Photonics - Introduction

V Sharma

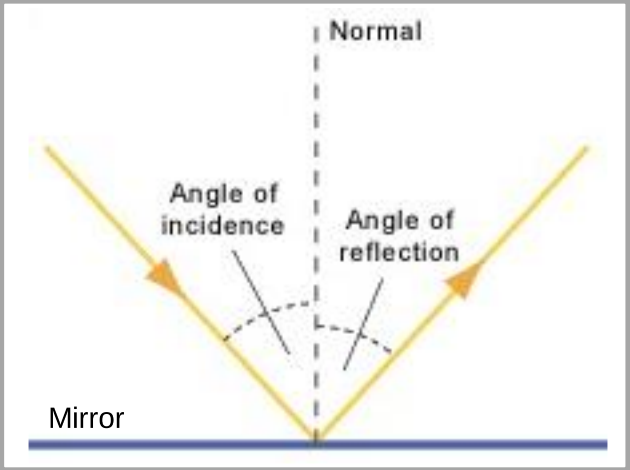
Textbooks:
"Optics" by E. Hecht, 4th edition (Addison-Wesley)

Grades:

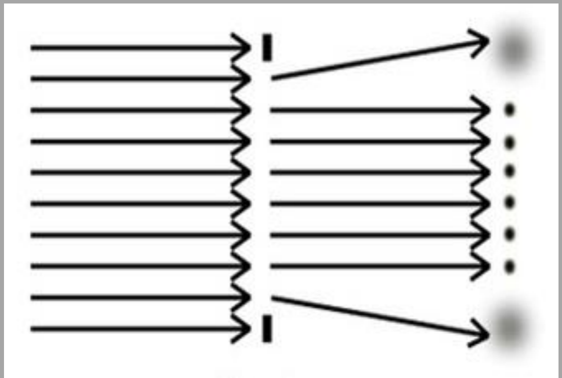
- 30% class exams (surprise) or/and assignments: continuous assessment ,
- 70% final exam → 28th NOVEMBER 2016

The History of Optics

Humans have been trying to understand light and its properties for millennia.

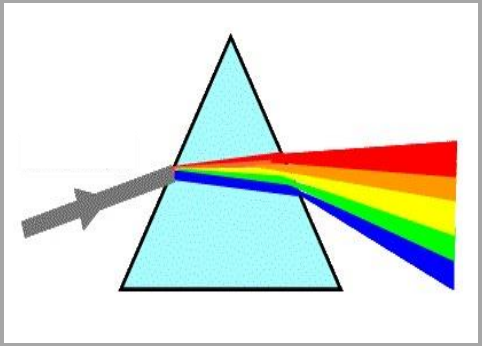


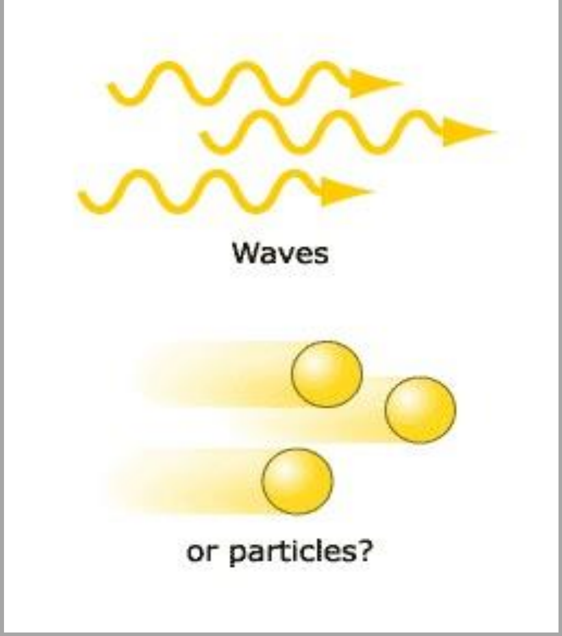
Reflection



Diffraction

Refraction and dispersion





Is light composed of waves or particles?

Optics in Ancient History

A mirror was discovered in workers' quarters near the tomb of Pharaoh Sesostris II (1900 BCE).

Lens from the Assyrian Palace of Nimrud (Iraq) (750 BCE).

Pyramid of Sesostris II

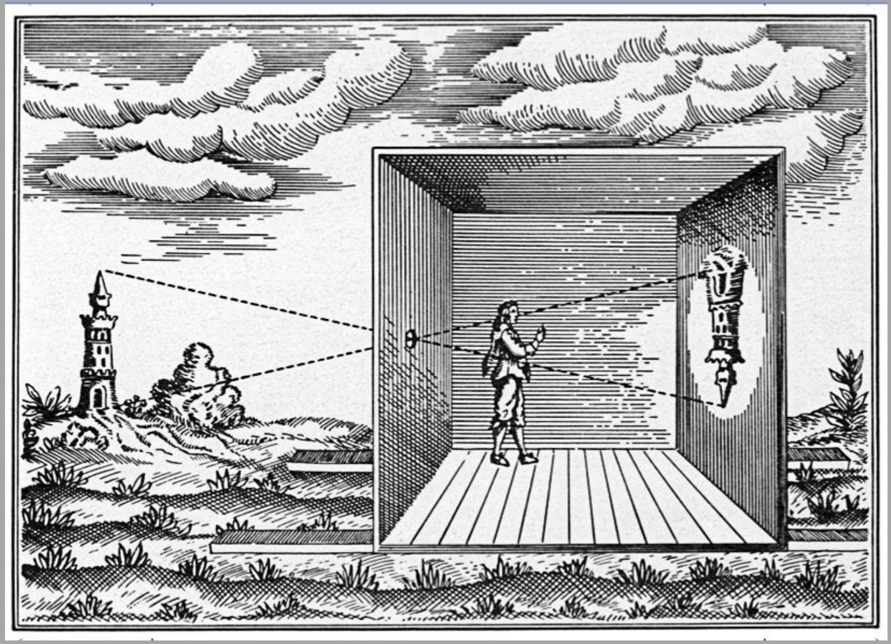
Ancient Greeks (500-300 BCE)

- Burning glass (refraction) mentioned by Aristophanes (424 BCE).
- Law of reflection: "Optics" by Euclid (300 BCE).
- Refraction in water mentioned by Plato in "The Republic."
- But Euclid thought that the eye emits rays that reflect off objects (simulacra).

The Pinhole Camera and Light Rays

The pinhole camera was first described by Chinese philosopher, Mozi (470 - 390 BCE).

