

welcome all of you for the fourth lecture on gravitation

So in the last three lectures we have spent a fair bit of time trying to understand the basic laws of dynamics basic laws of motion both kinematics and of dynamics and then we also discussed the nature of fundamental forces and how gravitation is a very important fundamental force because it binds all objects on the macroscopic scale it binds to the earth it binds the solar system together and it holds the galaxy together and galaxies also together gravitational law and its formulation essentially involves a knowledge of distances between bodies which are very very large

So we are speaking of the distance between the earth and the moon the earth and the sun
So on and

So forth and it also involves a knowledge of the masses of the objects

So while when you solve your problem these pieces of information are given to you when we formulate the law it is very important for us to know how these quantities are initially estimated and later determined with greater and greater accuracy

So with that in mind i spent a couple of lectures discussing how using trigonometry and some assumptions on the behavior of space that is it satisfies the euclidean postulates like such such as the sum of the three angles of a triangle is 180 degrees

So on and

So forth we can actually determine distances and it has been done by astronomers for more than 1500 years the determination of masses is a much more delicate job in fact masses are determined through the law because we cannot take a weighing pan and try to weigh what they find out what the weight of the sun or the moon or the earth is

So i will come to that later

So what we shall now do is to assume that we know how to determine the distances and then proceed to formulate the law today today's lecture is probably very important to you because we are going to see the logical structure in the formulation of the gravitational law how we can combine the galilean law of freely falling bodies which i discussed at great length in the last lecture together with kepler's laws the point is that we are combining one terrestrial law the freely falling body is done on the surface of the earth maybe a few hundred meters at most and kepler's law refer to planetary motion around the sun

So we are going to combine the these two and then formulate gravitational law with the help of centripetal force which is something that you have learned in your previous classes

So it is very very important

So at this point we should not forget that galilean law involves a very very important concept which i call principle of equivalence namely gravitational charge is equal to inertial mass

So please remember this word charge is used in a general sense your k the spring constant is like a charge your magnetic moment is like a charge because it gives you the strength with which your body couples to your force conventionally the word charge is not used it is replaced by the word mass that is how the principle of equivalence is formulated

So we say gravitational mass is equal to inertial mass which means that the acceleration of a body at least in the earth's gravitational field is independent of its mass

So i gave the example of a freely falling stone and a block of lead which was performed by galileo from the leaning tower of pisa we have to remember that

So what we have to now do is to formulate kepler's laws

So if you look at the screen you will see the formulation of kepler's law i have already discussed the equivalence principle kepler made use of the elaborate tables prepared by copenhagen tycho brahe and he tried to find a pattern trying to find a pattern is not an easy thing because it assumes an intelligent choice of coordinate system and in the ptolemaic model the concept of a coordinate system was very very complicated

So what is ptolemy's picture you have the earth you have the sun going around earth the planets going around us the stars going around and

So on and

So forth it doesn't matter which of them represents what now the initial assumption is that it is going around in a circle but then you find observations do not agree with the idea that it is going around in a circle after all if you look at the night sky and if you look at the motion of a planet like saturn or jupiter they do not even appear to move in the same direction

So with respect to earth saturn may be appearing to move in this direction let us say

this is the earth and this is saturn after a while you will actually find that it appears to move in the opposite direction

So this is what is called as retrograde motion in astronomy in indian astronomy this was called vakrigati because it is not moving the way it should be moving

So the solution given by the ptolemaic school was to say that well this is moving in a circular orbit at every point there is another circular orbit around which moves

So every point on this main circle acts as a center for another circle

So now you can keep on building more and more circles around every point you can build a circle around this point

So on and

So forth and each of these new circles was called an epicycle and a very elaborate model was built and basically if you want to completely describe the trajectory of a planet you need an infinite number of the epicycles at least a very very large number of the epicycles which are not of much use because these are merely geometric instructions which do not give us any insight however this was the model which was followed by

astronomers in the ancient days because there was a firm belief that the earth is at the center of the universe very very much as humans are at the center of evolution of all living objects living beings a radical departure to this actually was taken by kepler

So the formulation of kepler's law first of all assumes a heliocentric model when i speak of a heliocentric model i am not speaking of a model where the whole universe is going around the sun however attractive it may be our purpose is very limited and what we want to say is that planets are moving around the sun

So it is very tempting and it is very convenient to assume that the planets are moving in circular orbits with the sun at the center of course it is only an assumption and careful observations should either verify it or overrule it

