Nature of Light

Source:
http://learningscience.edu.hku.hk/Files/Light/Light_P(E).ppt

Nature of light

What am I?

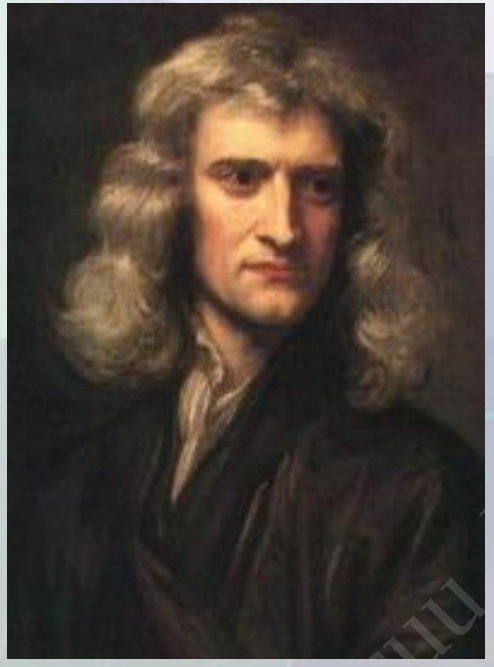
Waves?

Particles?

A long time ago ……

- Aristotle (384 - 322 B.C.), an ancient Greek thinker, thought that we saw the world by sending “something” out of our eye and that reflected from the object.
- In Plato’s time (427 – 347 B.C.), the reflection of light from smooth surfaces was known. He was also a Greek.
- The ancient Greeks (about 200 A.D.) also first observed the refraction of light which occurs at the boundary of two transparent media of different refractive indices.

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



Light is particles

No! Light is waves

Isaac Newton
1643 - 1727

Christian Huygens
1629 - 1695

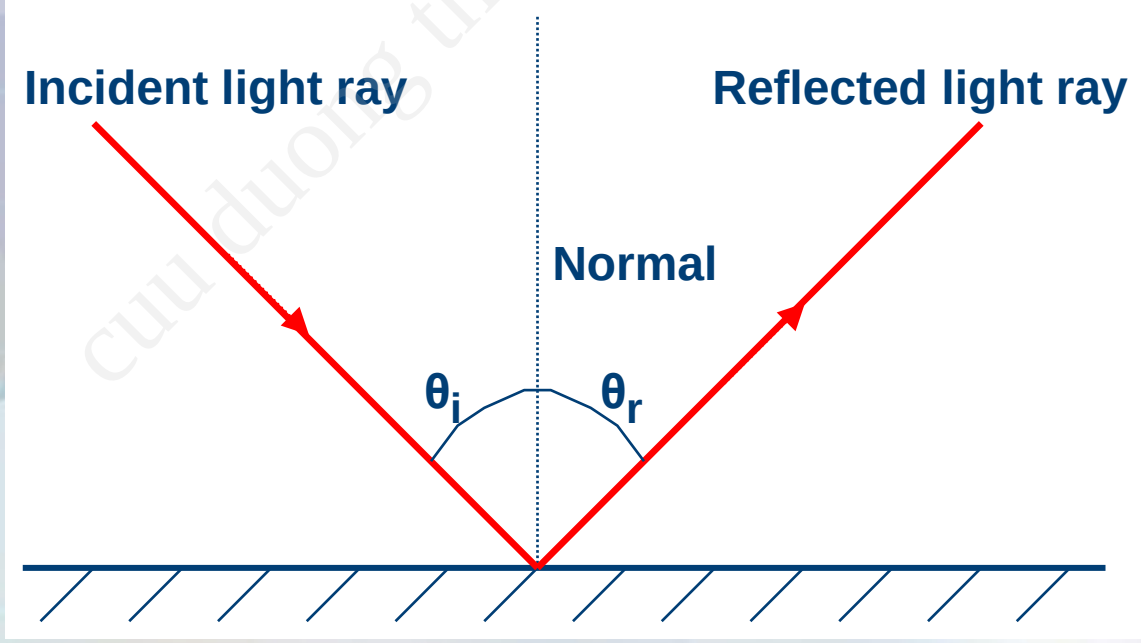
In the 17th century, some properties of light were well known already. For example:

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

Laws of Reflection

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

  angle of incidence = angle of reflection ($\theta_i = \theta_r$)

