Basics Quantum Mechanics

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Module No. # 01
Introduction and Mathematical Preliminary
Lecture No. # 01
Basic Quantum Mechanics: Wave Particle Duality

We will be discussing the basic concepts in quantum mechanics, and as we all know the concept of quantum mechanics started with the wave particle duality. So, we will first discuss the phenomenon of wave particle duality and give after that a heuristic derivation of the Schrödinger equation. A major portion of non relativistic quantum mechanics is just the solution of the Schrödinger equation for different potentials that we plan to do, and discuss applications in many diverse areas. At a later date we also would be doing the deduct spar and kept algebra, and using operator formulation discuss the Eigen value spectrum of the linear harmonic oscillator, and also of the angular momentum problem.

Today, we will discuss the wave particle duality, and we will start whether light is a wave or a particle. So, our course is on basic quantum mechanics and the first part is wave particle duality, and these are my email addresses.

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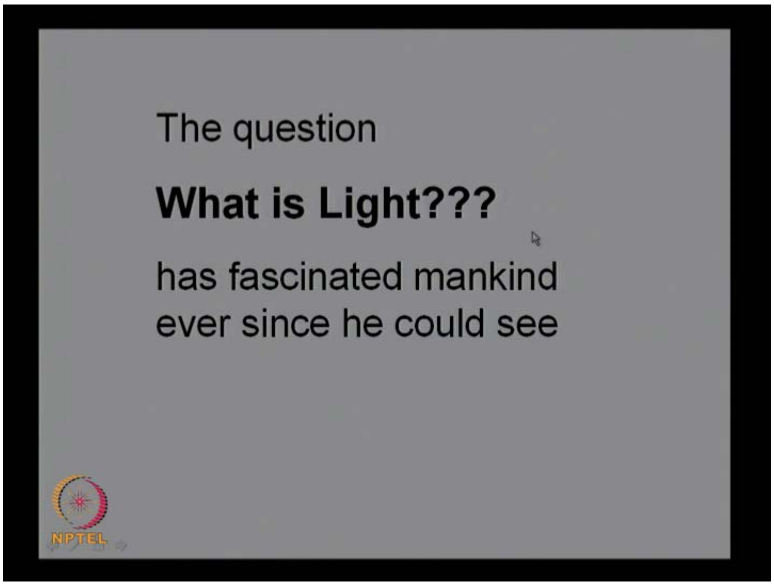

The question what is light, has fascinated mankind ever since he could see.

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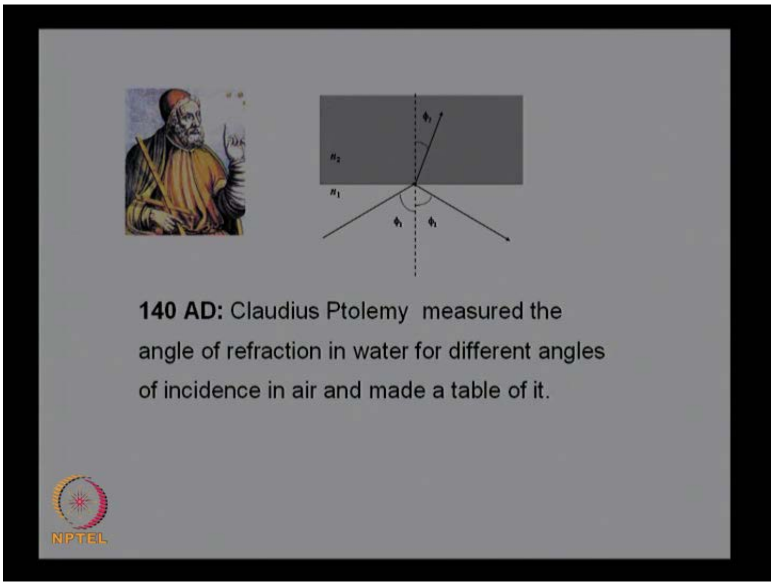

In 140 A D a Greek physicist by the name of Claudius Ptolemy measured the angle of refraction in water for different angles of incidence in air that means for different values of phi1, he measured the different the corresponding values of phi 2 and made a table of it.

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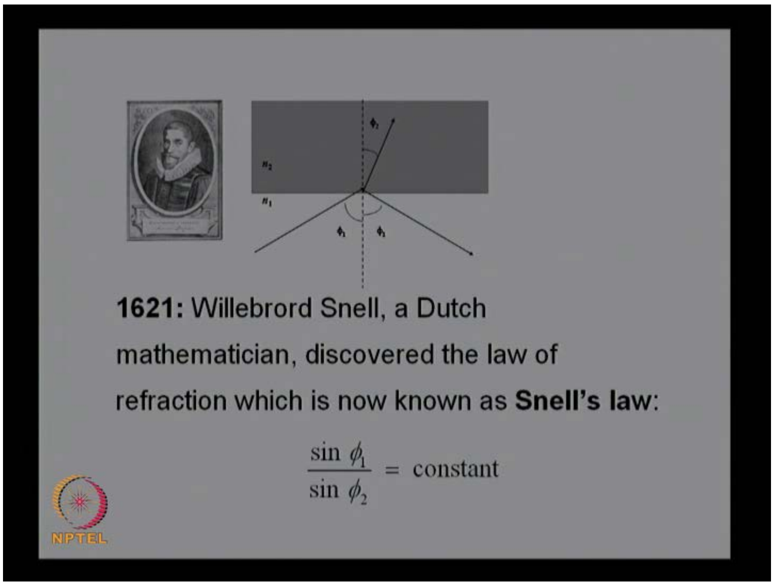

He could not find the relationship between the two and it was in the year 1621. As you all may be knowing, that Willebrord Snell a Dutch mathematician discovered the law of refraction which is now known as Snell's law. From the experimental data of phi 1 and phi 2, he could figure out sin phi 1, divided by sin phi 2 is a constant. So, such a law is known as empirical law which is based on experimental observations this law as I have just mentioned is known as Snell's law.

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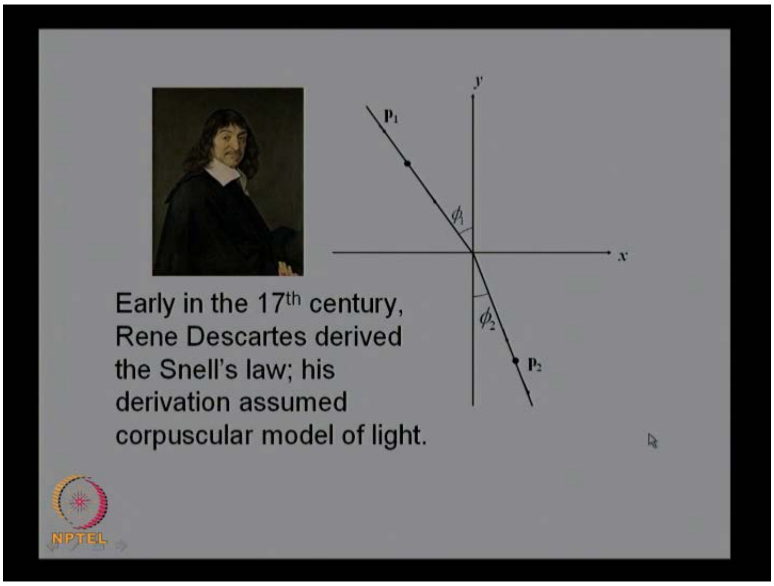

Early in the 17th century, the French scientist and mathematician René Descartes derived this Snell’s law his derivation assumed a corpuscular model of light. So, that when light is incident on a denser or rarer medium it undergoes reflection and he could derive from a simple kinematic consideration the Snell’s law.

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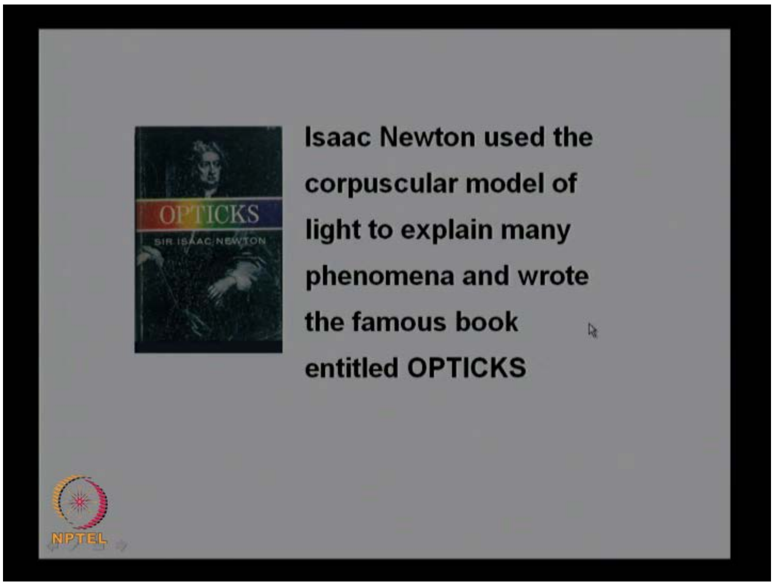

Then Isaac Newton also used the corpuscular model of light, to explain many phenomena and wrote the famous book entitled OPTICKS. This particular book became extremely popular and therefore, the corpuscular model of light which was which was put forward by Isaac Newton in this book came to be known as Newton’s model of light or corpuscular model of light .

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As we all know that because of the smallness of the wave length of light the object crust very sharp shadows. Now, if one the surface of the earth if shadow there is lot of light, that occurs due to phenomenon of scattering. This is a photograph on the surface of the moon and you can see here, that the shadows are absolutely dark almost no light enters the geometrical shadow and this is because there is no atmosphere on the surface of the moon. And light almost travels in straight lines and it is, because of this fact that corpuscular model was accepted and was believed it to be true for a very long period of time of course, as we all know now, that little bit of light does enter the geometrical shadow but because the wavelength is very small the light entering the geometrical shadow is extremely small and so therefore, light approximately travels in straight lines.

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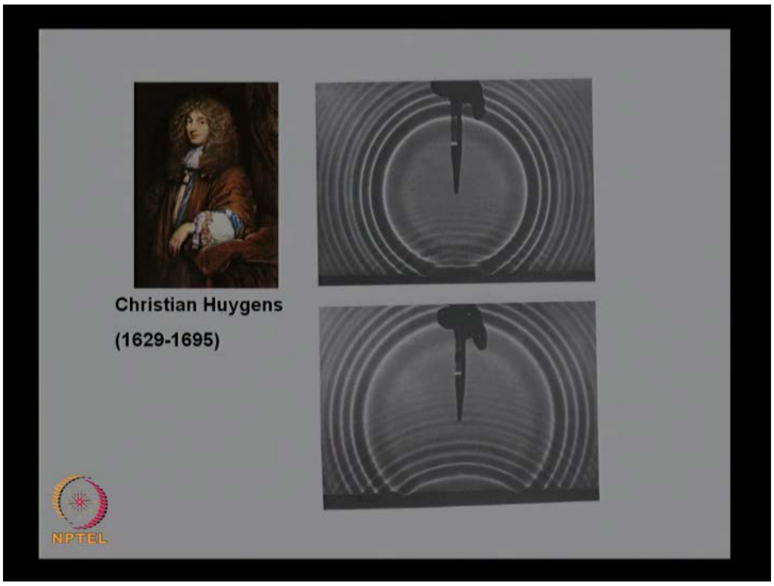

The wave model of light was first put forward by Christian Huygens. This is a photograph where there is a sharp needle which is made to vibrate on calm pool of water and as the needle keeps vibrating it sends out circular reports and this propagation of disturbance is known as wave. Now in this figure, in this case there wave fronts are circular that means all points on the periphery of the surface are vibrating in the same phase if this is a crest then all particle are at the maximum possible displacement. So, that is the locus of the points which are vibrating in the same phase is known as a wave front, and the distance between two consecutive crest or trust is the wave length.

