The Nature and Properties of Light

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IOCCG Summer Lecture Series
18 July - 29 July 2022, Villefranche-sur-Mer, France

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https://dstramski.scrippsprofiles.ucsd.edu/ https://scripps.ucsd.edu/labs/oceanoptics/

- 1978. MS in Oceanography, University of Gdansk, Poland
- 1978 - 1986. Research Scientist, Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland
- 1985. PhD in Earth Sciences, University of Gdansk, Poland
- 1986 -1988. Postdoctoral Fellow, Villefranche-sur-Mer, France
- 1988 -1989. Visiting Scientist, Université Laval, Québec, Canada
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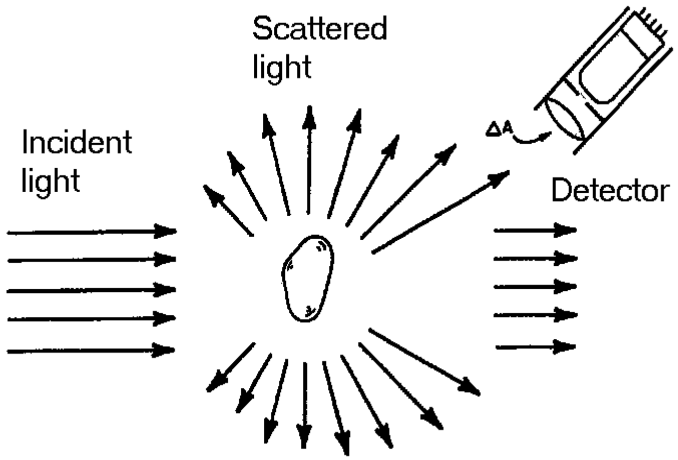
- 1996. "Poste Rouge" Visiting Scientist, Villefranche-sur-Mer, France
- 1997 – present. Professor, Scripps Institution of Oceanography, University of California San Diego, USA

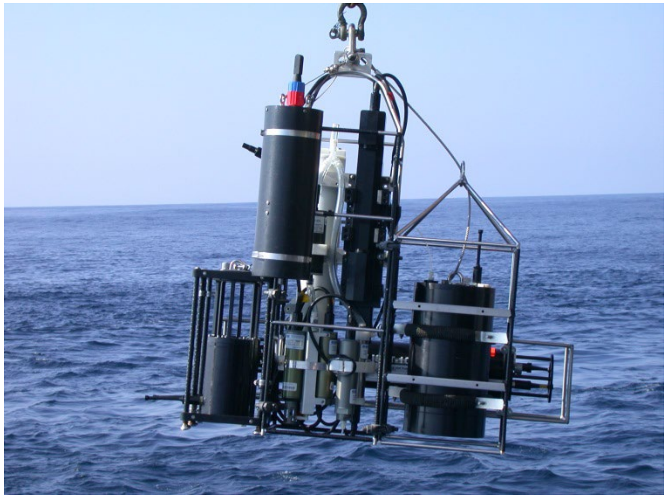
UNIWERSYTET GDAŃSKI PAN OBSERVATOIRE OCEANOLOGIQUE VILLEFRANCHE/MER UNIVERSITÉ LAVAL UNIVERSITY OF SOUTHERN CALIFORNIA 1880 SCRIPPS INSTITUTION OF OCEANOGRAPHY UCSD

OCEAN OPTICS RESEARCH LAB AT SIO

PARTICLE OPTICS



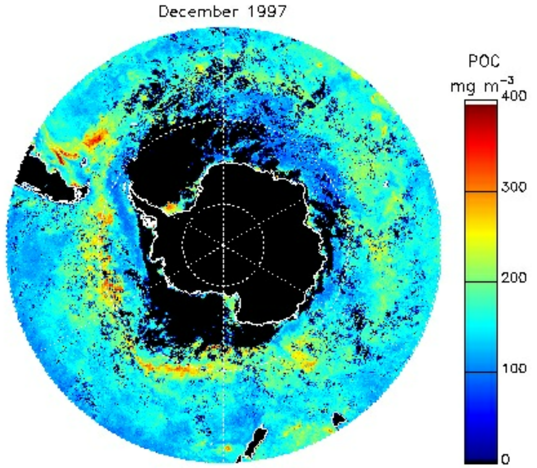
FIELD OBSERVATIONS



MODELING

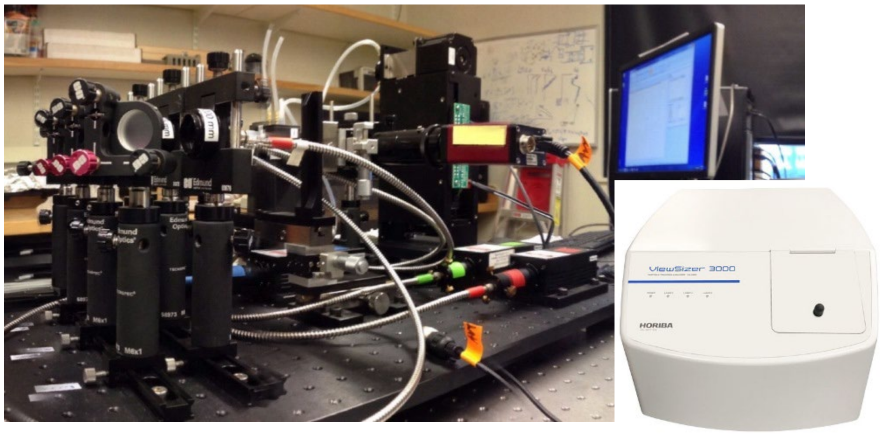
$$\cos\theta \frac{dL(z,\xi,\lambda)}{dz} = -c(z,\lambda)L(z,\xi,\lambda) + \int_{\Xi} L(z,\xi',\lambda)\beta(z,\xi'\rightarrow\xi,\lambda)d\Omega(\xi') + S(z,\xi,\lambda)$$

REMOTE SENSING



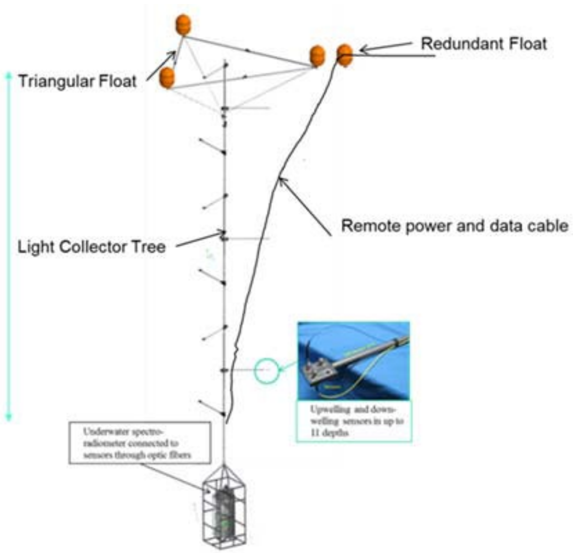
DEVELOPMENT OF NOVEL TECHNOLOGIES AND OPTICAL METHODS

Nanoparticle analysis

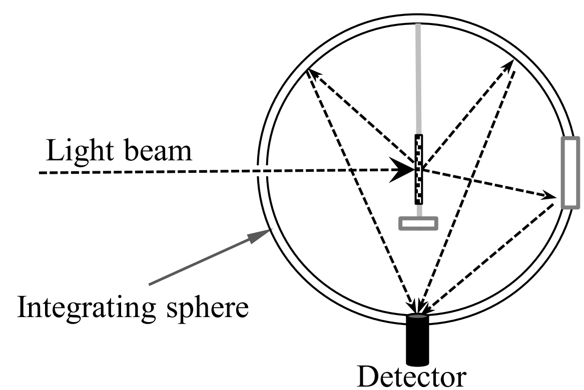


Wave focusing of sunlight

Near-surface light field



Light absorption by particles



What is ocean optics?

In principle it sounds straightforward, but in reality it's not…

Seawater is a highly complex medium containing a “witch's brew” of dissolved substances and suspended particles which strongly alter its optical properties and light propagation.

Microscopic particles

Ocean optics is a strongly interdisciplinary science combining physics, biology, chemistry, geology, and atmospheric sciences.

What is light?

"Every physicist thinks he knows what a photon is. I spent my life to find out what a photon is and I still don't know it"

"Physics should be made as simple as possible, but no simpler"

- Albert Einstein

A Brief History of Light

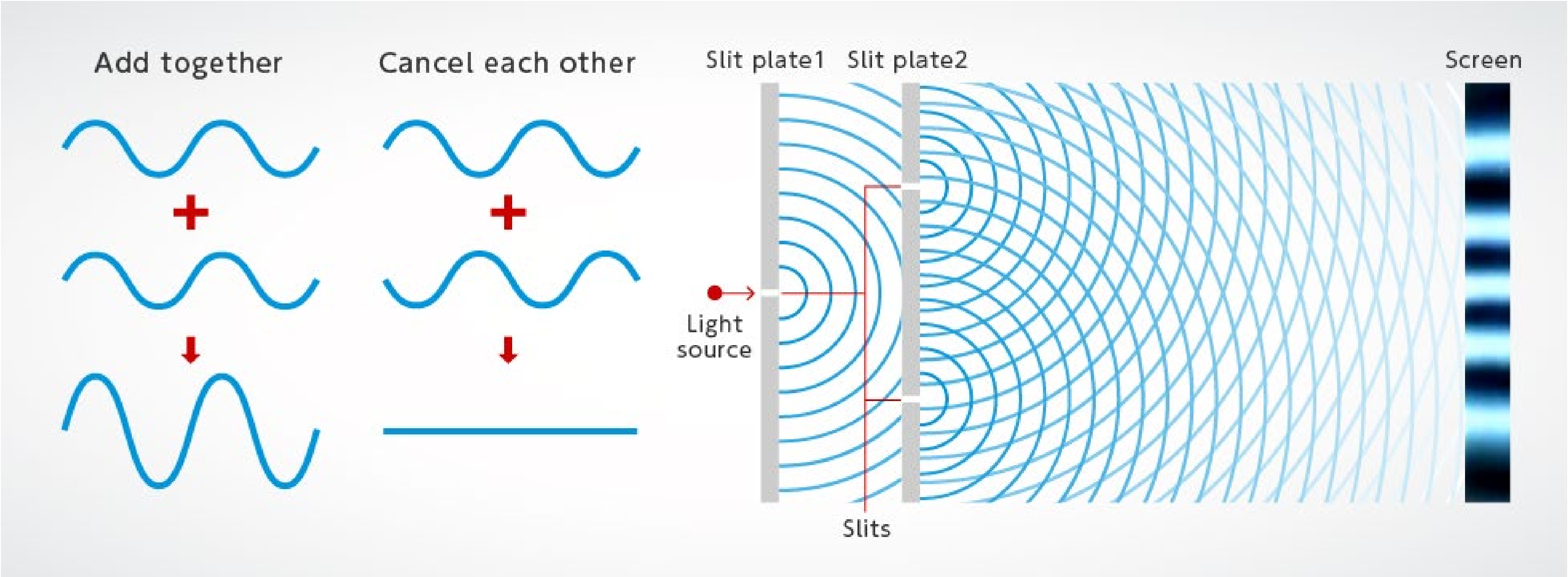
Is light a particle, a wave, both, or neither?

- ancient Greece, Democritus: Everything is made of particles (atoms)
- ~1000, Alhazen (Hasan Ibn al-Haytham): light is rays of particles
- 1630s, Descartes: light is waves
- 1670s, Newton: light is particles ("corpuscles")
- same time: Hooke, Huygens: light is waves
- early 1800s Young, Fresnel: light is waves (double slit interference, diffraction)
- late 1800s, Maxwell: light is propagating electric and magnetic fields; a wave
- 1900: Planck, emission of light is quantized (black body radiation)
- 1905: Einstein: light is absorbed as discrete quanta (photolectric effect)
- early-mid 1900's: quantum mechanics: both light and matter have both particle and wave properties ("wave-particle duality")
- Compton: X-rays scattered from electrons can be explained by a particle nature of X-rays, but not a wave theory
- 1926: Lewis (physical chemist) coined the term "photon" for the smallest unit of radiant energy
- mid-late 1900s: quantum electrodynamics (QED): light is photon "particles", but the photons cannot be localized; they take all possible paths from source to detector; they fill all of space between the source and detector, a single photon can interfere with itself (single-photon double-slit experiment)
- today, elementary particle theory: everything is particles, but all particles have wave properties

C. Mobley, Ocean Optics Web Book

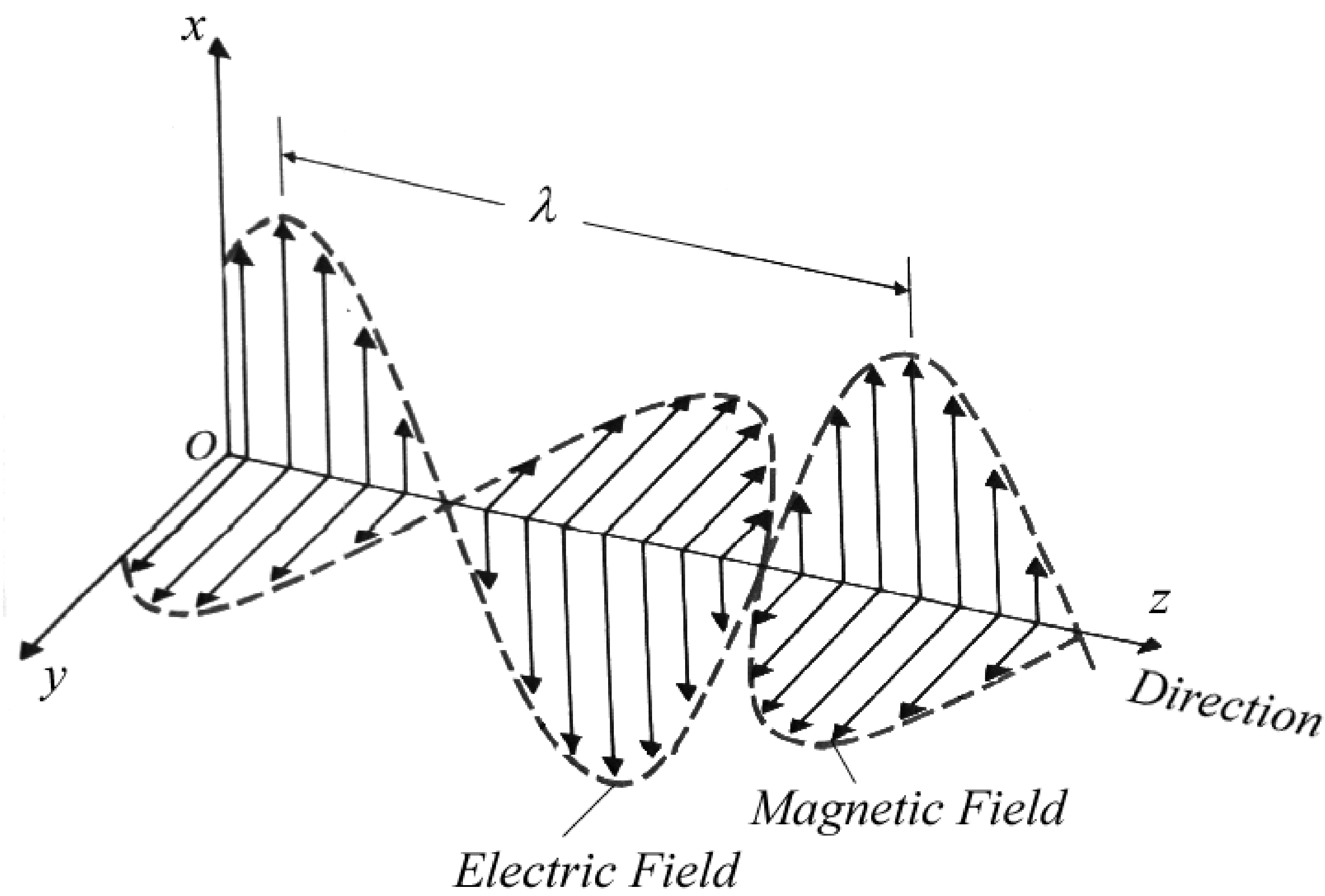
Thomas Young
(1773 - 1829)

In 1801, an English physicist Thomas Young asserted that light has the properties of a wave in an experiment called **Young's (Double-Slit) Interference Experiment**. This experiment showed that light beams (waves) passing through two slits (double-slit) add together or cancel each other and then interference fringes appear on the screen. This phenomenon can be explained if light is considered as a wave.