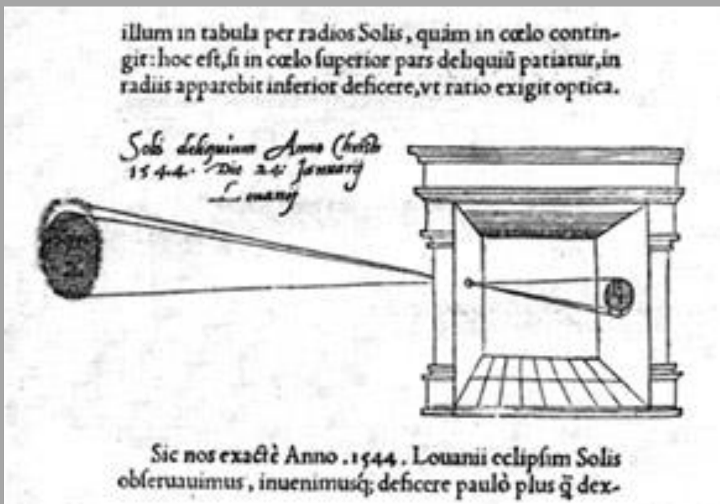
It could be an entire room or a small box.



Pinhole camera image

The pinhole camera, also called the camera obscura (“darkened room”), established the notion of **light rays** and **geometrical optics**.

The Camera Obscura

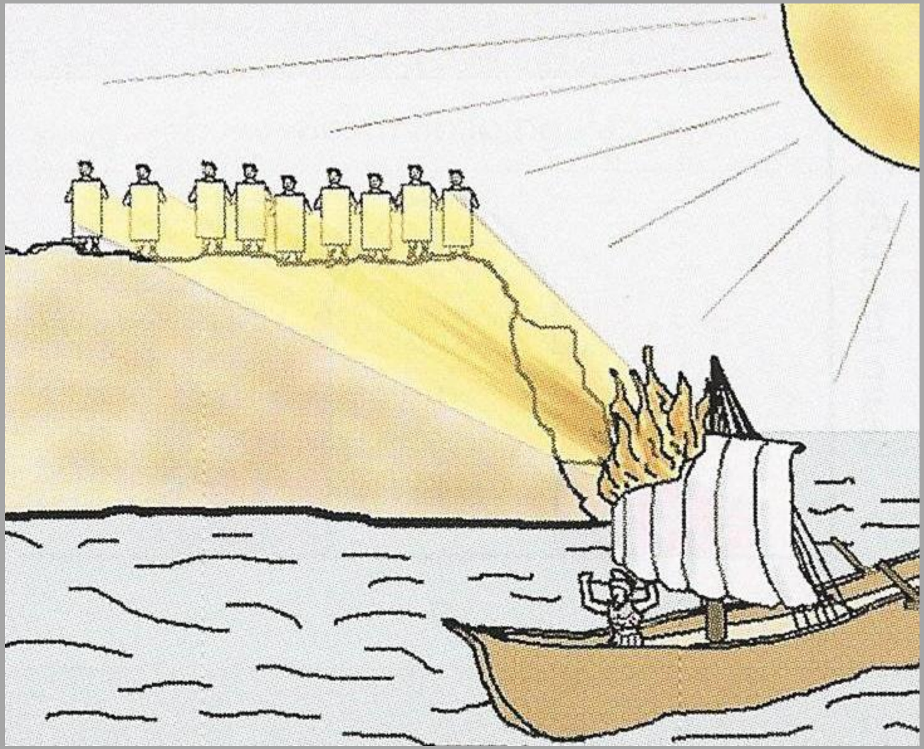


A dark room with a small hole in a wall. The term camera obscura means “dark room” in Latin. Renaissance painters used them to paint realistic paintings. Vermeer painted “The Girl with a Pearl Earring” (1665-7) using one.

A nice view of a camera obscura is in the movie, *Addicted to Love*, starring Matthew Broderick (who plays an astronomer) and Meg Ryan, who set one up to spy on their former lovers.

Ancient Greeks: Ancient Light Weapons

Early Greek and Roman historians report that Archimedes equipped several hundred people with metal mirrors to focus sunlight onto Roman warships in the battle of Syracuse (213-211 BCE).



This story is probably apocryphal.

Ancient Greeks: Ancient light weapons

And despite a failed attempt by the Discovery Channel's Myth Busters to replicate the feat, in 2005 MIT undergrads set up 127 mirrors in a courtyard to test the idea…

Ancient Greeks: Ancient light weapons

And despite a failed attempt by the Discovery Channel's Myth Busters to replicate the feat, in 2005 MIT undergrads set up 127 mirrors in a courtyard to test the idea…

This story is not apocryphal!

Optics in the Middle Ages: Alhazen

Arab scientist Alhazen (~1000 AD) studied spherical and parabolic mirrors.

Alhazen correctly proposed that the eyes passively receive light reflected from objects, rather than emanating light rays themselves.

He studied the process of sight, the structure of the eye, image formation in the eye, and the visual system.

He wrote a seven-volume treatise on optics in 1021.

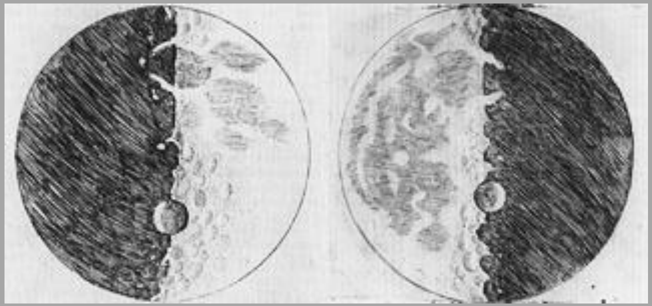
Abu Ali Hasan Ibn al-Haitham

Optics in Early 17th Century Europe: the Telescope

Hans Lippershey applied for a patent on the “Galilean telescope,” consisting of two lenses, in 1608.

Galileo (1564-1642) used one to look at our moon, Jupiter and its moons, and the sun.

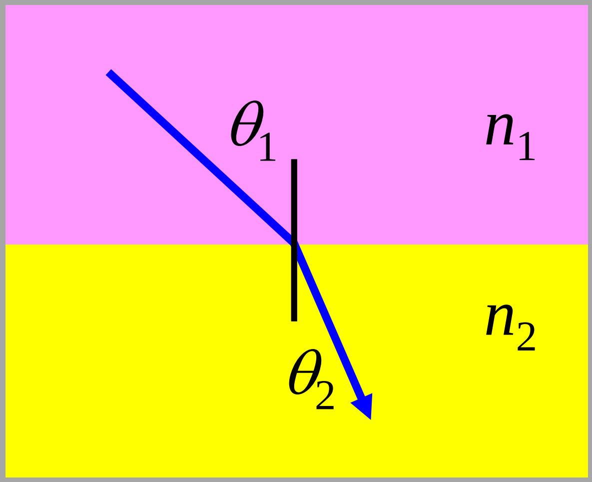
Two of Galileo’s telescopes



Galileo’s drawings of the moon

Willibrord Snell

Snell discovered the Law of Refraction, now named after him: “Snell’s Law.”



n_i is the refractive index of each medium.