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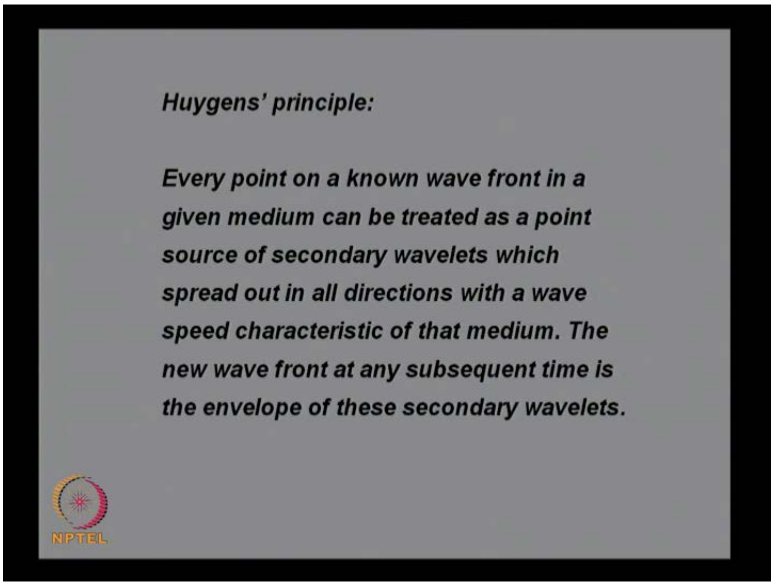

So, Huygens put forward the wave model of light and he said, he enunciated a very famous principle which is usually referred to as Huygens' principle according to which every point on a known wave front in a given medium can be treated as a point source of secondary wavelets which spread out in all directions with a wave speed characteristic of that medium. The new wave front at any subsequent time is the envelop of these secondary wave fronts.

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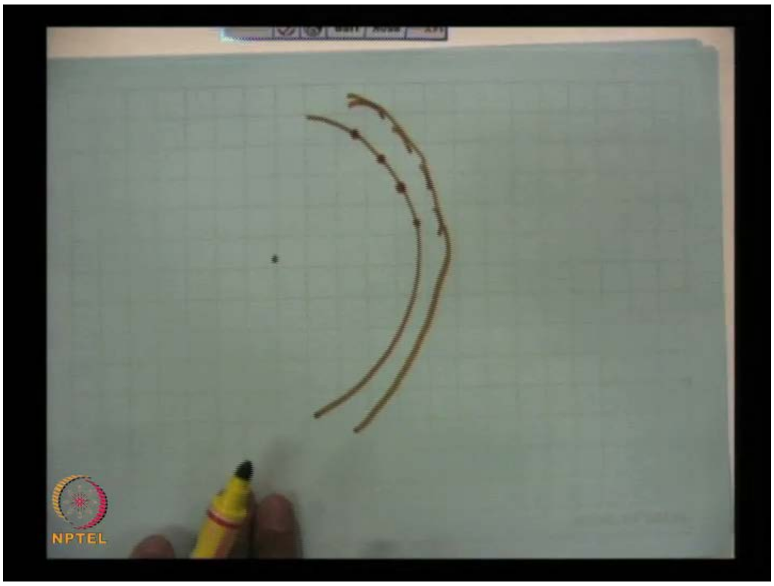

What I am trying to say is that if this is a source and at any particular intense of type this is a wave front then on each point of the wave front we assume that is a source of secondary wave lets and this are the secondary wavelets that are emanating from the source and envelope of this is the position of a wave front at a slightly later time.

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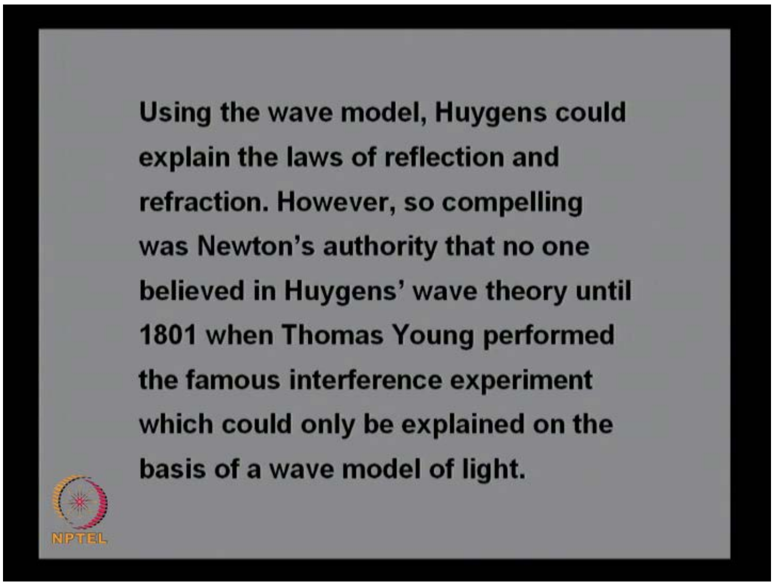

This principle is known as the Huygens principle although using the wave model Huygens Christian Huygens could explain the laws of reflection and refraction. Newton's authority was so compelling that no one believe in Huygens's theory until about 1801 when Thomas young performed the famous interference experiment which could only be explained on the basis of a wave model of light. With phenomenon of interference which cannot be explained on a classical particle model of light. So, when this experiment was performed by Isaac Newton it was believed people started believing that light indeed is a wave phenomenon.

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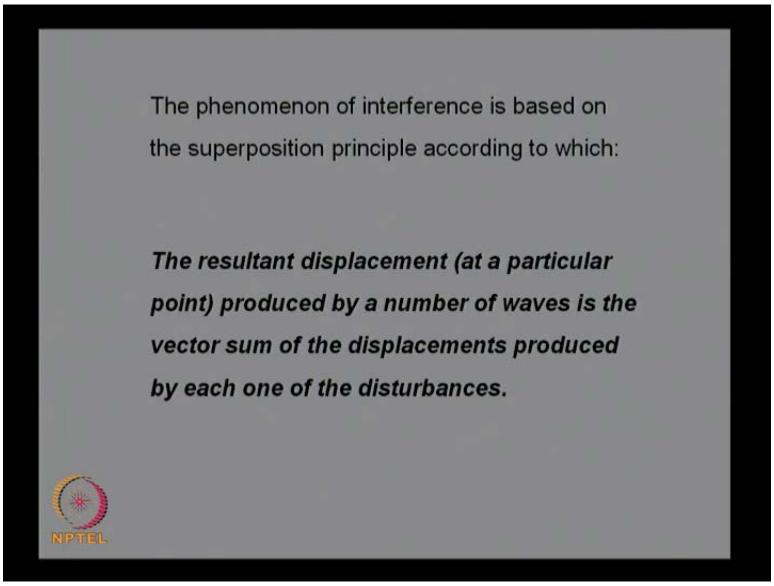

The phenomenon of interference is based on the superposition principle according to which the resultant displacement at a particular point produced by a number of waves is the vector sum of the displacements produced by each one of the disturbances, so this principle is known as the superposition principle.

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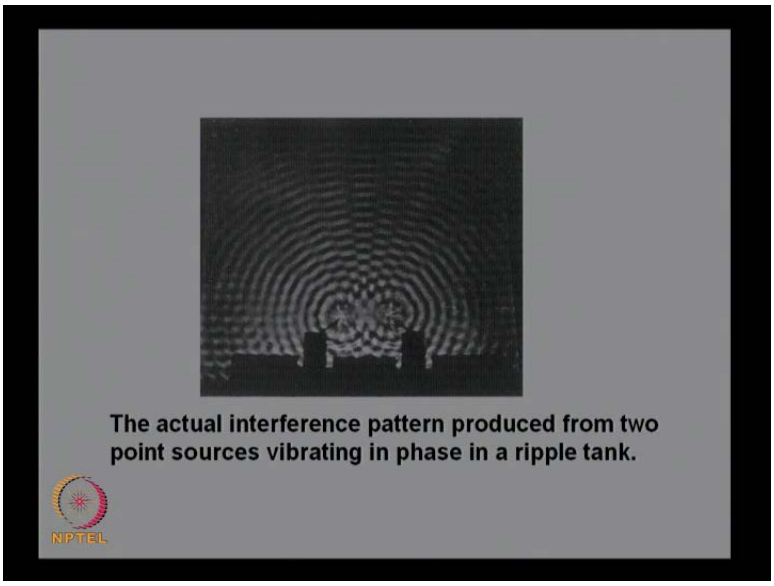

Here, I have two sources two pointers, which are suppose vibrating in phase on a calm pool of water each sensed out its own wave pattern because of the disturbance emanating from each point there is a displacement of the water molecule. Now if there more than one source, then the resultant displacement is the vector sum of the two displacements independently produced by the two sources this is known as the superposition principle.

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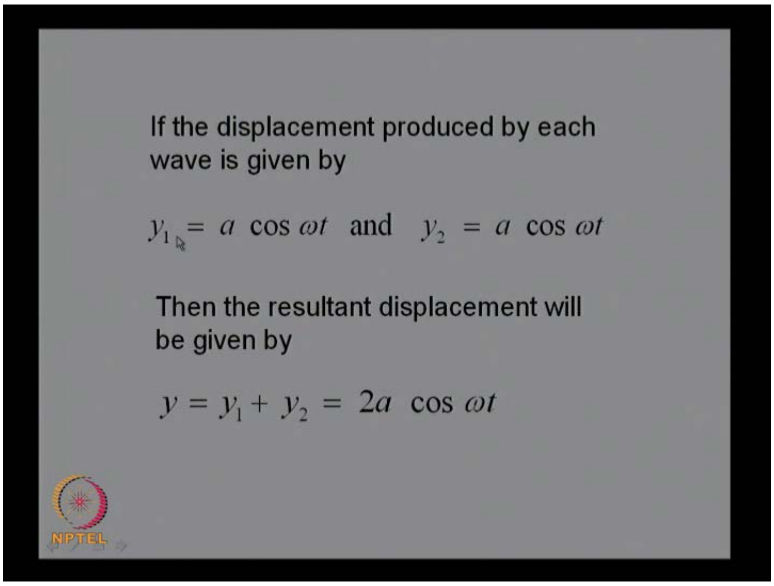

For example, if the displacement produced by each wave is given by at one particular point. The displacement produced by the first wave by the first source is given by a cos omega t and at that point the displacement produced by the other source is also a cos omega t. We say that because of the two displacements are vibrating in phase the two displacements are in phase, then the resultant displacement will be the algebraic sum of the two the amplitude will become 2a the intensity will become four times and we will have we will have what is known as a right phase. On the other hand, if the one source produces a displacement a cos omega t, and the other produces a displacement minus a cos omega t that means, the two displacements are outer phase then the resultant displacement will be again y 1 plus y 2 the algebraic sum of the 2 at it will be 0.

In general, if these two displacements are in two different directions then it will be the two vector sums of the two vectors. In this particular phase since the displacements are outer phase the resultant is 0 and we have what is known as a dark French.

So, here we have the actual interference pattern produced from two point sources vibrating in phase in a water tank. So, you have lines of nodes and anti nodes, and the nodes with displacement is always 0, the displacement produced by one source is outer phase or is pie outer phase, with the displacement produced by the second source therefore, the resultant is 0. So, the manifestation of the interference pattern is the consequence of the wave nature of the disturbance.

