

[Music] [Applause] welcome to the lecture module on optics

So far we have described propagation of light in terms of propagating rays or we described light in terms of ray optics propagation of light and the various effects that we have studied

So far in the earlier lectures in terms of ray optics but there are several effects such as interference for example which is responsible for color of soap films the colors that we see different colors in white light that we see of soap films or what is known as diffraction or polarization these are some of the effects which cannot be described by ray optics and then we have to move on to wave optics as I have discussed in the beginning of this course module that whenever there are certain areas which can be discussed by one approach whereas certain aspects can be discussed by another approach and

So now we move on to wave optics

So in wave optics we will

So here it is wave optics and let me first discuss the various topics that I am going to discuss in this course

So here

So the various topics which we will see is first we will begin with Huygens principle reflection and refraction of plane waves using Huygens principle Huygens's principle is the first time when light propagation was described in terms of waves then we move on to interference first we will discuss a little bit about superposition of light waves and then describe the Young's interference experiment in detail the Young's two slit experiment or Young's double slit experiment is this will be described in detail then we will move on to diffraction where we will describe single slit diffraction diffraction by a circular aperture and we will also discuss the resolving power of optical instruments and then finally we will come to the concept of polarization of light and we will discuss polarization by reflection there are different ways of obtaining polarized light but in this course we will discuss polarization by reflection and the Brewster angle

So before we proceed we will first discuss some historical milestones which led to the development of wave optics

So here are some of them which I have listed here in 1621 Snell gave the Snell's law Snell's law of refraction where we knew that it is an empirical relation based on experimental observations Snell came out with the relation that $\sin i$ by $\sin r$ is equal to n_2 by n_1 this we have discussed in detail in the earlier lectures and then in 1637 in 1637 the explanation of Snell's law was provided because Snell's law was an empirical relation based on experimental observation there was no theoretical support for that however in 1637 an explanation of Snell's law was given by Descartes based on a corpuscular corpuscular model of light which was later established by Newton and now it is known as Newton's corpuscular theory in 1678 Huygens put forward for the first time the wave theory of light wave theory of light where the propagation of light is described in terms of propagating waves however as we will see that Huygens could not answer certain questions such as what kind of waves are these and therefore the corpuscular theory prevailed even though Huygens put forward his wave theory in 1678 for about a century thereafter the corpuscular theory prevailed only in 1801 when Young presented his interference experiment the two slit interference experiment which gave a convincing experimental evidence that light is a wave of course subsequently in 1864 Maxwell put forward the theory of electromagnetic waves and then it was known that light is an electromagnetic wave which was subsequently experimentally verified later

So these are some of the milestones to see and although the Huygens wave theory is no more used in optics but the development of wave theory this was the foundation for the development of wave theory that is why it is a historical milestone as an extraordinary milestone we will first discuss the Huygens principle and Huygens theory of light propagation

So first recall that we will discuss a little bit about what we know about waves and wave propagation

So here what I have shown is recall that a plane wave can be expressed as ψ of x t the disturbance a wave is a propagating disturbance

So the ψ of x t can be represented as $a \cos(kx - \omega t)$ this $kx - \omega t$ is called the phase term

So this is the phase and this is the amplitude a is the amplitude and $kx - \omega t$

is the phase term where k is equal to $2\pi/\lambda$ λ is the wavelength of the wave and ω is the angular frequency which is equal to $2\pi\nu$ ω here is the angular frequency equal to 2π times ν where ν is the frequency at any instant t is equal to t_1 the surface of constant phase it is a plane wave why this is called as plane wave because the surface of constant phase which is called the wave front a plane wave is a propagating wave with plane wave fronts plane wave fronts wave front is a surface of constant phase therefore at any instant t is equal to t_1 the surface of constant phase is obtained by putting this phase term is equal to constant

So $kx - \omega(t - t_1)$ is equal to constant at an instant when t is equal to t_1 therefore this part is constant