Willibrord Snell (1591-1626, Netherlands)

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

17^{th} Century Optics: Descartes

Rene Descartes (1596-1659, France)

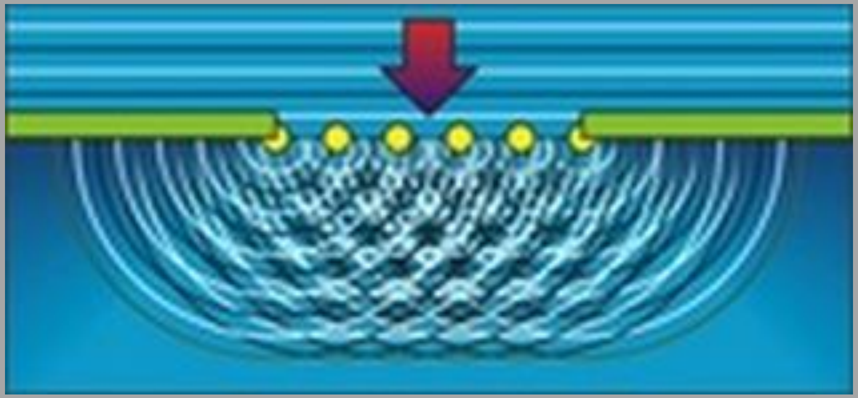
Sound was known to be a **wave**: a collective motion of particles.

Descartes reasoned that light must be like sound.

So he modeled light as pressure variations of unknown particles in an unknown medium (**aether**).

Christiaan Huygens

Huygens realized that light slowed down on entering dense media (media with high refractive indices).



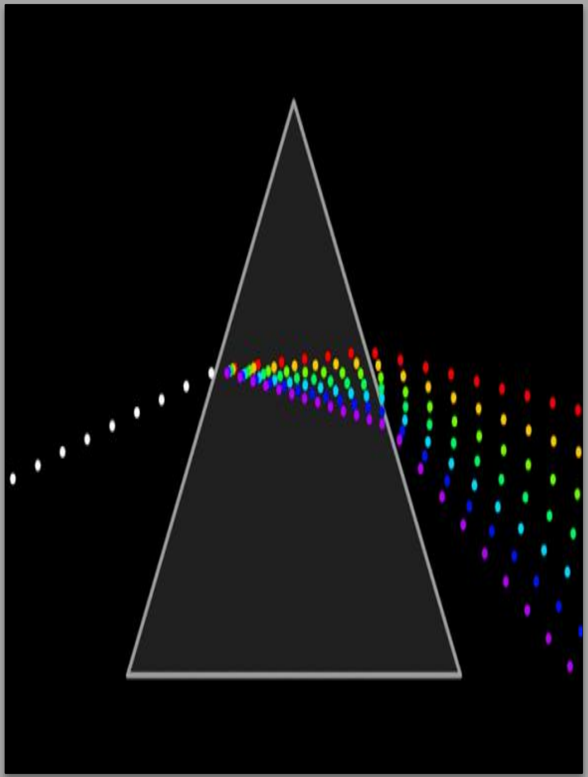
Christiaan Huygens
(1629-1695)

He also extended the wave theory of optics to diffraction, the tendency of light to bend around corners:

> Huygens' principle says that a wave propagates as if the wave-front were composed of an array of point sources each emitting a spherical wave.

Isaac Newton

Newton realized that white light is composed of all colors and invented a reflective telescope—an improvement over the Galilean telescope.



So did Newton think light was a wave?
Or a particle?

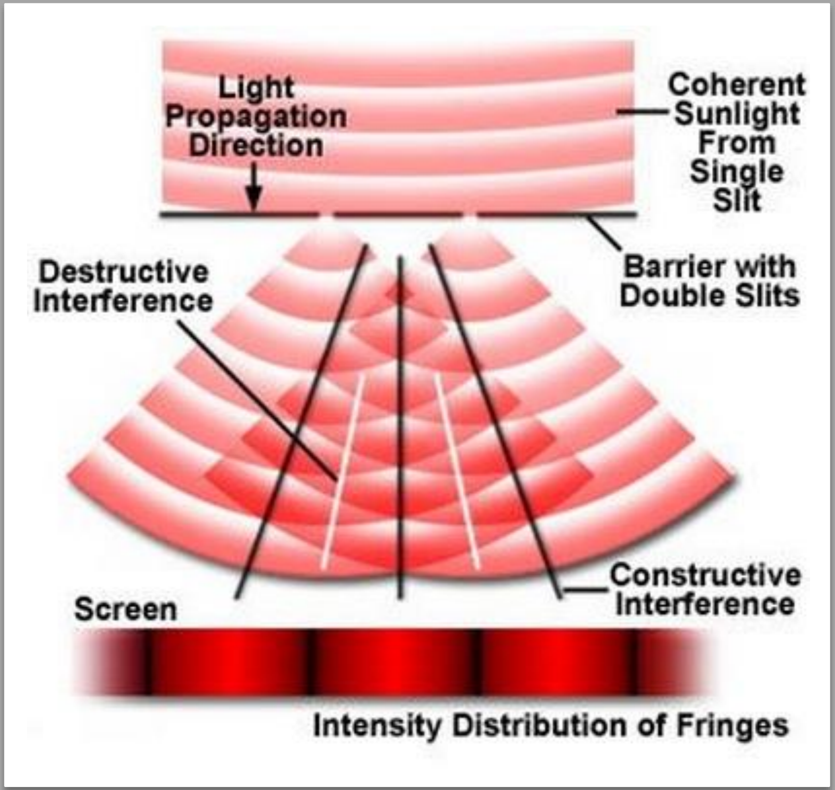
Isaac Newton
(1642-1727)

After remaining ambivalent for many years, he eventually concluded that light was made of particles.

18^{th} & 19^{th} Century Optics: Thomas Young

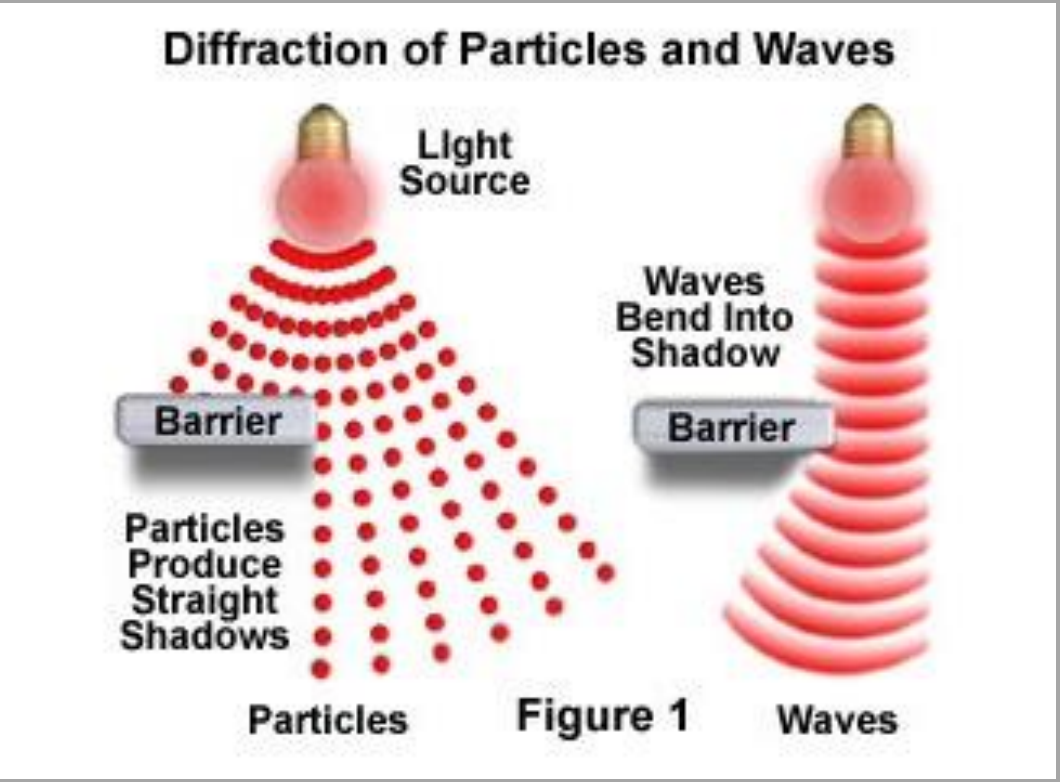
Young discovered **interference** of light—the ability of two light beams to either add or subtract.

