Fundamentals in Biophotonics

Light, photon-wave particle duality

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03.03.2025.

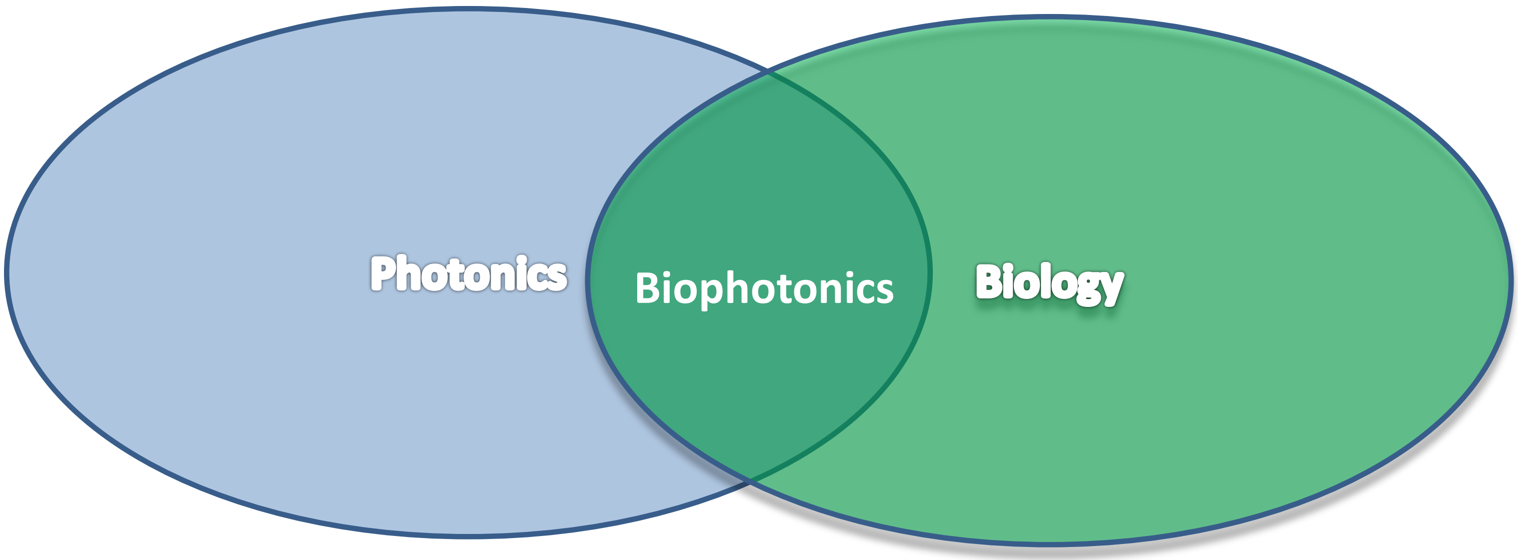
Schedule

https://docs.google.com/spreadsheets/d/1rYpU327ekuptJWSO3Ve7fA2KkFle4t6n/edit?gid=483657210#gid=483657210

Presentantion schedule						
Date	1st Student	Assigned Topic	2nd Student	Assigned Topic	3nd Student	Assigned Topic
17.02.2025.	INTRO SESSION					
24.02.2025	Selection of the topics /schedule of the topics /material preparation /No Class					
03.03.2025.	Lecture 1					
10.03.2025.	Lecture 2					
17.03.2025.	Lecture 3					
23.03.2025.	Lecture 4					
31.03.2025.	Lecture 5					
07.04.2025.	Lecture 6					
14.04.2025.	Lecture 7					
21.04.2025	Easter holidays(Vacances) Easter Monday(Jour férié)					
28.04.2025.	Lecture 8					
05.05.2025.	Lecture 9					
12.05.2025.	Tan Jiayi	SMLM	Dominguez Mantes Albert	SIM	Henking Caspar	STED
19.05.2025.	Kiris Alara	Light Sheet	Dao Alexandre Michel Van Nam	Light tweezers	Maximilian Grobbelaar	Optogenetics
26.05.2025.	Klose Chloé	Endoscopic tecniques	D'Agostino Alice	OCT	Salem Andrew	gle cell quantitative measurement
	Akeddar Hamza	SMLM-blinking				

Biophotonics

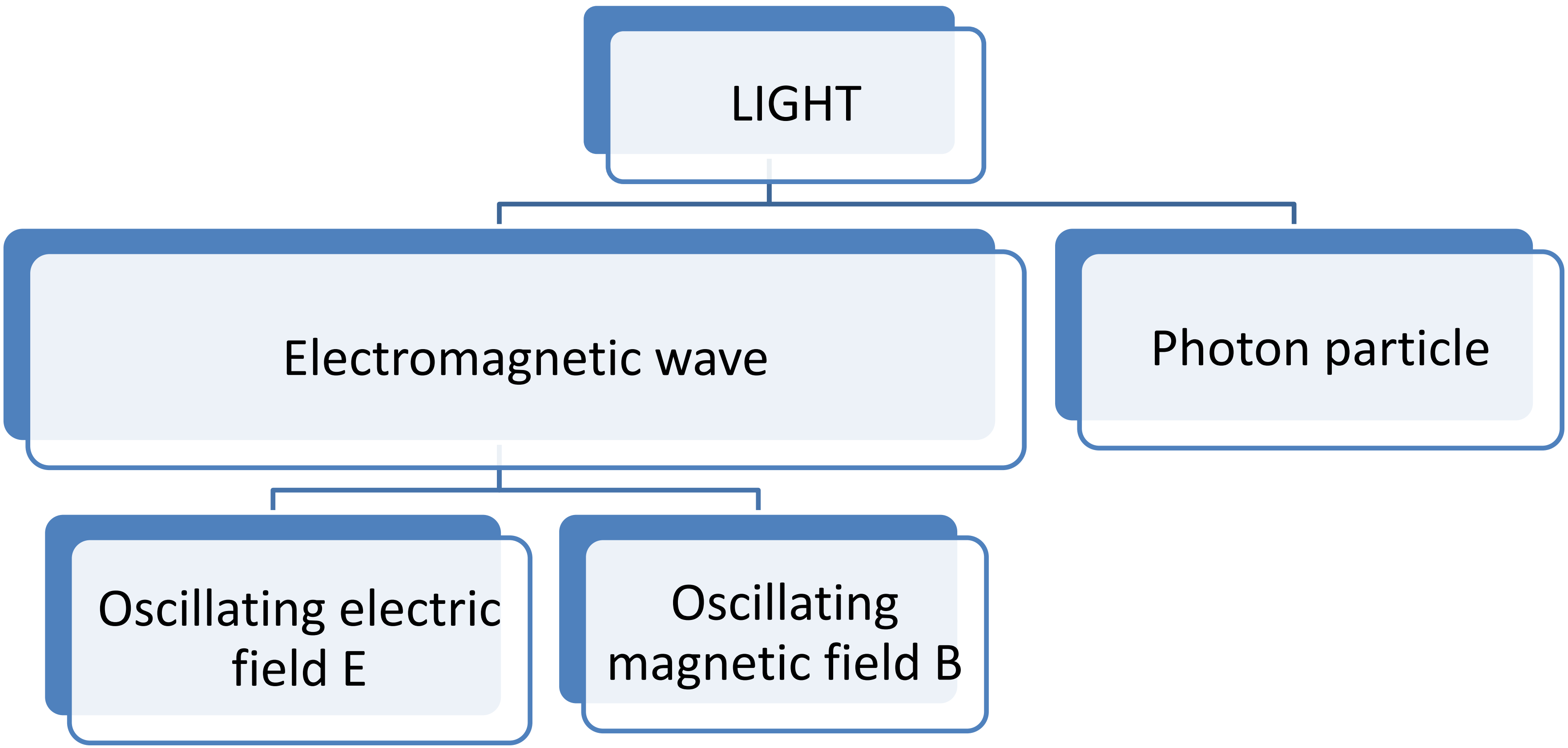
- Biophotonics, the ‘marriage’ between **photonics** and **biology**, is an emerging interdisciplinary frontier that deals with **interactions between light and biological matter.**
- Through the integration of four principle technologies, ***lasers, photonics, nanotechnology, and biotechnology***, ***biophotonics*** offers immense hope for the early detection and treatment of diseases and for new modalities of **light guided** and **light activated therapies.**



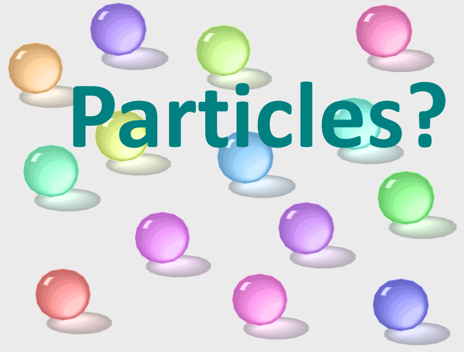
Interactions between light and biological matter

- An understanding of properties of light and matter forms very fundamental; basis to create an insight into the nature of interactions between light and biological systems

- NATURE Of LIGHT



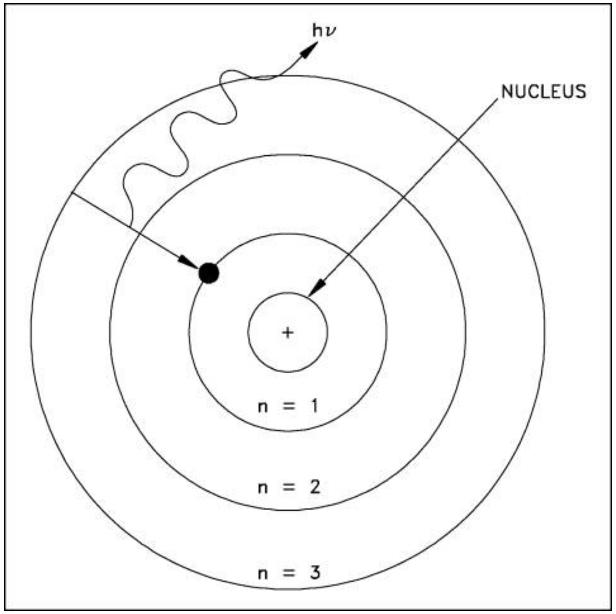
What is light?



