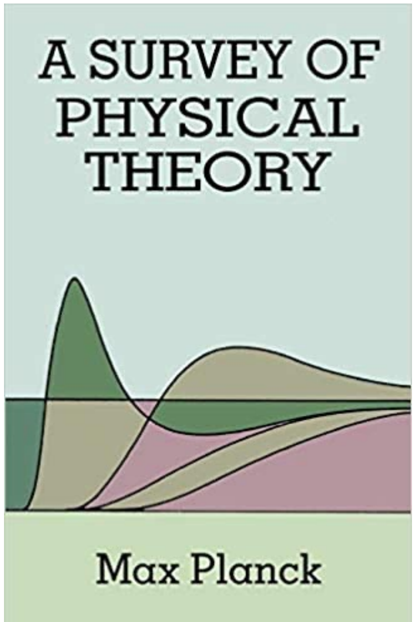
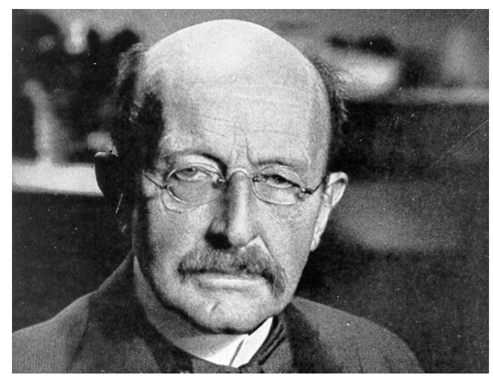
The Photon Theory of Light

“Life can only be understood backwards, but must be lived forwards”

Søren Kierkegaard (Danish philosopher
noted in his diary in 1843



"**----** knowledge must precede application, and the more detailed our knowledge -----, the richer and more lasting will be the results which we can draw from that knowledge."



Nobel Prize, 1918

A historical account of the photon theory of light

"without taking account of its historical development, an existing theory often appears almost as if it had "fallen from heaven. However, the question of the development of a theory is important not only to satisfy our curiosity but also because much can be learnt from it for the future".

G. Ludwig, Wave Mechanics, Pergamon Press, Oxford (1968)

ISBN: 978-1-62789-311-4

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The Physics of Light

While the terms "quantum physics" and "Theory of Relativity" are used casually every day, not many people know what they really mean. Yet these theories have had a profound impact not only on science and technology, but also on our world view.

This intriguing 6-part documentary series explores the concepts of physics from familiar theories, such as Newton's Law of Gravity, to the latest in scientific research, like string theory and M-theory. By connecting these studies with the medium of light, we can gain a deeper understanding not only of our immediate reality, but of the unseen realities that are hidden beyond our perception. Starting with Einstein's Theory of Relativity, *The Physics of Light* explores the true nature of light, peers inside the atom, and looks ahead to the most cutting edge theories in physics.

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Reference Books

Thirty Years that Shook Physics, The Story of Quantum Theory,
George Gamow, 1965, Ch 1, pp 6-28.

The Great Physicists from Galileo to Einstein,
George Gamow, 1961, Ch 7, pp. 225-236.

Introducing Quantum Theory, A Graphic Guide, J. P. McEvoy and O. Zarate, 2013.

Boltzmann's atom: the great debate that launched a revolution in physics,
D. Lindley, 2001

Catching the Light, The Entwined History of Light and Mind,
A. Zajonc, 1993. (selected chapters)

Electrodynamic*s* from Ampere to Einstein, Olivier Darrigol, Oxford Uni Press, 2000.

Theoretical Concepts in Physics, 3rd ed. Malcolm Longair, Cambridge Uni Press, 2020.

Reference Articles

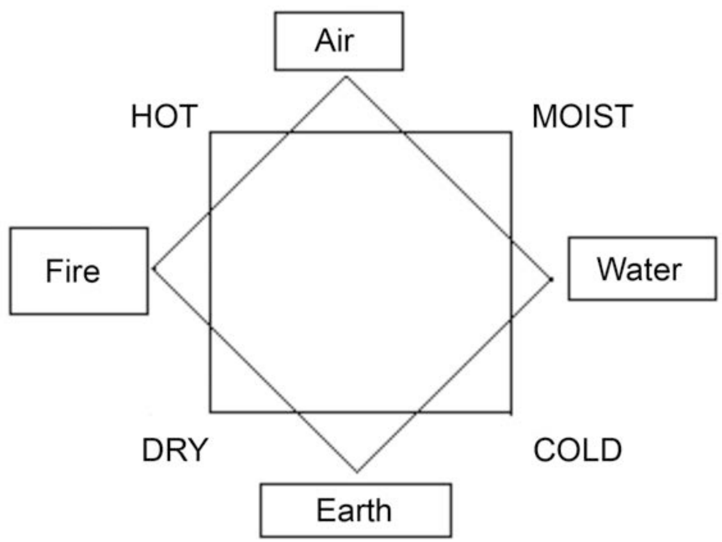
- *The Nature of Light, Max Planck*, A Survey of Physical Theory, Dover Publications, 1960, p. 89.
- The Origin and Development of the Quantum Theory, Max Planck, A Survey of Physical Theory, Dover Publications, 1960,. p.102.
- The History of Modern Physics: Vol 12, The Conceptual Development of Quantum Mechanics, Max Jammer, American Institute of Physics, 1989, pp 1-64.
- *The Story of the Photon*, N. Mukunda, Resonance, March 2000, p. 35.
- *Black-Body Radiation*, G. S. Ranganath, Resonance, Feb 2008, p. 115.
- *The Particle Nature of Radiation: Photon,* Optics, 6th ed. A. Ghatak, Mc Graw Hill, 2017, Ch 25, p. 25.3

Modern science starts with Greeks

Socrates, Plato, and Aristotle

The Ancient Greeks are seen, in the west, as our intellectual forefathers. From Greece was born philosophy, drama, western artistic aesthetics, geometry, etc., etc.

Matter is made up of four elements



Asians and Arabs had their own ideas

The Indian View of the Universe

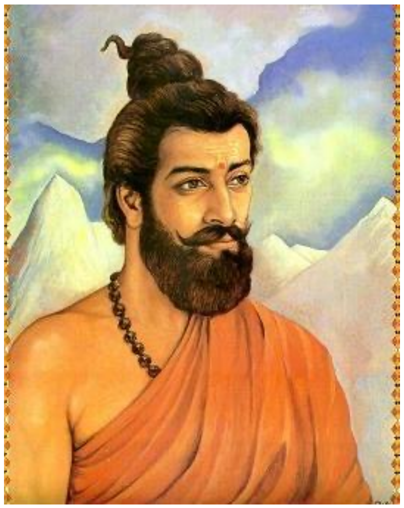
(*Taittirīya Upanishad* and *Aitareya Upanishad*, 6th century BC)

Five interconvertible elements make up the earth

Pancha Bhoota (Sanskrit: पञ्चभूत), five great elements, which, according to Hinduism, is the basis of all cosmic creation.

- **Prithvi** (Sanskrit: पृथ्वी:, Earth),
- **Jal** (Sanskrit: अप:, Water),
- **Agni** (Sanskrit: अग्नि, Fire),
- **Vayu** (Sanskrit: वायु:, Air),
- **Akasha** (Sanskrit: आकाश, Space).

Indian View: Tejas, Light and Fire



Acharya Kanada (Kashyap)
The Father of Atomic Theory

Vaiśeṣika Sūtra

Vatsayana, The Nyaya School

Between 6th and 2nd century BCE

- Light has no taste, no smell and no gravity.
- Light and heat are different forms of the same, Tejas.
- Light (Tejas) is constituted by infinitely small particles, something smaller and different than 'anu or paramanu' (atoms).
- These particles radiate themselves in all directions from their source and with inconceivable velocity.
- Light is the root, the nourisher, and the supporter of the tree of life.

Greek View: Light is made up of particles

Democritus
c. 460 – c. 370 BC

Sunlight is presumably, like fire, composed of small, swift-moving round atoms.

Vision occurs by means of the images flowing from objects. We see by the impact of images on the eye.

The air through which the object's image moves is infused with light particles from the sun and is imprinted on the eye.

Greek View: Light is made up of particles

Euclid, 300-265 BC


LA

PROSPETTIVA

DI EVCLIDE,

Nella quale si tratta di quelle cose, che per raggi diritti si veggono: & di quelle, che con raggi reflessi nelli Specchi *appariscono.*

Tradotta dal R. P. M. Egnatio Danti Cosmografo del Seren. Gran Duca di Toscana. Con alcune sue Annotationi de' luoghi piu importanti.

Insieme Con La Prospettiva Di

Eliodoro Larisseo

Cauata della Libreria Vaticana, e tradotta dal medesimo nuouamente data in luce.

IN FIORENZA.

Nella Stamperia de' Giunti.

MDLXXIII.

Con licenzia & Priuilegio.

Euclid's *Optics,* 300 BC

"The light and heat of the sun are composed of minute atoms which, when they are shoved off, lose no time in shooting right across the interspace of air in the direction imparted by the shove."

Euclid's view of vision: Eye to the object

- According to Euclid, the eye sees objects that are within its visual cone. The visual cone is made up of straight lines, or visual rays, extending <u>outward</u> from the eye. Visual rays is a cone of which the vertex is at the eye and the base at the surface of the objects seen.

- These visual rays are discrete, but we perceive a continuous image because our eyes, and thus our visual rays, move very quickly.

- That those things are seen upon which visual rays fall and those things are not seen upon which visual rays do not fall.

Middle eastern ancient (Christian) view of the universe

In the beginning God created the heavens and the earth.

Now the earth was formless and empty, darkness was over the surface of the deep, and the Spirit of God was hovering over the waters.

And God said, "Let there be light," and there was light.

God saw that the light was good, and he separated the light from the darkness.

God called the light "day," and the darkness he called "night."

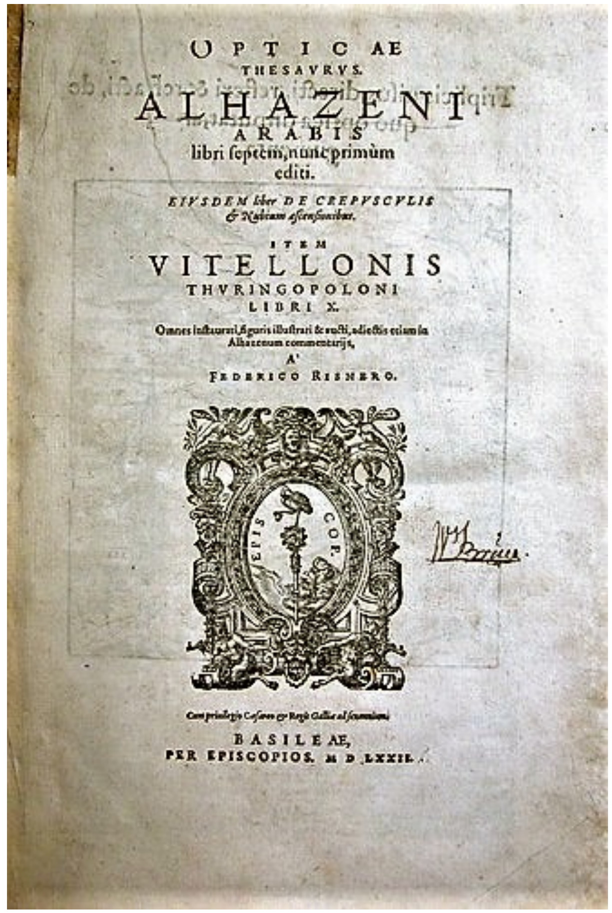
Genesis 1:3-5

Arabic view: Ḥasan Ibn al-Haytham on vision

Ḥasan Ibn al-Haytham
965-1040 AD

Euclid
~300-265 BC

Democritus
c. 460 – c. 370 BC



OPTICAE
THESAVRVS.
ALHAZENI
ARABIS
libri septem, nunc primùm
editi.

EIVSDEM liber DE CREPVSCVLIS
& Nubium ascensionibus.

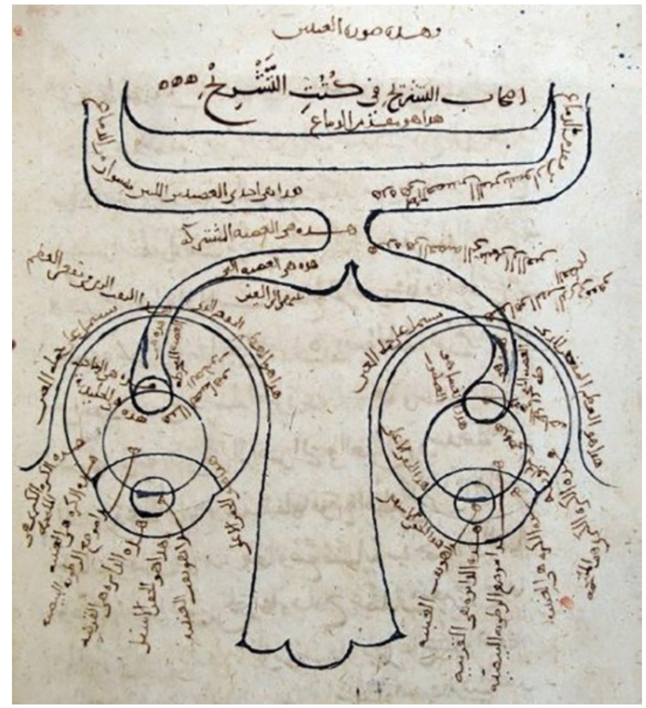
ITEM
VITELLONIS
THVRINGOPOLONI
LIBRI X.

Omnes instaurati, figuris illustrati & aucti, adiectis etiam in
Alhazenum commentarijs,
A'
FEDERICO RISNERO.

Cum privilegio Caesareo & Regis Galliae ad sexennium.

BASILEAE,
PER EPISCOPIOS. M D LXXII.

Book of Optics
7 volumes



Eye to brain

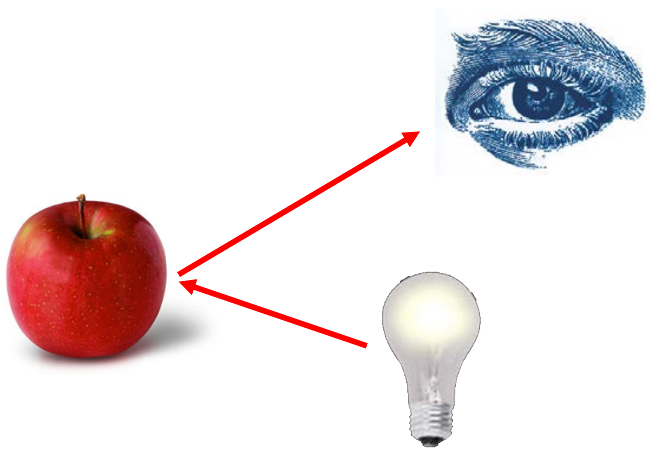
Ḥasan Ibn al-Haytham on light and vision

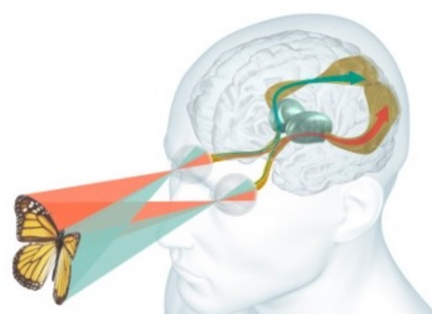
Light travels in straight lines

Vision occurs when light reflected from an object passes to one's eyes.

Vision occurs in the brain, rather than in the eyes.

The object sends an infinite number of rays of light to the eye, only one of these lines falls on the eye perpendicularly. All the rays other than the one that hits the eye perpendicularly are not involved in vision





Ḥasan Ibn al-Haytham on light and vision

https://www.youtube.com/watch?v=4Dk2CfO5PAY Smithsonian

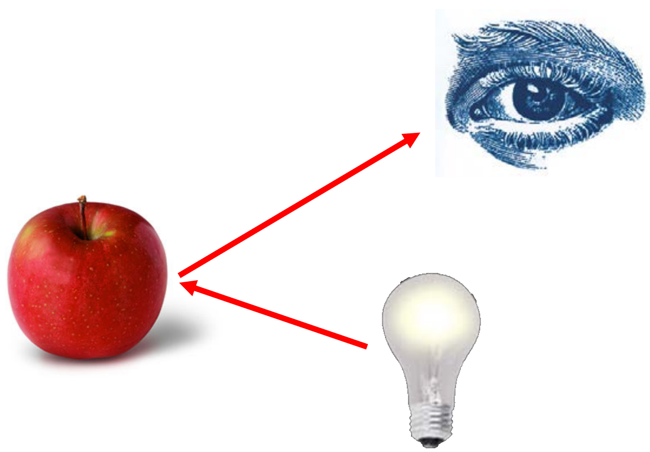
https://www.youtube.com/watch?v=YUpoccBrAc0 al-Haytham

https://www.youtube.com/watch?v=SxJ2OC7iXo0 Ben Kingsley

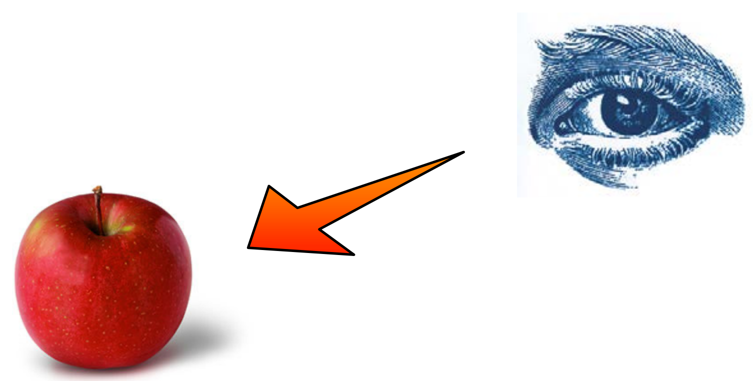
Which is correct, how would you verify?

"eyes receive light reflected from objects, rather than emanating light themselves" --- *Ḥasan Ibn al-Haytham*

"light emanates from eyes & hits the objects" --- *Euclid*



Ḥasan Ibn al-Haytham



Euclid

European view: What is Light

Pierre Gassendi (French)
1592–1655 AD

Light is composed of corpuscles (particles of matter) which are emitted in all directions from a source.

Light particles travel at unimaginably high-speed (qualitatively correct).

Vision is a function of rays of light atoms or image-bearing atoms that are received by our internal apparatus for vision.

Ḥasan Ibn al-Haytham
965-1040 AD

European view: What is sight?

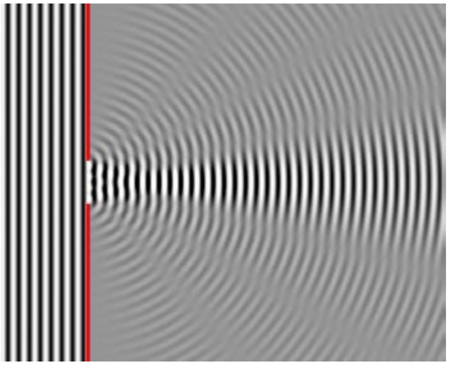
René Descartes (French)
1596 –1650 AD

- The universe is filled with some material (named 'plenum'), which pressed against the eyes. This pressure produces the phenomenon of sight. A bright object, like the Sun, generates pressure and that instantaneously is felt by the human eye.
- Objection: If sight is caused by the pressure of the plenum on the eye, then a person running at night should be able to see, because the runner's motion would make the plenum press against their eyes.

René Descartes, *The World and Other Writings*, English Translation, Cambridge Uni Press, 2004

Light diffracts: It is a wave

Francesco Maria Grimaldi
(Italian) 1618 –1663



- Allowed a beam of sunlight to pass through a small aperture in a screen and noticed that it was diffused in the form of a cone. The shadow of a body placed in the path of the beam was larger than that required by the rectilinear propagation of light.
- Light is propagated or scattered not only directly and by reflection and refraction, but also in a certain other mode, namely by diffraction.
- **Diffraction** describes the event of waves encountering an obstacle and the consequential bending around the object.

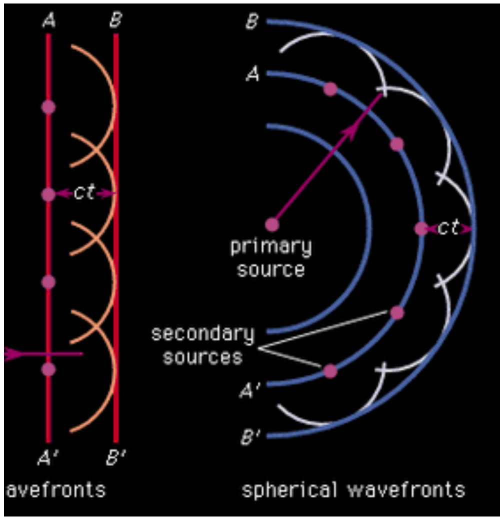
Light diffracts

Diffraction is the bending of a wave around the edges of an opening or other obstacle.

In 1678, Huygens proposed every point on a wavefront is a source of **wavelets** that spread out in the forward direction at the same speed as the wave itself. The sum of these secondary waves determines the form of the wave at any subsequent time. The new wavefront is a line tangent to all of the wavelets.

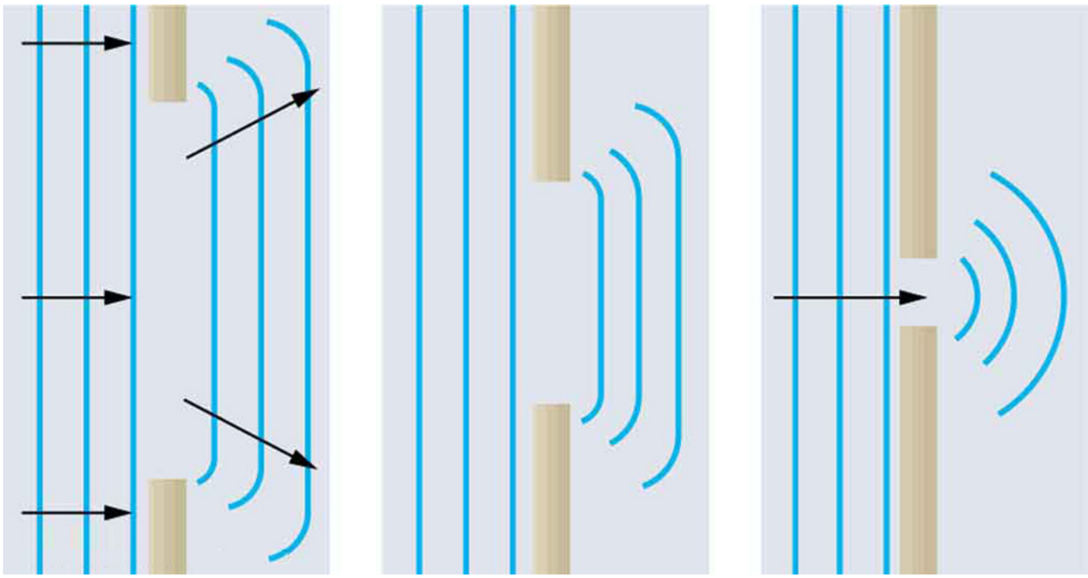
Christian Huygens (Dutch) 1629 to 1695

Francesco M. Grimaldi (Italian) 1618 –1663



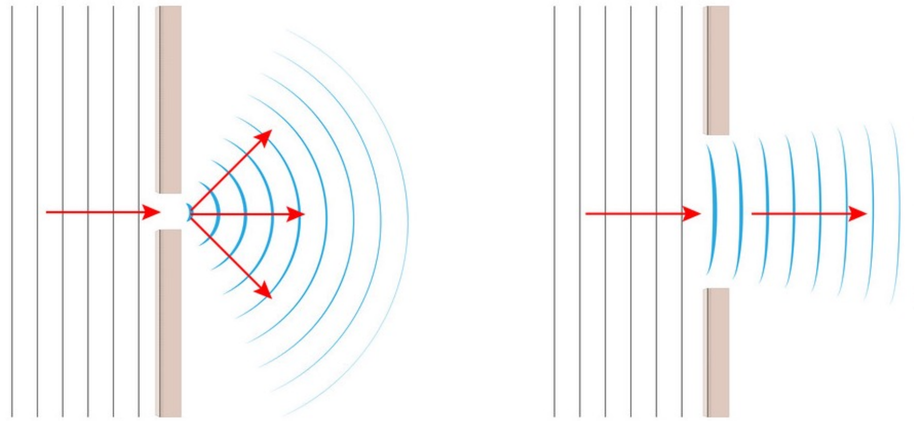
Light bends around corners

For plane waves entering a single slit, the waves emerging from the slit start spreading out, diffracting. The extent of spread depends on the slit opening size.



The edges of the wavefront bend after passing through the opening. The amount of bending is more extreme for a small opening, consistent with the fact that wave characteristics are most noticeable for interactions with objects about the same size as the wavelength.

Factors controlling light bending around corners



Wave impinges on a narrow slit Wave impinges on a broad slit

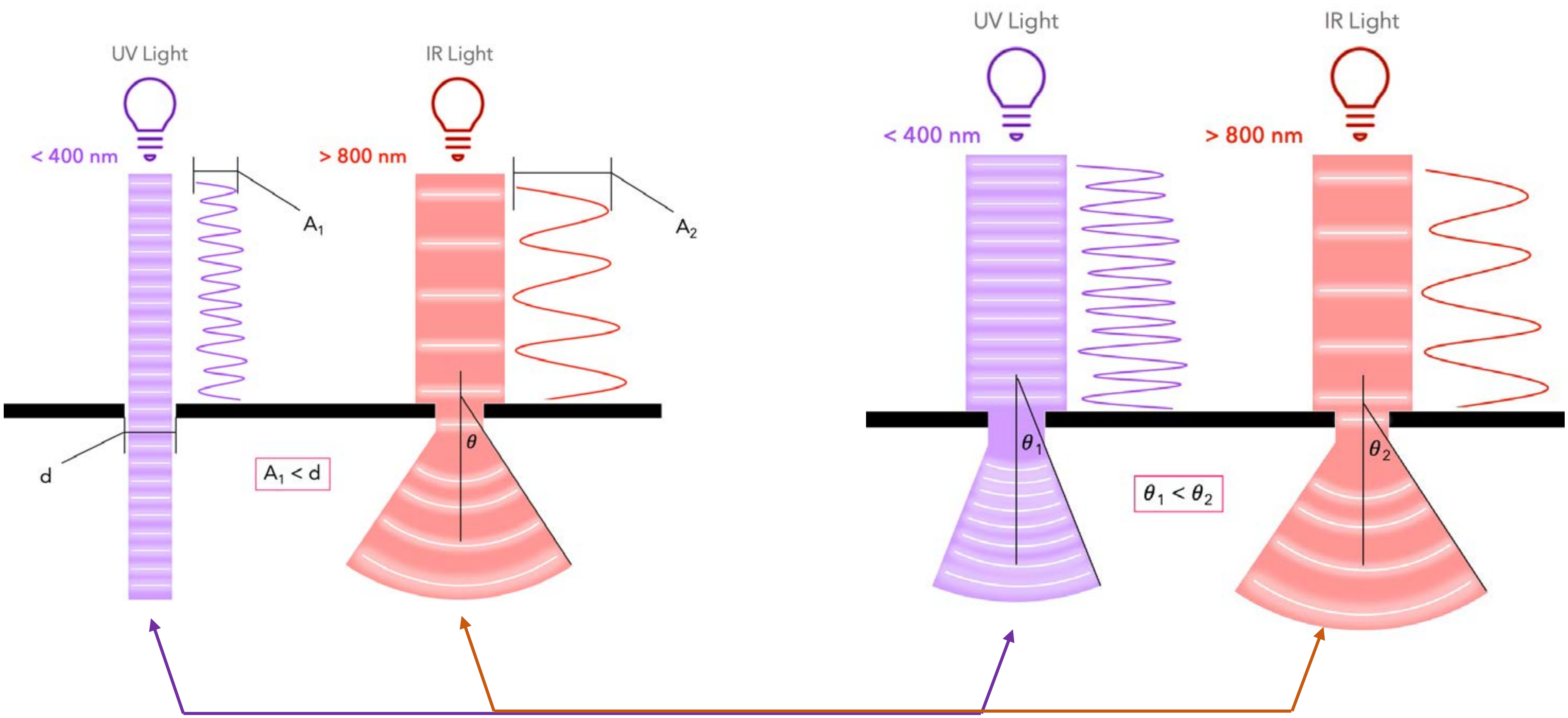
- **Amplitude** – for any diffraction to occur, the incident waves must have a higher amplitude than the slit width. If the wave is smaller than the slit width, no diffraction will occur.
- **Slit Width** – Assuming an incident plane wave, decreasing the slit width will make diffraction more dramatic, and increase the angle at which the waves spread from the slit.
- **Wavelength** – Decreasing wavelength, or increasing frequency has a similar effect as increasing the slit width. A lower wavelength decreases the diffracted angle

Mechanism of diffraction

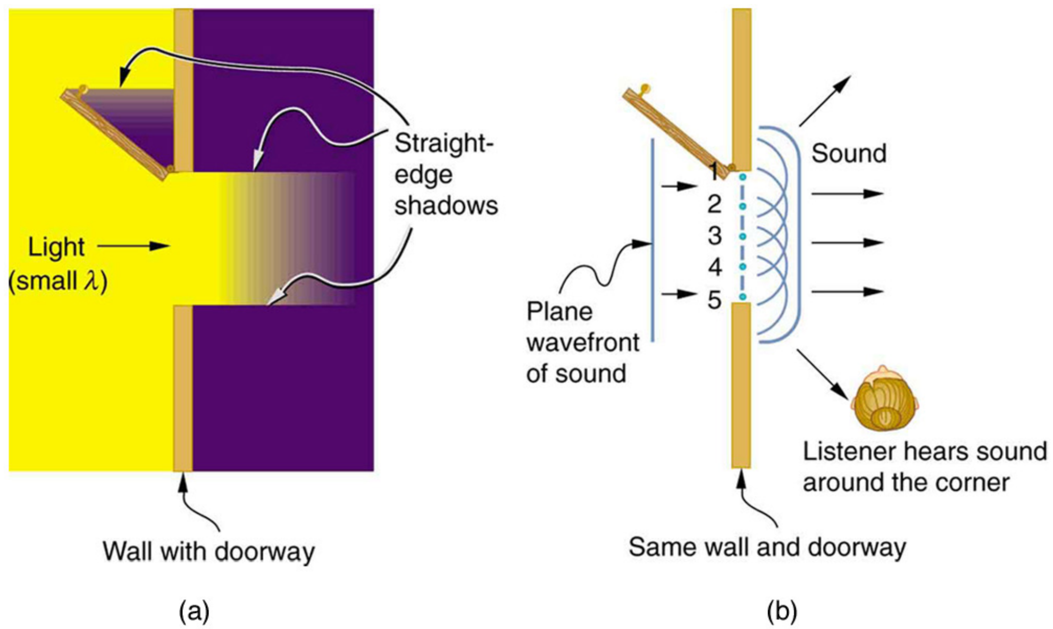
Factors controlling light bending around corners

Different amplitude and wavelength

Same amplitude and different wavelength

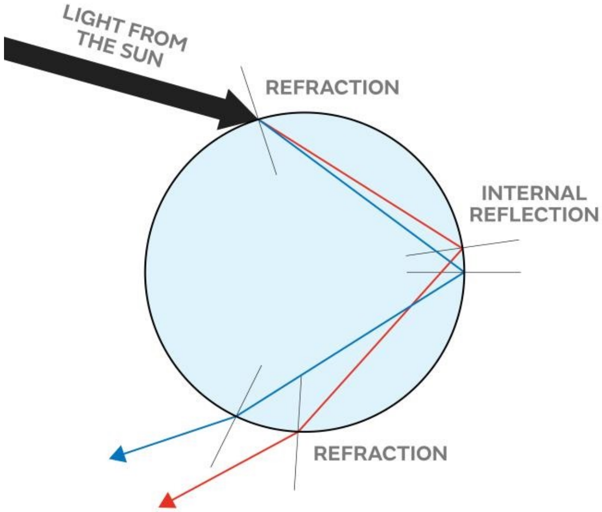


Difference between light and sound



- Light passing through a doorway makes a sharp outline on the floor. Since light's wavelength is very small compared with the size of the door, it acts like a ray.
- (b) Sound waves bend into all parts of the room, a wave effect, because their wavelength is similar to the size of the door.

