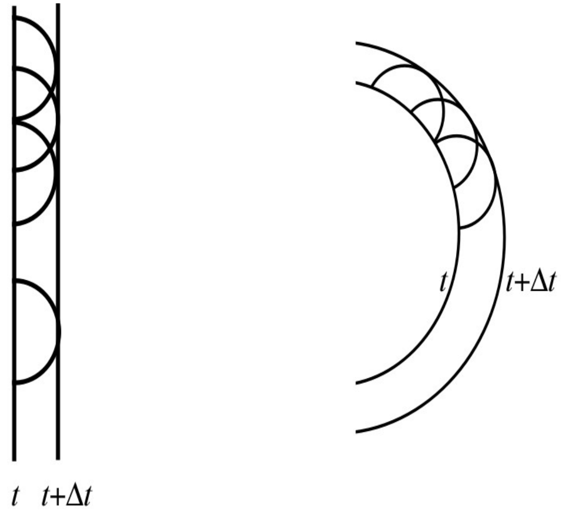
dispersion



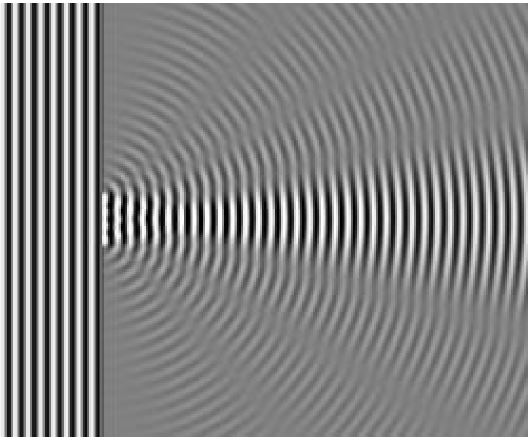
interference



Huygens principle



diffraction

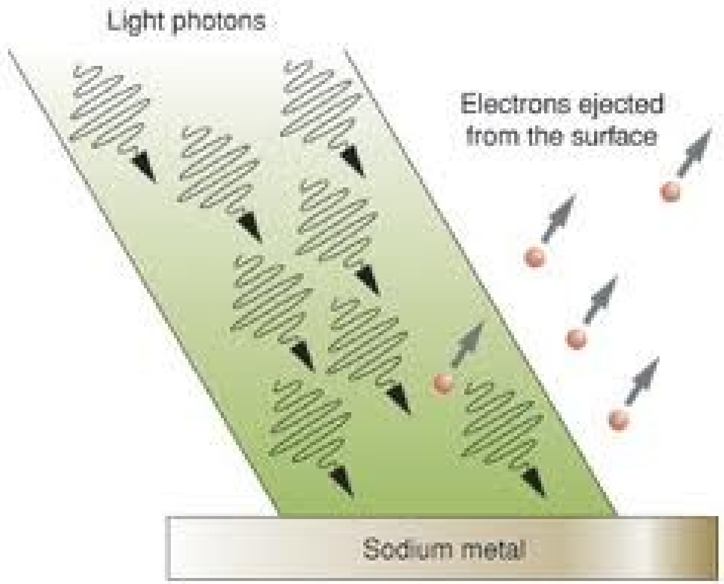


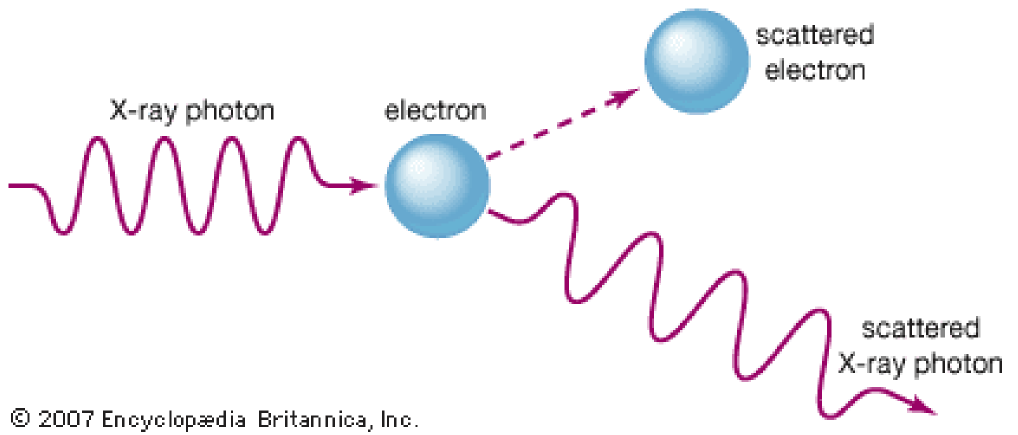
Augustin-Jean Fresnel, Robert Hooke,
Simeon Denis Poisson, Christian Huygens

Images: Wikimedia Commons

Quantitative Approach: particles...

Image: Wikimedia Commons



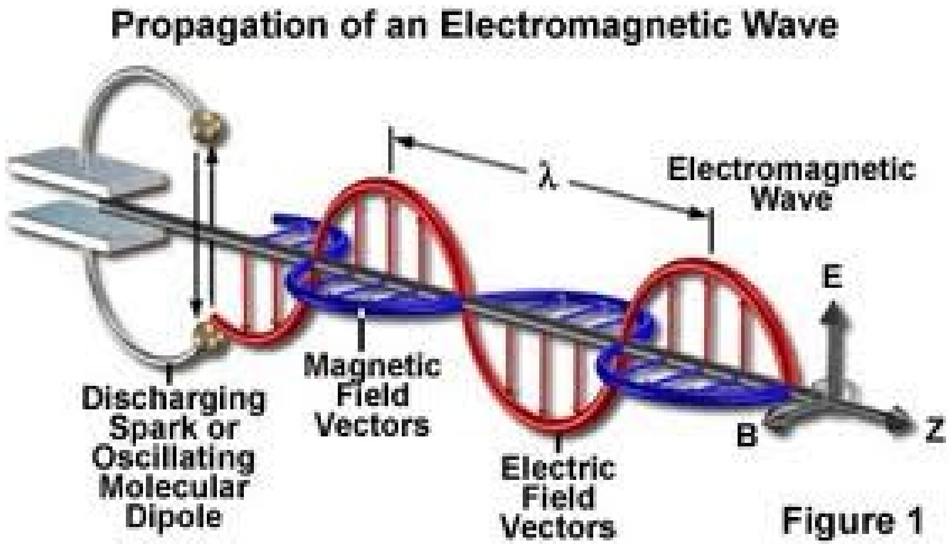


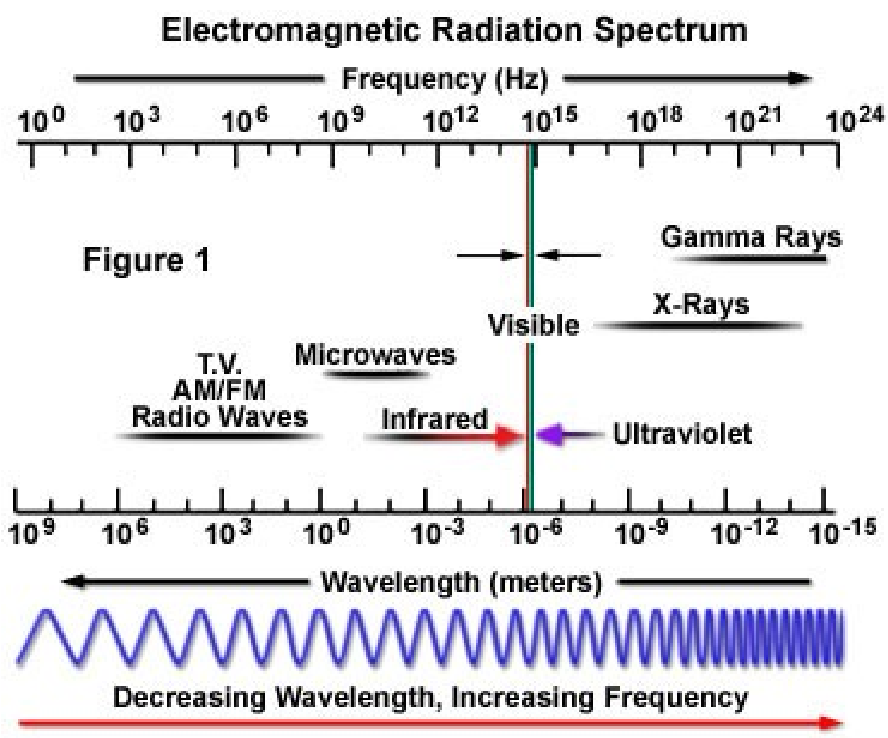
photoelectric effect

Compton effect

Albert Einstein, Arthur Holly Compton

...or electromagnetic waves?