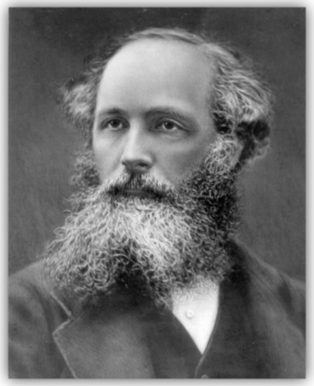


Electromagnetic wave

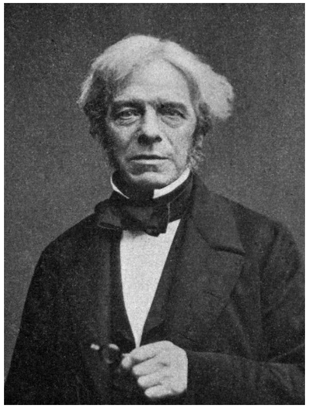
Time-varying electric and magnetic fields are coupled in an electromagnetic field radiating from the source



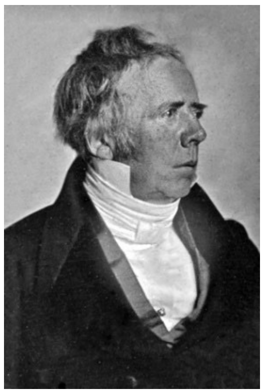
Maxwell equations:
How is an electromagnetic field produced?



James Clerk Maxwell
(1831 - 1879)



Michael Faraday
(1791 - 1867)



Hans Christian Ørsted
(1777 - 1851)

André-Marie Ampère
(1775 - 1836)

Johann Carl Friedrich Gauss
(1777 - 1855)

Electric fields are generated by:

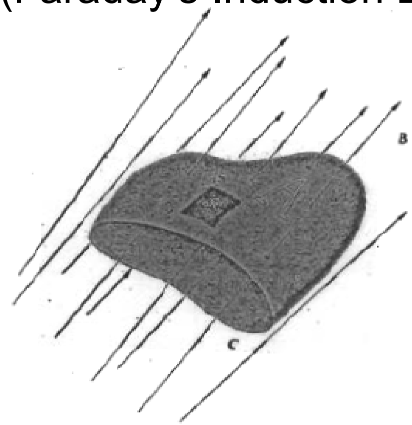
- Electric charges
- Time-varying magnetic fields

Magnetic fields are generated by:

- Charges in motion (electric currents)
- Time-varying electric fields

$\vec{B}$-field through an open area

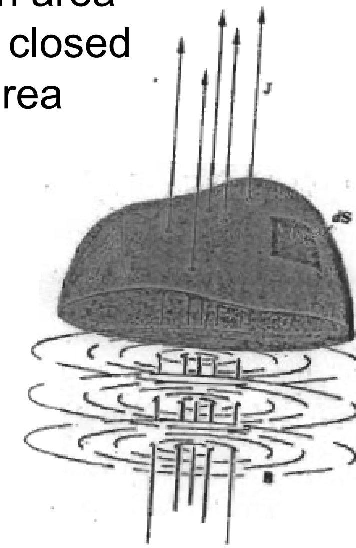
Time-varying magnetic field has an electric field associated with it (Faraday's Induction Law)



Current area density through an open area

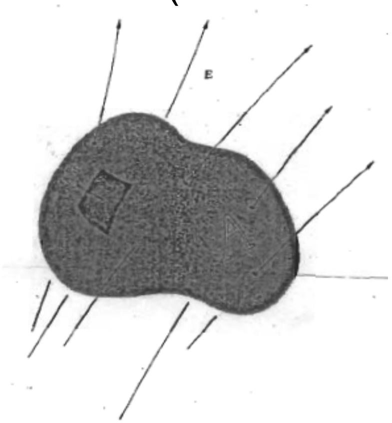
Current passing through an open area generates magnetic field along a closed curve that bounds the open area (Ampère's Circuital Law)

Moving charges are not the only source of magnetic field. Time-varying electric field is accompanied by a magnetic field (Maxwell's contribution)



$\vec{E}$-field through a closed area

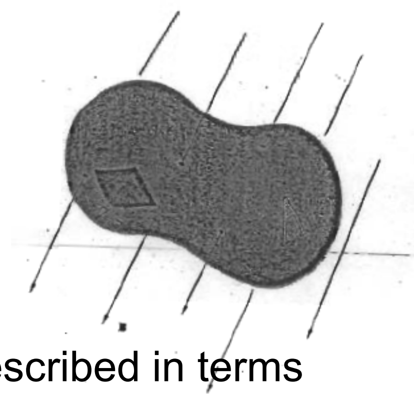
The net flux of electric field through a closed area is related to the total enclosed charge that consists of sources (+) and sinks (-) of electric field (Gauss's Law-Electric)



$\vec{B}$-field through a closed area

The net flux of magnetic field through a closed area is zero (Gauss's Law-Magnetic)

No isolated magnetic monopoles (sources or sinks of magnetic field) exist within the enclosed volume and they have never been found.



Magnetic fields can be described in terms of current distributions.

• From Maxwell's equations in differential form in free space (vacuum) we obtain

$$\nabla^2 \vec{E} = \mu_0 \epsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2}$$

$$\nabla^2 \vec{B} = \mu_0 \epsilon_0 \frac{\partial^2 \vec{B}}{\partial t^2}$$

where $\nabla^2 \equiv \nabla \cdot \nabla$ is the scalar operator known as Laplacian

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

• Example of one of six scalar equations

$$\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} = \epsilon_0 \mu_0 \frac{\partial^2 E_x}{\partial t^2}$$

• Wave equation if

$$\epsilon_0 \mu_0 = \frac{1}{c^2}$$

Inserting the experimentally determined values of ε_o and μ_o into $\varepsilon_o \mu_o = 1/c^2$ gives $c = 3 \times 10^8$ ms^{-1} which is the speed of light.

Maxwell observed (*A Dynamical Theory of the Electromagnetic Field*, 1864, §20):

"This velocity is so nearly that of light that it seems we have strong reason to conclude that light itself (including radiant heat and other radiations) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws."

This conclusion is one of the greatest intellectual achievements of all time: not only were electric and magnetic fields tied together in Maxwell's equations, but light itself was shown to be an electromagnetic phenomenon.

Poynting Vector

Energy transported by electromagnetic wave per unit time per unit area

- Poynting vector at time instant t

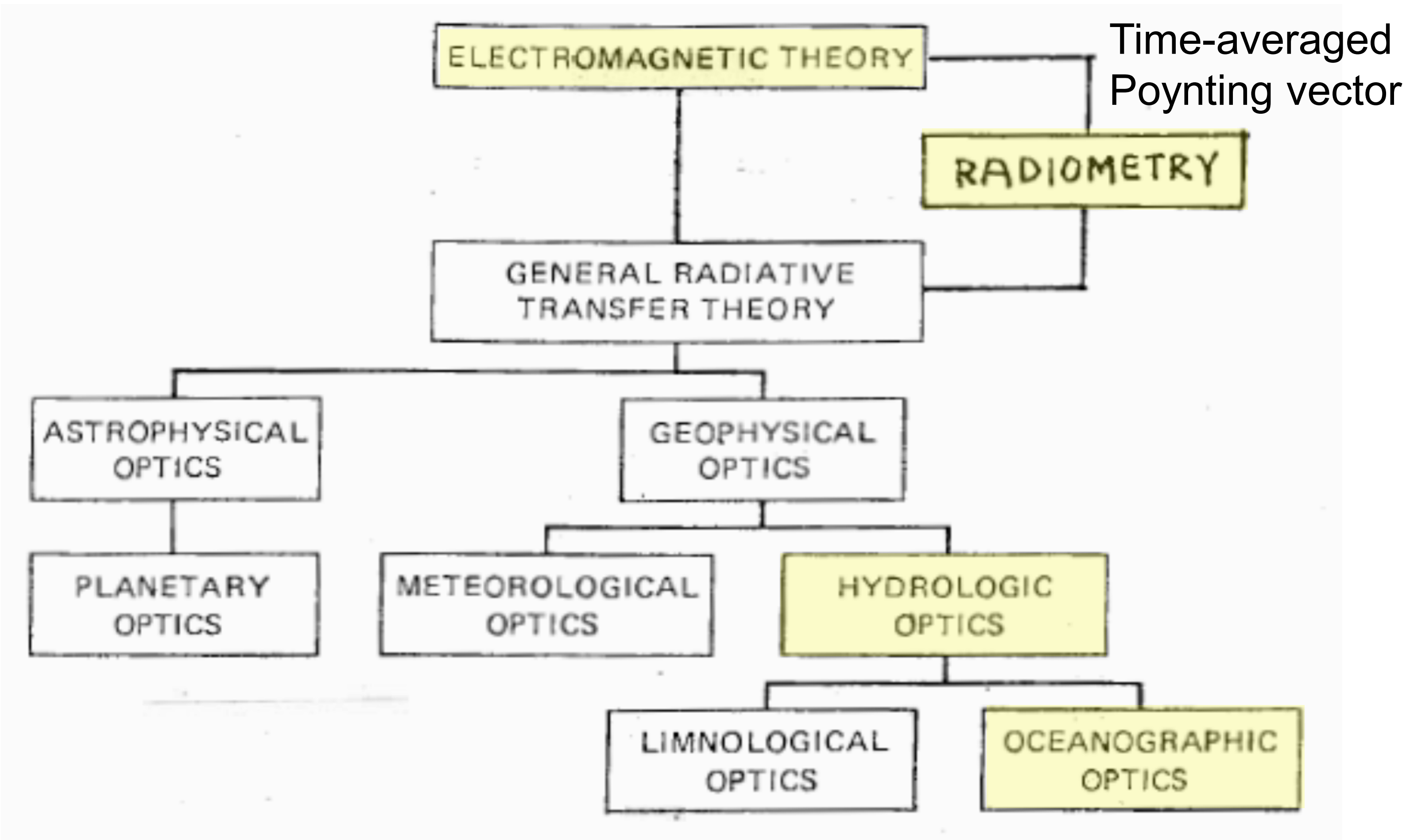
$$\vec{S}(t) = \frac{1}{\mu_0}\vec{E}(t) \times \vec{B}(t) = c^2 \epsilon_0 \vec{E}(t) \times \vec{B}(t)$$

- Time-average magnitude of $\vec{S}(t)$ is

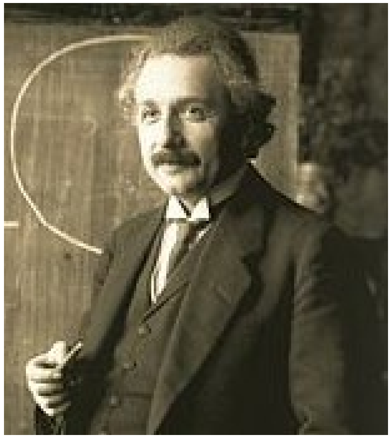
$$\langle S \rangle_T = \frac{c^2 \epsilon_0}{2} \left| \vec{E}_0 \times \vec{B}_0 \right| = \frac{c\,\epsilon_0}{2} E_0^2$$

squared amplitude of electric field

The bridge between ocean optics and classical electromagnetic theory in physics



(Preisendorfer 1976)

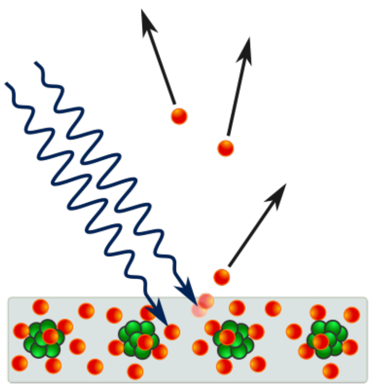


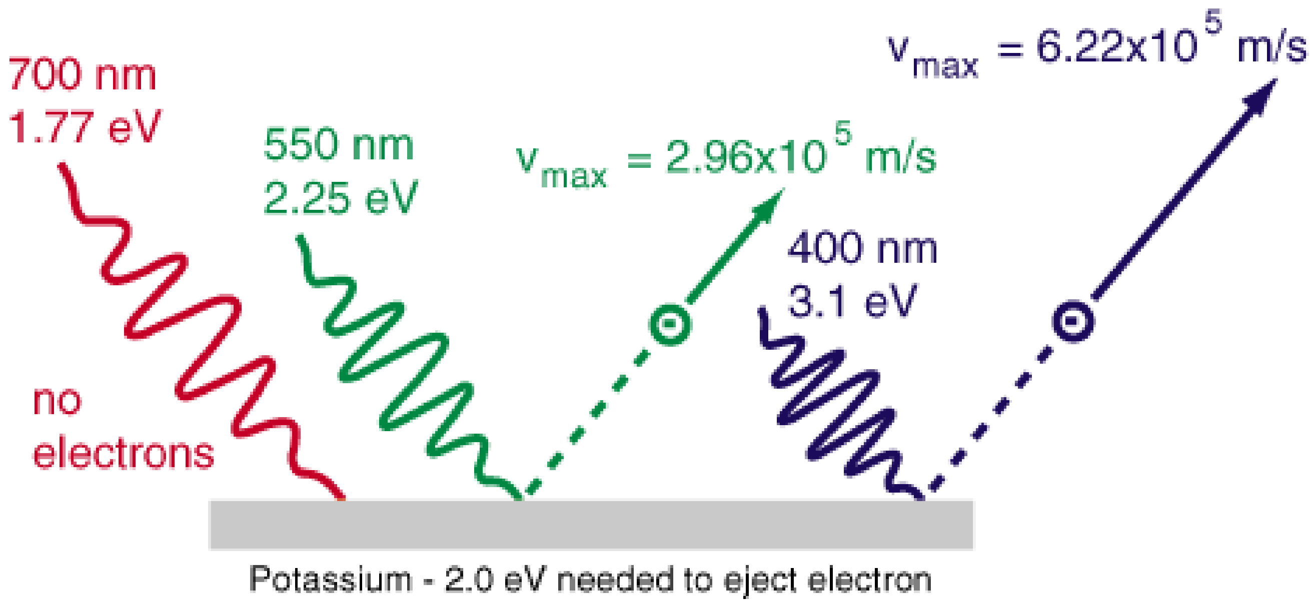
Albert Einstein (1879 - 1955)
Nobel Prize 1921

On a Heuristic Viewpoint Concerning the Production and Transformation of Light, *Annalen der Physik,* ***17*** *(6), 132–148 (1905).*

One of four Einstein's *Annus Mirabilis* (Miracle Year) papers published in 1905.

$$E_{photon} = h\nu$$





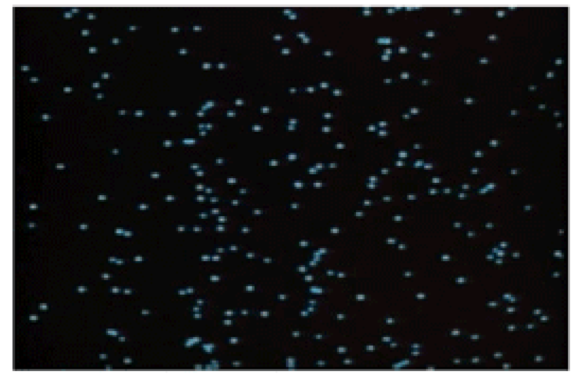
Photoelectric effect

$$1 \text{ ev (electronvolt)} = 1.602176634\times10^{-19} \text{ J}$$

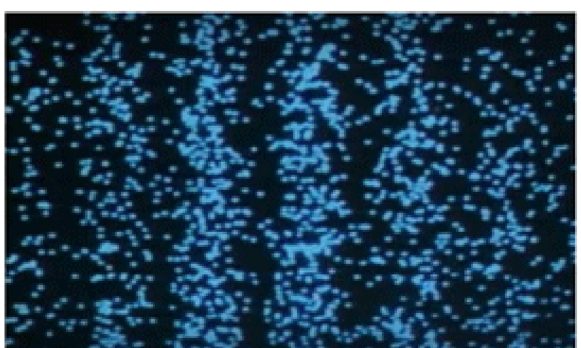
THE FUNDAMENTAL MYSTERY:
Single-photon interference in a double-slit experiment

Young's Interference Experiment or Double-slit Interference Experiment carried out using technology to detect individual light particles to investigate whether interference fringes appear even if the light is drastically weakened to the level having only one particle. Results from the experiment confirmed that one photon exhibited an interference fringe pattern (Hamamatsu Photonics, 1981).

