a very good morning to all of you

so today we have come to the last section of electricity and magnetism and that is electromagnetic waves

so today what i will do is i will discuss about electromagnetic waves what do they represent and what are these waves and what kind of frequencies etcetera etcetera

so recall we have been discussing the basic equations which describe electricity and magnetism

so let me write the four equations that we have obtained through the course on the lectures on electricity and magnetism and these are called maxwell's equations because maxwell added a term which i described last time as the displacement current and that is a very very important contribution that predicted the existence of waves which are now called electromagnetic waves

so let me first write down the maxwell's equations

so first of these equations is integral e dot d a charge enclosed by epsilon zero integral b dot d a is equal to zero integral e dot d l is equal to minus d by d t of phi b which is equal to minus d by d t of integral b dot d a and finally integral b dot d l is equal to mu zero i plus mu zero epsilon zero integral ah epsilon zero d by d t of integral e dot d a the four equations ah in form of integrals and these are the four maxwell's equations this is nothing but gauss's law we have used ah right in the beginning this tells me that the flux of electro electro electric field must be equal to the charge enclosed by epsilon zero

so let me draw a figure here

so if you have if you take a surface like this then the electric flux which is coming out of this these are the e fields this is integral e dot d a is equal to charge enclosed by psi

so it all it says is that the first equation says that the net electric flux coming out from a closed surface this integral of the closed surface must be equal to charge enclosed divided by epsilon zero

so depending on the sign of the charge the electric flux is pointing away from this surface or towards the surface

so the charge is positive then we know the electric flux is coming out if charge is negative the electric field lines are entering the volume entering the surface area also note that as we have discussed before ah if the net charge inside is zero the flux is zero and that does not imply the charges are zero i could have electric wheels with net flux being zero the second equation which is ah in magnetic field if i take another surface here then i find that integral b dot d l b dot d a must be equal to zero no network no net flux coming coming out because magnetic field lines are close lines as many field lines enter the volume as are coming out

so magnetic field lines are closed lines and

so it also implies that there are no magnetic charges that means no points from which magnetic field lines emerge or get converged in in other words we say that magnetic monopoles do not exist and

so magnetic field lines as we have seen before are always closed lines and

so if you take a closed surface the net magnetic flux through that surface will be zero

so this is the second law which you have written the third law which is faraday's law

so if you take a a loop and if you have magnetic field lines crossing that loop then this equation says integral e dot d l is equal to minus d phi b by d t that means a changing magnetic flux through this loop will induce an emf in the loop or a changing magnetic field will induce an electric field and the direction of

the induced emf is decided by lenses law because of the negative sign the induced emf is always to oppose the changes in flux that is faraday's law of induction and finally we had the fourth equation which was essentially if i draw another figure here and i had electric field lines crossing this integral b dot d l is equal to mu zero i plus mu zero epsilon zero d by d t of phi
 so magnetic fields get induced either by currents
 so that means currents can generate magnetic fields or changing electric flux can also generate magnetic fields this is the displacement current which we have discussed before this term is the displacement current which was introduced by maxwell and is a very very important modification of ampere's law remember we had initially discussed this part which was ampere's law to calculate the magnetic fields produced by currents and what we showed was that to be consistent you have to have another term in this equation which we call as the displacement current
 so these four laws of maxwell maxwell's equations describe all electromagnetism and they are a beautiful representation of the electrical and magnetic properties of the fields the materials etcetera now in free space if i look at a free space for example when there are no charges and no currents these equations become the following in free space this equation become integral e dot d a is equal to zero integral b dot d a is equal to zero integral e dot d l is equal to minus d by d t of integral p dot d a and integral b dot d l will be equal to mu zero epsilon zero d by d t of integral e dot d a
 so these equations only contain electric and magnetic fields in free space in the absence of any charges or in the absence of currents flowing charges i have these four equations and these four equations actually if you look at these two equations they couple electric and magnetic fields this electric field depends on magnetic field and magnetic field depends on electric field
 so these two equations actually couple the electric and magnetic fields and this is what as we will see later on results in the existence of new forms of waves which are called electromagnetic waves
 so these are the four maxwell's equations in ah what are called as integral form ah in an advanced course when you when you in your carrier when you go into an advanced course you will see that these equations convert can be converted into differential equations and they form the four fundamental equations of electromagnetism
 so what maxwell did was to generalize ampere's law and introduce the displacement current to be consistent and from here he actually derived a wave equation an equation which describes the existence of waves and he found that those waves which are waves of electric and magnetic fields have a certain velocity and the velocity of those waves was approximately three into ten power eight meter per second
 so this velocity which he calculated was
 so close to the measured velocity of light at that time that he propounded he boldly suggested that light waves are electromagnetic waves till that time light waves were not considered to be electromagnetic but he showed that from these equations you can predict the existence of waves which are called electromagnetic waves and the velocity of those electromagnetic waves we found out dependent depend on epsilon zero and mu zero and that velocity comes out to be
 so close to the known value of velocity of light at that time that he propounded that light must be an electromagnetic wave and this was in eighteen sixty and in 1888 heinrich hertz in germany did experiments to generate electromagnetic waves of much lower frequency and he showed that electromagnetic waves do exist and the experiments conducted by hertz were a dramatic