What is light?

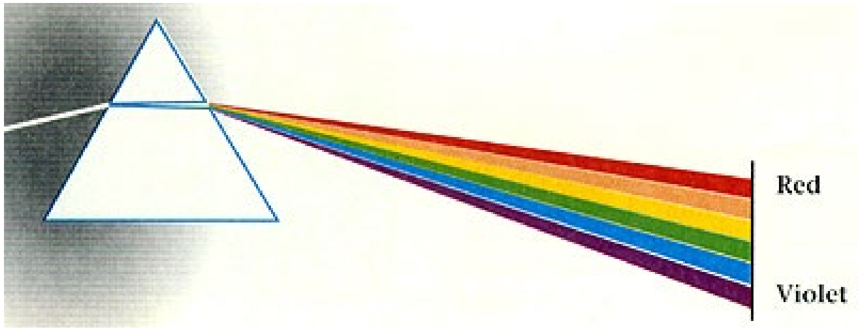
- Light is an **electromagnetic field** consisting of oscillating electric and magnetic disturbances that can propagate **as a wave** trough the vacuum as well as through the medium
- However, modern theory, of quantum mechanics also imparts **a particle like description** of light.

- What is a photon a how light is generated ?



What is light?

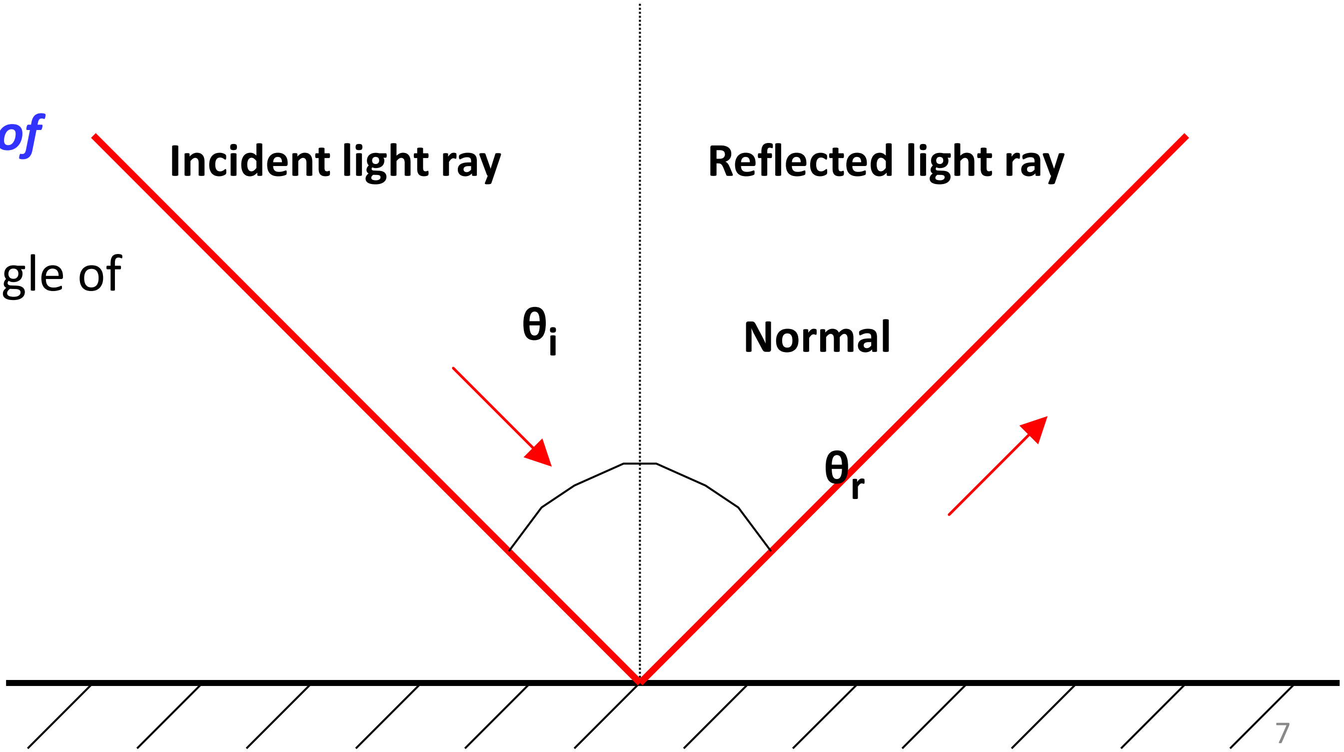
- 17th century known facts about light



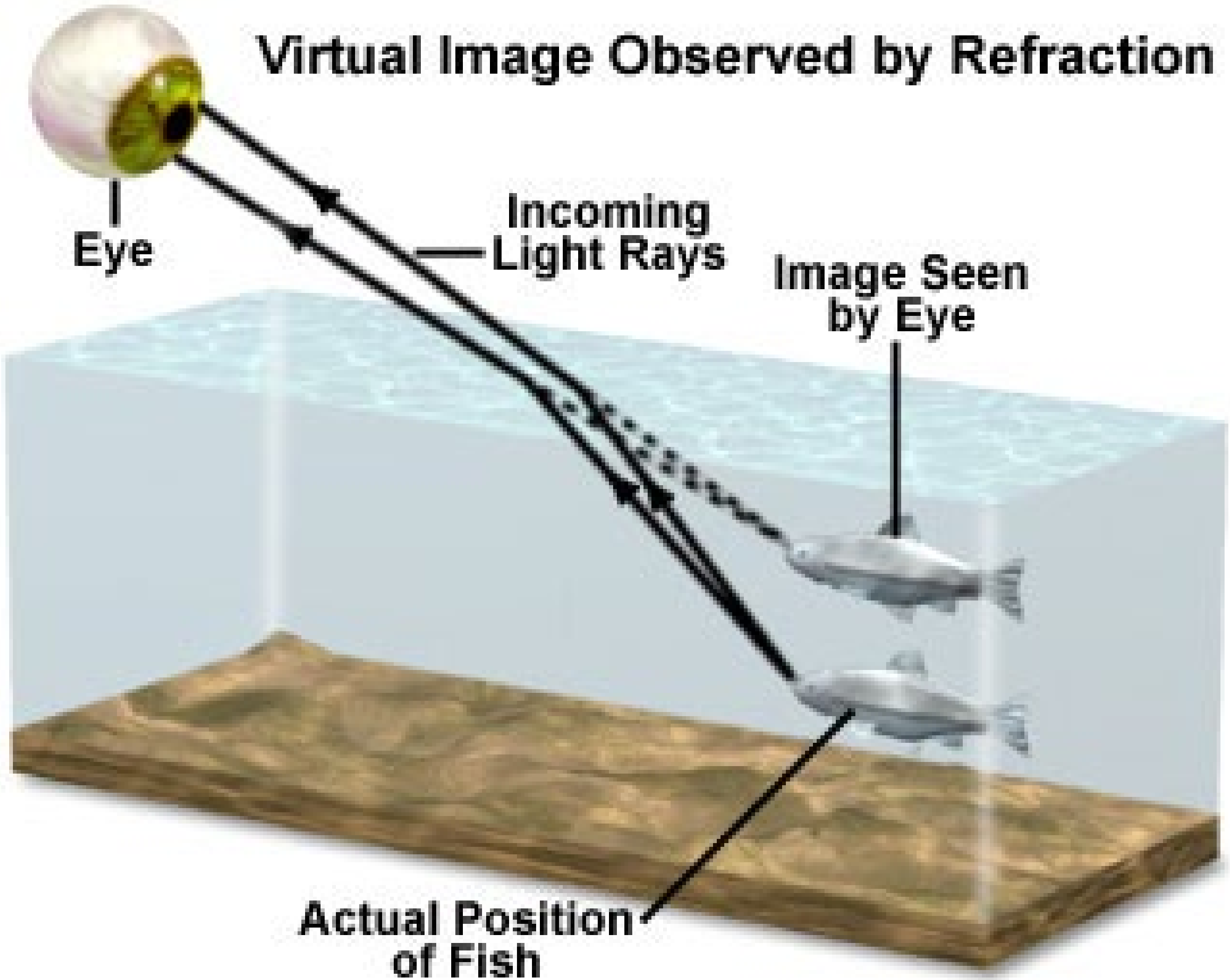
- Light has different colours.
- Light can travel through a vacuum.
- Light can be reflected and refracted, these processes are described by the *Laws of Reflection* and *Laws of Refraction*.

According to the ***Laws of Reflection***,

angle of incidence = angle of reflection ($\vartheta_i = \vartheta_r$)



Snell's Law



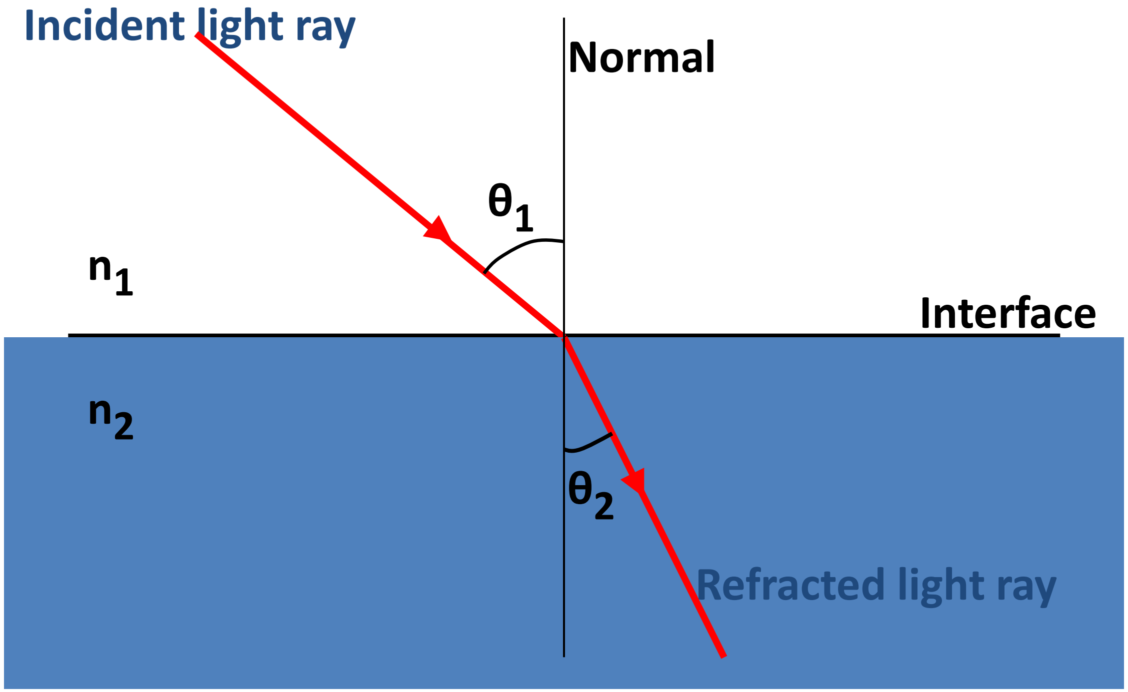
Virtual Image Observed by Refraction
Eye
Incoming
Light Rays
Image Seen
by Eye
Actual Position
of Fish

What is light?

