Select/Special Topics in Classical Mechanics

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Module No.# 05

Lecture No. # 16

Real Effects of Pseudo-Forces (ii)

Let us continue our discussion on the non-inertial frame of reference. We have already come to terms with the fact that forces which are not real pseudo forces they generate real effects and this business of carrying out observations in an accelerated frame of reference forces us to invent forces which do not exist.

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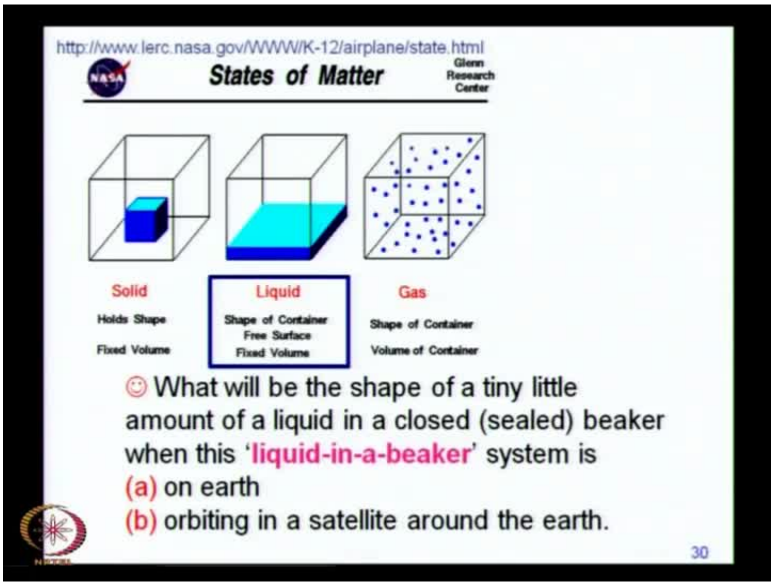

So, we have to look for a cause when there is no physical cause. Let us try to understand this, we talked about weightlessness last time, we talk about the difference between mass and weight and in particular, we talked about weightlessness, let us discuss this idea little bit further. We will talk about various states of matter, because it is matter which has got mass and when it is in a state determined when its dynamics is determined by gravity then it has weight.

So, matter comes in various forms like solids and these are characterized by the fact that it has got a shape of its own, it has got a certain volume then, there is a liquid and a liquid takes the shape of the container in which you keep it. So, you can tilt this and it will take a different shape but then no matter how you tilt it, you find that it has a free surface at the top. The liquid is characterized by this that if you tilt it, no matter how you tilt it, it will have a surface which is a free surface and that is a characteristic feature of a liquid. Then, you have a gas and what the gas does is to fill up the whole space that is accessible to it. Now, these are the usual states of matter, I will not talk about the (( )) and condensation so on.

So, you have these states of matter, what happened?

Covering the frame sir,

Which frame?

This frame sir,

Do you need did you get the previous slides,

Continue sir continue the with this,

So, we do not have to go back,

What happened in the previous lecture I do not know, it was ok.

So, these are the three usual states of matter and a gas fills up and occupies whatever space is available to it. We will focus our attention on a liquid; I motorize a question which is quite interesting in the context of liquids. The question is what will be the shape of a little amount of liquid that you keep in a beaker? There is a beaker which is a closed, let us say that you have got some container and you seal it. In this beaker you put a certain amount of liquid, something like this; you keep some liquid and it is kept inside this and you keep it over here on this table as we have done it now or else what would be more interesting is that all of us go on a ride in a satellite that will be fun whether we not do any experiments, but it will be fun.

If the satellite is orbiting around the earth and there we have some furniture, we have in our space suits and breathing oxygen and having what a dream, I love it. I do not think I want to come back to the discussion on today's class, because it is much more exciting to think about being an astronaut, I really wanted to be one.

So, if in a satellite you again have a liquid and then you keep it on a table and you ask the same question what will be the shape will it be as you see it over here if you tilt it you see how the shape changes - can you get it in the camera. Now, it continues to have a free surface, will the shape be the same if the same experiment was done not here on earth, mother earth gives us tremendous comfort and security, but if we are in the state of motion sitting in a satellite and going round the earth, we will be in a state of free form in some sense and we ask the same question what will be the shape of this tiny little amount of liquid.