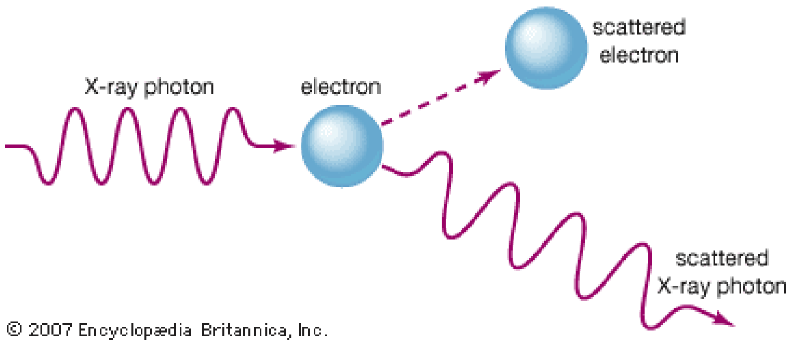


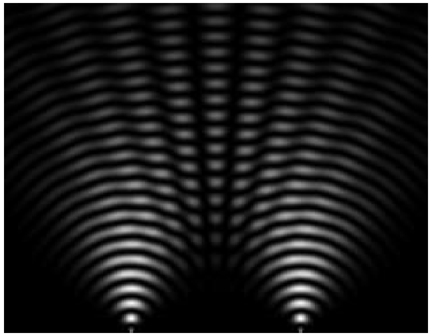


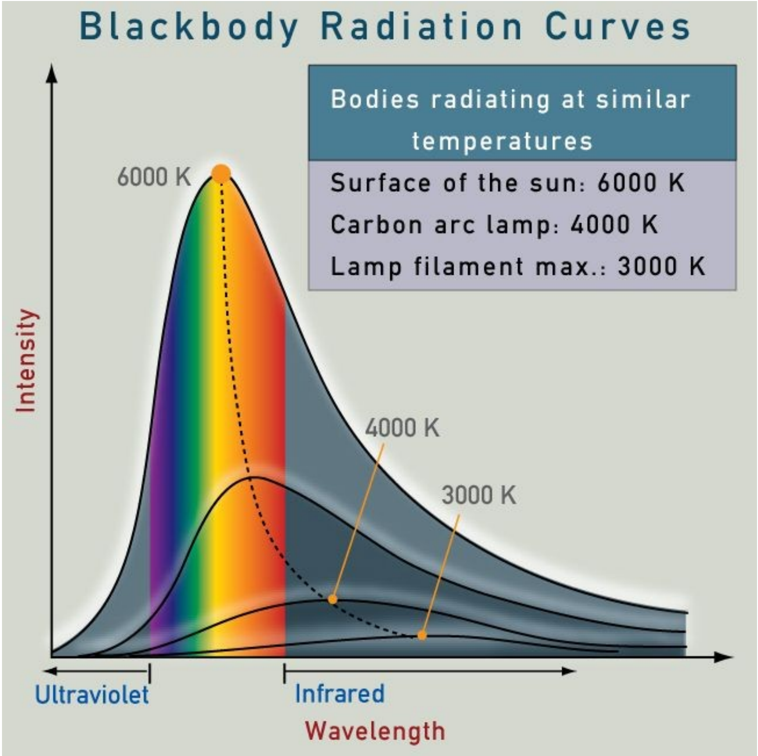
James Clerk Maxwell, Michael Faraday, Heinrich Hertz

Images: Wikimedia Commons

Answer:
dual nature (particles & waves)







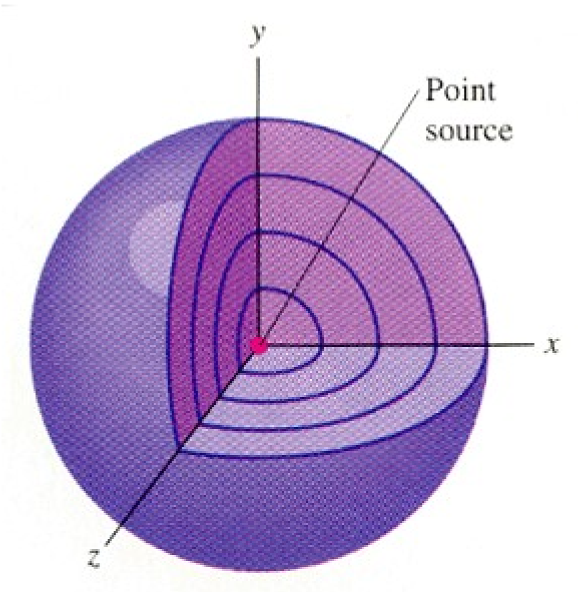
Max Planck, Davisson and Germer, Louis de Broglie

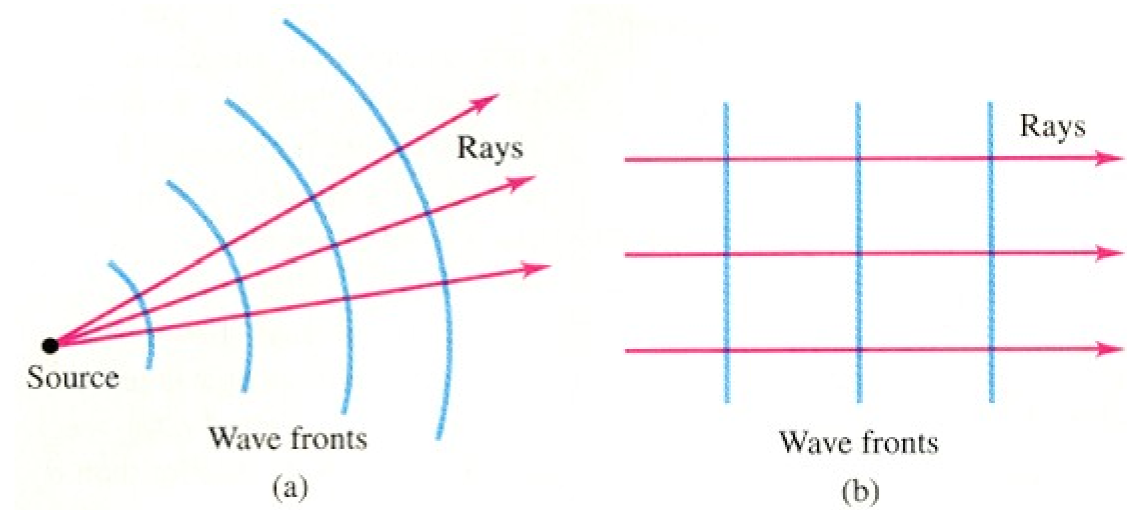
Quantum Electrodynamics (QED)
Richard Feynman, Freeman Dyson, Julian Schwinger, Shin-Ichiro Tomonaga

Images: Wikimedia Commons

Vocabulary

Wave front – set of points (in 3D – a surface) having the same phase



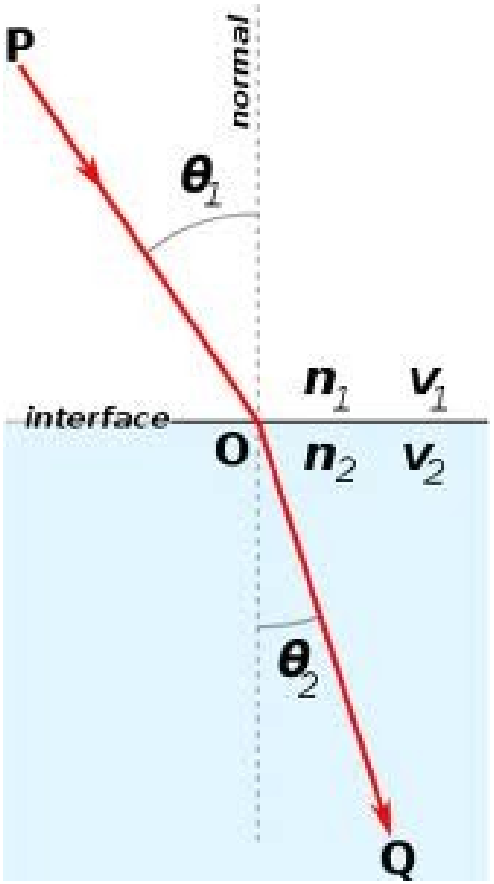


Ray – line along the direction of propagation of the wave

In isotropic and homogeneous materials rays are straight lines perpendicular to wave fronts