- Willebrord **Snell** discovered in 1621 that when a wave travels from a medium of refractive index, n_1, to one of different refractive index, n_2,

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

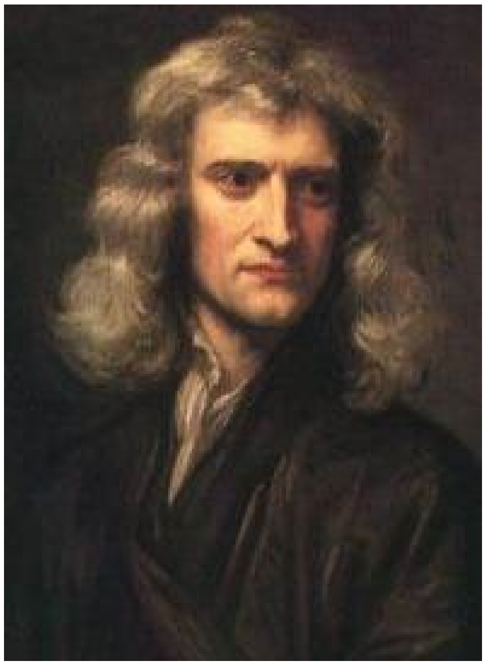
  This relationship is called Snell's Law



Light bends towards the normal when it travels from an optically less dense medium to an optically more dense medium.

What is light?

- In the17th century, two scientists had different views about the nature of light …



Light is particles

No! Light is waves

Isaac Newton
1643 - 1727

Christian Huygens
1629 - 1695

What is light?

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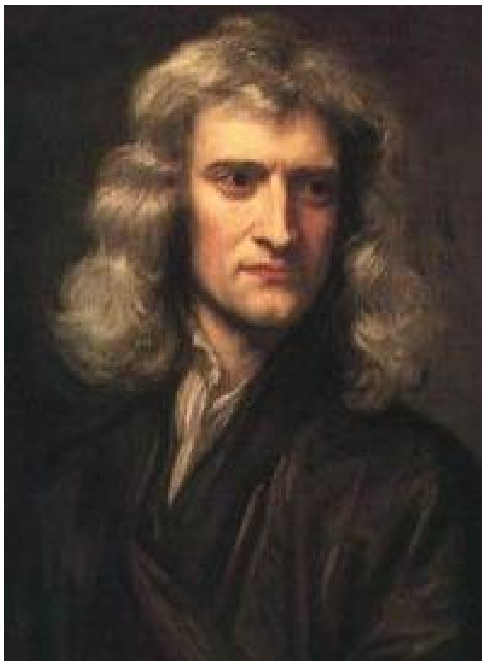

Light is particles

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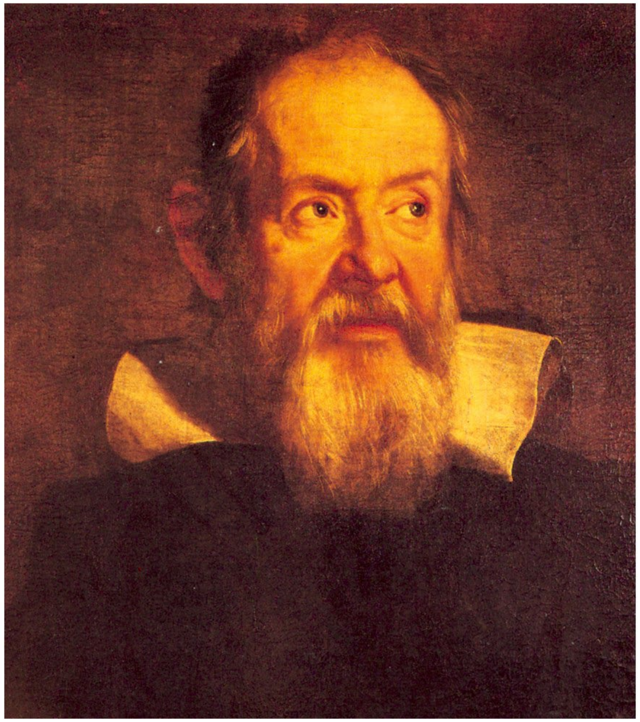
What is light?-Wave

- ***Light is an electromagnetic field consisting of oscillating electric and magnetic disturbances that can propagate as a wave trough the vacuum as well as through the medium.***
- How **fast** does light travel? How can this speed be measured?
- Every major scientist from Aristotle to Galileo to Newton to Michelson has pondered on the speed of light.



1564–1642

Galileo tried **unsuccessfully** to determine the speed of light using an assistant with a lantern on a distant hilltop

Why?

"I have not been able to ascertain with certainty whether the appearance of the opposite light was instantaneous or not; but if not instantaneous it is extraordinarily rapid – I should call it momentary."

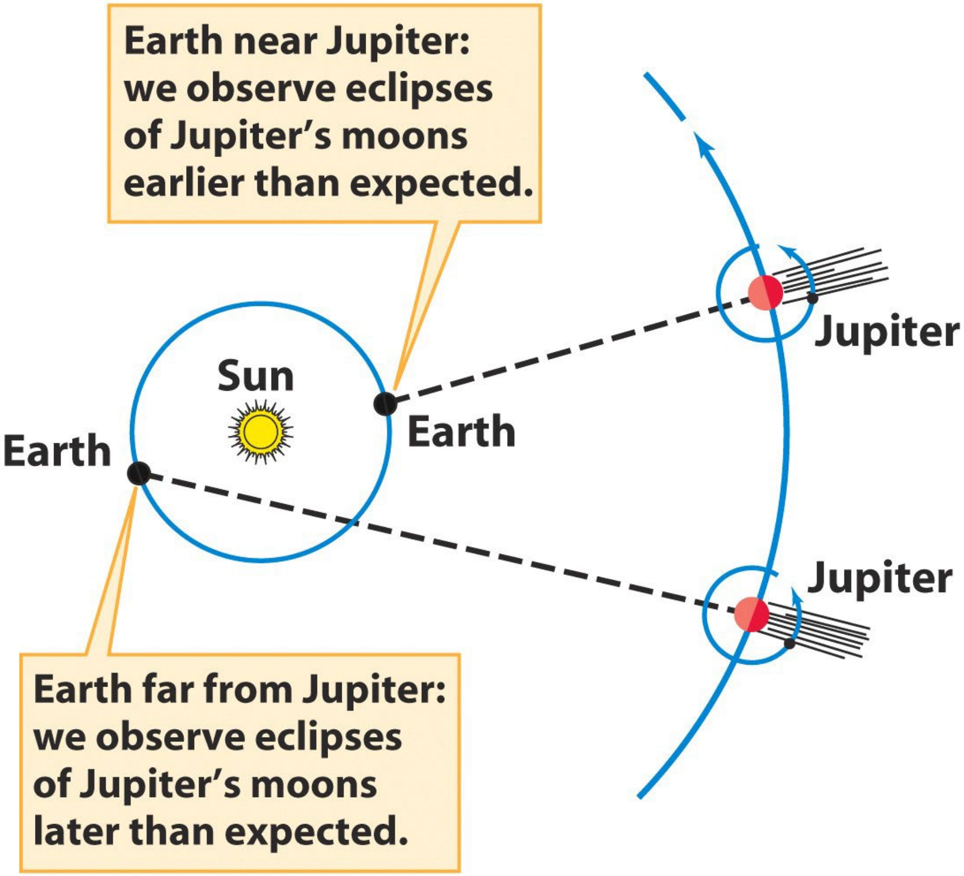
How fast does light travel? How can this speed be measured?