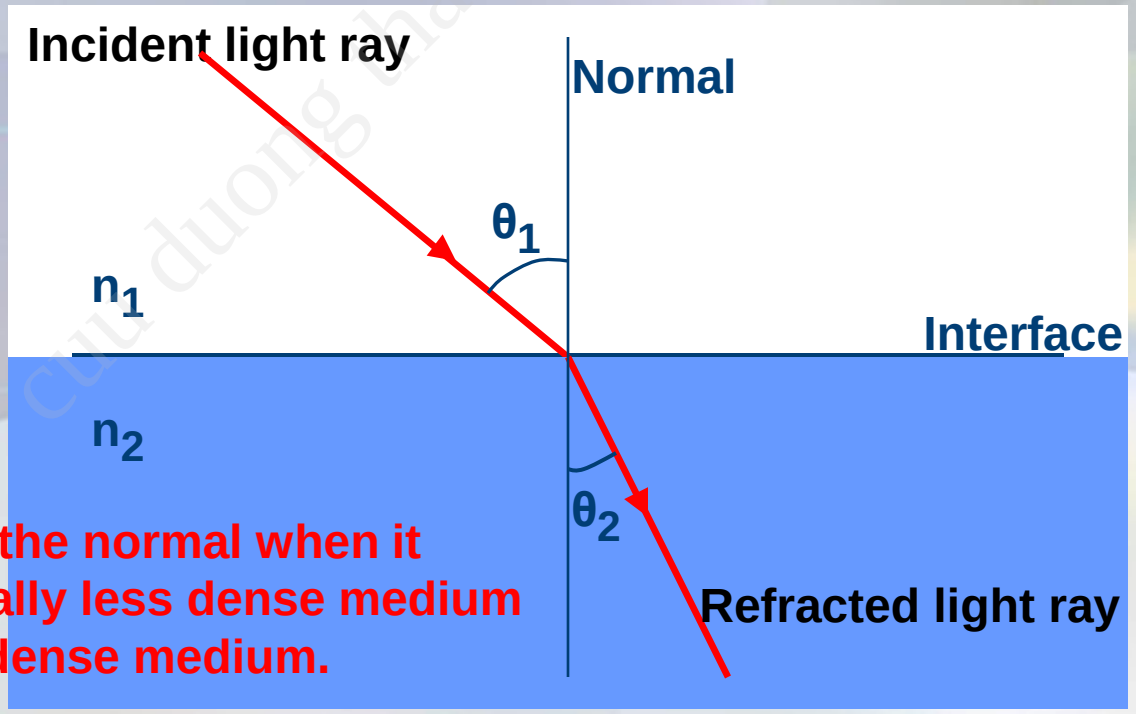


Laws of Refraction

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

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

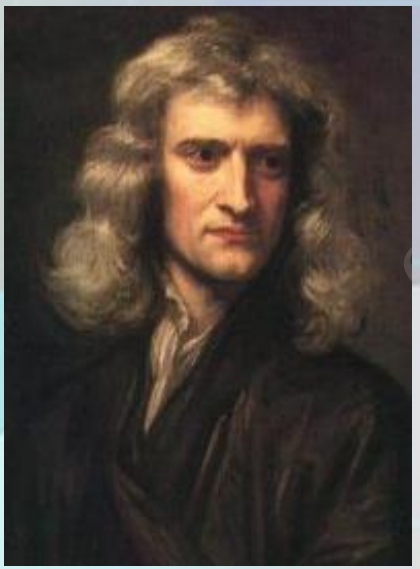
This relationship is called Snell's Law



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

Newton proposed his “particle theory of light” (or “corpuscular theory of light”) to explain the characteristics of light.

(source: “*Opticks”, published by Isaac Newton in 1704*)



I think light is a stream of tiny particles, called *Corpuscles* …

Particle Theory

Why does light have different colours?

- The particles of different colours have different properties, such as mass, size and speed.

Why can light travel through a vacuum?

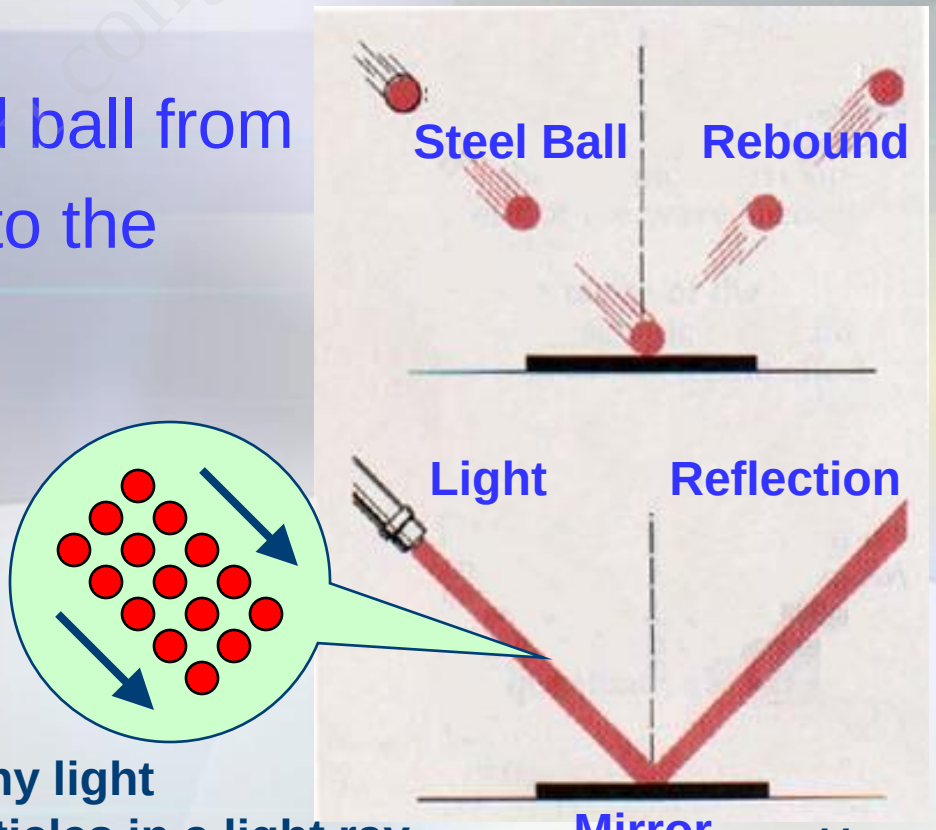
- Light, being particles, can naturally pass through vacuum. (At Newton's time, no known wave could travel through a vacuum.)

Why does light travel in straight lines?

- A ball thrown into space follows a curved path because of gravity.
- Yet if the ball is thrown with greater and greater speed, its path curves less and less.
- Thus, billions of tiny light particles of extremely low mass travelling at enormous speeds will have paths which are essentially straight lines.

How does the particle theory explain the Laws of Reflection?

- The rebounding of a steel ball from a smooth plate is similar to the reflection of light from the surface of a mirror.