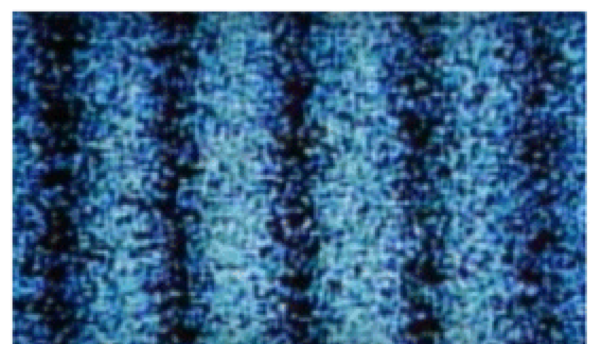
(a) t = 3 min



(b) a few minutes later

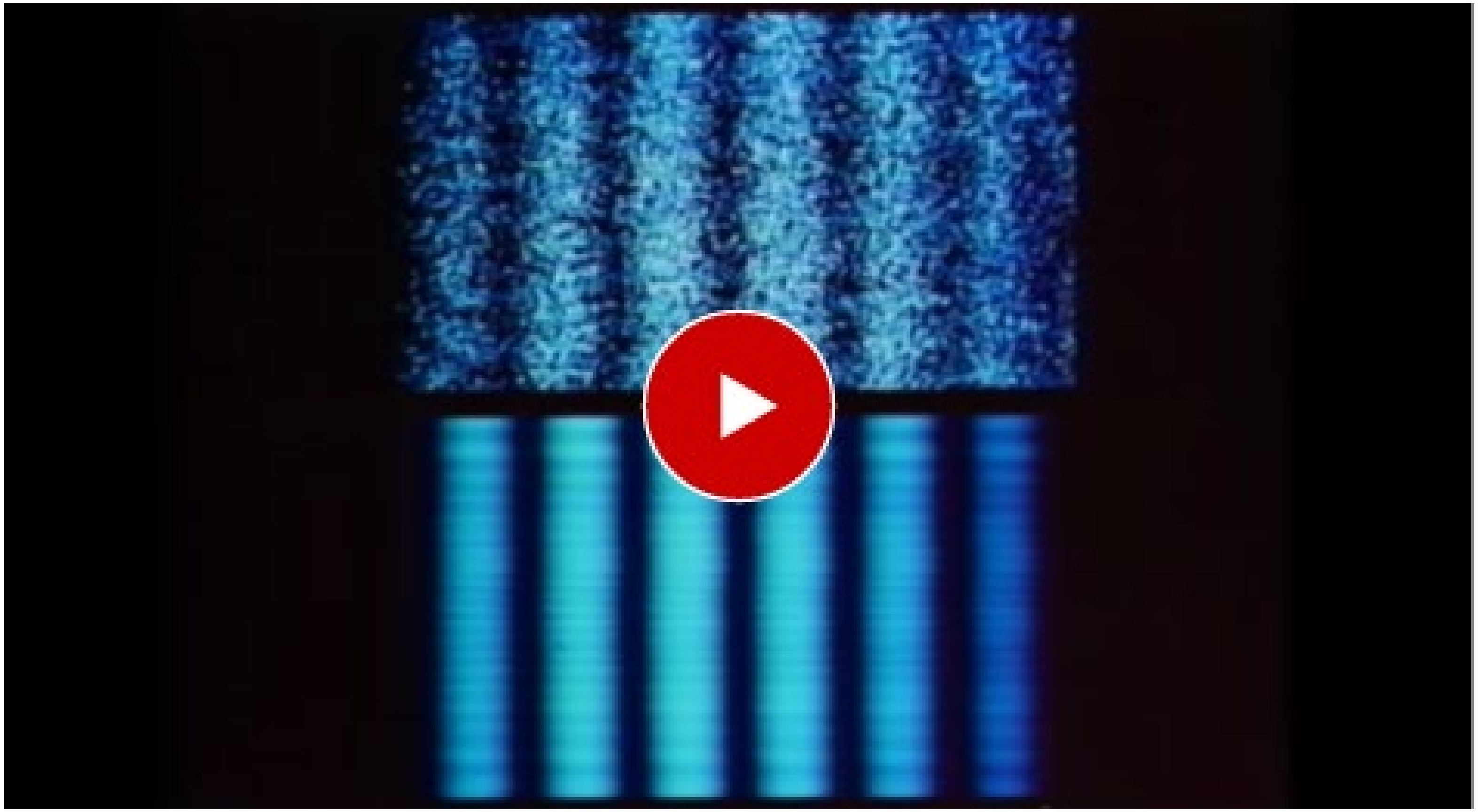


(c) t = 25 min



(d) t = 6 hours

Young's Double-Slit Interference Experiment with Single Photons (top)



Young's Interference Experiment with a very large number of photons (bottom)

http://photonterrace.net/en/photon/duality/

Watch the video at https://www.youtube.com/watch?v=I9Ab8BLW3kA

This experiment captured the dual nature of photon by a special camera for the first time ever.

Thinking About Light

- "Particle" and "wave" are idealized physics models for nature, but light is more complicated and behaves very strangely by human terms.

- "Position" and "time" and "path" are not defined and have no meaning for photons. Photons cannot be "localized" like electrons or other particles with a non-zero rest mass.

- Most physicists seem to regard photons as real, but they are careful not to view them as classical particles or waves. They have features of both, depending on what is measured, but they are neither.

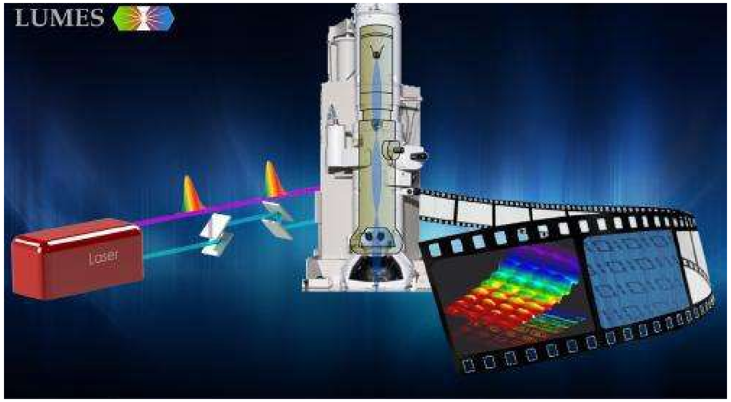
- You can say a photon was created at point A (e.g, emitted by an atom in a light bulb filament) and that it was absorbed at point B (e.g., in a particular pixel of a CCD array), but you can say nothing about how it got from A to B, e.g., all possible paths from A to B vs. filling all of space between A and B. Either way, the photon can pass through both slits of an interference filter and interferes with itself, and creates an interference pattern.

But…remember that much of what is said about photons on websites and even in some physics textbooks (and here!) is overly simplified, outdated, or just simply wrong.

Photons are defined by what they *do*, not by what they *are* !

The first ever photograph of light as both a particle and wave

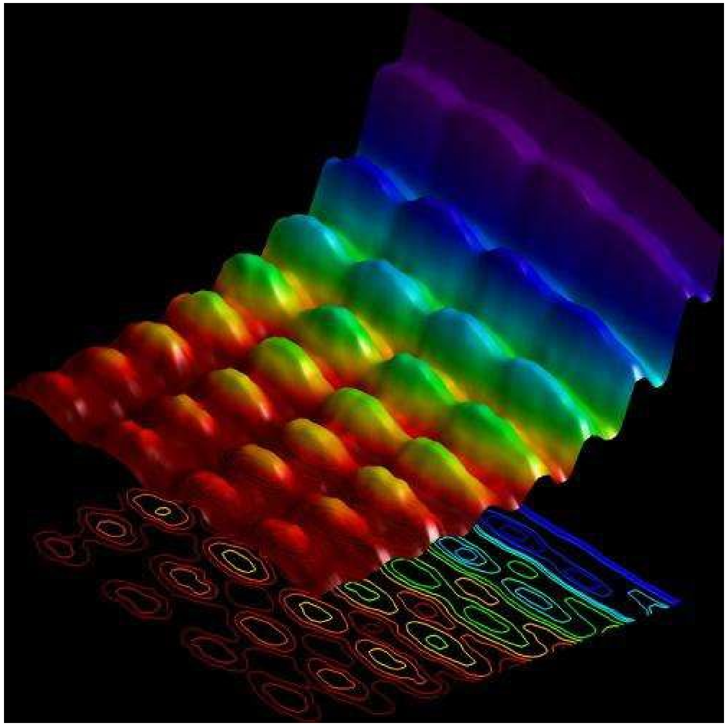
by Ecole Polytechnique Federale de Lausanne



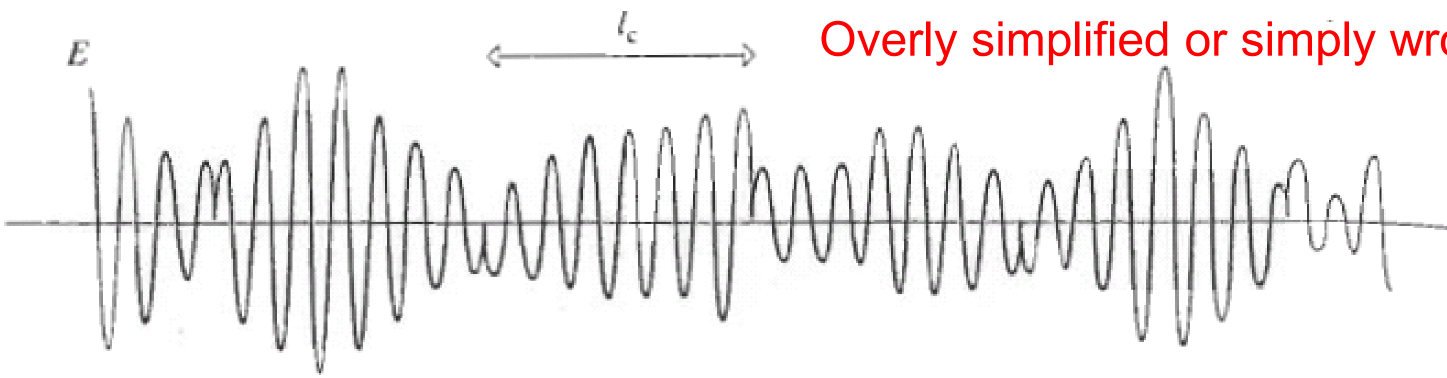
While many experiments have successfully observed both the particle- and wave-like behaviors of light, they have never been able to observe both at the same time.

Watch the video at:
https://phys.org/news/2015-03-particle.html

Published in *Nature Communications 6,* Article number 6407, 02 March 2015
DOI: 10.1038/ncomms7407



Electromagnetic radiation: A mix of photon particles with wave properties



Overly simplified or simply wrong!

What we need to know about photons is that the photon is a quantum of electromagnetic radiation (field) with energy q related to its frequency f (or ν) and wavelength λ :

$$q = \mathrm{h}\, f = \mathrm{h\,c} / \lambda$$

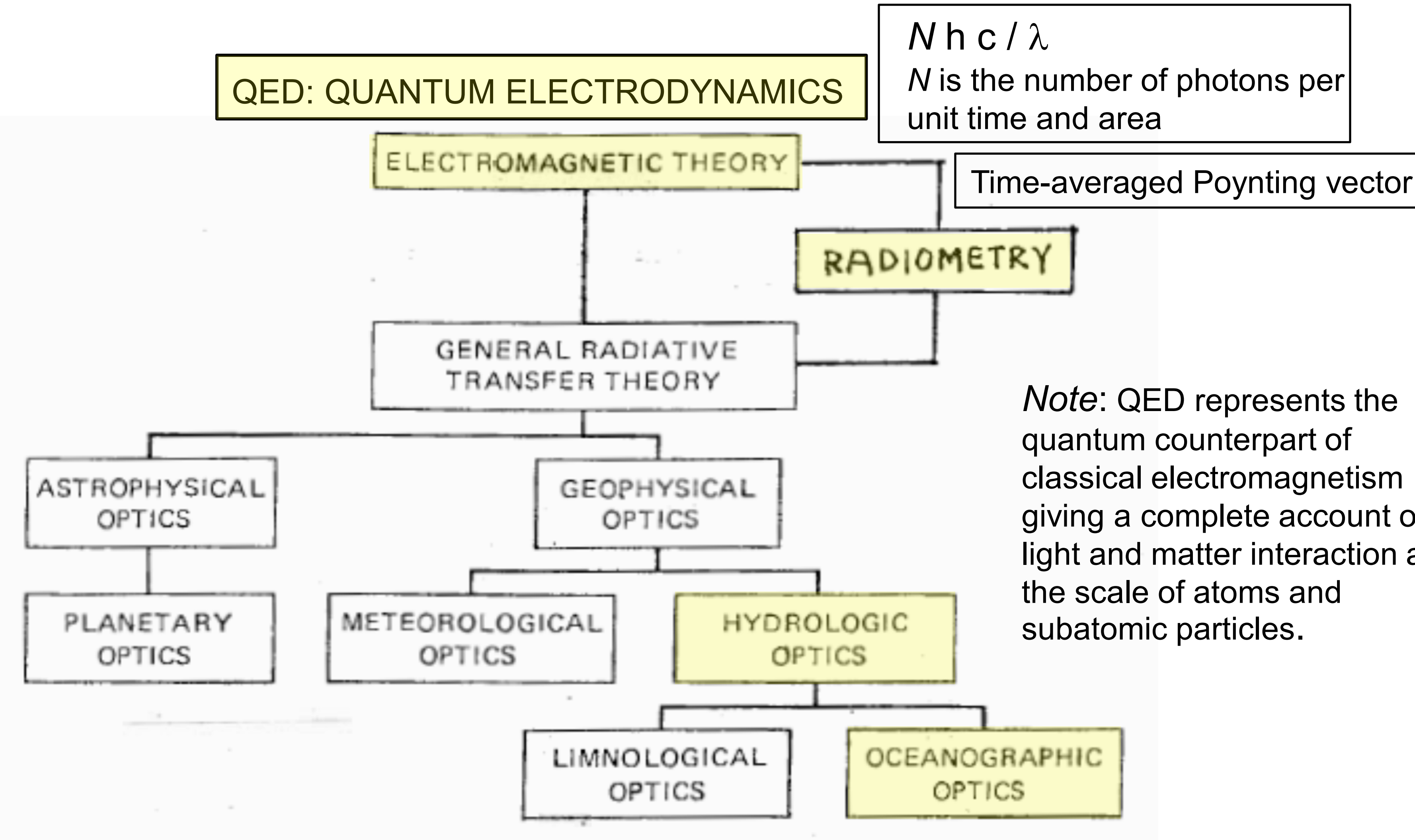
where h = 6.626 x 10^{-34} J s is Planck's constant and c = 2.998 x 10^{8} m s^{-1} is the speed of photons (phase velocity) in free space.