- Light travels through empty space at a speed of 300,000 km/s
- 299 792 456.2 ± 1.1 m/s

In 1676, Danish astronomer Olaus Rømer discovered that the exact time of eclipses of Jupiter's moons depended on the distance of Jupiter to Earth

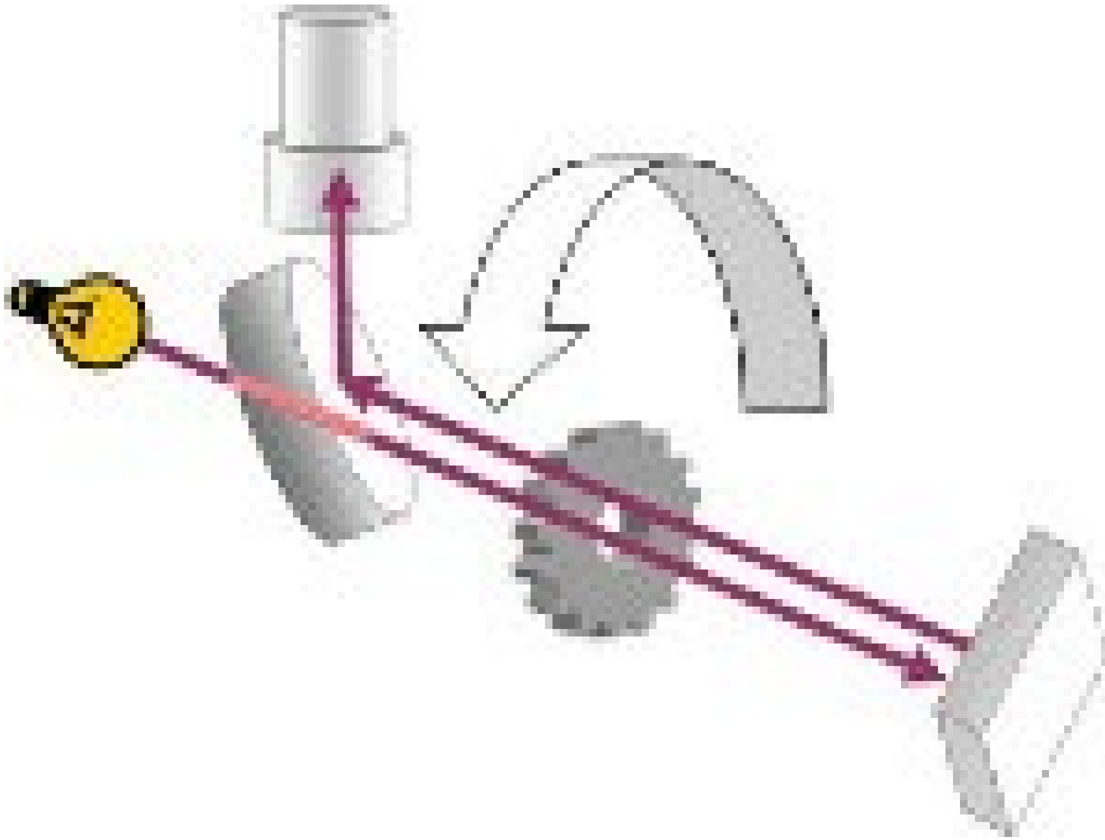
This happens because it takes varying times for light to travel the varying distance between Earth and Jupiter

Using d=rt with a known distance and a measured time gave the speed (rate) of the light



2.20×10^8 m/s which gives a percent error of about 26% from the currently accepted value.

How fast does light travel? How can this speed be measured?



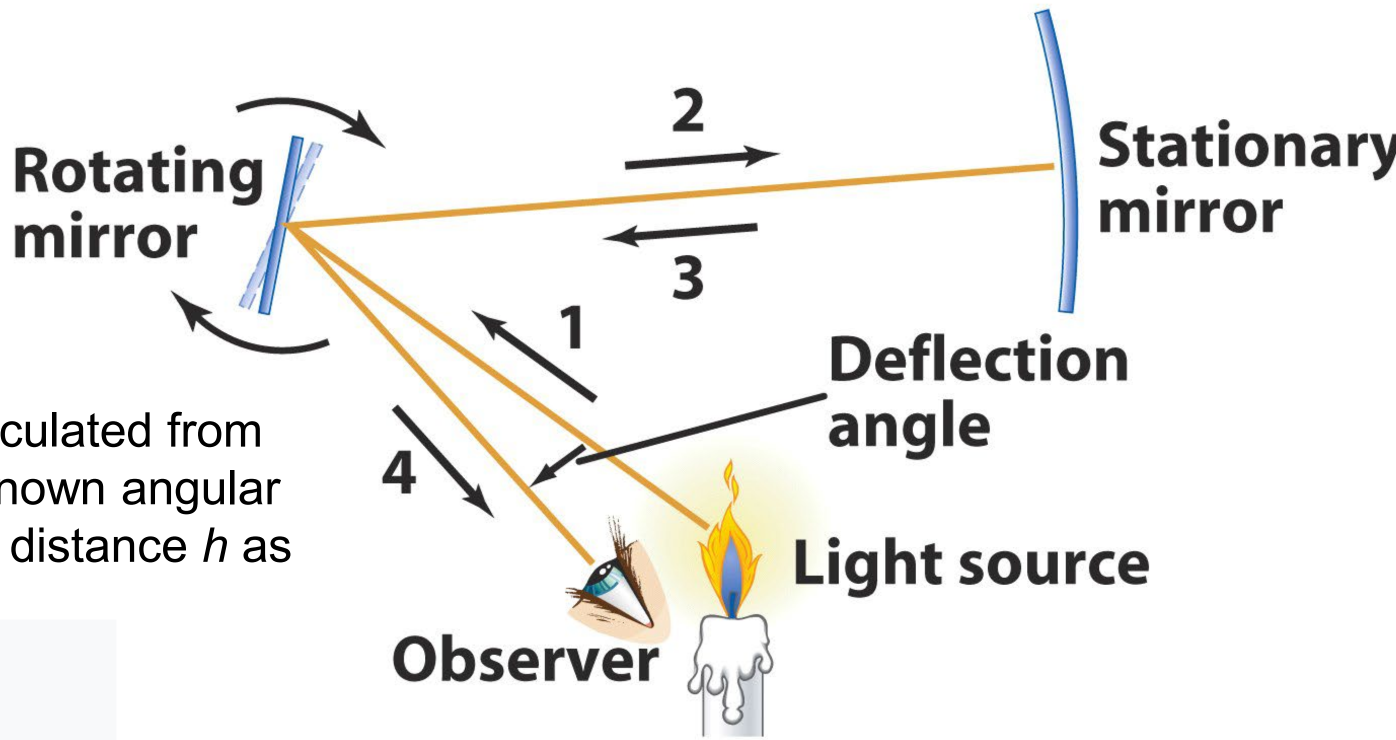
In 1850 Fizeau and Foucalt also experimented with light by bouncing it off a rotating mirror and measuring time

Using simple math he obtained a value of 3.15×10^8m/s; roughly 5% too high.

Leon Foucault

If the distance between mirrors is *h*, the time between the first and second reflections on the rotating mirror is $2h/c$ (c = speed of light). If the mirror rotates at a known constant angular rate ω, it changes angle during the light roundtrip by an amount θ given by

$$\theta = \frac{2h\omega}{c} = \omega$$



The speed of light is calculated from the observed angle θ, known angular speed ω and measured distance h as

$$c = \frac{2\omega h}{\theta}\ .$$

History of measurements of c (in km/s)

1675	Rømer and Huygens, moons of Jupiter	220,000[85][106]
1729	James Bradley, aberration of light	301,000[91]
1849	Hippolyte Fizeau, toothed wheel	315,000[91]
1862	Léon Foucault, rotating mirror	298,000±500[91]
1907	Rosa and Dorsey, EM constants	299,710±30[96][97]
1926	Albert Michelson, rotating mirror	299,796±4[107]
1950	Essen and Gordon-Smith, cavity resonator	299,792.5±3.0[99]
1958	K.D. Froome, radio interferometry	299,792.50±0.10[103]
1972	Evenson *et al.*, laser interferometry	299,792.456.2±0.0011[105]
1983	17th CGPM, definition of the metre	299,792.458 (exact)[81]

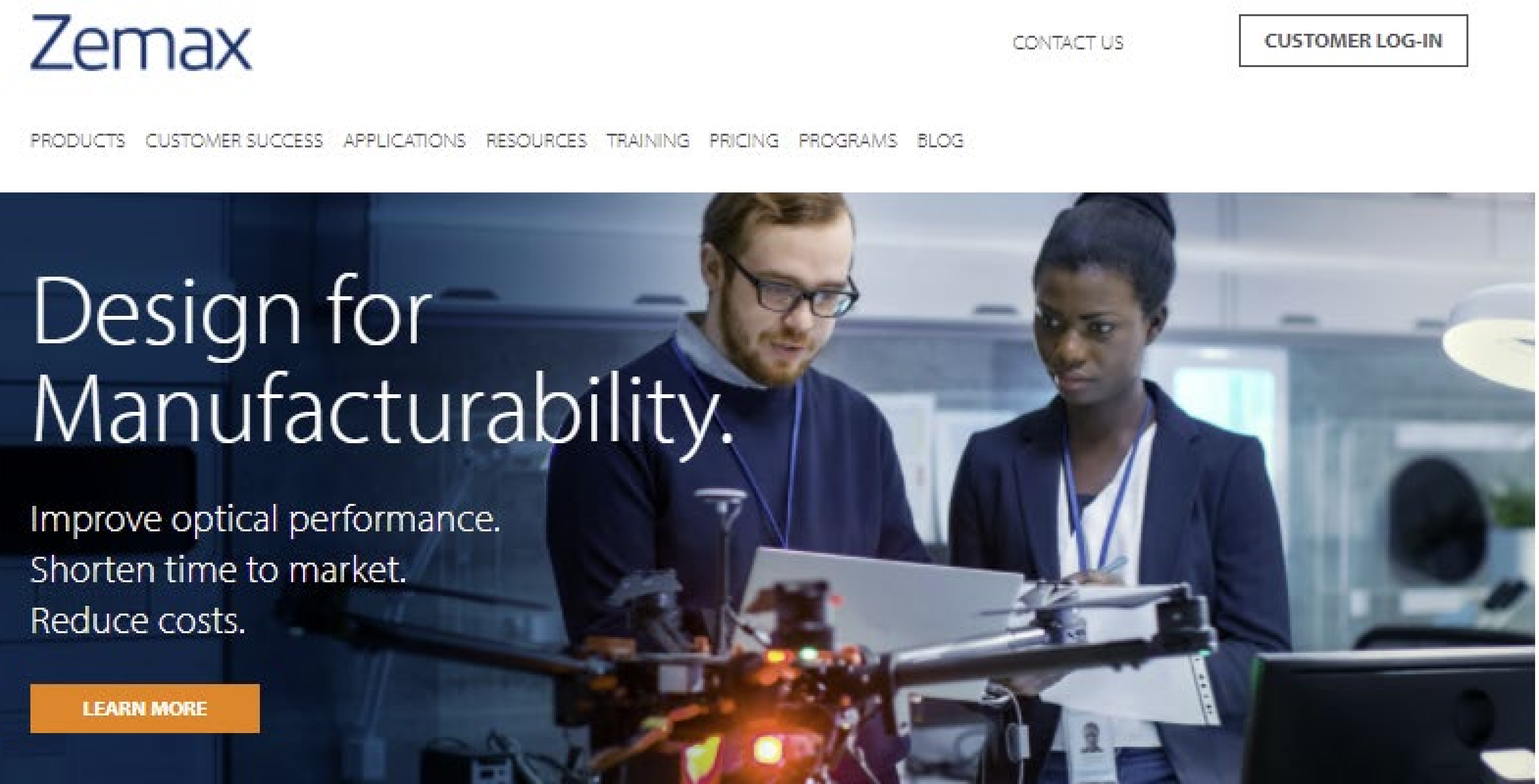
Now the speed of light is constant. It will never have to be measured again.