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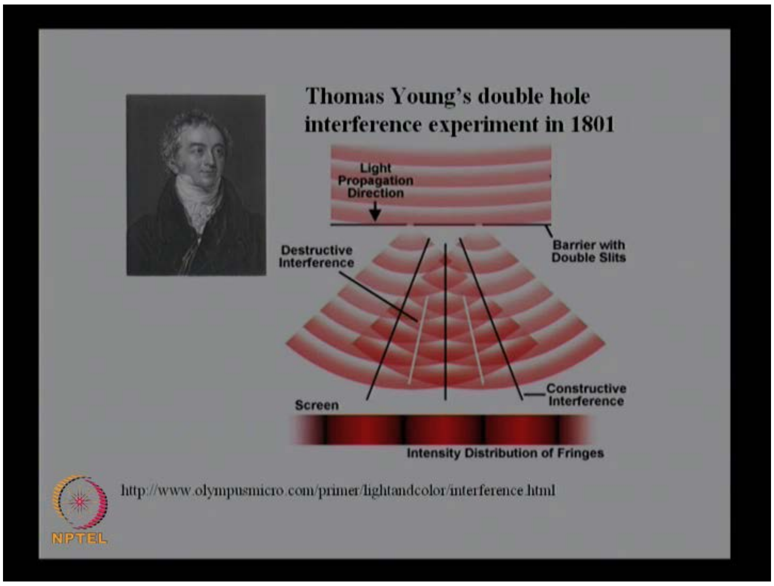

In 1801 Thomas young a brilliant British physicist carried out a very beautiful experiment which is known as young's double whole interference experiment, in which he allowed light to pass through two narrow wholes. So, this wave this act as source of secondary disturbance and almost spherical waves emanated from these 2 holes.

They produce an interference pattern these two points are in phase therefore, at some points the displacements added up to produce a maximum. And at some points on the screen the displacements added outer phase producing a dark French. Now this interference pattern of Thomas young clearly established that light does not does not propagate as tiny corpuscles because the corpuscles have to pass through either whole number one or whole number two and the interference pattern would never be observed. So, there are places that the intensities where the intensity is produced when one of the holes is kept closed and is is is is larger than the intensity produced when both the holes are open.

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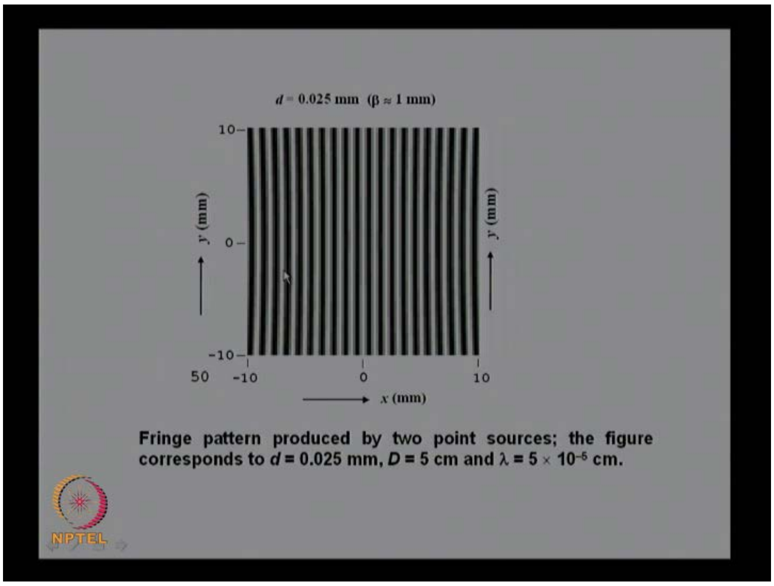

So, this led to what is known as the interference of light waves and the wave nature of light were almost firmly established. So, this is a typical computer generated interference pattern on the screen, you have dark and bright lines and this is a young's double hole interference pattern fringe pattern produced by 2 point sources. When the two point sources in this particular case is separated by point 0 .2 5 millimeter the distance between the source and the screen is 5 centimeter and the wave length of light is 5 into 10 to the power of minus 5 centimeter, and the corresponding fringe width as all of you would know would be approximately 1 millimeter.

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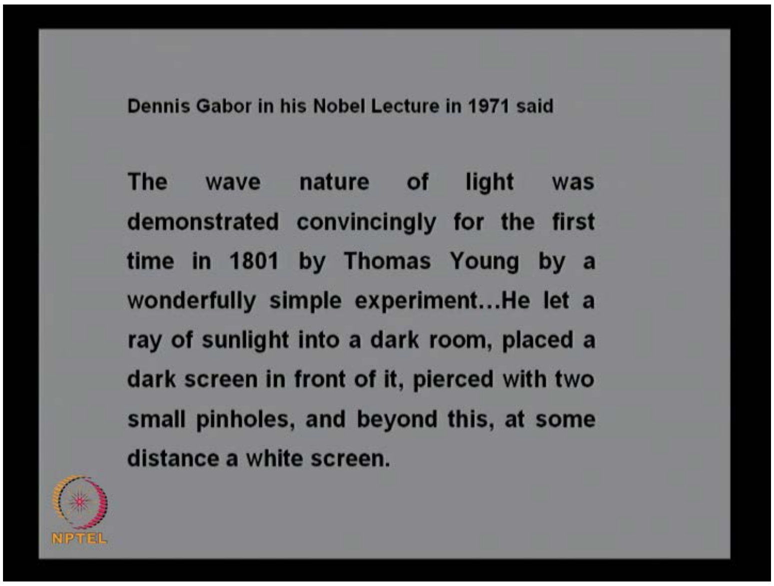

Dennis Gabor received the Nobel Prize in physics for holography in his Nobel lecture, which he delivered in December 1971 Dennis Gabor said the wave nature of light was demonstrated convincingly for the first time in 1801. By Thomas young by a wonderfully simple experiment, he let a ray of sunlight into a dark room placed a dark screen in front of it pierced with two small pinholes and beyond this at some distance a white screen.

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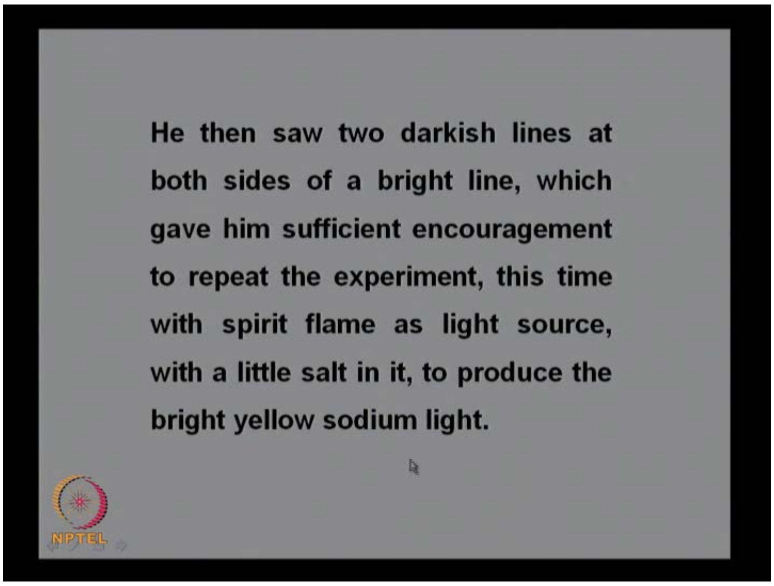

Please see that he carried out his first experiment with sunlight he then saw two darkish lines at both sides of a bright line, which give him gave him sufficient encouragement to repeat the experiment this time with spirit flame as light source with a little salt in it, to produce the bright yellow sodium light as you all know salt consists of sodium chloride and when you put this salt in the flame bright yellow light comes out, with a wave length around 6000 angstroms.

So, when he did this experiment using the sodium light this time he saw a number of dark lines regularly spaced the first clear proof, that light added to light can produce darkness and this is a characteristic of the wave nature of the light. Light added to light can produce darkness this phenomenon is called interference. Thomas young had expected it because he believed in the wave theory of light this is what Dennis Gabor wrote in his Nobel lecture in 1971.

So, this is the interference pattern of Thomas young once again he measured the wavelength and he found that the wavelength of sodium light was around half of a micron. micron is a millionth of a meter and because of the smallness of the wavelength of light, light was approximately these experiments were slightly difficult to perform and therefore, one has to use very sophisticated apparatus to get the interference pattern a visible interference pattern.

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Shortly after that Augustine Fresnel and Joseph Fraunhofer, they developed around 1810 or eighteen between 1810 and 1820 the diffraction theory. And Fresnel modified the Huygens's principle by saying that each point on a wave front is a second is a source of secondary disturbance which mutually interfere and because of that the phenomenon of diffraction occur.

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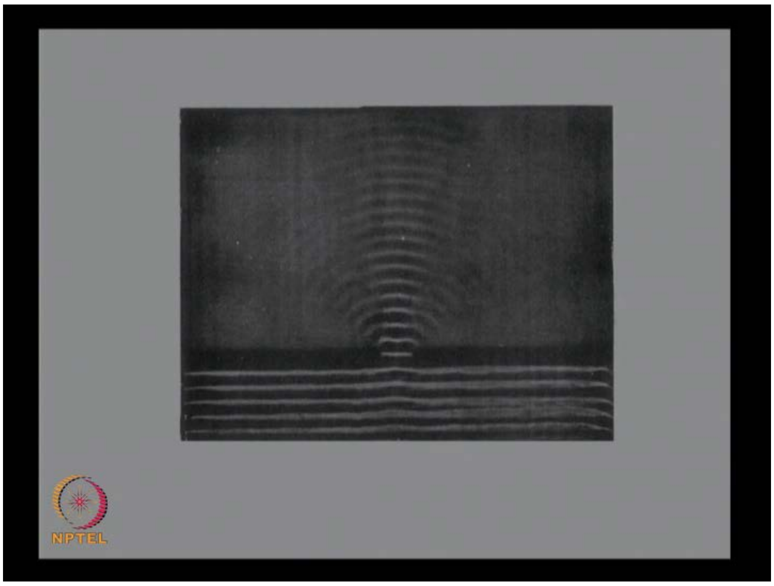

Here I have shown, I have tried to show the water waves spreading out from a narrow so this is the diffraction of the wave each can be assumed to be something like a point source and so the lights the water waves spread out in all possible directions.

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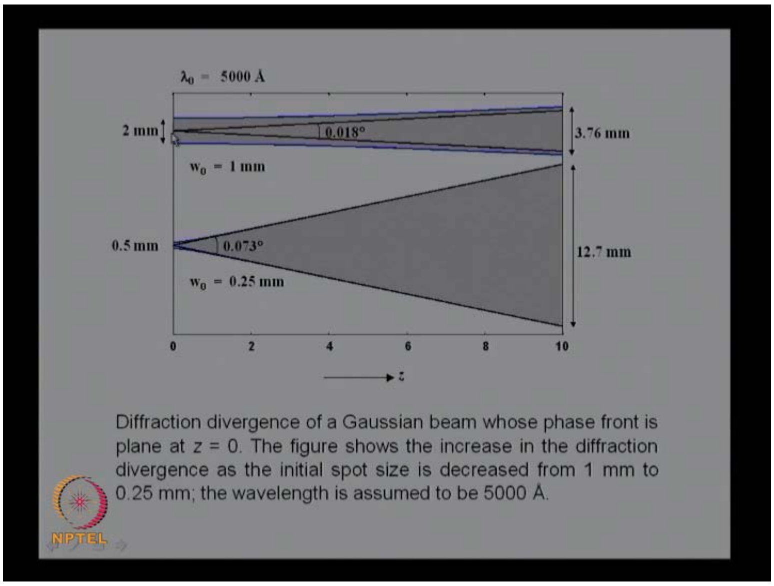

So, this is the diffraction of a Gaussian beam corresponding to these are computer simulated corresponding to a beam width of two millimeters and only half a millimeter. The spreading is very small with the beam width is about two millimeters the diffraction effects are small, and when they when the beam width becomes very small the diffraction effects become extremely pronounced and similarly, if you reduce the wavelength then the diffraction effects will become very small and therefore, if the limit of wavelength going to 0 we have the rectilinear propagation of light. So, light approximately propagates in straight lines and that is because the wavelength of the visible region of light waves is extremely small about half of a micron the red wavelength is about 0.7 microns the blue end of the wavelength has a wavelength of about 0.4 microns because that is extremely small length and therefore, diffraction and interference experiments are slightly difficult to carry out.