Thomas Young
(1773-1829)



His famous two-slit interference experiment proved convincingly that light is a **wave**.

It was known since the 17th century that light bends around corners.



http://micro.magnet.fsu.edu/primer/java/particleorwave/diffraction/

19^{th} Century: James Clerk Maxwell

Maxwell unified electricity and magnetism with his now famous equations.

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

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

James Clerk Maxwell
(1831-1879)

where $\vec{\mathscr{E}}$ is the electric field, $\vec{\mathscr{B}}$ is the magnetic field, c is the velocity of light, and no charges are present.

Using them, he showed that light is an **electromagnetic** wave.

Maxwell's equations simplify to the wave equation for the electric field.

$$\nabla^2 \vec{\mathcal{E}} - \frac{1}{c^2} \frac{\partial^2 \vec{\mathcal{E}}}{\partial t^2} = 0$$

which has a simple sine-wave solution:

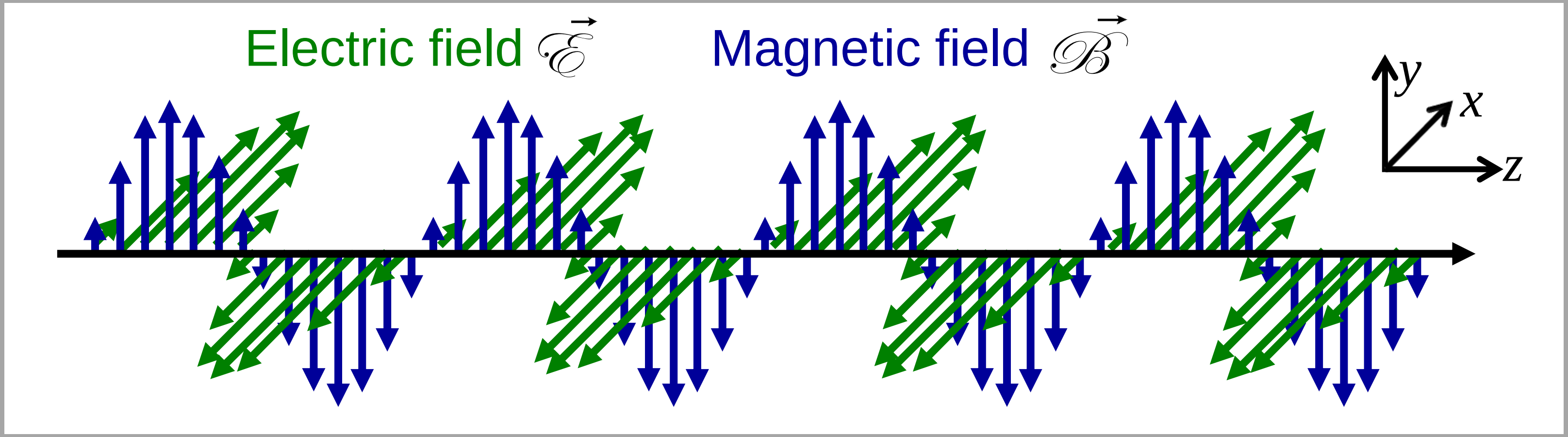
$$\vec{\mathcal{E}}(\vec{r}, t) \propto \cos(\omega t - \vec{k} \cdot \vec{r})$$

where $c = \omega / k$

The same is true for the magnetic field.

Light is an electromagnetic wave.

The electric and magnetic fields are in phase.

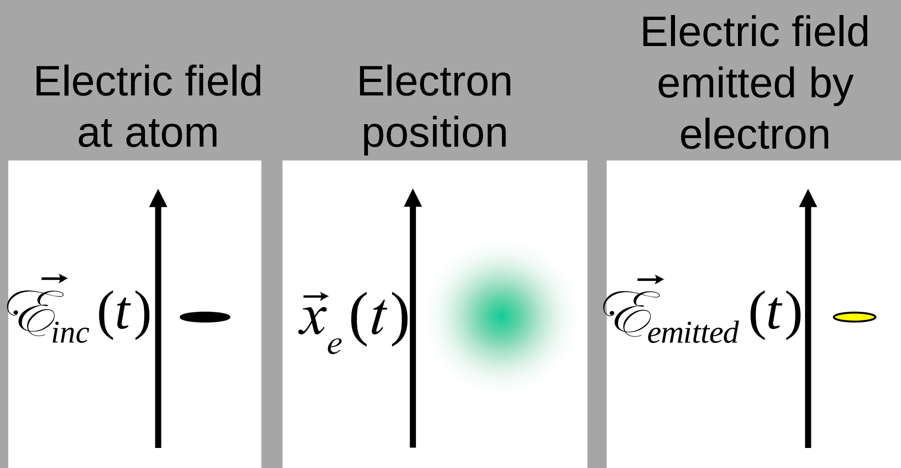


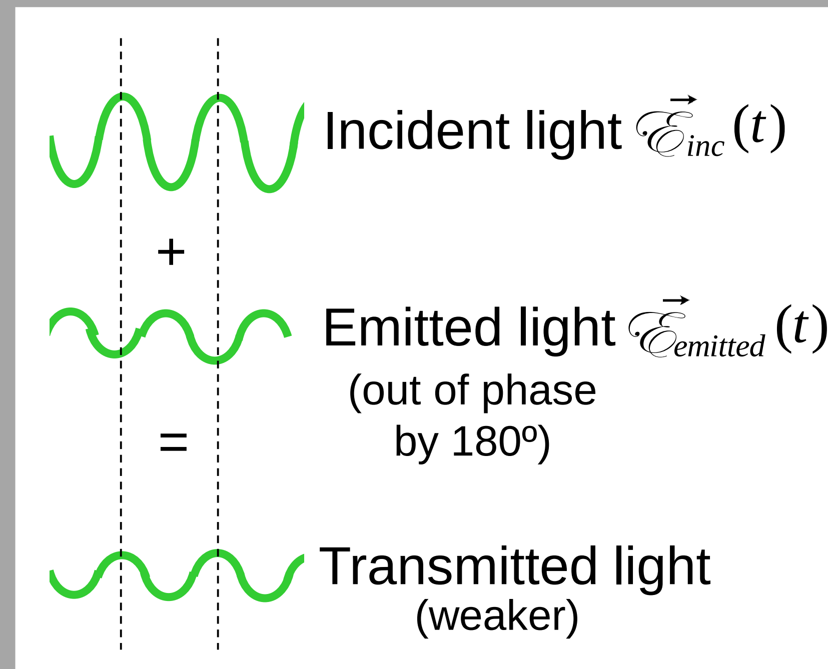
The electric field, the magnetic field, and the propagation direction are all perpendicular.

