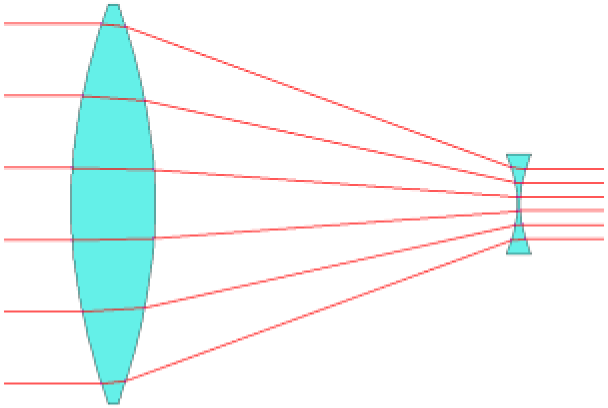
OPAC 101
Introduction to Optics

Chapter 1

The Light



http://www1.gantep.edu.tr/~bingul/opac101

Department of

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Sep 2020

PART I

THE NATURE OF LIGHT

R. Feynman, Lecture notes on Physics, Volume I, Chapter 37

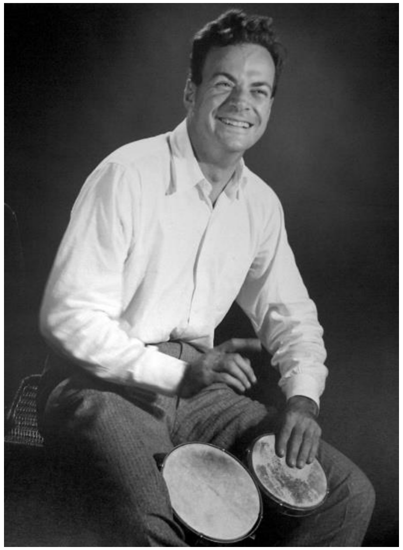
Newton thought that light was made up of particles, but then it was discovered, that it behaves like a wave. Later, however it was found that light did indeed sometimes behave like a particle.

Historically, the electron, for example, was thought to behave like a particle, and then it was found that in many respects it behaved like a wave.

So it really behaves like neither.

Now we have given up.

We say: “It is like neither.”



Richard Feynman

Light and Optics

- Light is the portion of electromagnetic radiation that is visible to the human eye and is an energy propagating in space as photons.

- Optics is the branch of physics which involves the behavior and properties of light and interactions of light with matter such as
  - illumination (= aydınlatma)
  - reflection (= yansıma)
  - refraction (= kırılma)
  - interference (= girişim)
  - diffraction (= kırınım)
  - polarization (= kutuplanma)
  - etc.

Optical Engineering

- Optical engineers make use of optics to solve problems and to design and build devices that make light do something useful such as lasers, telescopes, fiber optics communication systems, illumination systems etc.

- Today, the optical devices used in many fields such as
  - Astronomy
  - Medicine
  - Military
  - Illumination
  - Alignment
  - Metrology
  - Automation
  - Communication
  - Space applications
  - etc.

- So, we need technical people conversant with the optical field. These experts are called the Optical Engineers.

History of Light Models!

- Old name of optics was ***perspective*** = ***… den bakmak***

- There were 3 theories about light in antique age
  - Intromission (nesne-ışın kuaramı)
  - Extramission (göz-ışın kuramı)
  - Mediumistic (ortamcı kuram)

See also:

‘Işığın Öyküsü’ H.G.Topdemir, Tubitak Populer Bilim Kitabı

Time	Scientist	Description	Explains
B.C.300	Euclid	Light travels in straight line	Reflection
1200	Ibn-i Haysem	Light is a ray	Reflection, Refraction
1690	Huygens	Light might be some sort of a wave motion	Reflection, Refraction
1704	Newton	Light consists of small particles called Corpuscular.	Reflection
1800	Young	The first clear demonstration of the wave nature of light	Interference
1895	Maxwell	Light is a form of high-frequency electromagnetic wave	Reflection, Refraction, Interference, Diffraction
1900	Planck	Light is a particle carrying energy called “photons”	Black body radiation
1905	Einstein	Light is a particle (photon)	Photo electric effect
1923	Compton	Light is a particle (photon)	Compton scattering
1924	De Broglie	Light and matter have both wave and particle duality	All

History of Light Models!

Today, in practice, there are 3 models to describe the light as listed below:

Light Models

Name	Field of Science	Description
Wave Model	Wave Optics	Light is an electromagnetic wave
Ray Model	Geometrical Optics	Light travels in a fixed direction in a straight line called ray
Photon	Physical Optics	Light is a kind of particle carrying momentum.

Wave is a *disturbance* that travels through space

Mechanical Waves

sound

water

string waves …

Electromagnetic Waves

Light

Radio waves

X-ray …

Wave

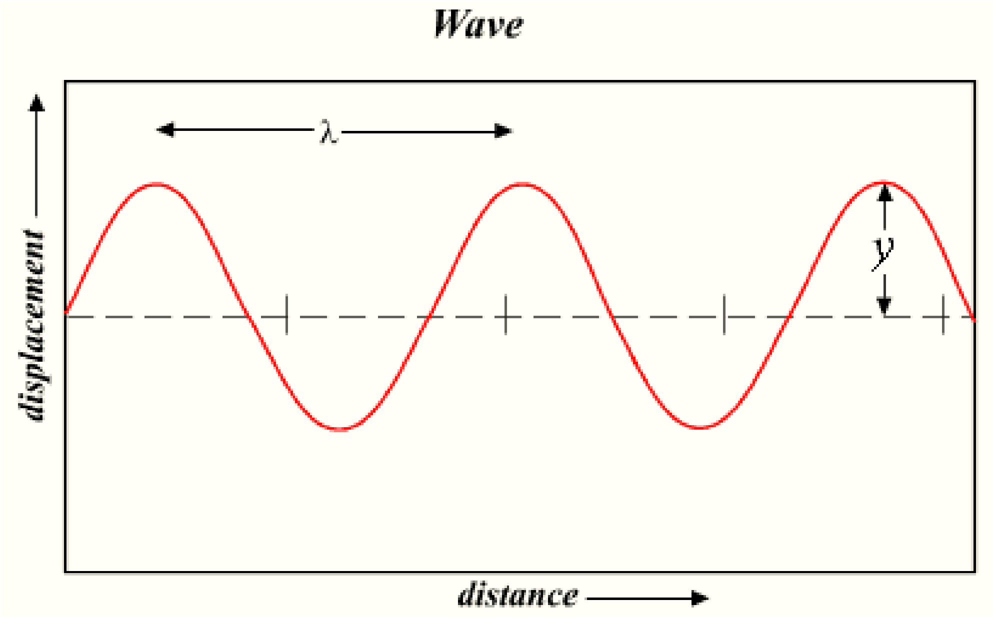
Quantum Mechanical Waves

to describe the probability density of a particle!

Gravitational Waves

disturbances in the curvature of space-time! (discovered in 2016)

Nature of Wave



λ : wavelength

ν : frequency (number of oscillations per second)

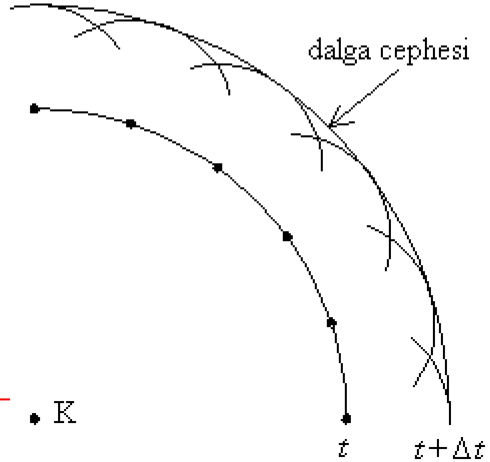
V : velocity of the wave --> $V = \nu \lambda$

For a light in vacuum V = c = 3×10^8 m/s (*we'll see later*)

Huygen’s Principle

In 1678, C. Huygens proposed a wave theory of light.
He believed that light was a wave and that this wave was propagated through a material called the 'aether'.
Since light can pass through a vacuum and travels very fast Huygens had to propose some rather strange properties for the aether: for example; it must fill all space and be weightless and invisible. For this reason scientists were sceptical of his theory.

He proposed that every point to which a luminous disturbance reaches becomes a source of a spherical wave; the sum of these secondary waves determines the form of the wave at any subsequent time.