Rain drops, rainbow and colors



"Others have seen him (Sun) riding in wisdom on his chariot, with seven colors as horses and six wheels to represent the whirling spokes of time".

The Prashna Upanishad
(1-4 century BC)

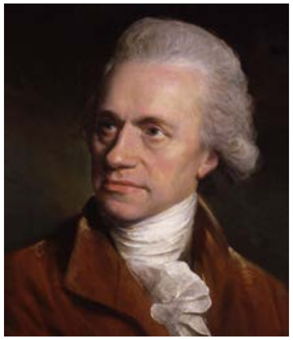
In the 1660s, Newton began a series of experiments with sunlight and prisms. He demonstrated that clear white light was composed of seven visible colors.

“If the Sun’s Light consisted of but one sort of Rays, there would be but one Color in the whole World”.

Newton (1660s)

Light is impure-a mixture of visible and invisible parts

In **1665**, **Isaac Newton**, took a glass prism and held it up to a beam of sunlight streaming through the window. He saw the sunlight that passed through the prism spread out into the colors of the rainbow - red, orange, yellow, green, blue and violet. Thus he showed white light is in fact a combination of seven **visible** colors.

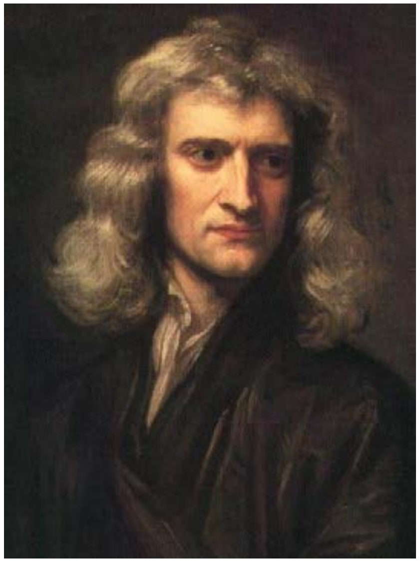


In **1800**, **William Herschel** discovered a form of light (or radiation) beyond red light, now known as infrared radiation. Herschel measured the temperature just beyond the red portion of the spectrum in a region apparently devoid of sunlight. To his surprise, he found that this region had the highest temperature of all. This region is now known as **infrared (IR)**.

In 1801, **J. W. Ritter** made a significant discovery while investigating rays beyond the violet color in the light spectrum. During his experiments, Ritter observed that these rays were capable of darkening paper impregnated with silver chloride. They are now known as **ultraviolet (UV)** and due have the ability to induce chemical reactions.

Light travels in a straight line: It is a particle

Corpuscular theory of light



Sir Isaac Newton (1643-1727)

René Descartes
1596 –1650 AD

Pierre Gassendi
1592–1655 AD

Francesco M. Grimaldi
1618 –1663

Christian Huygens
1629 to 1695

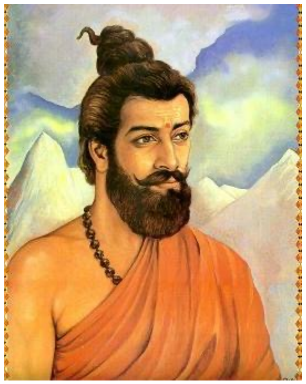
Sounds are propagated as readily through crooked pipes as through straight ones. But light is never known to follow crooked passages nor to bend into the shadow.

Light is a particle because the periphery of the shadows it created was extremely sharp and clear.

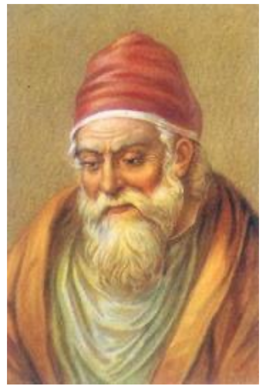
Newton argued that the geometric nature of *reflection* and *refraction* of light could only be explained if light were made of particles, because waves do not tend to travel in straight lines.

Every source of light emits large numbers of tiny particles that are elastic, rigid, and weightless.

Light is a particle ~500 BC to 1650


Kanada (Kashyap)
600-400 BC


Democritus
460 – 370 BC


Euclid
300 –265 BC


Pierre Gassendi
1592–1655 AD


al-Haytham
965-1040 AD

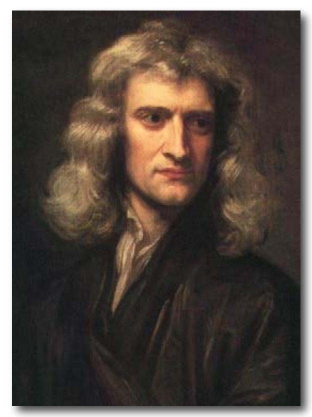

René Descartes
1596 –1650 AD

Light is a wave ~ 1650s


Francesco M.
Grimaldi 1618 –1663


Christian Huygens
1629 to 1695

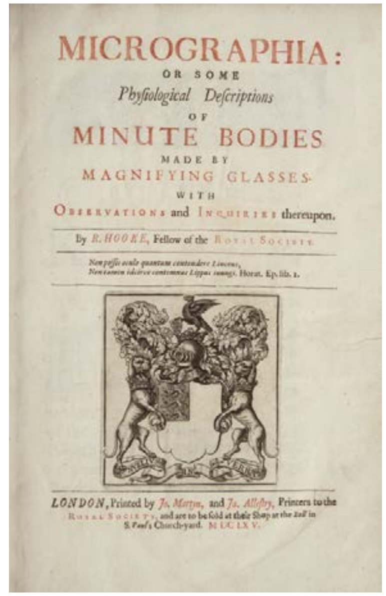

Robert Hooke
1635-1703


Isaac Newton
1643-1727


Thomas Young
1773 - 1829

Hooke (1635-1703) *vs* **Newton** (1643-1727)

Robert Hooke
1635-1703



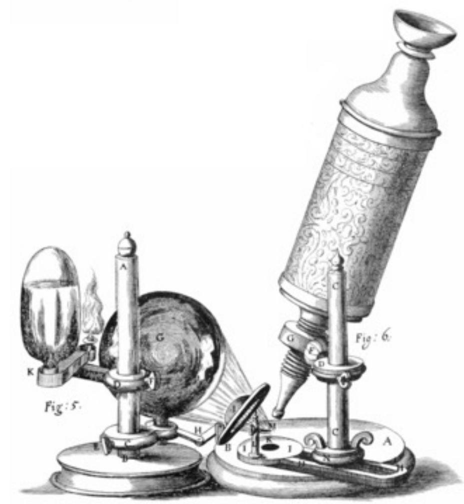
MICROGRAPHIA:
OR SOME
Physiological Descriptions
OF
MINUTE BODIES
MADE BY
MAGNIFYING GLASSES.
WITH
OBSERVATIONS and INQUIRIES thereupon.

By R. HOOKE, Fellow of the ROYAL SOCIETY.

Non possis oculo quantum contendere Linceus,
Non tamen idcirco contemnas Lippus inungi. Horat. Ep. lib. 1.

LONDON, Printed by *Jo. Martyn*, and *Ja. Allestry*, Printers to the ROYAL SOCIETY, and are to be sold at their Shop at the Bell in S. Paul's Church-yard. M DC LXV.

Micrographia
(1665)

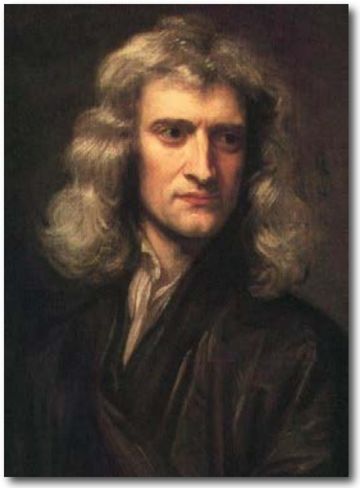


Hooke-microscope
Hooke was an early one to build and experiment with microscopes

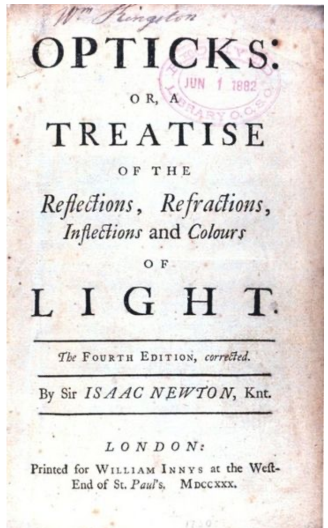
- Hooke opined that a combination of different amounts of red and blue originated the rest of the colors. This is different from Newton's suggestion that light is made up of seven coloors.

- Hooke proposed light is a wave because it diffracts while Newton said it is a particle."

What is light, particle or wave?

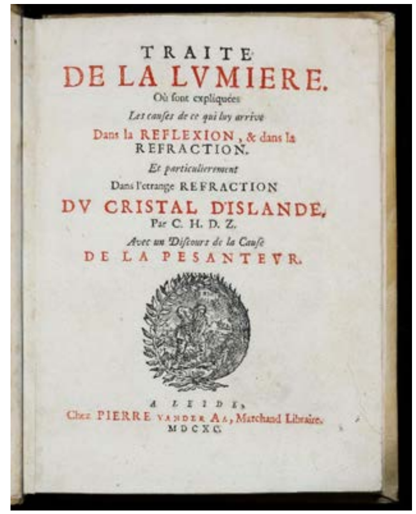


In the late 1672 Newton explained many of the properties of light by assuming it was made of particles.



OPTICKS:
OR, A
TREATISE
OF THE
Reflections, Refractions, Inflections and Colours
OF
LIGHT.
The Fourth Edition, corrected.
By Sir ISAAC NEWTON, Knt.
LONDON:
Printed for WILLIAM INNYS at the West-End of St. Paul's. MDCCXXX.

1704



TRAITE
DE LA LVMIERE.
Où sont expliquées
Les causes de ce qui luy arrive
Dans la REFLEXION, & dans la REFRACTION.
Et particulierement
Dans l'etrange REFRACTION
DV CRISTAL DISLANDE,
Par C. H. D. Z.
Avec un Discours de la Cause
DE LA PESANTEVR.
A LEIDE,
Chez PIERRE VANDER AA, Marchand Libraire.
MDCXC.

Treatise on Light (French)
1690

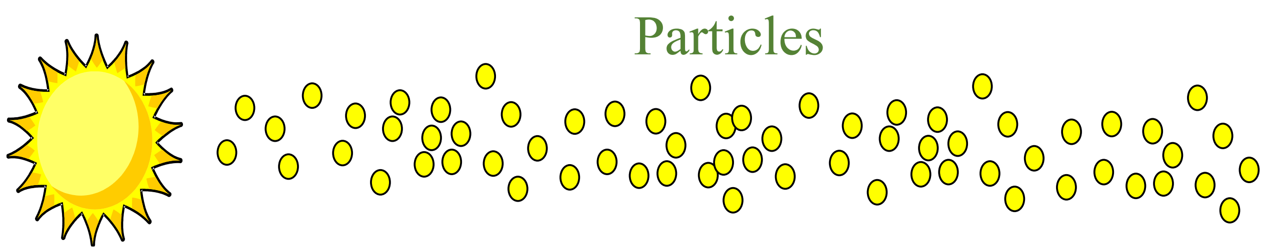
In 1678 Christian Huygens argued that light was a pulse traveling through a medium, a wave.

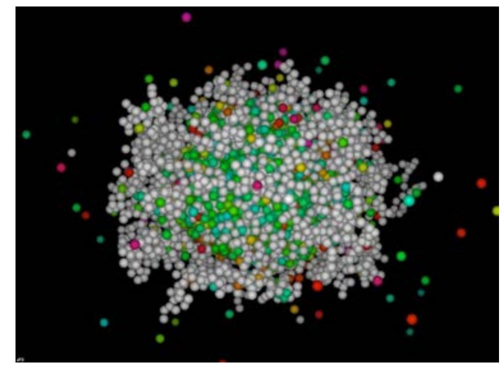
Because of Newton's enormous prestige, his support of the particle theory of light tended to suppress other points of view. This continued for 100 years.

What is light?

Kanada, Democritus, Euclid, Gassendi, Newton:

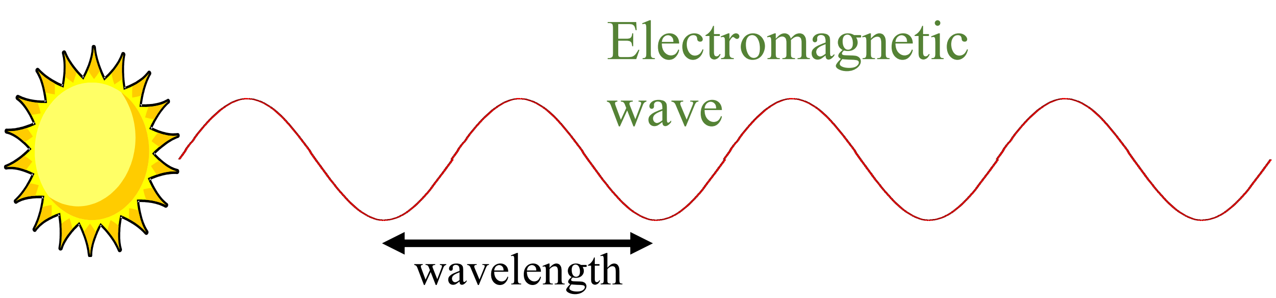
light is composed of a large number of particles





Grimaldi, Hooke and Huygens:

light is composed of waves



Light is ----

Isaac Newton

Seven colors that we can see (1665)

Seven colors plus one beyond red (*infra-red*) that we can't see (1800)

William Herschel

J. W. Ritter

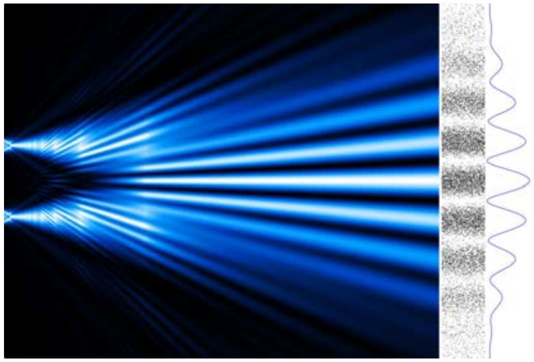
Seven colors plus one beyond violet (*ultra-violet*) that we can't see (1801)

Light is a wave

French physicist Augustin-Jean Fresnel asserted in **1815** that light is a wave and mathematically proved the phenomenon of light interference. He also hypothesized that space is filled with a medium known as **ether** because waves need something that can transmit them.

Augustin-Jean Fresnel
(1788 to 1827)

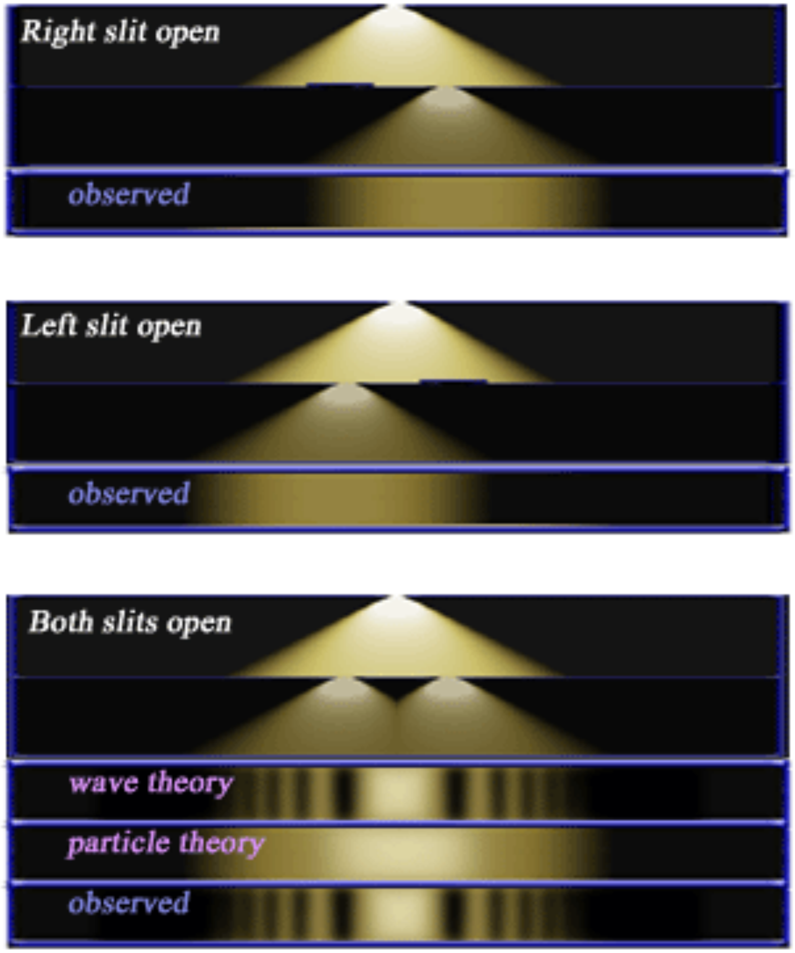
Thomas Young
(1773 to 1829)



With interference experiment, or double-slit experiment, in **1817** Young demonstrated interference in the context of light as a wave.

Light is a wave: A new evidence

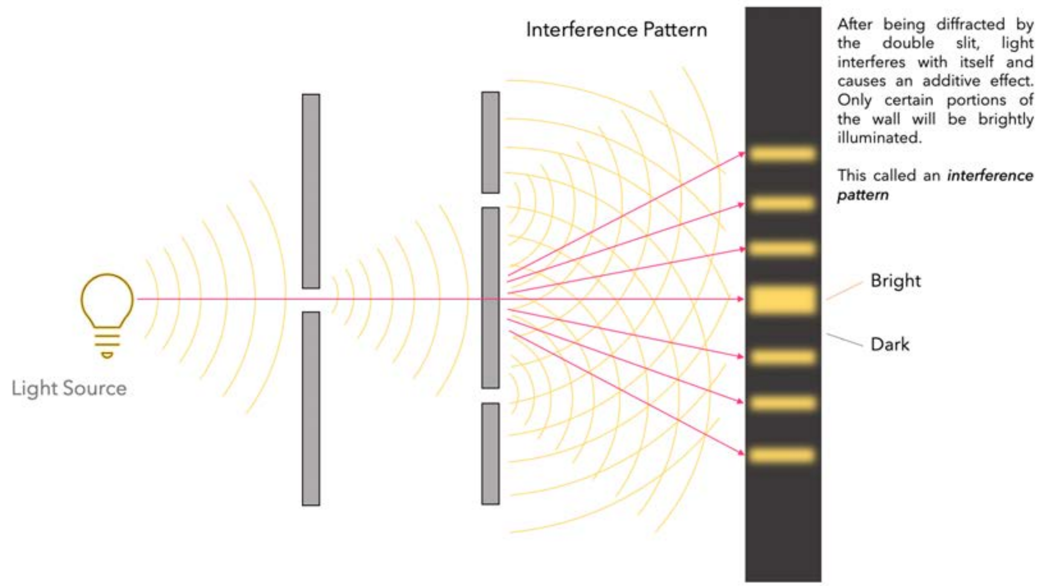
Thomas Young
(1773 to 1829)
(~200 yrs ago)

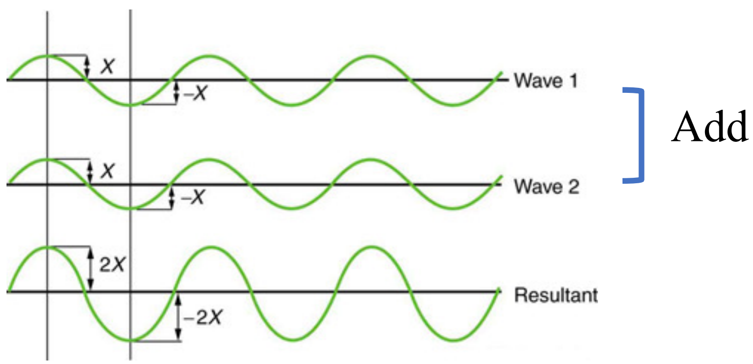


The bright and dark bands demonstrated that the slits were causing light waves to interfere with each other. Sometimes this interference is constructive and sometimes destructive. This leads to light waves adding together to create a bright patch and cancelling each other out creating dark patches.

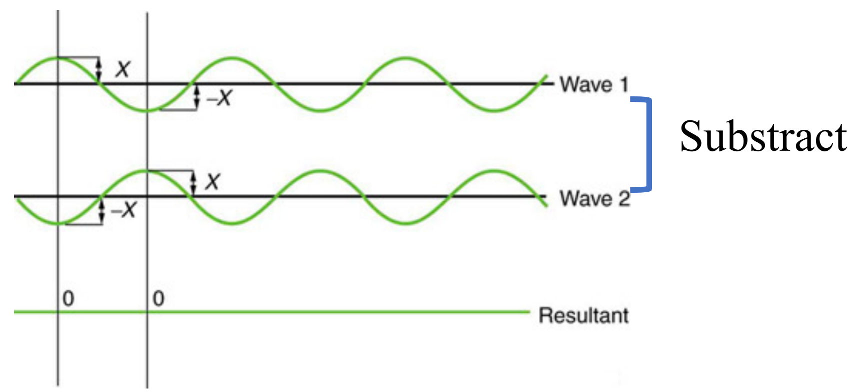
Double-slit experiment demonstrated interference in the context of light as a wave

Interference of light is a common phenomenon





The interference of two waves. When in phase, the two waves create constructive interference resulting in a wave of greater amplitude.



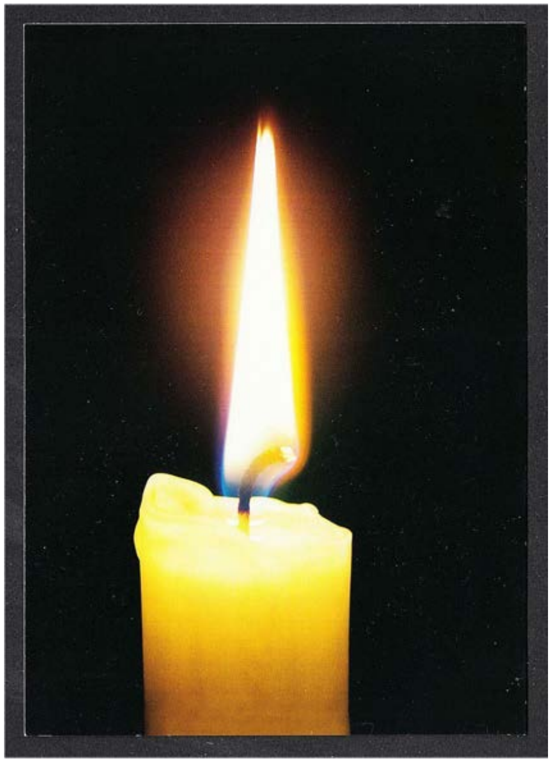
When 180° out of phase, they create destructive interference.

Web links

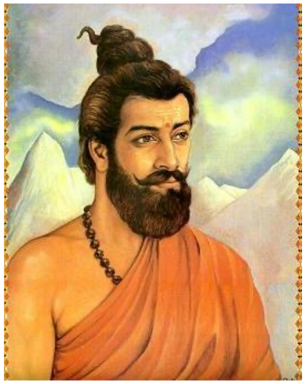
https://www.youtube.com/watch?v=ak7GB74Qlug

https://www.olympus-lifescience.com/en/microscope-resource/primer/java/polarizedlight/emwave/

https://www.olympus-lifescience.com/en/microscope-resource/primer/lightandcolor/

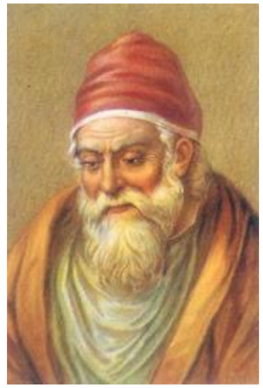


Wave or particle remains unresolved 500 BC to 1800 AD



Kanada (Kashyap)
600-400 BC

Democritus
460 – 370 BC



Euclid
300 –265 BC

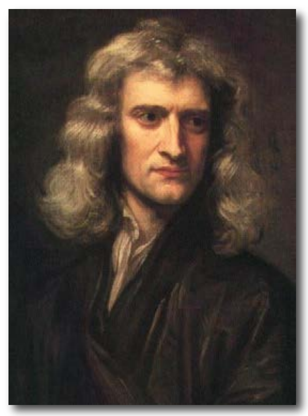
al-Haytham
965-1040 AD

René Descartes
1596 –1650 AD

Pierre Gassendi
1592–1655 AD

Francesco M. Grimaldi 1618 –1663

Christian Huygens
1629 to 1695



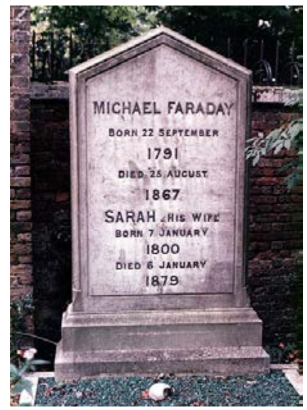
Isaac Newton
1643-1727

Robert Hooke
1635-1703

Thomas Young
1773 - 1829

What is light made up of?

Michael Faraday



The Electric Life of Michael Faraday, A. Hirshfield, 2006

Faraday Rediscovered, D. Gooding and F. A. J. L. James, 1985

Faraday, Maxwell, and the Electromagnetic Field: How Two Men Revolutionized Physics, N. Forbes and B. Mahon, 2014.