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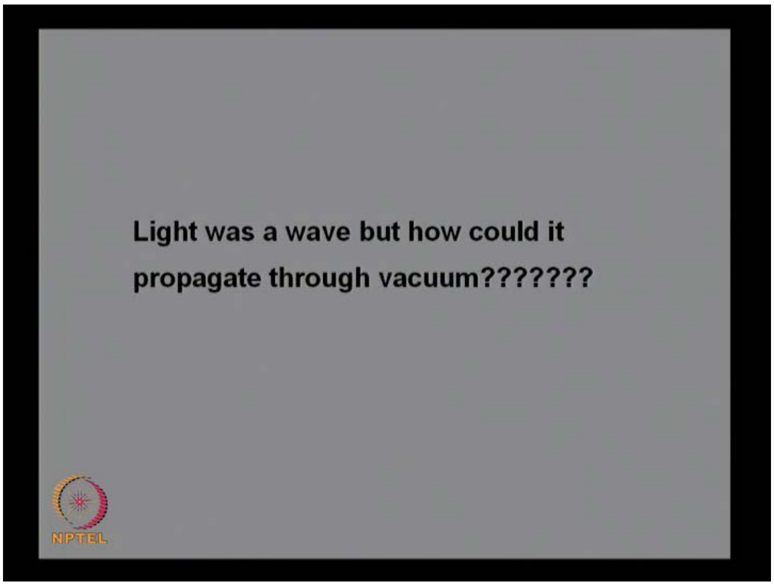

Then the main question that was that arose was that, if light was a wave how could it propagate through vacuum. Now, a wave as we know requires a medium the disturbance in the case of a water wave each molecule transfers the energy from one molecule to the other and that is how the disturbance propagates out. Now as we know that the sunlight the light that we receive from the sun in between earth and the sun there is empty space and how can light propagate through vacuum. You must be remembering the famous experiment in which you have if you put an electric bell inside an evacuated jar in which there are no air there is no air inside you will not be able to hear the sound of the bell, and that is because sound waves require a medium, sound waves cannot propagate through vacuum therefore, it was felt that any wave phenomenon would require a medium for its propagation and therefore, the main question arose that how light could propagate through vacuum.

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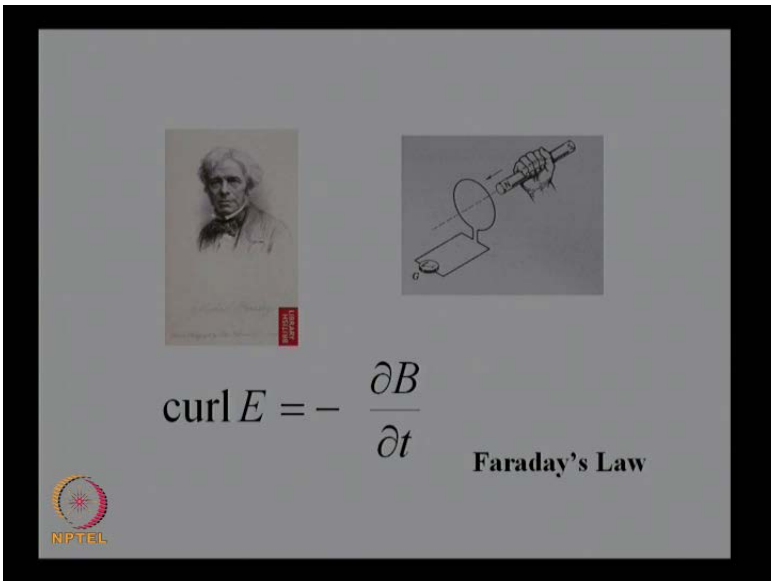

This led to the concept of the ether that it is an all pervading medium, which is present even in vacuum but as we all know now that the ether does not exist. So, will we will skip that discussion and we will straight away understand how try to understand how a light beam propagates through vacuum. During this period of time around 1810 and 1820 around that time the laws of electricity and magnetism were also getting developed. Michel faraday showed that a changing magnetic field produces a changing produces an electromotive force a changing electric field. So, in this experiment which I have tried to show that there is a magnet if you make it move up and down near a coil, then once the magnet starts moving up and down it generates an electromotive force and a current is produced in this.

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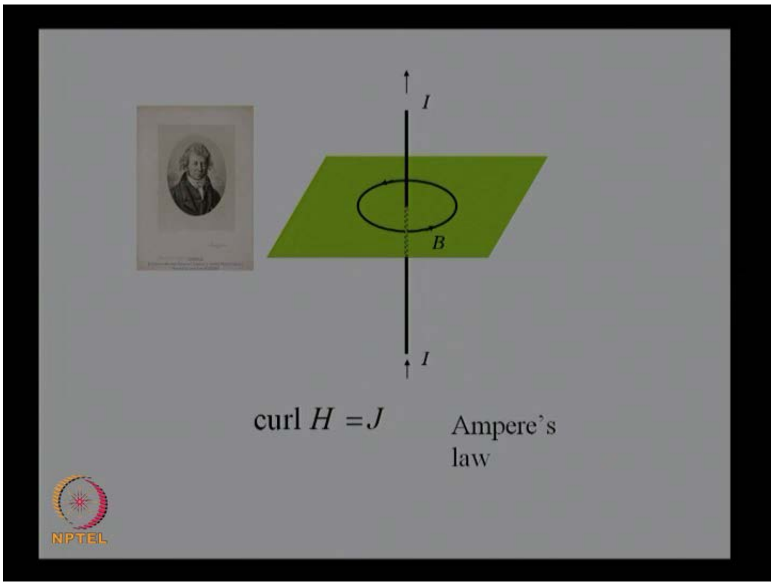

So, a changing magnetic field produces a changing electric field this law is known as faraday's law. And it was Maxwell who put it in the form of vector equation that curl of e is equal to minus delta b by delta t, e is the electric field and B is the magnetic induction. Around the same time ampere had discovered that, if there is a wire carrying current then it produces a magnetic field this is known as ampere's law and Maxwell again put this in a vector form in the form of a vector equation that curl of h is equal to J.

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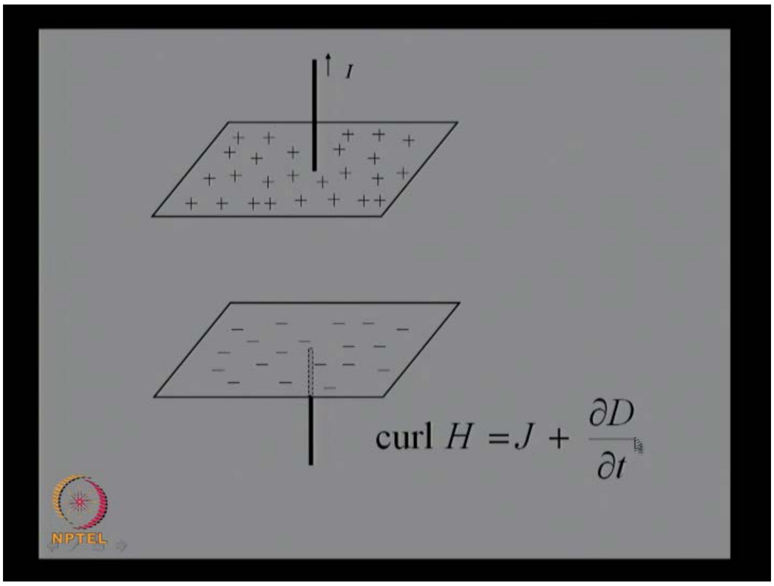

But, this had led to some inconsistencies he could not for example, derive what is known as the equation of continuity some of you would know that and because of that he had to introduce a term, which is known as the displacement current and he said that not only a current produces a magnetic field but a changing electric field will also produce a magnetic field. The introduction of this term revolutionized physics therefore, he modified ampere's law and added another term delta D by delta t, this term is Maxwell's contribution and this term is known as the displacement current.

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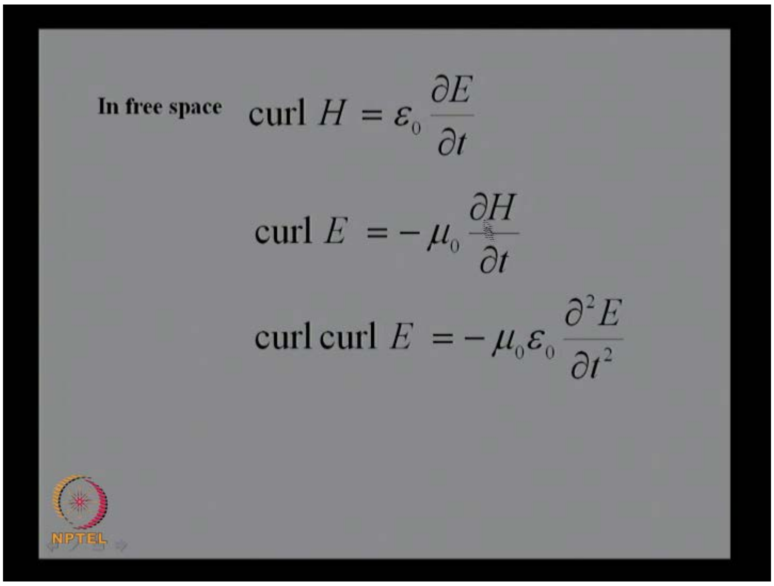

In free space the displacement vector D is equal to epsilon 0 times E where epsilon 0 is the directive permittivity of free space. And curl of E and I put the ordinary current J equal to 0, there are no currents curl of E is equal to minus delta B by delta t but B is equal to mu 0 times H. So, you get the faraday's law takes this form where e and h are the electric and magnetic fields, if you take the curl of this equation then you get curl E is equal to minus mu 0 delta by delta t curl h, and curl h is equal to so much so epsilon 0 delta by delta t of that that is delta 2 E by delta t square. So, because he introduced the concept of the displacement current he could arrive at an equation like this. Curl E is equal to grad did v minus Del square e divergence of E is equal to 0 in free space.

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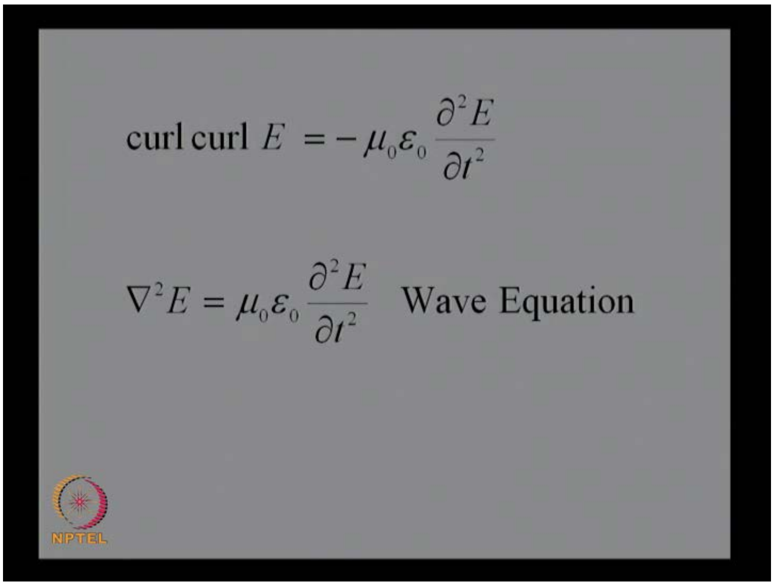

So therefore, this equation immediately led to Del square of E is equal to mu 0 epsilon 0 delta 2 E by delta t square this equation is known as the wave equation is known as the wave equation.