So i will put a question mark

So what is the first thing that kepler did he shifted the center of motion from the earth to the sun that is very very important

So this is a heliocentric model for planets by the same token it will be a geocentric model for the moon we assume that the moon is going around the earth and the earth in turn is going around the sun that is the assumption that we have to make if we want to understand keplerian law

So if you try to fit the observed positions in the sky of various planets what kepler found was

So we are discussing kepler's first law orbits are only nearly circular they are not exactly circular orbits that is what kepler found

So what are they kepler knew you know enough of coordinate geometry and geometry

So kepler was able to fit all the orbits to elliptical trajectories these are nearly circular we are not looking at orbits which are highly elliptical they are the far the farthest planets we are looking at mercury venus earth mars may be jupiter and saturn

So they can be fitted to elliptical orbits and you know that an ellipse i am drawing a exaggerated figure has two focal points

So this is a nearly elliptical orbit sun is slightly shifted from the center and this is the position of the sun an important point to notice at this juncture is that when i speak of an elliptical orbit on an elliptical trajectory ellipses are closed orbits

So orbits are closed the big question is are they really exactly closed for that you need even more precise observations astronomical observations which cannot be done just with the naked eye the answer is no there are perturbations even around the closed orbits that is not of any interest to us at this particular point they can be understood by refining the law of gravitation to include the perturbation coming from other planets

So on and

So forth

So at this point we shall assume that the motion is completely elliptical it is a closed orbit

So we have formulated the first law where sun is one of the focal points now i have to come to the second law which i am going to state

So what you do is i am not going to worry about elliptical orbits i am going to look at circular orbits

So assume that the sun is somewhere here and the planets are moving in a circular orbit and you ask what is the angle subtended by this object over a certain interval of time that is what you are going to ask now if you ask what is the angle subtended the angle

subtended is the same in equal intervals of time

So that means that it covers the same arc length in equal intervals of time

So if this is θ and it is t this is θ and it is t the same distance is covered which means that it covers equal area

So the planet sweeps equal area

So what do I mean by that in equivalent intervals of time

So let me show that schematically if I look at this area and call it A_1 and if I look at this area and I call it A_2 then A_1 is equal to A_2 . What Kepler found was that this is true even when the planet is moving in an elliptical orbit when the orbit is circular your angular velocity is a constant whereas when the orbit is elliptical the angle of velocity is not a constant it is going to change

So what Kepler found was that the velocity always adjusts such that equal areas are swept in equal intervals of time

So this is the second law which I will formulate the second law equal areas are swept in equal intervals of time please notice that the motion is not circular it is elliptic the angular velocity is not a constant but still equal areas are swept in equal intervals of time there is a third law which Kepler discovered which is the most astounding law and which is very very important for us the second law is also equally important Kepler found a remarkable universality

So a remarkable universality for all planetary orbits or for all planetary orbits and let me formulate that

So we come to the third law ok maybe I should use blue pen and that is

So let us say that

So this is not a good figure let me take circular orbits that is a simpler one

So let us say that the sun is situated at the center

So this is a circular orbit for a planet one this is a circular orbit for planet two

So on and

So forth

So we are formulating the third law now let us say the planet one is at a distance r_1 the planet two is at a distance r_2 in an elliptic orbit of course this distance is not fixed it is going to change its time

So there we are going to speak of the mean distance

So you calculate the distance at different positions and calculate the mean distance the mean distance is a constant for a circular orbit but the true distance is not the same as the mean distance for an elliptical orbit there will be some small variations because these ellipses are not highly deformed they are nearly circular that is what I told you and let the period taken by planet one be t_1 and let the period taken by planet two be t_2 So for example you can take r_1 and t_1 to be Mars r_2 and t_2 to be Jupiter Mars is an inner planet Jupiter is an outer planet with respect to the sun because Mars is much closer to the sun than Jupiter what Kepler discovered was that while for different planets the periods and the distances change there was one quantity that was invariant that is why I used the word universality

So irrespective of which planet you are going to choose you find that t^2 by r^3 is equal to constant t^2 by r^3 is equal to constant later when you people study the Bohr model in your next year you find another constant of this same kind which was a mysterious number in spectroscopy that was called the Rydberg constant and Dirac constant gave birth to quantum mechanics the Bohr model and the whole of quantum theory in a similar manner we are going to show how the third law which says that the ratio of the square of the period to the cube of the distance from the sun is a constant gives rise to the formulation of the third law