Many light particles in a light ray

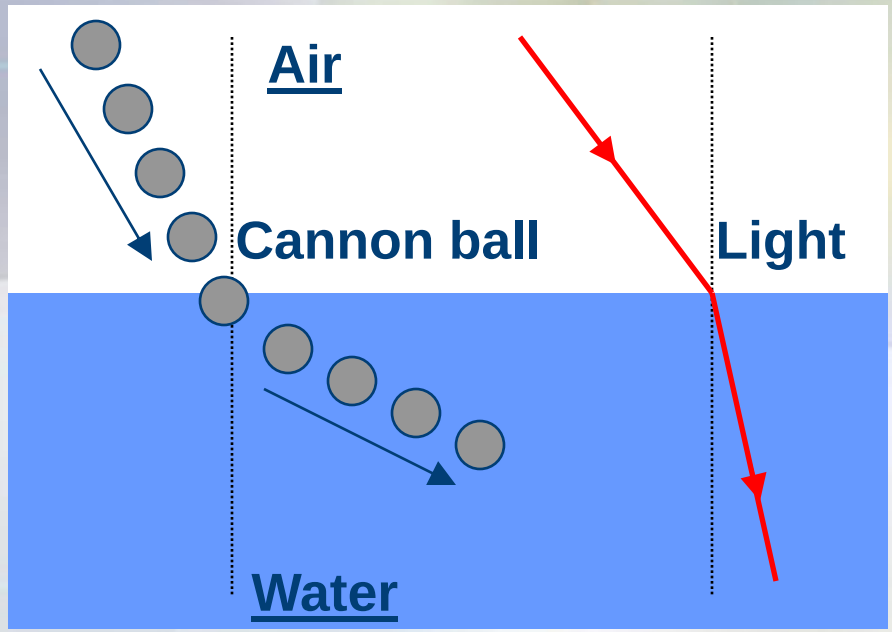
How does Newton's particle theory explain the Laws of Refraction?

- A cannon ball hits the surface of water, it is acted upon by a "refracting" force which is perpendicular to the water surface. It therefore slows down and bends away from the normal. Light does the opposite. Newton explained this observation by assuming that light travels faster in water, so it bends **towards** the normal.

  (What was the problem in this explanation?)

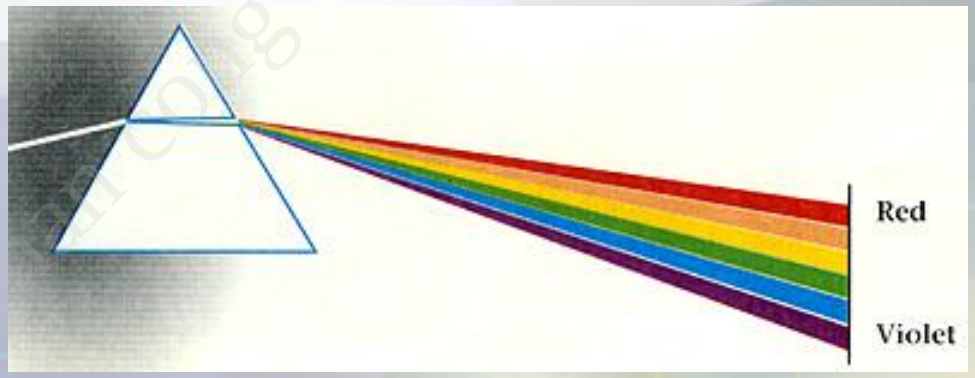
- The problem:
  Does light really travel faster in water?

  In fact nobody could measure the speed of light at the time of Newton and Huygens



Why does a prism separates a beam of white light into the colours of the rainbow?

Why does red light refract least and violet light refract most?



Newton's assumptions:

1. The light particles of different colours have mass.
   Red light particles have more mass than violet particles.
2. All light particles experience the same refracting force when crossing an interface.

Thus, red light particles with more inertia will be refracted less by the same force than violet light particles by the same force .

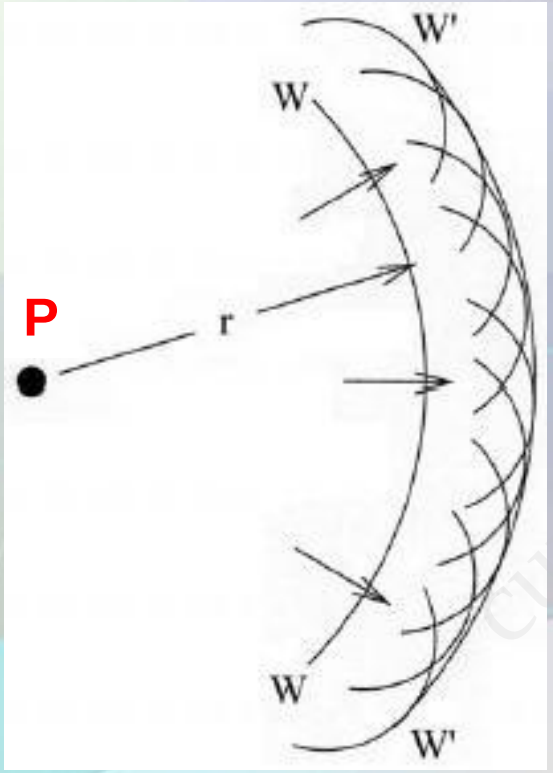
Let's see how Huygens used his "wave theory" to explain the characteristics of light …

(source: *Treatise on light*, published by Huygens in 1690)

I think light is emitted as a series of waves in a medium he called *"aether"*

("aether" commonly also called "ether")

How do waves propagate?