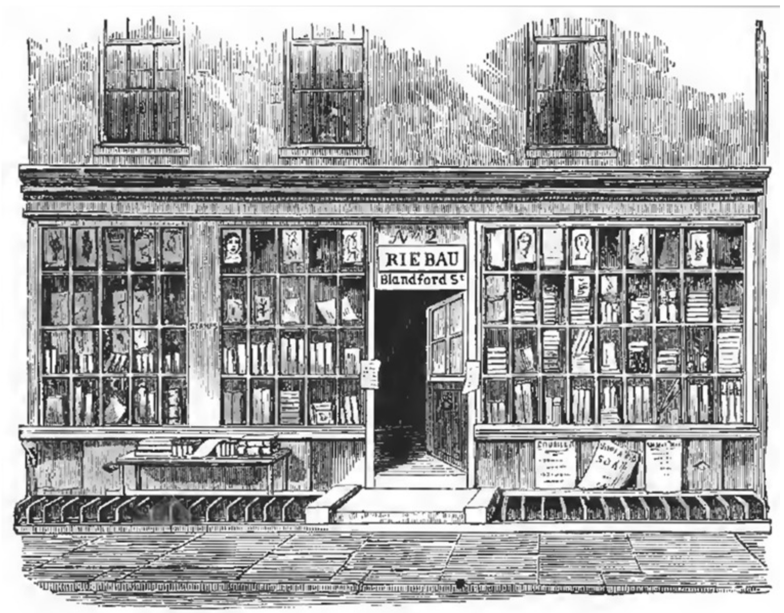
Lecture by Sir John Thomas
https://royalsociety.org/science-events-and-lectures/2017/12/genius-legacy-michael-faraday/

The Beginning

- Born near London on Sep 22 1791; three siblings
- Father a blacksmith, mostly unemployed and unhealthy
- Mother from a family of farmers
- Deeply religious, Sandemanian sect of Christianity
- Educated in rudimentary reading, writing and arithmetic, age 5-13
- Took up a job at age 13 as an errand-boy and book-binder for a local shopkeeper (Mr. Riebeau)
- At the age of 18 he has to care for the family and took up a job under Humphry Davy in London

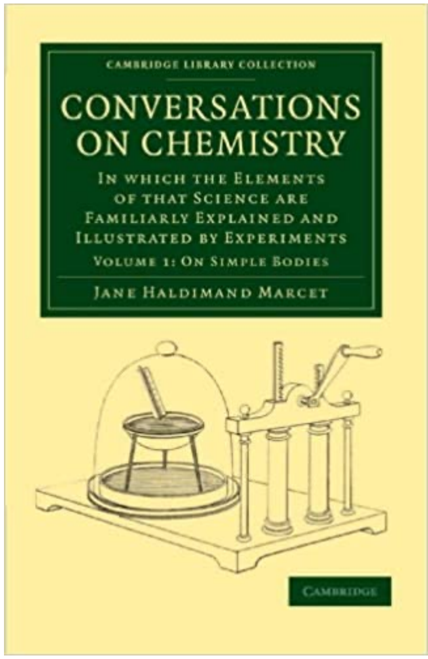
•*The Encyclopedia Britannica* – his source for electrical knowledge and much more

•*Conversations on Chemistry* – 600 pages of chemistry for ordinary people written by Jane Marcet based on Davy's lectures at the Royal Institution



Davy's lectures at RI recorded

Jane Marcet, 1769-1858

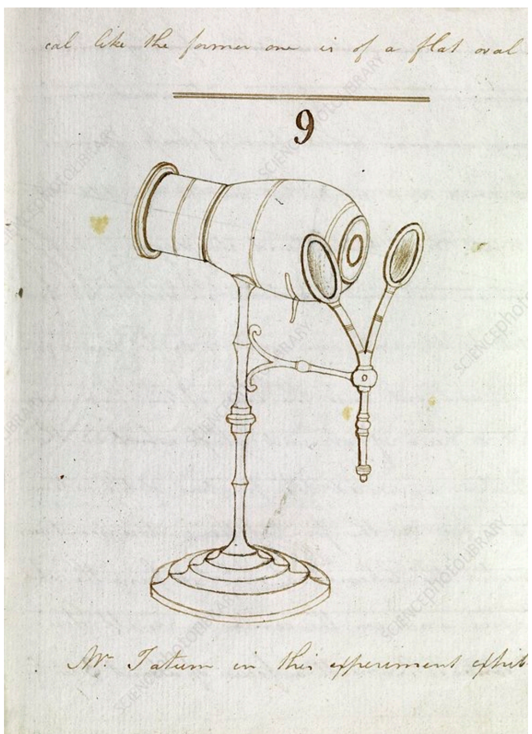


"the most wonderful and the most interesting phenomenon of nature are almost all of them produced by chemical powers"

Conversations on Chemistry, 1817

John Tatum's lectures (1772-1858) exposed Faraday to science

Tatum founded the City Philosophical Society in 1808 where Faraday and other local people received inspiration.



Faraday, a bookbinder's apprentice at the time, lacked a formal education and studied by reading books and attending lectures. He attended around 13 lectures by silversmith John Tatum (1772-1858) between February 1810 and September 1811. The notes Faraday made from these lectures formed four volumes and 300 pages and helped him start his career in science.

Getting Started

“My desire to escape from trade, which I thought vicious and selfish, and to enter into the service of Science, which I imagined made its pursuers amiable and liberal, induced me at last to take the bold and simple step of writing to Sir H. Davy, expressing my wishes, and a hope that if an opportunity came in his way he would favor my views; at the same time, I sent the notes I had taken of his lectures.” (1812)

Based on the letter Faraday wrote about the experience later in life after Davy’s death to J.A. Paris. (1829)

Davy's encouraging reply to Faraday

"Sir,– I am far from displeased with the proof you have given me of your confidence, and which displays great zeal, power of memory, and attention. I am obliged to go out of town and shall not be settled in town till the end of January; I will then see you at any time you wish. It would gratify me to be of any service to you; I wish it may be in my power.

I am, Sir, your obedient humble servant,
H. Davy."

Michael Faraday establishes that light is electromagentic

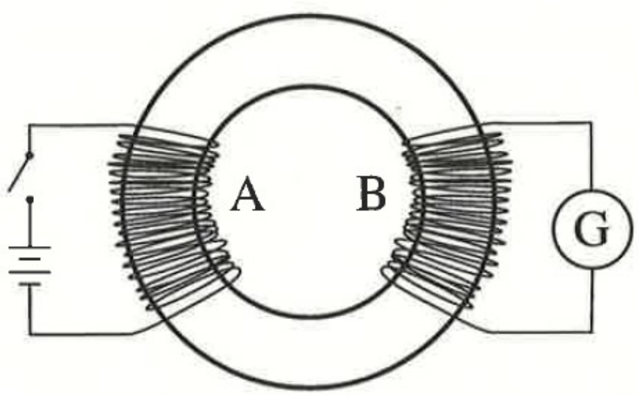
1791-1867

Series of pioneering discoveries during 1821-1831

The First Electromagnetic Induction

The basis of electric power generation

A crude observation into a full-blown discovery.

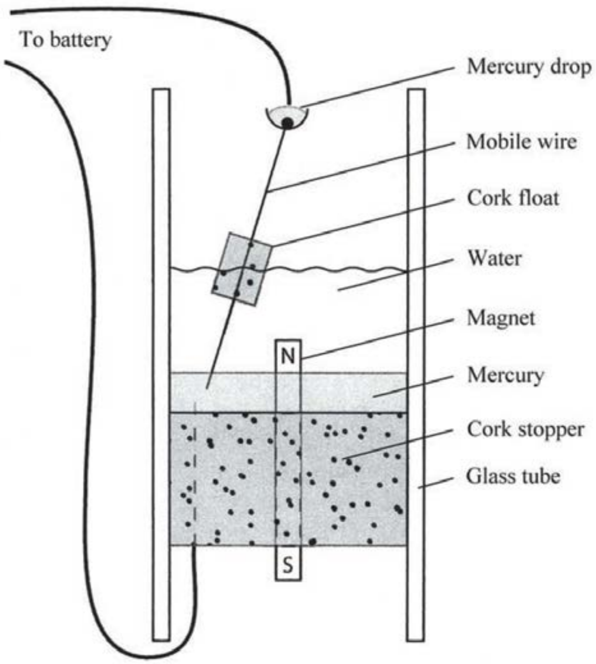


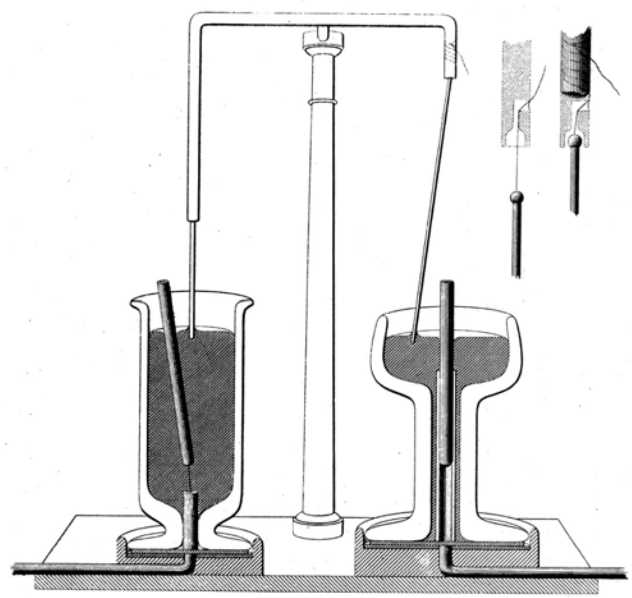
In the iron ring experiment the current in coil '**A**' produces magnetism in the ring. While this magnetism is being produced, and consequently is in motion, it is able to produce a current in coil 'B'. When the magnetism is raised to a steady state it becomes stationary and the current in coil B disappears.

Electricity to Magnetism **Magnetism to Electricity**

World's First Electric Motor-1821

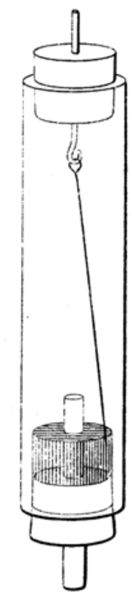
Electromagnetic rotation experiment of Faraday





Wire fixed
Magnet free

Magnet fixed
Wire free

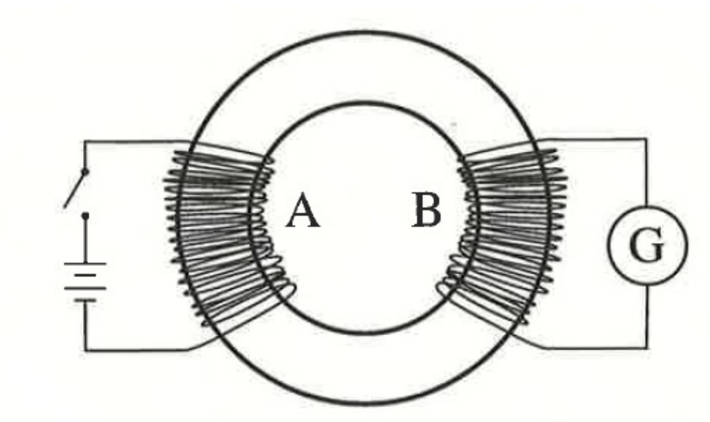


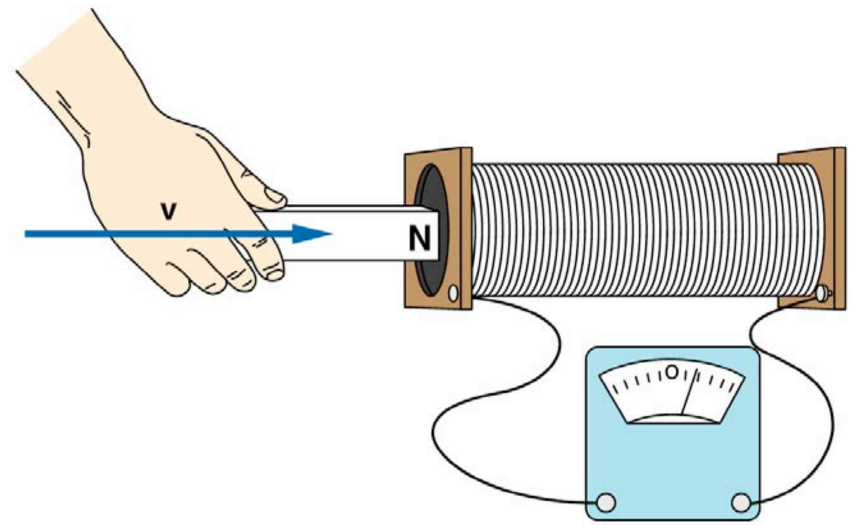
Gift model

Exploratory Experiments, Ampere, Faraday and the Origins of Electrodynamics, F. Steinle & A.Levine, 2005

Relative motion is important

Changing magnetic fields produced electric fields



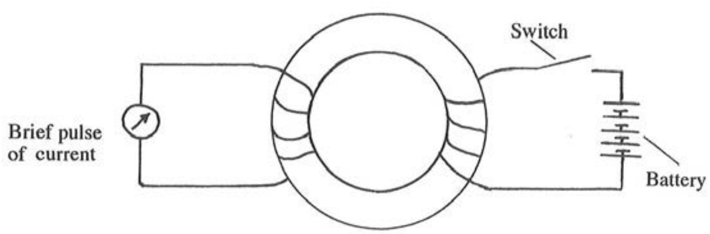


- A stationary magnet is a static phenomenon. Hence a stationary magnet cannot produce the converse of a steady current. If moving electricity produces magnetism, then moving magnetism will be necessary to produce electricity.
- It was Faraday's discovery that a changing magnetic force was needed.

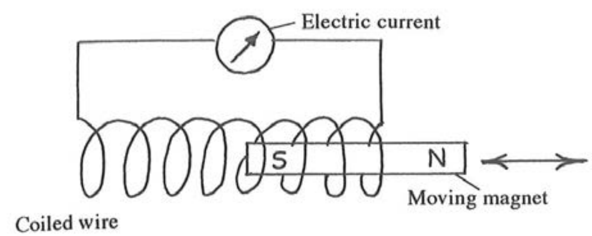
Consequences of invention of electromagnetic induction

Electrical Generator, Dynamo, Transformer

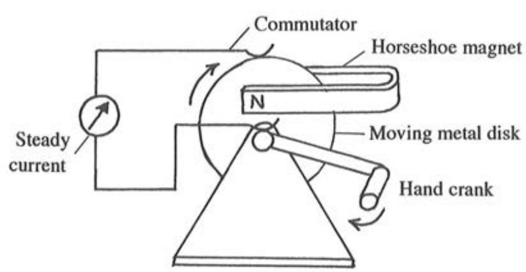
Faraday's Demonstration That Changing Magnetism Produces Electricity

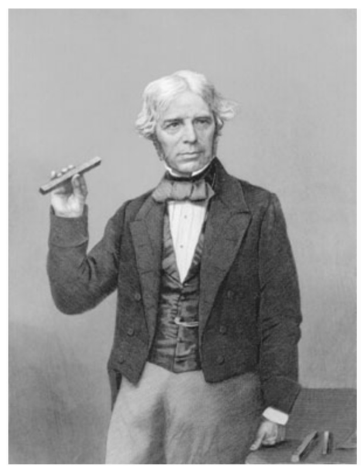


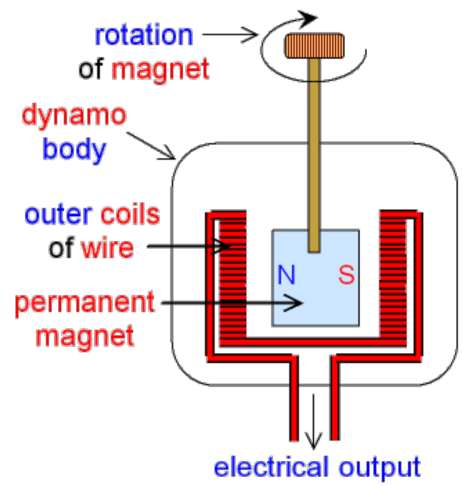
Faraday's Current Generation by a Moving Magnet



Faraday's Current Generator



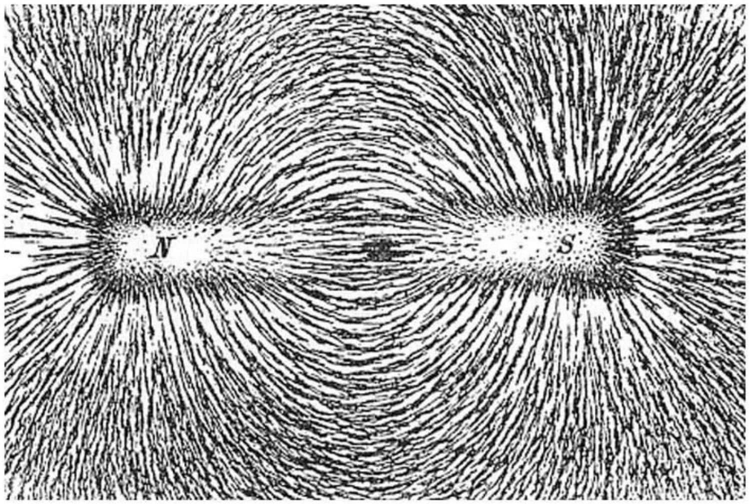




The basis of electricity and magnetism and do they communicate?

A struggle to conceptualize how forces could be transmitted across empty space.

Faraday's Lines of Forces

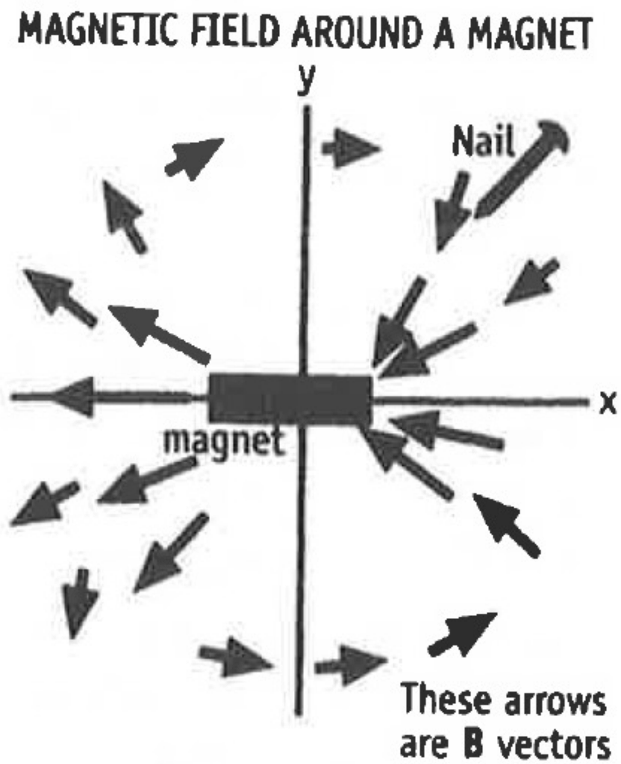


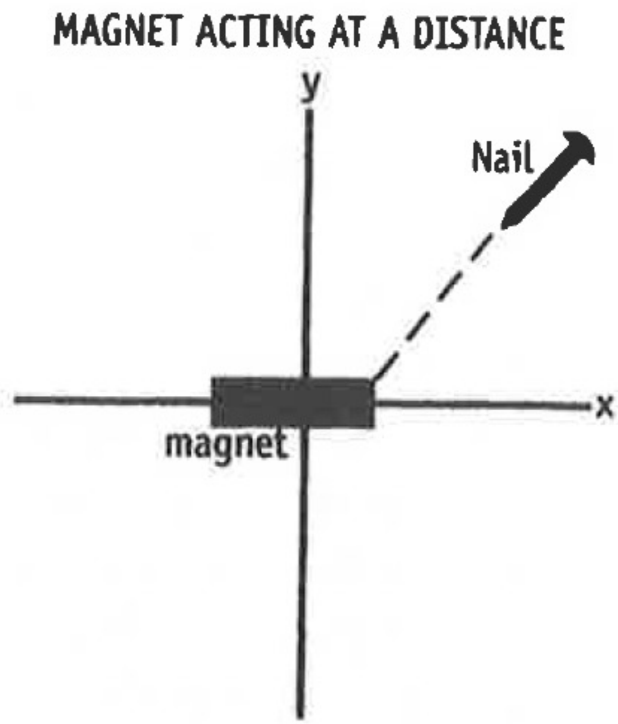
Magnetic lines of force

If iron filings are sprinkled around a magnet, they form discrete curves, originating at the poles and extending into the space surrounding the magnet.

Faraday's view
Field

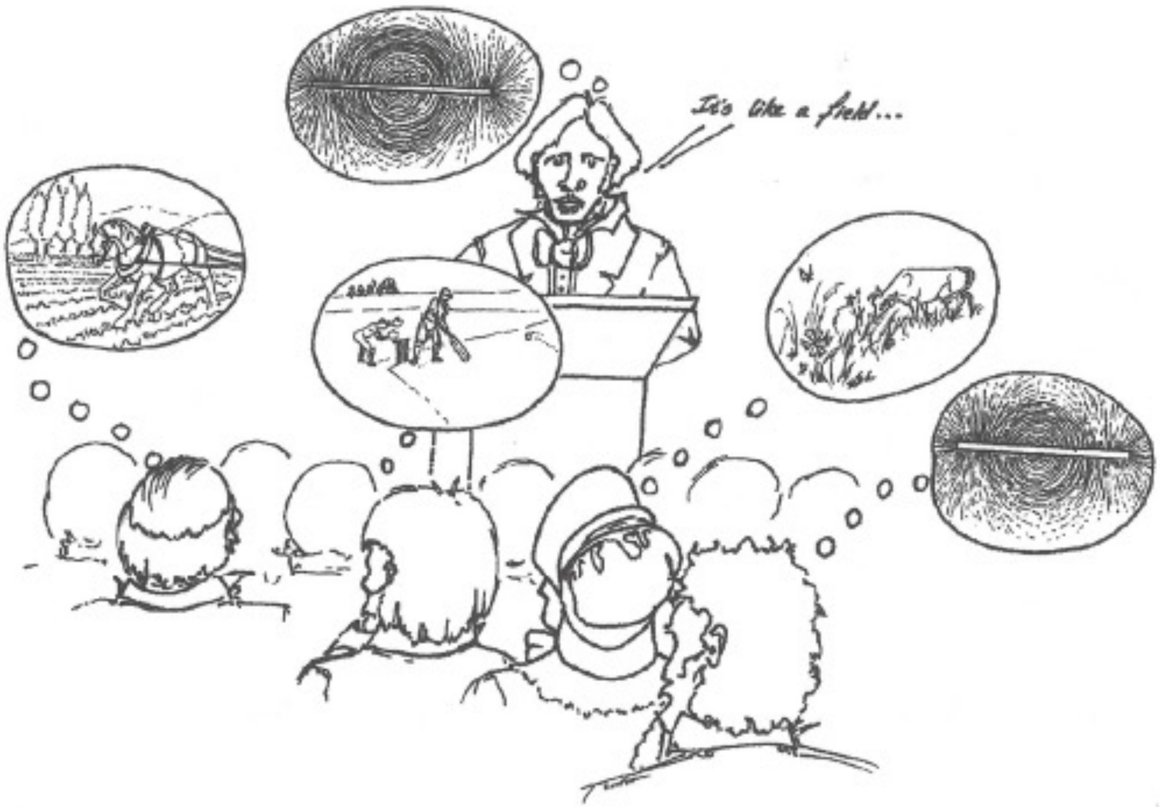
Newton's view
Action at a distance





Magnetic and electrical lines of force are curved, not straight lines.

What is a field----does anyone know?



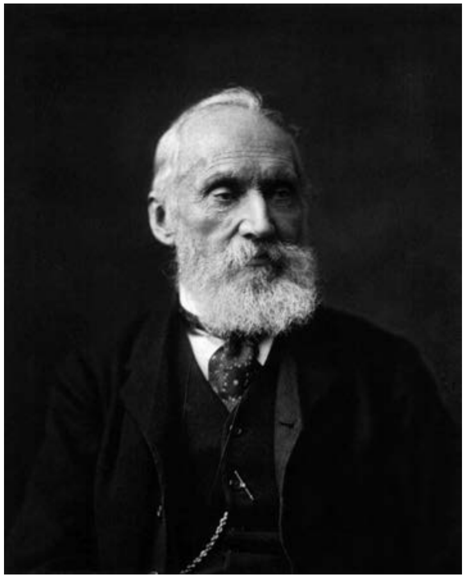
"*How few understood the physical lines of force*."

Faraday to his nice, 1855

Interaction of magnetic field and light

In 1845, Thomson mathematically analyzed Michael Faraday's magnetic lines of force and wrote a letter to him in August of that year explaining how his calculations predicted that magnetic fields should affect the plane of polarized light.

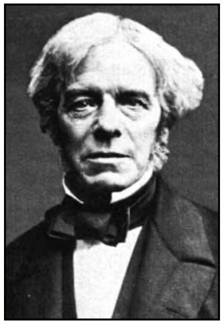
Faraday had many years before experimented with light and magnetism, but without observing any connection between the two. Encouraged by Thomson's prediction, Faraday decided to readdress the problem and began a new series of experiments in his laboratory.



William Thomson (Lord Kelvin) 1824-1907

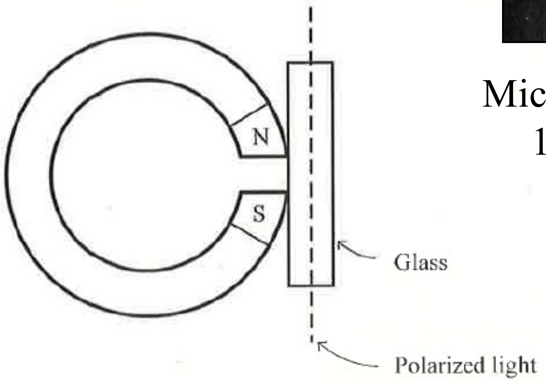
Effect of Electricity and Magnetism on Light

Light is an electromagnetic wave

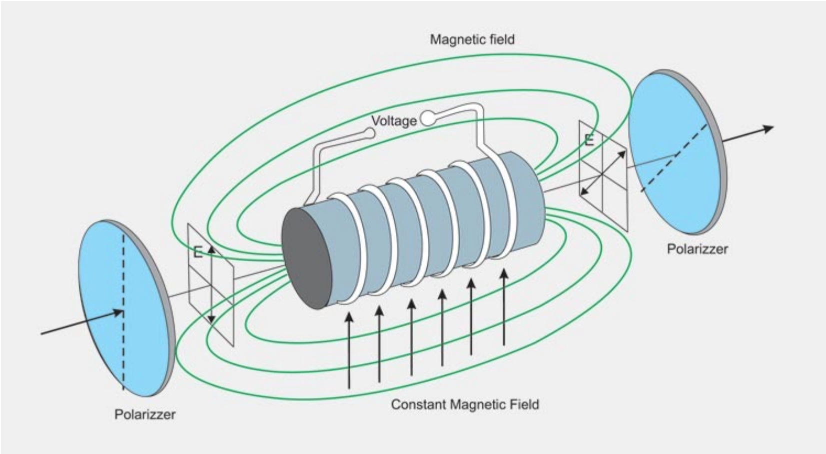


Michael Faraday
1791-1867

Faraday Effect: Magnetic field rotates plane polarized light



In 1845, Michael Faraday discovered that the plane of polarization of linearly polarized light is rotated when the light rays travel along the magnetic field direction in the presence of a transparent dielectric, an effect now known as Faraday rotation

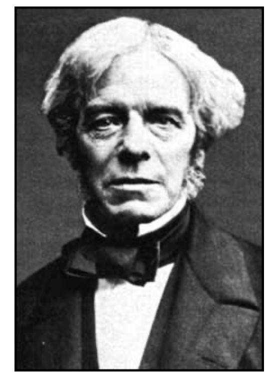


What is light?

A link between magnetism, electricity and light established

To Ampere, Nov 1845

"I happen to have discovered a direct relation between magnetism and light, also electricity and light---and the field it opens is so large & I think rich that I naturally wish to look at it first"



Michael Faraday
1791-1867

Claiming the precedence: Establishing for the first time a link between magnetism and light

In March 1832, Faraday asked the secretary of the Royal Society to deposit a note in his safe.

"I am inclined to compare the diffusion of magnetic forces from a magnetic pole to the vibrations upon the surface of disturbed water or those of air in the phenomenon of sound; *i.e*. I am inclined to think the vibratory theory will apply to these phenomena, as it does to sound and, most probably, to light."

This proposal is very close to saying light propagates as waves not in straight lines. This idea is different from Newton's theory of action at a distance. Light travels in straight lines.

Lines of force

Faraday

Faraday rejected several long-held Newtonian assumptions.

- dismissed action at a distance.
- scrapped the need for the ether.

Faraday lacked the classical education of his colleagues, his theories forged a new path away from traditional Newtonian force relations. He moved away from traditional scientific thought of his day

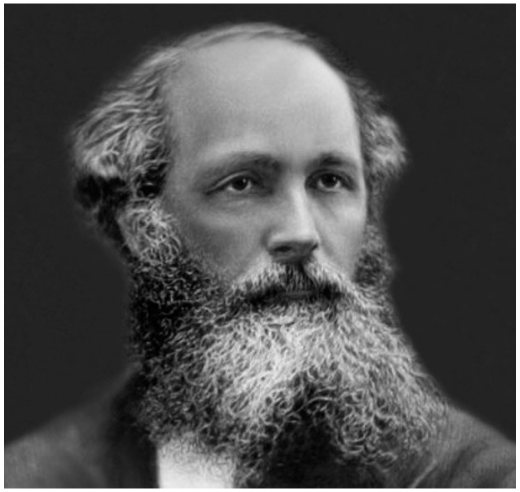
Biot

If you look for exact knowledge in his theories you will be disappointed- flashes of wonderful insight you meet here and there, but he has no exact knowledge himself, ----

Airy

Faraday should brush up on his mathematics and leave theoretical physics to the properly trained.