Huygens' Principle

He assumed that the secondary waves travelled only in the "forward" direction and it is not explained in the theory why this is the case. He was able to provide a qualitative explanation of linear and spherical wave propagation, and to derive the laws of reflection and refraction using this principle, but could not explain the deviations from rectilinear propagation that occur when light encounters edges, apertures and screens, commonly known as diffraction effects.

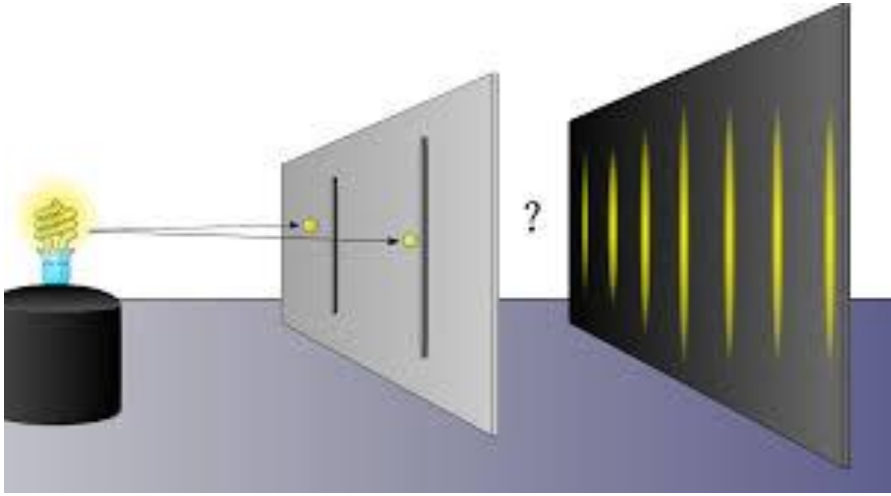
See also:

1. The course web page for the Turkish descriptions of the principle.

2. http://www.schoolphysics.co.uk/age16-19/Wave%20properties/Wave%20properties/text/Theories_of_light/index.html

Electromagnetic Waves

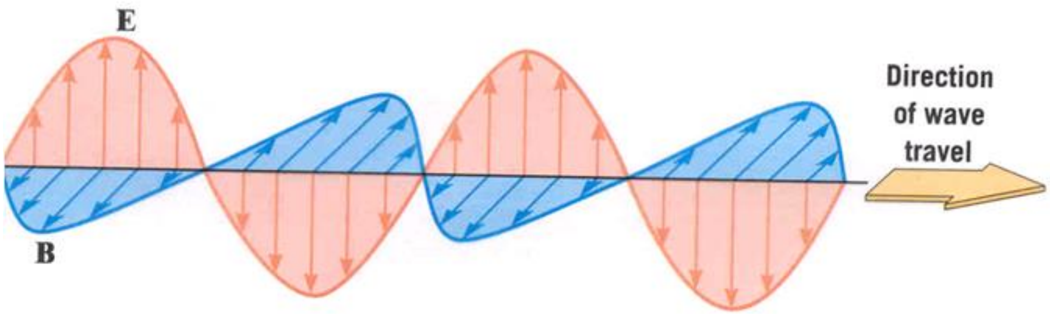
In 1800, Thomas Young made the double-slit experiment İn which an opaque screen with two small, closely spaced openings was illuminated by monochromatic light from a small light source.
The “shadows” observed are a complex interference pattern like those produced with water waves.



Electromagnetic Waves

James Clerk Maxwell first theoretically postulated EMWs (in 1862). These were confirmed by Heinrich Hertz experimentally (in 1886).

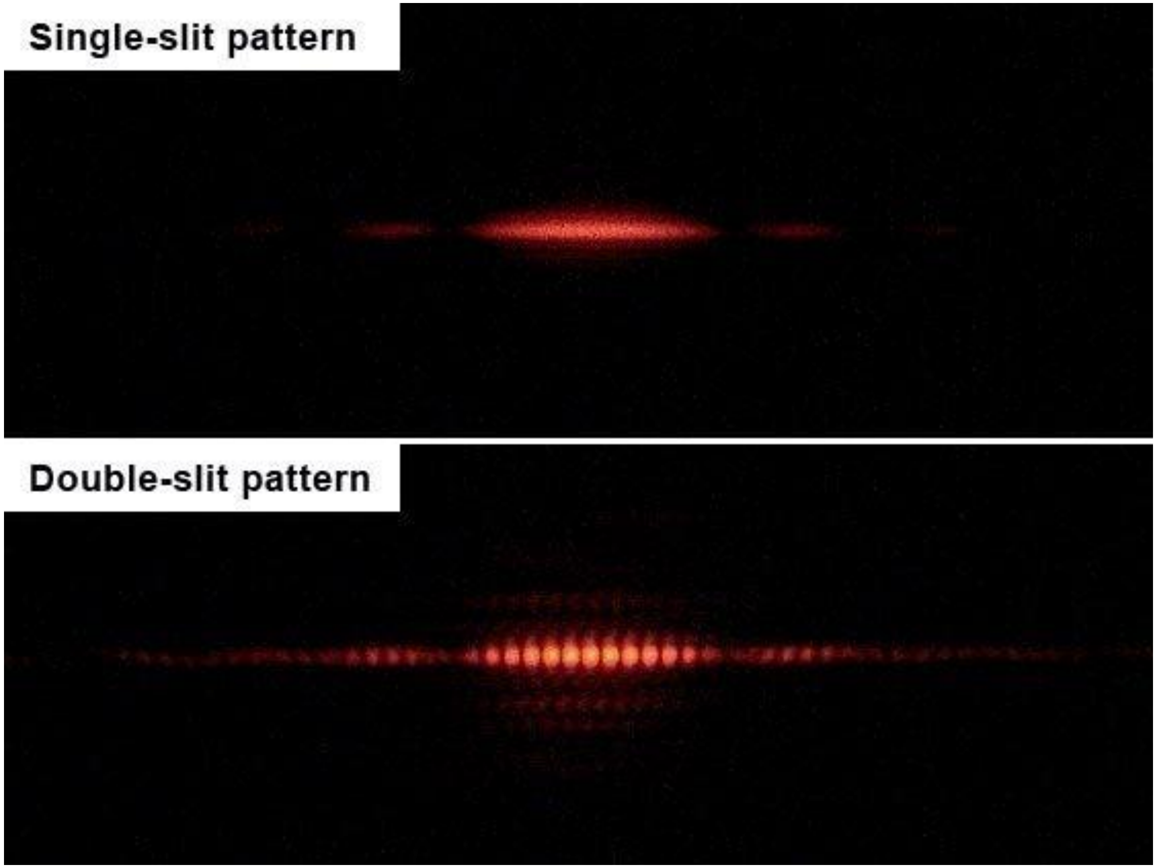
Name	Differential equations
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$



Light is an electromagnetic wave that is visible to the human eye

Interference and Diffraction

Certain optical phenomena may be accurately described by the hypothesis that *light is an electromagnetic wave*. These phenomena include diffraction and interference. Figure below shows a single slit and a double slit interference pattern on the screen for the same wavelength:



Photon: Quantum Theory of Light

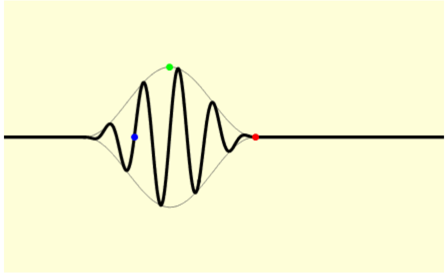
In 1900, Max Planck was used the idea that hot object emit light only as discrete packets of energy called **photons**.

Energy of photon is given by:

$$E = h\nu = \frac{hc}{\lambda}$$

h is the Planck's Constant (h = 6.6 x 10^{-34} J.s)
c is the speed of light

The photon idea is later used by Einstein and Compton.