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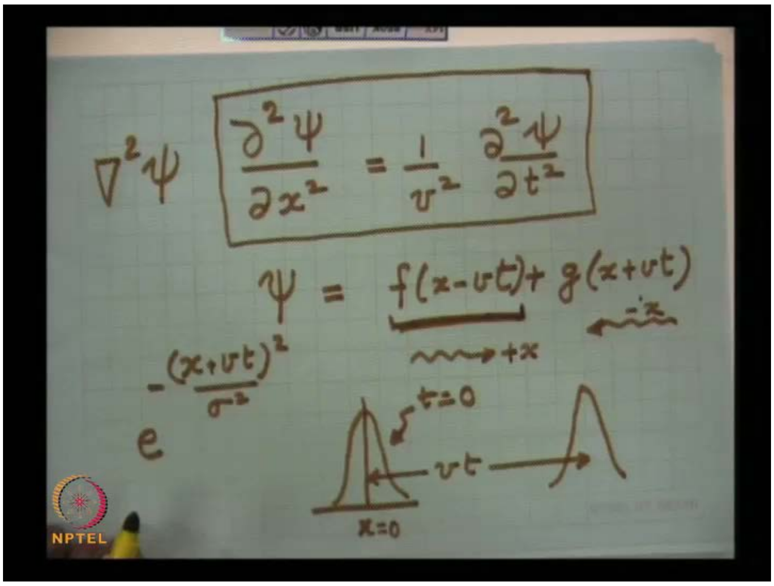

Now, if you ask a mathematician what is a wave then he is going to say a wave is a solution of this equation say one dimensional delta 2 psi by delta x square is equal to 1 over v square delta 2 psi by delta t square. This is a partial differential equation and the solution of this equation the most general equation is f of x minus v t and plus g of x plus v t where f and g are arbitrary functions of their arguments. In this term x and t do not appear independently only as x minus v t, and in this term and one can show by direct substitution that f of x minus v t satisfies this equation, g of x plus v t satisfies this equation. This first term represent a wave propagating in the plus x direction this represents a wave propagating in the minus x direction let us for example, take an arbitrary function like e to the power of minus x minus v t, whole square by sigma square. If I take this function then t equal to 0 the displacement is centered around x is equal to 0, this is t equal to 0, at a later time the origin gets shifted by v t so at a later time the pulse propagates a distance v t in time t.

So, this is known as the wave similarly, if I take x plus v t by whole square by sigma square then that will be displacement propagating in the minus x direction. So, this equation is known as the wave equation actually one dimensional wave equation in the three dimensional wave equation the delta- delta 2 psi by delta x square is represented is replaced by del square psi. Because the most general solution of this equation is given by f of x minus v t and g of x plus v t.

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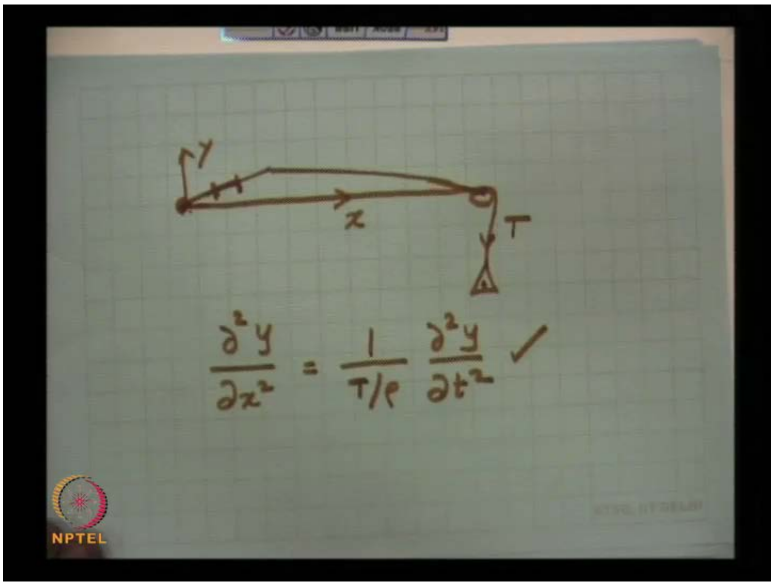

This term represents a disturbance propagating in the plus x direction with velocity v and this term represents a disturbance propagating in the minus x direction with velocity v. Now if you take for example, a sonometer wire and as you must have done this experiment this sonometer wires and the tension. So, there is a mass here and this is at a tension this is fixed at this point.

If you pluck the wave and if you displace it like this and then apply Newton's laws of motion. Then this, let us suppose is x axis and this is y axis, then over for you apply Newton's laws of motion to a small region of this string then one can derive an equation of this type delta 2 y by delta x square is equal to 1 over t by delta 2 y by delta t square, for small displacements. Where t is the tension and rho is the mass per unit length. Once I derive this equation once I am able to derive this equation I can predict the existence of transverse waves on the string and, if I compare with the wave equation I can associate this with the velocity v square therefore, this will imply that the velocity of the transverse waves on a string is equal to under root of t by rho.

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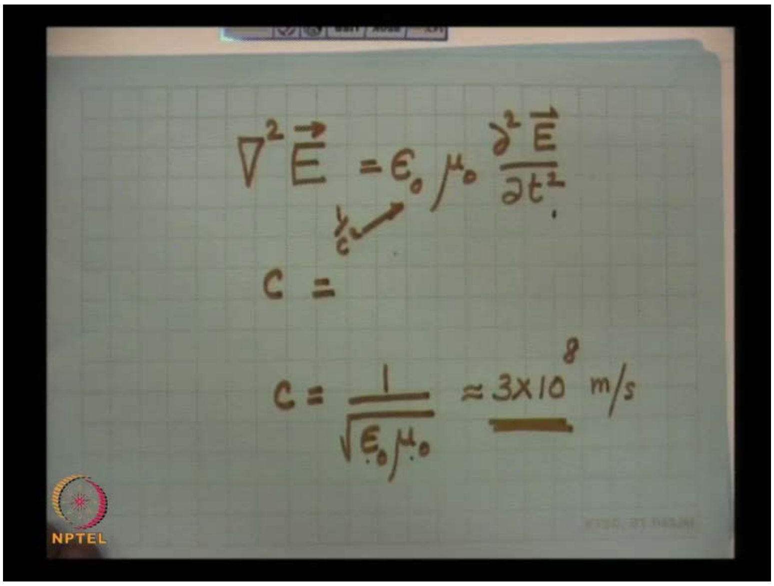

So, when Maxwell derived an equation of the type Del square e which is the three dimensional equation Del square E is equal to epsilon 0 mu 0 delta 2 E by delta t square in free place. So, he derived the wave equation from laws of electricity and magnetism and therefore, he predicted the existence of electromagnetic waves this was a very important contribution electromagnetic waves were. This was around 1860 or 1863 the electromagnetic waves were first produced by Heimlich hertz in 1887 by an r c circle. So, he derived the wave equation and he predicted the existence of electromagnetic waves and then he said that the velocity of electromagnetic waves will be equal to not this quantity will be one over c square therefore, the velocity of electromagnetic waves in free space will be one over epsilon naught mu naught predicted that.

As I will show you when you substitute the values of epsilon 0 and mu 0, you get a value of about 3 into 10 to the power of 8 meters per second. At that time the French physicists faze had measured the velocity of light in air and that number that faze had got was very close to this value. Just the sole fact that these two numbers cannot be accidentally equal, led Maxwell to propound that light is an electromagnetic wave.

This is one of the greatest syntheses in the development of science, on one side your laws of electricity and magnetism and other side you have light waves. So, both used to be studied independently, what Maxwell found that he could predict the existence of electromagnetic waves and when he wrote down that when he calculated the velocity of these waves, he found that the velocity of these waves was about 3 into 10 8 10 to the power of 8 meters per second which was very close to the value of the velocity of light waves and therefore, he said light must be an electromagnetic wave.

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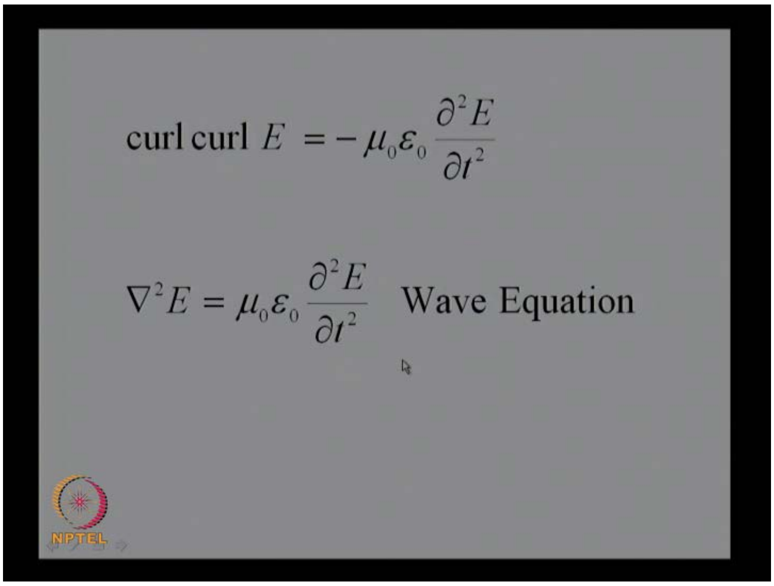

So let me go back to my slides. So, Maxwell derived this equation.

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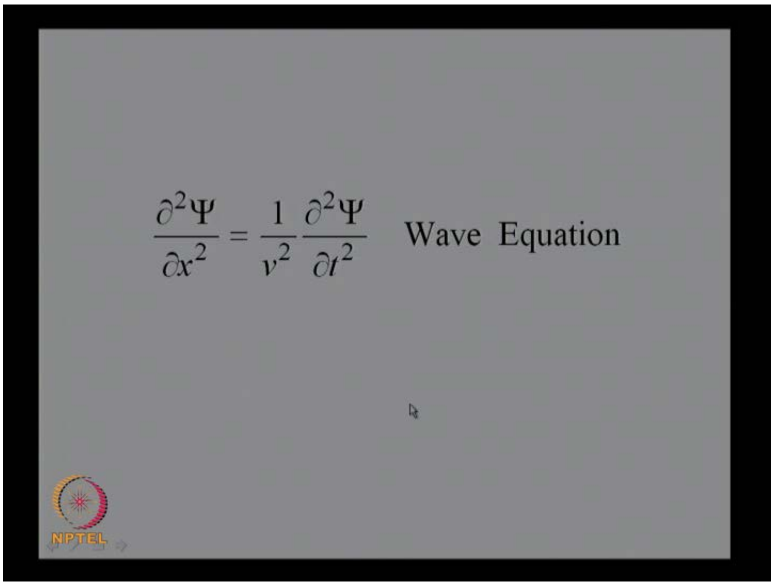

And therefore, as I said this equation if you ask a mathematician what is what is a wave? He will say a one dimensional wave is a solution of this equation.