confirmation of the predictions of maxwell's electromagnetic theory and today we find electromagnetic waves all around us and we will as we will go through a little bit of discussion of these electromagnetic waves we will start to understand the importance of these electromagnetic waves and our basic understanding of the physics behind the description of electromagnetic waves now before i move on to electromagnetic waves ah you have done in class 11 discussed about waves waves on a string for example or acoustic wave sound waves

so i would like to recall some of the discussions you must have had in class 11 on waves before we move on to discussing electromagnetic waves

so let us look at waves waves on a string now if you take a string a long string and if you take a string and push it like pull it up like this and leave it then you will develop a wave for example you can have a wave at this time a little later what you will find is this disturbance moves here and a little later this distance moves here and there a little later the system

so this disturbance is moving like this and that represents the wave

so what you have done is you have taken a string and pulled it up and taken it up and lower dot rovered it generating a disturbance and that disturbance moves in this direction with a certain speed called the speed of the wave and this is a wave on a string

so what is happening is the wave the wave has been generated by moving the string up and down and in that process you have given energy to the string and that energy is propagating in the wave along the string in this direction

so there are two things one is the string is moving up and down with a certain velocity and energy the wave is moving to the right with a certain different velocity now this is one type of wave i can generate different types of waves but the most most important are the sinusoidal waves

so these air waves are something like this for example this could be a function of x this is y

so i have a string which is ah which is along the x axis and i take the end of the string and move it up and down periodically

so i move the string up and down periodically and in that process generate what are called as sinusoidal waves i can describe the sinusoidal waves by the following equation the displacement of the string at any value of x and time is given by a sine k x minus omega t now i am sure you have discussed this in your earlier class that the displacement of the string from the equilibrium position this is the equilibrium position of the string

so the string is moved up and down periodically and in that process i generate waves on the string which are sinusoidal waves because the dependence on time and space is sign is a sine function these are sinusoidal waves and a is called the amplitude of the wave a is called the amplitude of the wave the maximum displacement and this quantity case k x minus omega t is called the phase k x minus omega t is equal to the phase of the wave and

so this is let me let me explain what i what i have drawn is this shape of a string at some instant of time say t is equal to zero

so this represents a sinusoidal wave of amplitude a and described by a sine k x minus omega t

so this gives me the displacement of the string from the equilibrium position as a function of space and time

so let me try to draw two pictures here one is i look at this wave at a given instant of time like here let me redraw the figure here

so the general wave is described by x y of x t is equal to a sine k x minus omega t

so at t is equal to zero some arbitrary time which i call t is equal to zero y of x t is equal to zero will be a sine k x