- Source Wikipedia

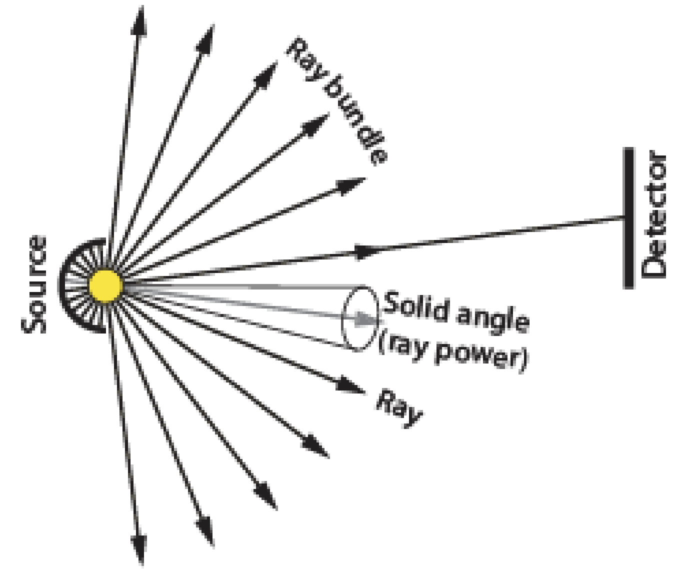
Geometrical optics

- Ray optics is a powerful and visual method to describe optical systems with extents a much larger than the wavelength λ, that is in the limit of $\lambda \ll a$.

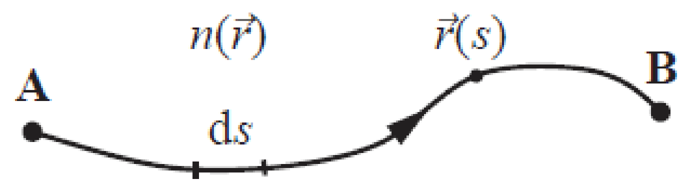
- The importance of ray optics results from the simplicity of its basic rules and the broad usefulness for analyzing and designing optical systems. Therefore, many optical **systems in industry are designed with advanced ray tracing programs that implement the rules of geometrical optics.**



Geometrical optics-short recapitulation



- The optical power emitted by a light source is assigned to rays traveling away from the source. As illustrated in **Figure each ray transports a fractional power equal to the optical power emitted into the solid angle assigned to the ray leaving the source**.
- All-together, the rays carry the optical power of **the source** in the form of a ray bundle. Rays can be observed if they reach an optical detector. **The detector** receives the optical power of the incident rays, that is the power assigned to these rays and transmitted through the optical system.



Along a physical path $\vec{r}(s)$ from point **A** to point **B,** the ray travels the physical distance

$$d = \int_{\mathbf{A}}^{\mathbf{B}} \mathrm{d}s = s(\mathbf{B}) - s(\mathbf{A}),$$

where $\mathrm{d}s$ is the differential element of length along the path $\vec{r}(s)$. The rays travel from **A** to **B** in time interval $\Delta t = \int_{\mathbf{A}}^{\mathbf{B}} n(\vec{r}(s))\,\mathrm{d}s/c_0.$ This time interval is proportional to the

optical path length

$$\mathrm{OPL} = \int_{\mathbf{A}}^{\mathbf{B}} n(\vec{r}(s))\,\mathrm{d}s.$$

Geometrical optics-short recapitulation

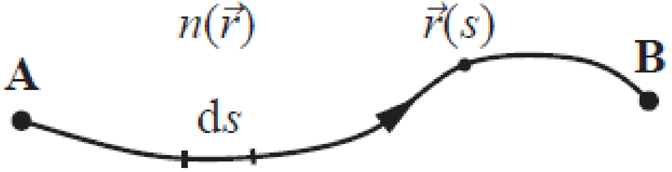
- In a homogeneous medium, the refraction index $n(\vec{r})$ is constant and the OPL is the product $\mathrm{OPL} = nd.$

Pierre de Fermat found that rays travel along a path $\vec{r}(s)$ from **A** to **B** such that the OPL is invariant with respect to neighboring paths, which is known as

Fermat's principle.

In other words, the rate of OPL change is zero upon small path variations.

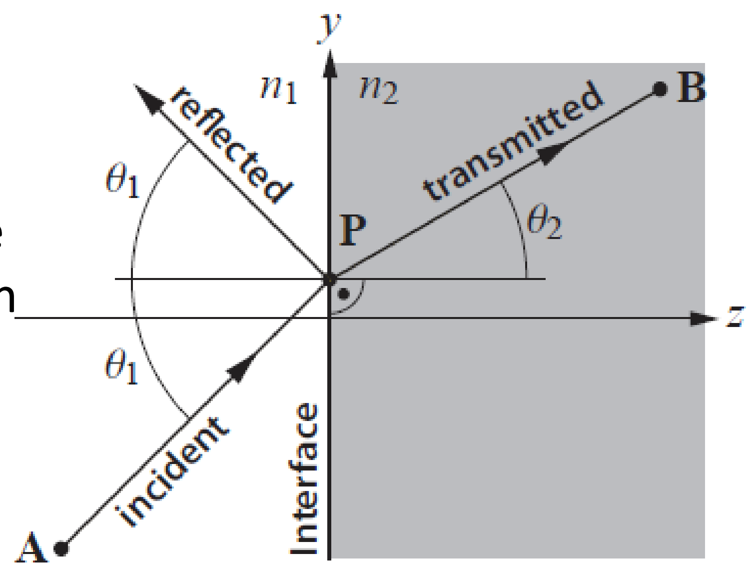
$$\delta(\mathrm{OPL}) = \delta \int_{\mathbf{A}}^{\mathbf{B}} n(\vec{r}(s))\, \mathrm{d}s = 0$$



Geometrical optics: Refraction and reflection

- By applying Fermat's principle, we derive the law of refraction and reflection.
- A ray connecting point **A** = (y_1, z_1) with point **B** = (y_2, z_2) via point P = (y, 0) on the optical interface at z = 0 between the two media with refraction indices n_1 and n_2. For an arbitrary position y, the **OPL** from **A** to **B** is given by

$$\mathrm{OPL} = n_1\sqrt{z_1^2 + (y - y_1)^2} + n_2\sqrt{z_2^2 + (y_2 - y)^2}.$$



According to Fermat, we find P by setting zero the derivative of the OPL with respect to the unknown coordinate y.

$$\frac{\partial}{\partial y}\mathrm{OPL} = \frac{n_1(y - y_1)}{\sqrt{z_1^2 + (y - y_1)^2}} - \frac{n_2(y_2 - y)}{\sqrt{z_2^2 + (y_2 - y)^2}} = 0$$

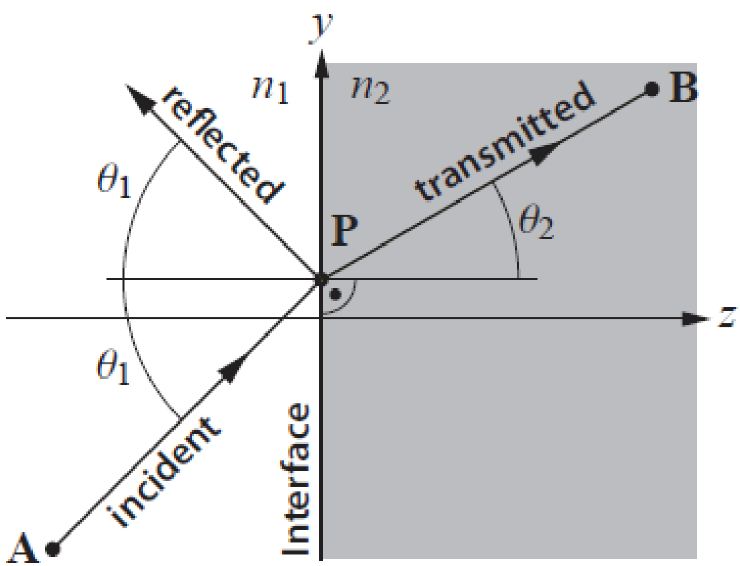
We notice that the ratio $(y - y_1)/\sqrt{z_1^2 + (y - y_1)^2}$ can be expressed by the sine of the incidence angle θ_1.

Geometrical optics: Refraction and reflection

Correspondingly, the exit angle of the transmitted ray is $\theta_2 = (y_2 - y)/\sqrt{z_2^2 + (y_2 - y)^2}$

These angles are measured with respect to the interface normal in P(y, 0). Insertion into equation

$$\frac{\partial}{\partial y}\mathrm{OPL} = \frac{n_1(y - y_1)}{\sqrt{z_1^2 + (y - y_1)^2}} - \frac{n_2(y_2 - y)}{\sqrt{z_2^2 + (y_2 - y)^2}} = 0$$



leads then to **Snell's law of refraction** at an interface.