James Clerk Maxwell



James Clerk Maxwell
(1831-1879)

The Man who Changed Everything: The Life of James Clerk Maxwell, Basil Mahon, 2003

Faraday, Maxwell, and the Electromagnetic Field: How Two Men Revolutionized Physics, N. Forbes and B. Mahon, 2014.

Men of Science, J. G. Crowther, 1936, Ch. 5.

Einstein's Heroes: Imagining the World through the Language of Mathematics, R. Arianrhod, 2005

"One scientific epoch ended and another began with James Clerk Maxwell"

A. Einstein

"From a long view of the history of mankind seen from, say, ten thousand years from now there can be little doubt that the most significant event of the nineteenth century will be judged as Maxwell's discovery of the laws of electrodynamics."

R. Feynmann

Knowns and unknowns about light before Maxwell

Knowns

- Light responds to electricity and magnetism (Faraday rotation)
- Light is a mixture of various visible and invisible radiations (visible, UV and IR radiations)
- Light travels like a wave (double slit expt); particle idea dropped
- Electric field generated between two metal plates and magnetic field generated by magnets are independent of each other.
- Electricity and magnetism creates fields and don't follow the Newtonian principle of 'action at a distance' (Faraday)

Unknowns

- The speed of light
- Connection between electric and magnetic fields
- Connection between electric and magnetic fields and light
- Likely existence of other rays of light in addition to visible, UV and IR

James Clerk Maxwell
(1831-1879)

- In 1861, Maxwell extended Faraday's proposal by mathematically deriving that changing electric fields produced magnetic fields and in fact the two phenomena should be perceived as a single entity.

- This means oscillating electric fields would produce magnetic fields. Oscillating magnetic fields would produce electric fields.

- A moving electric charge would thus produce a magnetic field.

Maxwell's Equations of Electromagnetism

Gauss' Law for Electrostatics

$$\oint \vec{E}\cdot d\vec{A} = q/\epsilon_0$$

Gauss' Law for Magnetism

$$\oint \vec{B}\cdot d\vec{A} = 0$$

Faraday's Law of Induction

$$\oint \vec{E}\cdot d\vec{s} = -\frac{d\Phi_B}{dt}$$

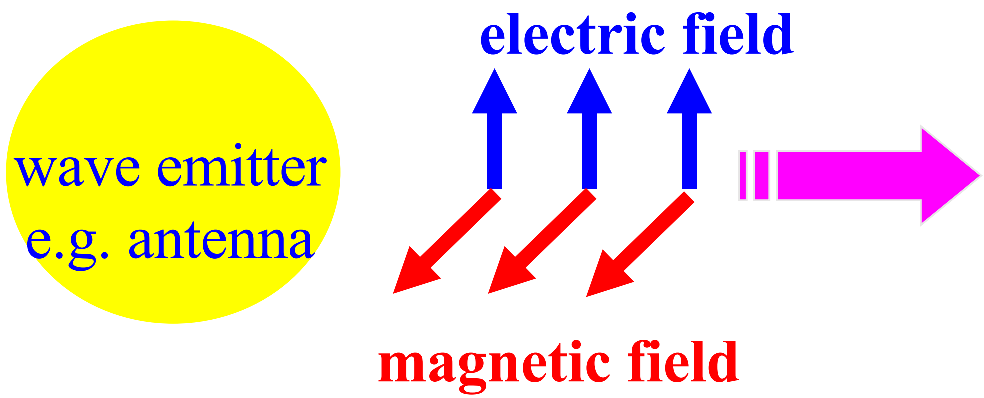
Ampere's Law

$$\oint \vec{B}\cdot d\vec{s} = \mu_0\epsilon_0\frac{d\Phi_E}{dt} + \mu_0 i$$

Maxwell explained electric and Magnetic fields in mathematical equations

- Electric charges produce electric fields (Coulomb's Law)
- Electric currents (moving charges) produce magnetic fields (Ampere's Law)
- An electromagnetic wave is a combination of electric and magnetic fields that vibrate together in space and time in a synchronous fashion and propagate at the speed of light
- Maxwell's equations showed that electricity and magnetism are two sides of the same coin, and that light is that coin in movement.

The generation of an electromagnetic wave



- The electromagnetic wave is a *transverse wave*, the electric and magnetic fields oscillate in the direction perpendicular to the direction of propagation
- The time varying electric field generated the time varying magnetic field which generates the time varying electric field and so on and so on . . . .
- The electric and the magnetic part stimulate each other producing a cycle.

Maxwell predicts the speed of light

Where the speed of light "c" is given through constants from both electricity and magnetism.

$$c = 1/\sqrt{\varepsilon_o \mu_o}$$
$$= 3\times10^{8}\ m/s$$

Maxwell's Laws

Four equations describe the behaviors of electricity and magnetism

1. Coulomb's Law of static electricity
2. All magnets have both north and south poles
3. Electricity produces magnetic effects
4. Moving magnets produce electricity

These equations lead to prediction of waves:

1. Waves travel 186,000 miles per second
2. Light is a consequence of electricity and magnetism switching back and forth

James Clerk Maxwell
Light is a traveling electromagnetic wave

- Unified electromagnetism and light.
- Explained the existence of invisible forms of light.
- Electromagnetic waves propagate in free space at $c = 3 \times 10^8$ m/s.
- ***E*** and ***B*** are always perpendicular to each other, and perpendicular to the direction of propagation.
- Based on the double slit experiments of Thomas Young and the equations of Maxwell, by 1900 most scientists believed that light behaved as a wave.

Maxwell: Light is an electromagnetic wave

Faraday to Ampere, Nov 1845

"I happen to have discovered a direct relation between magnetism and light, also electricity and light---and the field it opens is so large & I think rich that I naturally wish to look at it first"

Maxwell to Faraday, October 1861

"I think we have now strong reason to believe, whether my theory is a fact or not, that the luminiferous and the electro-magnetic medium are one. In other words, light is indeed an electromagnetic undulation-a *ray-vibration*, as you had called it in 1846."

Maxwell Publication in 1865

"The electromagnetic theory of light, as proposed by Faraday, is the same in substance as that which I have begun to develop in this paper, except that in 1846 there were no data to calculate the velocity of propagation."

https://www.youtube.com/watch?v=WqefMRAxt2k

Summary: The Laws of Electricity and Magnetism

- Laws of electricity
  - Electric charges produce *electric* fields (Coulomb)
  - Electric fields begin and end on charges
- Laws of magnetism
  - Currents produce *magnetic* fields (Ampere)
  - Magnetic field lines are closed loops
  - A changing magnetic field can produce a current (*induced currents*) (Faraday)
  - A changing electric field can produce a magnetic field (Maxwell)

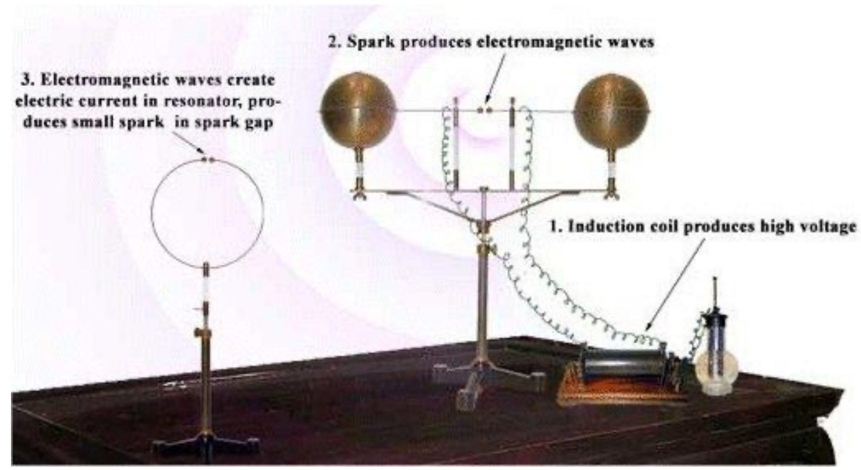
Heinrich Rudolf Hertz

- 1857 – 1894 (lived for 37 yrs)
- German physicist
- First to generate and detect electromagnetic waves in a laboratory setting in 1887.
- As predicted by Maxwell he established the existence of **radiowaves**.
- Established the phenomenon of photoelectric effect

Hertz
1857-1894

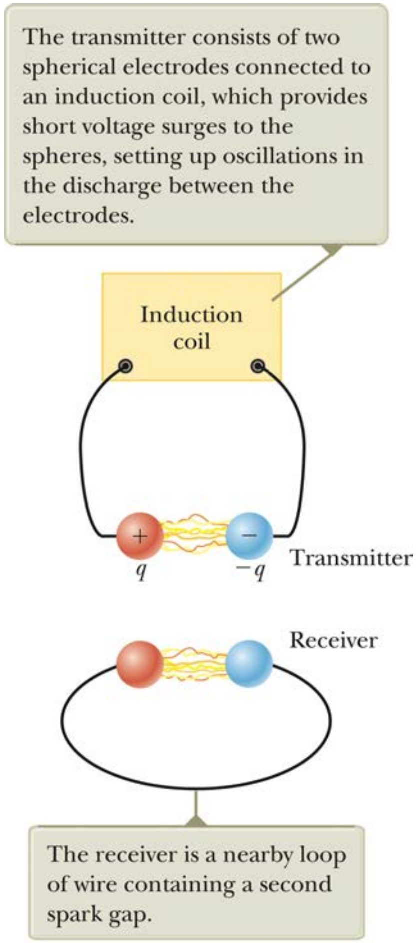
Accidental Discovery

In 1888, in a corner of his physics classroom at the Karlsruhe Polytechnic in Berlin, Hertz generated electric waves using an electric circuit; the circuit contained a metal rod that had a small gap at its midpoint, and when sparks crossed this gap violent oscillations of high frequency were set up in the rod. Hertz proved that these waves were transmitted through air by detecting them with another similar circuit some distance away. He also showed that like light waves they were reflected and refracted and, most important, that they traveled at the same speed as light but had a much longer wavelength. These waves, originally called Hertzian waves but now known as radio waves, conclusively confirmed Maxwell's prediction on the existence of electromagnetic waves, both in the form of light and radio waves.



A great number of modern developments, like radio, television and Wi-Fi were spun out of Hertz's simple demonstrations.

Experimental support for light as wave



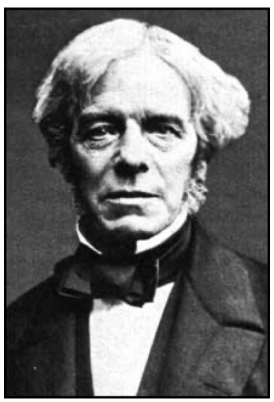
Hertz accidently discovered in1888

- Sparks were induced across the gap of the receiving electrodes when the frequency of the receiver was adjusted to match that of the transmitter.
- Hertz thought that if Maxwell was right, this would radiate electromagnetic waves through air. In a series of other experiments, Hertz also showed that the radiation generated by this equipment exhibited wave properties.
- Interference, diffraction, reflection, refraction and polarization
- He also measured the speed of the radiation.
- It was close to the known value of the speed of light.

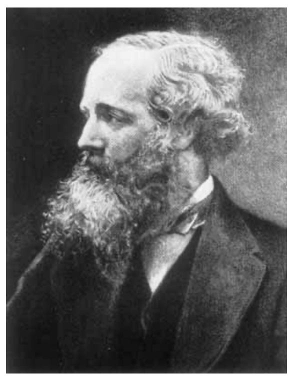
"*I do not think that the wireless waves I have discovered will have any practical application*."

Light is indeed electromagnetic waves

- Hans Christian Oersted finds that an electric current deflects a compass needle. (1820)
- Andre Marie Ampère finds that parallel wires carrying current produce forces on each other. (1820)
- Faraday laid the groundwork with his discovery of electromagnetic induction. (1846)
- Maxwell explained theoretically that light is an electromagnetic wave (1865)
- Heinrich Hertz showed experimentally that EM waves exist travels at the speed precited by Maxwell. (1887)



Michael Faraday
1791-1867



James Clerk Maxwell
1831-1879

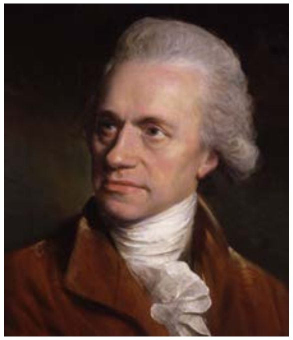
Heinrich Rudolf Hertz
1857-1894

Over and Beyond the Rainbow

Visible rays (1665)

Isaac Newton

Infrared (1800)



F. W. Herschel
1738-1822

Ultraviolet (1801)

J. W. Ritter
1776-1810

H. R. Hertz
(1857-1894)

Radiowaves (1886)

J. C. Bose
(1858 - 1937)

Microwaves (1894)

W. C. Röntgen
(1845 - 1923)

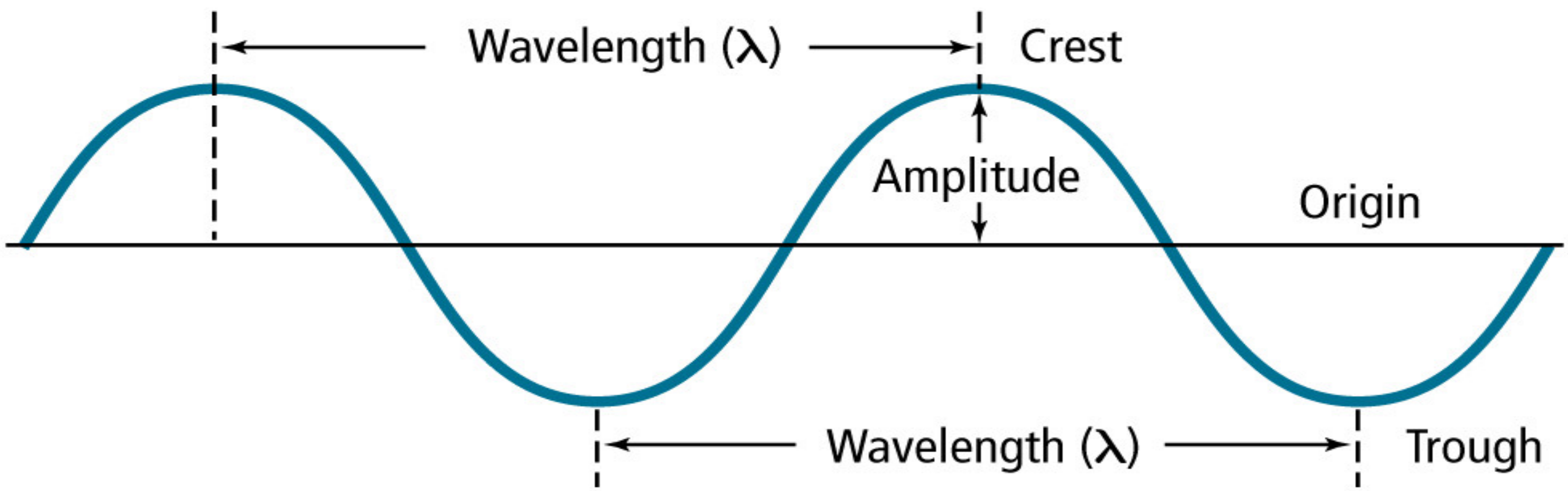
X-Rays (1895)

Paul Villard
(1860 - 1934)

γ-Rays (1900

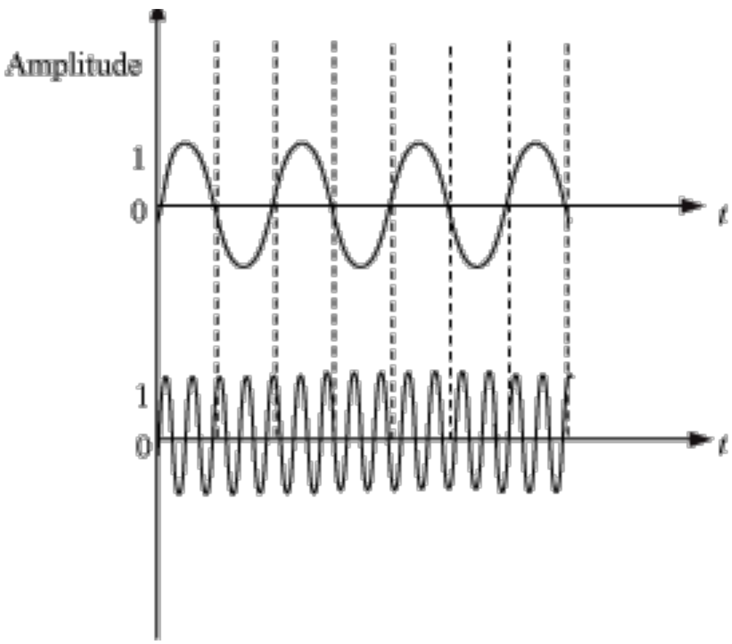
The Wave Nature of Light

- The amplitude is the wave's height from the origin to a crest.

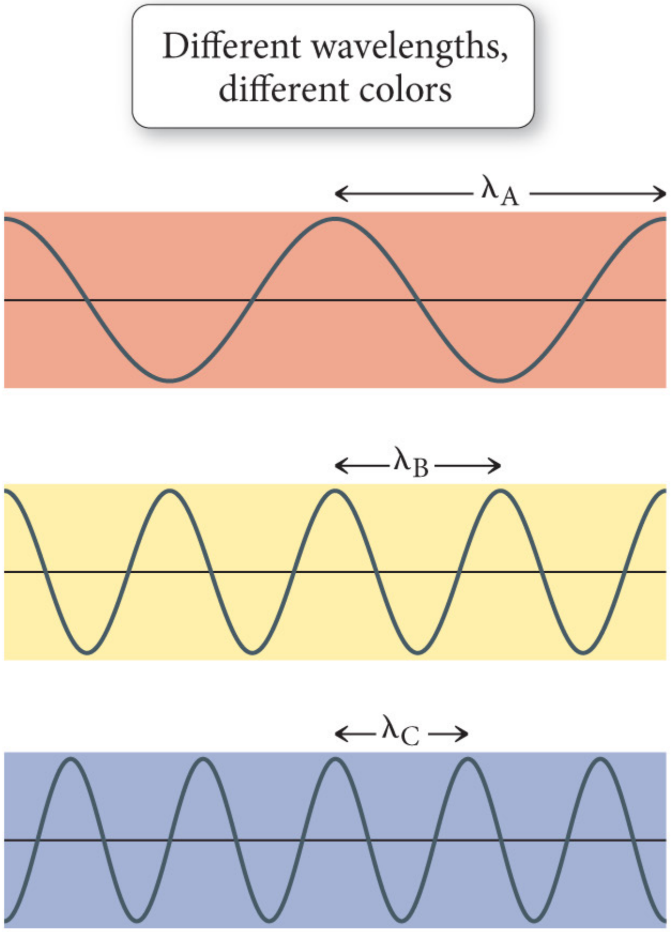


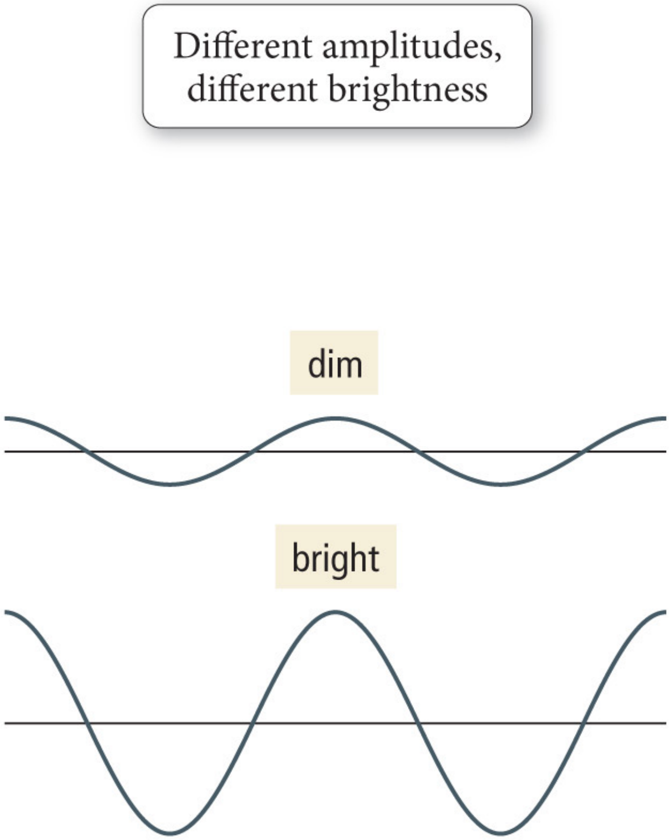
The Wave Nature of Light

- The frequency (ν) is the number of waves that pass a given point per second.
- Wavelength and frequency are inversely related—the shorter the wavelength, the higher the frequency.
- Light is a type of energy that travels through space at a constant speed of 3.0×10^8 m/s (186,000 mi/s).
- Classical: Energy carried by a light wave is proportional to the *Amplitude* of wave. $E \propto A^2$



Amplitude and Wavelength

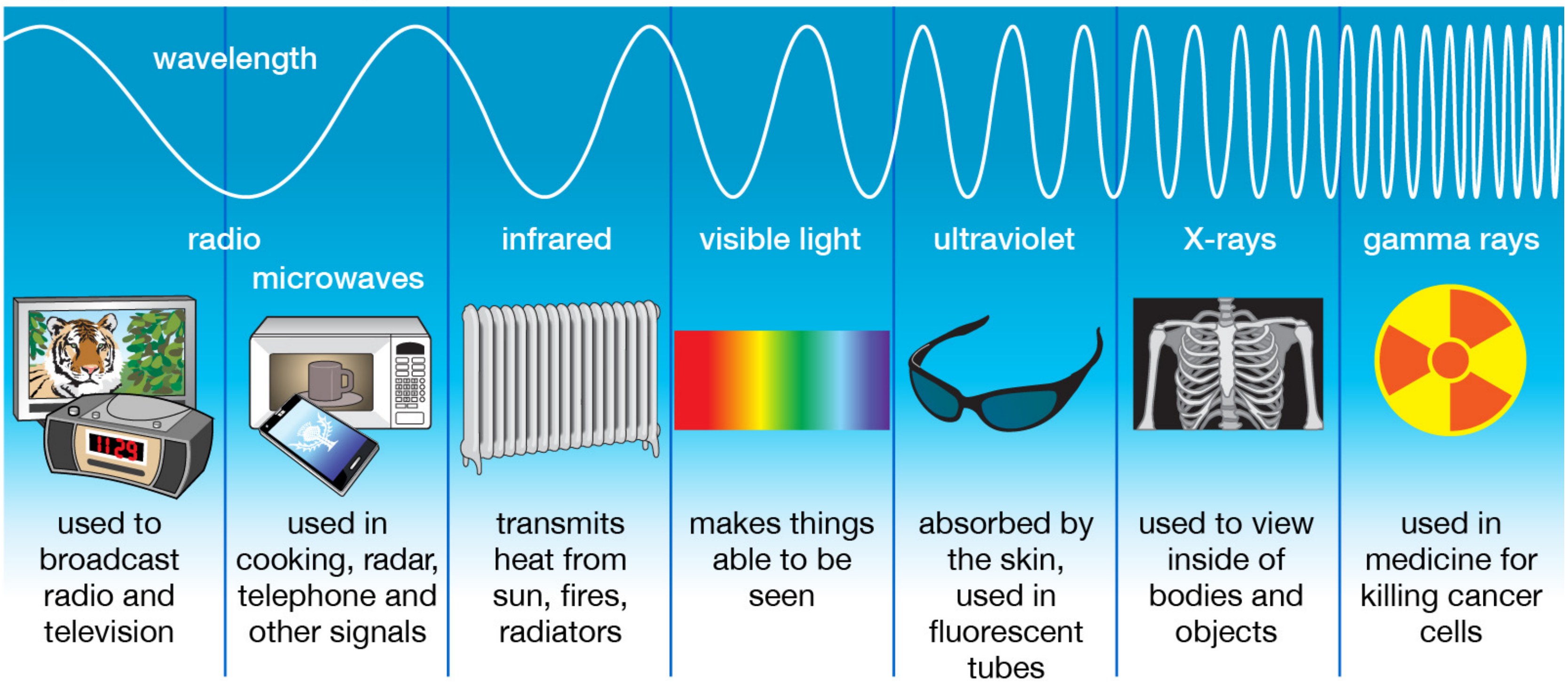




Uses of electromagnetic radiations of different wavelengths

$$\lambda = c/\nu \qquad \nu = c/\lambda$$

Types of Electromagnetic Radiation



How does light wave travel?

- Ocean waves — water molecules
- Sound — molecules in air
- Light — **plenum** later **aether**

René Descartes 1596 –1650

Believed that an invisible substance, called the plenum, permeated the universe. Light is a disturbance that traveled through the plenum.

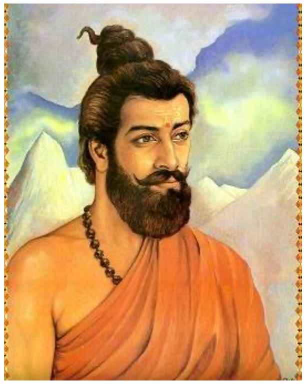
Robert Boyle
Christiaan Huygens
J. C. Maxwell
H. Hertz
H. Lorentz

Plenum was changed to aether and Thought to be the medium through which light propagates. The universe is filled with a fluid called aether. This idea was supported by numerous scientists

End of aether came due to Albert Einstein's theory of relativity (1905)

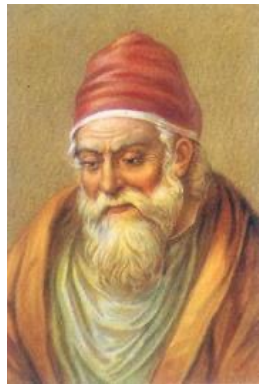
Speed of Energy Transmission

Wave or particle remains unresolved 500 BC to 1800 AD



Kanada (Kashyap)
600-400 BC

Democritus
460 – 370 BC



Euclid
300 –265 BC

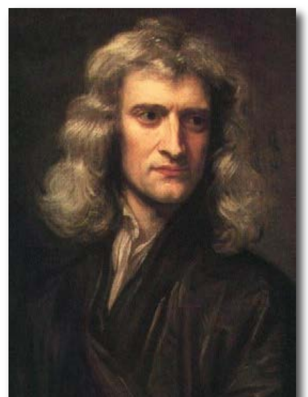
al-Haytham
965-1040 AD

René Descartes
1596 –1650 AD

Pierre Gassendi
1592–1655 AD

Francesco M.
Grimaldi 1618 –1663

Christian Huygens
1629 to 1695



Isaac Newton
1643-1727

Robert Hooke
1635-1703

Thomas Young
1773 - 1829

Light is an electromagnetic wave

Michael Faraday
1791-1867

James Clerk Maxwell
1831-1879

Heinrich R. Hertz
1857-1894

F. W. Herschel
1738-1822

J. W. Ritter
1776-1810

J. C. Bose
(1858 - 1937)

G. Marconi
(1874 - 1937)

K. F. Braun
(1850 - 1918)

Paul Villard
(1860 - 1934)

W. C. Röntgen
(1845 - 1923)

What we know thus far

Light is a wave.

Faraday experimentally showed that electricity and magnetism are related.

Faraday proposed light is electromagnetic.

Maxwell theoretically established the connection between electricity and magnetism and predicted the speed.

Hertz established that there are electromagnetic waves that we can't see and many were identified.

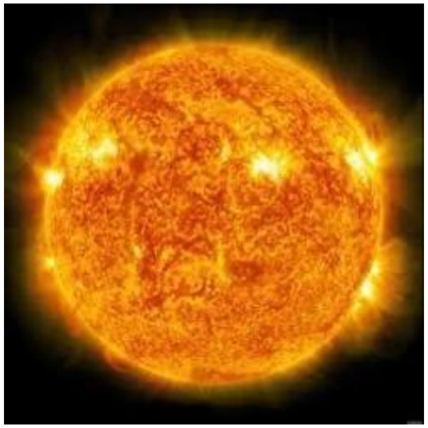
Hertz measured the speed of electromagnetic wave and confirmed Maxwell's prediction.

Light travels at different frequencies but all the same speed.