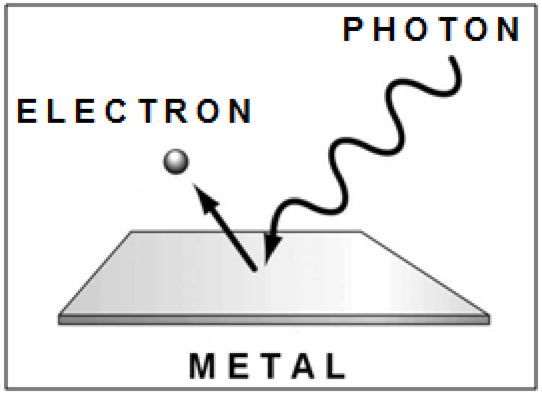


a wave packet

Light is an energy propagating in space as particles

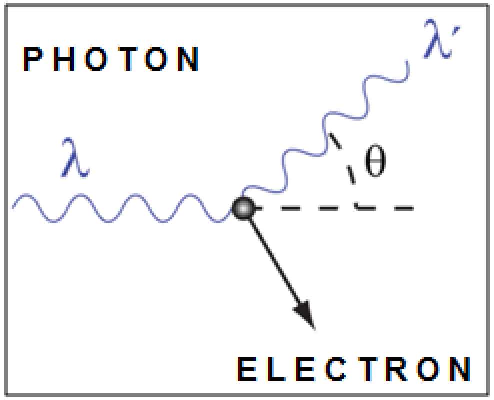
Photon

- **1905 Photoelectric Effect (*A.Einstein*)**
  Kinetic energy of the ejected electron:



$$K \leq h\nu - w$$

- **1923 Compton Scattering (*H.Compton*)**
  Wavelength of the scattered photon:



$$\lambda' = \lambda + \frac{h}{m_e c}[1 - \cos\theta]$$

Interaction of photon with matter

- http://www.youtube.com/watch?v=4p47RBPiOCo
- http://phet.colorado.edu/en/simulation/photoelectric

Particle-Wave

In 1924, Louis de Broglie suggested that
a particle with momentum *p* had an associated
wavelength:

$$\lambda = \frac{h}{p}$$

Light behaves like waves in its propagation and in the phenomena of interference and diffraction;

however, it exhibits particle-like behavior when exchanging energy with matter, as in the Compton and photoelectric effects.

Particles (mass, m>0)

[Particle side] Special Relativity says:

$$p = \frac{\sqrt{E^2 - m^2c^4}}{c}$$

[Wave side] Quantum Theory says:

$$\lambda = \frac{h}{p}$$

E = *total energy of particle*
E_K = *kinetic energy of particle*
p = *momentum of particle*
m = *rest mass of particle*
c = *speed of light*
v = *speed of particle*

Combined Theory:

$$\lambda = \frac{h}{p} = \frac{hc}{\sqrt{E^2 - m^2c^4}}$$

$$\mathrm{v} = \frac{pc^2}{E} = c\sqrt{1 - \frac{m^2c^4}{E^2}}$$

$$E_K = (\gamma - 1)mc^2$$

$$\gamma = \frac{1}{\sqrt{1 - \mathrm{v}^2/\mathrm{c}^2}}$$

Photons (m = 0)

$$p = \frac{E}{c}$$

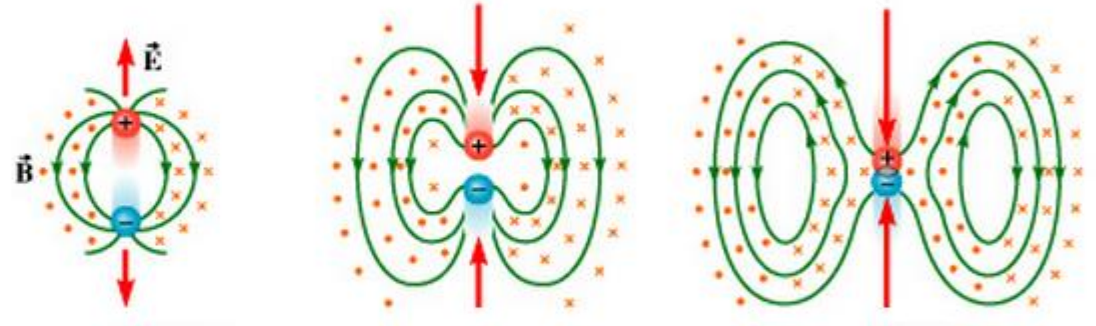
$$\lambda = \frac{h}{p} = \frac{hc}{E}$$

The energy of a photon is not a function of its speed but rather of its wavelength.

$$\text{v} = \frac{pc^2}{E} = c$$

The speed of a photon is c = 3×10^8 m/s.

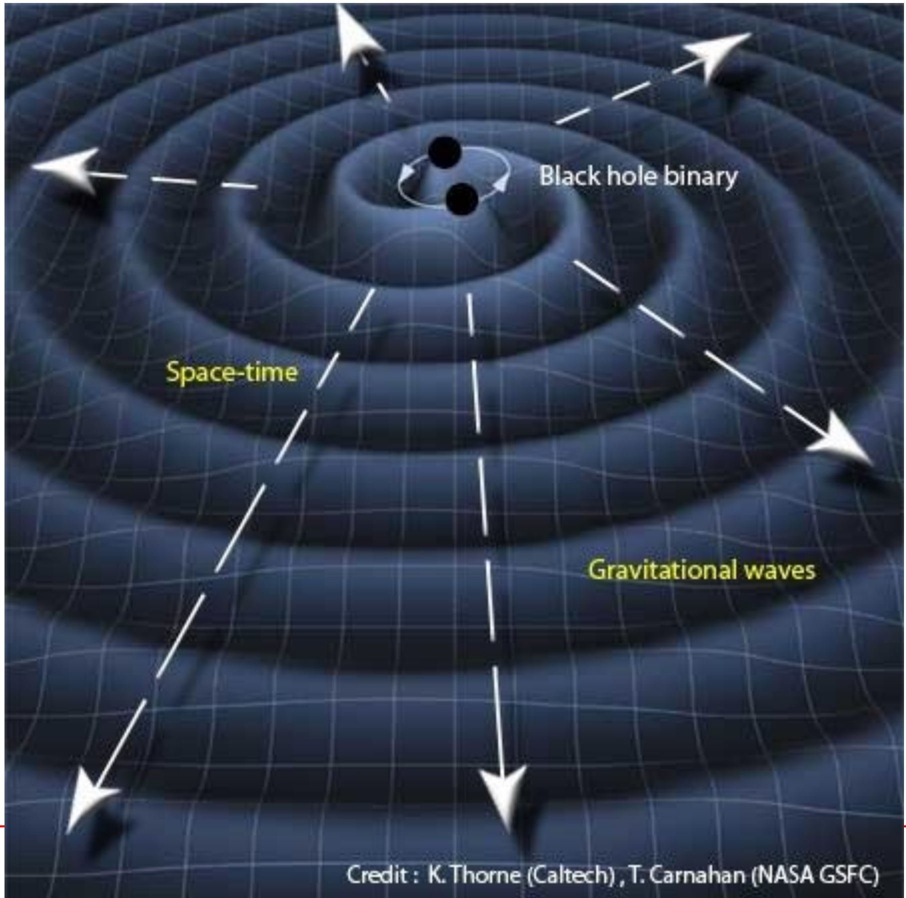
EM Wave Production



EM Waves are made up time-varying electric and magnetic fields.