So this implies kx is equal to constant or x is equal to constant because for the given wave k is equal to $2\pi/\lambda$ is a constant and therefore x equal to constant represents surfaces of constant phase x equal to constant if we plot here that x is equal to constant are planes which are perpendicular to the x axis and that is why it is a plane wave

So at a t is equal to t_1 we have a plane which is here which is shown here is the surface of constant phase or the wave front the wave front is a plane now at a later time So these are planes perpendicular to the x axis what is shown here at a later time t as t increases let us say at t is equal to $t_1 + \Delta t$ x has to increase as t increases x has to increase if this term has to remain constant

So if we are tracking this wave front then the wave front is defined by this equal to a constant some constant value and therefore if t increases x has to increase which means as t increases x increases for a given wave front in other words the wave will move in the positive x direction

So this where k is called the propagation constant or the phase constant because the phase constant multiplied by the distance travelled here would give the propagation phase it is also at any given instant

So that is a plane wave plane wave propagating in the x direction what about waves propagating in an arbitrary direction k

So let us see waves propagating in an arbitrary direction k

So here and I have put waves propagating in an arbitrary direction k that is k is here So x, y, z axis is shown such plane waves can be represented by ψ is equal to $a \cos(k \cdot r - \omega t)$ now k is propagating in an arbitrary direction which means it will have three components k is a vector with the three components k_x, k_y, k_z and r So r is the position vector which is also given by $i x + j y + k z$ and $k \cdot r$ therefore is equal to $k_x x + k_y y + k_z z$

So $k \cdot r$ is equal to $k_x x + k_y y + k_z z$ if this is a plane wave this must be constant at a given time that will give us the wave front which is a plane

So therefore that implies $k \cdot r$ must be equal to a constant

So what is $k \cdot r$ $k \cdot r$ is $k_x x + k_y y + k_z z$ which is equal to constant and we know that this is the equation of a plane we know that the equation of a plane is $a x + b y + c z$ is equal to constant represents a plane and therefore this represents a plane k here $k \cdot r$ is equal to constant k here is perpendicular to the planes $k \cdot r$ is equal to constant implies k is perpendicular to the planes its direction represents the direction of propagation of the wave and the magnitude of this k vector is the same what we have discussed earlier as $2\pi/\lambda$ the magnitude of the propagation vector is $2\pi/\lambda$ is the propagation constant

So the point to note is the propagation vector k is perpendicular to the wave front which is true even in the earlier case we did not show it as a vector because k was along the x direction and the wave was propagating along the x direction but k in this case is also a vector but having only one component and k is perpendicular to the wave frame So this is the representation of a plane wave propagating in an arbitrary direction now let us look at spherical waves

So we have seen plane waves propagating along a particular direction and plane waves propagating in an arbitrary direction and now spherical waves

So what is a spherical wave a spherical wave can be represented in this fashion as before if we extend the definition of the wave spherical wave must mean a wave with a wave front which is a sphere

So the wave fronts must be surface of sphere and let us see a representation like this whether it represents surfaces of sphere is surfaces of spheres or not

So ψ of r is equal to $a \frac{e^{i(kr - \omega t)}}{r}$ surface of constant phase at any

given instant t is equal to t_1 is $k r$ is equal to constant as before earlier we had $k \cdot r$ and before that we had $k x$ now we have $k r$ equal to constant because this part is constant here at a given instant and this implies that r is a constant r is equal to constant represents surface of a sphere of radius r

So schematically shown here that this these are of course this is a cross section in 2d but these are r is equal to constant represents a surface of a sphere and therefore spherical waves are represented by the phase term which is $k r$ minus ωt what about the r which is here

So we will see in a minute as t increases therefore in this expression we see as t increases r has to increase

So that the phase remains constant because we are tracking a particular wave front a particular wave front is defined by the phase phase here equal to a constant and therefore as t increases r increases