So we are in position of these three laws and it was verified to a very great accuracy

So it is a very thrilling result but now the question is how do we understand these three laws

So what we have at our disposal is excellent observations and universal patterns common to all planetary motions common to all planetary motions and how many universal patterns did we see three patterns ellipse equal areas in equal times and thirdly t^2 by r^3 is equal to constant whenever there is such a universality remember Jupiter is very big Jupiter is much more massive Mercury is a very small planet almost gaseous Earth is quite a solid

So in spite of all that if all of them should depict the same behavior as always a good question to ask is if there is such a common underlying theme their motion must be

governed by a common law and this is this law which newton set forth to find out and of course there is a fourth one these three are patterns i should say plus one result namely all these were independent of the mass of the planet mercury is very light jupiter is extraordinarily heavy you can probably put 12 earths in jupiter

So it is
So big and
So heavy its almost a star
So to say but still we find that their acceleration is independent of their mass and then they move in elliptical orbits the bodies sweep equal areas in equal intervals of time i have just now explained that to you and finally there is this funny relation that the square of the period of a planet divided by the cube of its mean distance is a constant and we have to understand that obviously the way to understand is through the concept of a force

So what we have to do is combine kinematics
So all these are kinematical results kinematical results with mechanics rather dynamics kinematics is about trajectory acceleration angular velocity angular acceleration position etcetera etcetera dynamics is about force and let us remember the two important laws that we are going to use now the first law is of course of not any interest to us because there is a force acting if there were no force acting all the planets would have been moving with straight line orbits
So we would never have been able to see the same moon again and again or jupiter or saturn or mars
So remember the second law which says that dp by $dt = F$ where p is my momentum and the second law is also very important the force acted upon by a on b is minus the force acted upon by b on a
So the third this third law of motion is essentially a statement of conservation of momentum we told you
So what we are going to do now is to make use of the two laws and try to understand what the common underlying theme is
So this will be our mission for today
So let me sort of give you a brief summary of what we are going to do and what we have discussed
So far
So the first thing is that the motion of the kinematics of planets is independent of their mass kepler employed the heliocentric model for the planetary system let us not worry about the rest of the universe then he discovered the three laws that is what we had what we now want to do is to make use of all the laws together with independence of mass make a simplification and try to get at the gravitational law
So that is why i have highlighted the word simplification
So what is the simplification that i am going to do at this juncture i am going to ignore the fact that they are elliptical i am going to assume that they are spherical we are not going to lose any generality in that to get the law because once you get the law you can always verify whether that law correctly gives you the elliptic orbits once an object is in a circular motion we know that if you use the second law equal areas being swept in equal intervals of time is tantamount to constant angular velocity and that is tantamount to a centripetal force a uniform centripetal force
So we will make use of that then i am going to make use of the third law and deduce precisely what the nature of that force is
So now you see a full fledged interaction between kinematics and dynamics
So this is something which is truly enjoyable and that is what we want to do we are also going to use the third law to establish a reciprocity
So let me explain that
So please stare at the screen for a while i have written something in a very cryptic form which i am going to explain by working out
So what i am showing here is that suppose m_a you know a body a
So let us call it as a planet a has a mass m_a and a body b has a mass m_b what are we saying we are saying that the force exerted by a on b is the negative of the force exerted by the body b on a but in gravitational case when a moves in the field of b its acceleration is independent of m_a and when b moves in the field of a its acceleration is independent of m_b
So let me write that here

So there is a planet a and there is a planet b this has a mass m_a this is a mass m_b
So what are we saying newton's third law says f_a on b when i write this arrow a is acting on b is equal to negative of f_b on a
So i will put a vector sign although it is not very important at this particular point the acceleration of a is independent of mass m_a the acceleration of b is independent of mass m_b

So what will i do first i will look at if b upon a

So i am asking for the force exerted b by b on a what should this be this should be proportional to m_a how do i know that this must be proportional to m_a because this is nothing but m_a into its acceleration a_a of a now if it is proportional to m_a when i equate these two the proportionality constant goes away and my acceleration of a is independent of its mass

So the force that is exerted by b on a is proportional to m_a now let us make use of the symmetry which is essentially what the third law is my force on a because of b should be proportional to m_b but then there are negatives of each other