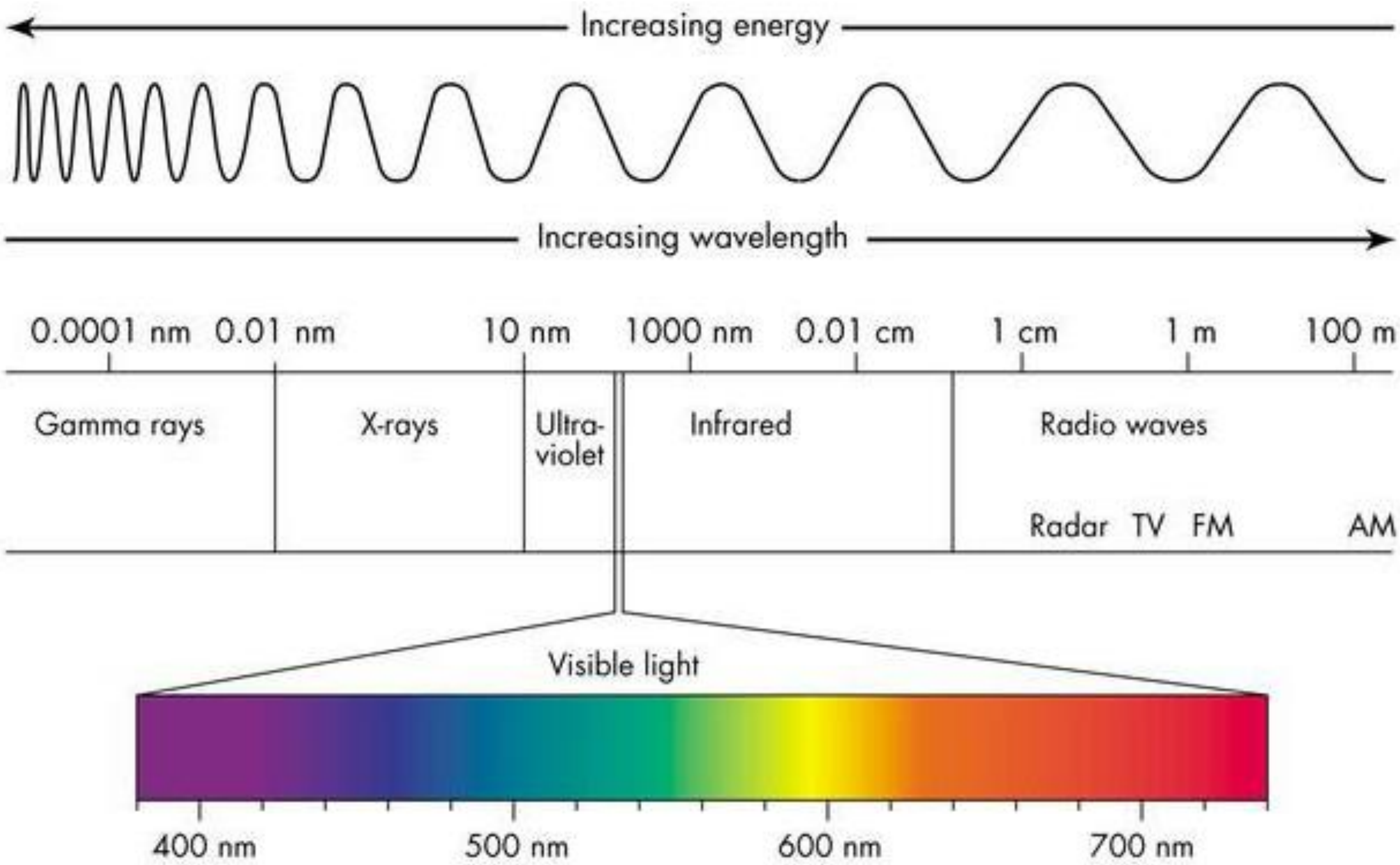
EM Waves are produced by accelerating charges.

Similarly Gravitational Waves are produced by accelerated massive objects (like black-holes).



EM Specturum

The electromagnetic spectrum is the range of all possible frequencies of electromagnetic radiation. Optics covers the wavelength range of electromagnetic spectrum from 10 nm to 1 mm.



Remind

$$c = f\lambda$$

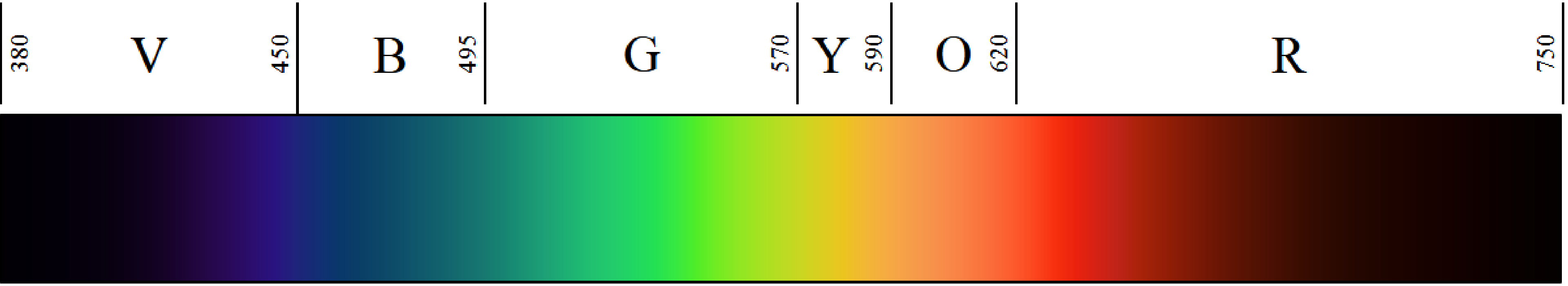
EM Specturum

Visible Radiation (light)

* have a wavelength ranging from 380 nm (**violet**) to 760 nm (**red**).

* is typically absorbed and emitted by electrons in molecules and atoms that move from one energy level to another.

* The sun and stars emit most of their radiation as visible light.



Radio waves (from λ = 100 m to λ = 1 m)

* are generated by such electronic devices (such as LC oscillations)
* are utilized by antennas of appropriate size
* are used for transmission of data, via modulation.
  + *Radio, Television, Mobile Phones, Wireless Networking, Radar, …*

Microwaves (from λ = 1 m to λ = 1 mm)

* include both UHF and EHF.
* are generated by electronic devices
* are absorbed by molecules that have a dipole moment in liquids.
  + *In a microwave oven, this effect is used to heat food.*

Infrared (from λ = 1 mm to λ = 750 nm)

* hot objects can radiate strongly in this range
* is absorbed by molecular vibrations.
  + *The water in the Earth's atmosphere absorbs so strongly in this range that it renders the atmosphere effectively opaque*

Ultraviolet, UV (from λ = 380 nm to λ = 10 nm)

* can break chemical bonds.
* Sun emits a large amount of UV radiation.
  Earth absorbes most of them on the atmosphere's ozone (O_3) layer.
  + *Sunburn is caused by the disruptive effects of UV radiation on skin cells.*

UV-A refers to the wavelength range 380 nm-315 nm

UV-B to the range 315 nm-280 nm

UV-C to the range 280 nm-10 nm

X-rays, Röntgen Radiation(from λ = 10 nm to λ = 0.01 nm)

* can penetrate solid objects
* can damage or destroy living tissues and organisms
* can be used to take images of the inside of objects
  + *Diagnostic radiography and crystallography.*
  + *Neutron stars and accretion disks around black holes emit X-rays, which enable us to study them.*

Gamma-rays (from λ < 10 pm)

* are produced by sub-atomic particle interactions
  + *radioactive nuclei (such as ^{60}Co and ^{137}Cs)*
  + *electron-positron annihilation*
  + *neutral pion decay*
  + *cosmic rays*
  + *fusion*
  + *fission*

* can highly penetrate solid objects
  + *irradiation of food and seed for sterilization*

* produce serious damage when absorbed by living tissues

* can also demage DNA of a cell
  + *radiation cancer therapy and*
    some kinds of diagnostic imaging such as PET scans.

EXAMPLE

What is the energy in Joule and eV of

(a) a visible light of 500 nm and (b) a radio wave of 1 m of wavelength.

SOLUTION

(a) $$E=\frac{hc}{\lambda}=\frac{(6.6\times10^{-34}\text{ J.s})(3\times10^{8}\text{ m/s})}{500\times10^{-9}\text{ m}}=3.96\times10^{-19}\text{ J}$$

Since 1 eV = 1.6x10^{-19} J $$E=\frac{3.96\times10^{-19}\text{ J}}{1.6\times10^{-19}\text{ J/eV}}=2.48\text{ eV}$$

(b) $$E=\frac{hc}{\lambda}=\frac{(6.6\times10^{-34}\text{ J.s})(3\times10^{8}\text{ m/s})}{1\text{ m}}=1.98\times10^{-25}\text{ J}=1.24\times10^{-6}\text{ eV}$$

EXAMPLE

A half-wave antenna works on the principle that the optimum length of the antenna is half the wavelength of the radiation being received. What is the optimum length of a car antenna when it receives a signal of frequency 94.7 MHz?

SOLUTION

Wavelength is:

$$\lambda = \frac{c}{f} = \frac{(3\times 10^{8}\ \mathrm{m/s})}{94.7\times 10^{6}\ \mathrm{Hz}} = 3.16\ \mathrm{m}$$

Thus, to operate most efficiently, the antenna should have a length of:

$$L = \frac{3.16\ \mathrm{m}}{2} = 1.58\ \mathrm{m}$$

For practical reasons, car antennas are usually one-quarter wavelength in size.