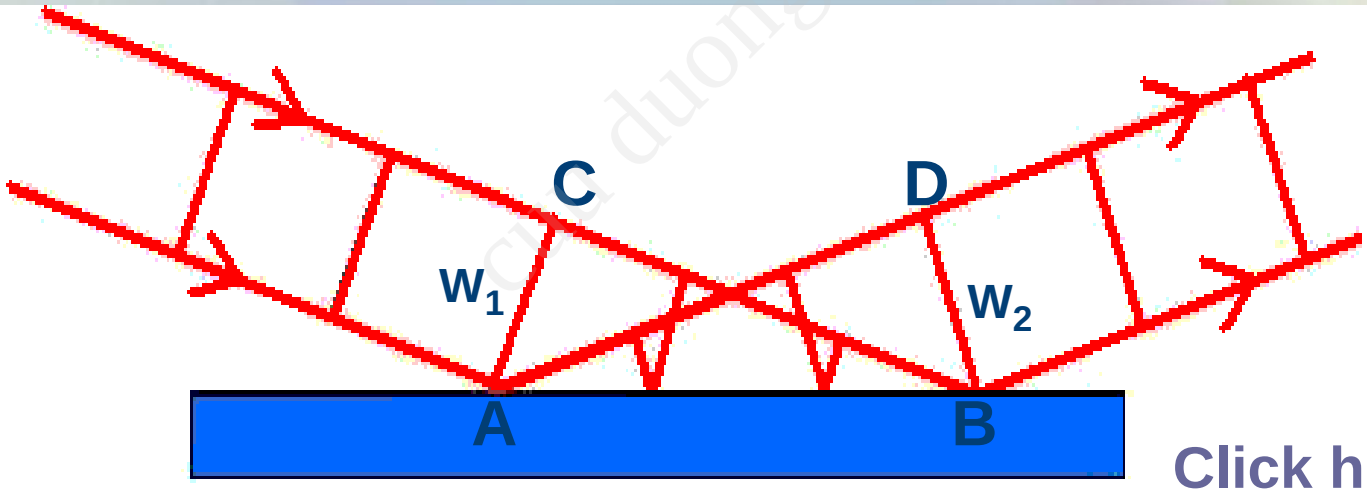
A wave starts at P and a “wavefront” W moves outwards in all directions. After a time, t, it has a radius r, so that r = ct if c is the speed of the wave.

Each point on the wavefront starts a secondary wavelet. These secondary wavelets interfere to form a new wavefront W’ at time t’.

How can wave theory explain the Laws of Reflection?

When wavefront W_1 (AC) reaches point A, a secondary wave from A starts to spread out. When the incoming wavefront reaches B, the secondary wave from A has reached D, giving a new wavefront W_2 (BD).

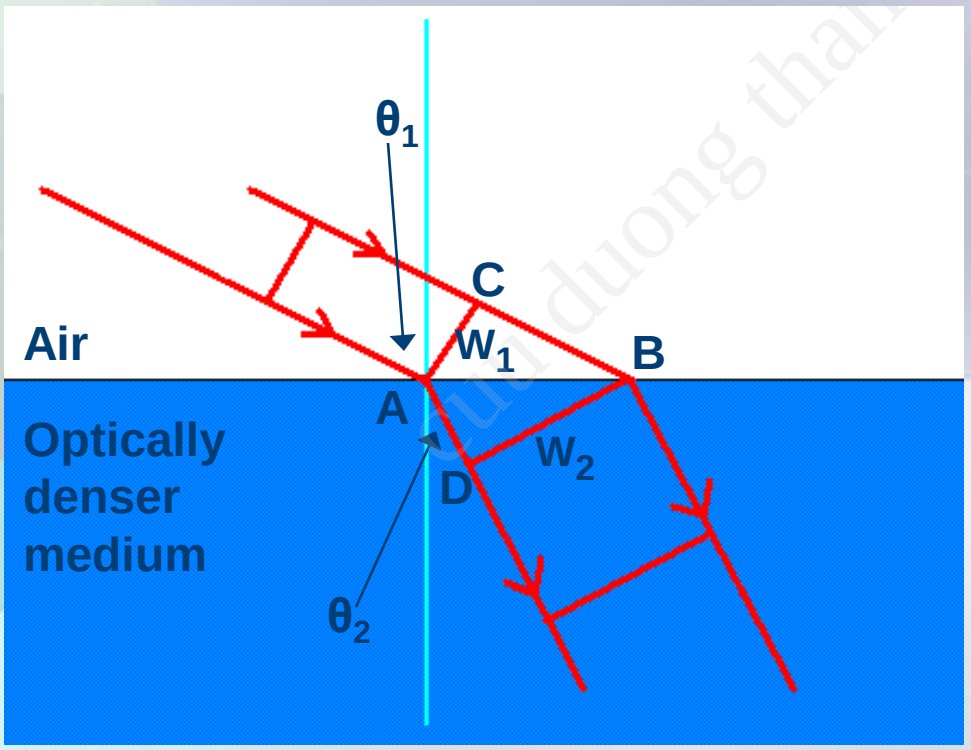
Angle of incidence = Angle of reflection can be proved by geometry. Refer to the appendix of the worksheet or your textbook for the proof.



Click here for animation

How can wave theory explain the Laws of Refraction?

Wavefront W_1 reaches the boundary between media 1 & 2, point A of wavefront W_1 starts to spread out. When the incoming wavefront reaches B, the secondary wave from A has travelled a shorter distance to reach D. It starts a new wavefront W2. As a result the wave path bends towards the normal.

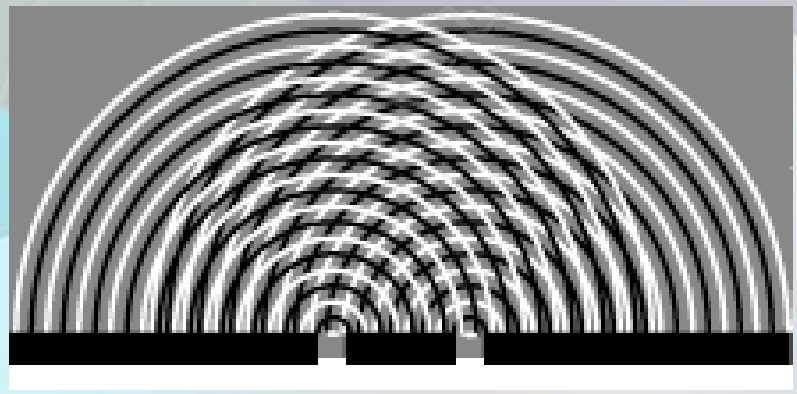


$n_1 \sin\theta_1 = n_2 \sin\theta_2$ can be proved by geometry. Refer to the appendix of the worksheet or your textbook for the proof.