So that this remains constant for a given wave and therefore the waves as t increases are increases which means the wave is expanding the spheres are expanding outwardly with the propagating time this is typical of point sources if i take a point source here it would give light it would emit light a point source at the then it would emit light in all directions the wave fronts are in the form of spheres expanding spheres

So that is represented by ψ of $r t$ is equal to a by r into $\cos k r$ minus ωt we come back to this r now this r in the denominator takes care of the decrease in intensity we know that the intensity is equal to ψ square and that means a square by r square which is proportional to a square by r square and therefore we also know that the intensity decreases power or intensity decreases inversely as r square that is it is proportional to 1 by r square and therefore the amplitude must be proportional to 1 by r that is why we have a r in the denominator here

So this is about the spherical wave with this we come to eigens principle now with these ah basics we look at the Hygens principle now how to propagate waves

So here is Heightens principle this is not a specific statement but it means the the the essential of Heightens principle essential aspects of Heightens principle all points on a wave front act like point sources that give out secondary wavelets which propagate outward with the speed of the wave the wave front at a later time Δt is given by the surface tangent to these secondary wavelets we will come back to this statement we will illustrate what does this mean and then we will come back to this statement and then we will understand it fully

So let us see let us consider propagation of plane waves using Heightens principle

So here propagation

So we will come back to this statement after a while

So propagation of plane waves using Heightens principle

So let me consider here keep

So consider propagating plane wave

So here is the wave front

So the plane waves are coming like this

So let me show two wave fronts

So plane waves at a later time

So plane waves are propagating like this now if this is the wave front at t is equal to t_1 one the wave front plane wave front which is propagating in a particular direction and therefore the k vector the propagation

So this is these arrows represent the direction of k and this could be the x direction in that case the wave is represented by a $\cos k x$ minus ωt

So here is the propagating direction

So according to Heightens principle every point on the wave front act like source of secondary wavelets that is act like point sources of secondary wavelets

So what i am showing here is point sources

So point sources of sec if this is a point source we know that this will give out spherical waves

So this will give out

So spherical waves like this

So each point source gives out spherical waves like this

So i am drawing the spherical waves and therefore at a time

So let me bring the statement again all points on the wave front on a wave front act like point sources that give out secondary variate point sources which means spherical

wavelets it will give out which propagate outward with the speed of the wave and that means in a time at a later time t is equal to t_1 plus Δt the spherical waves which are here would have moved

So the radius of this sphere here radius of this sphere would be v times Δt

So this will be equal to the radius the radius which I have shown here of these spheres at a later time Δt would be equal to v times Δt and the statement says the wave front at a later time Δt is given by the surface tangent to these secondary wavelets which means if I draw a surface like this which is tangent to the secondary wavelets then this would represent the wave front at the time t is equal to t_1 plus Δt please let me repeat the wave front is plane at t is equal to t_1 according to Huygens' principle every point on the wave front here would represent would act like point sources and give out secondary wavelets the wave front at a later time Δt that is t_1 plus Δt is given by the tangent to these secondary wavelets

So you have a tangent which is here and they will be propagating outward

So the wave fronts are propagating outward we can see here that we could also draw a tangent here just for curiosity but that means the wave front at a later time could be on this side but we know that the wave is propagating in this direction and therefore Huygens conveniently said that there is no amplitude in any direction except in the direction of propagation the amplitude is finite only here

So let me show this slightly bigger

So here is one of the point sources that is one of the point sources on the wavelet

So here is the wave front on which we are

So this spherical wave is propagating outwards but if the wave is propagating in this direction Huygens said he assumed he postulated that the amplitude would be finite only here that is which is at the point of the tangent and there is no amplitude anywhere else this is of course Huygens' assumption there to avoid the issue of backward propagation in this case and therefore he said that the amplitude is finite only here in the direction of propagation and therefore the new wave front will be represented by this

So this will here is the blue line which will represent the new wave front at a later time t_1 plus Δt if you continue this at a later time t_1 plus $2\Delta t$ then we have to draw spheres of radius equal to v times two times Δt or alternatively you could consider secondary point sources here point sources on the second wavelet and draw again spheres like this in the spherical waves coming out of the point sources and then they are tangent to the tangent to these secondary wavelets would represent the wave the wave front at a later time