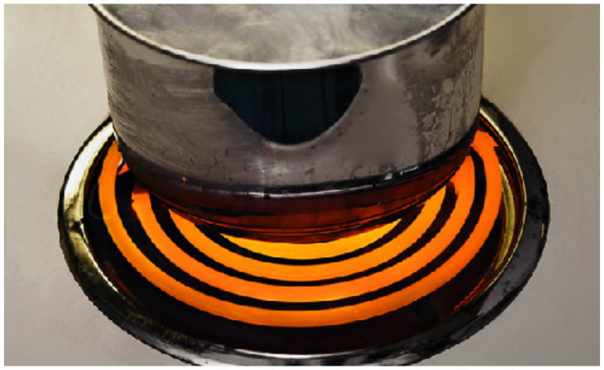
Heat is Light

Figure 1: Campfires emit radiant "energy" in the visible and infrared spectrum, which upon interaction with your skin is felt as "radiant heat".[1]

Generation of Light



Sun



Electric heating element

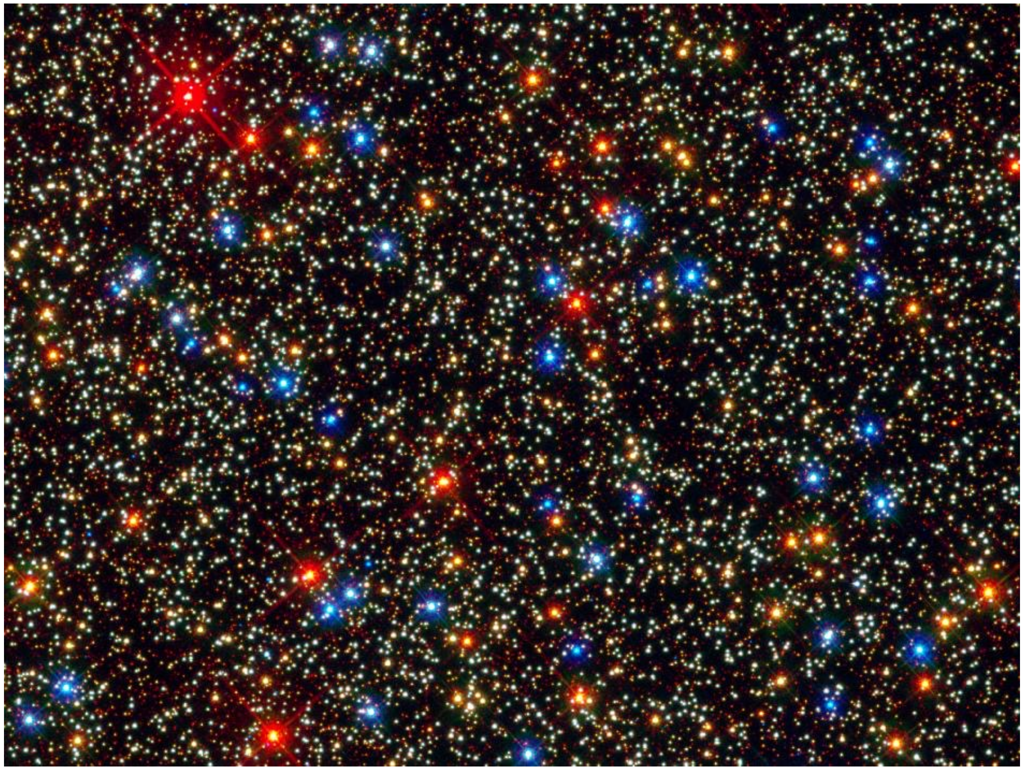
Cook-out grill

Light bulb filament

Hot solid bodies give out radiation

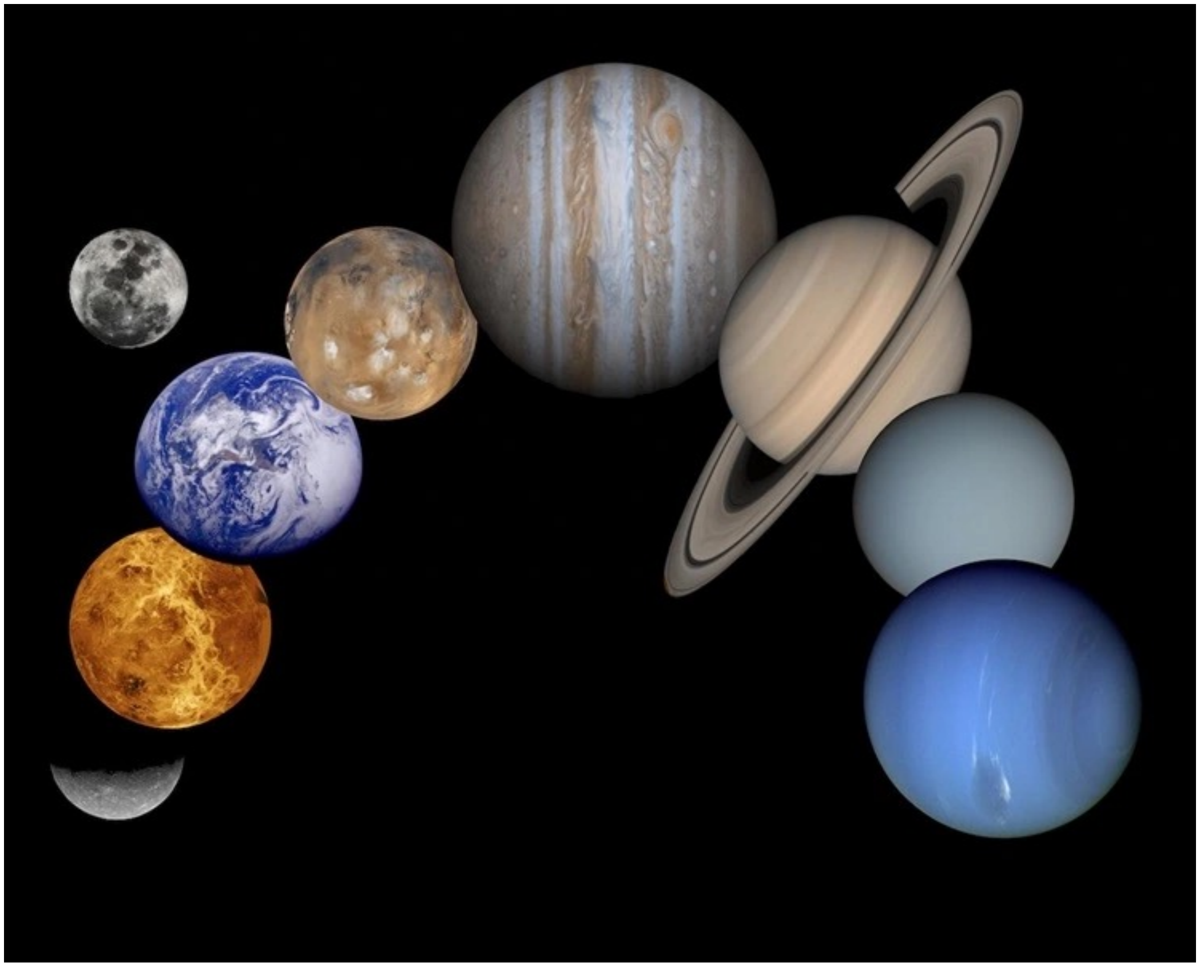
Temperature and color distribution of galaxy

Color of the star is related to surface temperature



Constellation of Orion

Why are the planets in our solar system so different in colors?



Kirchoff and Blackbody Radiation

An object at any temperature is known to emit thermal radiation.

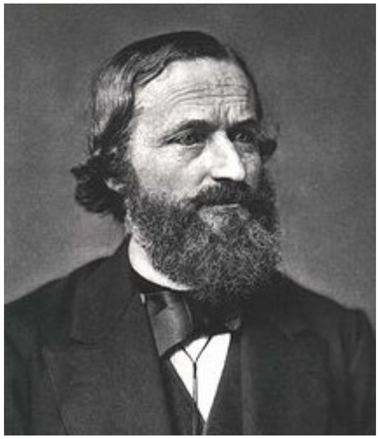
The thermal radiation consists of a continuous distribution of wavelengths from all portions of the electromagnetic spectrum.

A **black body** is an ideal system that absorbs all radiation incident on it.

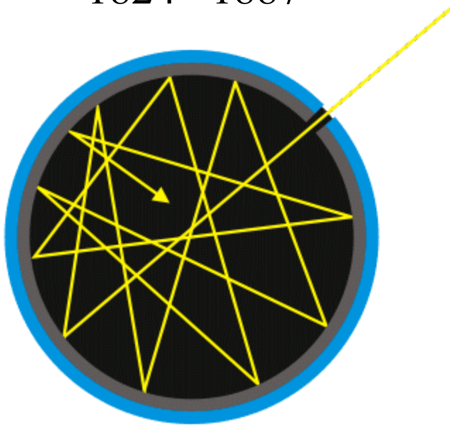
"*A good absorber is a good emitter*" *(Kirchhoff)*

A material with emission/absorption (E/A) as ONE is called 'Black Body'.

An example of such a thing would be an enclosed cavity, the internal surface of which continuously emits and absorbs radiation of all frequencies.



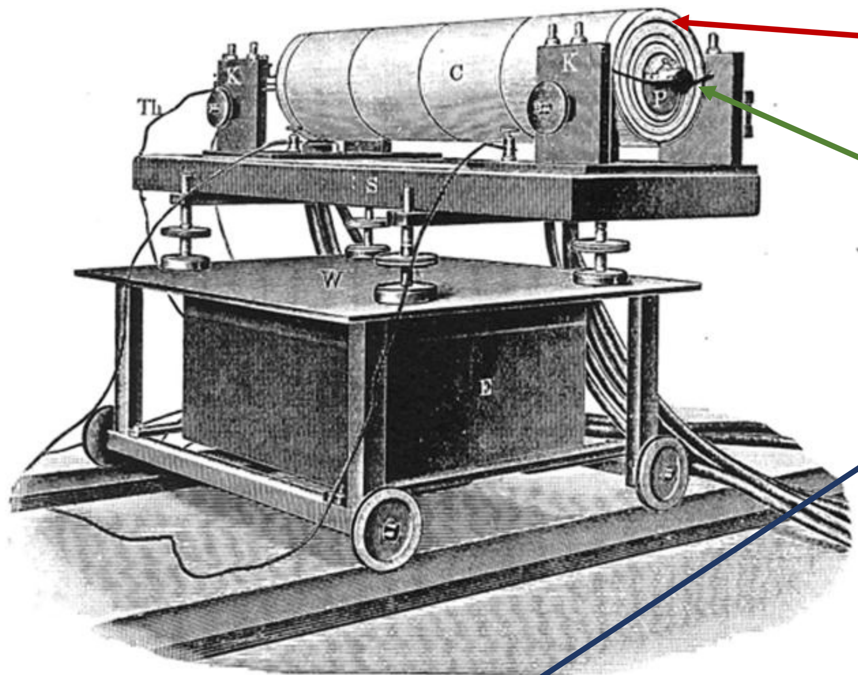
Gustav R. Kirchhoff
1824 –1887



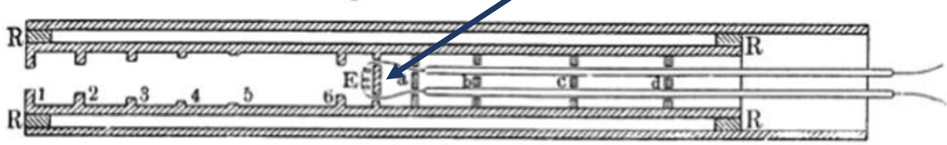
Conceptual Black Body

Black body is a hypothetical perfect radiator that absorbs all incident light and, therefore, emits all of that light when maintained at a constant temperature in order to preserve equilibrium.

Apparatus of Lummer and Kurlbaum to measure the spectrum of black-body radiation. An electrical current heats the filament E located in a tube inside the cylinder C to a fixed temperature T, giving rise to black-body radiation inside this cylinder. The spectrum of this radiation is observed by some radiation exiting through the hole at one end along the axis of the cylinder.



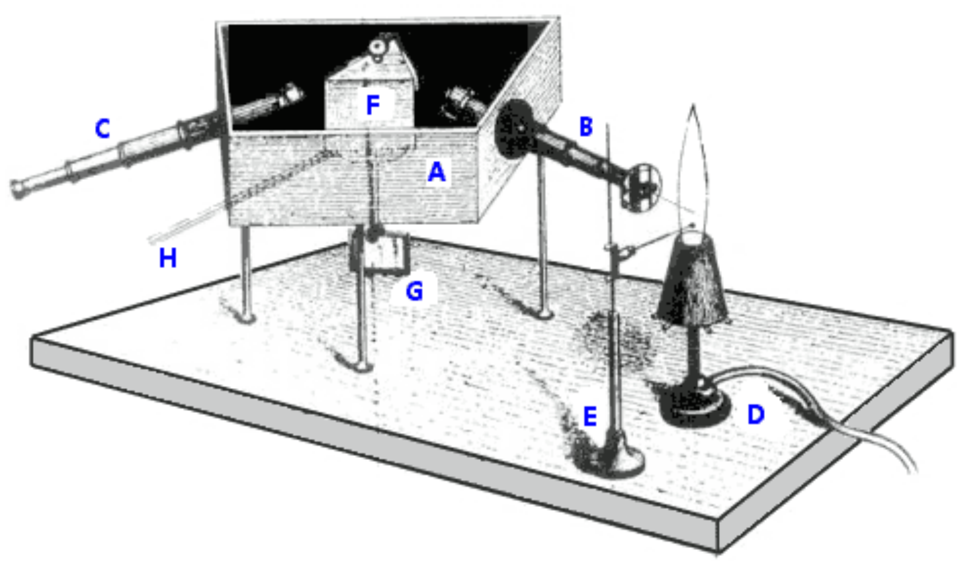
Schwarzer Körper nach Lummer-Kurlbaum.



Strahlungsrohr.

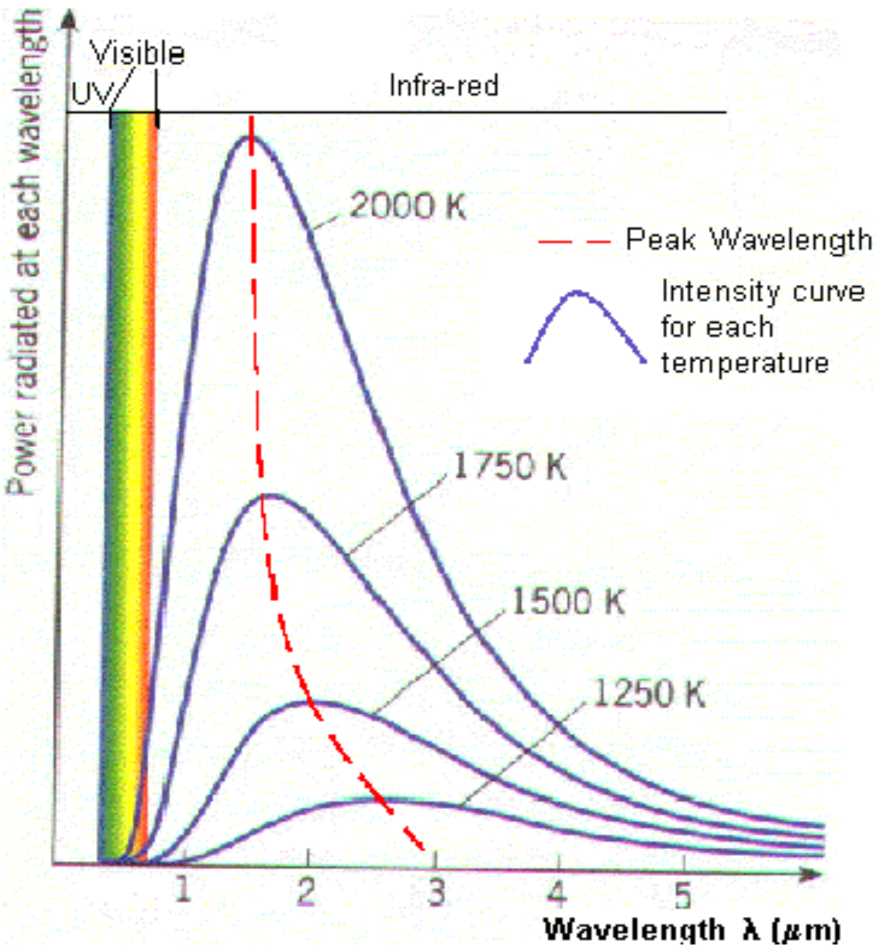
The first UV-Vis absorption spectrometer

The Bunsen-Kirchhoff Spectroscope with Bunsen Burner (1859)



A) Box, colored black on the inside; (B) & (C) Telescopes; (D) Bunsen Burner; (E) Sample Holder; (F) Prism; (G) Mirror; (H) Handle to rotate prism and mirror.

Black-Body Spectrum at different temperatures



Robert Kirchhoff, 1860

The spectrum (wavelength and intensity) depend on the temperature.

The hotter the black body, the shorter the peak wavelength.

A black body emits all wavelengths of light but not equally; there is always a wavelength in which the radiation peaks.

The peak height increases and shifts to shorter wavelengths as the temperature of the black body increases.

The Stefan-Boltzmann Law

Connects temperature to the amount of energy released

$$E = \sigma T^4$$

where σ is a constant

(the Stefan-Boltzmann constant) which has a value of

$5.67 \times 10^{-8}\ W \cdot m^{-2} \cdot K^{-4}$

and T is the absolute temperature (in Kelvin)

Wien's Law

Connects temperature to the maximum of emission wavelength

$$\lambda_m = a/T$$

where λ_m is the WAVELENGTH in the spectrum at which the energy peak occurs

T is the absolute TEMPERATURE of the body, and

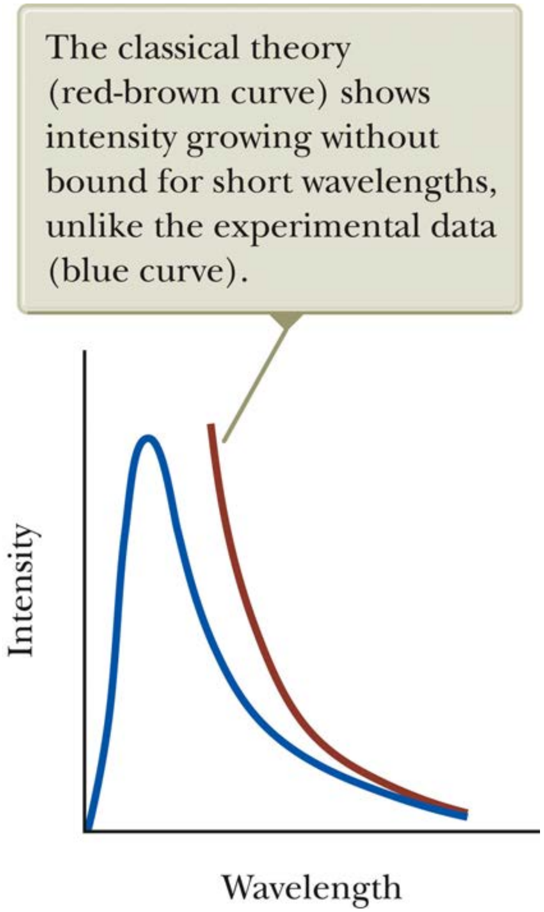
a is a constant (with a value of 2898) (if λ_m is expressed in micrometers.)

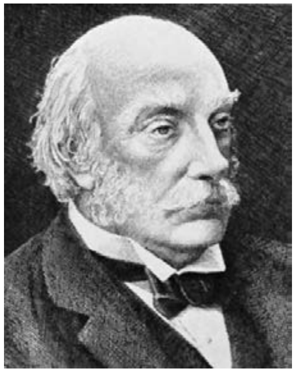
The hotter the body, the shorter the wavelength

The cooler the body, the longer the wavelength

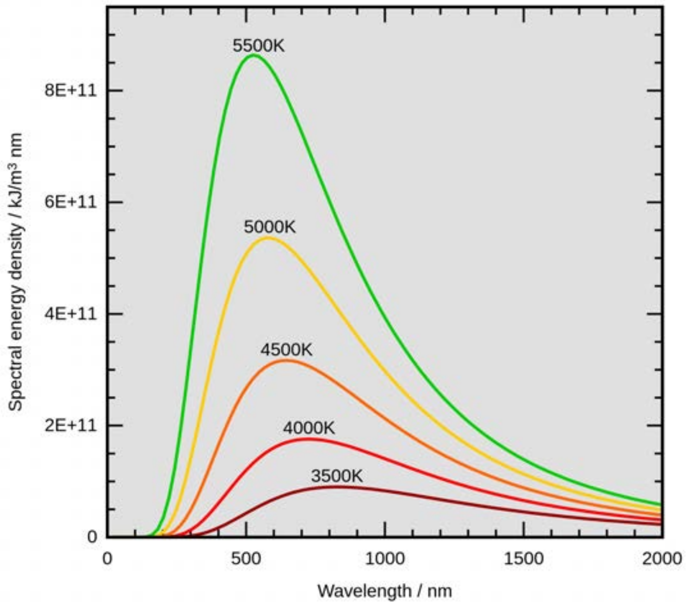
Wien displacement law, useful for instance in determining the temperature of the sun and stars. As per the equation the Sun's temperature is calculated to be 5700 K. The discovery was awarded Physics Nobel Prize in 1911.

Another attempt to fit the spectrum





The Lord Rayleigh
Nobel Prize 1904

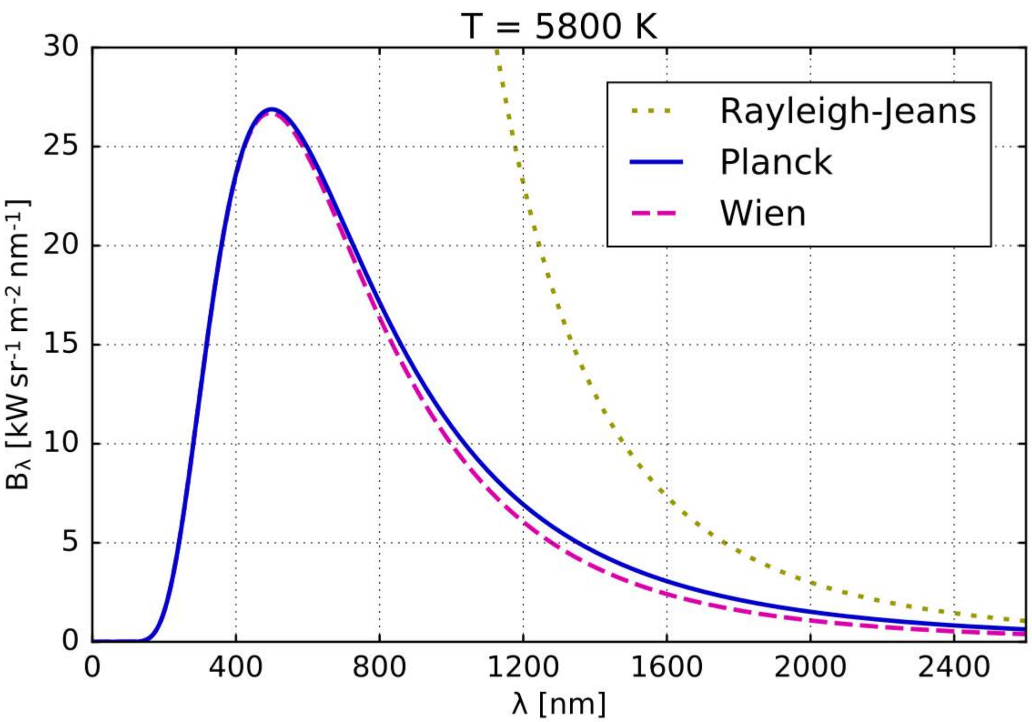


Rayleigh-Jeans law

$$B_\lambda(T) = \frac{2ck_B T}{\lambda^4}$$

The theory did match experimental data for longer wavelengths but failed miserably for shorter ones. This is known as the "Ultraviolet Catastrophe," a name given by Paul Ehrenfest in 1911.

Where is the problem?



Comparison of Rayleigh–Jeans law with Wien approximation and Planck's law, for a body of 5800 K temperature.

Wien's Law $\lambda_{peak} = \{hc/(4.965\ k)\}/T$

Wien formula fits the shorter wavelength but fails the longer wavelength side of the spectrum.

Rayleigh-Jeans law $$B_\lambda(T) = \frac{2ck_B T}{\lambda^4}$$

Rayleigh-Jeans formula fits the longer wavelength but fails at shorter wavelength but fits at longer wavelength

Both formulae were developed using the well accepted **classical physics principle—equipartition of energy** (1/2kT).

Equipartition Theorem (Classical Physics)

"The total energy contained in the assembly of a large number of individual particles exchanging energy among themselves through mutual collisions is shared equally (on the average) by all the particles."

Motion

Clausius and other physicists of 1800s had imagined all the atoms in a gas moving at the same speed. They knew this wasn't true, that in fact atoms would move with a range of speeds, but they didn't have the mathematical sophistication to tackle the full problem.

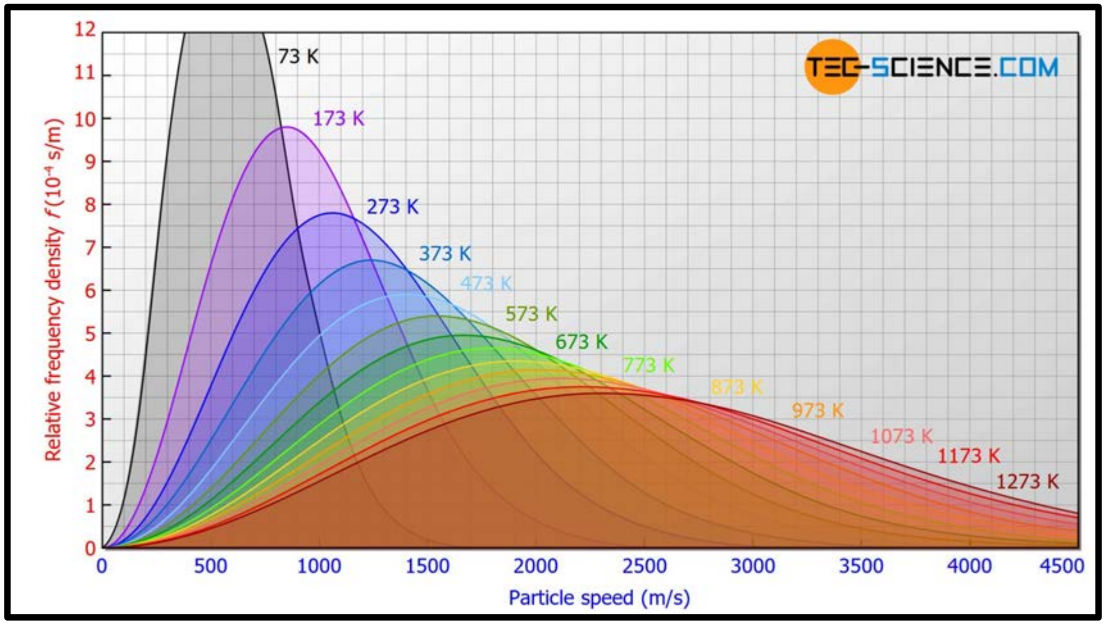
Energy

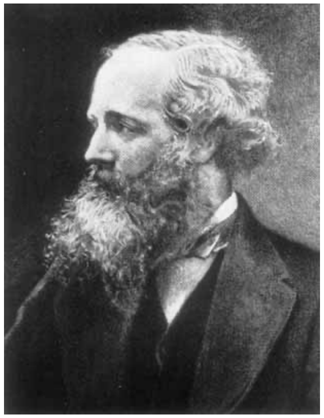
The theorem of equipartition of energy states that molecules in thermal equilibrium have the same average energy associated with each independent degree of freedom of their motion.

Every particle has a translational energy of $KE_{avg} = \frac{3}{2}kT$

Maxwell-Boltzmann Distribution

Statistic/Probabilistic Approach





James Clerk Maxwell
(1831-1879)

L. Boltzmann
(1844-1906)

"The true logic for this world is the Probabilities. … This branch of Math., which is generally thought to favor gambling, dicing, and wagering, and therefore highly immoral, is the only 'Mathematics for Practical Men,' as we ought to be." *Maxwell, 1850*

Planck noticed the similarity

Temperature dependence of velocity of molecules: Maxwell-Boltzmann distribution

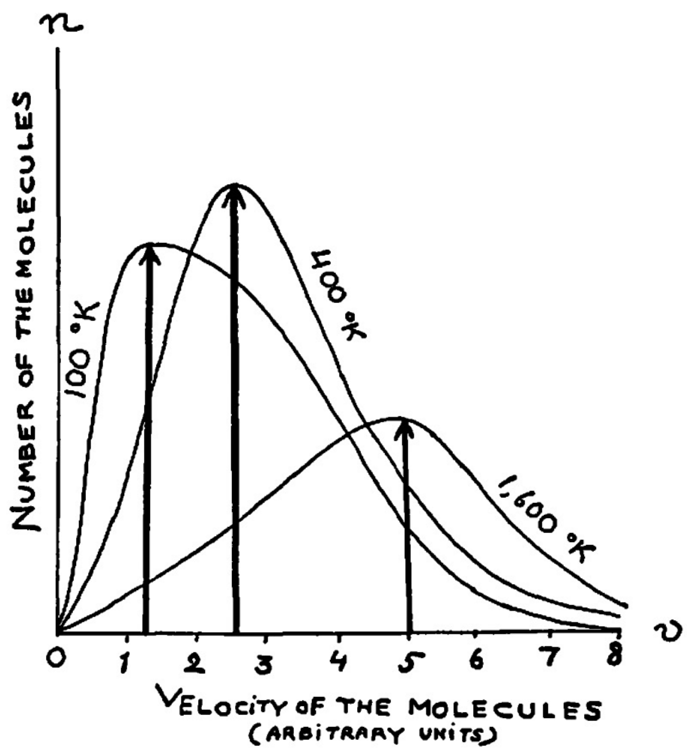


Fig. 1. Maxwell's distribution: the number of molecules having different velocities v is plotted against the velocities for three different temperatures, 100°, 400°, and 1600°K. Since the number of molecules in the container remains constant, the areas under the three curves are the same. The average velocities of the molecules increase proportionally to the square root of the absolute temperature.