Click here for animation

If light behaves as waves, diffraction and interference should be seen. These are two important features of waves. This was known in the 17th century.
(You can see this easily with water waves in a "ripple tank")

- The wave theory of light predicts interference and diffraction. However, Huygens could not provide any strong evidence to show that diffraction and interference of light occurred.



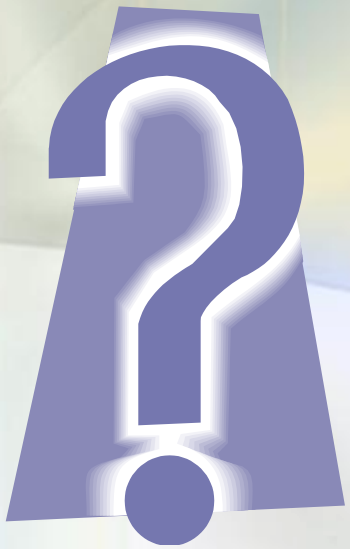
Diffraction and interference of water waves

The “ Laws of reflection” and the “Laws of refraction” are examples of laws. The “particle theory of light” and the “wave theory of light” are examples of theories.

What is a scientific law?

What is a scientific theory?

What are the differences between them?



What is a scientific law?

Scientific laws are descriptions of relationships among phenomena or patterns in nature

e.g. Ideal Gas Law $PV = nRT$

What is a scientific theory?

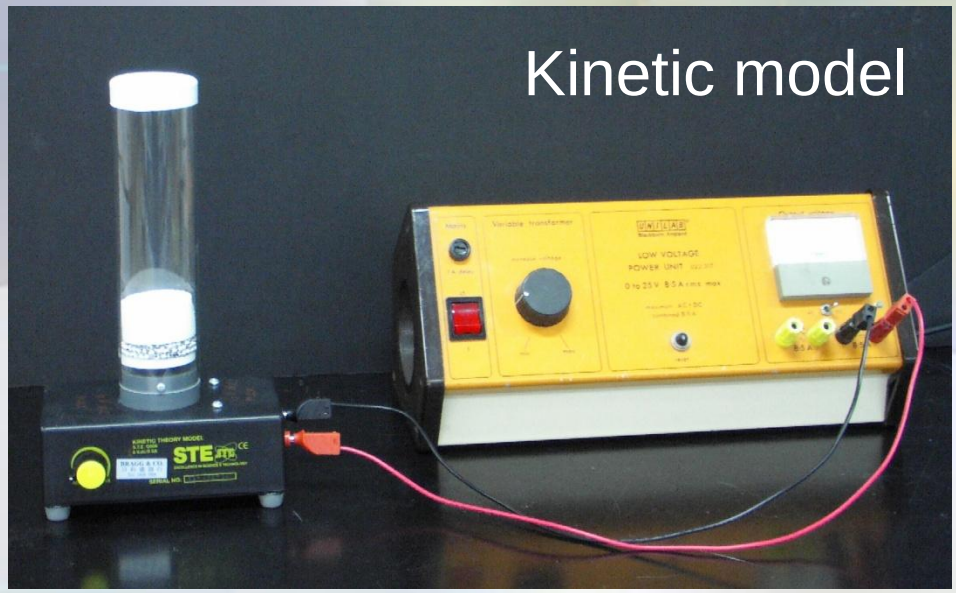
Scientific theories are the explanations of those relationships and patterns

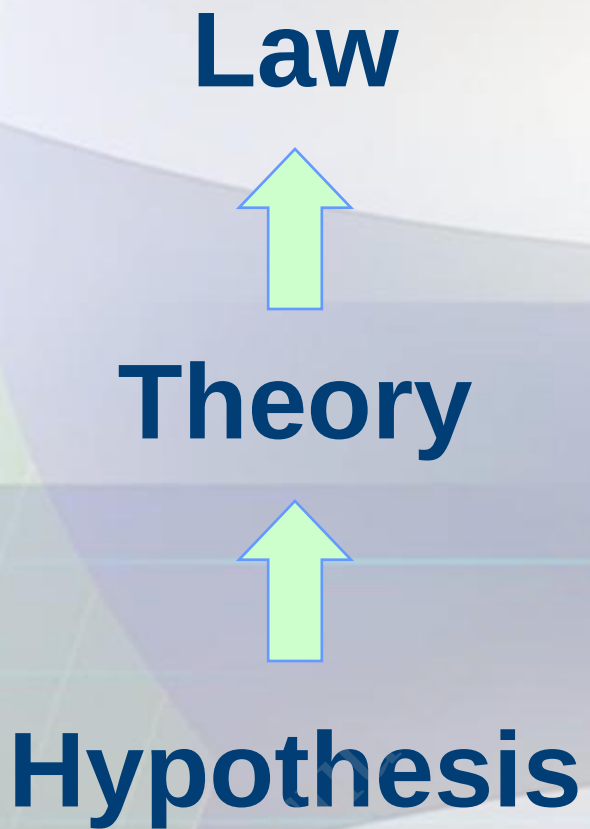
e.g. Kinetic Theory

Law and theory

The Ideal Gas Law **describes** the relationships among P, V, and T of ideal gases.

Kinetic Theory **explains** these relationships (i.e. the Ideal Gas Law).





Hierarchical relationship?

Scientific theories and laws are **different kinds** of knowledge.

A theory will not turn into a law or *vice versa*!

If you were one of the scientists in the 17th century, would you believe the “particle theory of light” or the “wave theory of light”? Why?

Hint: Which theory has a greater ability to explain the characteristics of light?

Newton was the “winner”….. (at that time!)

- Newton’s particle theory of light dominated optics during the 18th century.
- Most scientists believed Newton’s particle theory of light because it had greater explanatory power.
- Let’s consider the reasons……

(1)Waves do not travel only in straight lines, so light cannot be “waves”.

- Sounds can easily be heard around an obstacle but light cannot be seen around an obstacle. Light, unlike sound, does not demonstrates the property of diffraction and it is unlikely to be a type of wave.