Reflection and Refraction

Fermat's principle: *Light follows the path of least travel time.*

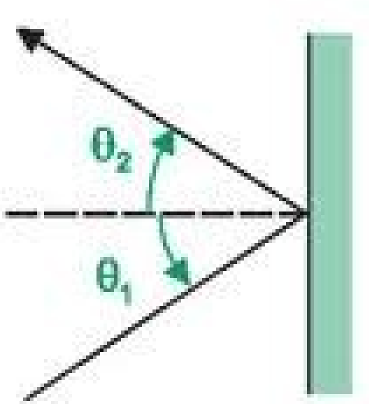


Law of refraction (Snell's law)

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} \qquad n_i = \frac{c}{v_i}$$

Law of reflection

$$\theta_1 = \theta_2$$



NB. *All rays and the line normal to the boundary lie in the same plane.*

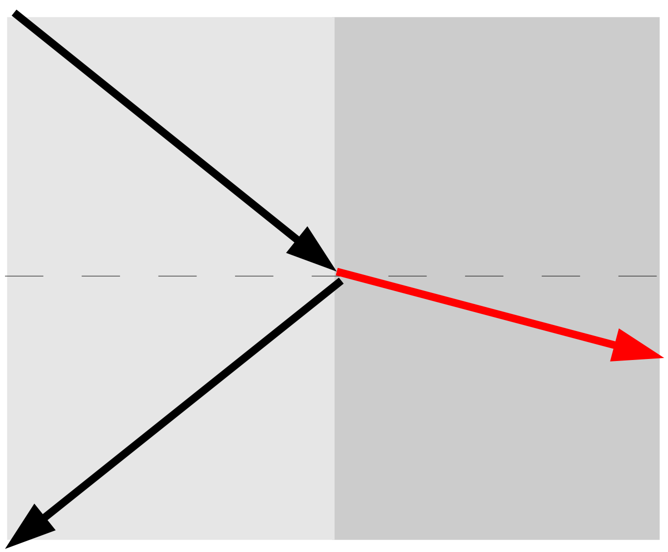
Discussion

Snell's law

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

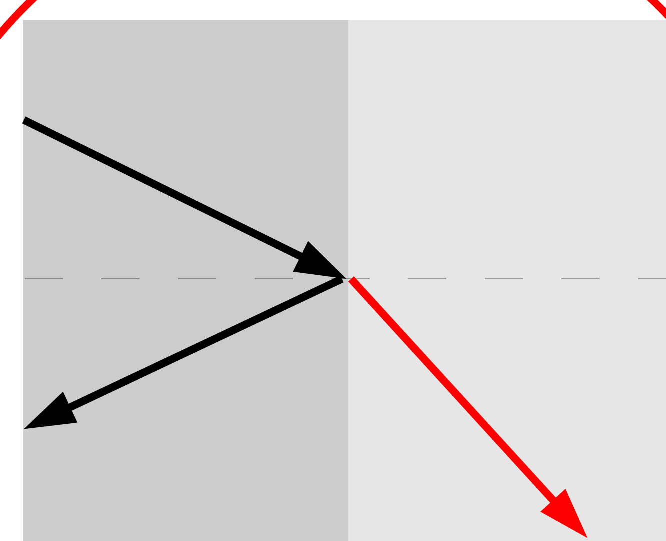
$$n_i = \frac{c}{v_i}$$

$$n_1 < n_2$$



refracted ray bends toward the normal

$$n_1 > n_2$$



refracted ray bends away from the normal

NB. *For normal incidence, all angles are zero.*

Index of Refraction
(also called Refractive Index)

Table 18 INDEX OF REFRACTION

(λ = 5893 Å; Temperature = 20 °C except as noted)

Material	Refractive index
air, dry (STP)	1.00029
alcohol, ethyl	1.360
benzene	1.501
calcite	1.6583
	1.4864
canada balsam	1.530
carbon dioxide (STP)	1.00045
carbon disulfide	1.625
carbon tetrachloride	1.459
diamond	2.4195
glass, crown	1.5172
flint	1.6270
glycerol	1.475
ice	1.310
lucite	1.50
quartz	1.544
	1.553
quartz, fused	1.45845
sapphire (Al_2O_3)	1.7686
	1.7604
water, distilled	1.333
water vapor (STP)	1.00025

Image source: http://boomeria.org/physicstextbook/

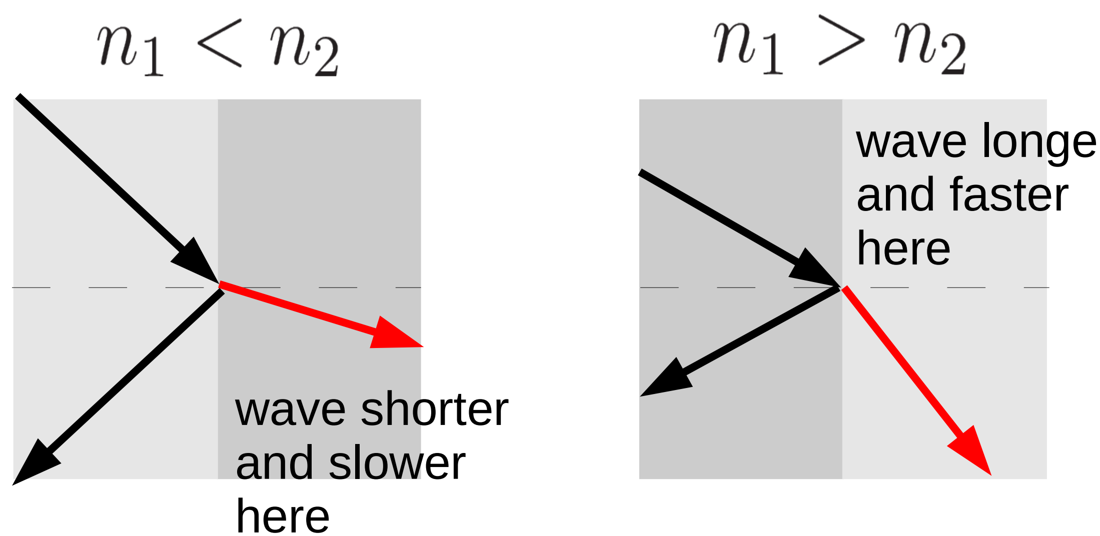
Index of Refraction

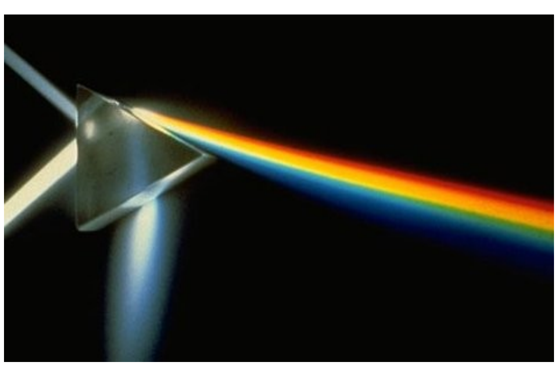
(1) The frequency f of the wave does not change when passing from one material to another.

(2) The wavelength λ is different in different materials.

$$v = \lambda f$$

$$\frac{c}{\lambda_0} = \frac{v}{\lambda} \Rightarrow \lambda = \frac{\lambda_0}{n}$$