So this would be the wave front at a later time t is equal to t_1 plus 2 times Δt and

So on in other words this represents this explains the propagation of plane waves in the direction of k with time evolution of the wave with time

So we come back once more just to the statement that all points on a wavefront act like point sources that give out secondary wavelets which propagate outward with the speed of the wave the wave front at a later time Δt is given by the surface tangent to these secondary wavelets I suppose it is now clear

So let me draw the ah let me put a pre drawn diagram the same diagram which I have pre drawn

So you can see here just for clarity

So this was the wave front at t is equal to t_1 at a later time t is equal to t_1 plus Δt

So this I picked up three points here of course every point there acts like a point source but I have just shown three points and spherical waves which are emanating from here and we draw a tangent to all the wavelets which give us the wave front at a later time Δt t_1 plus Δt and if you continue then at a later time t is equal to t_1 plus $2\Delta t$ you get the wave front here and in the direction of propagation

So the new wave front at a later time Δt is the envelope tangent to all the secondary wavelets this is an important statement which we will apply in the subsequent propagation and the amplitude of the wave at the tangent only that is the assumption that that was required for Huygens to show that the wave is propagating only in the forward direction now let us look at propagation of a spherical wave

So propagation of a spherical wave using Huygens' principle

So as before

So let me take a sphere here

So approximately

So this is the point source and which has given out a spherical wave front which is propagating outwards because light is emanated from here it is a point source and we have just seen that it gives out spherical waves which can be represented as a by r into $\cos k r$ minus ωt

So this is problem now let us apply Huygens principle according to Huygens principle let me use a different color here

So we have point sources we consider point sources on this and then these point sources give out secondary wavelets this

So I am showing the forward half because he has said the wave propagates the secondary wavelets outward in the forward direction because the k is in this direction and according to Huygens the amplitude will be present only at the tangent

So I have drawn here wave fronts wavelets these are secondary wavelets and the new wave front will be a tangent a surface which will be tangent to all the secondary wavelets to all the secondary wavelets and that would be again a sphere

So if this is a sphere then this will be a sphere at a later time $t + \Delta t$

So let me put the put a pre drawn diagram which will make it more clear

So here is the spherical wave

So the spherical wave at t is equal to $t + \Delta t$ is here and we have point sources here

So I have consider I have shown here and the radius the radius here if it is at a later time Δt the radius of these spheres here will be equal to $v \Delta t$ where v is the speed of the wave in the medium

So that is how the spherical waves are propagating outward and the statement again that the new wave front at a later time is the envelope which is tangent to all the secondary wavelets

So this is I have drawn them by hand and here is a diagram we can see which is drawn using a computer

So we can see that this is at a time Δt and this is at a time $2 \Delta t$ and you have wavefront which is tangent to all the secondary wavelets

So plane wave propagation in this direction

So these are shown as dotted because they are not to be considered in this direction

So we have in the direction of k the amplitude of the wave is present only at the tangent that is Huygens assumption and therefore here we can see this is the original wave here spherical wave and at a later time Δt we have the new wave which is tangent to all the secondary wavelets all right

So propagation is fine

So this way we are able to or Huygens was Huggins was able to explain or describe the propagation of plane waves spherical waves or in general propagation of light waves but do the this principle or do Huygens principle or do this way of propagation does it satisfy the law of reflection and the law of refraction because Snell's law was already known and therefore does it satisfy the law of reflection and refraction which were already known at that time

So let us see explain the laws of reflection and refraction using Huygens principle as explained by Huygens

So here is a plane wave incident on a mirror

So what is being shown is a beam of light which is incident here and these are plane wave fronts wave fronts here and incident on a mirror plane wave incident on a mirror $p q$ is the surface of a mirror at a certain time $t + \Delta t$ at a certain time $t + \Delta t$ the wave front has just reached here $a b$ let me call this is the wave front at a time $t + \Delta t$ now this end of the wave front will take some more time to reach the other end