so i what i have done is i have i take a snapshot of this string at a time which i call t is equal to zero i take a snapshot and that snapshot of the string ah displacement of the string from the equilibrium position is given by a sin k x
 so let me draw the figure again here
 so a sin k x will look something like this
 so this is the amplitude a look here the sine function varies between plus one and minus one
 so it goes from plus a to minus a
 so this is y as a function of x it is a sinusoidal function and which repeats after every this distance this distance is referred to as wavelength wavelength of the wave
 so please remember this is a snapshot of this string at t is equal to zero if i had a very fast camera i could have taken a very short exposure of the string at some incident of time which i call t is equal to zero and i will see an image of the string like this this is the amplitude and this is the wavelength
 so you can see here the sine function at this point x was zero
 so the amplitude is zero the as x increases the amplitude increases like a sine function then after this distance the sine function repeats itself
 so in going from here to here the the quantity k x phase must have varied by two pi because the sign function repeats itself whenever the angle changes by two pi
 so this distance must be such that k x must be equal to two pi
 so let me if i call this distance as lambda i must have k lambda is equal to two pi or k is equal to two pi by lambda and this quantity k is called the wave number or propagation constant
 so this describes it is related to wavelength through k is equal to two pi by lambda and it defines that how much is the distance over h the period the period of wave along the distance direction
 so after every distance lambda the wave repeats itself
 so the distance from this point to this point is lambda the distance from this point to this point is lambda the distance between these two points is lambda
 so whenever you take two points of equal phase the distance between them at a given instant of time is given by the wavelength of the wave
 so that is the wavelength now let me look at another picture what will the string look like from one given point
 so let me look at ah at x is equal to zero
 so i position myself at some point which i call x is equal to zero and
 so this is at a position at this point on the string and look at this how the string varies as a function of time
 so y let me recall y of x t we have written as a sine k x minus omega t
 so at x is equal to zero we have y of zero t is equal to minus a sin omega t
 so if i position myself at a point which i call x is equal to zero the amplitude of the string depends on time of the fight of the form minus a sin omega t
 so if i plot this function again this is y as a function of now time at x is equal to zero goes like this this is minus a sin omega t
 so this is a here and that is minus a and
 so as you can see here the string moves up and down and repeats itself after a certain time which i call t capital d the time period
 so the string goes up and down at a given instant at any point on the string and repeats itself after every time capital t
 so capital t must be such that the quantity omega t changes by two pi in going over time capital t at this point t was zero at this point t must be such that

omega t must have become equal to two pi

so i can write omega times t is equal to two pi or omega is equal to two pi by t and if i call the frequency nu is equal to one by t this becomes omega is equal to two pi nu

so omega is called the angular frequency and u is called the frequency

so omega is equal to two pi nu

so this quantity omega which appears in this equation is nothing but two pi times the frequency and k which appears here is nothing but two pi by wavelength

so i can write this equation in a it containing wavelength and frequency

so let me write y is equal to y of x t is equal to a sine now k x is two pi by lambda x minus two pi nu t that is omega t

so this i can write as a sine two pi ah two pi into x by lambda minus nu t

so this is the equation in terms of wavelength and frequency otherwise the equation can also be written this is same as equation as this a sine k x minus omega these two are the same equations this is written in terms of wave number and angular frequency this is written in terms of wavelength and frequency

so please differentiate between these two figures one showing the shape of the string at a given time as a function of x this is a snapshot of the string at any instant of time the shape of the string how it will look at a given instant of time and this other figure which is how the string at any point moves that means i position myself at a point on the string and see how that point on the string moves up and down as a function of time and that is as a function of time here this is a function of space coordinate here

so we must be very careful in analyzing these two figures one is a shape of the the displacement of the string as a function of position the other is the displacement of the string as a function of time

so these two are important aspects now i want to show you that this is a propagating wave that this wave is propagating

so my equation is y of x t is equal to a sine k x minus omega t

so i want to draw how the string will look at a certain instant of time say t is equal to 0 and a slightly later instant of time

so let me draw how the

so at t is equal to zero y of x t will be a sine k x which we have drawn before

so this is a function of x

so it looks like this

so this is at t is equal to zero now slightly later time say at t is equal to t one y of x t will be a sine k x minus omega t one

so slightly later time t one i plot i lock i look at the string y of x t is a sine k x minus omega t one this was at t is equal to zero

so i had sin k x this is the t is equal to t one

so i have sine k x minus omega t one now this is the same sine function as this except that it is displaced

so this was this argument of zero at x is equal to zero this argument will be zero x is equal to omega t one by k

so what will happen is the string will now look something like this

so this is at t is equal to t one please note that at x is equal to zero now it is minus a sin omega t one

so that is a negative displacement and the function becomes zero

so this point has moved to this point and this point now where is this point this point will be

so suppose i call this x naught x one

so this point x one is such that k x one minus omega t one is equal to zero at this point the argument of the sign function was zero k x is equal to zero at this point k x one minus omega t one is again zero the same point has moved here