Speed of Light

Electromagnetic theory tells us that the speed of light in free space (vacuum) is given by:

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \approx 3 \times 10^8 \text{ m/s}$$

For vacuum, in SI units:

$\mu_0 = 4\pi \times 10^{-7}$ m.kg/C^2

$\varepsilon_0 = 8.85 \times 10^{-12}$ C^2.s^2/m^3.kg

The exact value is

$$c = 2.99\,792\,458 \times 10^8 \text{ m/s}$$

Some of the best measurements of c in history

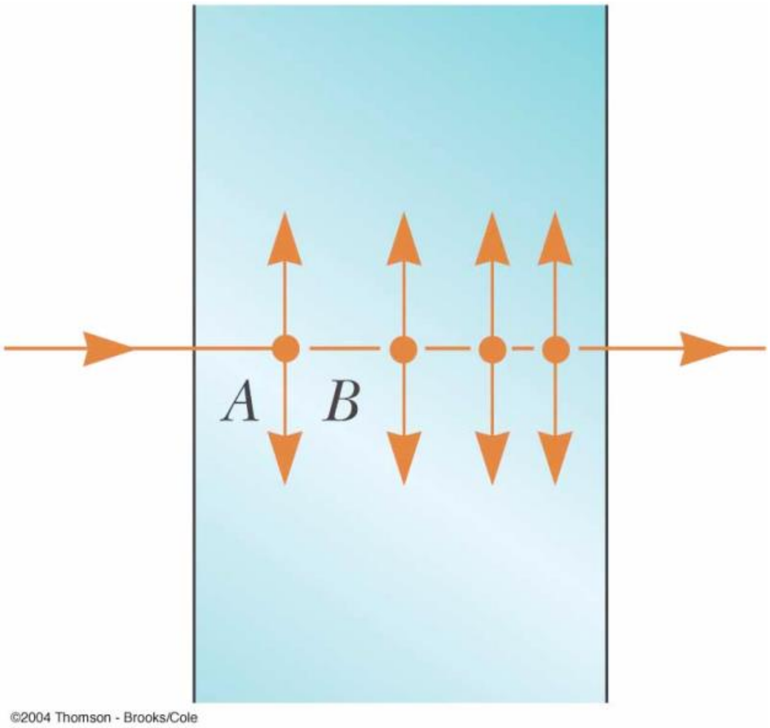
Date	Author	Method	Result (km/s)	Error
1676	Olaus Roemer	Jupiter's satellites	214,000	
1726	James Bradley	Stellar Aberration	301,000	
1849	Armand Fizeau	Toothed Wheel	315,000	
1862	Leon Foucault	Rotating Mirror	298,000	+-500
1879	Albert Michelson	Rotating Mirror	299,910	+-50
1907	Rosa, Dorsay	Electromagnetic constants	299,788	+-30
1926	Albert Michelson	Rotating Mirror	299,796	+-4
1947	Essen, Gorden-Smith	Cavity Resonator	299,792	+-3
1958	K. D. Froome	Radio Interferometer	299,792.5	+-0.1
1973	Evanson et al	Lasers	299,792.4574	+-0.001
1983		Adopted Value	299,792.458	

PART II

THE INDEX OF REFRACTION

Light in a Medium

- The light enters from the left
- The light may encounter an electron
- The electron may absorb the light, oscillate, and reradiate the light
- The absorption and radiation cause the average speed of the light moving through the material to decrease



Light passing from one atom to another in a medium. The dots are electrons, and the vertical arrows represent their oscillations.

Index of Refraction

- The speed of light in any material is less than its speed in vacuum.

- The index of refraction, *n*, of a medium can be defined as

$$n \equiv \frac{\text{speed of light in a vacuum}}{\text{speed of light in a medium}} = \frac{c}{v}$$

- For a vacuum: $n = 1$
  For other media: $n > 1$
  For air: $n = 1.000293 \approx 1$
  For water: $n = 1.333$

Indices of Refraction[a]

Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		*Liquids at 20°C*	
Cubic zirconia	2.20	Benzene	1.501
Diamond (C)	2.419	Carbon disulfide	1.628
Fluorite (CaF_2)	1.434	Carbon tetrachloride	1.461
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361
Gallium phosphide	3.50	Glycerin	1.473
Glass, crown	1.52	Water	1.333
Glass, flint	1.66		
Ice (H_2O)	1.309	*Gases at 0°C, 1 atm*	
Polystyrene	1.49	Air	1.000 293
Sodium chloride (NaCl)	1.544	Carbon dioxide	1.000 45

[a] All values are for light having a wavelength of 589 nm in vacuum.

See also: **http://refractiveindex.info**

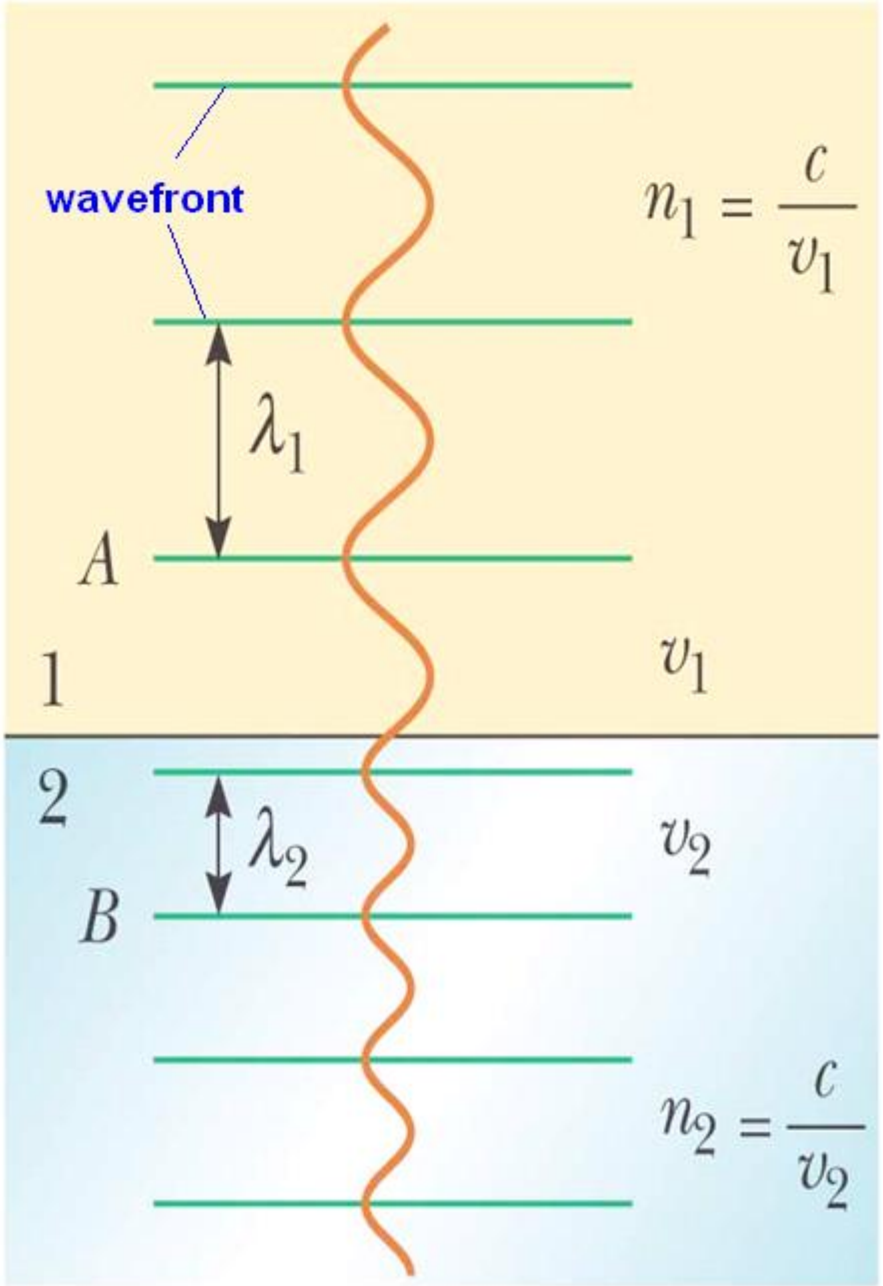
- As light travels from one medium to another, its frequency <u>does not</u> change

- Both the wave speed and the wavelength <u>do</u> change

- The wavefronts do not pile up, nor are created or destroyed at the boundary, so f must stay the same.

- $v = f\lambda$ on both sides

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$



EXAMPLE

What are the speed and wavelength of the light in water ($n = 1.333$) if its wavelength in the vacuum is $\lambda = 500$ nm?