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

Hence, a ray incident at an angle θ1 is refracted at the interface to an exit angle

$$\theta_2 = \arcsin\left(\frac{n_1}{n_2}\sin\theta_1\right).$$

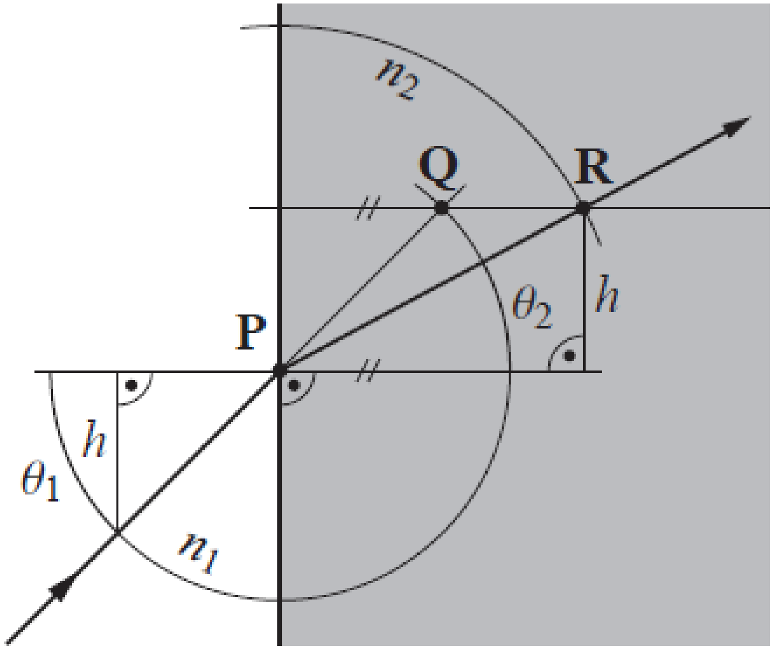
In case of a **reflective interface, the reflected ray stays in medium 1**. Therefore, we can simply set n2 = n1 and find the angle for the reflected ray as being equal to the incidence angle θ1.

How to construct refracted rays?

We start with

- the intersection point **P** of the incident ray and the interface. We prolongate the incident ray and intersect it with a circle of radius n_1 around **P.**

- The intersection point **Q** defines the distance $h = n_1 \sin \theta_1$ from the interface normal through **P.** Next, we draw a line through **Q** parallel to the interface normal and intersect



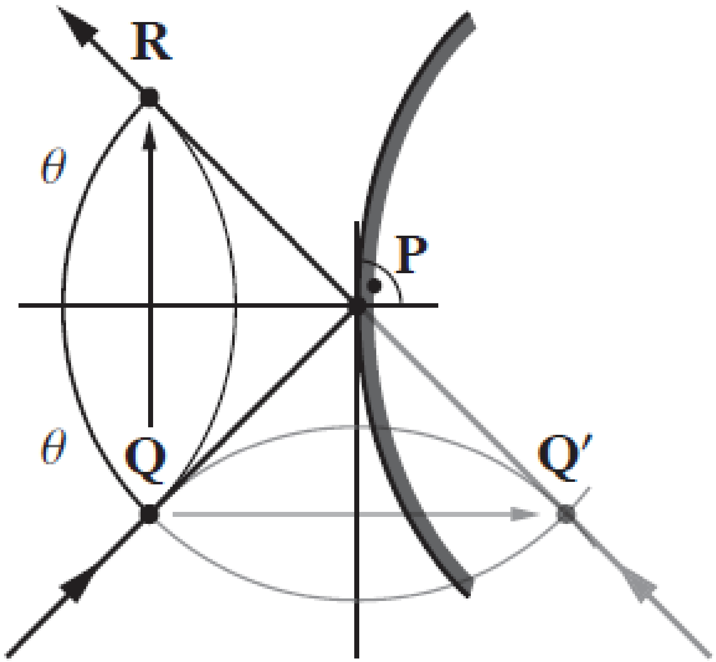
it with a circle of radius n_2 around **P**. This defines point **R** that is at the same distance $h = n_2 \sin \theta_2$ from the interface normal as **Q**, which fulfills ***Snell's law***. The refracted ray is then the straight line from **P** through **R**.

How to construct reflected rays?

We start with

- with the intersection point **P** of the incident ray and the mirroring interface. We reflect a point **Q** on the incident ray at the interface normal through **P** and draw the reflected ray from **P** through the reflection **R.**

- Alternatively, we reflect **Q** at the interface tangent through **P**. Then, the reflected ray starts at **P** but appears to come from **Q’,** the virtual mirror source of **Q.**

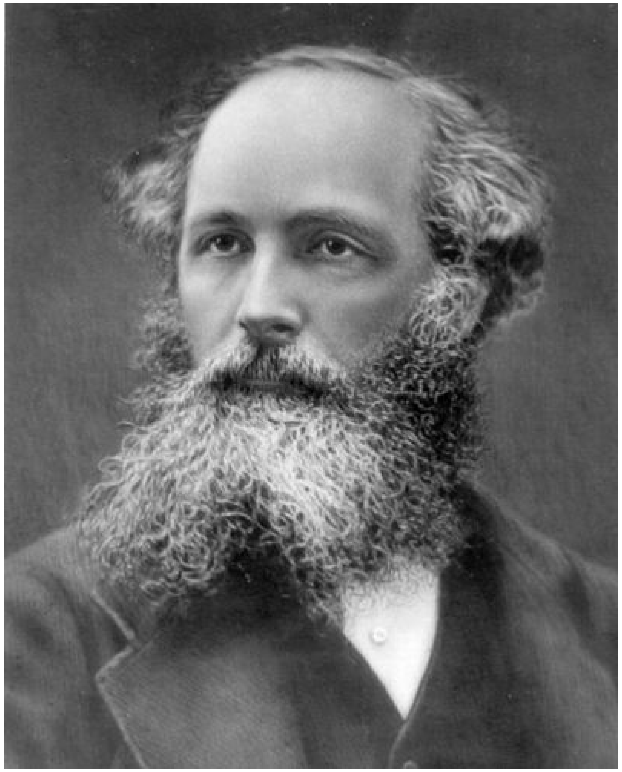


The Nature of Light

- In the 1860s, the Scottish mathematician and physicist James Clerk Maxwell succeeded in describing all the basic properties of electricity and magnetism in four equations
- This mathematical achievement demonstrated that electric and magnetic forces are really two aspects of the same phenomenon, which we now call **electromagnetism**

$$\vec{\nabla} \cdot \vec{E} = 0 \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{B} = \mu\varepsilon \frac{\partial \vec{E}}{\partial t}$$



where $\vec{E}$ is the electric field, $\vec{B}$ is the magnetic field, ε is the **permittivity,** and μ is the **permeability** of the medium.

As written, they assume no charges (or free space).

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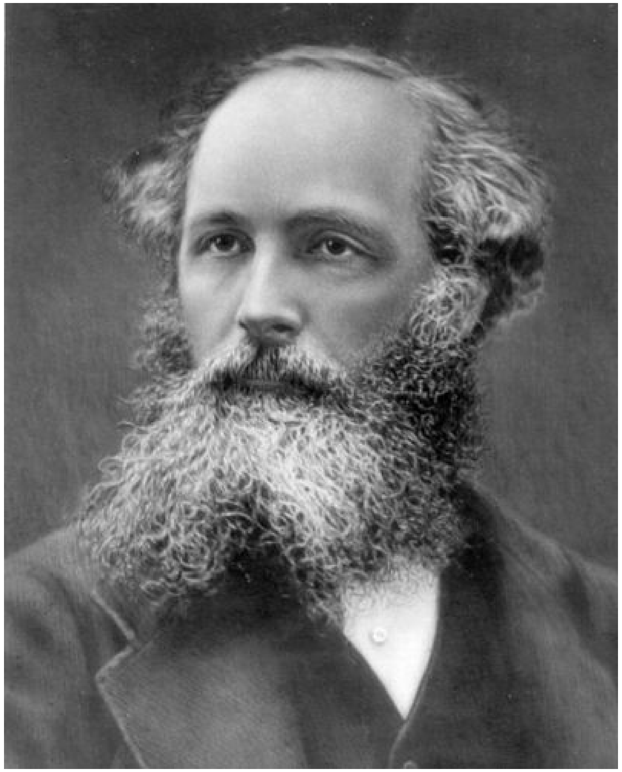

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The Nature of Light

- Maxwell was able to derive the speed of EM waves in vacuum. EM waves do not need a medium to travel through.

ε_0 = permittivity of free space (E field)

μ_0 = permeability of free space (M Field)

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

$$= \frac{1}{\sqrt{\left(8.85 \times 10^{-12}\ \mathrm{C^2/Nm^2}\right)\left(4\pi \times 10^{-7}\ \mathrm{Tm/A}\right)}}$$

$$= 3.00 \times 10^{8}\ \mathrm{m/s}$$

When Hertz found this solution, he recognized that the value of this quantity was the speed already known for light, which strongly suggested that light was a wave, and part of the electromagnetic spectrum, along with radio waves.

Wavelength and Frequency

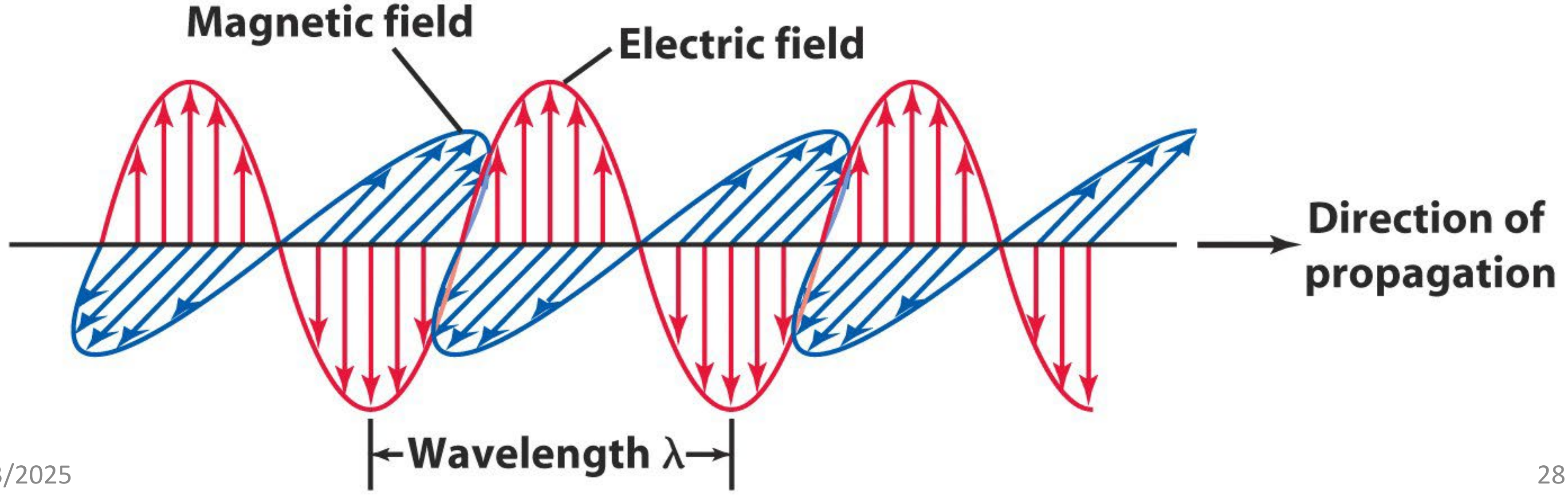
- **Frequency and wavelength** of an electromagnetic wave

$$\nu = \frac{c}{\lambda}$$

ν= frequency of an electromagnetic wave in [Hz]