(2) Light, unlike sound waves, can travel through a vacuum. Particles can travel through a vacuum.

- In the 17th century, it was believed that waves could not travel through a vacuum. It was difficult for people at that time to believe that waves could travel through the "*ether*", which was the imaginary "medium" that light travels through, proposed by Huygens.

(3) Particle theory of light can explain why there are different colours of light.

- Huygens could not explain why light has different colours at all. He did not know that different colours of light have different “wavelengths”.

- Though Newton’s explanation was not correct (particles of different colours of light have different mass and size), his particles theory could explain this phenomenon logically in the 17th century.

(4) Reputation of Newton

- People tend to accept “authority” when there is not enough evidence to make judgement. Newton’s particle theory could only explain refraction by incorrectly assuming that light travels faster in a denser medium. No one could prove he was wrong at that time.
- *The uncertainty about the speed of light in water remained unresolved for over one hundred years after Newton's death.*

Summary: From the debate over the nature of light between Huygens and Newton, we can learn that …

- Scientific laws are descriptions of patterns and phenomena of the nature. *(e.g. Laws of reflection, Laws of refraction)*
- Scientific theories are explanations of such patterns and phenomena. *(e.g. particle theory of light, wave theory of light)*
- A good theory should have strong explanatory power.

  (Newton's particle theory of light has a greater explanatory power than Huygens' wave theory of light.)
- People tend to submit to authority when there is not enough evidence to make judgment.

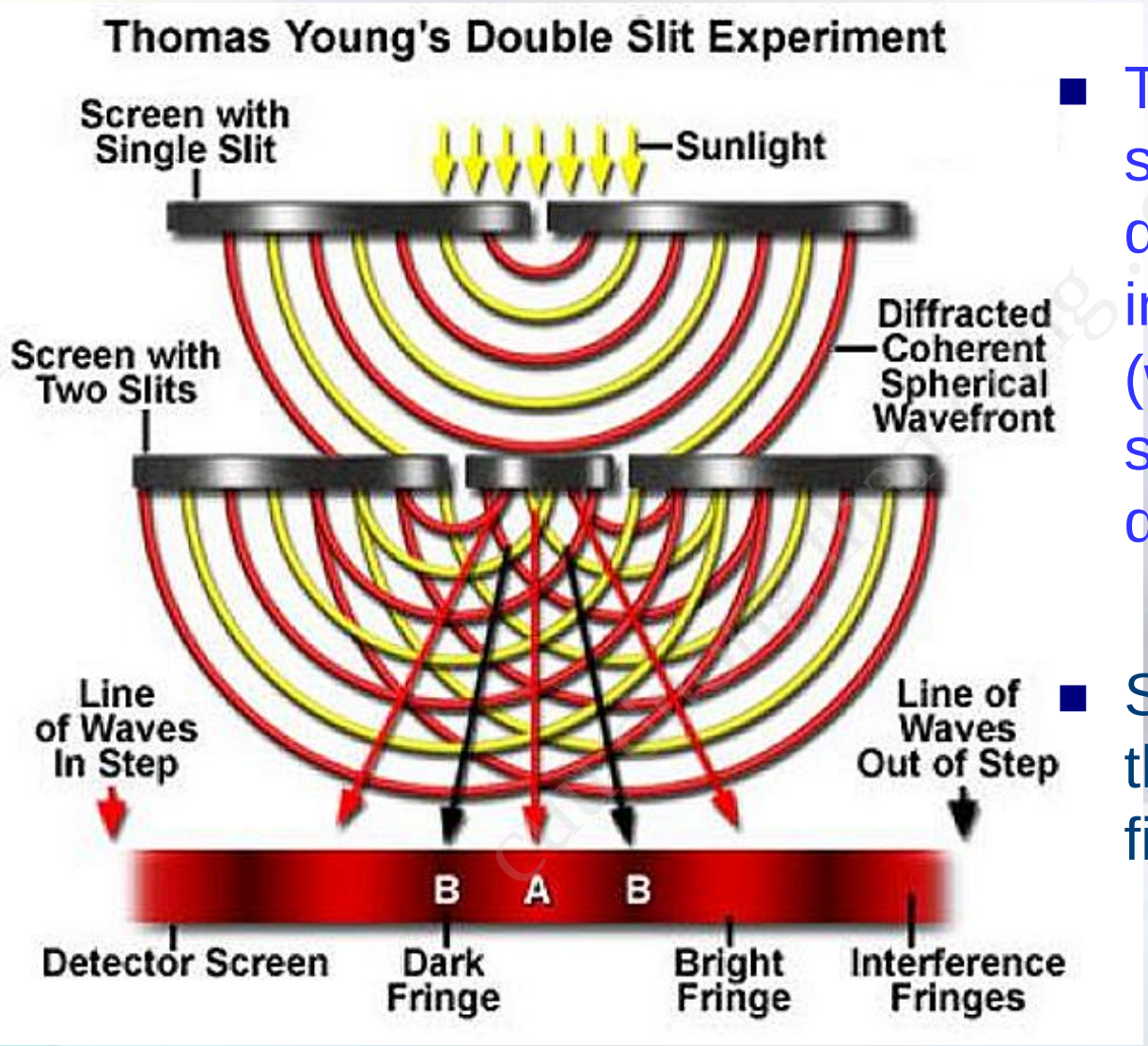
  (People believed Newton's theory due to his reputation in science.)

However, the wave theory of light was re-examined 100 years after Newton's particle theory of light had been accepted……

Light is not particles!