SOLUTION

Speed:

$v = c / n = 3x10^8 / 1.333 = 2.25x10^8$ m/s

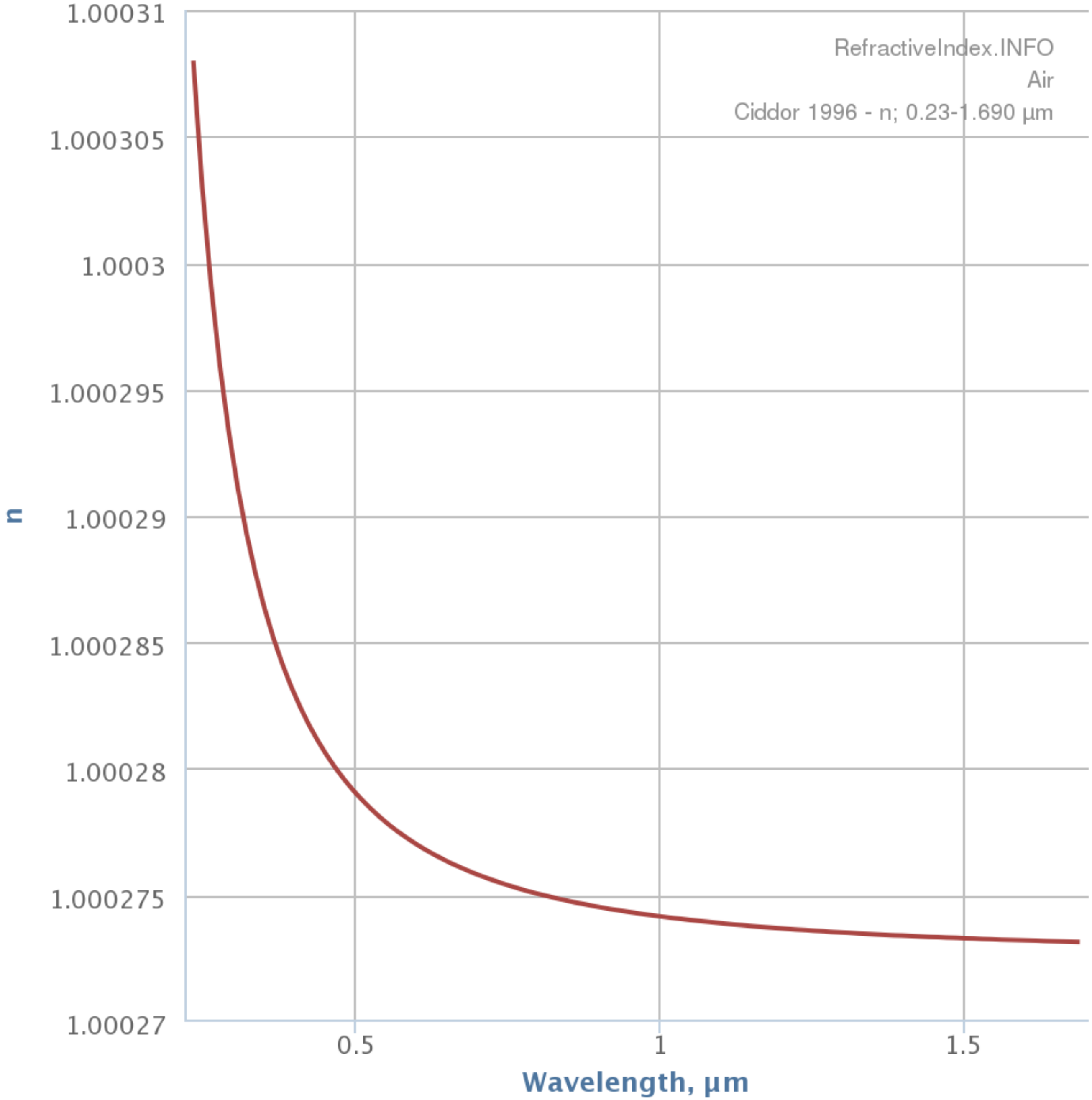
Wavelength:

$\lambda_n = \lambda / n = 500$ nm $/ 1.333 = 375$ nm

Dispersion

n depends on wavelength.

n = f(λ)



http://refractiveindex.info

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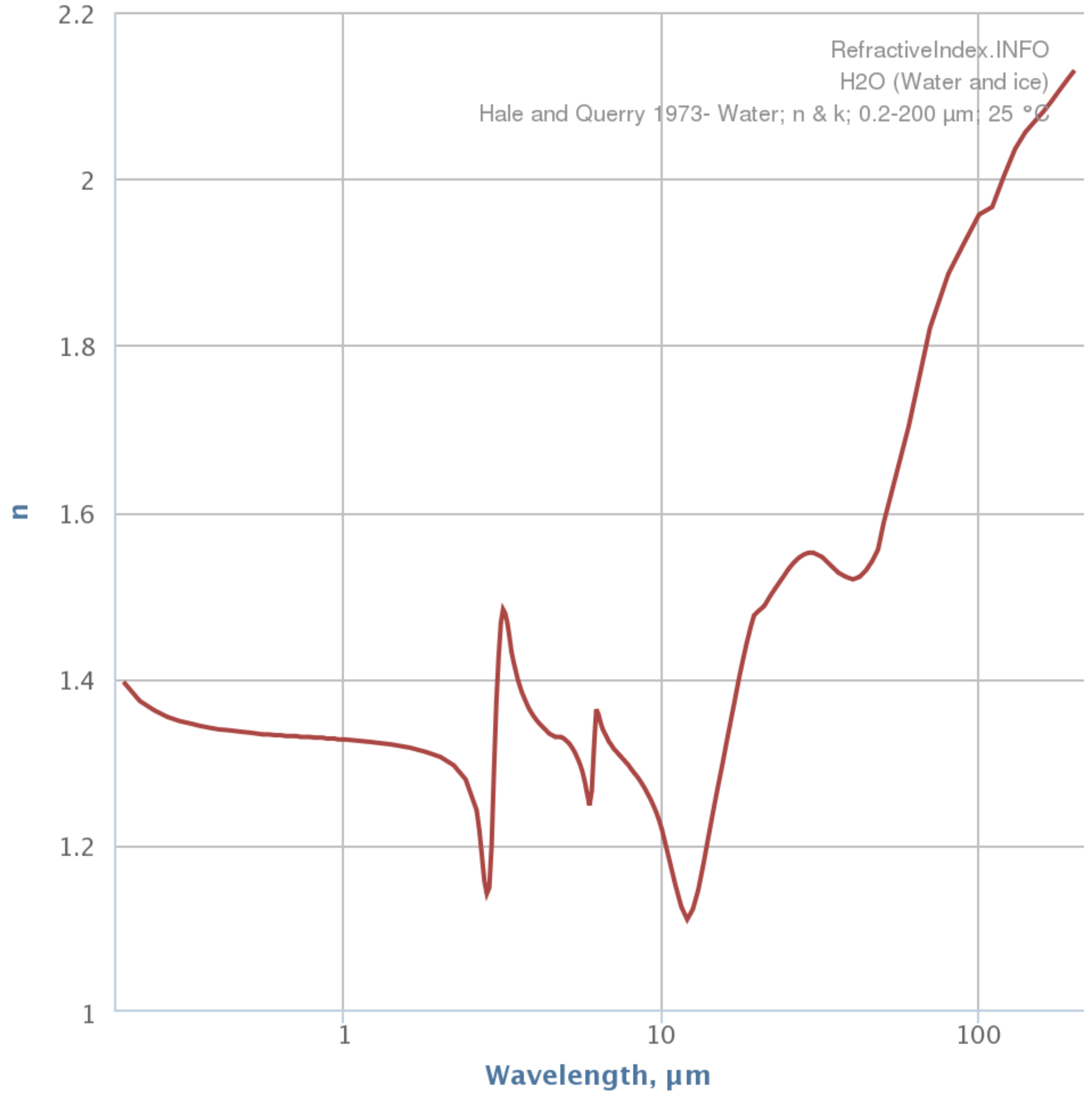