Temperature dependence of wavelength of emitted light: Blackbody radiation

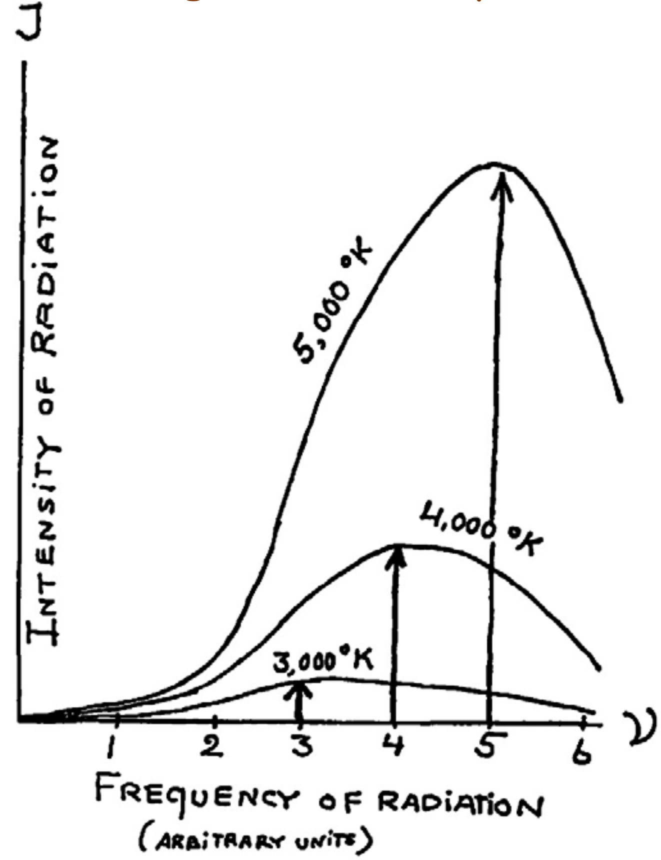


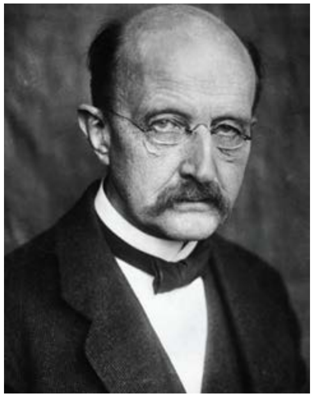
Fig. 2. The observed distribution of radiation intensities for different frequencies ν is plotted against the frequencies. Since the radiation energy content per unit volume increases as the fourth power of the absolute temperature T, the areas under the curves increase. The frequency corresponding to maximum intensity increases proportionally to the absolute temperature.

Planck's Theory of Blackbody Radiation

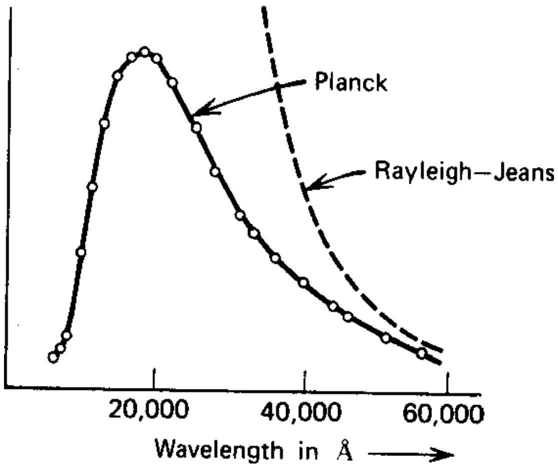
- In 1900 Max Planck developed a theory of blackbody radiation that leads to an equation that correctly predicted the intensity and wavelength of the radiation with temperature.

- To achieve this, he moved away from well established principles of classical physics, equipartition theorem.

- For the first time he analyzed the data based on probabilities (modern statistical physics due to Boltzman) that was looked down upon at that time.



Max Planck



Planck's Assumptions

The absorption and emission are done by oscillators present in the blackbody.

The oscillators emit or absorb energy when making a transition from one state to another.

The oscillators with E/A of one generate standing waves of different wavelengths depending on the temperature.

Absorption and emission wavelengths are quantized. They are not done in piece-meal; *i.e.*, oscillator states can't be populated by several partial absorptions in steps.

The absorption and emission energies of an oscillator can have only certain discrete values E_n. It is not continuous as in x = 1, 2, 3 etc;. but jumps as in nx where for *eg*. n=2 and x is 1, 2, 3; then the numbers are 2, 4, 6. Notice they are not continuous.

According to Planck distribution of energies follows the equation below

$$E = h\nu$$

ν is the frequency of oscillation

h is Planck's constant (note ν is multiplied by a constant h)

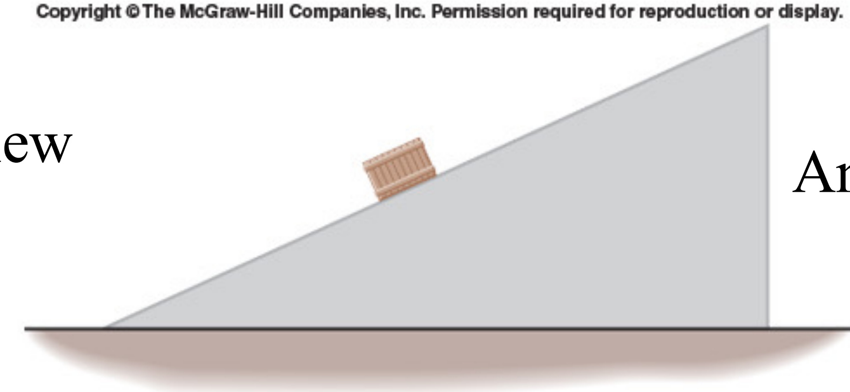
Planck's Radiation Law

$$B(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

- B = Spectral density of electromagnetic radiation emitted by a black body; the cgs unit $erg \cdot s^{-1} \cdot sr^{-1} \cdot cm^{-2} \cdot Hz^{-1}$.
- h = *Planck's constant* = 6.63×10^{-34} *Joule - seconds*
- k = *Boltzmann's constant* = 1.38×10^{-23} *Joule* $-K^{-1}$
- c = *velocity of light* = $3 \times 10^{+8}$ *meter - seconds*$^{-1}$
- T = *temperature* [K]
- λ = *wavelength* [meters]

Classical View Compared to Quantum Mechanical View

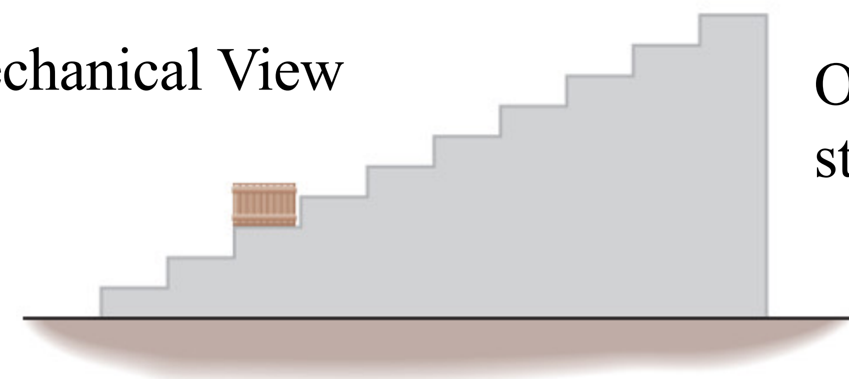
Classical View



Any energy is possible

(a)

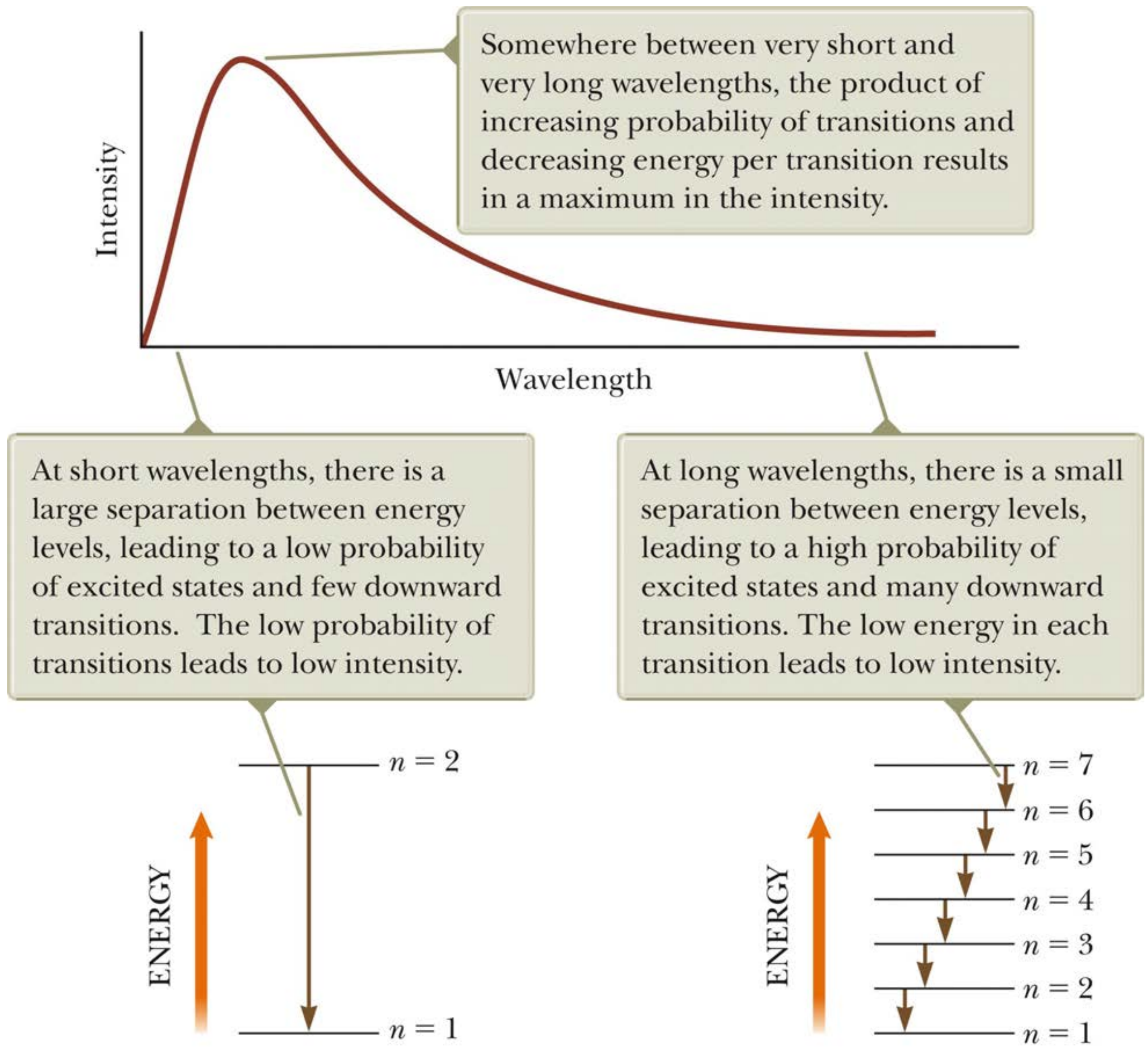
Quantum Mechanical View

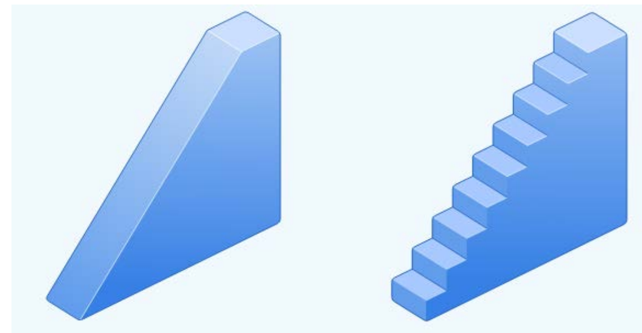


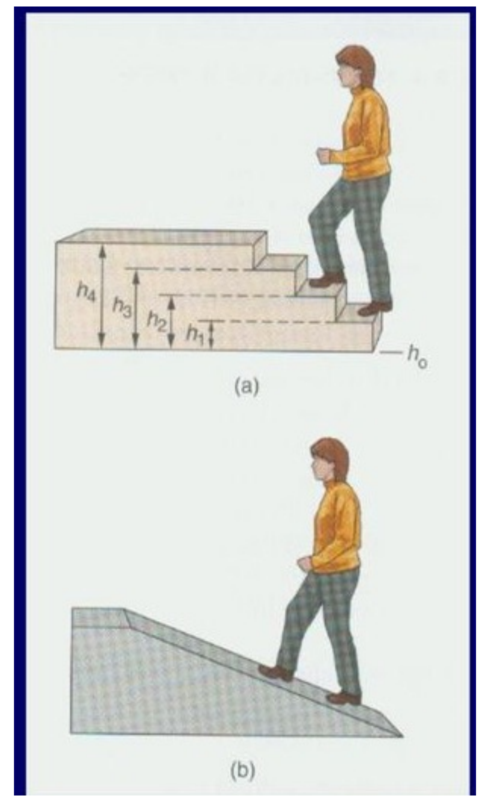
Only a few energy states are allowed

(b)

Planck's Model







Summary of Blackbody Radiation

- Classical BB presents a "ultraviolet catastrophe"
- The spectral energy distribution of electromagnetic radiation in a black body can't be explained in terms of classical Maxwell EM theory, in which the average energy in the cavity assumes continuous values of $<e> = kT$
- To solve the BB catastrophe one has to assume that the energy of individual radiation oscillator in the cavity of a BB is quantized as per $E_n = nh\nu$. One photon crarries energy of hν and n photons nhν.
- This picture is in conflict with classical physics because in classical physics energy is in principle a continuous variable that can take any value between $0 \rightarrow \infty$
- One is then lead to the revolutionary concept that

ENERGY OF AN OSCILLATOR IS QUANTISED

The Nobel Prize in Physics 1918

Max Planck

"in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta."

"Planck's radiation theory is, in truth, the most significant lodestar for modern physical research, and it seems that it will be a long time before the treasures will be exhausted which have been unearthed as a result of Planck's genius."

Nobel Prize Award ceremony speech by President of the Royal Swedish Academy of Sciences, on June 1, 1920

Planck's radiation theory is, in truth, the most significant lodestar for modern physical research, and it seems that it will be a long time before the treasures will be exhausted which have been unearthed as a result of Planck's genius.

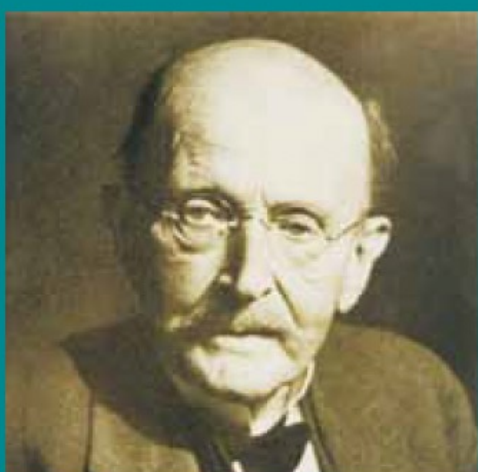
Nobel Prize Award ceremony speech by
President of the Royal Swedish Academy of Sciences, on June 1, 1920

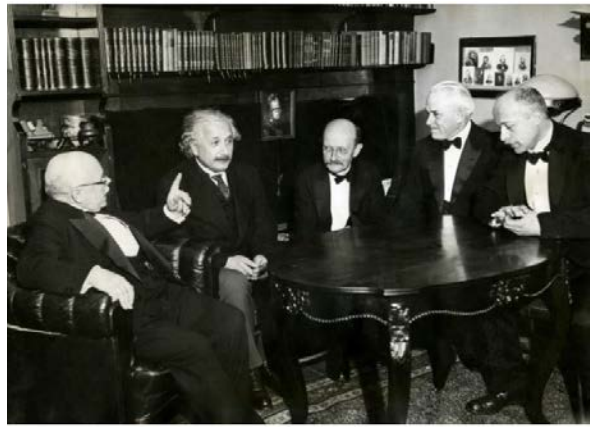
This marked a turning point in the history of physics. The importance of the discovery although not appreciated at first, its validity gradually became overwhelming as its application accounted for many discrepancies between observed phenomena and classical theory.

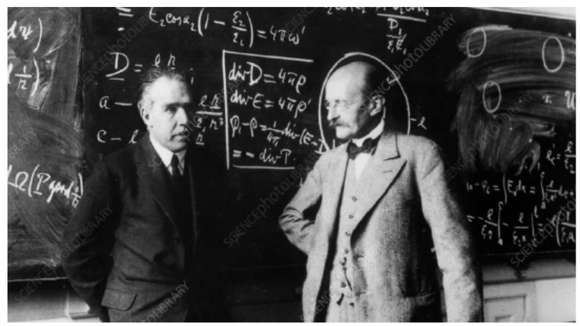
Who is Planck?

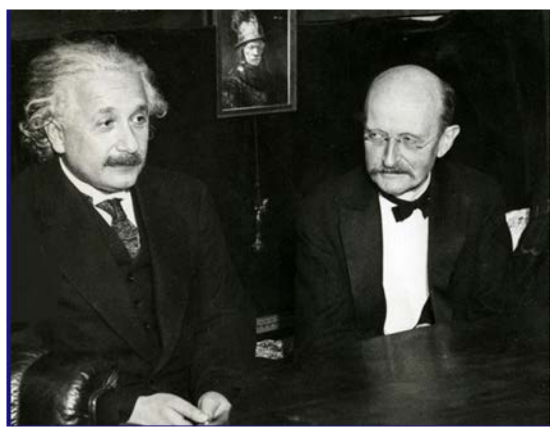
“h”

Planck is famous for a very important formula. The formula contains “Planck’s Constant,” or “h.” It is part of his theory on light and energy. The constant can be found on Planck’s tombstone in Germany. It reads: $h = 6.626 \times 10^{-34}$ Joules seconds (J s)









German physicist Max Planck publishes his groundbreaking study of the effect of radiation on “blackbody”, and the quantum theory of modern physics is born.

Scientists, such as Einstein, Bohr, de Broglie, Schrodinger and Dirac, advanced Planck’s theory and made possible the development of the quantum theory that maintains that energy is both matter and a wave.

Quantum mechanics takes a probabilistic view of nature, sharply contrasting with classical mechanics, in which all precise properties of objects are, in principle, calculable.

Maxwell-Boltzmann Distribution

https://www.khanacademy.org/science/physics/thermodynamics/temp-kinetic-theory-ideal-gas-law/v/maxwell-boltzmann-distribution

Video

https://www.khanacademy.org/science/physics/thermodynamics/temp-kinetic-theory-ideal-gas-law/a/what-is-the-maxwell-boltzmann-distribution

Text

Teaching videos on black body radiation

Blackbody Observations - https://youtu.be/FRd28CLvMQM

Rayleigh Jeans Law - https://youtu.be/kHz6zbDqifQ

Planck Energy Distribution - https://youtu.be/tAZYKNKkxs4

Summary - https://youtu.be/KR8SmZ5fGIg

Further support for quantization of energy

Nobel Prize in Physics 1922

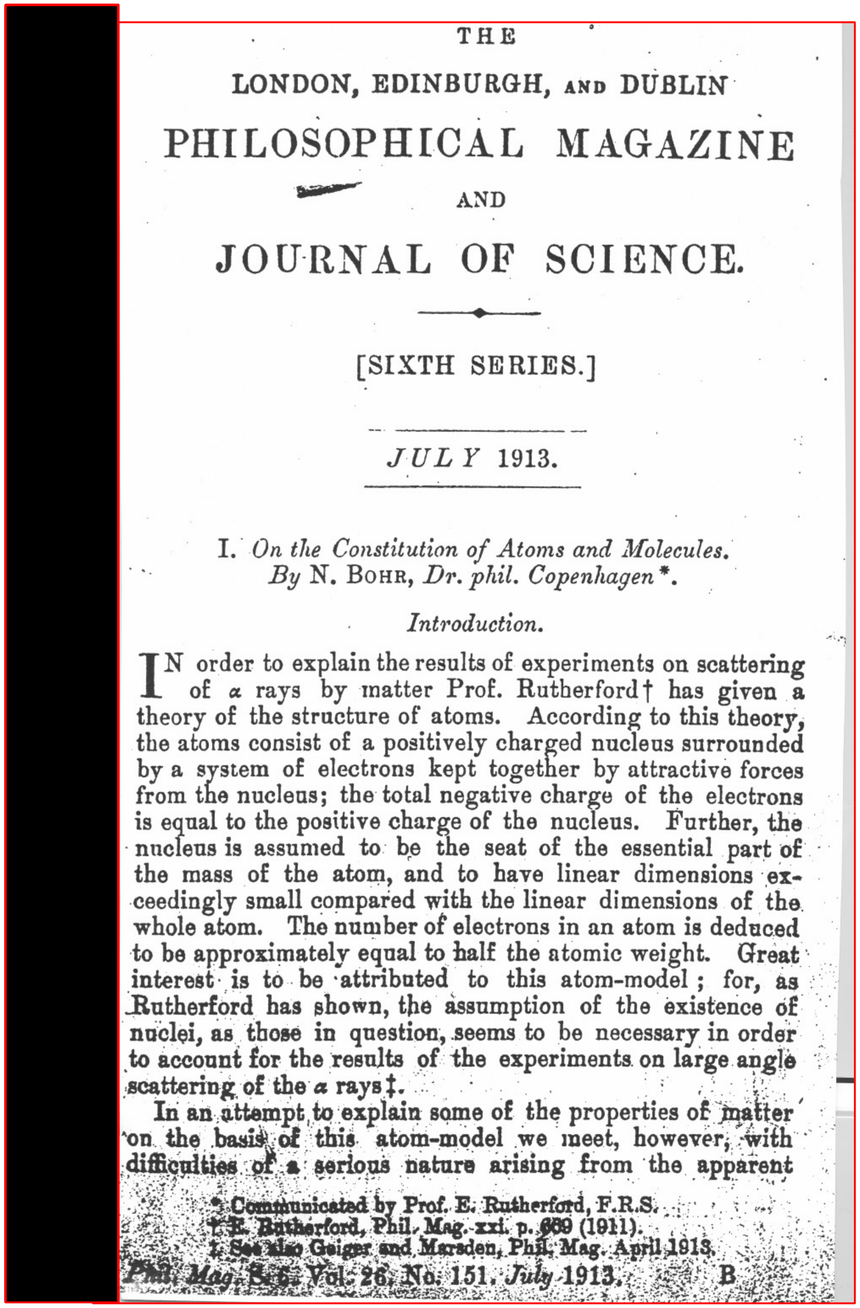
Nobel Prize in Physics 1918

Planck

- Oscillators present in blackbody absorb and emit light in packets. The absorption and emission energies are quantized, and it can't take all values.
- The energy of photons absorbed and emitted can be expressed in the form: $E = h\nu$
- What is an oscillator?

Bohr

- Absorption and emission in an atom are due to electronic transitions.
- Oscillators are in a way electrons in materials.



THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[SIXTH SERIES.]

JULY 1913.

I. *On the Constitution of Atoms and Molecules.*
By N. BOHR, *Dr. phil. Copenhagen* *.

Introduction.

IN order to explain the results of experiments on scattering of α rays by matter Prof. Rutherford † has given a theory of the structure of atoms. According to this theory, the atoms consist of a positively charged nucleus surrounded by a system of electrons kept together by attractive forces from the nucleus; the total negative charge of the electrons is equal to the positive charge of the nucleus. Further, the nucleus is assumed to be the seat of the essential part of the mass of the atom, and to have linear dimensions exceedingly small compared with the linear dimensions of the whole atom. The number of electrons in an atom is deduced to be approximately equal to half the atomic weight. Great interest is to be attributed to this atom-model; for, as Rutherford has shown, the assumption of the existence of nuclei, as those in question, seems to be necessary in order to account for the results of the experiments on large angle scattering of the α rays ‡.

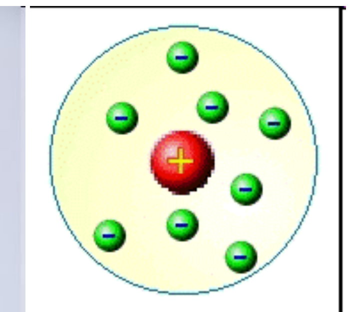
In an attempt to explain some of the properties of matter on the basis of this atom-model we meet, however, with difficulties of a serious nature arising from the apparent

* Communicated by Prof. E. Rutherford, F.R.S.
† E. Rutherford, Phil. Mag. xxi. p. 669 (1911).
‡ See also Geiger and Marsden, Phil. Mag. April 1913.

- Bohr interpreted some experimental results that had been known for nearly thirty years.
- It had been known for most of the nineteenth century that elements, when vaporized by heat and made to glow, displayed "line spectra" of this sort. The so-called Balmer series of hydrogen lines had been found in 1885.
- Remarkably, Bohr was able to derive his formula from his quantum model of the hydrogen atom.

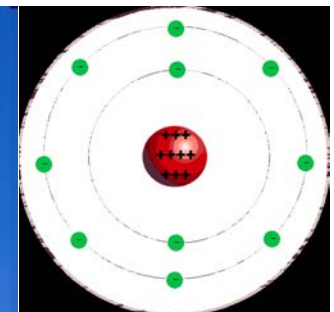
Bohr Model

The studies of light revealed that electrons can have only specific energies and only certain allowable orbits to represent those energies. In other words, energy is "*quantized*" in atoms. *It can only be absorbed and released in specific amounts, not any amount!*



Rutherford Model

Before the quantum model of the atom.



Bohr Model

The quantum model of the atom rungs of a ladder.

The Bohr Planetary Model

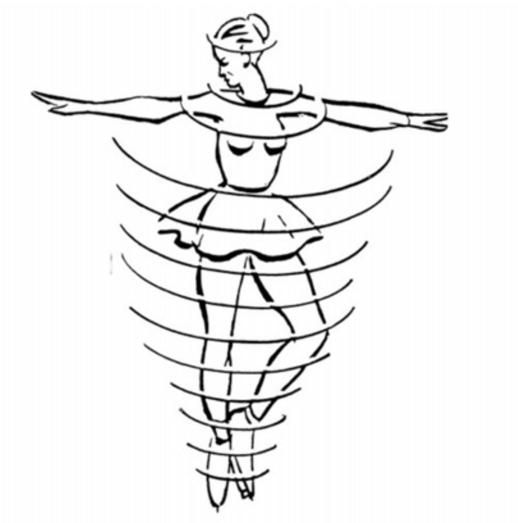
- Bohr suggested that the electrons in an atom orbit the positively-charged nucleus, in a similar way to planets orbiting the Sun.

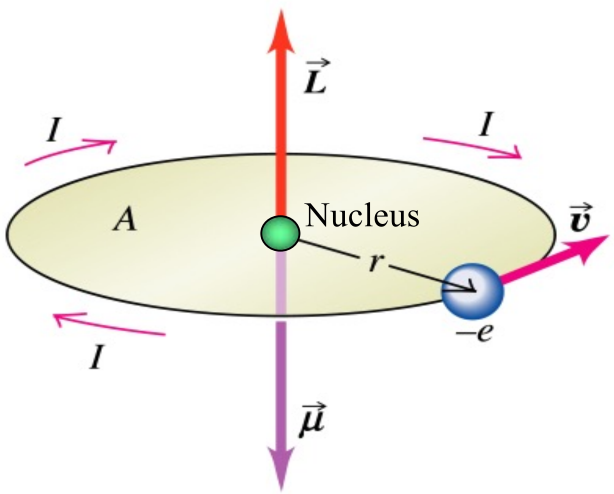
- Bohr made the bold assumption that the **orbital angular momentum** of the electron is quantized.

- Since v is perpendicular to r, the orbital angular momentum is just given by L = mvr.