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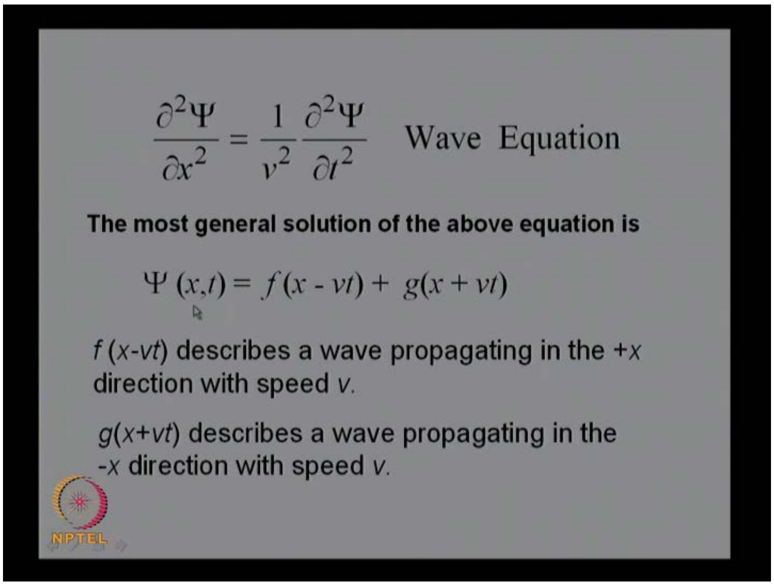

Because the most general solution is f of x minus v t, and g of x plus v t f of x minus v t describes a wave propagating in the plus x direction with speed v, and g of x plus v t describes a wave propagating in the minus x direction with speed v.

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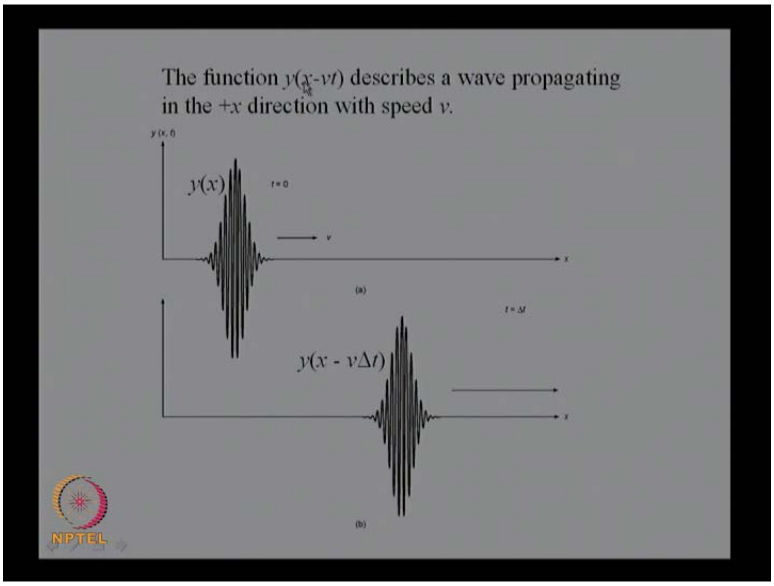

This is a typical wave a function y of x minus v t, so if you put t equal to 0 y of x and at a later time as at a later time as I had mentioned just now the whole pulse shifted by a distance v delta t.

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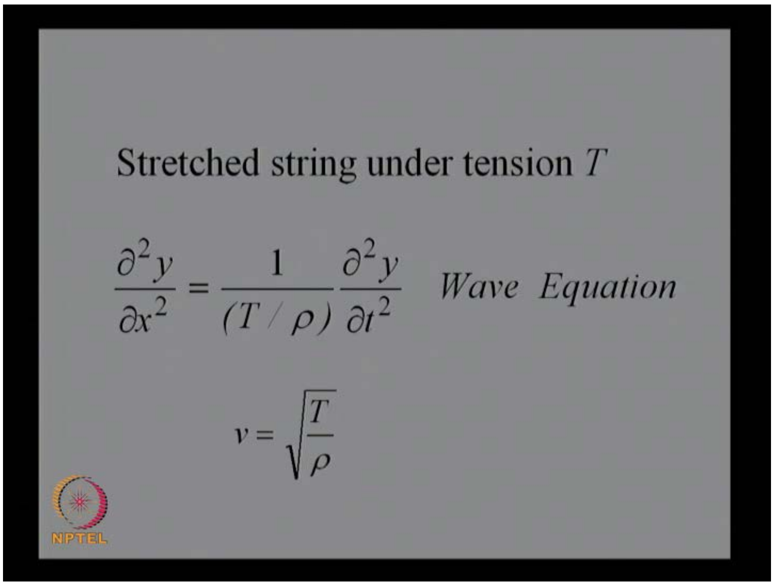

And therefore, v represents the velocity of the waves. So, as I mentioned that if you had a stretched string under tension T then using Newton's laws of motion you can derive this equation and therefore, you can predict the existence of a transverse waves on a string and the velocity of these waves will be given by under root of T by. Here T is the tension in the string and rho is the mass per unit length.

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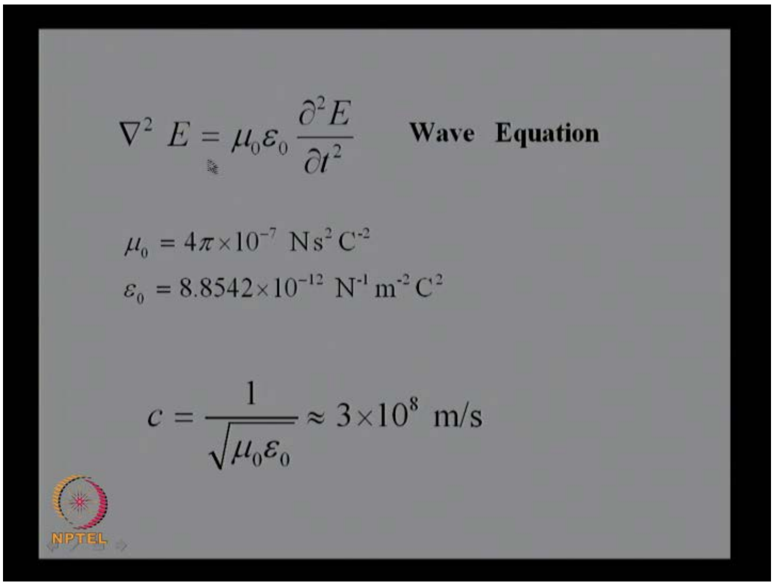

So, when Maxwell derived this equation after that with the known values of mu 0 this I am using m k s system of units during that time people did not use the m k s system of units. The value of mu 0 is 4 pi into 10 to the power of minus 7 in m k s system of units and the value of epsilon 0 is 8 point 8 5 4 2 into 10 to the power of minus 12.

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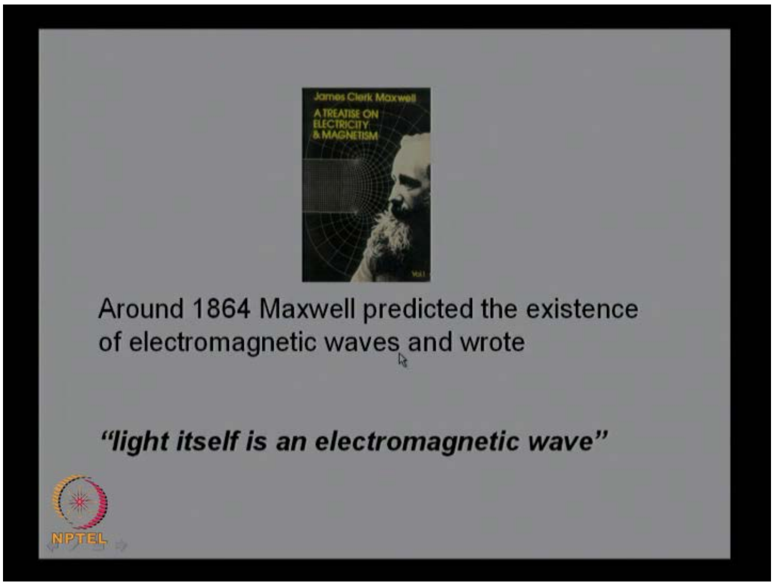

When you substitute these values in this equation, you get a value equal to three into 8 10 to the power of 8 meters per second. So, around 1864 Maxwell predicted the existence of electromagnetic waves which were later detected by Heimlich hertz in 1887 and he wrote that light itself is electromagnetic waves that these two numbers cannot be accidentally equal and therefore, light itself is an electromagnetic wave.

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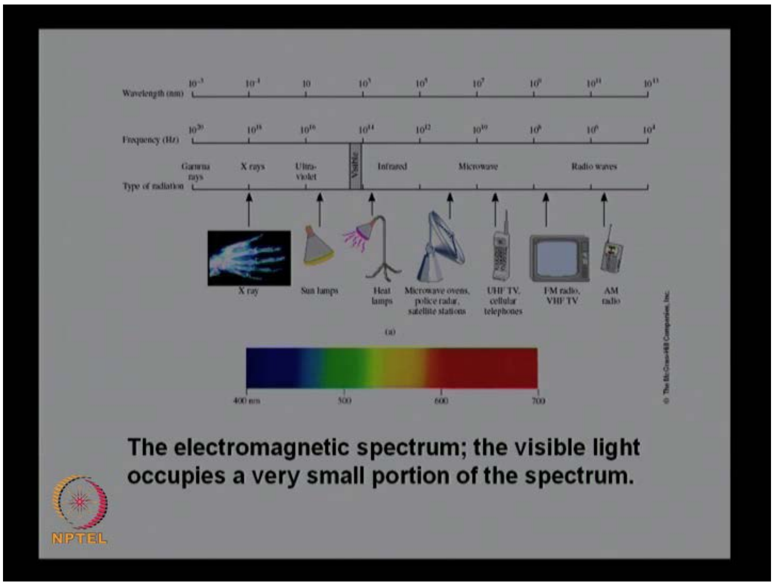

So, now we know that from gamma rays, to x rays, to ultra violet, to visible to infra red to micro wave to radio waves they are all part of the electromagnetic spectrum they all travel with an identical velocity in vacuum that is a constant that is 3 into 10 to the power of 8 meters per second. The only difference is the gamma rays have a very high frequencies x rays have a slightly lower frequency. The visible region of the spectrum that to we which our retina is sensitive occupies a very small portion of the electromagnetic spectrum, this is the blue end of the spectrum and this part is shown here in detail. And the t v waves correspond to this the am radio corresponds to this wave length which has a very high wave length and very small frequency.