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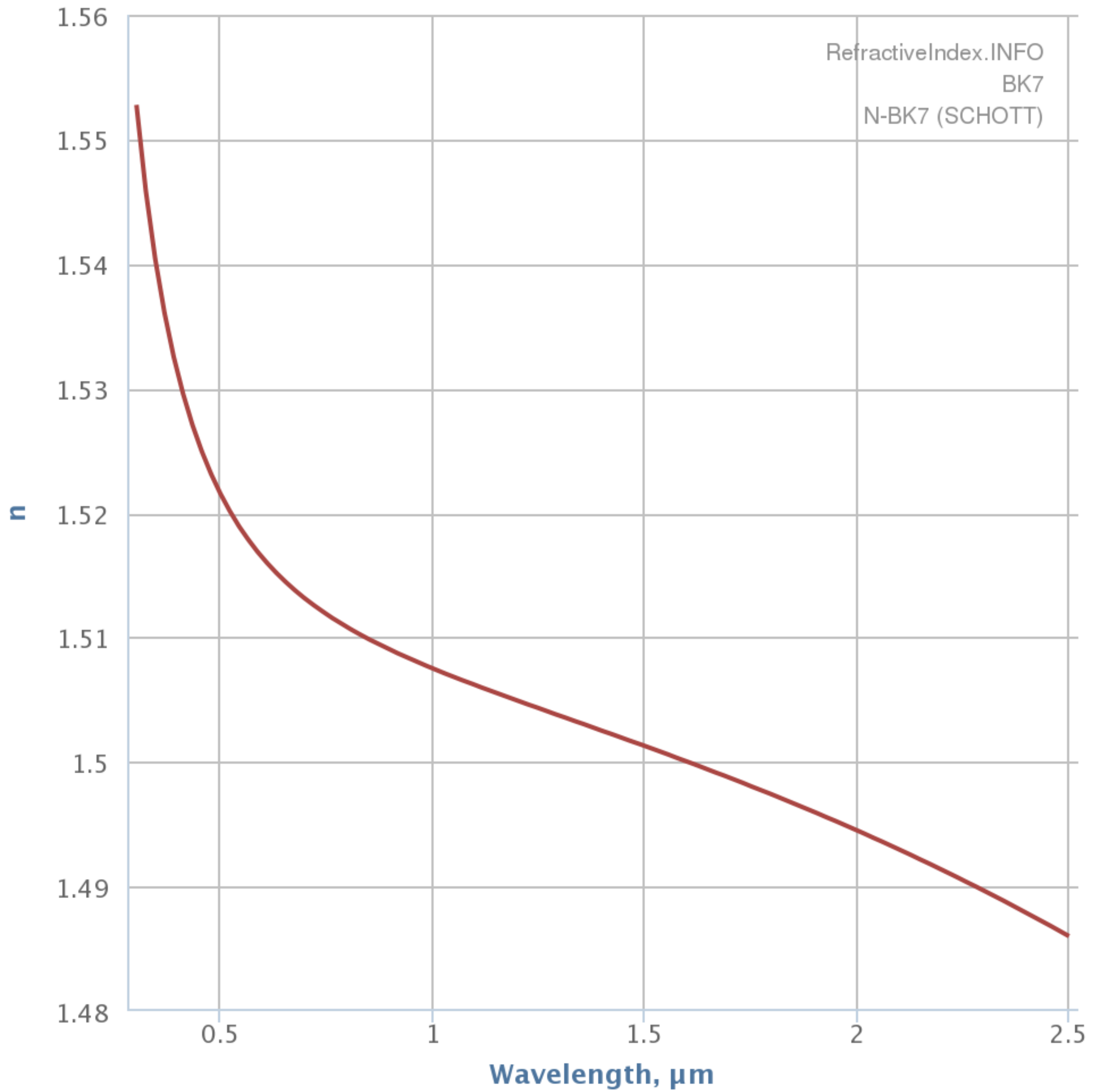

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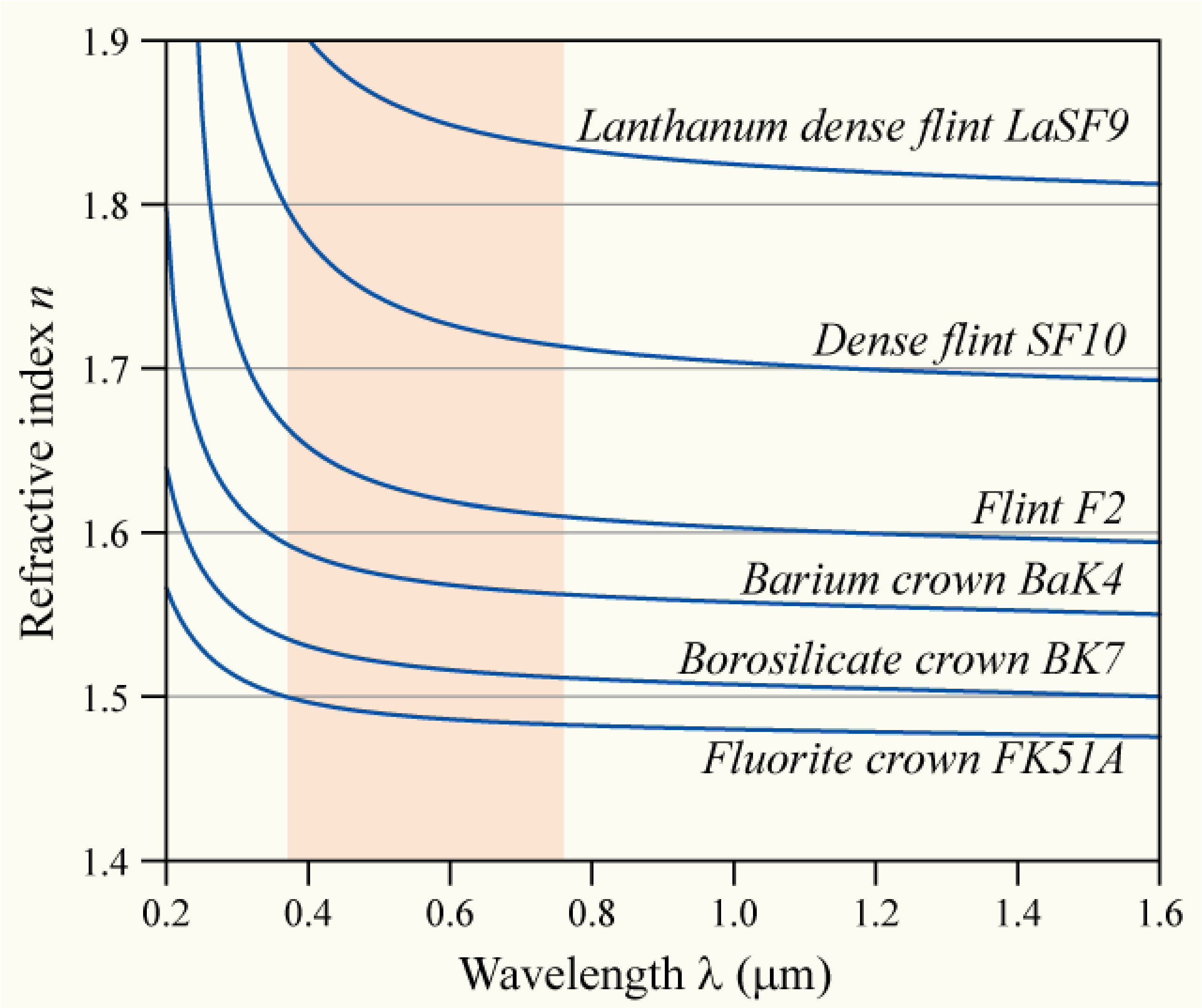