- Bohr suggested that this is quantized, so that:

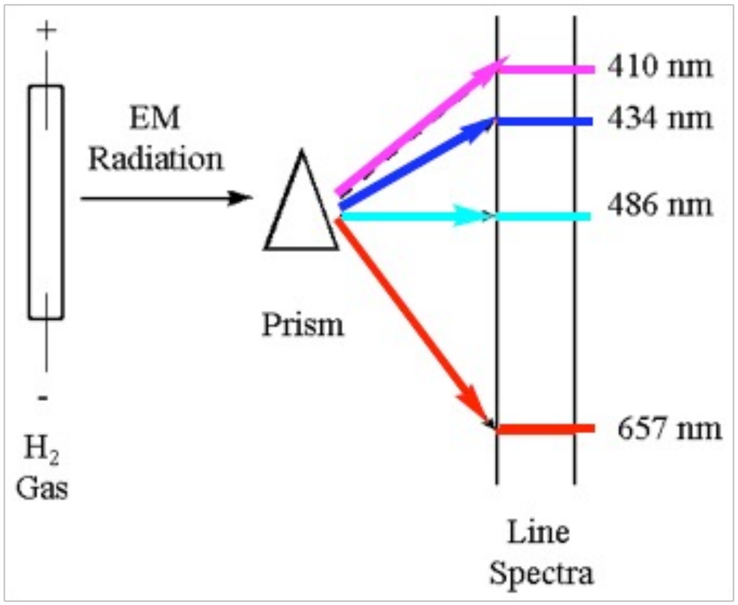
$$mvr = \frac{nh}{2\pi} = n\hbar$$

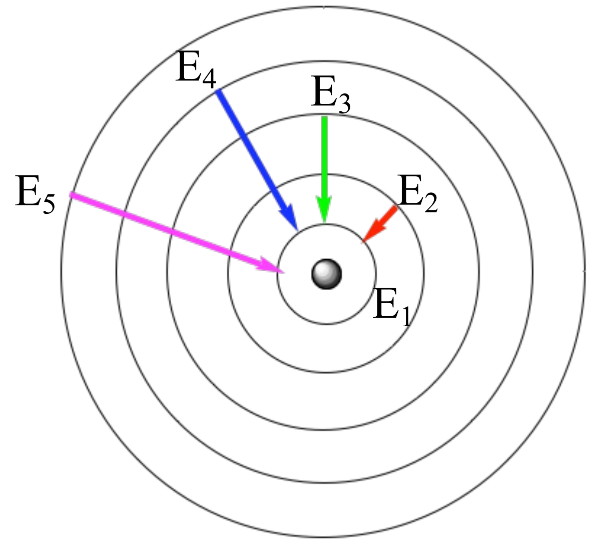




Bohr Model of H Atom

Atomic orbitals replace oscillators



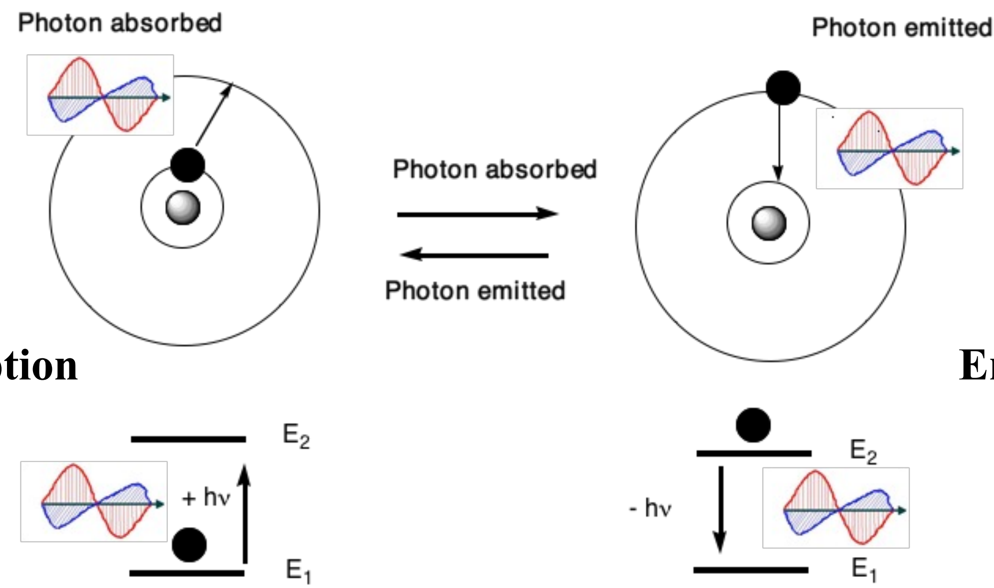


Planck's oscillator emission and absorption are in fact electronic transitions between orbitals of fixed energies. Transition energies are quantized.

Light is emitted when an electron jumps from a higher orbit to a lower orbit and is absorbed when it jumps from a lower to higher orbit.

The energy and frequency of light emitted or absorbed is given by the difference between the two orbit energies, e.g., $E(\text{photon}) = E_2 - E_1$ (Energy difference)

Electronic transitions are quantized
Atomic orbitals replace oscillators



Absorption **Emission**

Light is emitted when an electron jumps from a higher orbit to a lower orbit and is absorbed when it jumps from a lower to higher orbit.

The energy and frequency of light emitted or absorbed is given by the difference between the two orbit energies, e.g., $E(photon) = E_2 - E_1$ (Energy difference)

The basis of all photochemistry and spectroscopy!

What we know thus far

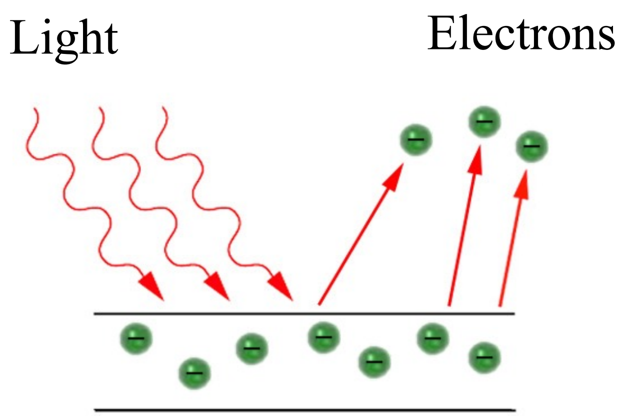
Light is a wave

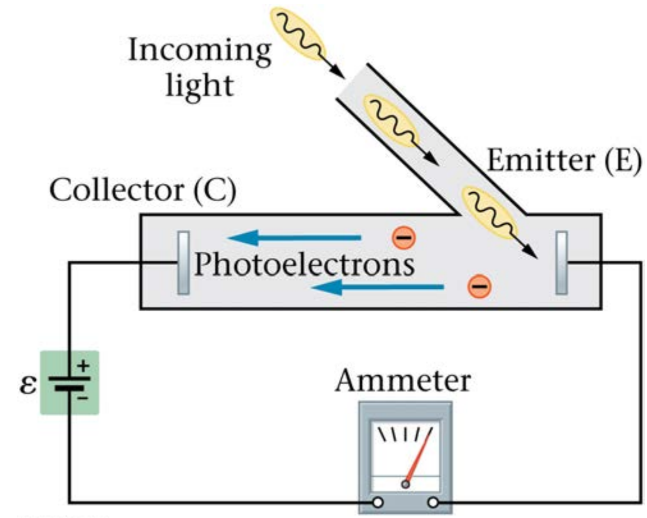
Light is electromagnetic

Light absorption and emission are quantized

Light induces electronic transitions
(oscillators are in fact electrons)

Photoelectric Effect





Metal's electrons near the surface are ejected upon light absorption

In 1887 **H. Hertz** of Germany was the first person to detect the photoelectric effect. He knew something negatively charged species was coming out. At that time electrons were unknown. So not known what was being ejected.

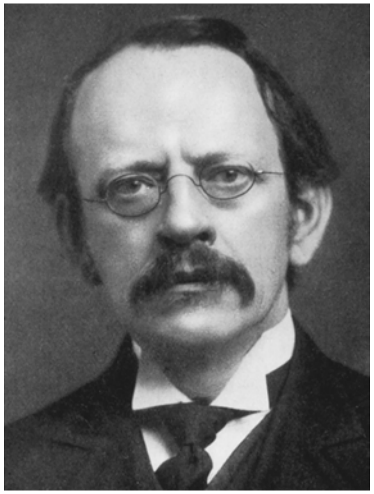
In 1899**, J. J. Thompson** of England, demonstrated that ultraviolet light hitting a metal surface caused the ejection of electrons

In 1905 **Einstein**, then a young patent clerk in Switzerland, explained the phenomenon.
In 1921 **Einstein** received the Nobel Prize after Robert Millikan confirmed the work.

Photo-Electric Effect

Heinrich Hertz
(1857-1894)

In 1887 Hertz notices that the charged objects illuminated with UV light loses charge.

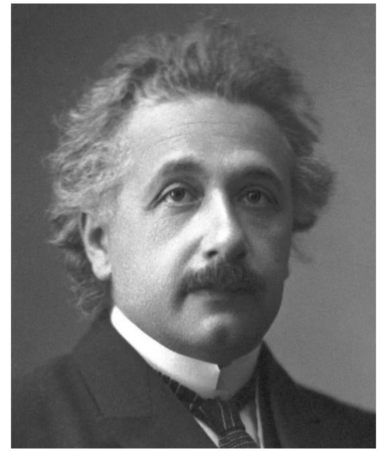


J. J. Thomson
(1856-1940)
Nobel Prize 1906

In 1889 Thompson notices that UV light releases electrons from cathode.

Philipp Lenard
(1862-1947)
Nobel Prize, 1905

From 1892-1894 worked as Hertz's assistant. In 1902 Established the importance of the wavelength of light in releasing electrons from a surface and showed that the velocity of released electrons is independent of the intensity of the light.



A. Einstein
(1879-1955)
Nobel Prize 1921

In 1905 theoretically explained the photoelectric phenomenon on the basis light is a particle.

R. A. Millikan
(1868 – 1953)
Nobel Prize 1923

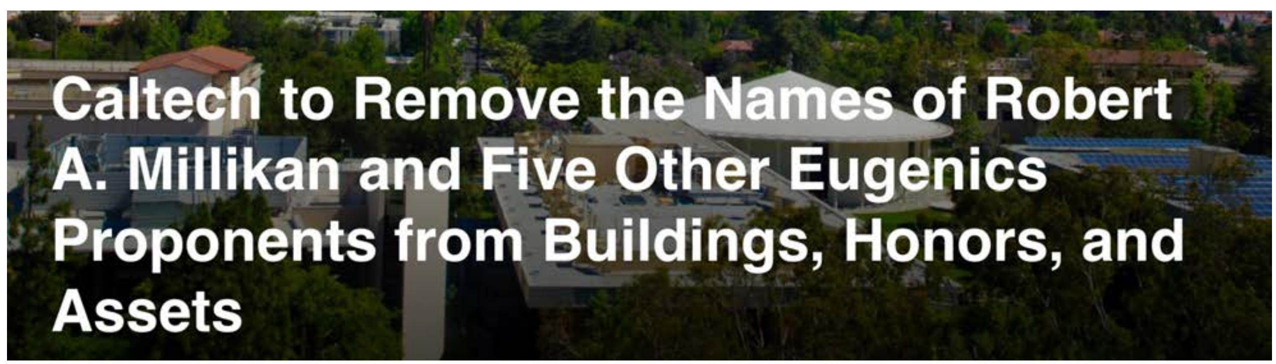
In 1914 experimentally confirmed Einstein's predictions and measured the value of *h*.

Philipp Lenard

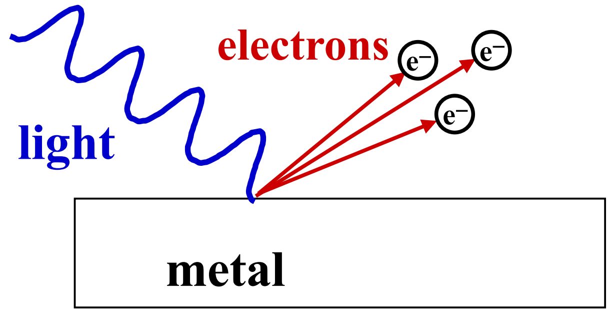
- Anti-semitic
- Supporter and advisor to Hitler
- Proponent of Nazi ideology
- Did not believe in Einstein's works, had open quarrels with him

R. A. Millikan

- Data selection, ethical issues
- Racism issues



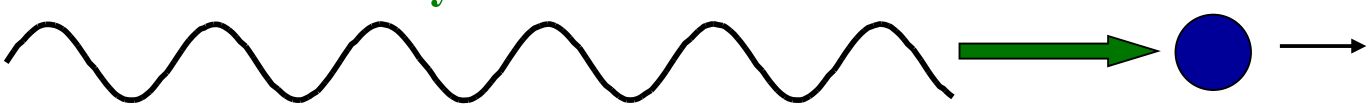
Classical Theory – Light is a wave - Predictions



Only intensity matters

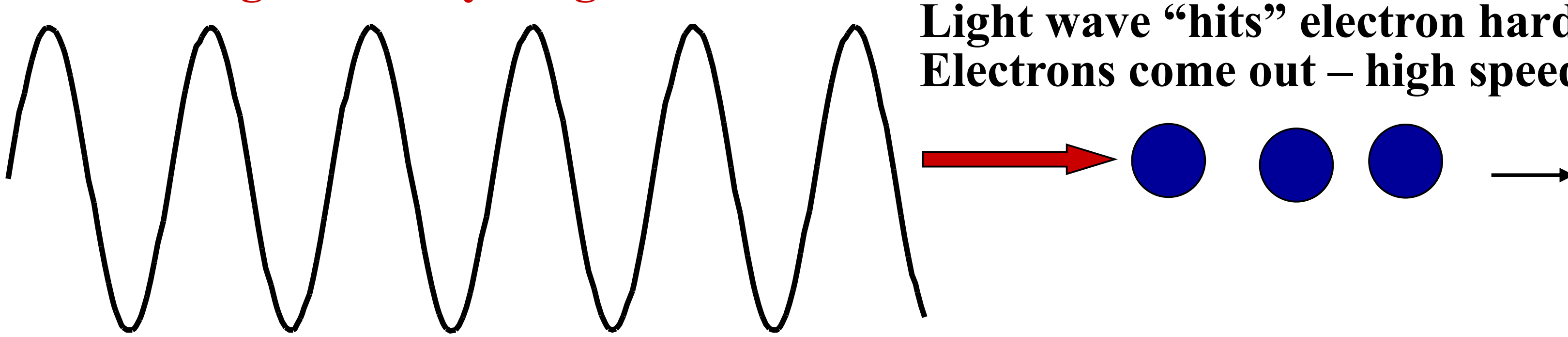
Light wave "hits" electron gently.
Electrons come out – low speed.

Low Intensity - Small Wave



High Intensity - Big Wave

Light wave "hits" electron hard.
Electrons come out – high speed.



Analysis of Photoelectric Effect Based on Classical Mechanics-1

- Dependence of photoelectron kinetic energy on light intensity

    Classical Predictions

    - Wavelength is not critical, intensity alone matters. Higher intensity at longer wavelength should work.
    - At low light intensities, measurable time interval should pass between the instant the light is turned on and the time an electron is ejected from the metal (time delay). Energy needs to be built up.

- ***Experimental Results***
    - Electrons are emitted almost instantaneously, even at very low light intensities if the wavelength is correct.

Analysis of Photoelectric Effect Based on Classical Mechanics-2

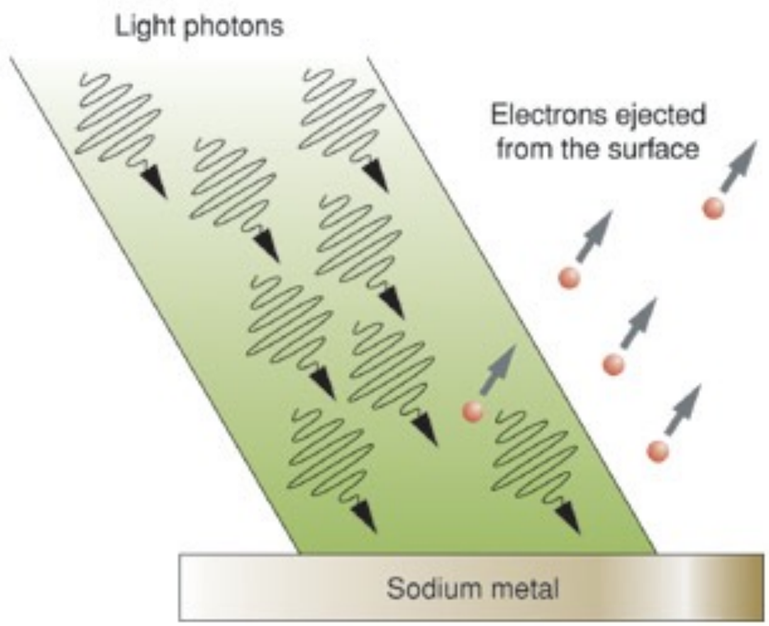
Dependence of photoelectron kinetic energy on light frequency

- ***Classical Predictions***
  - There should be no relationship between the frequency of the light and the electron's kinetic energy.
  - The kinetic energy should be related to the intensity of the light.
- ***Experimental Results***
  - The maximum kinetic energy of the photoelectrons increases with increasing light frequency.
  - The maximum kinetic energy of the photoelectrons is independent of the intensity. If the wavelength is below the stopping potential intensity will play no role. If the If the wavelength is above the stopping potential more number of electrons would come with the same kinetic energy.

Einstein's Model of Light: Photon Torpedoes

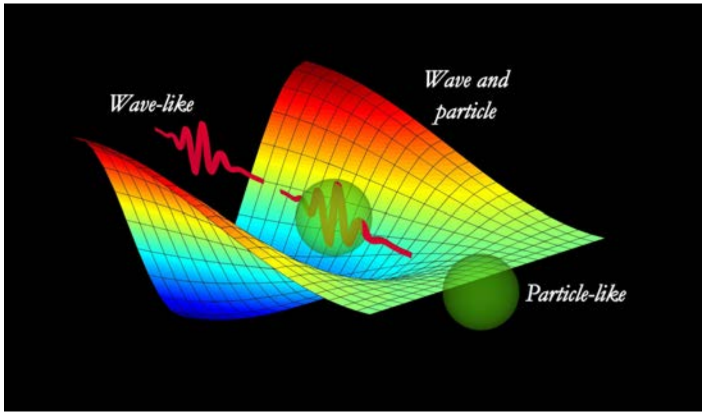
Light travels as a wave and hits like a **particle**.
$E = mc^2$.

Light energy comes in packets. Each photon has an energy of $E = h\nu$



Light itself is quantized, not only absorptions and emissions.

Needed energy must be provided in a single photon. For example, if 100 kcal/mole is needed for an action, 5x20 kcal/mole will not work. One photon of 100 kcal/mole is needed.



One photon interacts only with single electron

Light has a wave-particle duality behavior.

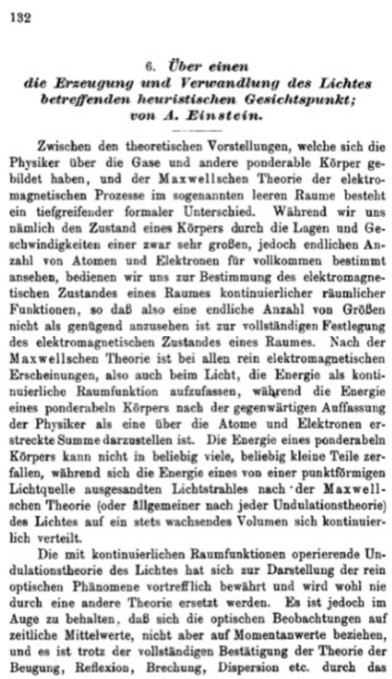
Einstein's View on Photoelectric Effect

Einstein, 1905

"---- the production of cathode rays (electrons) by light can be conceived in the following way: The body's surface layer is penetrated by energy quanta whose energy is converted at least partially into kinetic energy of the electrons. The simplest conception is that a light quantum transfers its energy to a single electron----"

"when a light ray starting from a point is propagated, the energy is not continuously distributed over an ever-increasing volume, but it consists of a finite number of energy quanta, localized in space, which move without being divided and which can be absorbed or emitted only as a whole".

Not only absorption and emission are quantized (Planck), but light itself is quantized



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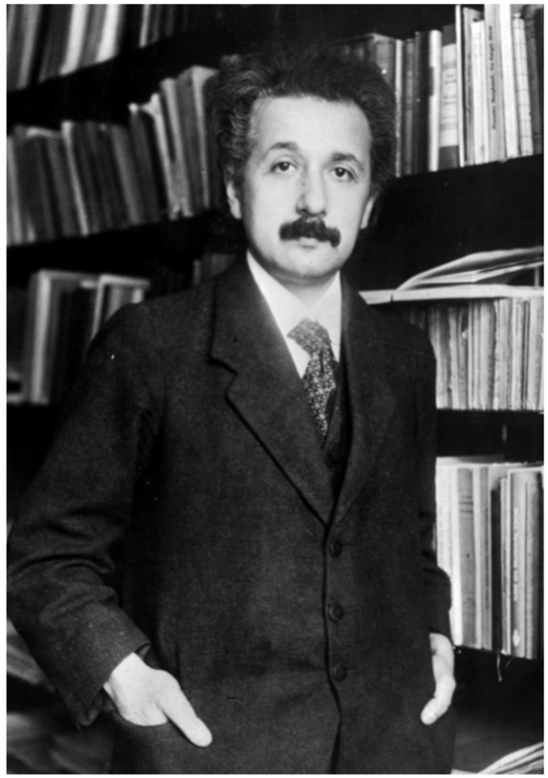
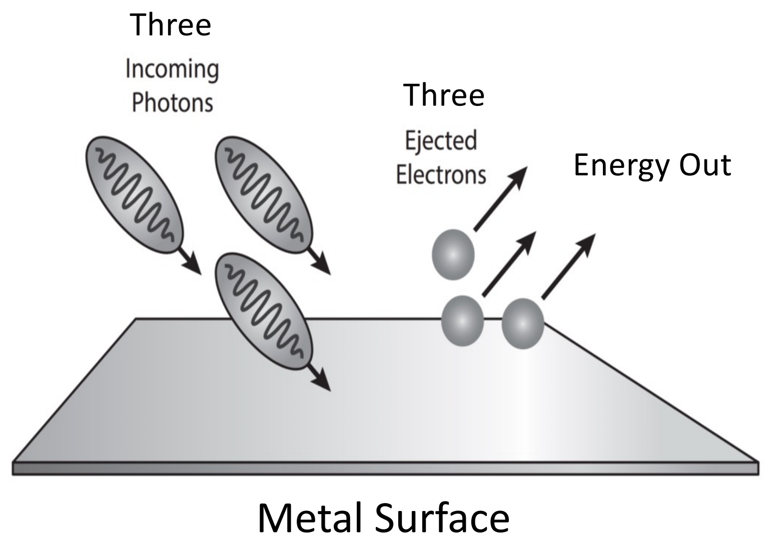
6. ***Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt; von A. Einstein.***

Zwischen den theoretischen Vorstellungen, welche sich die Physiker über die Gase und andere ponderable Körper gebildet haben, und der Maxwellschen Theorie der elektromagnetischen Prozesse im sogenannten leeren Raume besteht ein tiefgreifender formaler Unterschied. Während wir uns nämlich den Zustand eines Körpers durch die Lagen und Geschwindigkeiten einer zwar sehr großen, jedoch endlichen Anzahl von Atomen und Elektronen für vollkommen bestimmt ansehen, bedienen wir uns zur Bestimmung des elektromagnetischen Zustandes eines Raumes kontinuierlicher räumlicher Funktionen, so daß also eine endliche Anzahl von Größen nicht als genügend anzusehen ist zur vollständigen Festlegung des elektromagnetischen Zustandes eines Raumes. Nach der Maxwellschen Theorie ist bei allen rein elektromagnetischen Erscheinungen, also auch beim Licht, die Energie als kontinuierliche Raumfunktion aufzufassen, während die Energie eines ponderabeln Körpers nach der gegenwärtigen Auffassung der Physiker als eine über die Atome und Elektronen erstreckte Summe darzustellen ist. Die Energie eines ponderabeln Körpers kann nicht in beliebig viele, beliebig kleine Teile zerfallen, während sich die Energie eines von einer punktförmigen Lichtquelle ausgesandten Lichtstrahles nach der Maxwellschen Theorie (oder allgemeiner nach jeder Undulationstheorie) des Lichtes auf ein stets wachsendes Volumen sich kontinuierlich verteilt.

Die mit kontinuierlichen Raumfunktionen operierende Undulationstheorie des Lichtes hat sich zur Darstellung der rein optischen Phänomene vortrefflich bewährt und wird wohl nie durch eine andere Theorie ersetzt werden. Es ist jedoch im Auge zu behalten, daß sich die optischen Beobachtungen auf zeitliche Mittelwerte, nicht aber auf Momentanwerte beziehen, und es ist trotz der vollständigen Bestätigung der Theorie der Beugung, Reflexion, Brechung, Dispersion etc. durch das





Albert Einstein
Nobel Prize, 1921

Annalen der Physik, **1905**, 26 years old, six weeks before submission of his Ph. D. thesis

If photon is particle, does it have mass ?

Since photons have particle-like properties, they should have mass.

The (relativistic) mass of photons can be calculated from Einstein's equation for special relativity.

$$E = mc^2 \qquad m = \frac{E}{c^2} \qquad E = h\nu = \frac{hc}{\lambda}$$

$$m = \frac{hc/\lambda}{c^2} = \frac{h/\lambda}{c} = p/c = \text{Momentum/C}$$

Photon has ZERO mass at rest; it has mass when it is moving at the speed of light, C. (relativistic mass)

If photon is particle, does it have momentum ?

$$\mathbf{p} = \mathbf{m} \times \mathbf{v}$$

where m = mass of the object and v = velocity of the object.

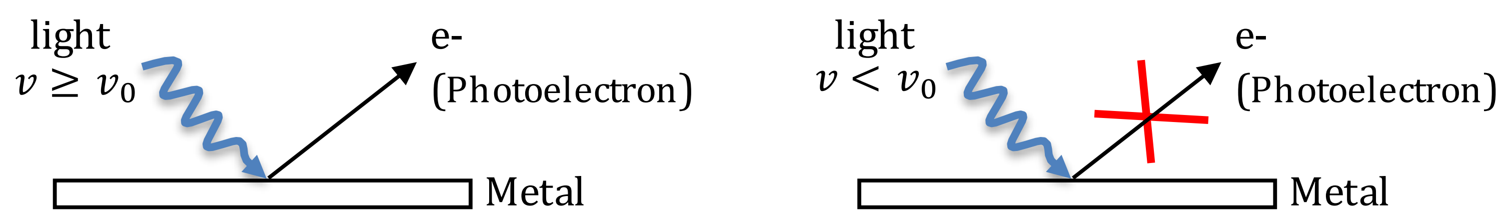
$$\mathbf{m} = \frac{h/\lambda}{c} \qquad \mathbf{p} = \frac{h/\lambda}{c} \times \mathbf{v}$$ where v = c (speed of light)

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

$h = 6.626\ 070\ 15 \text{ x } 10^{-34}$ J Hz^{-1}

Photon momentum is small, since p = h/λ and *h* is very small. It is for this reason that we do not ordinarily observe photon momentum. Our mirrors do not recoil when light reflects from them.

Einstein's prediction about the energy of released electron



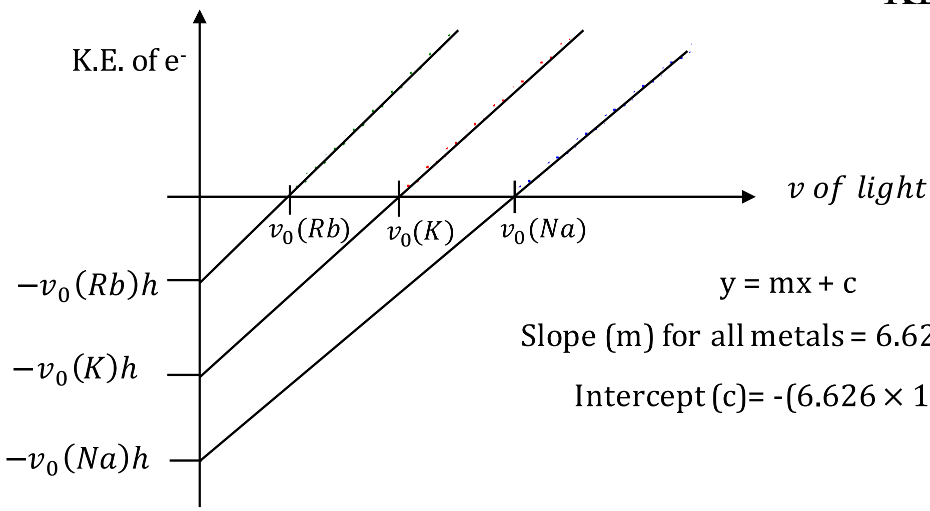
Photoelectrons are only ejected for frequency of light greater or equal to a particular frequency (depends on the metal)

If the frequency is less than that threshold frequency then no photoelectron is ejected.

$$KE_{max} = h\nu - h\nu_o \qquad h\nu \geq h\nu_o$$

Einstein predicted a linear relationship between the kinetic energy of the released electron and the frequency of irradiation (***hν***) with the slope being equal to ***h*** and the intercept being the work function of the metal ($h\nu_o$)

Einstein analyzed plots of K.E. of photoelectrons as a function of frequency for different metals (1905)



$KE = h\,v - h\,v_0$

y = mx + c

Slope (m) for all metals = 6.626×10^{-34} Js = h

Intercept (c)= $-(6.626 \times 10^{-34} \times v_0)$

1. Slope is same for all the metal and is equal to Planck's constant (h)

2. $KE = h\,v - h\,v_0$

   Incident energy ($h\,v$) — Threshold energy (Work function) ($h\,v_0$)

3. The surface takes only h v_0 and that needs to be delivered in one packet.

4. Light is made up of energy "packets" called photons, light energy is quantized

Other Scientists' Reactions to Einstein's Explanation of the Photo-Electric Effect

Most physicists believed that light is a wave and did not want to go back to particle idea.