So if this is Δt if the time taken is Δt then this will be equal to $v \Delta t$ the point a this is the wave front $a b$ is the wave front the point a has already touched the mirror and therefore light does not propagate beyond the other side because this is a mirror it is a reflector and therefore the secondary wavelets will start coming out in this direction

So the secondary wavelets will be emitted in this direction

So they will start propagating in this direction with increasing time as this end approaches here the wave front which has already reached here creates secondary wavelets and they start propagating coming out in this direction because this is a reflector for example by that time the wave front the point b reaches here this end of the wave front here I have I have taken two points on this wave front

So here at approximately one third the separation is approximately one third two third of the total distance and this point reaches here by the time the point b of the wave front by the time the wave front reaches here we see that this will reach here and as this propagates further this will start giving out secondary wavelets

So this starts giving out secondary wavelets and by the time the wave front reaches here this point has reached o2 o2 is another point which will start giving out secondary wavelets

So this is the secondary wavelet

So this keeps giving out secondary wavelets and finally when this end of the wave front reaches here this has already given out secondary wavelets this has given out secondary wavelet

So how much time what would be the radius for example this will take this is

So each segment the time taken to travel this is Δt by 3 because Δd is the total time taken from b to c for the light we have to travel from b to c therefore the time taken by the wave front to travel here

So Δt by 3 this time the time corresponding to this distance of propagation is also Δt by 3 and this will also be because i have taken three sometimes you can take only one point midpoint or four points whatever any number of points can be taken

So i have just taken three different points and therefore this radius here will be v into Δt by 3 v into Δt by 3 will be the radius of the wave front which is here and this will be equal to v times 2 times v into 2 Δt by 3 and this radius here will be equal to Δt is the time taken here and therefore that will be equal to v into Δt and therefore v into Δt is this distance

So the radius will be obviously larger

So we have according to Huygens principle

So we have shown the wave fronts here of the secondary wavelets these are the secondary wavelets propagating outward from the points which we have considered according to Huygens principle the new wave front

So that we see the statement that we have written that the new wave front is given by

So the new wave front will be the new wave front at a later time Δt is the envelope tangent to all the secondary wavelengths

So the envelope which is tangent to all the secondary wavelets

So here is the envelope i am drawing the envelope the tangent to all the secondary wavelets is a straight line

So we can see that it is tangent here it is tangent here and it is tangent here

So this will be the wave front of the reflected wave which is a plane which is a plane wave front once this is plane wave front we know that it will start propagating in this direction with plane waves like this

So plane waves which are travelling in this direction which are parallel to this as time progresses

So i will show a more clearer diagram here

So this is how i have shown you how to draw the plane wave front on refraction reflection from a mirror

So let me show you a pre drawn figure here

So we can see here that the three points which i had taken here i have taken only three points in the previous case i had taken four points just to illustrate that there are

So many wave fronts and the tangent would give the tangent to all the wave fronts would represent the wave front after reflection

So in this case here i have shown only three wave fronts here three points

So one end

So the end point here end point midpoint and this

So end point midpoint and

So there are only three points which are shown here and you can see the incident wave and the reflected wave

So b o three from here to here b o three is equal to Δt times v if Δt is the time re for it to travel here which is also equal to the radius o h of this wave front because when this was at b the point has already touched o 1 here the other end of the wave front is at o 1 therefore it immediately starts giving out secondary wavelets and therefore this is equal to o one h which is also equal to o one f here because this is a sphere

So one h or one f

So by the time the incident wave front reaches from b to o three the explanation is written here b two o three the secondary wavelets from o one reach h from o two to the point k from o2 to the point k here and

So on and the surface tangent to these wavelets give the reflected wave front which is shown here which is a plane and therefore subsequently it will propagate as we have already illustrated

So this represents reflection by a mirror but let us see whether this satisfies the law of reflection