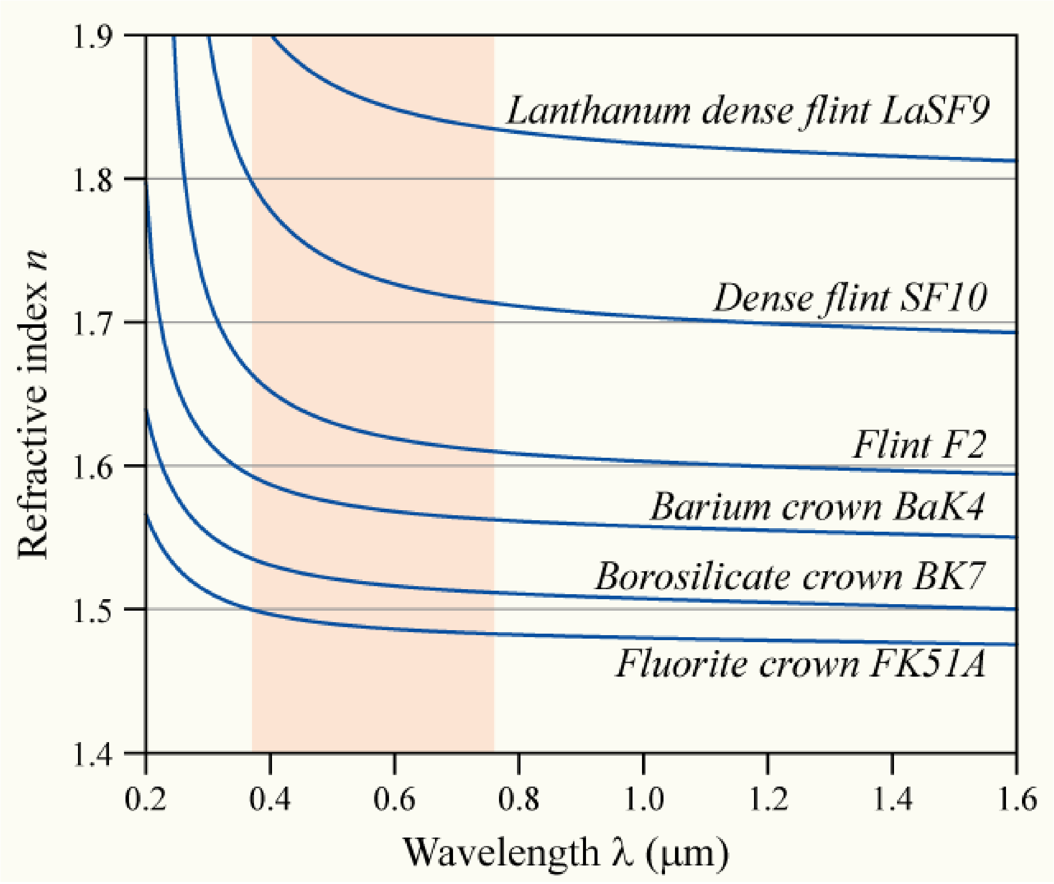



phys.utk.edu

In general, the index of refraction depends on the wavelength – **dispersion.**

Dispersion

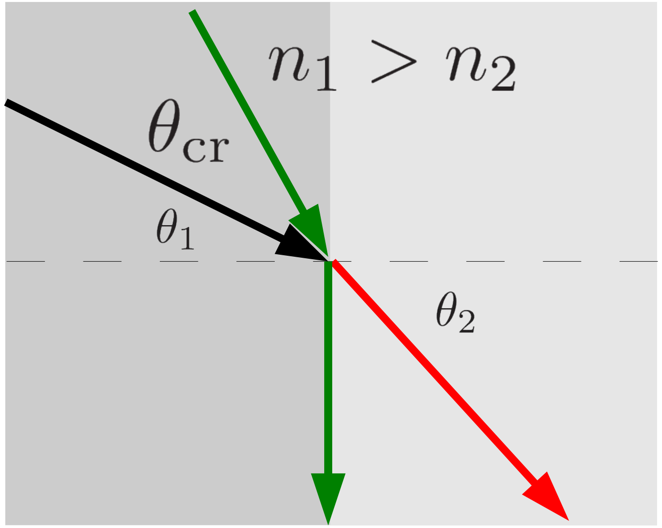
In most materials, *n* decreases with increasing wavelength.



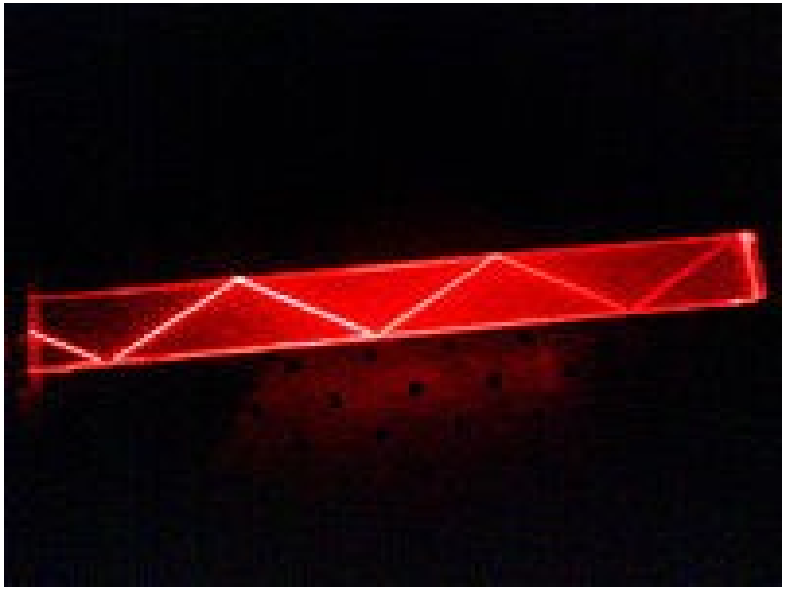
can be modelled by driven harmonic oscillators

Discussion:
Total Internal Reflection

Consider light incident upon a medium of smaller index of refraction.



applications: fiber optics



Snell's law $$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

total internal reflection for

$$\theta_1 \geq \theta_{cr}$$

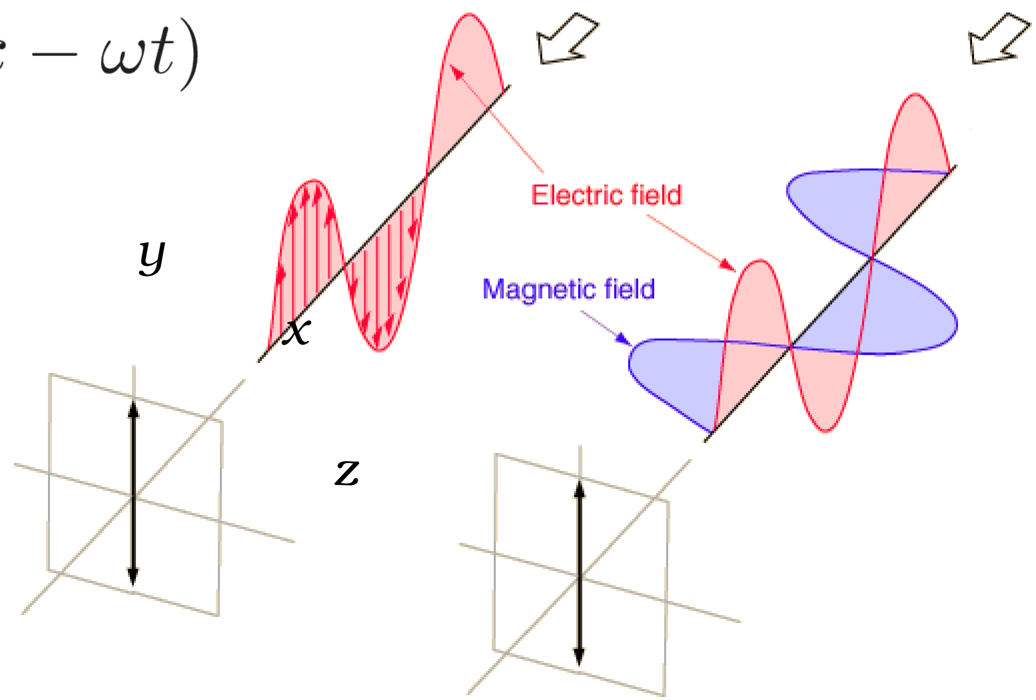
$$\sin\theta_{cr} = \frac{n_2}{n_1}$$

Polarization of Light: Linear Polarization

Recall that, polarization of the electromagnetic wave is determined by the direction of the **electric field** vector.