The speed of photons (phase velocity) in water is $v_w = c / n_w$
where n_w is refractive index of water $n_w = c / v_w$ (n_w is approximately 1.34 in the visible spectrum)

The energy q_w of photon in water is:

$$q_w = q = \mathrm{h}\, f = \mathrm{h}\, v_w / \lambda_w \quad \text{where } \lambda_w = \lambda / n_w$$

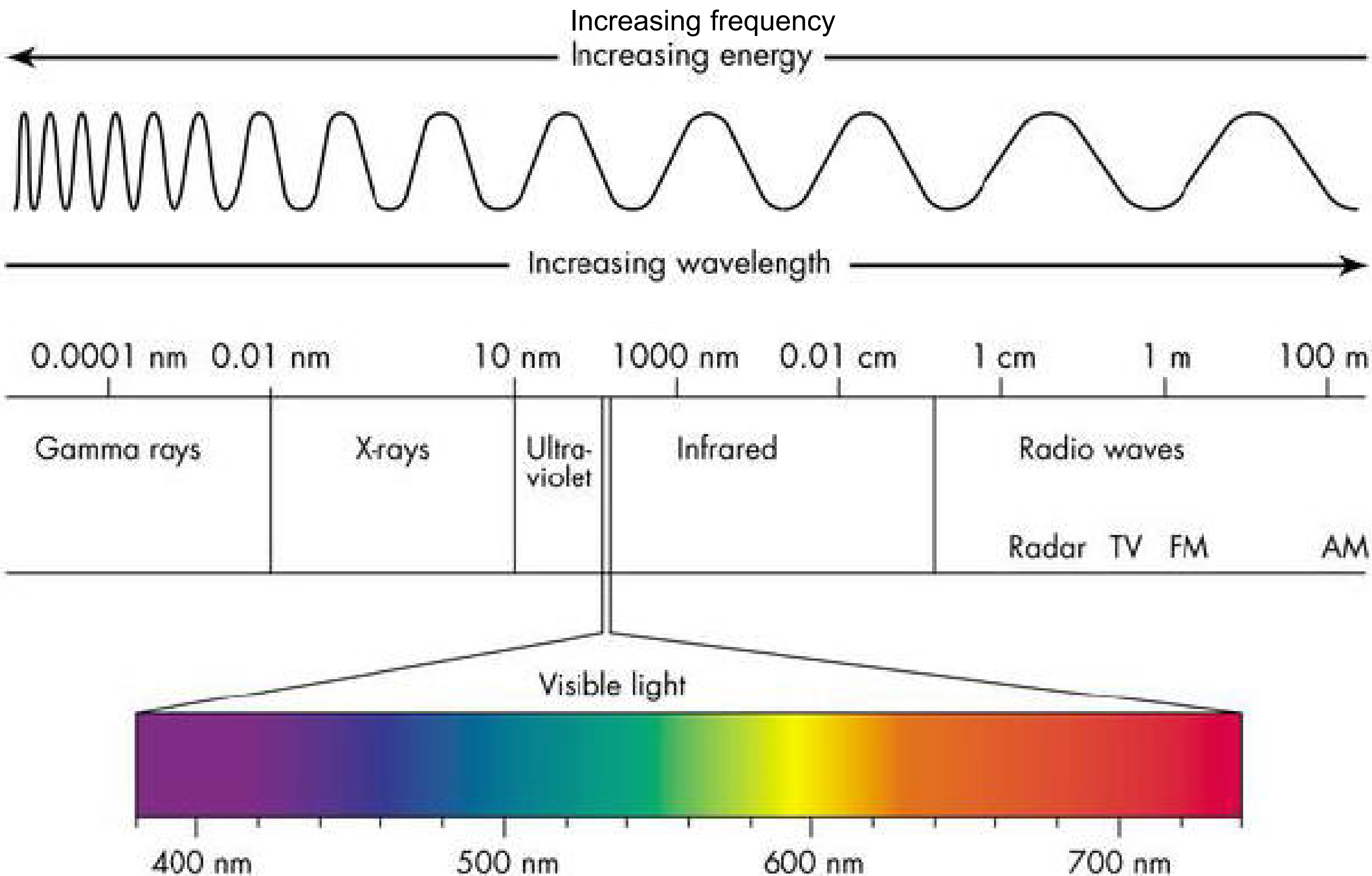
The bridge between ocean optics and classical electromagnetic and quantum electrodynamic theories in physics



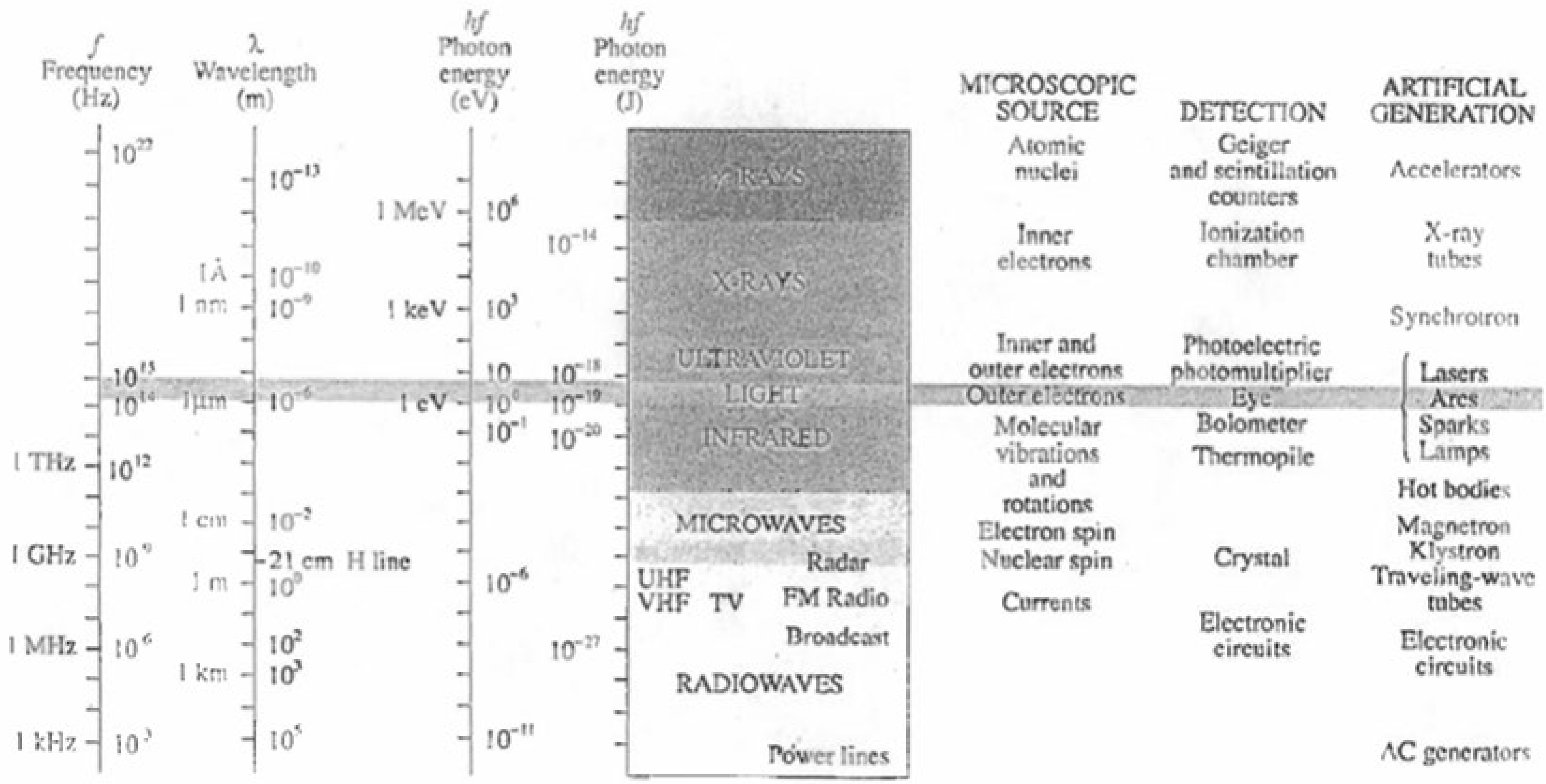
Note: QED represents the quantum counterpart of classical electromagnetism giving a complete account of light and matter interaction at the scale of atoms and subatomic particles.

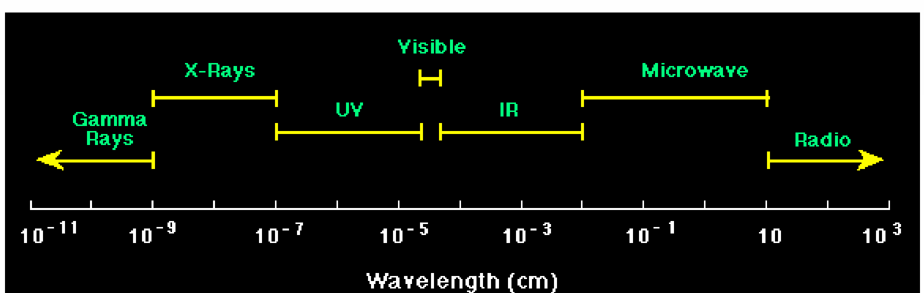
(Preisendorfer 1976)

The Electromagnetic-Photon Spectrum



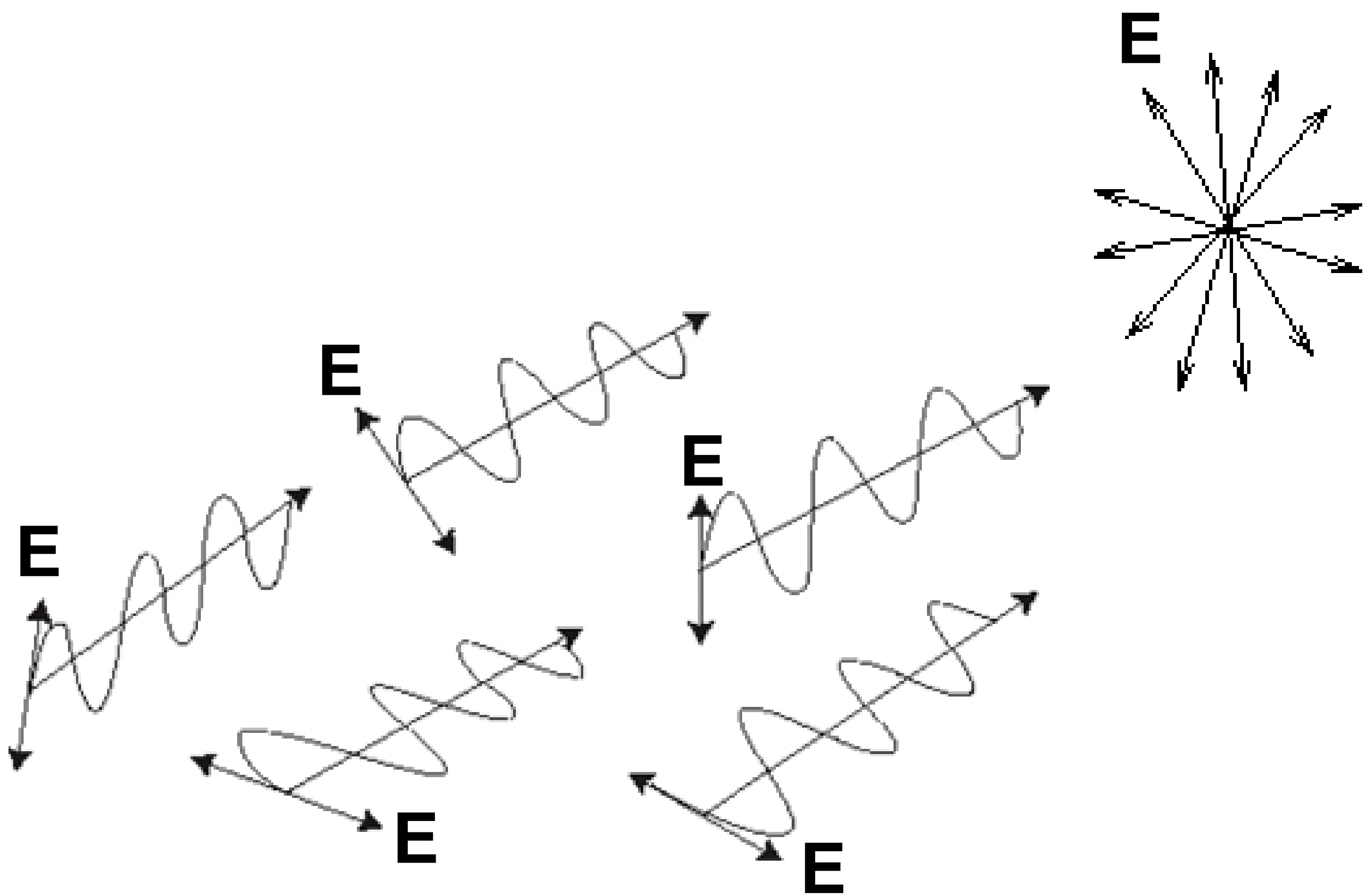
The electromagnetic-photon spectrum





(Hecht 1994)

Randomly polarized (unpolarized) light is a jumble of random, rapidly changing **E**-fields



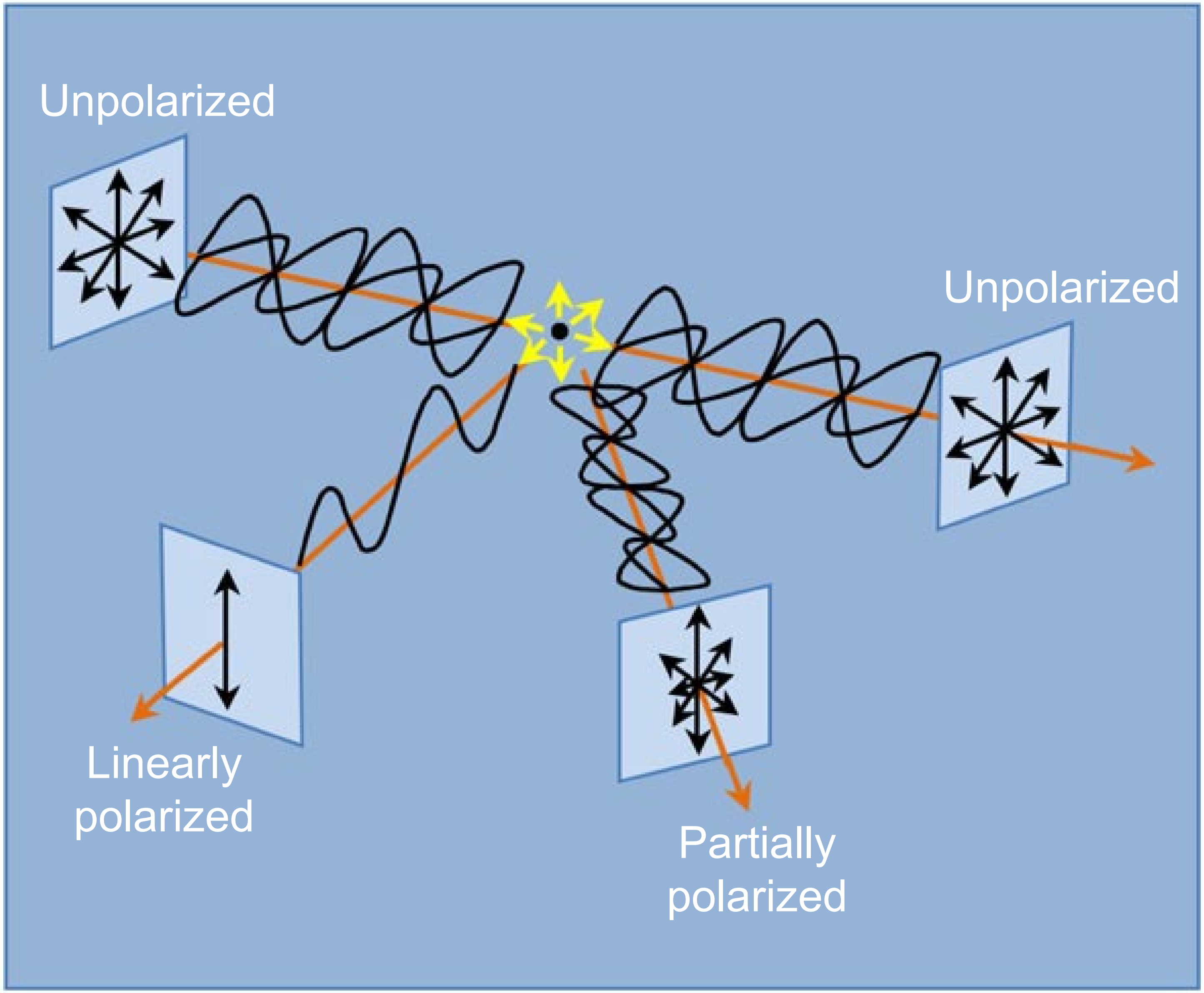
Polarization by transmission (polarizing filters)