and
 so x one and t one are related
 so x one k x one must be equal to omega t one or x one by t one is equal to omega by k now what is x one by t one what we see is the wave which was at this point this point was over here at t is equal to zero has moved to this point in a time t one every point on the string if you look at any point on the string it has moved by a certain distance in a time t one and
 so this must represent the velocity or speed of the wave
 so velocity of the wave is equal to omega by k omega pi k is the velocity of the wave
 so that means in this equation one is that it represents a wave a propagating wave as you can see here a little later for example if i were to draw the same figure a little later it will go like this
 so this is moving this side is moving like this the entire wave is moving in the positive x direction
 so at t is equal to zero t is equal to t one t is equal to t two and
 so on
 so as time progresses the entire wave seems to be moving like this
 so it represents a propagating wave and the velocity of propagation is omega by k i can actually represent this in terms of two pi nu omega was two pi nu and k is two pi by lambda which is equal to nu lambda
 so this is the equation which you must have derived velocity is equal to nu lambda velocity is related to the frequency and wavelength of the wave by v is equal to nu lambda
 so what we see is this particular form of an equation represents a wave a propagating wave propagating along the x direction because at t is equal to zero the wave was in certain position at a slightly later time the wave has moved in the forward direction towards positive x direction and
 so this represents a propagating wave propagating along the plastics direction now i will leave it you to ah to discuss that a wave represented by y of x t is equal to a sine k x plus omega t represents a wave going in minus x direction
 so if this is a wave going in the if this is the wave going in the plus x direction i would like you to show argue like i have done that this is a wave which is going in this direction
 so depending on the sign between the space dependent and the time dependence part the wave is represented the wave is either going in the plus x direction or minus x direction and that is a wave which is going in the negative x direction
 so please have a argument and try to plot figures and to show that this is a wave going in the minus x direction
 so what we have seen is this is a nice representation of a propagating wave and this wave is is what is this wave after all this wave is nothing but how the string goes up and down as a function of time
 so there is a string which is going up and down and that disturbance on the string is actually propagating in one direction either the plus x direction or the minus x direction
 so that is a sinusoidal wave and sinusoidal waves are very important waves because ah later on in your studies you will see that any form of wave can be represented as a sum of different sinusoidal waves this is a very very important concept in physics that you can represent any wave as a superposition of different sinusoidal waves or different frequencies and this
 so study of sinusoidal waves is very important from the point of view of physics also note some interesting aspect here
 so let me draw this string again pi as a function of x now if you see here the string is is moving like this

so a little later as we draw before moved into this position
so the string which was for example at this point the string which is here has moved here up like this and as you can see here the maximum extension of the string is also here the the equilibrium position of the string was like this now it is stretched in this direction
so maximum stretching is taking place here and the point is also moving up and down at the greatest velocity at this point
so in propagating waves the potential energy of the string is contained in the extension of the string in the tension which is extending the string and the kinetic energy is determined by the energy of motion of the string up and down and as you can see here the point where the kinetic energy is maximum is also the point where the potential energy is maximum
so maximum stretching appears here at the point of intersection with the axis here and that is also the point where the velocity of the string is maximum in upward or downward direction
so for example you can you can calculate the for the velocity you can calculate d y by d t which is equal to
so let me take let me draw in this in a separate slide here
so let me take a wave in the plus x direction y is equal to y of x t a sine k x minus omega t
so if you calculate the velocity of the string is actually given by d pi by d t which is minus a omega cos k x minus omega t why the displacement of the string how does the displacement of the string vary with time and how does the stretching of the string vary with position that means how does y depend on x that is stretching and that is given by a times k times cos k x minus omega and as you can see here both of them are described by the same cosine function points where the velocity is maximum where the cosine function is one is all the it's also the point where d y by d x is maximum where the cosine function is one this determines the kinetic energy of the string that determines the potential energy of the string and they are in phase
so you find that in propagating waves the potential energy and kinetic energy are both in phase and as the wave propagates it carries this energy
so this was a very brief ah description of waves that you must have studied in class 11 i would urge you to go back and pick up the class 11 book and see for yourself ah different properties of waves that you must have discussed at that time you must have discussed for example waves in gas sound waves in a gas for example you may have discussed superposition of waves and
so on
so i would urge you to go back and refresh your memory as far as the waves are concerned because now we will be discussing ah very very important class of waves called electromagnetic waves now electromagnetic waves are quite different from the waves that you must have discussed till now waves on a string for example you must have seen waves on a on a water surface
so in a string what happens is the string is moving up and down and in that process there is a wave which is moving
so the string is not moving in the forward direction string is only moving up and down and the wave is going in a certain direction now remember these are called transverse waves because the string moves up and down in the vertical direction while this wave moves in the horizontal direction the direction of propagation of the wave is perpendicular to the direction of motion of the string and
so this is the transverse wave
so i could have the string moving up and down and the wave propagating like this or i could have a string going forward and backward and the wave