$$\mathbf{E}(\mathbf{r}, t) = E_0 \hat{n}_y \cos(kx - \omega t)$$

$$\mathbf{B}(\mathbf{r}, t) = -B_0 \hat{n}_z \cos(kx - \omega t)$$

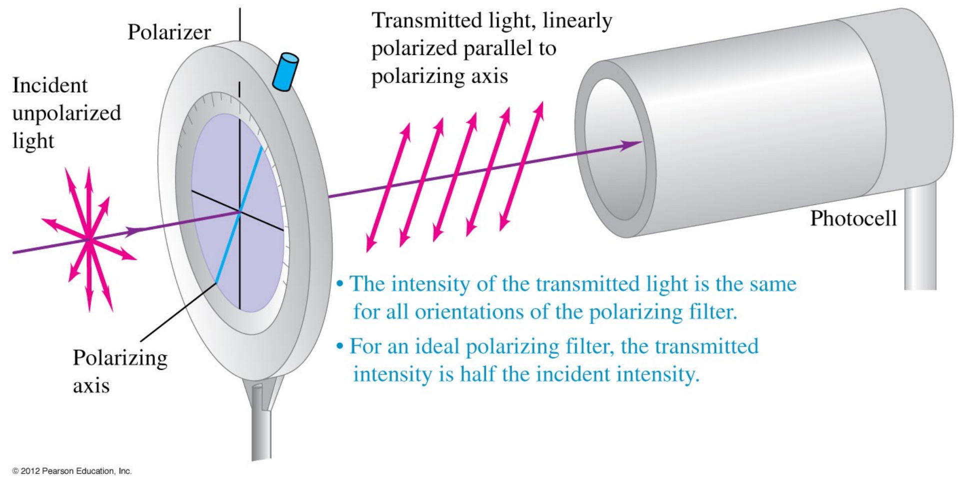


e-m wave polarized
in the *y* direction

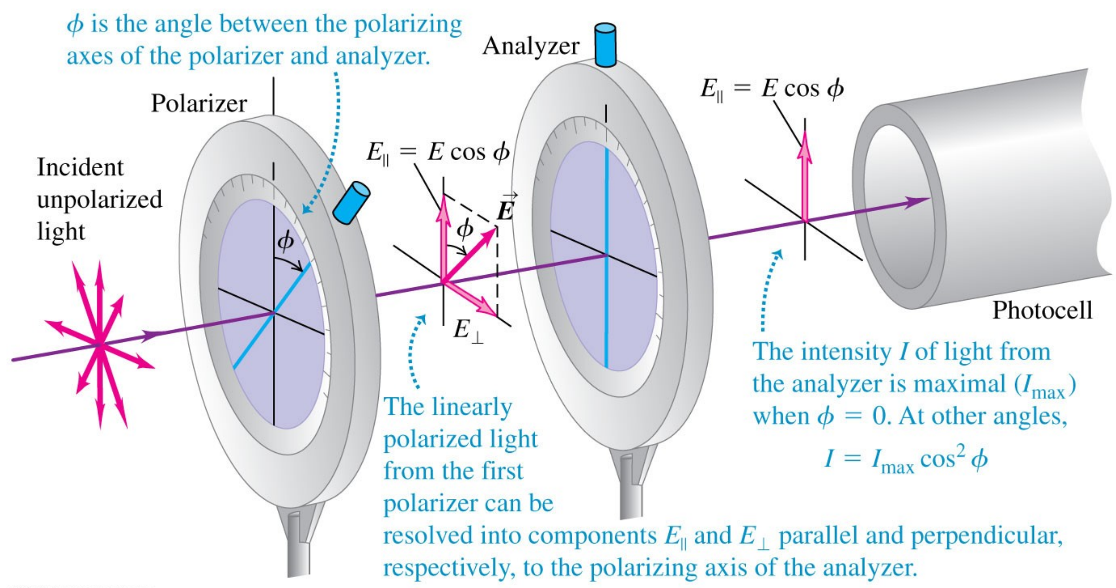
http://hyperphysics.phy-astr.gsu.edu/

Polarization and Malus' Law

single polarizer



polarizer + analyzer

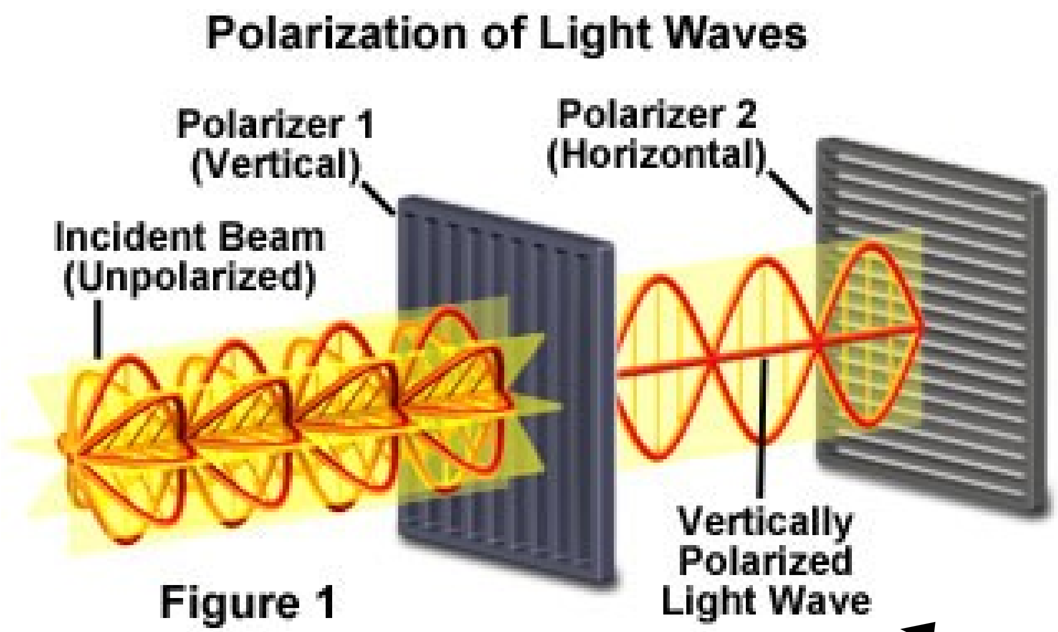


Malus' law

$$I = I_0 \cos^2 \phi$$

NB. I_0 is the intensity of the linearly polarized light incident on the analyzer

Polarizers and Malus' Law
Unpolarized (Natural) Light



$$I_{\text{polarized}} = \frac{1}{2} I_{\text{unpolarized}}$$

linear polarization

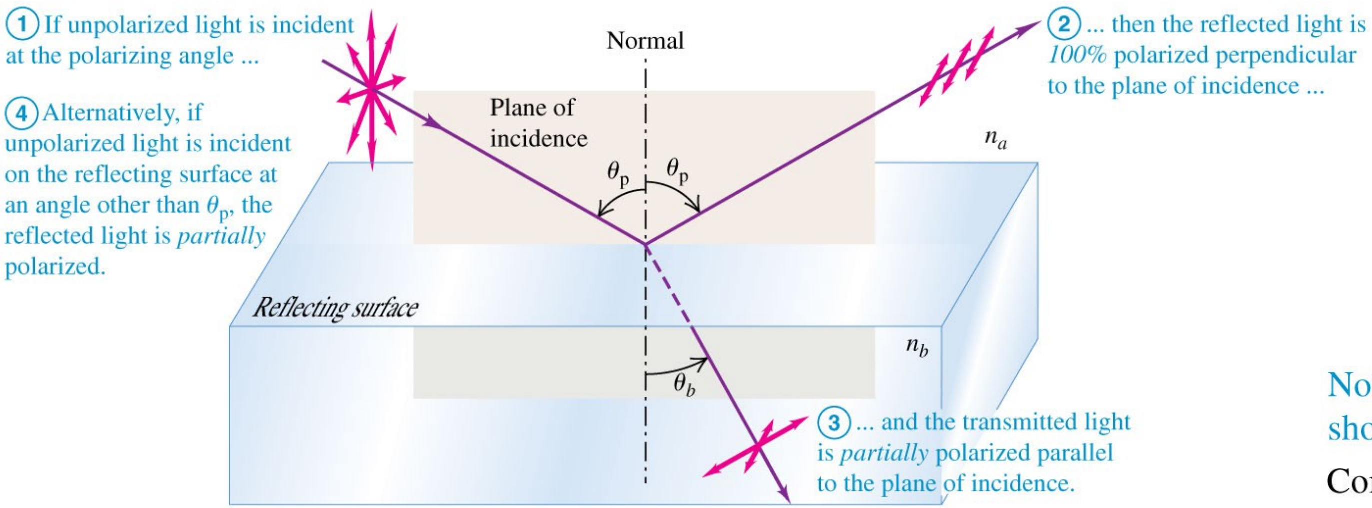
unpolarized light = statistical mixture of waves polarized in all possible, equally-probable, directions