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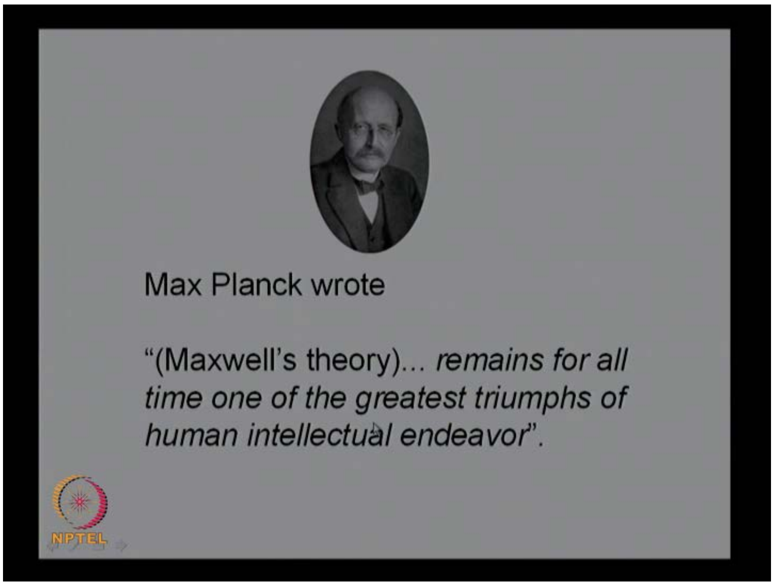

So, this is the entire electromagnetic spectrum the visible light occupies a very small portion of the spectrum. Max Planck who is one of the great physicist, of the early 20th century he wrote that Maxwell's theory remains for all time one of the greatest triumphs of human intellectual endeavor. So, by the turn of the 19th century people finally, thought that they understood what light really was and therefore, the question what is light seemed to be finally, answered that light is an electromagnetic wave. You can measure the wave length by carrying out interference experiment or a diffraction experiment and these experiments are slightly difficult to perform because light approximately travels in straight lines because the wave length of light is small. The interaction of the electromagnetic wave with medium was studied and from Maxwell's equations one could derive Snell's laws and everything, it is interaction with solid interaction of light wave with solid, calculation of the refractive index from first principles anything seemed to be pretty done and people felt that they finally, had the answer to the they finally, understood what light really was.

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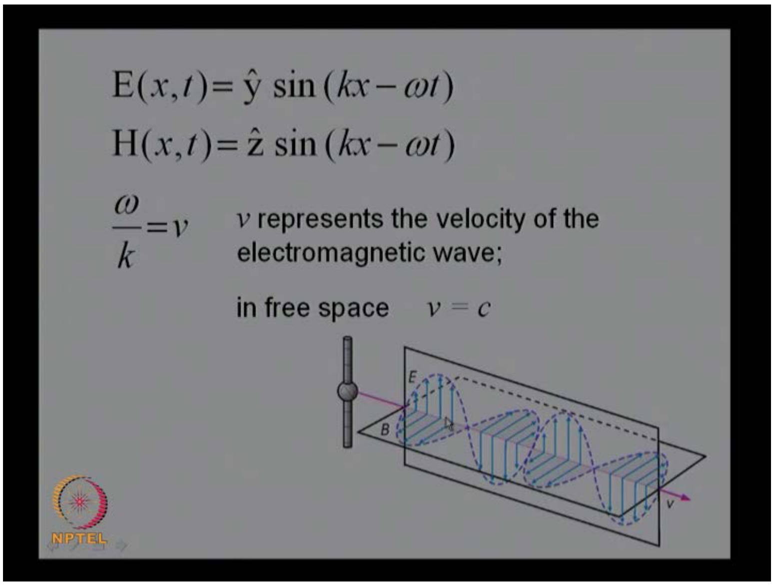

This was around the end of 19th century, and so this is how a light wave propagates through a vacuum associated with a light wave there is a changing this is propagating in the x direction, there is a changing electric field, and a changing magnetic field, and how can it propagate through vacuum it is the propagation of fields. A changing electric field produces a changing magnetic field, produces a changing electric field because the law because of Maxwell’s equations and therefore, that is how it is the propagation of fields therefore, and one can one understood how light can propagate through vacuum.

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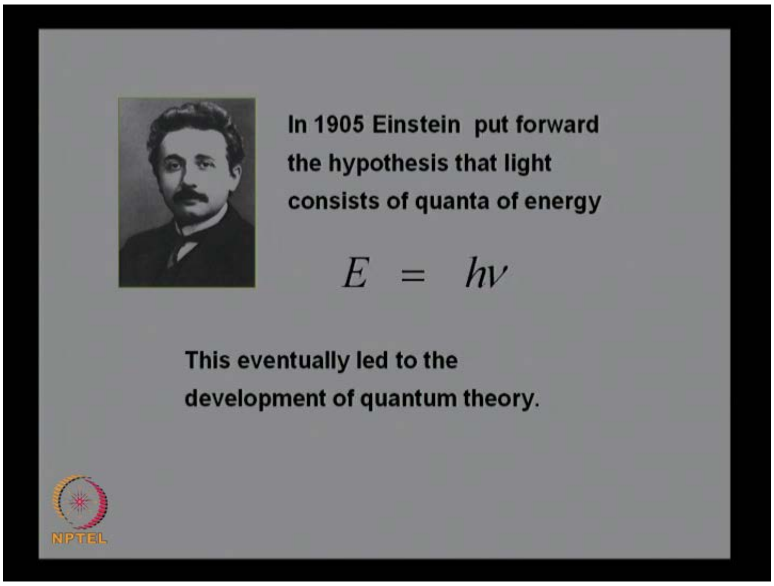

Then in 1905 Einstein put forward the hypothesis that light consists of quanta of energy packets of energy. These packets of energy came later came to be known as photons. The word photon was introduced in 1926 by an American chemist by the name of Gilbert Lewis. So, what Einstein said was that that he did could he developed theory and said that according to his theoretical model light consists of a quanta of energy, e is equal to h nu when nu is the frequency and h is the Planck's constant.

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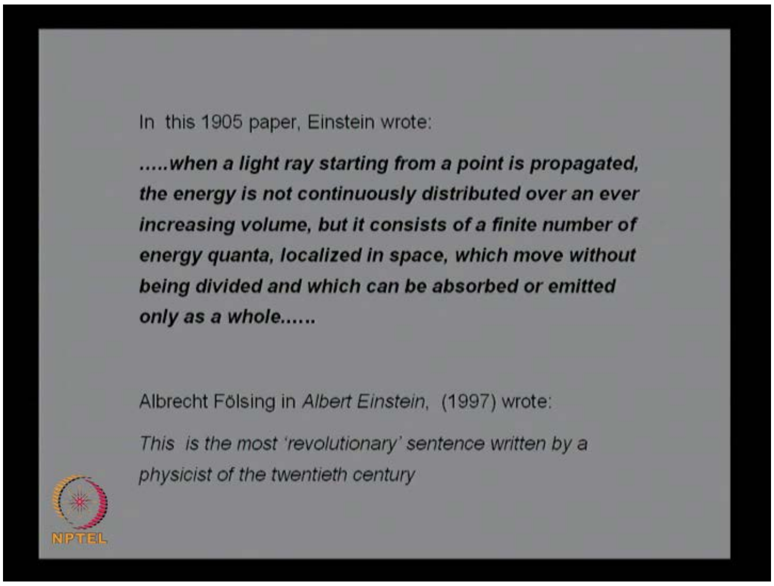

And this eventually led to the development of quantum theory as we will try to see. In this 1905 paper Einstein wrote and this is what he wrote this is actually the German translation of his original 1905 paper and he wrote, let us read this carefully when a light ray starting from a point is propagated, the energy is not continuously distributed over an ever increasing volume. But it consists 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. This is what he wrote in his 1905 paper and one of the biographers Albrecht flossing he has written a very nice book on Albert Einstein, and he wrote and he has written now this is the most revolutionary sentence written by a physicist of the 20th century.

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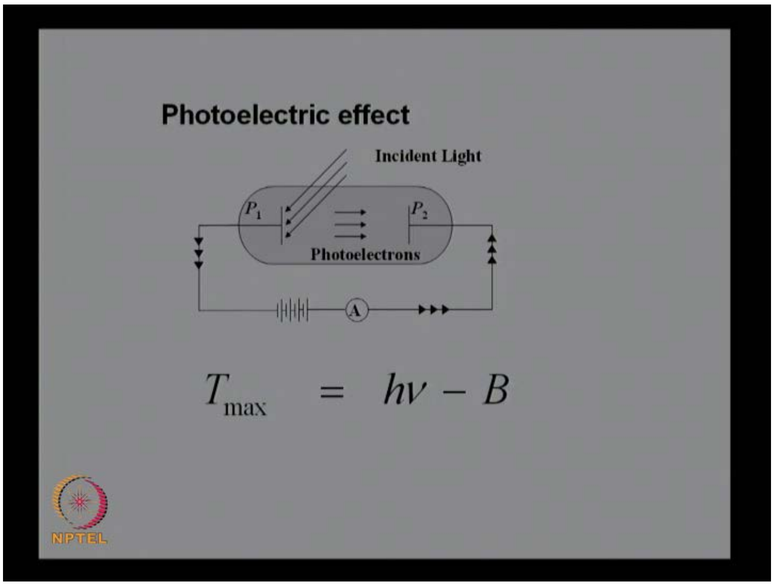

And using this model of light Einstein explained the phenomenon of photoelectric effect which was carefully carried out by a physicist by the name of Philipp Lenard. And he said Einstein said that what is photoelectric effect, you have let us suppose sodium or cesium plate and you shine light on it. In the maximum kinetic energy of the emitted photoelectron will be h nu when nu is the frequency of the incident light wave minus a constant which depends on the metal, this value of this constant b will be different for different metals. So, this equation tells us initially people thought that photoelectric effect can be understood on the basis of wave theory, because light carries energy and it transfers a part of the energy to the electron the electron gets ejected out of the metal.

But the peculiar fact peculiar experimental observation made was that no matter how intense the light beam is unless its frequency is greater than a critical frequency no photo electrons will be emitted. I repeat no matter how intense the incident light beam be unless the frequency of the light wave is greater than a critical frequency no photo electrons will be emitted.

And the maximum kinetic energy of the emitted electrons will depend not on the intensity but on the frequency of the incident radiation this equation is known as the Einstein's photoelectric equation. And as I will mention to you later in a few slides that Einstein did not get the noble prize for his theory of relativity did not get the noble prize for the concept of the quantum for the concept of the photon he got the noble prize for this photoelectric equation, it is for this equation that he got the 1921 noble prize in physics. So, this equation these equation very careful experiments were carried out by Millikan in the United States and he verified this equation with a tremendous degree of accuracy and because Einstein had had put forward this law it came to be known as Einstein's equation and he was given the noble prize for this.

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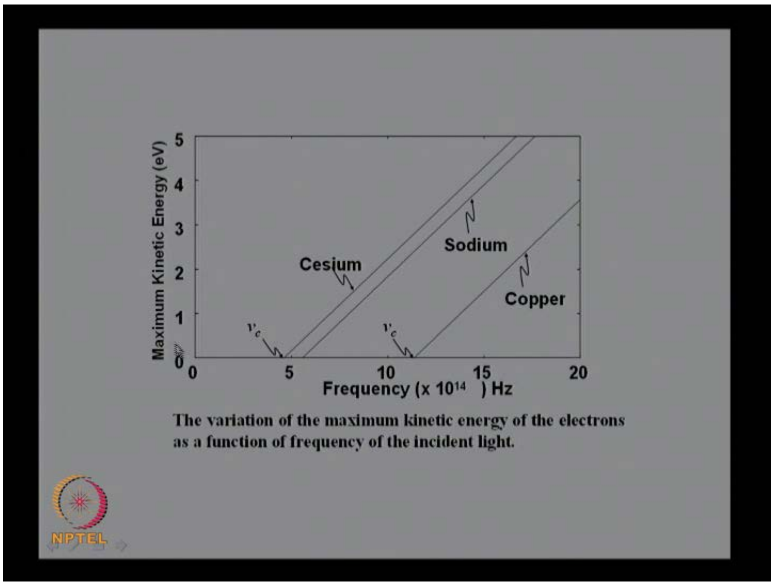

So, these are the curves these are the straight lines actually for cesium sodium and copper on the vertical access is the maximum kinetic energy in electron volts and then the horizontal access is the frequency of the incident light wave. So, as you can see for each curve there is a critical frequency therefore, for cesium that is about this value is 4.9 into 10 to the power of 14 hertz. So, unless the frequency is greater than that no filter electrons will be emitted. And the maximum kinetic energy of the photo electron is not dependent on the intensity but is dependent only on the frequency of the incident light wave these experiments were first done by Lenard Philipp Lenard.