But it was still thought that light was a vibration of some sort of medium, aether, just as sound waves are vibrations in air.

The Interaction of Light and Matter

Light excites atoms, which then emit more light: interference!

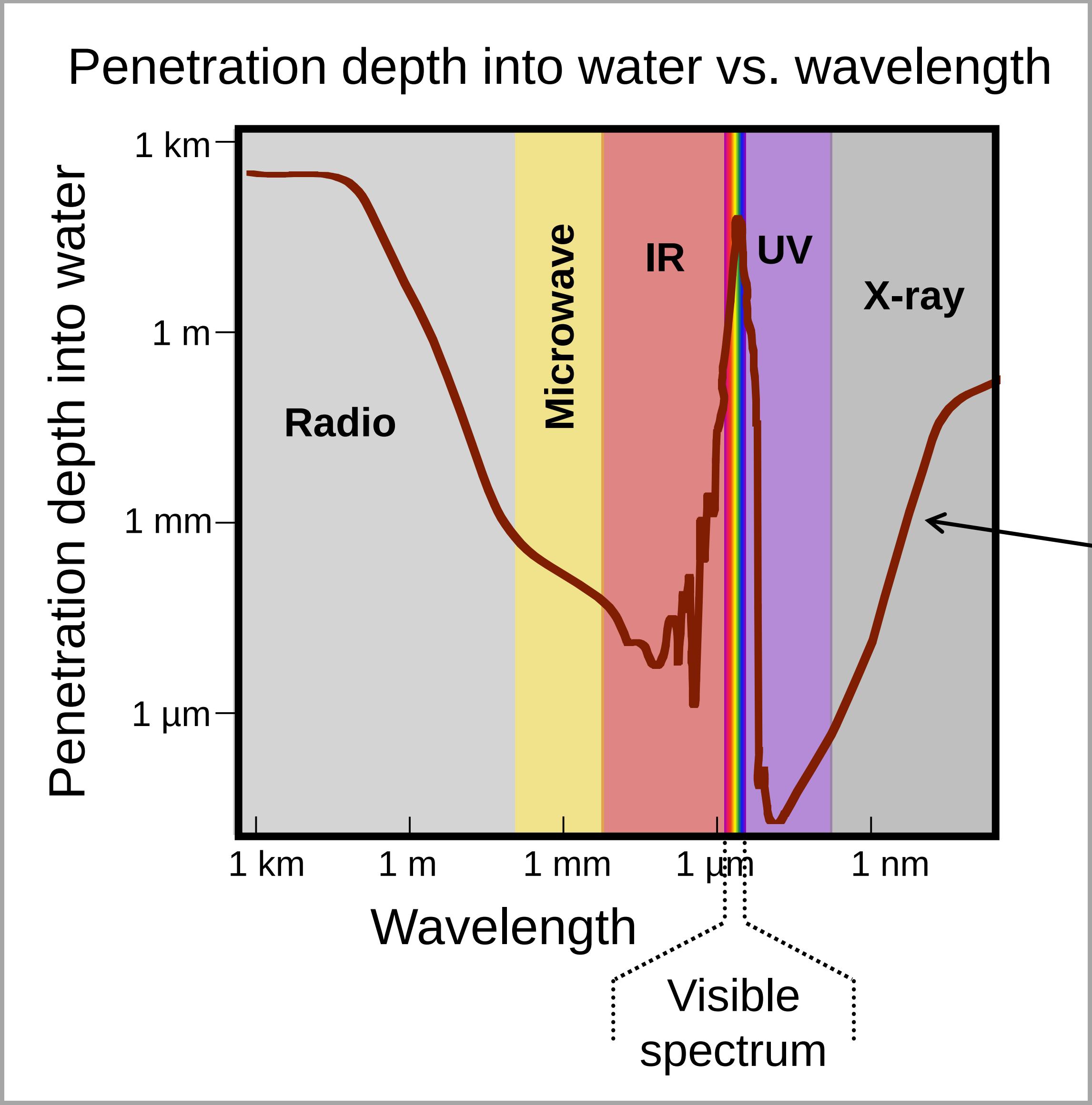




On **resonance** (the light frequency is the same as that of the atom)

The crucial issue is the **relative phase** of the incident light and this re-emitted light. If these two waves are ~180º out of phase, **destructive interference** occurs, and the beam will be attenuated—**absorption**.
If they're ~±90º out of phase: the speed of light changes—**refraction**.

Absorption of light varies massively with wavelength.

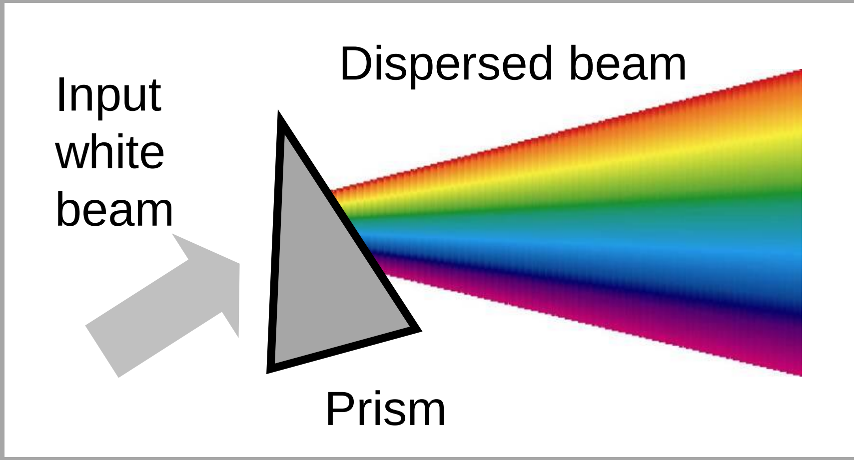


Water is clear in the visible, but not in other spectral regions.

Notice that the penetration depth varies by over ten orders of magnitude!

Knowledge of a medium's internal vibrations are all that is necessary to understand such curves.