PART III

RAY and WAVE APPROXIMATIONS of LIGHT

Ray Approximation

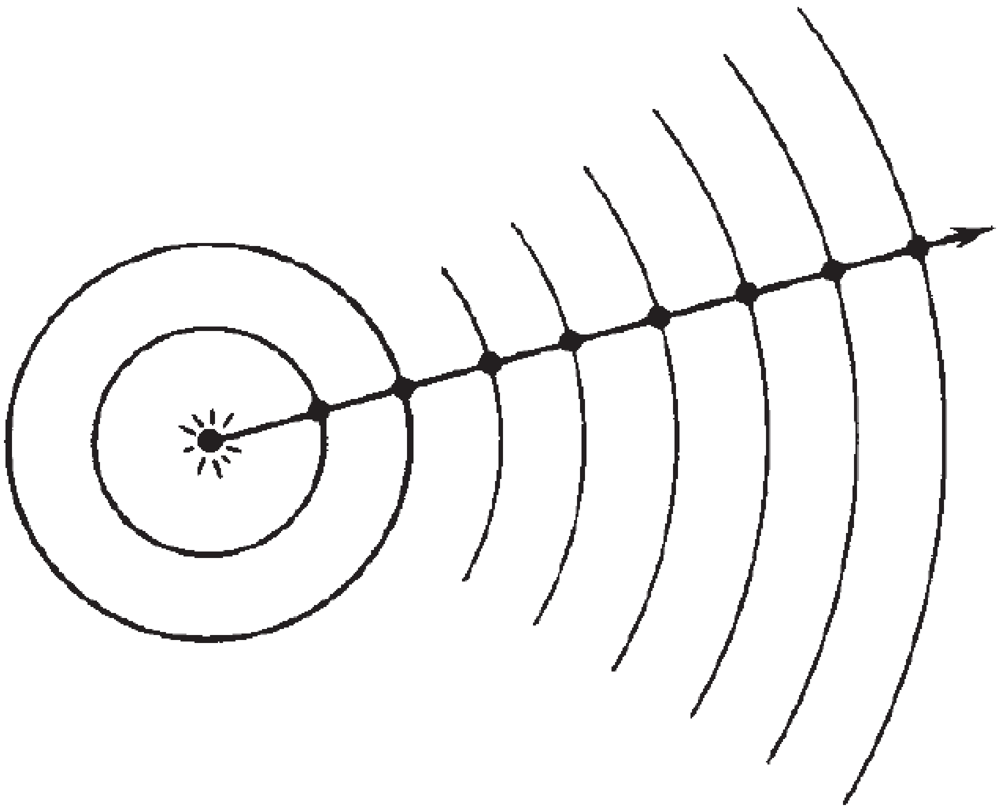
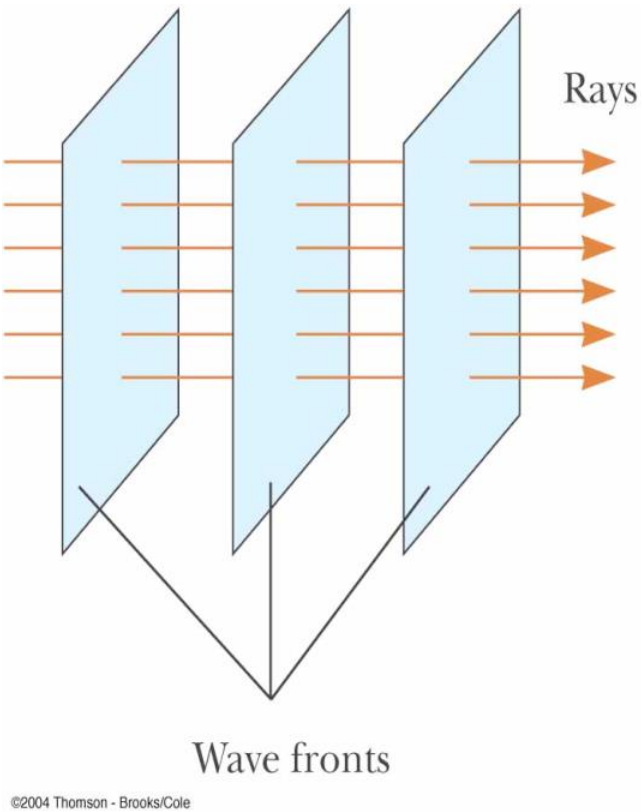
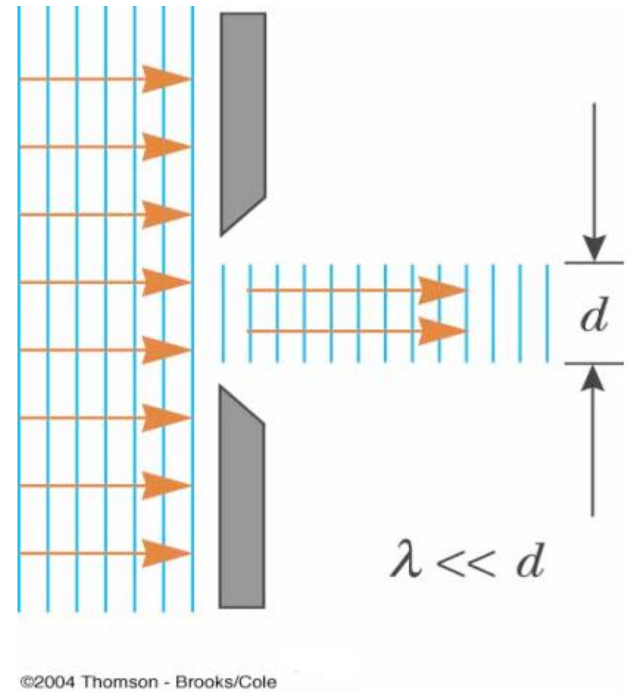


Figure 1.3 Light waves radiating from a point source in an isotropic medium take a spherical form; the radius of curvature of the wave front is equal to the distance from the point source. The path of a point on the wave front is called a light ray, and in an isotropic medium is a straight line. Note also that the ray is normal to the wave front.

Ray Approximation



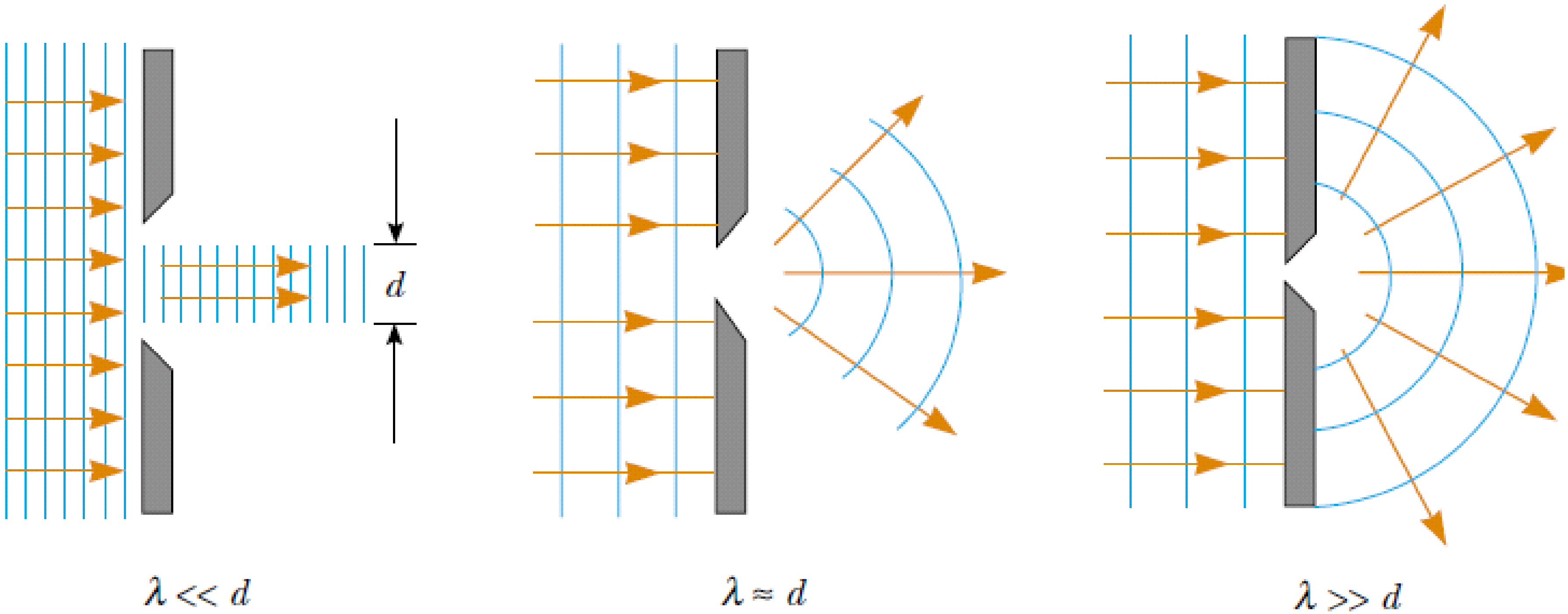


The rays are straight lines perpendicular to the wave fronts

If a wave meets a barrier and if $\lambda \ll d$ then the light behaves like a ray.

This approximation is good for the study of mirrors, lenses, prisms, etc.

Wave Approximation



if λ ~ *d* or λ >> *d* then we cannot use the ray approximation since the light can make interference or diffraction.

http://phet.colorado.edu/en/simulation/quantum-wave-interference