So what are we going to write we are going to say that the force whether a acts on b or b acts on a now i am not interested in the sign i am only interested in the magnitude it must be proportional to m_a into m_b that is the statement this is very very fundamental and we already got a very nice description of the strength part what is the next thing that we are going to do the next thing that we are going to do is to make use of the circular orbit

So let us remember the kinematics of the circular orbit

So if i have a circular orbit at any given point my velocity is tangential and the force is radial is inward radial this is my force and this is my velocity

So force is inward radial the acceleration is always in the direction of the force therefore my acceleration is also inverted radial both are inverted radial if there were to be a centrifugal force that would have been outward radial centrifugal force is an inertial force it is a pseudo force it is not a real force but here we are speaking of real forces produced by real bodies and that is a centripetal force that is inward

So we know what this is but when i say that is inward i only fix the direction i do not fix the magnitude i do not fix how it changes with the distance

So what do i know i know that it is proportional to m_a i know that it is proportional to m_b i know that it is inward

So what do i do let us say that i locate the center of the orbit at the origin and this is my circular orbit i need not have written a three dimensional figure and this is my unit vector r then my f sorry radius vector r my f is proportional to minus r only then it will be inward and my acceleration will also be proportional to minus r plus r is this direction minus r is this direction this is cf this is minus f if you feel like

So this is something that we have to remember

So how do i write the force now i write my force to be

So let us say i look at my body a here and like locate my body b here and the radius is f my f is nothing but minus g that is a constant of proportionality then i will write a mass mass of the body a mass of the body b i am looking at the force exerted by a on b

So i have already written this therefore i will put the unit vector r and then i will multiply it by an unknown function f of r this corresponds to the centripetal force

So what is the condition on f of r my f of r is greater than zero because the sign has already been accommodated well if you want to call this r_a and if you want to call this r_b then you will have to define r_b minus r_a and write its negative that is what i have done in my slide in my computer slide but never mind about this we have almost got the law

So what we have done is to consistently and repeatedly use the second law the third law the keplerian law and the concept of centripetal force

So now if you can somehow determine this f of r bingo we have got the law of motion and what is it that we have left out the only law that we have left out is the third law of motion

So we shall invoke that here

So that is what we have to do

So what we have to do is to make use of the third law okay

So what we are going to do is to assume that it has a certain dependence even otherwise it can be found out but it is convenient to assume that f of r has a certain dependence and then we will deduce what kepler's third law is

So our mission is determination of f of r

So let us say that f of r is proportional to r to the power of n of course Newton said that it is proportional to 1 over r squared n equal to minus 2 and that is what we have actually I am going to return to Kepler's second law to get equal areas in equal intervals of time through this again the centripetal force automatically guarantees that we will do that in a while

So let us see what the argument is

So I will show you the basic things that I have written on the slide again and then I will work it out

So here the left hand side is my centripetal force my right hand side involves the unknown function I am looking at an orbit with a fixed radius

So everything is absorbed in k I want to cancel my m I have kept it I know the relation between angular velocity and the period and I am going to use that in order to determine f of r

So this is a snapshot of what I am going to prove and here I am going to work it out in great detail

So let me write that down

So what do I have I have my force is equal to $m \omega^2 r$ I am assuming a circular orbit because equal areas are in equal intervals of time my ω is a constant let us not forget that that means the period is a constant T and this quantity is nothing but we are only writing the magnitude we are not worried about the direction anymore because I have already declared that it is a centripetal force

So this is m and this is the mass of the other object I am sure you people can figure out then there is a g I have already written that and then I have my f of r

So that is what I have to write and how to equate them

So this is the statement that the acceleration is independent I can combine this the mass of the other object and g into constant k because we are looking at the motion in a given period therefore what we have is $\omega^2 r$ is equal to some constant into f of r

So we have incorporated the second law of motion and the circular orbit what I have to now do is to employ the fact that ω is equal to 2π by T

So what does it imply this implies ω^2 is equal to $4\pi^2$ by T^2

So let me substitute

So what I will be saying

So we are saying that $\omega^2 r$ was a constant into f of r and this tells me that $4\pi^2 r$ by T^2 is equal to constant into f of r

So in other words r by T^2 is some other constant k' into f of r that is what we found out now what do you have to do all that I have to do is to argue that T^2 by r^3 is a constant I have r into T^2