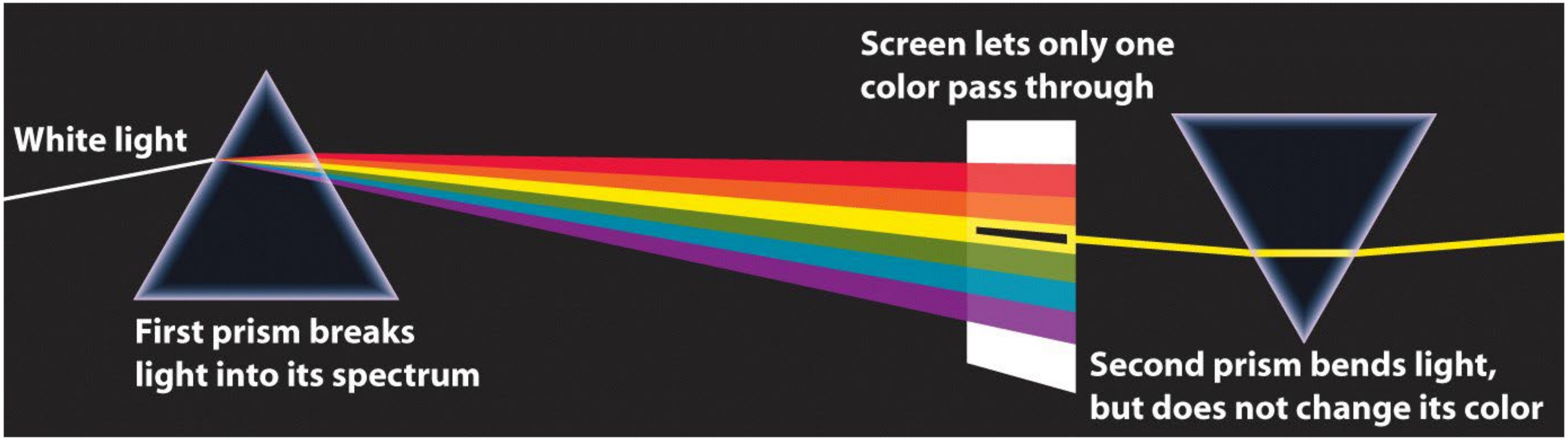
c= speed of light =$3x10^8$ [m/s]

λ= wavelength of the wave in [m]

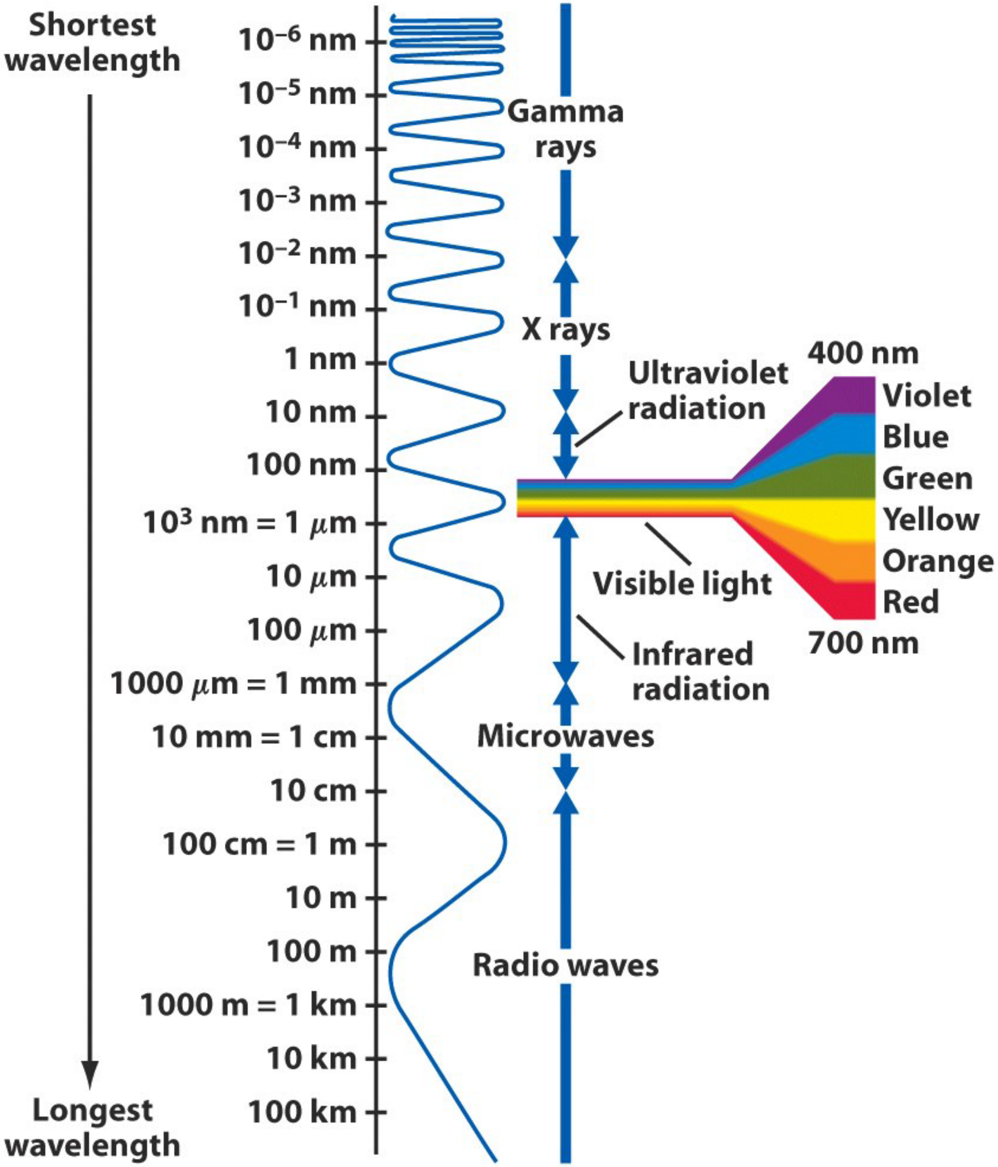


Light is electromagnetic radiation

- Light is electromagnetic radiation and it is characterized by its wavelength (λ)



Electromagnetic spectrum



- Because of its electric and magnetic properties, light is also called **electromagnetic radiation**
- Visible light falls in the 400 to 700 nm range
- Stars, galaxies and other objects emit EM radiation in all wavelengths

So, why can we only see a small portion of these E-M waves?