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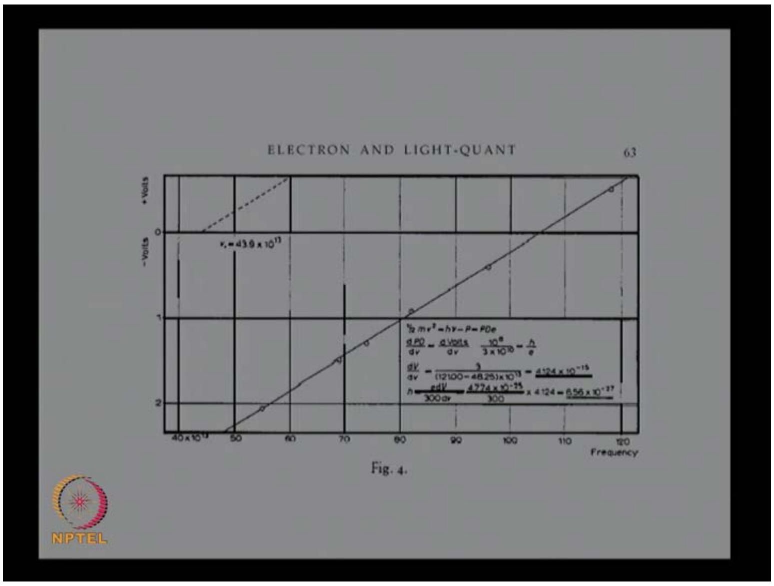

And then very carefully done by Robert Millikan, and these are from the noble lecture this particular figure is from the noble lecture of Robert Millikan.

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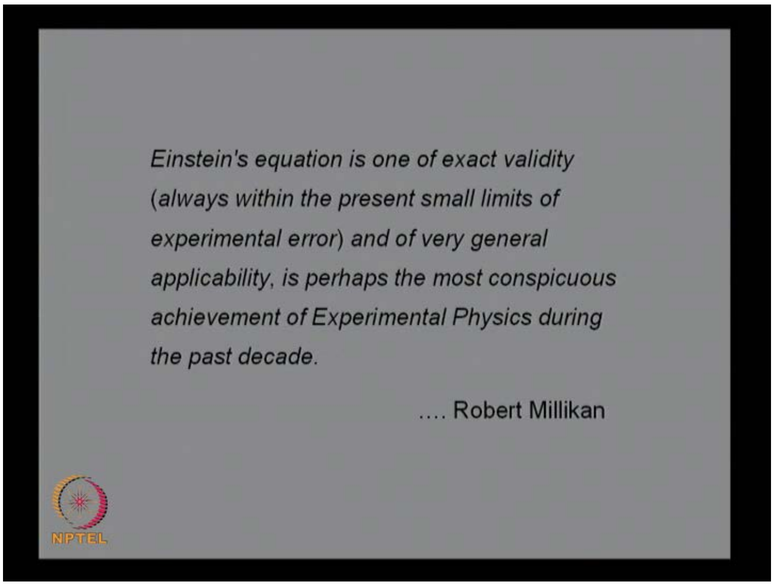

And Robert Millikan wrote that Einstein’s equation is one of exact validity. Always within the present small limits of experimental error and of very general applicability is perhaps the most conspicuous achievement of experimental physics during the past decade in fact Robert Millikan got the noble prize for his for this for these experiments.

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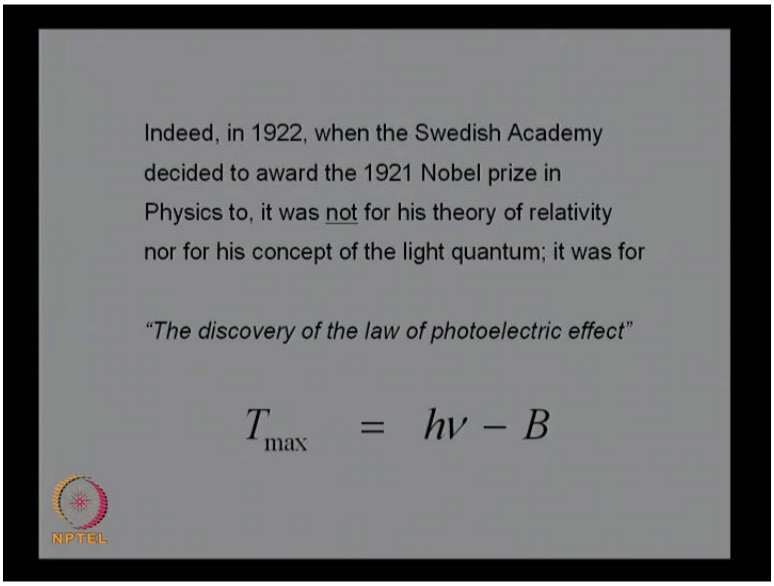

Indeed as I mentioned earlier in 1922 when the Swedish academy decided to award the 1921 noble prize in physics to Albert Einstein. I'm this to Albert Einstein it was not for his theory of relativity nor for his concept of the light quantum it was for the discovery of the law of photoelectric effect.

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So, this is a photograph of Einstein with Millikan this is a photograph of Millikan and this is Michelson. So Einstein was the first person who introduced the wave particle duality. The wave model of light was very well established and the wave model of light was very well established and at that point of time Einstein put forward the photon concept and this changed everything. Initially no one really believed Einstein's photon concept and even max Planck did not believe that it was put on a form foundation, only after Compton had carried out very careful scattering experiments in which he showed that the energy of the photon is not only h nu but its momentum is h nu by c Arthur Compton this is known as I mean, these experiments these scattering experiments are known as the is known as the Compton effect for which Compton later got the noble prize. That was around nineteen twenty three twenty four that Compton carried out this experiments and it was after these experiments were performed people finally, realized thought but by then Einstein had already received the noble prize but people did not believe the concept of the photon.

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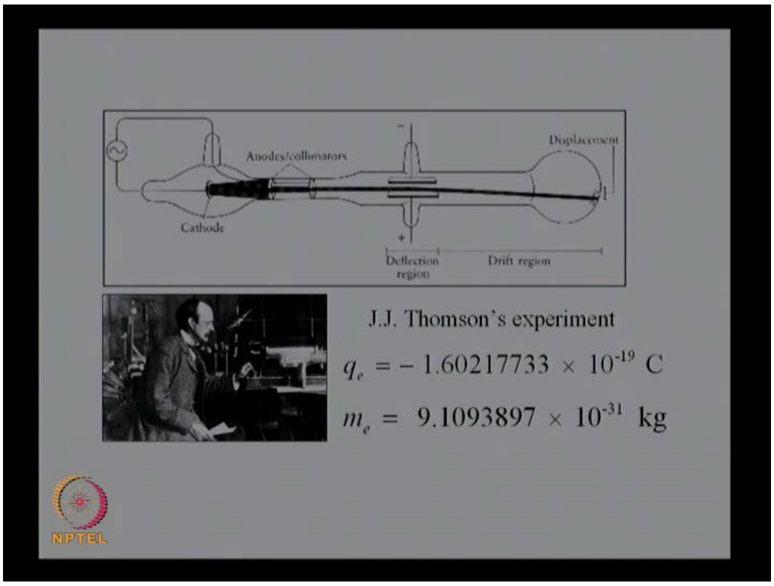

So, I end this lecture by saying that around 1897 J J Thomson the famous British physicist discovered the electron. He measured the charge of electron and the charge mass of the electron, now we know the charge and the mass to ten decimal places. So, the charge is minus 1 point 6 0 2 1 7 7 3 3 into 10 to the power minus 19 coulomb the mass is also very accurately known it can be deflected by an electric field and a magnetic field and on the screen you can see a spot so on. The on the back of your mind you know the charge of the electron you know the mass of the electron and therefore, you feel that it is a particle.

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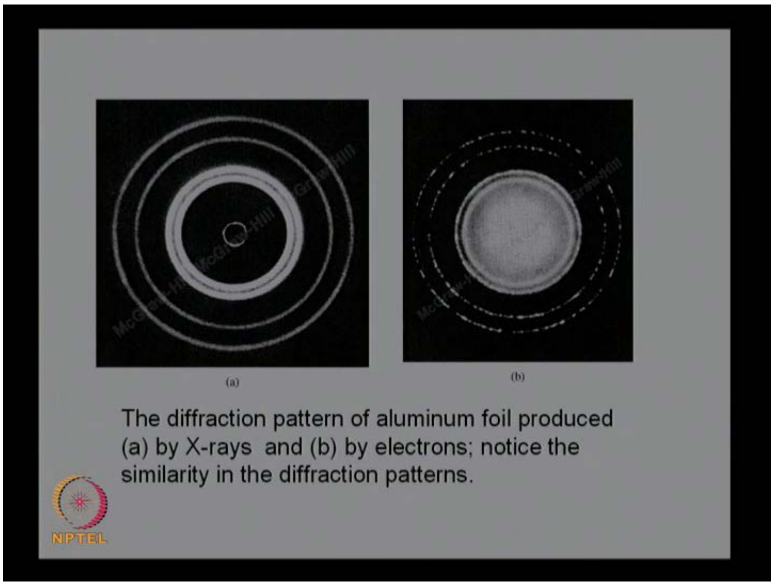

But then these are of course, later experiments, on the left is the diffraction pattern of aluminum foil produced by x rays which are electromagnetic waves, and on the right picture right picture is the diffraction pattern by an aluminum foil by electrons therefore, this experiment shows that light electron also behaves like a wave but these experiments were performed must later around 1927 or so on.

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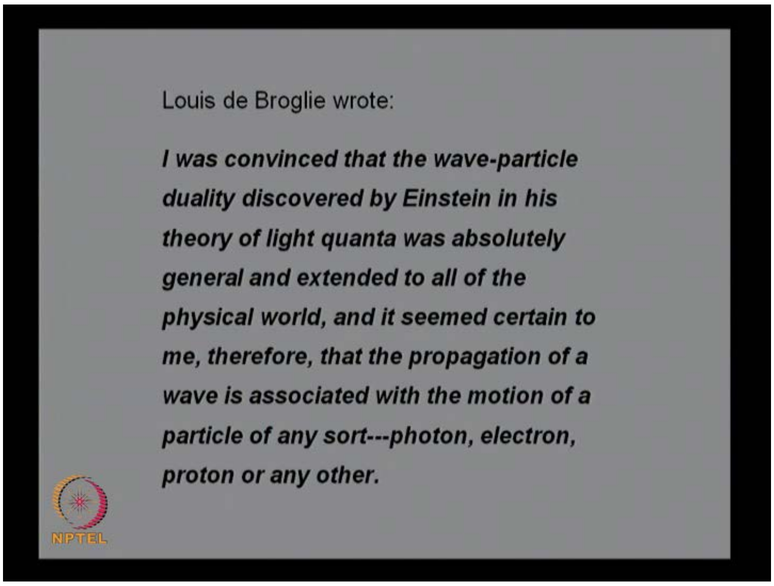

So, de Broglie wrote that I was convinced that the wave particle duality discovered by Einstein in his theory of light quanta was absolutely general and extended to all of the physical world and it seemed certain to me therefore, that the propagation of a wave is associated with the motion of a particle of any sort photon electron proton or any other. So, two points wave particle duality was first put forward by Einstein and then de Broglie said that it is not only applicable to photons and this was around 1922-23 in his p h d thesis for which he was given the noble prize. That is applicable to electrons and protons and it is this wave particle duality that led to the development of quantum theory so in the next lecture we will discuss the development of the quantum theory.

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