The original data used to generate the idea were actuallyless clear than they implied.

Even though it proved his own theory, Planck himself was skeptical.

R. S. Millikan spent ten years trying to disprove Planck's proposal, but finally grudgingly published data supporting it in 1916.

Einstein finally won the Nobel Prize for this work in 1921 for photoelectric effect and Millikan won the Nobel Prize in 1923 for it (and oil-drop experiment).

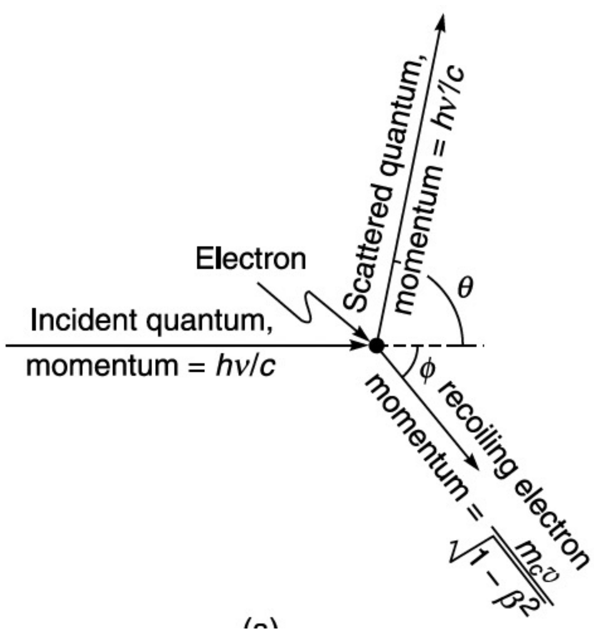
Photon Particle Collisions - The Compton Effect

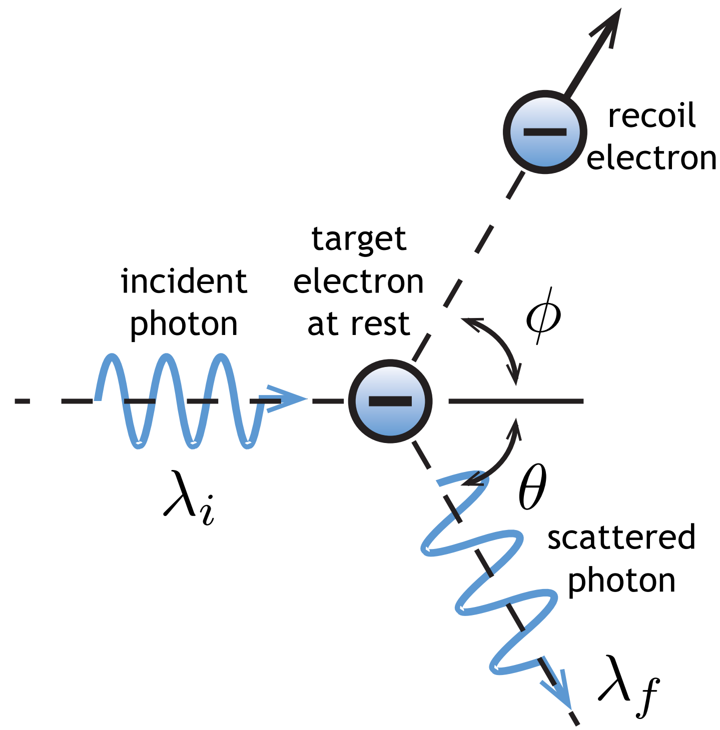
In 1922 Arthur Compton was able to bounce an X-ray photon off an electron. The result was an electron with more kinetic energy than it started with, and an X-ray with less energy than it started with. A photon can actually interact with a particle! A photon has momentum!!

A. H. Compton (1892-1962)
Nobel Prize, 1927

Professor, Uni Chicago
President, MIT
Washington Uni

Compton showed that when X-rays impinged on matter,
the scattered X-ray did not have the same wavelength !

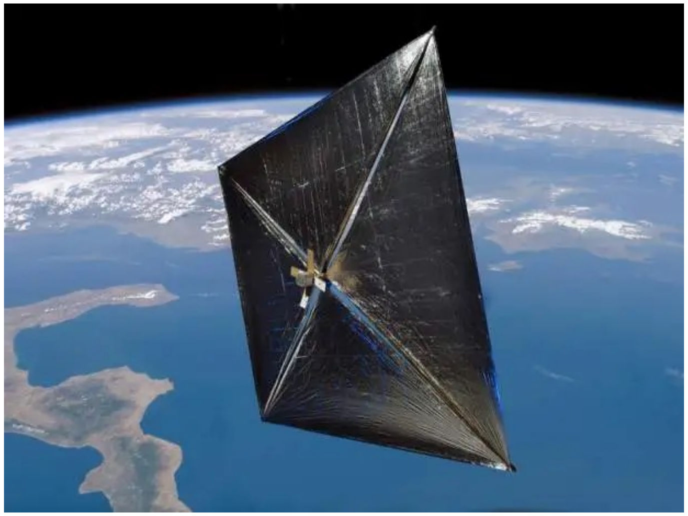




Compton found that if you treat the photons as if they were particles of zero mass, with energy $E = hc/\lambda$ and momentum $p = h/\lambda$ the collision behaves just as if it were two billiard balls colliding ! (with total momentum always conserved)

Solar sail

Solar sailing is a revolutionary way of propelling a spacecraft through space. Light is made up of particles called photons. Photons don't have any mass, but as they travel through space they do have momentum. When light hits a solar sail — which has a bright, mirror-like surface — the photons in that light bounce off the sail. As the photons hit the sail their momentum is transferred to it, giving it a small push. As they bounce off the sail, the photons give it another small push. Both pushes are very slight, but in the vacuum of space where there is nothing to slow down the sail, each push changes the sail's speed.



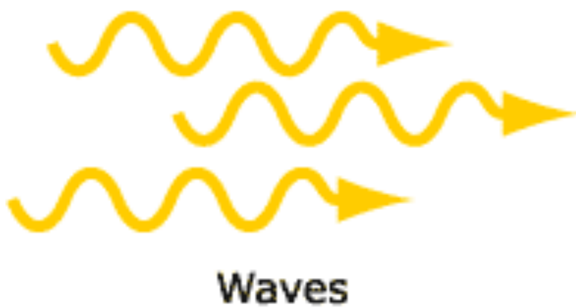
https://www.youtube.com/watch?v=Ndx_6J4uo2M

https://www.planetary.org/articles/what-is-solar-sailing

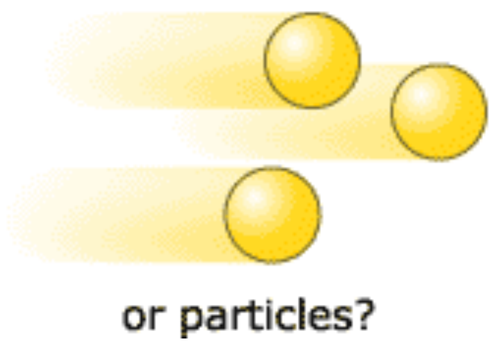
Nobel Prize in Physics Awarded to 3 Scientists for Work on Electrons

Their work "allows us to address fundamental questions" such as the time scale of the photoelectric effect for which Einstein received the 1921 Nobel, the awarding committee chair said.

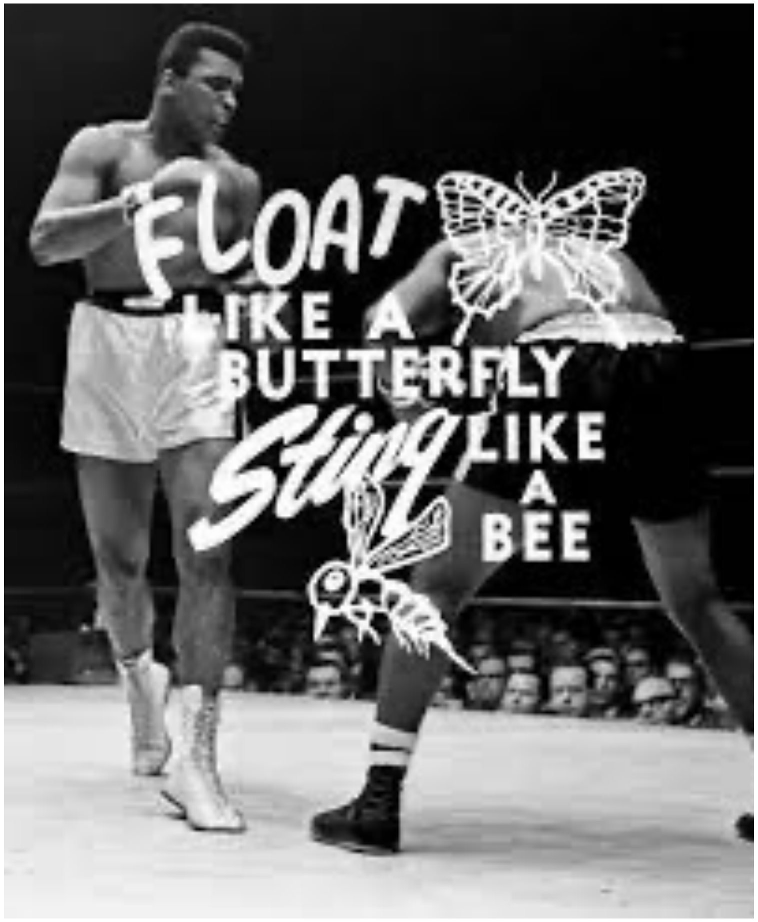
Light is always both a Wave and a Particle !



-Light behaves like a wave when it propagates through space



-And as a particle when it interacts with matter

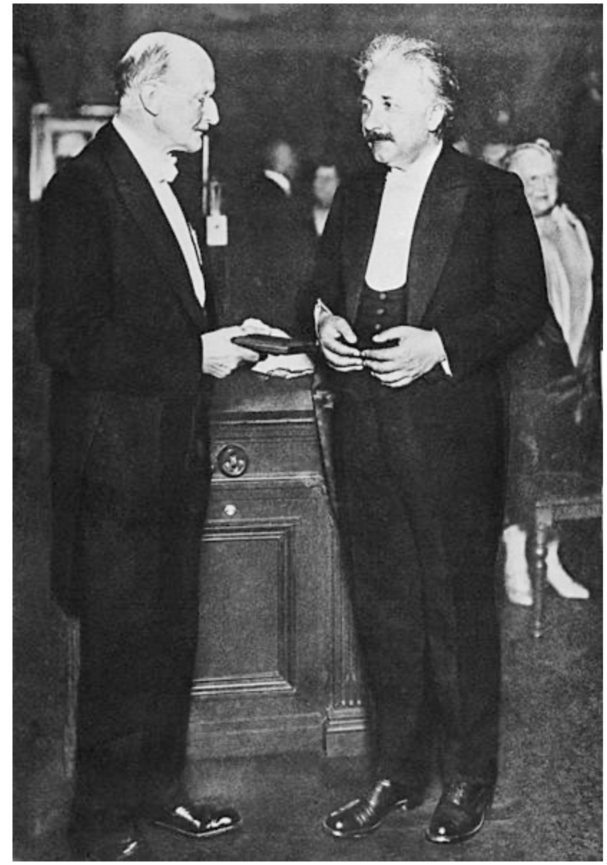


Muhammad Ali

- Historically, light was thought of as a stream of particles until Young's experiments proved light has wave-like properties.

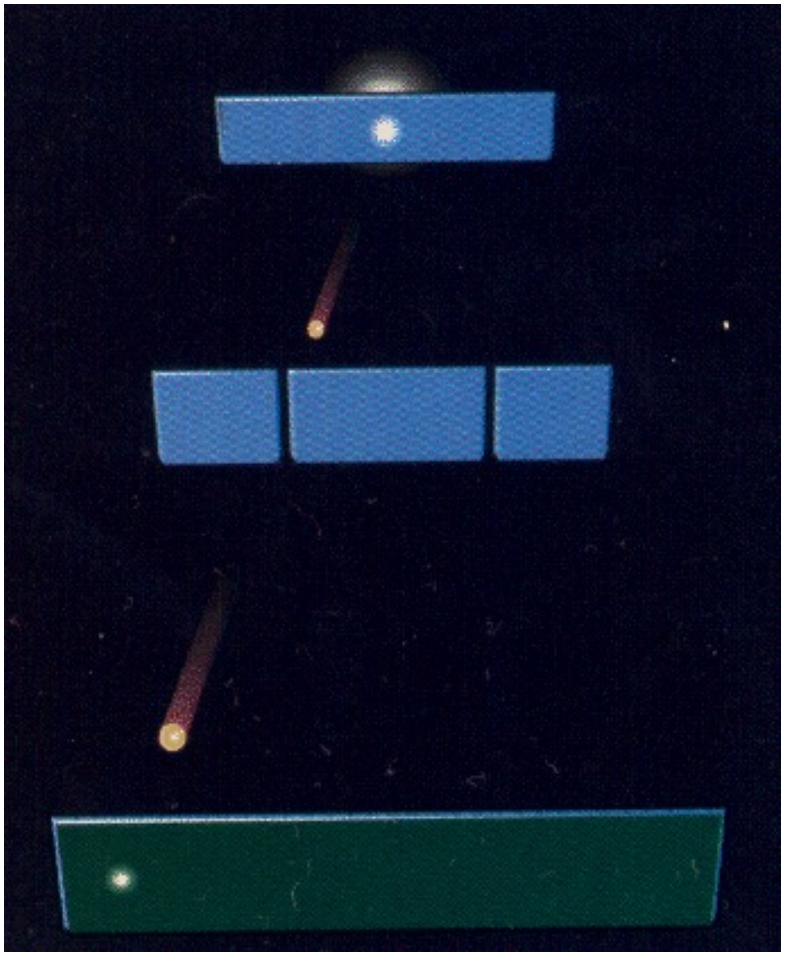
- Planck was working with the wave notion of light when he related the energy of **blackbody radiation** to the frequency of emitted light. $E = h\nu$

- Einstein began to consider the particle viewpoint again when trying to explain the **photoelectric effect**. $E = mc^2$

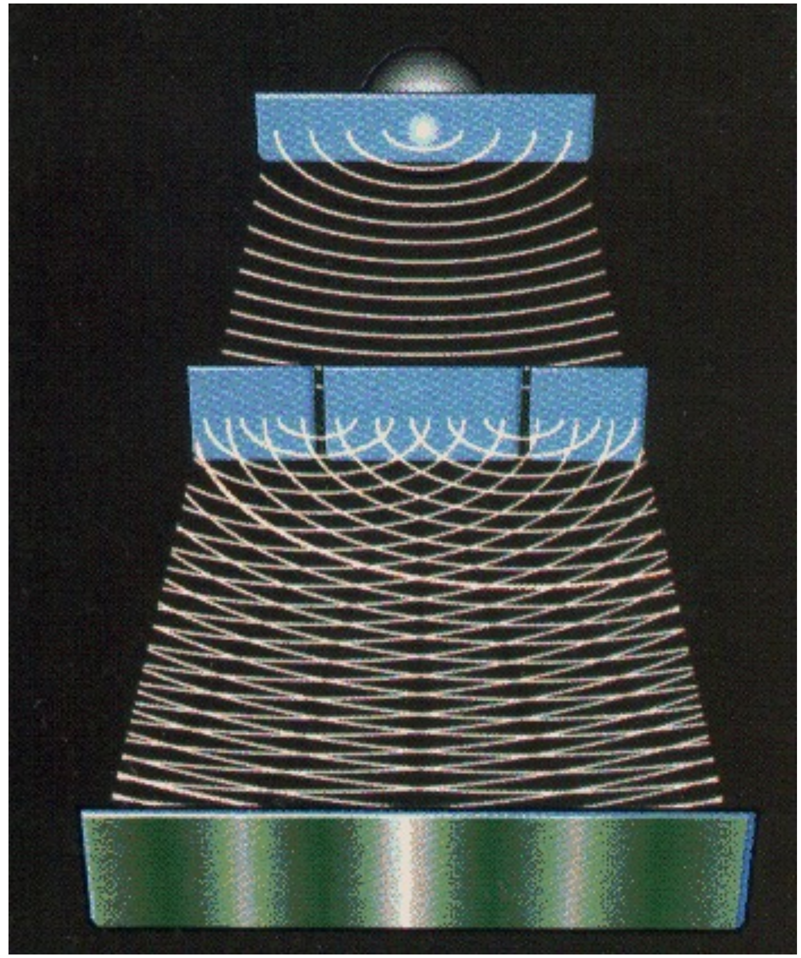


Max Planck and Albert Einstein
Berlin, June 1929

Interference: The Double Slit Experiment

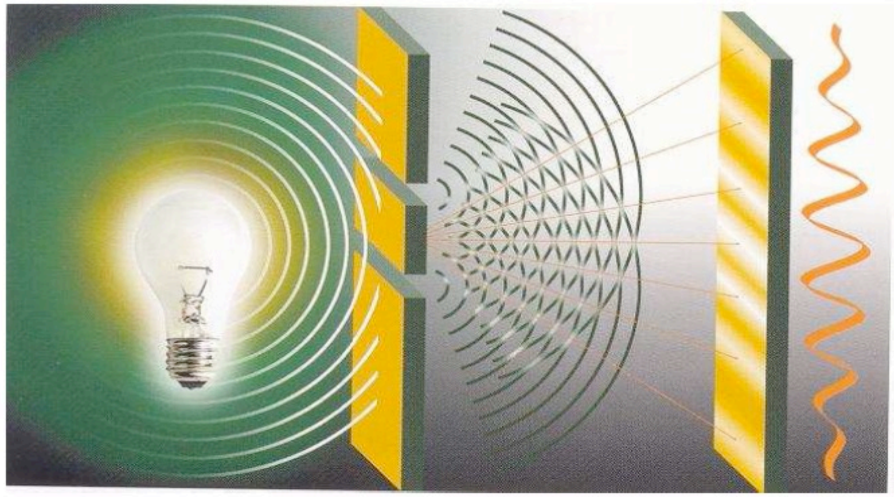


particle?



wave?

Double Slit Experiment



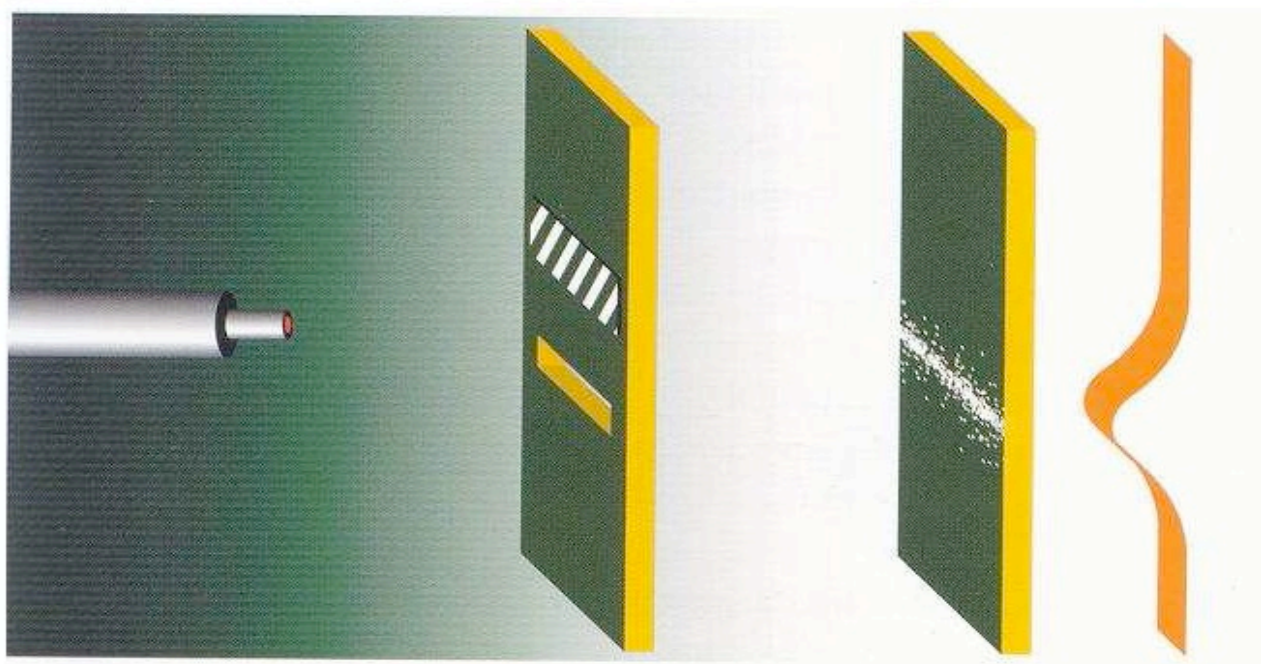
From: Quantum (J. Al-Khalili)

- What happens if we close one or the other slits?
- What happens if we send one photon at a time towards the two slits?
- What happens if we monitor which slit the single photon entered?

The double slit experiment with single photon (strange results)

Double Slit Experiment

What happens if we close one of the slits?

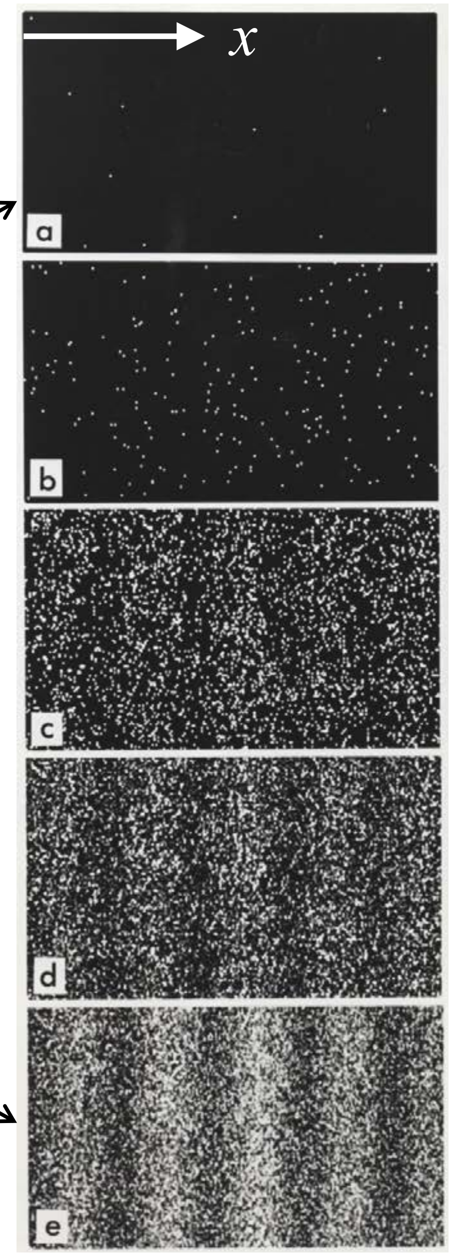


No interference pattern. Just the diffraction pattern from the single open slit.

The Double Slit Experiment with Single Photon

- What happens if we send one photon at a time towards the two slits?
- We see individual “hits” corresponding to each photon
- But as the photons arrive one by one over time, they build up an interference pattern

Very few photon



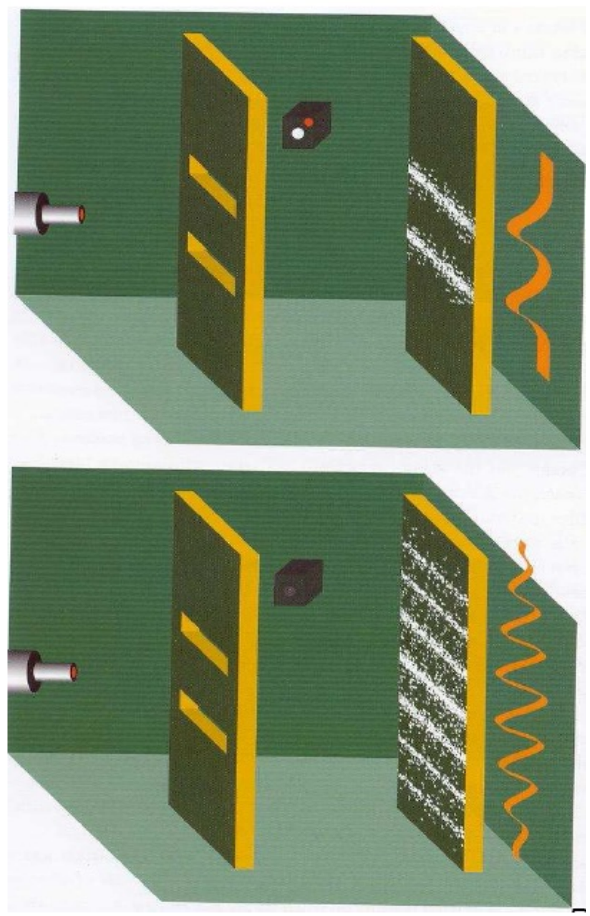
Many photons

Double Slit Experiment

- What happens if we monitor which slit the single photon entered?

Detector on

No interference pattern



Detector off

Interference pattern

The double slit experiment with single photon (strange results)

- The pattern on the screen is an interference pattern characteristic of waves
- So light is a wave, not particulate
- But repeat the experiment one photon at a time
- Over time, the photons *only land on the interference peaks*, not in the troughs
  - consider the fact that they also pile up in the middle!
  - pure ballistic particles would land in one of two spots

The double slit experiment with single photon (strange results)

1. Jim Al-Khalili https://www.youtube.com/watch?v=A9tKncAdlHQ
2. Niel Johnson, Double slit https://www.youtube.com/watch?v=O81Cilon10M
3. Neil deGrasse Tyson, Nova https://www.youtube.com/watch?v=Ms-CVF540fo
4. Light-Summary-1 https://www.youtube.com/watch?v=e5_V78SWGF0
5. Electron-Summary-2 https://www.youtube.com/watch?v=FlIrgE5T_g0

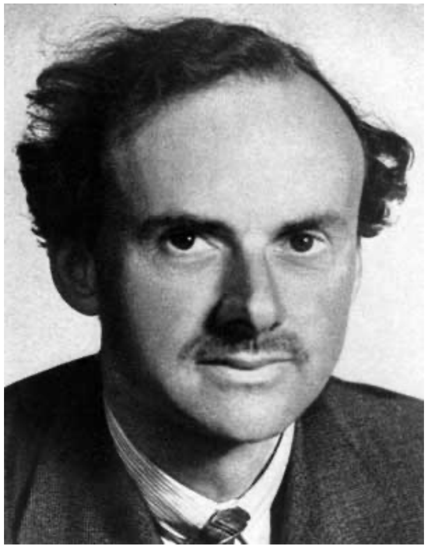
Being in Two Places at the Same Time…

Photons don't interfere with each other. They interfere with themselves.

This is a famous statement by the great 20^{th}-century physicist, Paul Dirac.

It means that each photon acts like a **wave** (that is, extends over space) at the slits and so interferes with **itself** to produce the two-slit pattern.

This is true of all wave/particles (wavicles).

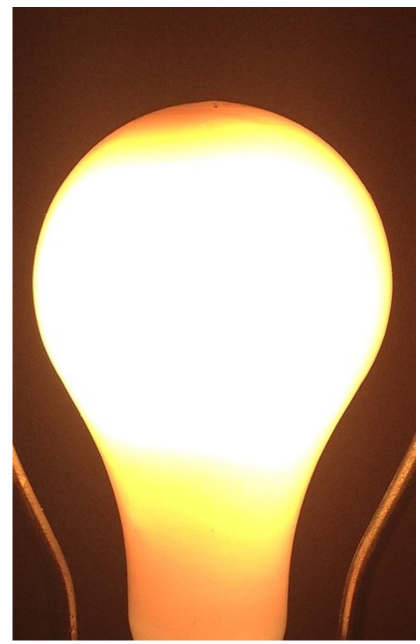


Paul Dirac (1902-1984)

Nobel Prize, 1933

Liquid water is made up of molecules. Amount is measure in terms of mole (M). One mole contains 6.022×10^{23} molecules (**Avogadro**'s number). Weight of one M depends on the weight of the molecule.

Light is made up of photons. Light is measured in terms of **Einstein**. One Einstein is the energy in one mole (6.022×10^{23}) of photons. Energy of one E depends on the frequency of photon.



Photon

"Thus light is something like raindrops-each little lump of light is called a photon-and if the light is all one color, all the "raindrops" are the same size."

Richard P. Feynman
Nobel Prize, 1965

"For the rest of my life I will reflect on what light is."

(1917)

"All the fifty years of conscious brooding have brought me no closer to the answer to the question, 'What are light quanta?' Of course today every rascal thinks he knows the answer, but he is deluding himself."

"As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality."

Albert Einstein