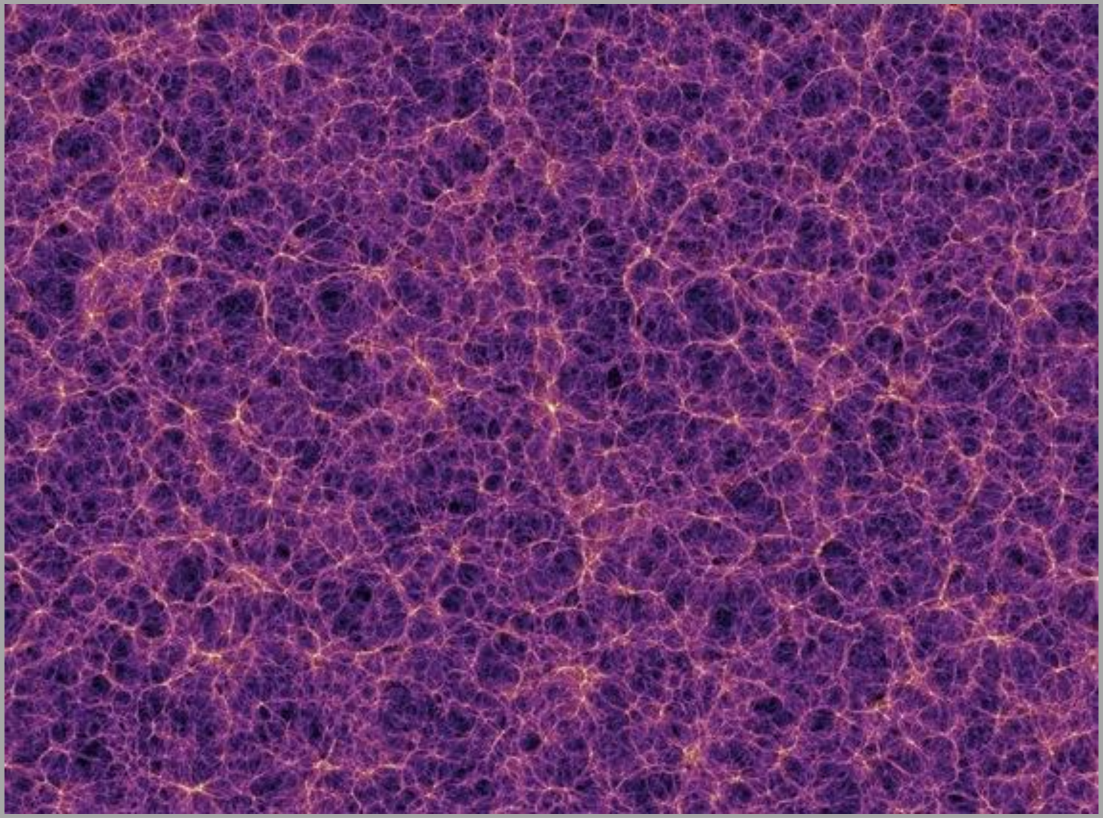
Variation of the refractive index with wavelength (dispersion) causes the beautiful prismatic effects we know and love.



Again, knowledge of a medium's internal vibrations are all that is necessary to understand the dispersion of the refractive index.

So light is definitely a wave.

But what exactly is waving? Aether. But what exactly is aether?

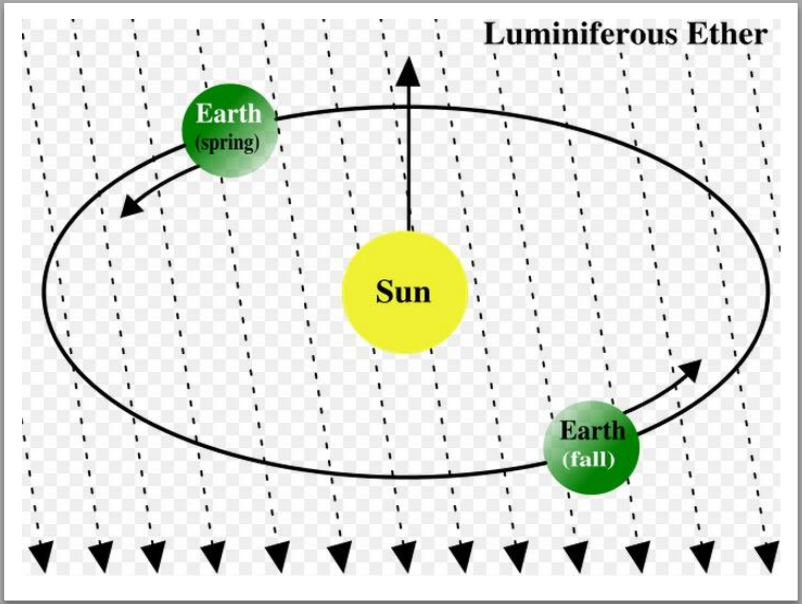


By the late 19^{th} century, nothing was known about the aether.

Even measuring the earth’s velocity relative to it could be helpful.

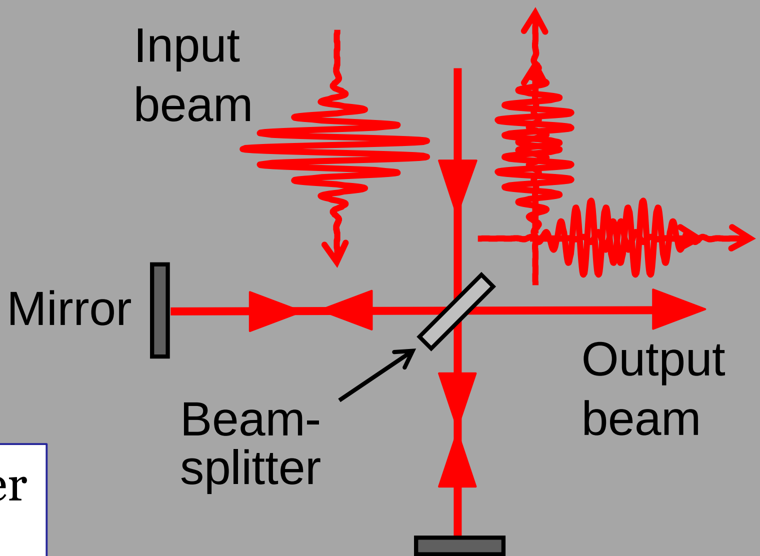
Michelson & Morley

Using an interferometer, they found that the earth's velocity with respect to the aether was zero, no matter the direction of the earth's motion, shedding doubt on the existence of the aether.