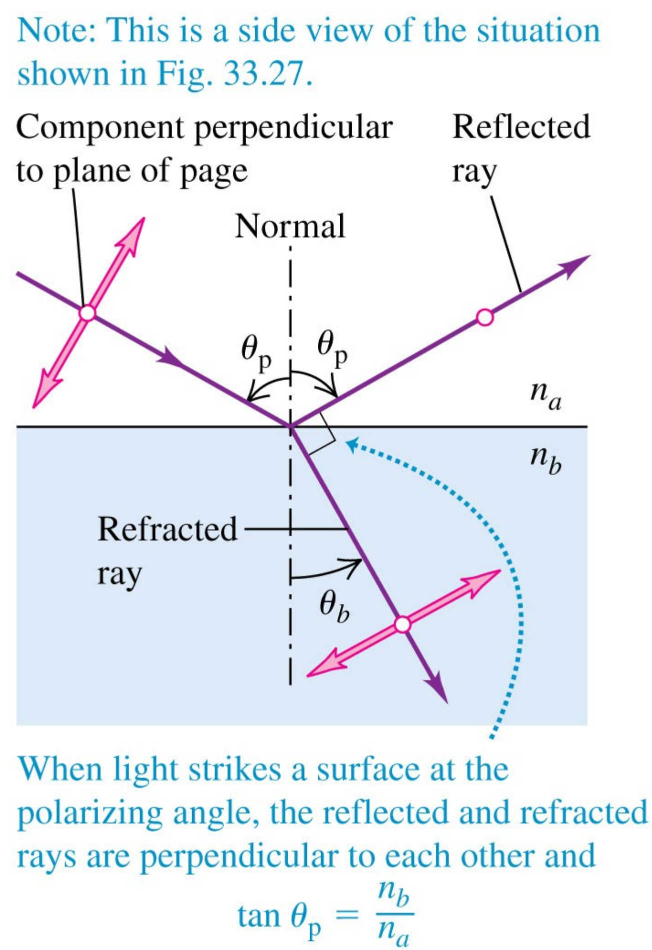
$$I_{\text{pol}} = \lim_{N\to\infty} \left(\frac{I_{\text{unp}}}{N} \cos^2\phi_1 + \frac{I_{\text{unp}}}{N} \cos^2\phi_2 + \cdots + \frac{I_{\text{unp}}}{N} \cos^2\phi_N \right)$$

$$I_{\text{pol}} = I_{\text{unp}} \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \cos^2\phi_i = I_{\text{unp}} \langle \cos^2\phi \rangle = \frac{I_{\text{unp}}}{2}$$

Images: rfid.net

Polarization by Reflection





Snell's law
$$\frac{\sin\theta_p}{\sin\theta_b} = \frac{n_b}{n_a}$$

for light incident at polarizing angle
$$\theta_b + \theta_p = \frac{\pi}{2}$$

Brewster's law
$$\theta_p = \arctan\frac{n_b}{n_a}$$

Applications in Photography

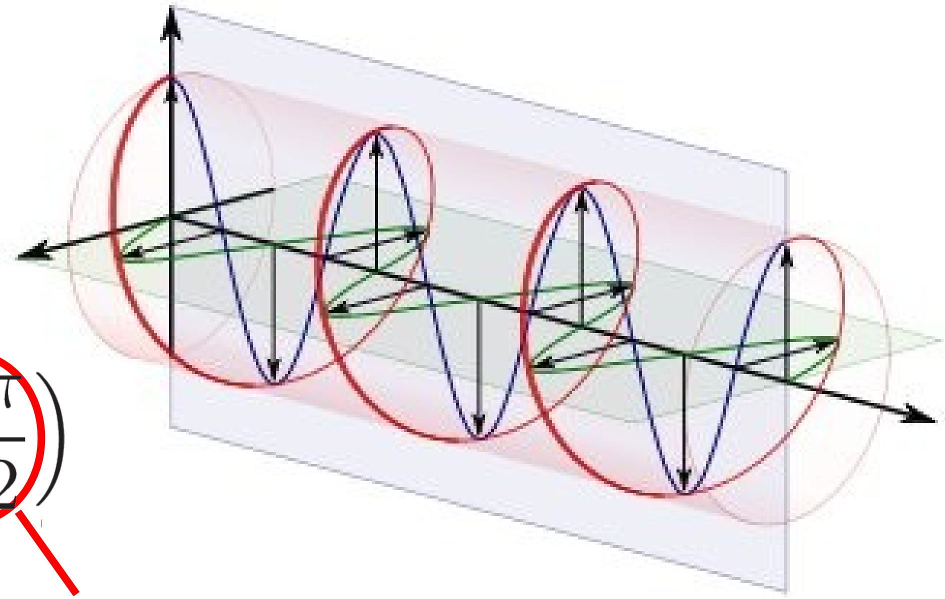
eliminates reflexes

photography.ca

photography101.org

Circular Polarization

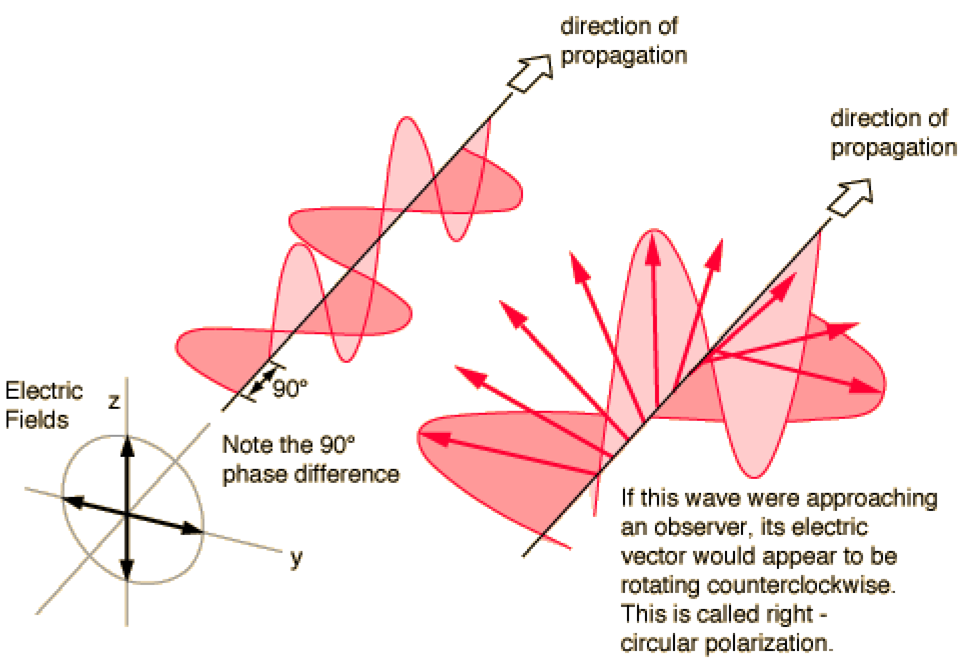
Superposition of two e-m waves



$$\mathbf{E}_1(\mathbf{r},t) = E_0 \hat{n}_y \cos(kx - \omega t)$$

$$\mathbf{E}_2(\mathbf{r},t) = E_0 \hat{n}_z \cos\left(kx - \omega t - \frac{\pi}{2}\right)$$

phase difference
(quarter of a cycle)



http://hyperphysics.phy-astr.gsu.edu/

Circular Polarization

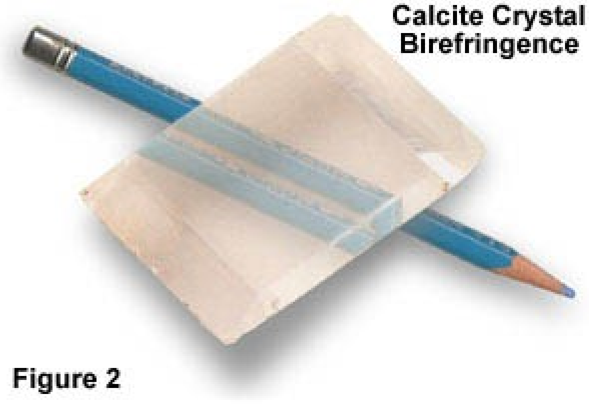
Practical implementations of quarter-cycle phase shift.

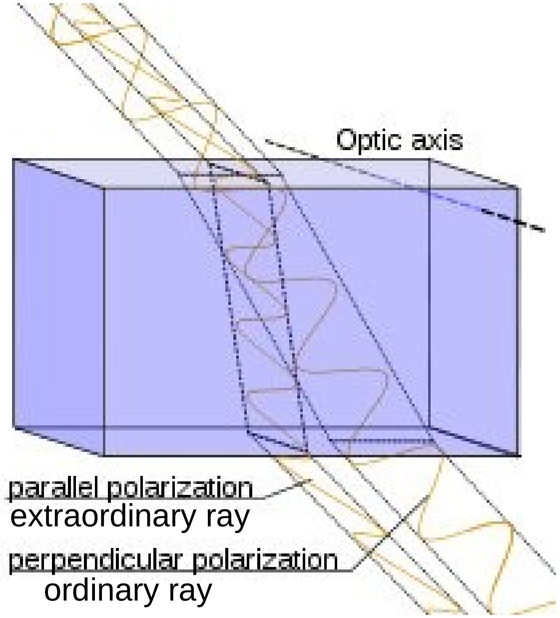
radio frequencies

Use two perpendicular antennas
with a phase-shifting module.

light

Use a *birefringent* crystal
(e.g. calcite or quartz);
refractive index different
for different polarizations
of incident light.