Relationship Between Long-Chain Molecule Orientation and the Orientation of the Polarization Axis

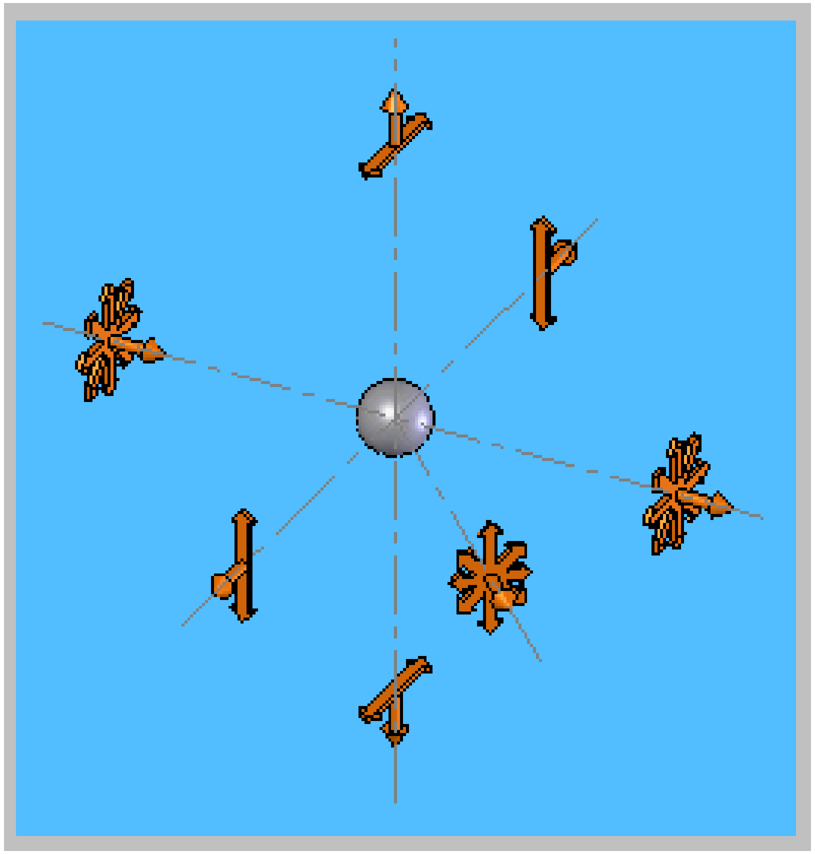
When molecules in the filter are aligned vertically, the polarization axis is horizontal.

When molecules in the filter are aligned horizontally, the polarization axis is vertical.

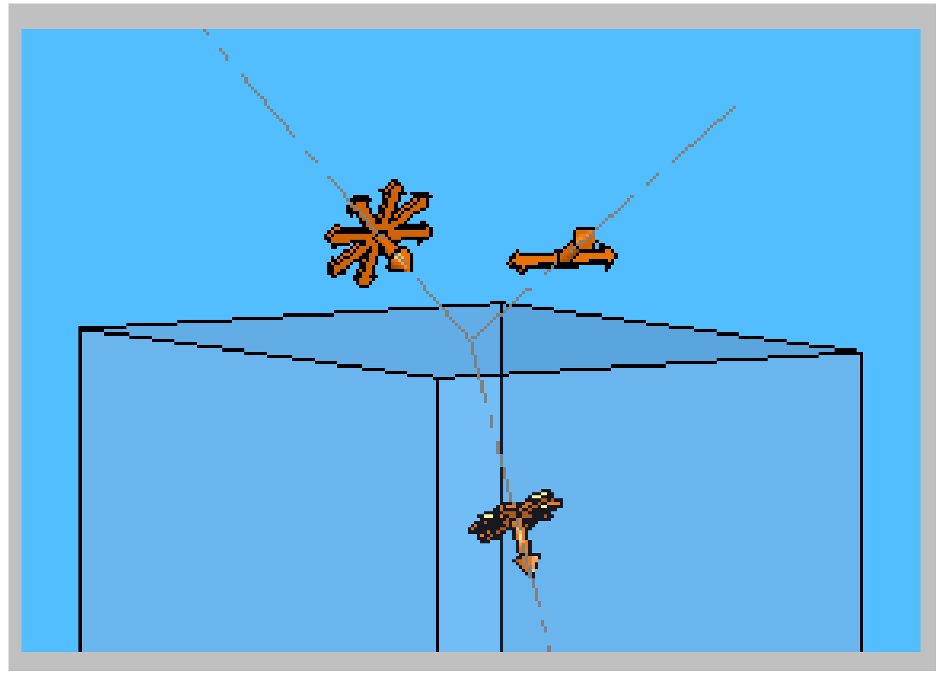
Polarization by scattering



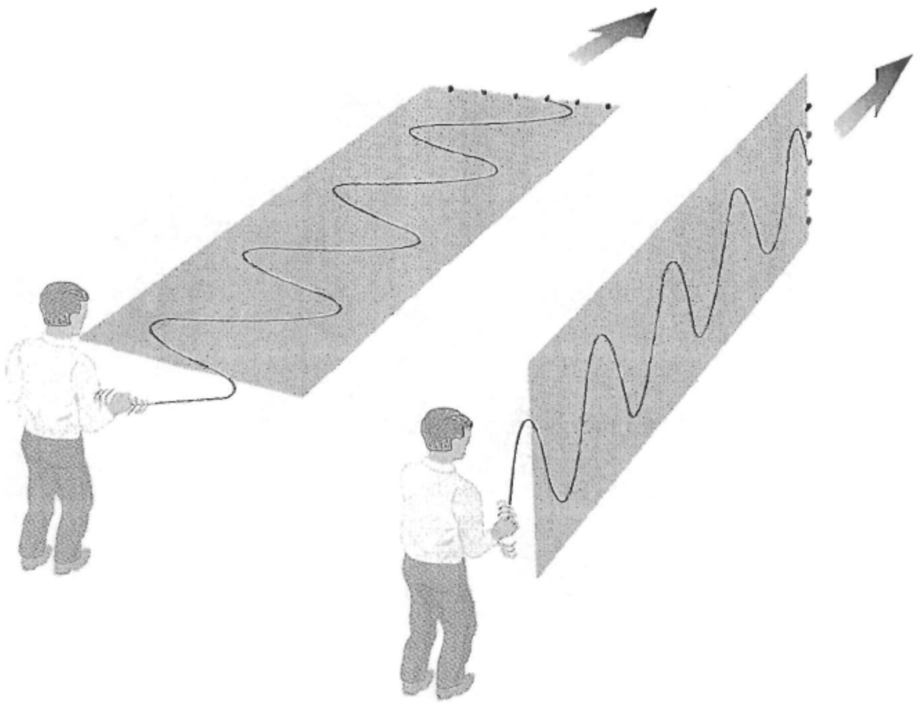
Polarization by scattering

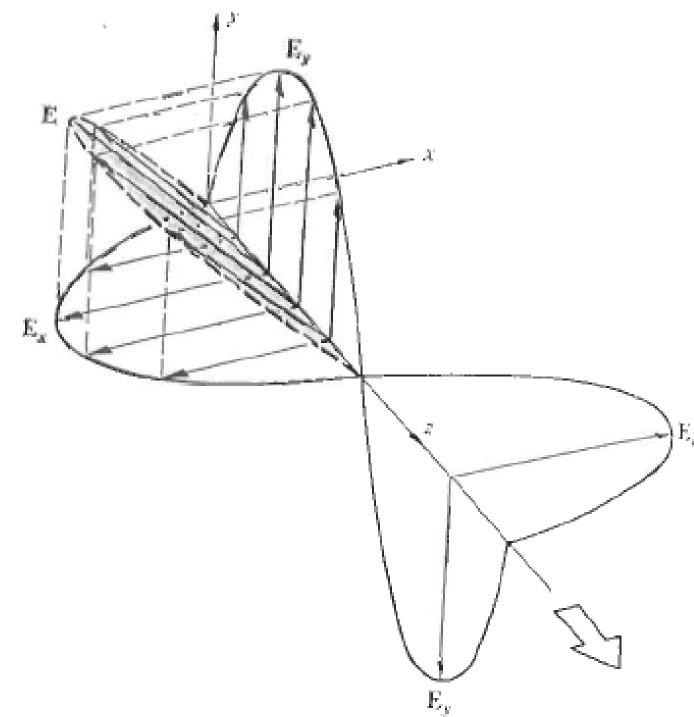


Polarization by reflection



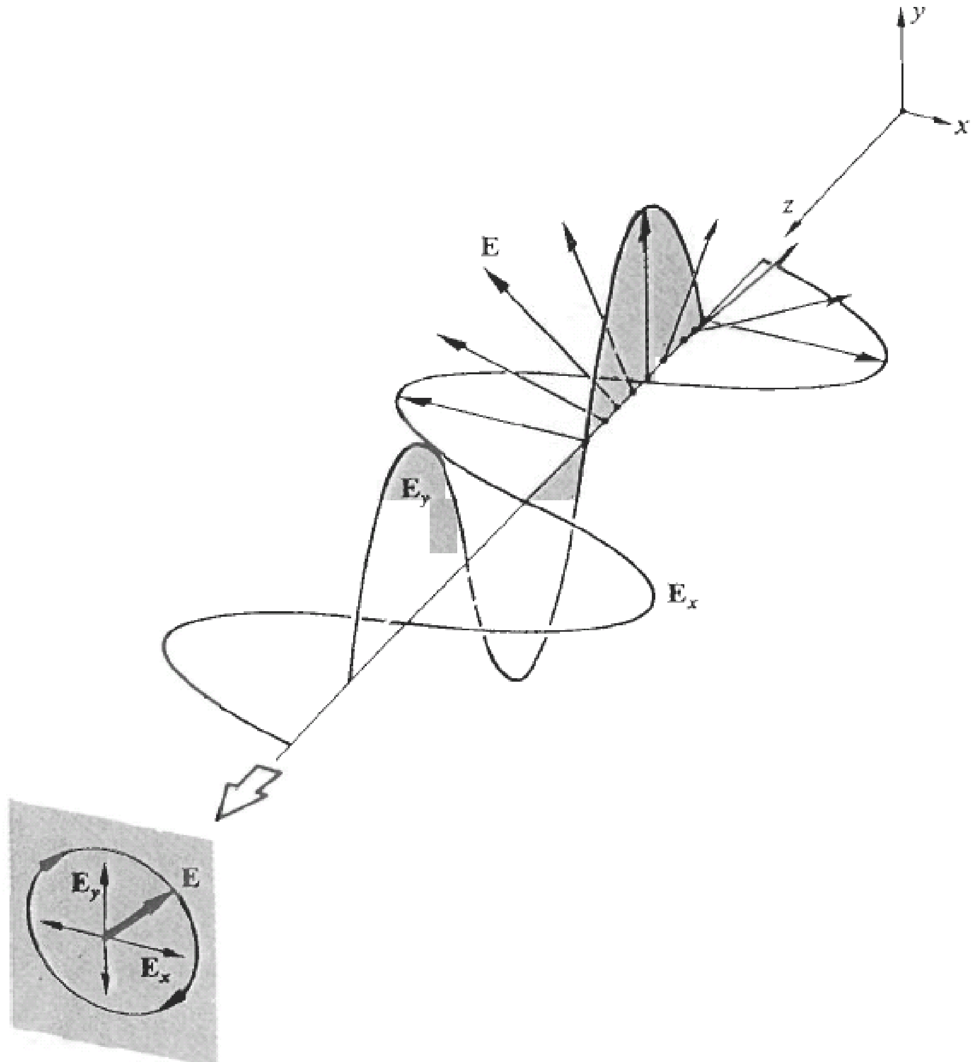
Plane-Polarized or Linearly-Polarized Light





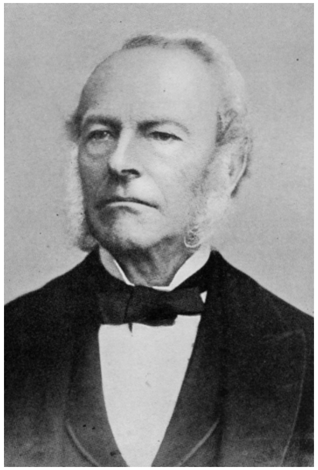
(Hecht 1998)

Right-circular light



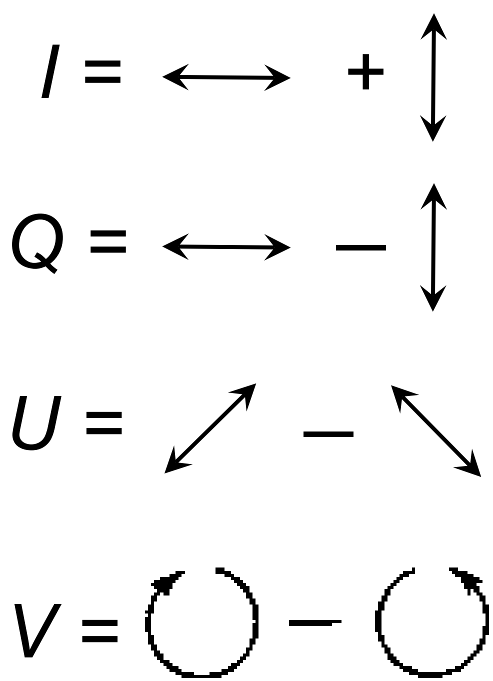
(Hecht 1998)

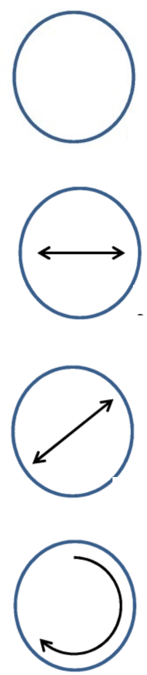
Stokes vector



George Gabriel Stokes
(1819 – 1903)

$$\vec{E}_x(z,t) = E_{0x}\hat{\imath}\cos(kz - \omega t)$$
$$\vec{E}_y(z,t) = E_{0y}\hat{\jmath}\cos(kz - \omega t + \xi)$$
$$S = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} \langle E_{0x}^2 \rangle + \langle E_{0y}^2 \rangle \\ \langle E_{0x}^2 \rangle - \langle E_{0y}^2 \rangle \\ \langle 2E_{0x}E_{0y}\cos\xi \rangle \\ \langle 2E_{0x}E_{0y}\sin\xi \rangle \end{pmatrix}$$