So let me put a better figure now

So here

So lets see whether it satisfies the law of reflection this is the incident wave front this is the reflected wave

So now we have seen here a b is the wave front just before it touches here a b and this is the reflected wave front fc if this is the normal to the mirror and the beam is incident like this which means this represents the angle of incident i here then this will be i because this is 90 degree

So this is this angle here is also i because the whole angle from here to here is 90 minus i therefore this must be i and this is i similarly if this is r then this angle has to be r

So this angle is 90 minus i here and this angle is r for this triangle here because this is 90 degree and this angle is r therefore the remaining angle here is 90 minus r 90 minus r here and therefore this angle must be r

So that is how we have this equal to i and this equal to r and therefore in the triangle abc triangle a b c sine i this angle is i therefore sine i is equal to b c that is the opposite b c divided by e c hypotenuse here which is equal to b c is v into delta t the time the distance equal to v into delta t bc equal to v into delta t divided by is similarly in the triangle a f c a f c where f c is the reflected wave front sign r this angle sine r is equal to a f divided by ac af divided by ac which is equal to v into delta t by ac and therefore it simply means that sine i is equal to sine r or i is equal to r which is the law of reflection

So the law of reflection is satisfied by heightens construction and propagation using the higgins principle now let us look at the law of refraction

So law of reflection it is satisfied now let us look at law of refraction

So here it is refraction at an interface between two transparent media

So as before

So this time i am not drawing because it is shown here incident wave front is here is coming here and by the time this travels from here at this interface the secondary wavelet start coming out

So the secondary wavelets come out and when b reaches here the secondary wavelet reaches here note that the refractive index are different n1 and n2 n2 is greater than n1 if n2 is greater than n1 we already know by snell's law that the ray will bend towards the normal or the beam will bend towards the normal

So if it has to bend towards the normal then if n2 is greater than n1 v2 should be less than v1 if we do not assume v2 less than v 1 this distance here a d will a d will be smaller compared to b c here only if we assume that v 2 is smaller than v 1 because this distance a d is equal to v two times delta t unless this distance is smaller this wave front will not bend towards this and experimentally we already know that if there is an incident ray like this then it will bend towards the normal if the second medium is of higher refractive index therefore it is essential to assume that v two is less than v one and if we assume v two is less than v one then this travels a distance a d and similarly these points will travel the corresponding distance and the tangent to all the secondary wavelets this this and this here shown is the wave front of the refracted wave at this point and subsequently if this is plane it will propagate as a plane wave

So wave front in the second medium is tangent to all the secondary wavelets and that is how the wave propagation refraction at an interface between two dielectrics is two media of refractive index n1 and n2 are described using the heights principle

So i keep a more clearer picture of the same picture to show the law of refraction here

So the law of refraction by heightens principle

So see this this was the incident wave and ah wave front and then this is the refracted waveform

So we can see as before in triangle a b c a b c here sine i here will be equal to bc by

this

So $v_1 \Delta t$ by ac is v_1 into Δt now we have two media this is of refractive index n_1 and velocity v_1 here it is n_2 and v_2

So $v_1 \Delta t$ by ac in triangle adc this triangle in the second medium sine r this angle sine r the refracted angle this angle is the same as this angle and therefore sine r will be equal to ad by ac which is $v_2 \Delta t$ by ac that means sine i by sine r therefore will be equal to v_1 by v_2 which is equal to n_2 by n_1 by snell's law because snell has by snell's law we know that $\sin i$ by $\sin r$ is equal to n_2 by n_1 .