propagating like this

so these are two different types of transverse waves one which is displaced along the y direction and propagating along x the other is displacement along z direction and propagating along x

so you can have two different transverse waves sound waves represent what are called as longitudinal waves where there are compressions and rarefactions which are propagating in the wave

so when i speak i am generating sound waves

so there are waves of compressions and vary fractions in the hair which is surrounding me here and those compressions and rarefactions are such that air molecules are

so for example when i speech when i speak the air molecules are moving like this and the sound wave is propagating in the forward direction

so these are called longitudinal waves the displacement of the particle is along the direction of motion of the wave now electromagnetic waves are also transverse waves now unlike in waves on a string which requires a string for propagation of the wave or sound waves where you need gas or some kind of a medium in which you have to propagate electromagnetic waves can propagate in free space light is a form of electromagnetic wave and we are getting light from the sun we are getting light from stars which are millions of light years away

so we are getting light from all around the place and please remember there is hardly any anything in between the outside the solar system and the solar system between the stars and us or between sun and us

so these waves are able to propagate in free space and

so they are a completely different type of wave they do not need a medium to propagate of course the presence of a medium can change their propagation properties but you do not need a medium to propagate and

so these electromagnetic waves are characterized by electric variation of electric and magnetic fields in space

so these are the waves which are electromagnetic waves are very waves in electric and magnetic fields they are represented by electric and magnetic fields and not displacement of a string or pressure in a gas they do not need a medium and they are actually nothing but electric and magnetic fields which are propagating in space carrying energy and momentum

so before we discuss more details what i would like to do is to draw a figure to show you what how electromagnetic waves are represented and describe a bit about the figure

so that you understand very clearly what is the meaning of the figure that we plot ok

so couple of things which i need to mention before i plot the figure the electric and magnetic fields are perpendicular to the propagation direction that is why they are called transverse waves the electric and magnetic fields of the wave are perpendicular to the propagation direction electric field is perpendicular to the magnetic field and this vector e cross b is along the direction of travel of the wave

so electric and magnetic fields are perpendicular to the propagation direction electric and magnetic fields are perpendicular to the propagation direction electric field is perpendicular to the magnetic field and electric field cross magnetic field is along the propagation direction

so that means electric field magnetic field and propagation direction form a right hand coordinate system and also electric field and magnetic field are in phase

so the electric field and the magnetic field are always in phase in this propagating waves just like i showed you in the string the kinetic energy and

the potential energy are in phase in a propagating wave here the electric and magnetic fields are in phase

 so let me draw a figure which represents an electromagnetic wave and then try to describe to you what this what is the meaning of that ok

 so let me draw the the electric field

 so this is the electric field and let me draw the magnetic field which will look like this

 so let me draw some vectors here

 so these are they represent electric fields magnetic fields are perpendicular

 so please note that

 so if i call this x y z

 so this is the electric field and this is the magnetic field and that is

 so please note this figure what i have drawn is how does the electric field vary with position this is at some instant of time remember just like i drew for these waves on a string i take some instant of time which i call t is equal to zero and plot how the electric field varies with position and how the magnetic field varies with position

 so you can see here first thing is the electric field the wave is actually propagating along the z direction it's a very propagate direction we will discuss that and the electric field is perpendicular to the propagation direction the magnetic field is perpendicular to the propagation direction

 so the wave is a transverse electromagnetic wave its a transverse wave because electric fields and magnetic fields are perpendicular to the propagation direction the electric field and magnetic field are perpendicular to each other