Unpolarized: transmits intensity of any incident light

transmits only horizontal light

transmits only linear light at 45º

transmits only R-polarized light

Degree of polarization

$$p = \frac{\sqrt{Q^2 + U^2 + V^2}}{I},$$

$$p_{\mathrm{lin}} = \frac{\sqrt{Q^2 + U^2}}{I},$$

$$p_{\mathrm{circ}} = \frac{V}{I}$$

Some Simple Stokes Vectors:

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} I \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Unpolarized light

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} I \\ I \\ 0 \\ 0 \end{bmatrix}$$

Polarized along *l*

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} I \\ -I \\ 0 \\ 0 \end{bmatrix}$$

Polarized along *r*

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} I \\ 0 \\ 0 \\ I \end{bmatrix}$$

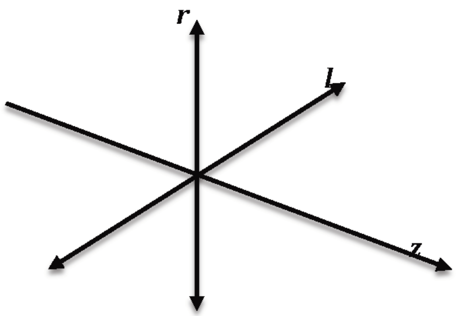
Right Circularly polarized light

$$I = I_l + I_r$$

$$Q = I_l - I_r$$

$$U = I_{45} - I_{-45}$$

$$V = I_{RCP} - I_{LCP}$$



Simplest light field: plane wave propagating in z-direction:

Let: $\delta = \delta_r - \delta_l$

$$E_l(z,t) = a_l \cos(\omega t - kz + \delta_l)$$

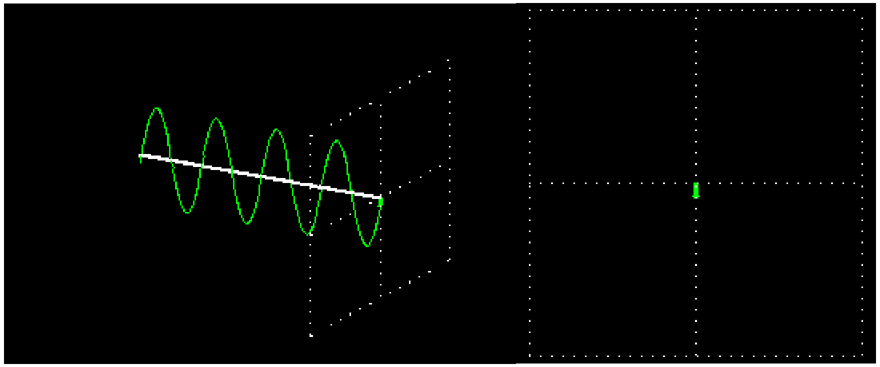
$$E_r(z,t) = a_r \cos(\omega t - kz + \delta_r)$$

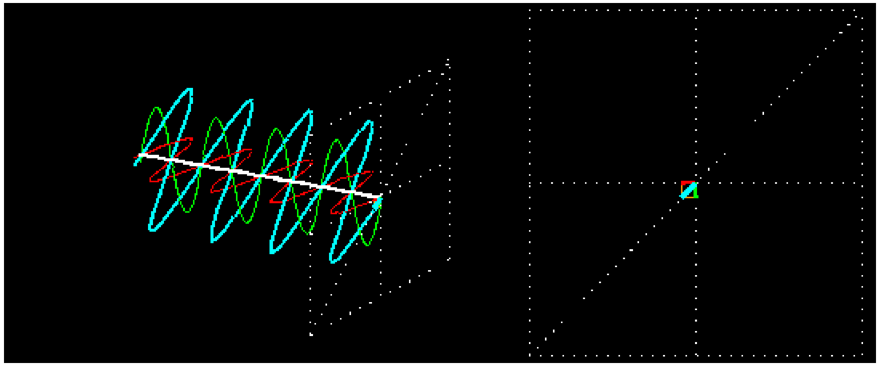
Some simple cases can be seen:
δ=0,(or a_l or a_r=0) light is linearly polarized
δ=π/2, a_l = a_r light is circularly polarized
Everything else is called elliptically polarized

EMANIM animates electromagnetic waves in vacuum and in matter

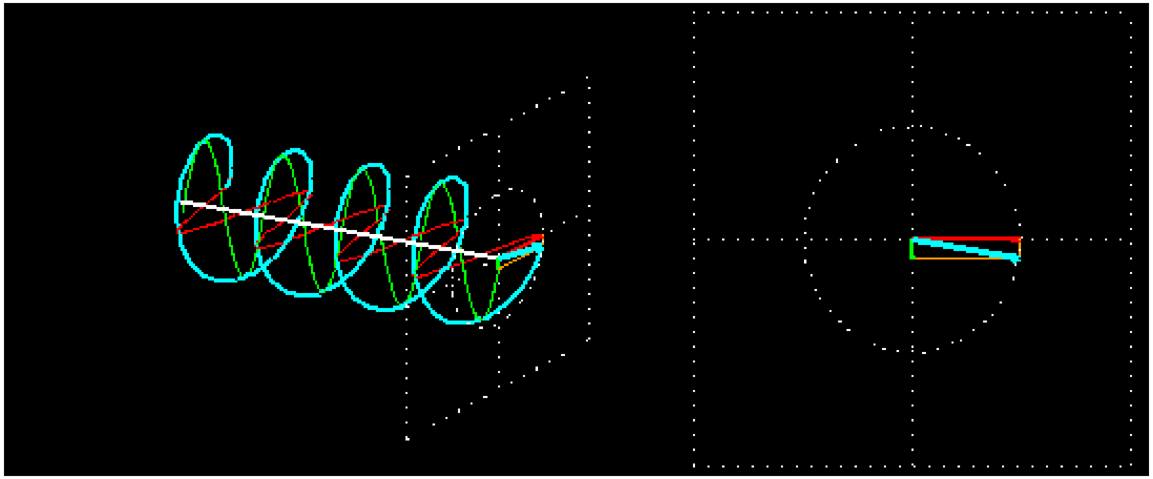
Go to: https://emanim.szialab.org/index.html

Linearly polarized light





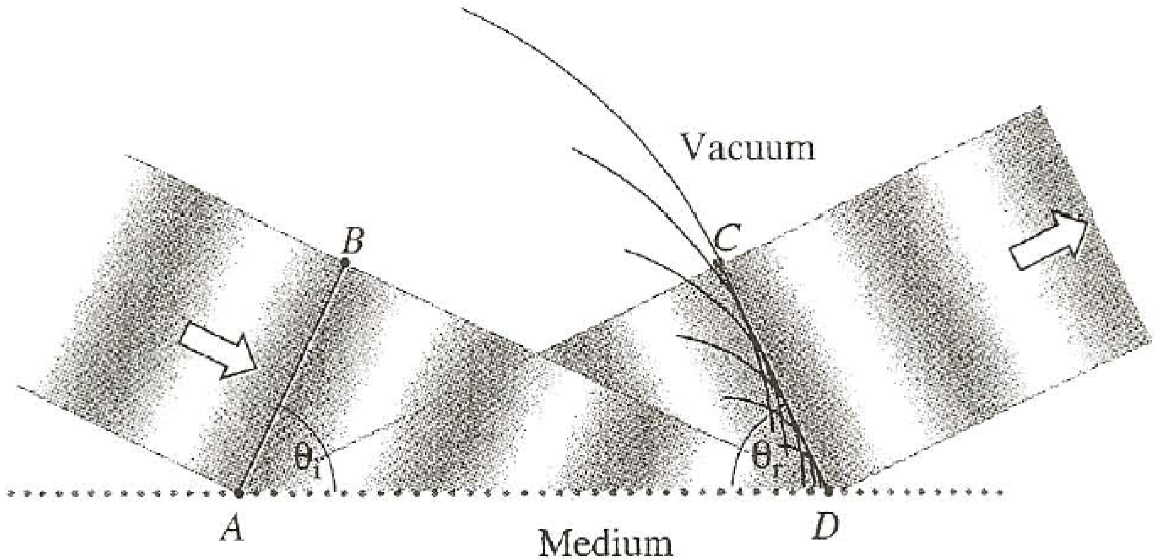
Right-circularly polarized light



We can think of waves and the overall pattern they produce (rather than being a *real* wave field) as a theoretical device that, wonderfully enough, tells us where the light will end up

Reflection at the boundary between the media of different densities (refractive index)

Christian Huygens
(1629 - 1695)

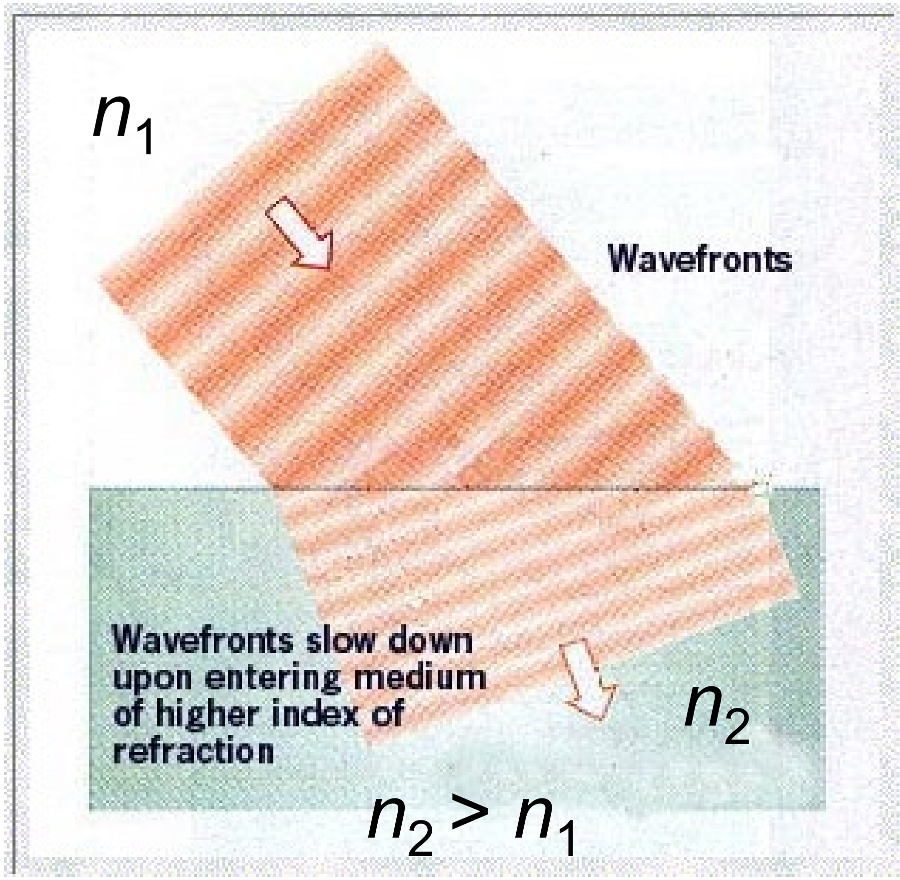


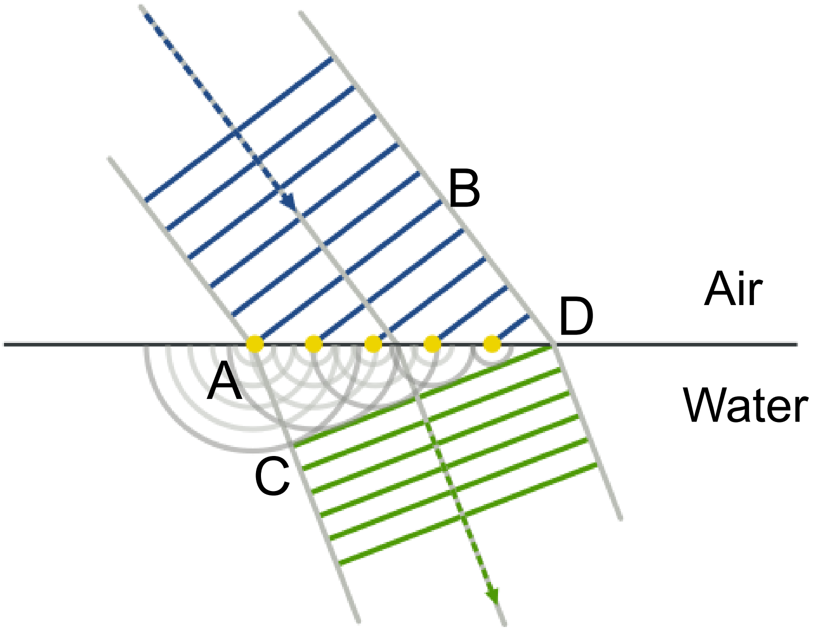
Wavefront geometry for reflection. The reflected wavefront $\overline{CD}$ is formed of waves scattered by the atoms on the surface from A to D. Just as the first wavelet arrives at C from A, the atom at D emits, and the wavefront along $\overline{CD}$ is completed.

Angle of incidence = Angle of reflection

Both angles measured between the direction of beam propagation and normal to the surface

Refraction



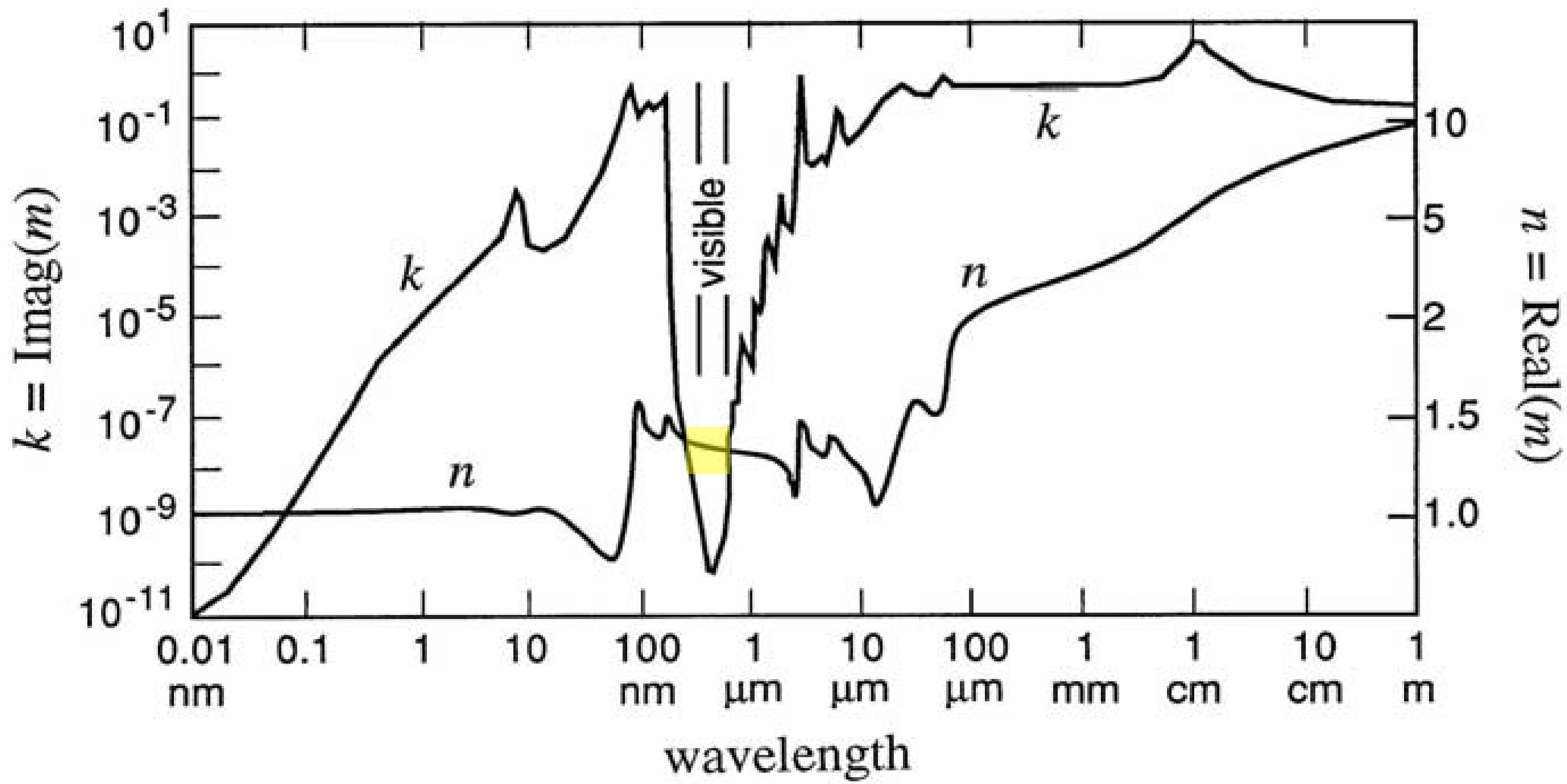


Snell's law

$$n_1 \sin(i) = n_2 \sin(r)$$

n_1 – refractive index of air (close to 1); n_2 – refractive index of water (close to 1.34);
i – angle of incidence; r – angle of refraction
Both angles measured between the direction of beam propagation and normal to the surface