Albert Michelson (1852-1931)

Edward Morley (1838-1923)

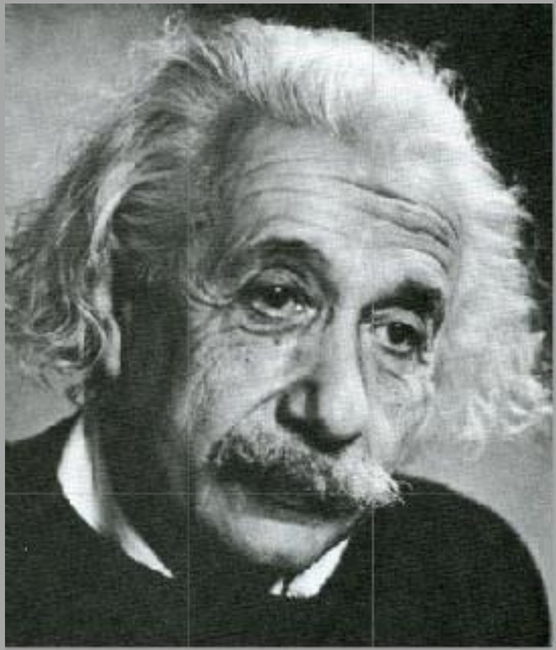


1) The speed of the Earth relative to the aether was zero.
2) The speed of light was independent of direction.

20th Century Optics: Albert Einstein

Einstein showed that light:

is a phenomenon of empty space and has a velocity that's constant, independent of observer velocity.

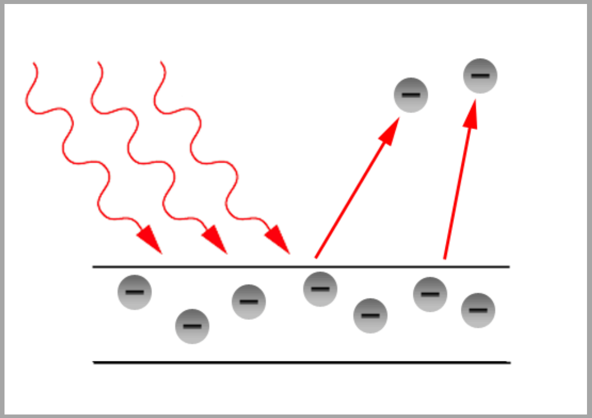


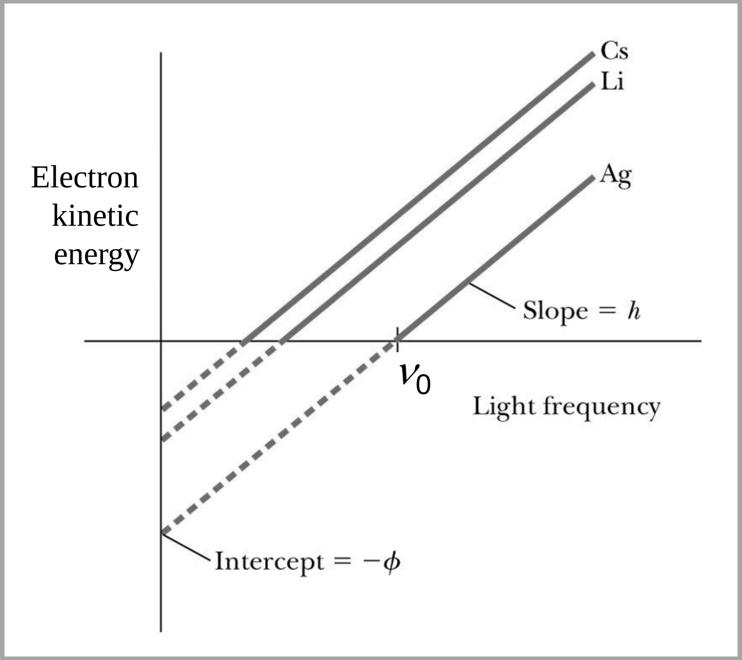
Albert Einstein (1879-1955)

Bye bye aether!

Einstein Again

The photoelectric effect: Incident light shining on a material transfers energy to electrons, ejecting them.





Einstein showed that the kinetic energy (K) of the ejected electrons could only be explained if the energy absorbed from light is $h\nu$:

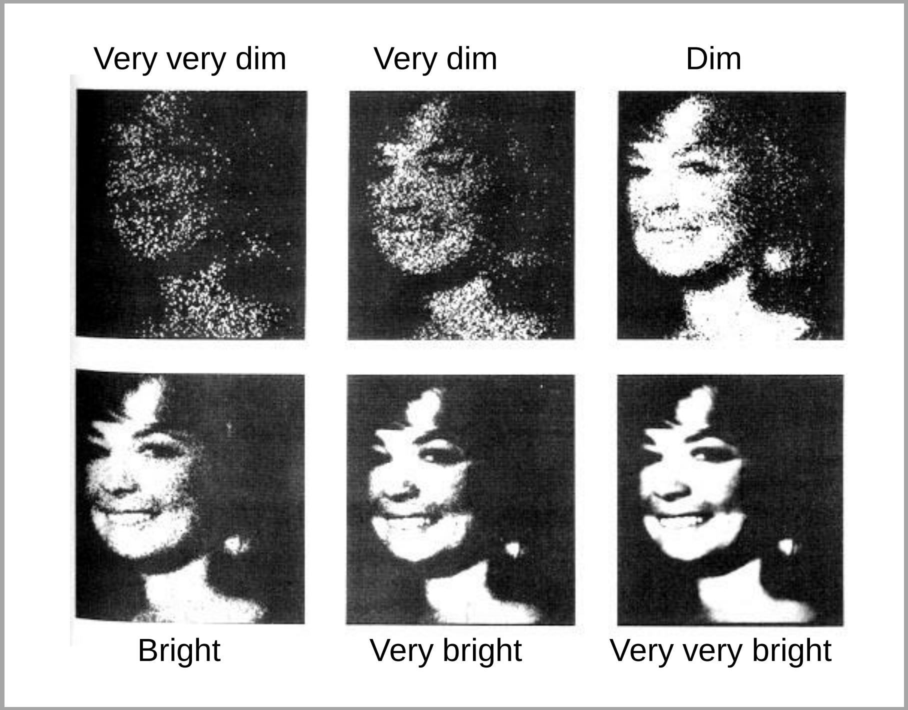
$$K = h\nu - \phi$$

where ϕ is the material's potential energy to be overcome before an electron could escape.

Thus, Einstein showed that light is also a particle (in addition to being a wave).