 so electric field is perpendicular to magnetic field at every point here here everywhere electric field and magnetic field are perpendicular to each other and electric field

 so electric field is pointing along x direction in this figure magnetic field is pointing along y direction

 so e cross b which is x cap i cap cross j cap has to be k cap and

 so the wave is propagating along z direction

 so electric field magnetic field and the propagation direction form a right handed coordinate system x y z electric field magnetic field propagation direction ok now one has to be little careful in re in sort of trying to figure out this figure because it is a very abstract figure in the following sense please note that these arrows only represent the magnitude and direction of the electric and magnetic fields at every point on the axis of this wave

 so this arrow implies that the electric field at this point has a large magnitude and is prop and is pointing in the upward direction at this point the electric field at this magnitude and pointing in downward direction at this point the magnetic field is along the y direction and has this magnitude

 so all these fields are actually fields at various points along the axis and these are the magnitude and direction of the electric and magnetic fields please remember that these arrows only represent the magnitude and direction of the fields and do not represent any displacement of any object in the case of with the vibrations of a string waves on a string the the the y versus x was actually a plot of displacement of the string as a function of position at different points

 so the the position of the string was being marked there here in the figure there is no displacement there is nothing connecting these two points this arrow represents the fact that at this point the electric field has just magnitude and direction at the same point the magnetic field has

 so much magnitude and direction similarly here the electric field has the

 so much magnitude and direction this magnetic field has

so much magnitude and direction

so these are all nothing but electric and magnetic fields represented along the axis but by these arrows and they do not this line does not represent a displacement of a particle or a displacement of a medium or anything

so this one must be very very careful and this whenever you look at a figure of electromagnetic waves please keep this in mind that unlike the case of vibrations of a string there is nothing which is displacing up and down all that it implies is as the wave propagates for example like this at this point if the electric field is if the wave is propagating like this if the electric field is pointing up magnitude field is pointing here and at this point if the electric field has a certain magnitude there is a certain magnitude of magnetic field at a little later time maybe the electric field is pointing down and the magnetic field is pointing in another direction

so you have essentially the electric and magnetic fields at this point will vary with time

so for example electric field will start from zero increase in magnitude in the upward direction and then again become zero and increase as a negative direction at this point and oscillate with time for a sinusoidal electromagnetic wave which i will write down in equation at every point the electric field and magnetic fields will vary sinusoidally with time

so if i look at a point if i position myself at a point and if i had a detector for electric field that detector will tell me that as a function of time the electric field is varying it starts from some value keeps on increasing to a maximum then becomes 0 then starts to increase in the negative direction becomes a maximum becomes zero again and periodically oscillates like simple harmonic motion but there is nothing moving it is simply the magnitude and direction of electric fields similarly at the same point when the electric field is increasing magnetic field is also increasing but in the perpendicular direction

so the electric field is pointing up the magnetic field is pointing towards me

so that e cross b is in the direction of motion if the electric field is pointing up and magnetic field is pointing towards you the directional propagation must be here

so please remember electric and magnetic fields are perpendicular to propagation direction electric and magnetic fields are both perpendicular to each other electric field cross magnetic field vectors must be along the propagation direction and this figure is a very important figure that you will find in your textbook and at every place this is a figure which represents a bit of abstract figure this line does not represent any motion of or displacement of any object all it says is it is a point connecting the tips of the electric vector as a function of position here and at the tips of the magnetic vectors as a function of position

so at this point when the electric field has this magnitude magnetic field at this magnitude at this point the electric field has this magnitude magnetic field at this magnitude

so keep this in mind when you are looking at this figure like this and this is a very very important aspect that we must remember when we are looking at such figures now let me write down an equation now i in principle we could use those maxwell's equations and derive any equation which predicts the existence of these waves but that is beyond the scope of this course here

so what i will do is i will write down the solution of these those equations in the form of an electromagnetic wave and show you that those equations are consistent with the maxwell's equations that we have written earlier

so i will write the solutions and show you that

so those solutions are representing waves which we are called as

electromagnetic waves and those solutions are consistent with the maxwell's equations we wrote earlier

so let me write down ah electromagnetic

so sinusoidal waves and these are electromagnetic waves again

so ah if i

so let me draw the figure again here

so i had x y and z

so i drawn the electric field wave like this and magnetic field wave

so magnetic field is in this plane the electric field is in this plane

so i will write for example e is equal to i cap e zero sin k z minus omega t and v vector is equal to j cap v naught sign