So what shall I do I shall multiply it by r^3 and I shall multiply it by r^3 and make it constant because this quantity is nothing but r^3 by T^2 if T^2 by r^3 is a constant r^3 by T^2 is also a constant it is nothing but the reciprocal

So this is what I have

So what does it imply this implies f of r into r^3 equal to constant

So we have to box it we have to box it and frame it in a golden frame because we are almost on the verge of arriving at Newton's law

So if f of r into r^3 equal to constant what do we conclude we conclude that f of r is proportional to 1 over r^3 that is what we conclude

So if f of r is proportional to 1 over r^3 there is a constant of proportionality there are which can be absorbed in g therefore what does it imply this implies my gravitational force magnitude wise is nothing but $g m_a m_b$ by r^2 which is exactly what Newton wrote

So now I can complete this argument by also fixing the direction

So let me fix that I have this my body a is here my body b is here

So this is r_a this is r_b this is r_a by r_b

So we are showing the vectors correctly then

So my f this is a and this is b the body f_a acting on b is minus $g m_a m_b$ by r_a by r_b squared that is what I have into unit vector \hat{r}_{ab} which is probably the most celebrated law in physics this is the universal law of gravitation which we shall know extend to all bodies having masses

So we started with the Galilean law which looked at freely falling bodies in the earth's

gravitational field then we looked at the planetary motion now what we are going to do is to say that what is valid at the terrestrial scale and what is valid at the celestial scale should perhaps be valid at all length scales this is of course a generalization an assumption some kind of an inductive argument and we will postulate that this law is the correct law which is valid between any two massive bodies irrespective of what the distance between them is irrespective of what their masses are that is a very very important thing that means a final vindication of the formulation of this law will come only when gravitational law is verified at all length scales with bodies of varying masses at this point i would like to caution you people that although the argument is so straightforward

So simple and

So convincing it almost looks like a derivation of newton's law please remember this is not a derivation this is only a motivation like all fundamental laws this law also cannot be derived it is an extraordinarily important thing and that is why it is called as a law law of conservation of energy cannot be derived it is a fundamental law you can formulate it law of conservation of momentum cannot be derived maxwell's equations which you are going to study the coulomb law the bioshock law these cannot be derived ampere's law they cannot be derived they are fundamental laws that is why we call them maxwell's laws loss of electrodynamics in a similar manner law of gravitation can also not be derived these equations are set up what do we mean by setup you make a number of observations and to ask for the simplest and the most convincing logical way of formulating them and if we are lucky nature accepts this formulation which we will verify by looking at phenomena that take place in the laboratory or in the sky at various levels and that convinces that this law is correct

So for example if you have an inquisitive mind you should be able to ask how do i know for sure that this law is the same when i look at two bodies which are separated by a micrometer you could ask that question in a similar manner you could also ask the question how am i sure that if i make very very careful measurements that this law is accurate even at the astronomical scale for example i told you in doing this we assume that the orbits are closed but the orbits are not closed

So if i look at the motion of a planet for example it is not only acted upon by the sun it is also acted upon by the other planets because of which the orbit need not be closed So a big question is what would happen if i look took all the effects into account do i get a complete agreement or there is a or is there a mismatch

So what i am trying to emphasize is that physics is a continuously evolving experimental science with which the theoretical construction or the formulation tries to catch up So that is exactly what happened when einstein gave his general theory of relativity he found that the orbit of mercury there was a small discrepancy very very tiny discrepancy which could not be explained by newton's law and he had to produce he had to actually develop a brand new theory in a similar manner we should be able to ask a question whether there are variations in the gravitational field over a micrometer scale or a meter scale there are occasions when people claim that they have actually found such a variation but luckily those claims have not been substantiated

So it appears that gravitational law is quite robust around this length scale of course if you go to extraordinarily small scales gravitation probably will get a correction it is getting a correction at the galactic scales but still you see that the sweep of gravitational field is enormous let us say from a meter to hundreds of thousands of kilometers and there is no wonder that newton called it the law of universal gravitation So what we have done is to set up a law using everything that we know and at this point we should not forget the genius of newton because he formulated every single concept that was necessary the laws of motion the concept of inertia he made use of the centripetal force and he formulated the law of gravitation and it is for this reason that newton is considered to be probably the greatest physicist that has been that human kind has ever seen

So far however there is a small reconciliation that we have to do we have not yet completed that once we did that we are ready to work out applications and that should actually be the end of the discussion of gravitation as far as we are concerned