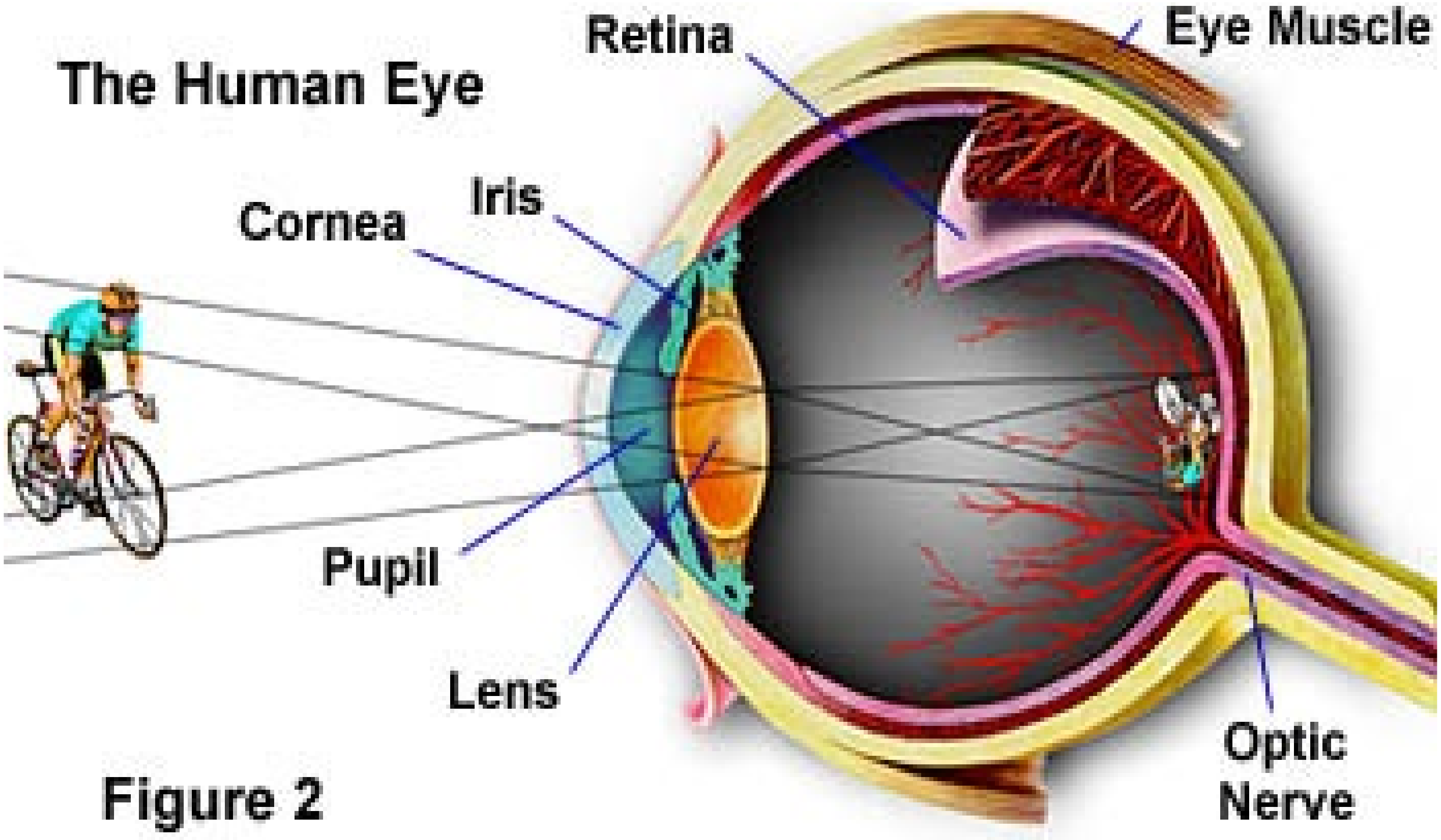


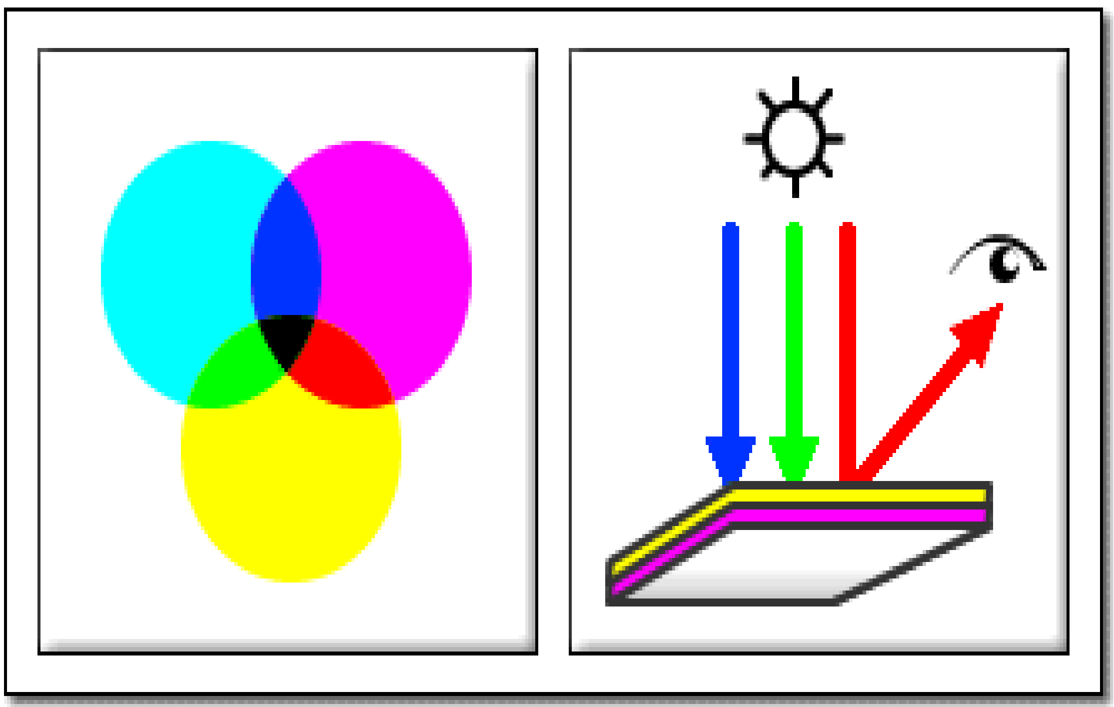
Figure 2

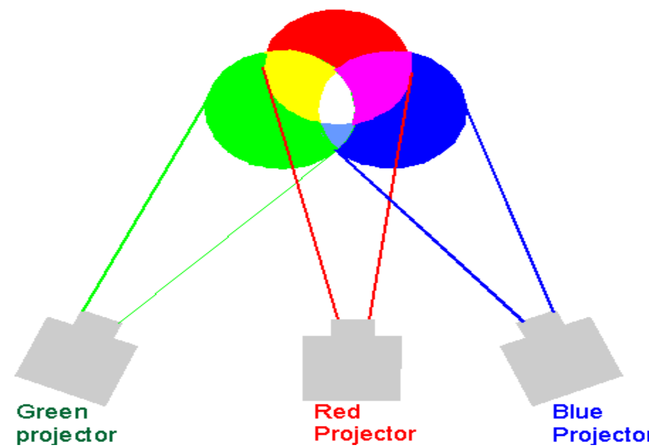
Color by Addition of Light

- 3 Primary Colors of <u>Light</u>
- Red
- Green
- Blue

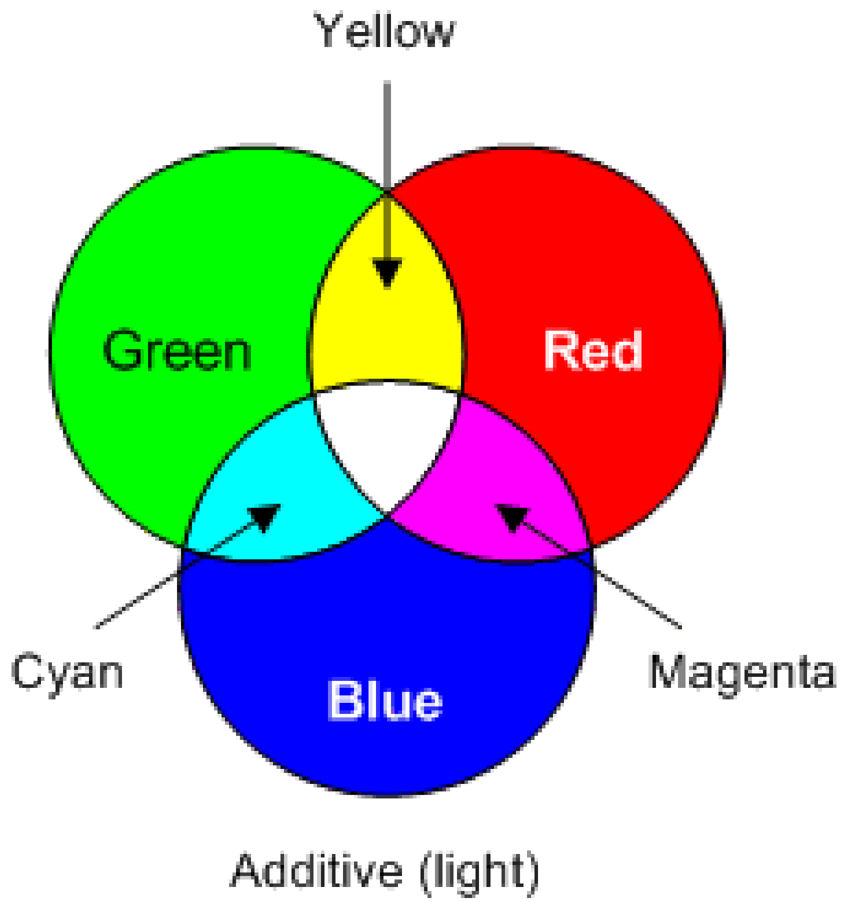
- 3 Complimentary Colors of <u>Light</u>
- Yellow = red & green
- Cyan = green & blue
- Magenta = blue & red

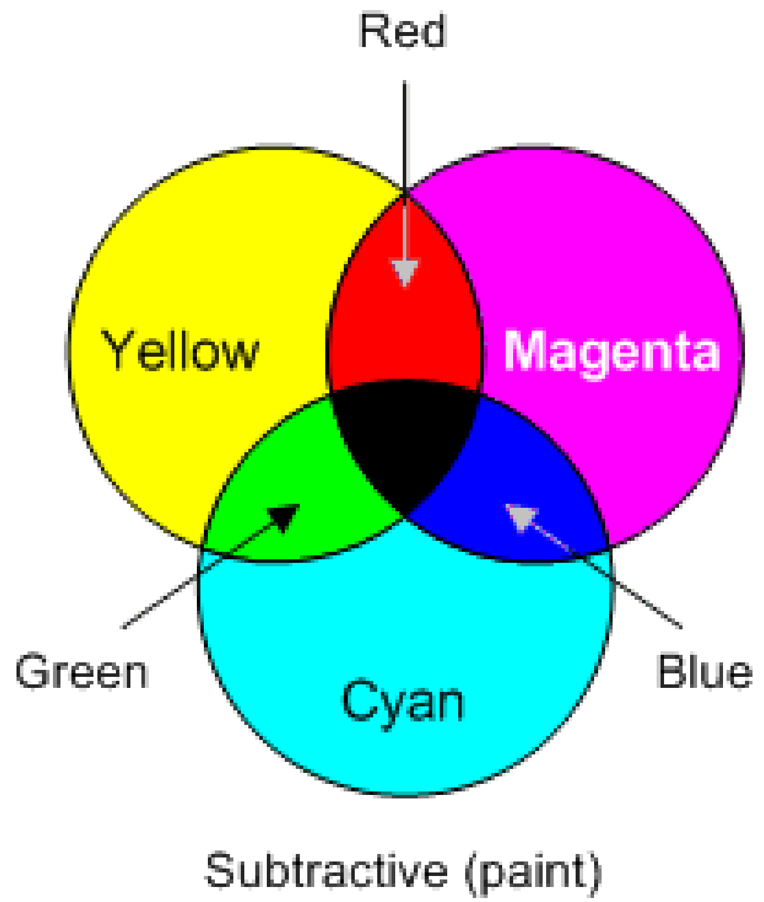
- White = red & green & blue





Color by Addition and Subtraction





Additive and subtractive color combinations

What color is the dress ?

http://blogs.discovermagazine.com/d-brief/2015/02/27/what-color-is-the-dress/

Visible light

- We know that the light waves enter our eye, and stimulate parts of it that cause a electrical impulse to be sent to the brain which creates this visual image.

- We know that when waves run into a boundary they are partially transmitted and partially reflected.

- Light behaves as a wave, so it to is reflected.

- Therefore, **an object does not need to emit photons itself to be seen, it just has to reflect/scatters light back to our eyes where we can detect it.**

- Objects that do not allow light to pass through them are called **opaque.**
- Objects that allow light to pass through them are considered **transparent**.
- Objects in between are called **translucent**

A person in infrared -color coded image -red is hottest


FLIR