Refractive Index of Water



(Mobley 1994)

Refractive index of water, *n*, for the extreme values of pressure *p*, temperature *T*, salinity *S*, and light wavelength λ encountered in hydrologic optics

The extreme values of *n* are 1.329128 and 1.366885, so *n* varies by less than 3% over the entire parameter range relevant to hydrologic optics

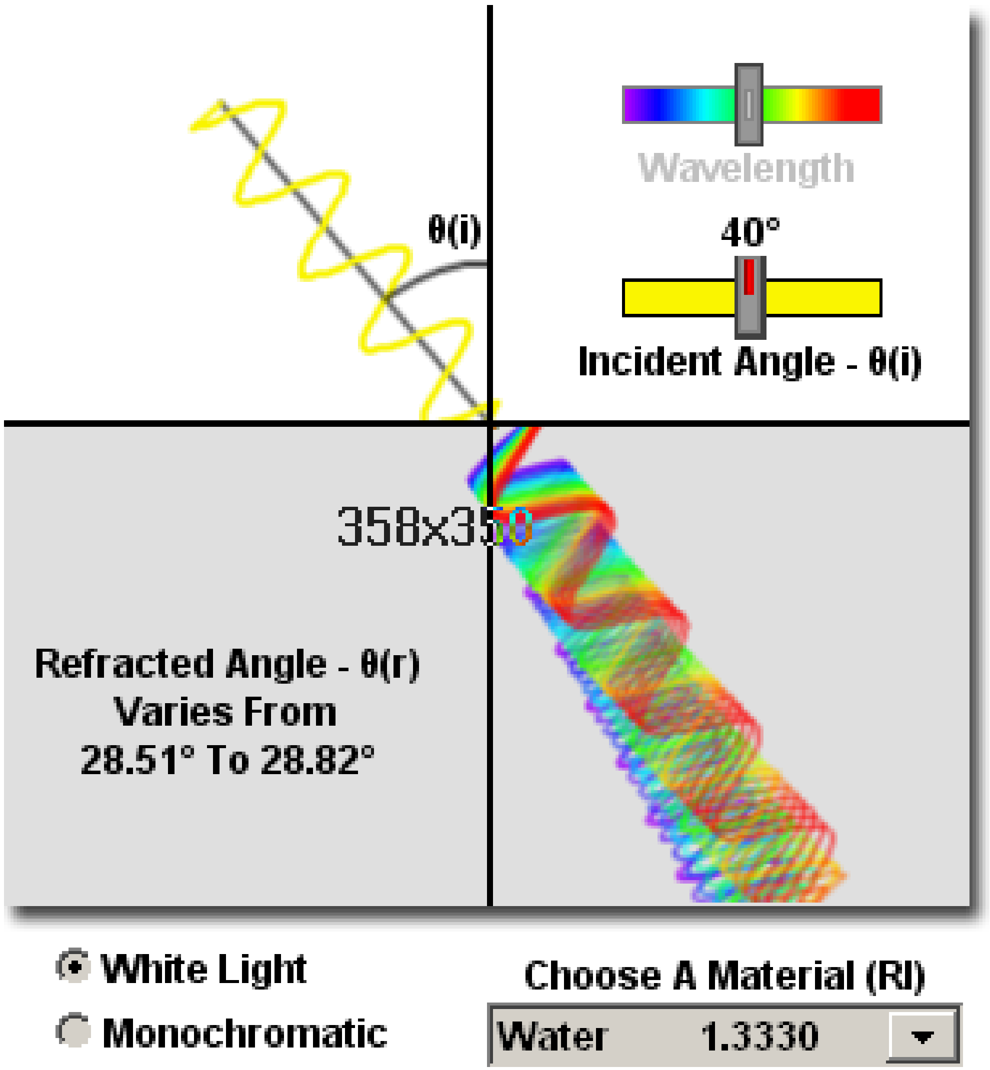
Typically, for most ocean optics applications the constant value of *n* = 1.34 is assumed. This value is very close to the mean value of the first 8 values in the table which correspond to pressure of 1 atm (approximately near-surface conditions)

p (Pa)	T (°C)	S (‰)	λ (nm)	n
1.01×10^5	0	0	400	1.344186
1.01	0	0	700	1.331084
1.01	0	35	400	1.351415
1.01	0	35	700	1.337906
1.01	30	0	400	1.342081
1.01	30	0	700	1.329128
1.01	30	35	400	1.348752
1.01	30	35	700	1.335316
1.08×10^8	0	0	400	1.360076
1.08	0	0	700	1.346604
1.08	0	35	400	1.366885
1.08	0	35	700	1.352956
1.08	30	0	400	1.356281
1.08	30	0	700	1.342958
1.08	30	35	400	1.362842
1.08	30	35	700	1.348986

[a] Reproduced from Austin and Halikas (1976).

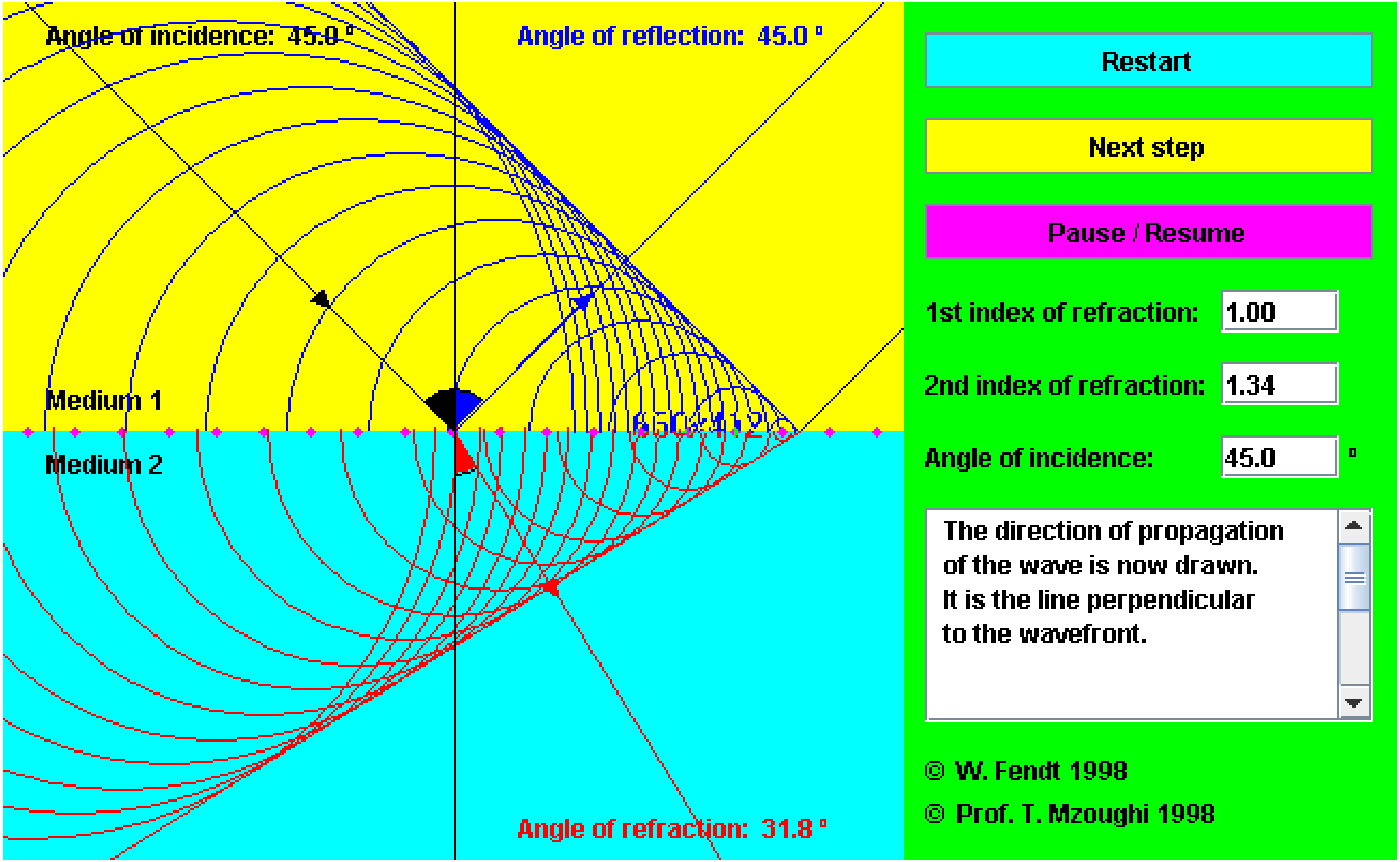
(Mobley 1994)

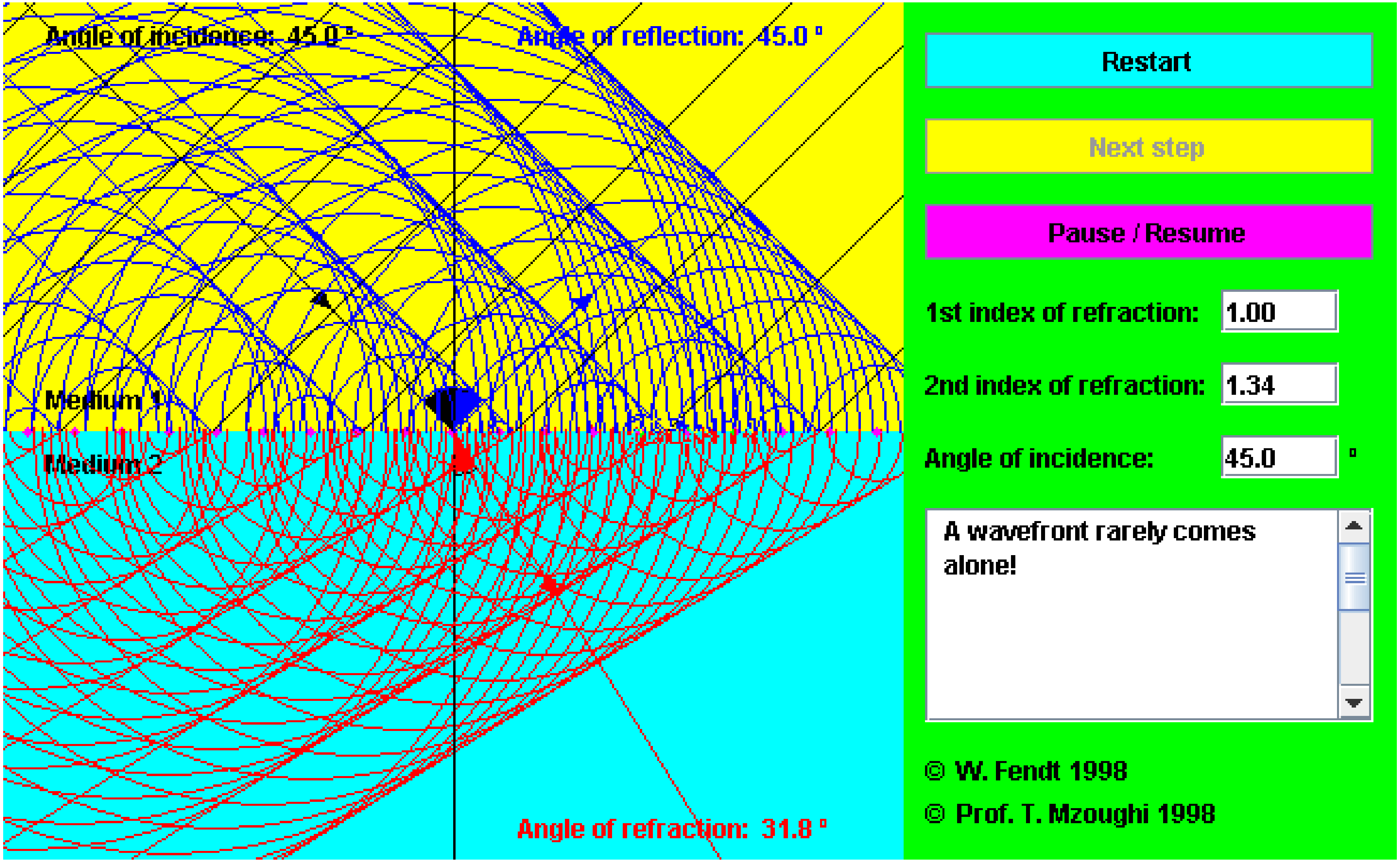
Dispersion


Wavelength
40°
θ(i)
Incident Angle - θ(i)
358x350
Refracted Angle - θ(r)
Varies From
28.51° To 28.82°
White Light
Monochromatic
Choose A Material (RI)
Water 1.3330

Reflection and Refraction of Light (Visualization of Huygens Principle)