So what is the reconciliation that i have to do let me see if i have a slide on that okay this is the formulation that i have written i have written it slightly differently here i have put a cube the distance between a and b in the denominator and i have put the full vector whereas when i worked it out i put a unit vector here and i put a square usually

it is called the inverse square law and that is what we have done ok now the reconciliation is that the minute i write f is equal to minus $g m m$ by r square let me not worry about the vector sign force is falling with the inverse square distance So let us say that you have a very massive object earth and there is the proverbial apple which is falling

So apple is falling towards the earth and what is apple 3 meters 4 meters

So that is the height

So let me write another figure

So i have the earth and there is a tree and an apple is falling

So we are speaking of something like 10 meters let us say maximum i mean we do not find an apple tree which is 10 meter tall but let us say somebody went on the top of a building and dropped what is the thing that we find we find that this acceleration is a constant it is independent of this height but newton says that it should fall as the square of the distance therefore we have to reconcile the galilean law which says that acceleration is a constant that is why you denote it by g acceleration due to gravity with the inverse square distance and that is a very easy thing to do

So let me do that for you and then we will see what the other applications are

So what are we saying i am going to draw an extraordinarily exaggerated picture

So my center of the earth is here the radius is r and an object is falling radially inverse and this distance is h

So it even this figure is not to the scale therefore at any given time the total distance is r plus h this is the total distance this appears to be very simple but actually this is one of the most complicated concepts what is the complication in this earth is an extended object it is not a massive object whereas in my formulation i always showed the body and body to be point masses i was able to define a distance now let me draw another picture if my earth is here and if my body is here which distance are we supposed to calculate this distance this distance this distance this distance in fact what we should do is we should look at the force coming from each of these massive small unit units of mass and we should be able to find out and we do not have the where with all to do that i don't know how to integrate basically and it might interest you to know that even newton did not know how to do it newton invented differential calculus archimedes invented integral calculus but newton did not know how to do this integration of course it is very very tempting to say that when the earth is going around the sun sun can be taken to be a point object but i cannot take the earth to be a point object when a stone is falling from a hundred meter tall place i cannot do that

So newton did not publish his ears for almost 15 or 20 years because he wanted to prove that whenever there is a spherical distribution of mass we can assume that all the mass is concentrated at the center

So what are we saying this is a very very important result it follows from what is called as gauss's law which you will study in your 12 standard

So let us say that there is a spherical uniform spherical distribution uniform mass density of radius r now if i look at an object which is sitting somewhere here okay and this distance is r the question is what is the force on r the force on r is as if all the mass was concentrated at the circle at the center of the sphere

So the force is given by $g m m$ by r square where r is the distance from the centre and this is the total mass

So what are we saying this m is ρ into total volume which is nothing but 4 by 3 pi r cubed ρ you are given a uniform mass density this volume is the mass of this object r small r is the distance between this center of the sphere and m you have to prove this and newton did not know how to prove this and being a very honest person with very high standards for himself he did not publish the result until he gave a proof for this he gave an extraordinarily beautiful geometric proof we will not worry about that it is too early for you at this stage for us to give this proof

So if you are going to make an assumption now we can reconcile the falling body problem falling body

So what is my force my force rather my acceleration is nothing but minus g mass of the earth divided by i did not worry about minus also r plus h whole square

So this is what i have and what are we saying we are saying that h is much much smaller than r because r is the radius of the earth and h is the height above the center

So what is it that we have to do at this particular point very simple we have to make a binomial expansion all of you are familiar with binomial expansion the zeroth order

approximation that we can do is to say ignore h

So zeroth order approximation since h is much much less than r take h approximately equal to 0 that is not a nice statement to make take h by r approximately equal to 0 because it is a very very small number then a is given by g by r square which must be your acceleration due to gravity

So we have already reconciled to a certain extent how we are able to get a constant acceleration and this is the number that is given to you to be what 10 meter per second square 9.8 meter per second squared

So on and

So forth

So if you know the mass you can find out the gravitational constant if you know the gravitational constant you can find the mass but then we can do better than that as I told you by making a binomial expansion I would like to discuss that

So probably since that would take a little bit more time and you people would like to revise whatever we have done

So far let us stop at this particular point and resume our studies with the law of falling body and then go on to look at applications involving satellite motions artificial satellites escape velocity

So on and

So forth bye you