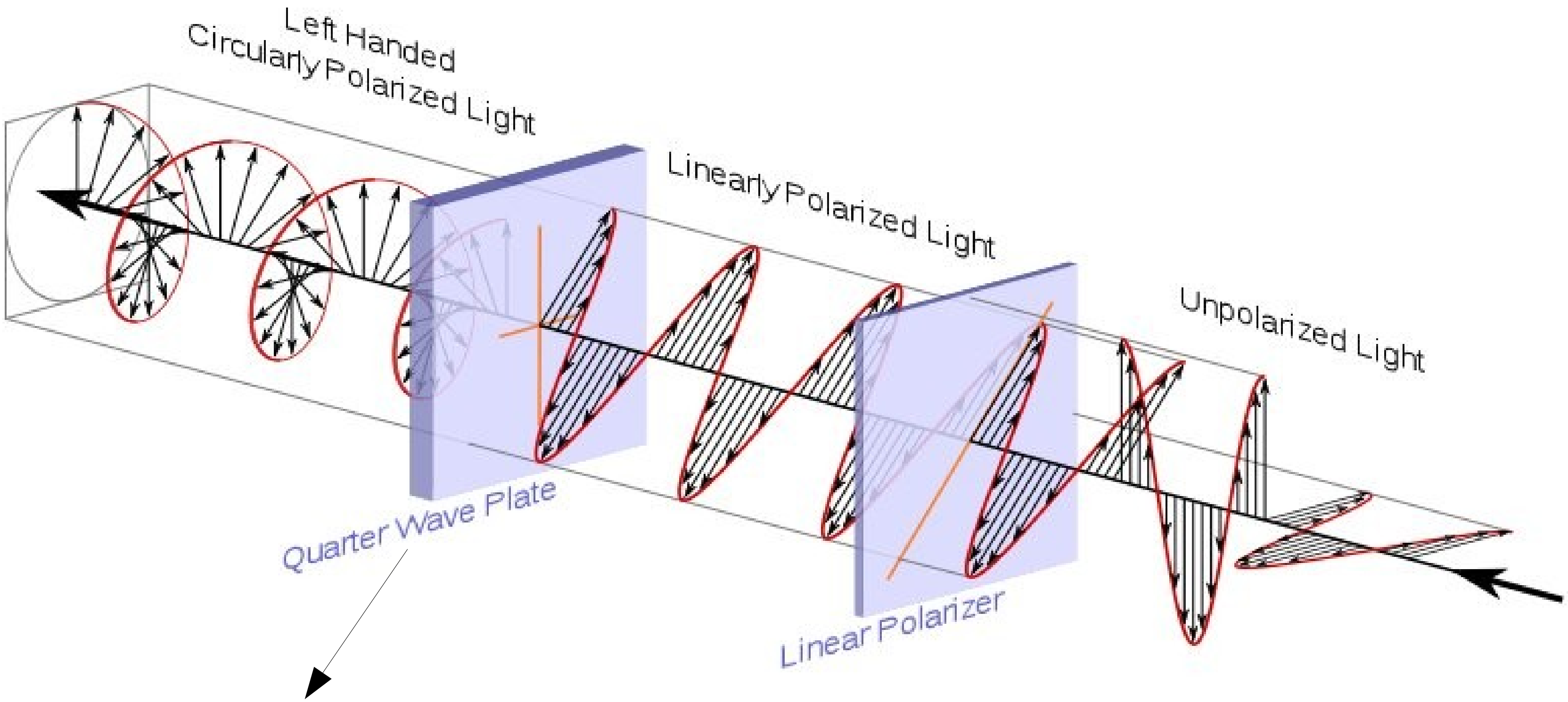




Images: wikimedia, www.olympusmicro.com, www.hellotrade.com

phases differ!

Circular Polarization

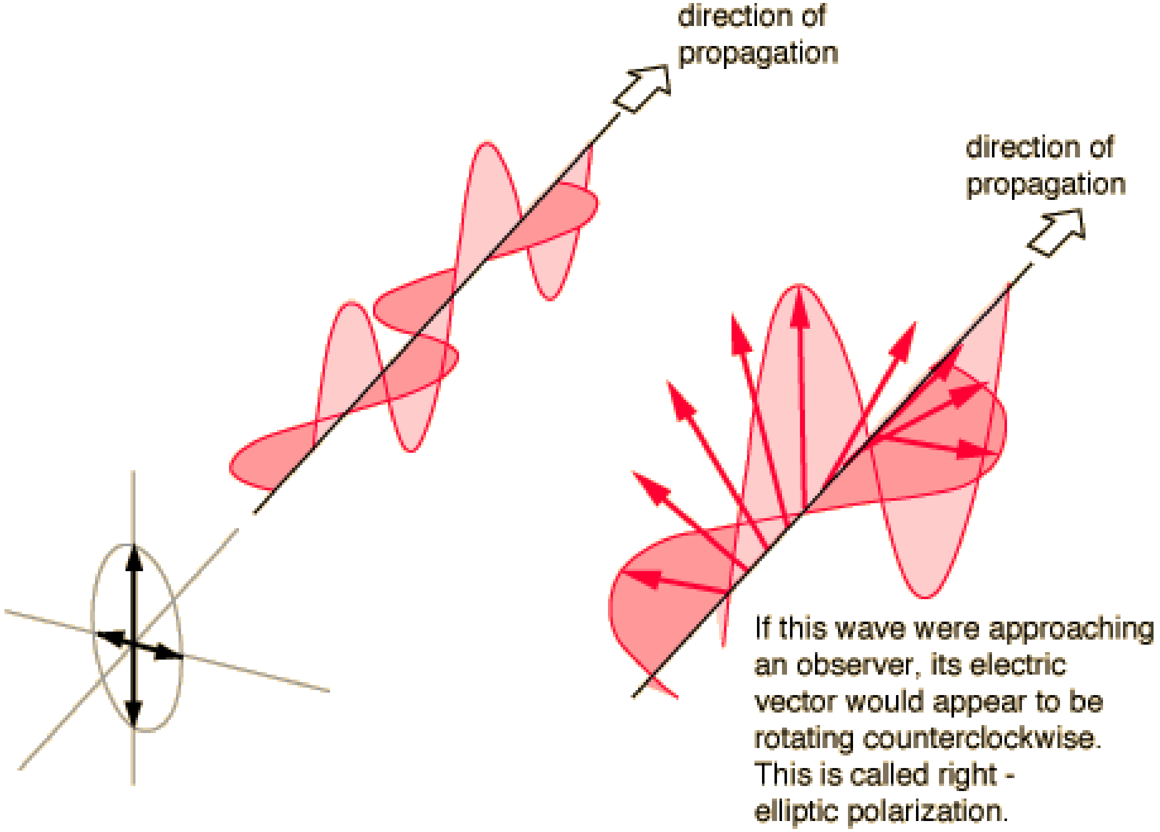


birefringent crystal with a thickness
corresponding to the quarter-cycle phase shift

* Theoretical description of birefringence: consider dielectric permittivity as a 2^{nd} order tensor (matrix) rather than a scalar (consequently, the refractive index also has a tensor structure).

Elliptical Polarization

Elliptically polarized light is a superposition of two e-m waves of *unequal* amplitude, linearly polarized in perpendicular directions, differing in phase by 90°.