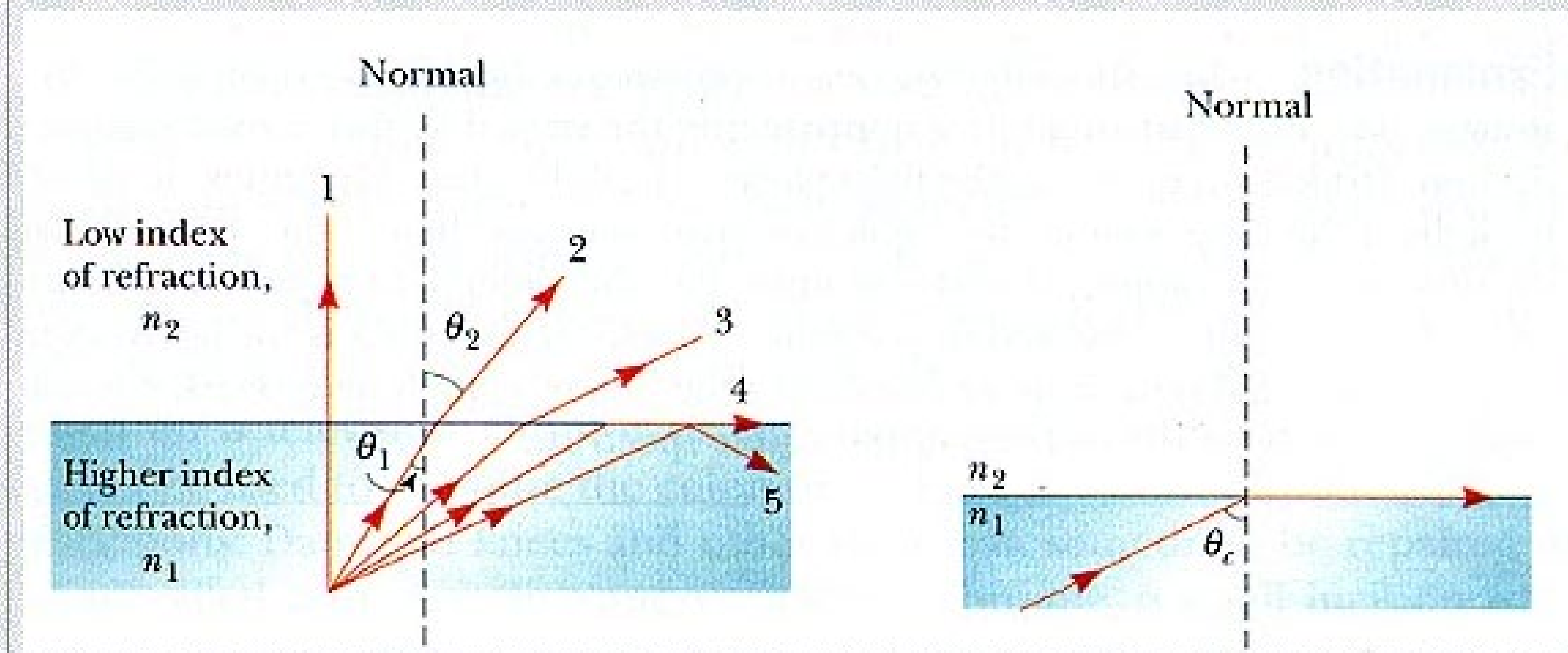
Go to: https://www.walter-fendt.de/html5/phen/refractionhuygens_en.htm





https://www.walter-fendt.de/html5/phen/refractionhuygens_en.htm

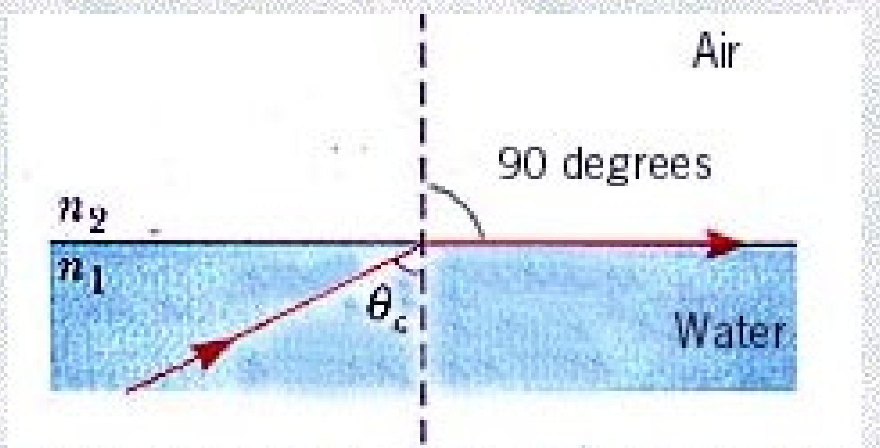
Internal Reflection



Ray 4 is the first to be 100 % reflected; it's angle of incidence is called the *critical angle*.

If n_2 = 1 (atmosphere) and n_1 = 1.34 (ocean) the critical angle is about 48.3^o

Crictical Angle Calculation



What must be θ_1 to get θ_2 = 90 deg ?

Snell's Law:

$n_1 \sin \theta_1 = n_2 \sin \theta_2$

$= n_2 \sin 90$

$\sin \theta_1 = n_2 / n_1$

Assume water to air:

$n_1 = 1.33$ $n_2 = 1.00$

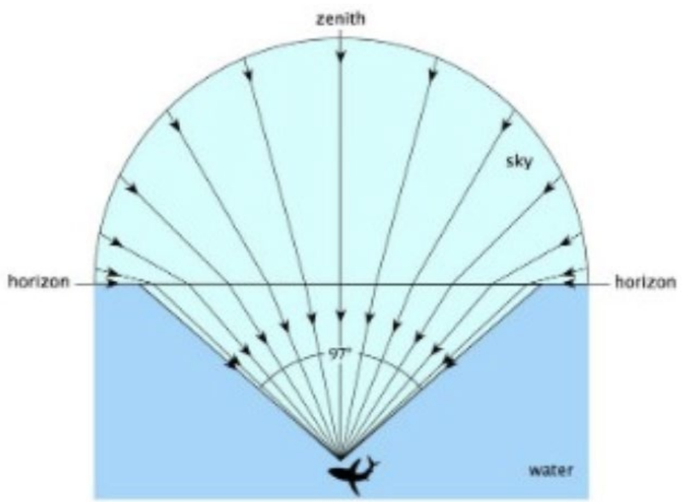
$\theta_1 = \sin^{-1} (0.752)$

= 48.8 degrees

θ_c = critical angle

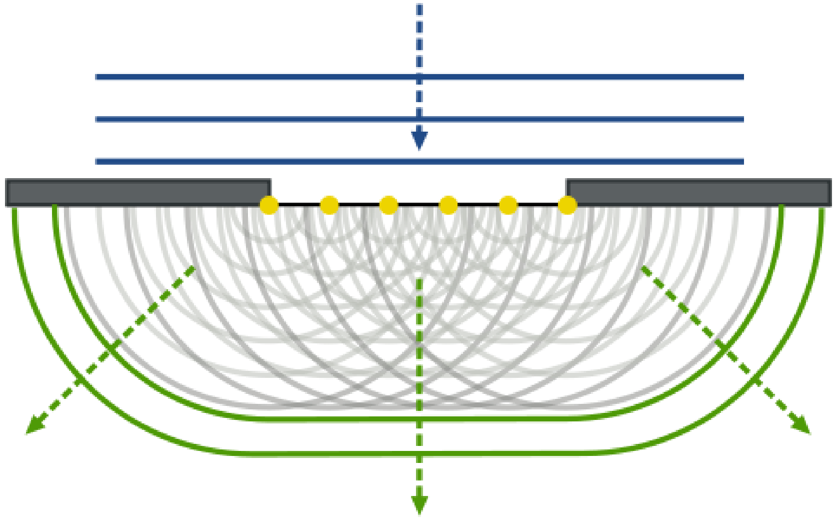
= 48.8 degrees

View straight up from underwater. The above-water hemisphere is visible, compressed into a circle (Snell's window) bounded by the critical angle. Everything outside the critical-angle circle is reflected from below the water.

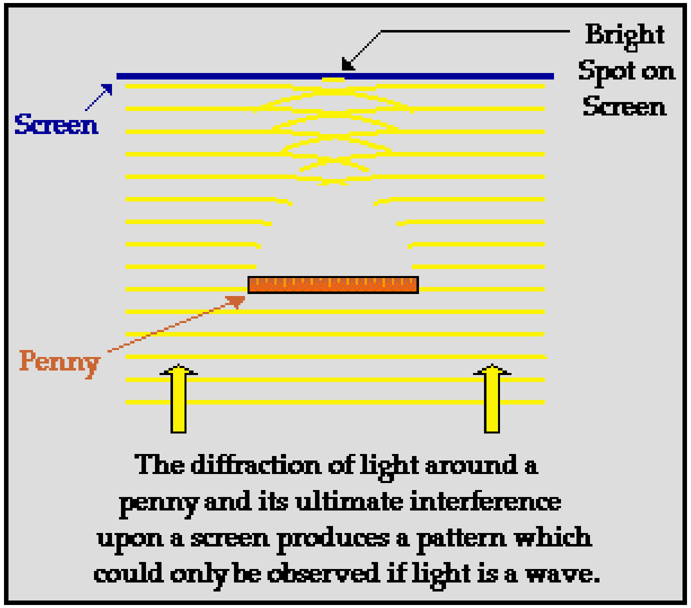


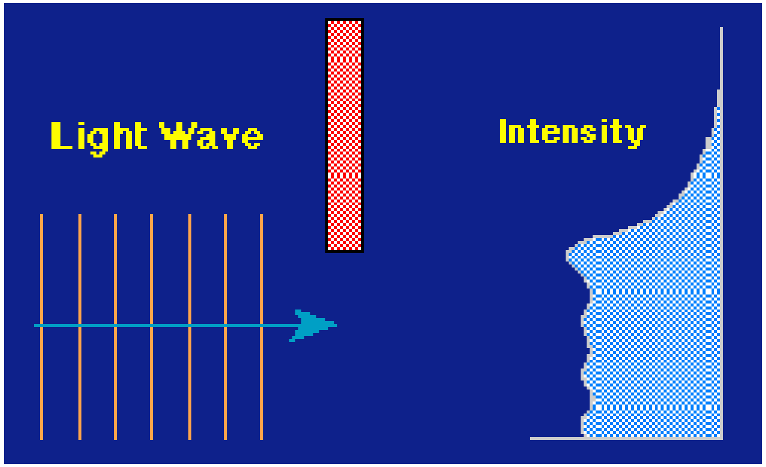
Wave focusing of sunlight

Diffraction



Augustin-Jean Fresnel
(1788 - 1827)

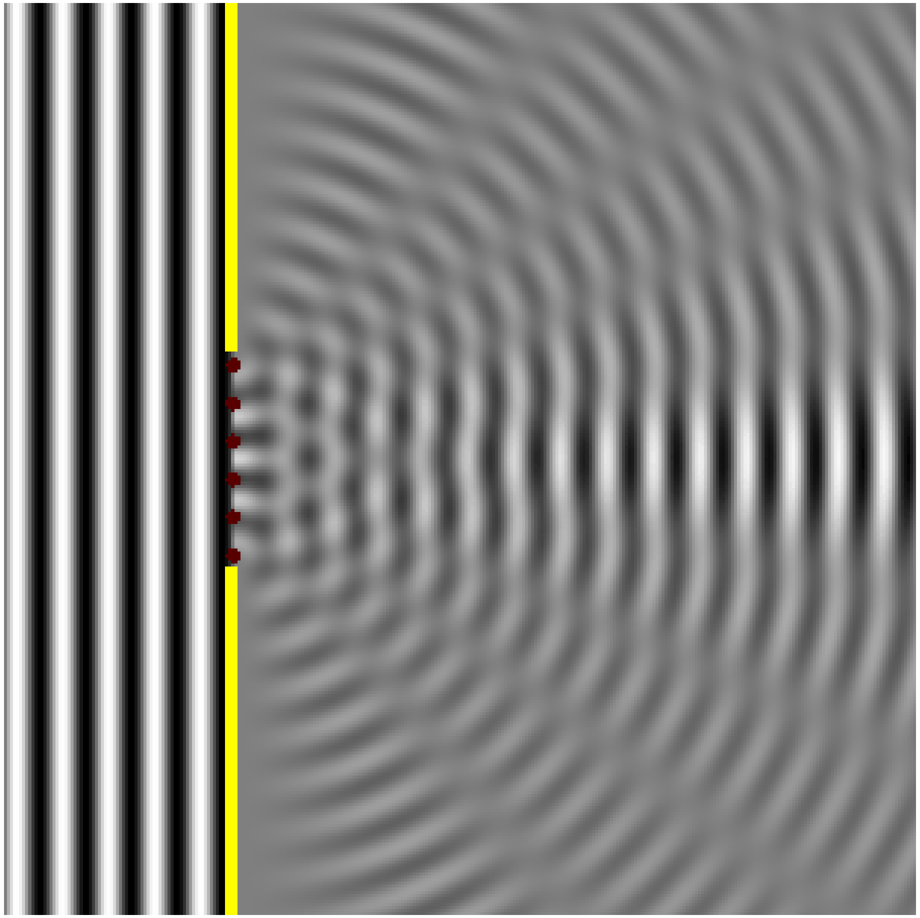




The intensity of light behind the barrier is not zero in the shadow region due to diffraction (light wave has a capability to "bend around corners")

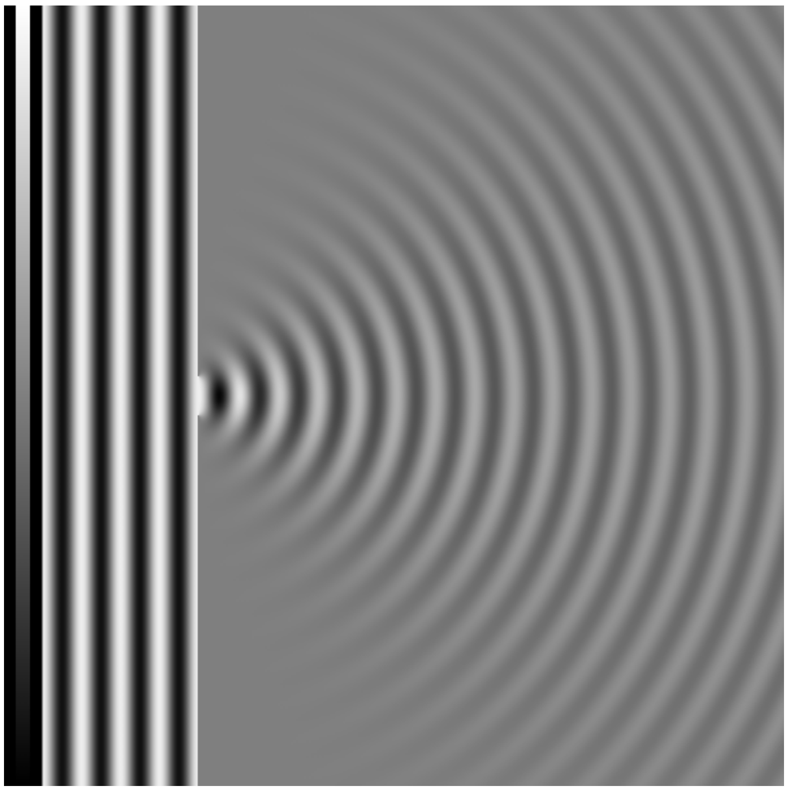
https://www.youtube.com/watch?v=47vw28-UEuw

Huygens proposed that every point of the wavefront becomes a source of a secondary spherical wave, and the sum of these secondary waves determine the form of the wave at any subsequent time. Huygens assumed that the secondary waves travel only in the "forward" direction.

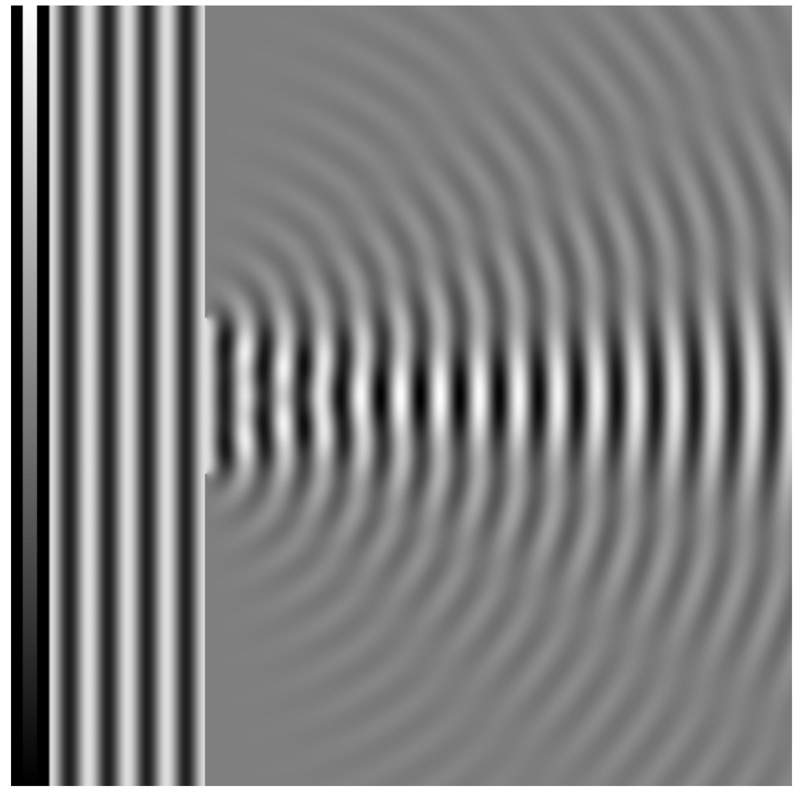


Approximation of a diffraction of a planar wave on a single slit

Slit width = 1 wavelength



Slit width = 4 wavelengths



Diffraction simulation with adjustable light wavelength and slit width:

Go to: https://www.compadre.org/osp/EJSS/4480/268.htm

Diffraction