so these are equations which are very similar to the equations we had written for waves on a string we have to write for electromagnetic waves we have to write an equation for the electric field as a function of position and time and the magnetic field as a function of position and time this is a wave propagating along the z direction please remember in the case of the waves on a string i had written it as k x minus omega t which represented waves along the x direction here i am writing k z minus omega t that means this is a wave propagating in this direction in the plus z direction these are sinusoidal waves because they are sine functions as you can see both are in phase because both are sin k z minus omega t their directions are such that if e is along i cap b is along j cap

so e and b are perpendicular to each other and both of them are perpendicular to the propagation direction which is along z cap direction wave is propagating alongside electric field is along

so electric field is along this direction this is the electric field direction and this is the magnetic field direction here

so magnetic field seems to be in the magnetic field is in the visor plane the electric field is in the exact plane they are in phase they are perpendicular to each other and e cross b is nothing but i cross j which is along k cap direction which is the propagation direction

so as before k is equal to two pi by lambda lambda is called the wavelength of the electromagnetic wave and omega is equal to two pi nu mu is called the frequency of the electromagnetic wave

so in this k is two pi by lambda lambda is the wavelength of the electromagnetic wave omega is two pi nu nu is the frequency of the electromagnetic wave k is called the propagation constant or wave number and omega is called the angular frequency of the electromagnetic wave

so the electromagnetic waves are now destroyed by these and these are one type of solution of electromagnetic waves these are called sinusoidal waves and ah these are this is represents one type of wave now here as we have discussed before this quantity the velocity of the wave is equal to omega by k this ratio omega by k represents the velocity of the wave and these two represent sinusoidal waves electromagnetic waves the first equation represents the electric field variation with position and the second equation represents magnetic field variation with position now i want to before we discuss these waves in both general i would like to show a figure a slide which shows you the type of electromagnetic waves at various frequencies and various wavelengths

so this is the electromagnetic spectrum this is a spectrum here ah in this direction the frequencies are increasing which means the decreasing wavelength here as you can see frequency and wavelength are inversely related to each other the velocity is a product of frequency and wavelength

so as the frequency increases from left to right in this figure the wavelength decreases

so you can have waves of different frequencies and different wavelengths ah here

so there are starting from very low frequencies electromagnetic waves can occupy where frequencies are very high values

so they have we have given different names for waves of different frequencies here you have what are called as radio waves with frequencies of the order of a megahertz 10 to the power 6 hertz then you have microwaves with frequencies of the order of a gigahertz 10 to the power 9 hertz then you have an infrared region here which is which has wavelength which is frequency slightly less than visible and this is the visible region of the electromagnetic spectrum

so this is the complete electromagnetic spectrum the visible wavelengths are here and the frequencies range from about 4 10 to the power 14 hertz to 7. 5 10 or 14 hertz and then comes ultraviolet in this region about 10 per 16 hertz frequencies then we have x rays which are 10 per 18 hertz frequency and then we have gamma rays which are 10 per 20 hertz frequencies

so you can have electromagnetic waves of varying the frequencies and the visible spectrum to which our eyes are sensitive forms a very small fraction of the entire electromagnetic spectrum

so this is as the frequency increases here the wavelength drops down and you can actually calculate and show the wavelength of these waves are much much shorter than the wavelengths of these waves and i will leave it you to calculate the corresponding wavelengths knowing the speed of these waves because we will now in the next class what we will do is discuss in more detail starting from this equation which i wrote down of the electromagnetic waves electric and magnetic fields i will show you that these two equations are consistent with the maxwell's equations and i will show you that omega by k which is the velocity of these waves is related to epsilon zero and mu zero the dielectric permittivity of free space and dielectric permeability of free space epsilon zero and mu zero and that is where maxwell connected electricity magnetism and optics he showed that optical waves must be electromagnetic waves because he found out that the speed of these waves are is

so close to the speed of light waves that light must be electromagnetic wave
so i will stop my class here right now and we will just continue with our discussions starting from these two equations and i will show you we will calculate the relation between electric and magnetic fields here and i will show you that the velocity of the waves of these waves is nothing but the velocity of of light in free space thank you very much you