So v_1 by v_2 is equal to n_2 by n_1 n_2 is larger than n_1 and therefore v_2 is smaller than v_1 if n_2 is greater than n_1

So the velocity of light has to be smaller in this medium now eigens principle successfully explained both the law of reflection and the law of refraction which were already known during his time

So that was the plus point however heighten had some difficulty he could not answer what type of waves are these because it was known also that these light waves can propagate through vacuum without any medium then what type of waves are these and therefore the corpuscular theory prevailed because corpuscular theory had an explanation for what type of waves are these and therefore the higgins theory although although put forward in 1678 although put forward as early as 1637 it could not be accepted for more than a century until 1801 when thomas young put forward his famous experiment which is the double hole experiment or the double slit experiment to prove that to convincingly demonstrate that light is a wave

So we will discuss a little bit more on this now before we go to thomas young's experiment we will see the application of huygens principle to light passing through apertures

So let me illustrate light passing through an aperture with by using the higgins principle

So what i am discussing now is see consider plane waves incident on an aperture aperture means a stop which with a certain opening

So here is a stop for example it could be a screen or it could be an opaque plate with an opening here plane waves are incident here plane waves are incident on this aperture according to huygens principle when the plane wave reaches here

So when it has reached here

So let me use the blue color here we have point sources the further propagation is discussed using the secondary wavelets the point sources which are here are blocked by the aperture

So there is a aperture which is here

So which is which blocks its a finite is a plate of finite thickness or some obstacle and the wavefront which is here start giving secondary wavelets

So they give out because we have to see how it will propagate across this across the aperture

So this gives out secondary wavelets

So with the time these secondary wavelets will become larger and larger and the tangent to all these

So they will further become more and more

So these each one of the secondary wavelet again acts as point sources and therefore these give out wavelets which are like this and we know that the wavefront at a later time is given by a surface which is tangent

So let me use the black color to draw the tang which is tangent to all the secondary wavelets

So it looks like this it is tangent to all the secondary wavelets but what we have seen is the wave front now has a curvature wave front has a curvature which means although originally it was propagating like this now it is the k vector or the propagation direction which is normal to the wave front also has components in the in the direction which is away from the original direction here if we see this more carefully what it means is that at a if i plot the wave front at a later time it would further become like this

So what it means is the wave is also propagating in the geometrical shadow of the aperture what is this word i have now introduced the word geometrical shadow geometrical shadow geometrical shadow what it means is if the waves are incident like this they are propagating in this direction then because of the aperture there is a shadow and this

wave should have come directly here as far as if i use the ray theory for example rectilinear propagation of light i should have seen light only coming here and whatever is the remaining part

So if i use a different color here

So this portion here is the geometrical shadow of this aperture there is an aperture here and there is a geometrical shadow which means as far as the geometry is concerned the straight rays or the straight lines would go here and here because it is a plane wave which was incident here but we see that according to Huygens principle when we construct the wave front the wave front also propagates into the geometrical shadow in other words there is light propagating into the geometrical shadow which as we will see later is nothing but diffraction that is the phenomena of diffraction and therefore Huygens principle was able to explain diffraction that is light propagating into geometrical shadow of the apertures i have some diagrams here which will illustrate it more clearly

So let me show you some diagrams here Huygens secondary wavelets at an aperture

So here

So this is drawn using a computer

So plane waves are incident here there is an aperture here

So we have considered different point sources here and then constructed the secondary wavelets which are spheres originating from the point sources as you can see there are no point sources here on the other side because this is an aperture and therefore the surface tangent to all the secondary wavelets looks like this it is somewhat plane here but it also has curvature in this direction which means the wave is also propagating into the geometrical shadow the geometrical shadow would have been here

So this is the region where the light should have come but light is also propagating into the geometrical shadow if you reduce the aperture size if we reduce for example this is the opaque screen if we reduce the aperture size then we see that it spreads more it was almost flat here and a little bit of curvature at the other ends but now you see that the flat region becomes smaller it more and more looks like a sphere it is more moving towards a spherical wave and if i reduce the aperture further

So let's reduce the aperture further and we can see that if the aperture size is reduced the Huygens construction gives us wave fronts which are approaching a spherical wave incident wave is a plane wave and if you reduce it to a very small hole then we almost have spherical waves which are emanating from the holes this is contrary to what is expected from the ray theory