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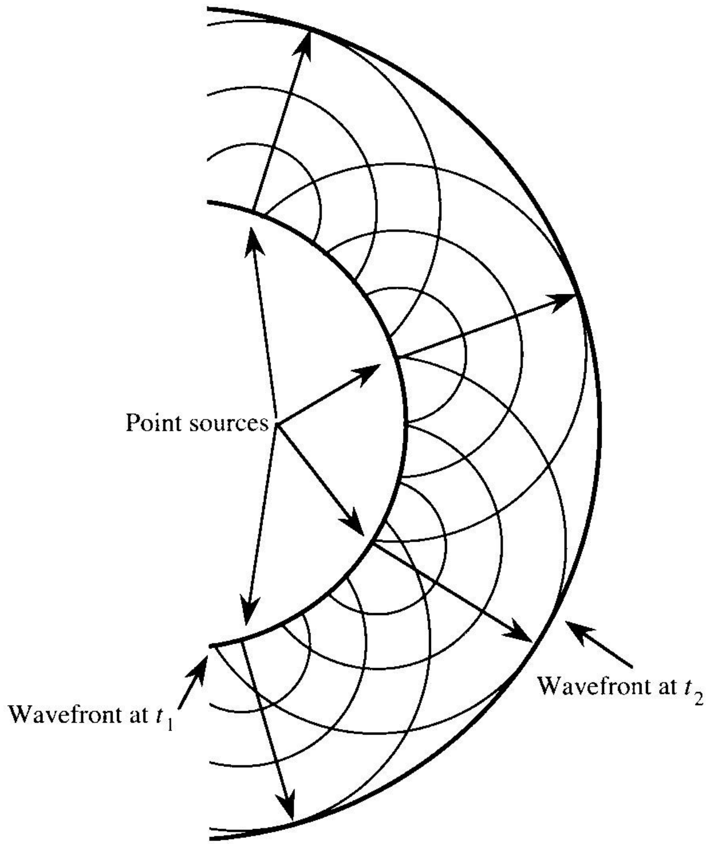
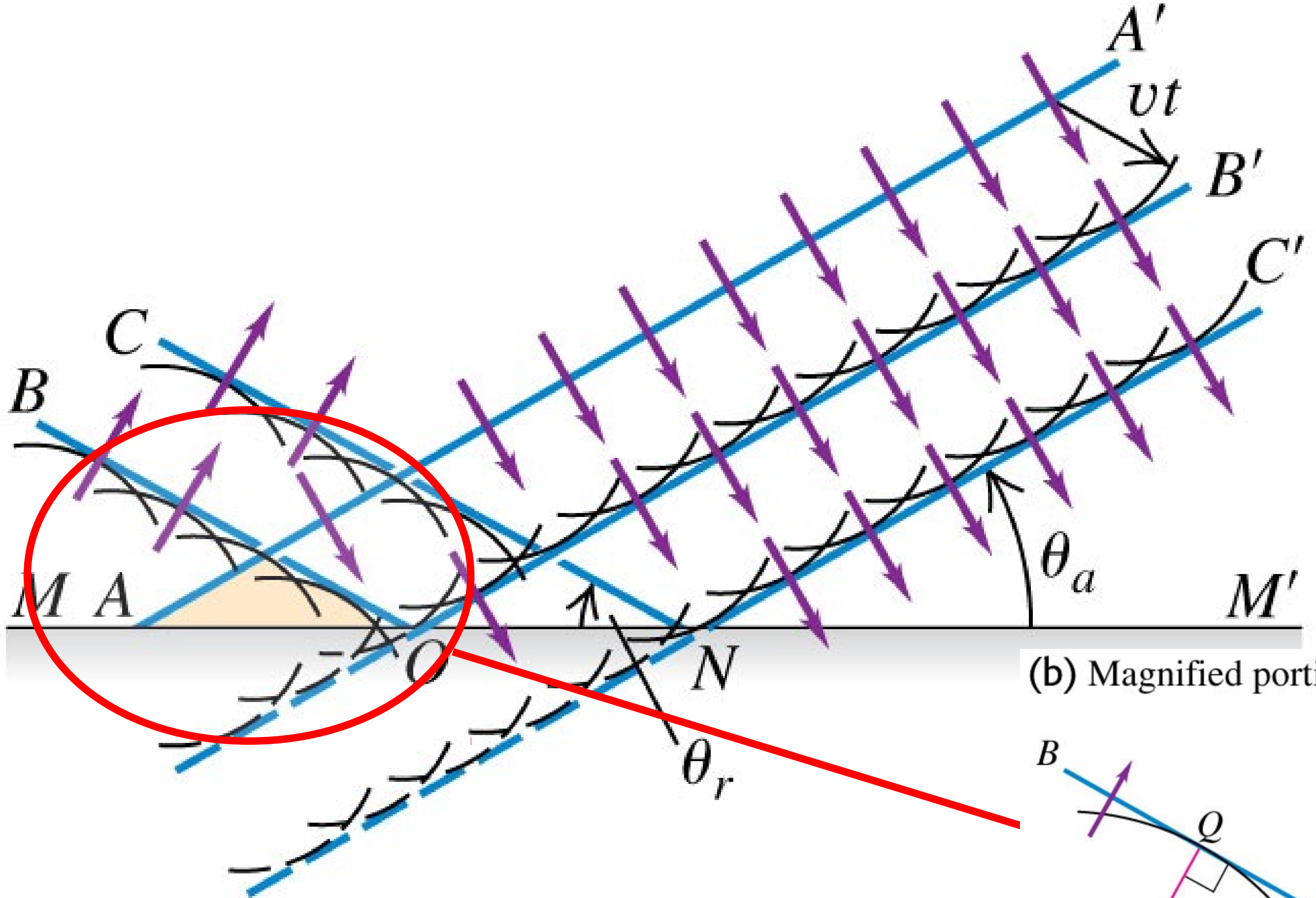
Huygens' (or Huygens-Fresnel) Principle

Every point of the wavefront may be considered as a source of secondary wavelets that propagate out in all directions with speed equal to speed of propagation of the wave.

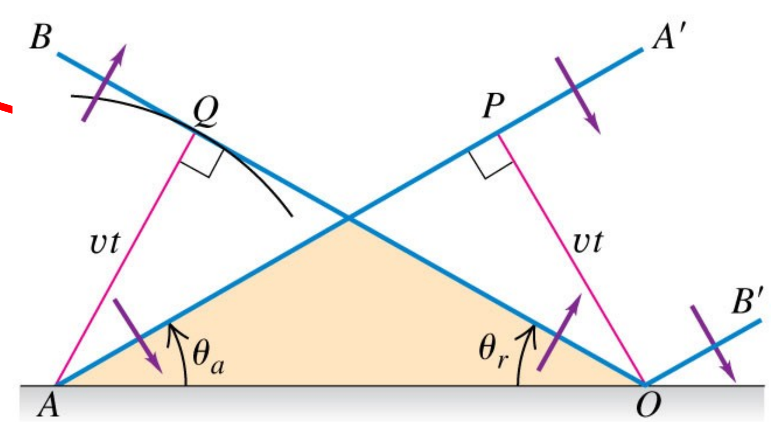


Huygens' principle: Reflection

(a) Successive positions of a plane wave AA' as it is reflected from a plane surface

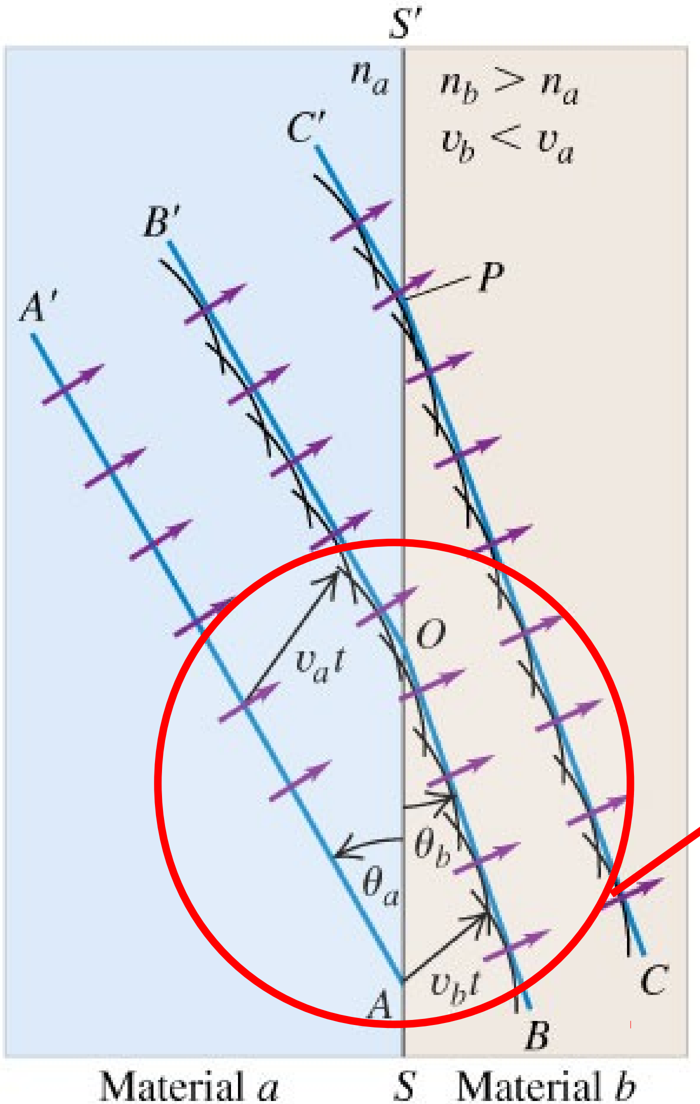


(b) Magnified portion of (a)



Huygens' Principle: Refraction

(a) Successive positions of a plane wave AA' as it is refracted by a plane surface



(b) Magnified portion of (a)