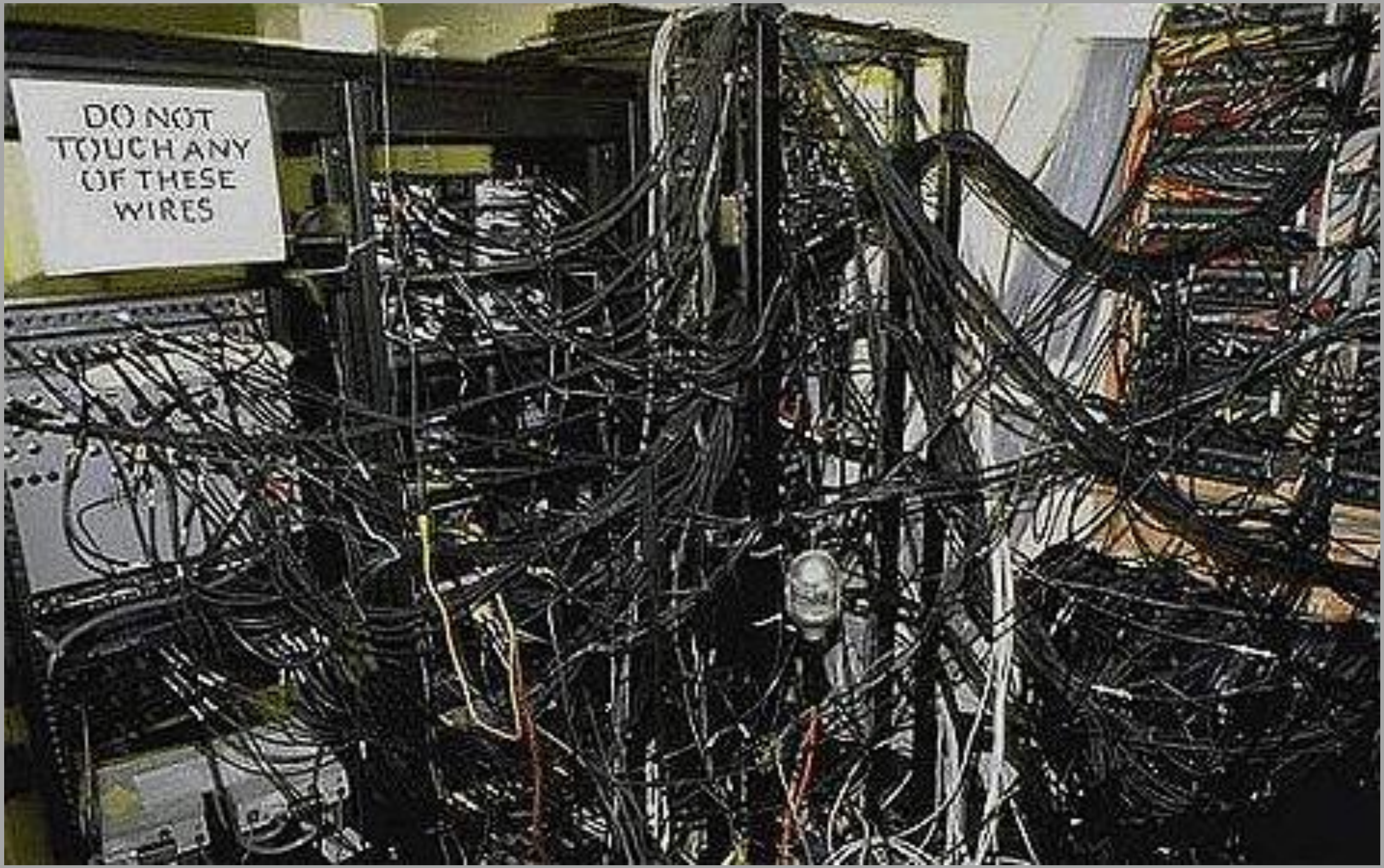
Proof of this fact is that photographs taken in dimmer light look grainier.

When we detect very weak light, we find that it's, in fact, made up of particles.

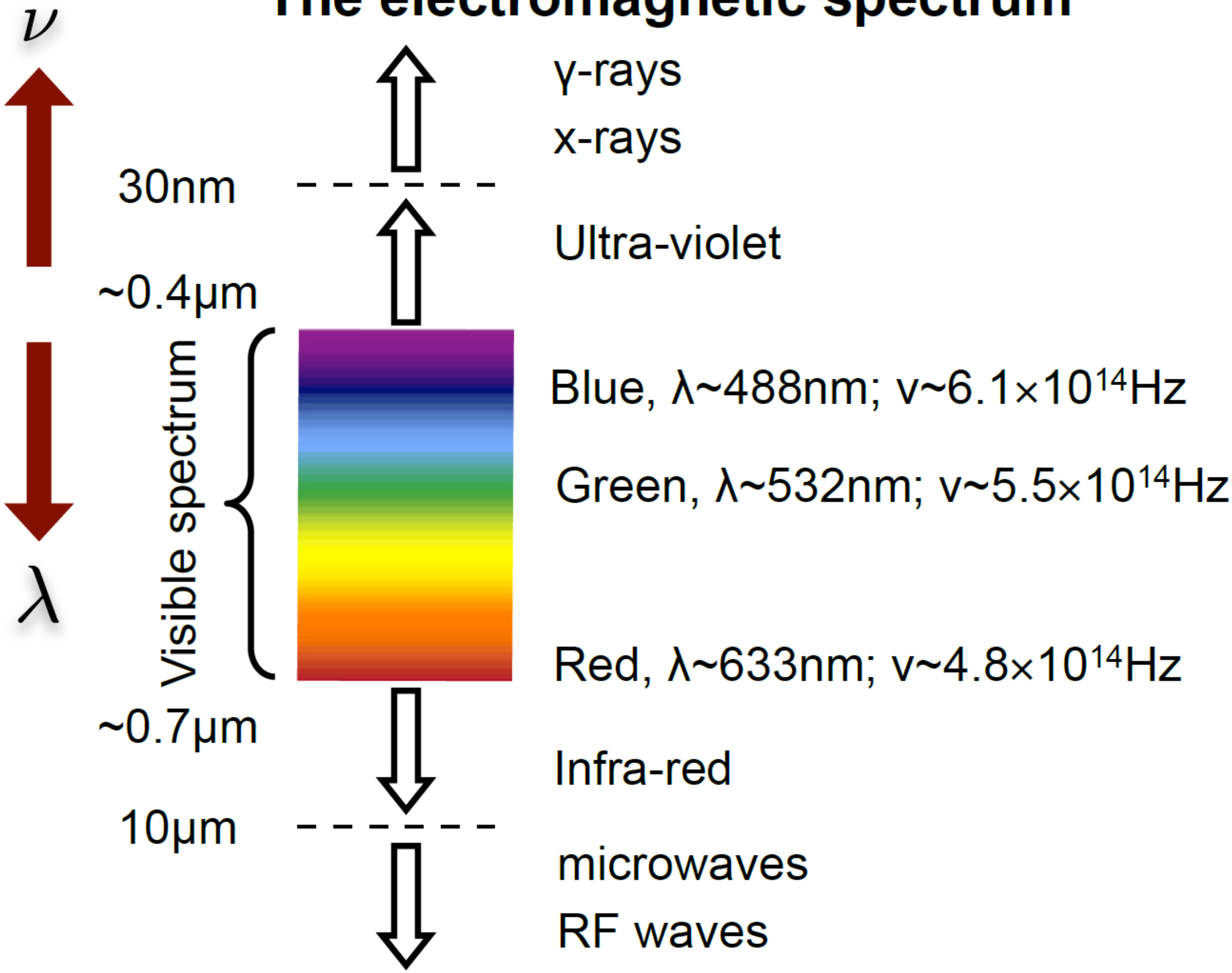


So light is a wave and a particle!

Why study optics? Fiber optics will soon replace most wires.



The electromagnetic spectrum



Electromagnetic Spectrum Song

https://www.youtube.com/watch?v=bjOGNVH3D4Y

“Light is, in short, the most refined form of matter.”

Louis de Broglie