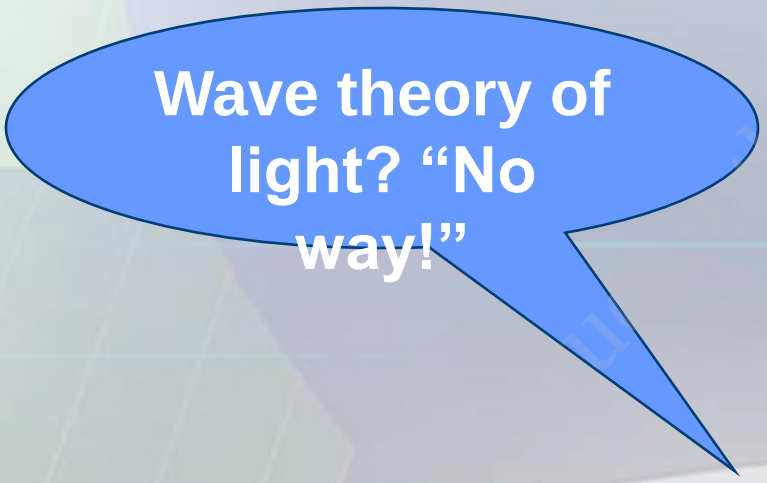
Thomas Young

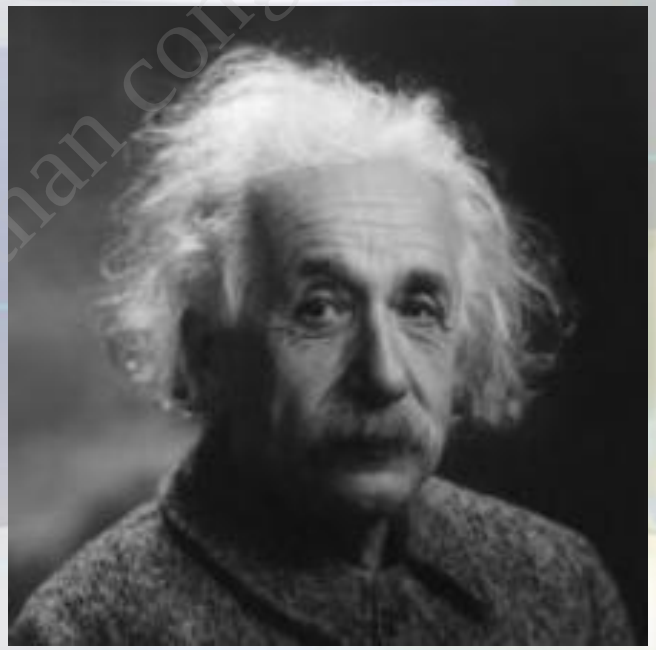
1773 - 1829



- Thomas Young successfully demonstrated the interference of light (which Huygens failed to show), by his famous double-slit experiments.
- Since then the wave theory of light has been firmly established.

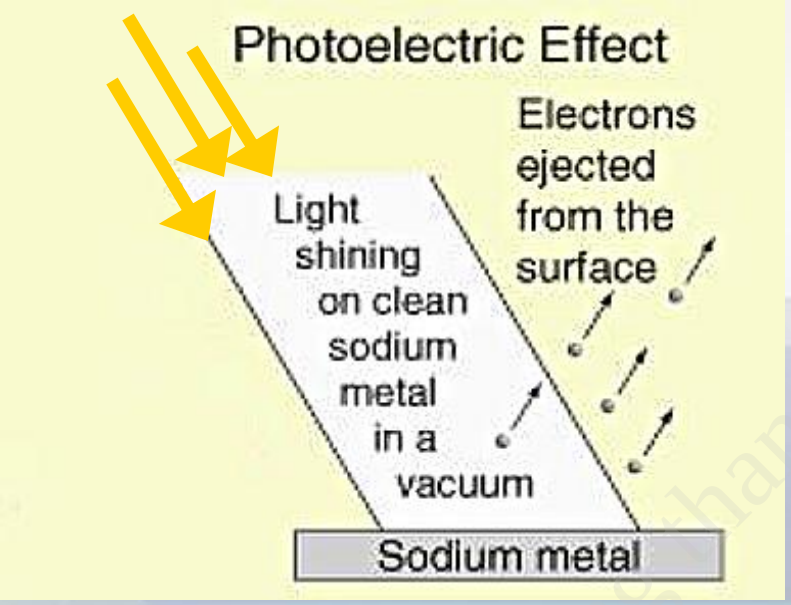
The wave theory of light was widely accepted until 1905……