So we see that the wave front is becoming more and more spherical these observations were made by many scientists and many researchers at that time and they were getting convinced that each light must be a wave but there was no concrete evidence there were no experimental evidence in with regard to light although there were mechanical waves ocean waves which were seen to exhibit this kind of behavior but there were no experiments which could prove that light is a wave

So a further observation here with the two holes i showed you in the last diagram there is one pin hole or one small aperture here giving out almost spherical wavelets and if we what would happen if there are two holes eigen secondary wavelets from two holes in a screen

So if we draw spheres which are from the two holes then we observe observe that there are directions where

So what is shown here solid line and dashed line the dashed line represents wave fronts corresponding to troughs if a sinusoidal wave propagates like this it has troughs and crests the amplitude is minimum here and amplitude is maximum here this corresponds to So the two points are pi difference in phase the phase difference between the maxima and the minima is pi

So what is shown here are troughs

So wave front corresponding to trough and wave front corresponding to crest which means if i put $\cos(\omega t - kx)$ assume that this is the x direction then the phase front here corresponds to $kx - \omega t = \text{constant}$ this represents $kx - \omega t = \text{constant}$ the constants are different if this is this constant is pi then this constant is two pi that is the meaning of crest and trough

So i have shown here the wave fronts corresponding to the minima and maxima

So correspondingly if we see the wave fronts here the dashed line here corresponds to troughs and solid line here solid curves correspond to crest

So if you plot these these spheres then there are directions where you see that the solid line meets solid line the dashed line meets dashed line solid line meets solid line dash line meets dashed line and

So on whereas there are directions where you see that if one when it when the two intersection point of the wave fronts one is a solid and another is a dashed line here solid line dash line solid line dash line

So there are directions where the crest due to one overlaps with the trough due to the other and there are directions along which the crest due to one that is one hole one point corresponds to crushed due to the other point which means these there must be directions where there are bright light coming that is the maxima and maxima coinciding and the minima and the maxima and minima coinciding which means there would be no light So the intake what is expected here is an intensity variation if we keep a screen here So thomas young gave the double hole experiment in eighteen zero one first with sunlight from a small opening in the roof and then with sodium light and the wave nature of light was convincingly demonstrated for the first time by young's experiment and of course subsequently he also explained the newton's rings in 1802 by the wave theory now let me explain a little bit as it apparently the young's experiment was done the first time when he saw sunlight coming from the roof

So this is sunlight coming from the roof he placed an aperture here he placed a plate which had two holes two small holes here

So two small this is sunlight from the roof sunlight from the roof apparently these are the sequence of events which led to the young's double hole experiment and then he could see on a screen placed here in a dark room sunlight coming from a small aperture in the roof and there is a plate with two small holes and he could see a bright fringe here that is a bright intensity in at the center here and then he could see some colors and then So what i am showing here is the intensity variation i am plotting some intensity variation we will discuss this in more detail

So what i have plotted is this is a screen on the screen that is on a lets say a cardboard sheet or something that if you plot the intensity he could see a bright intensity peak a bright peak at the center here and then he saw some colors here and then there is uniform illumination far away from here this is now very well understood why he saw such a and we will discuss this in greater detail in the next class in the next lecture but this is what young saw and then what he did

So this is first sequence the in the then what he did was he used a spirit lamp So spirit lamp here

So there is a flame which is flame of the spirit lamb and then sprinkled he sprinkled nacl that is salt nacl he sprinkled nacl onto the flame of the spirit lamp which gave the bright yellow color corresponding to bright yellow light corresponding to the sodium here and now he placed an aperture with the two small holes very close by two small holes and on the screen here he could see a large number of bright and dark intensity maxima and minimas intensity maximas and minimas due to the bright yellow color of sodium

So this is a spirit lamp on which he sprinkled salt and then he saw due to the bright yellow light he could see bright and dark fringes here that is maximas and minimas on a screen placed here

So this as we will discuss in more detail in the next lecture is a convincing evidence that light is a wave thank you you