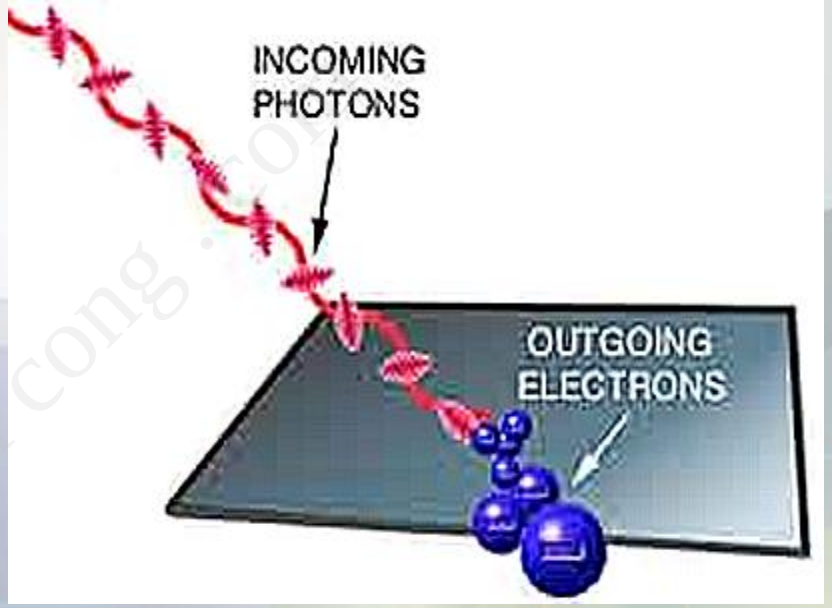




Albert Einstein

1879 - 1955



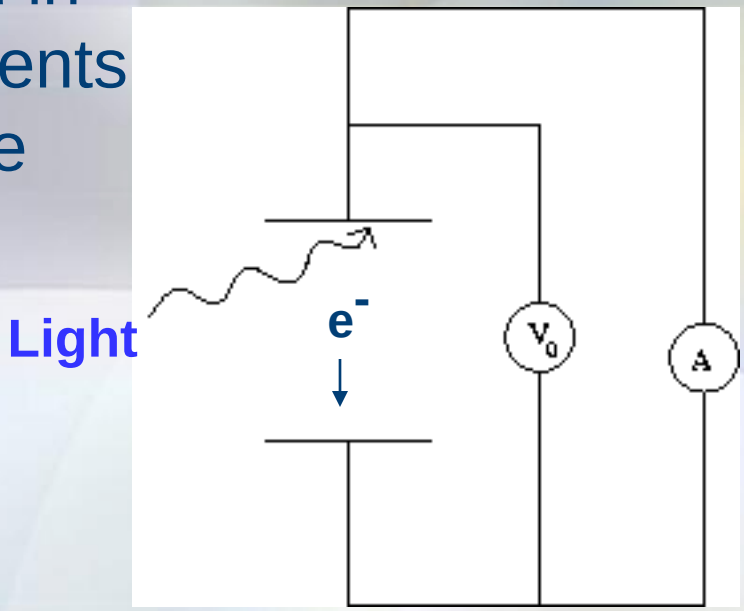


- **The photoelectric effect** is observed when light strikes a metal, and emits electrons.

  Einstein used the idea of photons (light consists of tiny particles) to explain results which demonstrate the photoelectric effect.

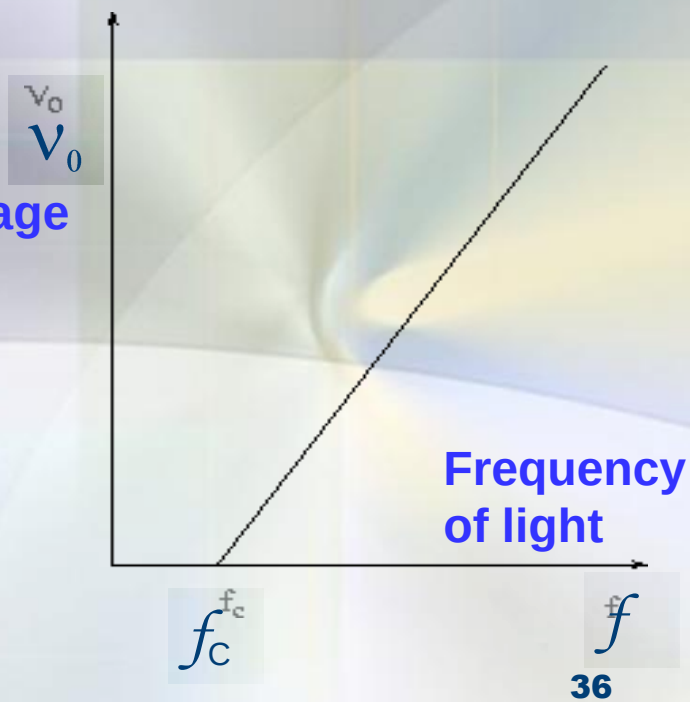
- In the setup investigating the photoelectric effect (as shown below), the intensity of the light, its frequency, the voltage and the size of the current generated are measured.

- What evidence did Einstein find in his photoelectric effect experiments that helps to support the particle theory of light?



Results from photoelectric effect experiments

- For certain metals, dim blue light can generate a current while intense red light causes no current at all.
- Below a certain “cut off” frequency of light (f_c), no voltage is measurable.
- Why does the wave theory of light not explain the result?



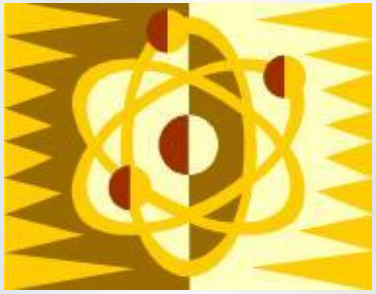
Einstein's explanation

- Electrons are knocked free from the metal by incoming photons, with each photon carrying an amount of energy E that is related to the frequency (ν) of the light by

$$E = h\ \nu$$

Where *h* is Planck's constant (6.62×10^{-34} J seconds).

- Only photons of high enough energy (above a threshold value) can knock an electron free. e.g. blue light, but not red light, has sufficient energy to free an electron from the metal.)



Albert Einstein provided a piece of convincing evidence for the particle nature of light ……
Has the story ended yet?
Is light particles or waves?

Light is not particles,
not waves, but BOTH!

Louis de Broglie

1892 - 1987

- Louis de Broglie in 1924 proposed that particles also have wave-like properties, this was confirmed experimentally three years later.
- Most scientists did not understand de Broglie's Ph.D. dissertation at that time. One scientist passed it on to Einstein for his interpretation. Einstein replied that de Broglie did not just deserve a doctorate but a Nobel Prize!
- De Broglie was awarded the Nobel Prize in 1929.

Summary

Aristotle (Light was emitted from our eyes)

↓

Christian Huygens (Wave theory of light)

↓

Isaac Newton (Particle theory of light)

↓

Thomas Young (Wave theory of light)

↓

Albert Einstein (Particle theory of light)

↓

de Broglie (Wave-particle duality of all matter)

Summary: What can we learn from the historical development about the understanding the nature of light?

- **Evidence** (e.g. Young's double slit experiment, photoelectric experimental results…etc) can establish or refute a theory.
- Gathering scientific knowledge (the nature of light) is **hard work, building upon the hard work of other scientists in the past or present**. (collaboration across time)
- **Scientific knowledge is ever changing**, sometimes even revolutionary (Einstein discovered the particle nature of light, de Broglie discovered the wave-particle duality of all matter)