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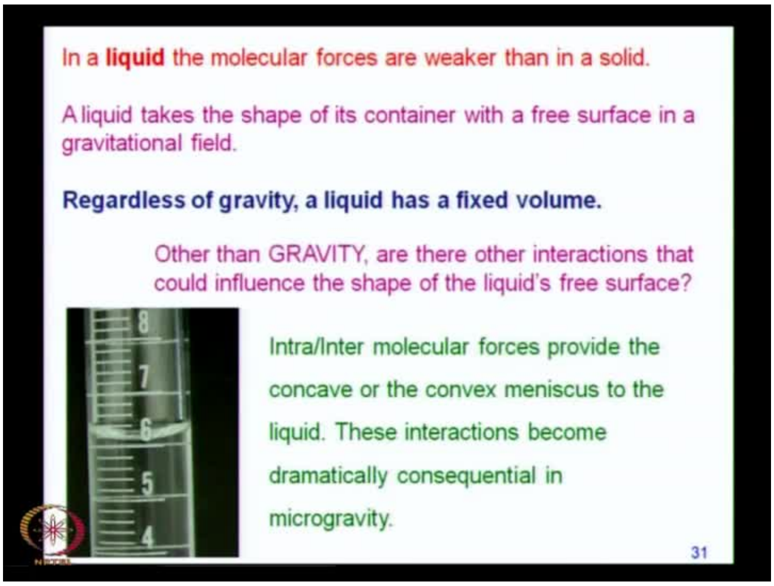

Now, this question has to do with the fact that whenever we do physics, we always have to work with some approximations. There are very few problems in physics which I have got exact solutions - very few, I always make some approximation and the manner in which you make an approximation is, whenever you have terms which are additive you neglect the weaker terms compare to the stronger terms.

Over here, when you say that the liquid has taken the shape, in general sense that it is flat we have already made an approximation because, we are only taking gravity into account, it is because of gravity that the liquid has the shape as you see over here, but then there are other forces of the liquid.

These intermolecular forces which are rather weak and then, there are intermolecular forces and intramolecular forces. Intramolecular forces are the molecular forces between the molecules of the same spaces; then, intermolecular forces are molecules of different kinds, there are different kinds of molecules that you are talking about because they are molecules of the liquid which is inside it but then it is in contact with the beaker or with the container with this bottle in these case. So, it is in contact with something and there will be some molecular forces between the liquid and the container as well and what is the relative strength of these two forces with respect to each other and with respect to gravity.

These are the questions that we did not consider explicitly, when we simply say that the shape of the liquid is that it will have a free surface, it will be flat and this is what we call as the horizontal plane, so this is the common vocabulary that we make use. What is going to happen is that when it is in a state of weightlessness or the so called weightlessness all of forces must be taken into account because they may not be very strong compared to gravity over here. But, when the effect of gravity is weak as happens in a state of weightlessness then, the relative importance picks up and that becomes a determining factor.

These other interactions which are responsible to generate the shape of a liquid are the cohesive forces and the adhesive forces. In fact, even here these are the forces which give the so called meniscus to the free surface. The free surface is not exactly flat, it has a certain meniscus and the meniscus is either concave or convex and that depends on whether the intermolecular forces, whether the adhesive forces are stronger or the cohesive forces within the molecules of the liquid are stronger, so depending on that the meniscus is either concave or convex.

In a state of free fall the gravity plays lesser role because the entire system is accelerated toward the center of the earth. The whole system is in a state of free fall just like Sergei Bubka, when he is going over the bar it is a free fall and this orbiting satellite is also in a state of free fall. The only forces which will determine the shape that the liquid will take are these intermolecular forces.

Now, the question will be whether the force the adhesive forces between the liquid and the container are strong or the cohesive forces between the molecules of the liquid themselves these are strong, which of the two is stronger because gravity will not play much role. Depending on this if the molecules of liquid have a stronger attraction between themselves then it will just form a globule which will remain suspended somewhere inside this container without really touching the walls.

On the other hand, if the adhesive forces are stronger the molecules of the liquid will spread all along the internal surface of the closed beaker leaving a cavity in the middle, it is a very strange thing but, that is exactly what will happen if the adhesive forces are stronger. Some of you will hopefully become astronauts and see this for yourself.

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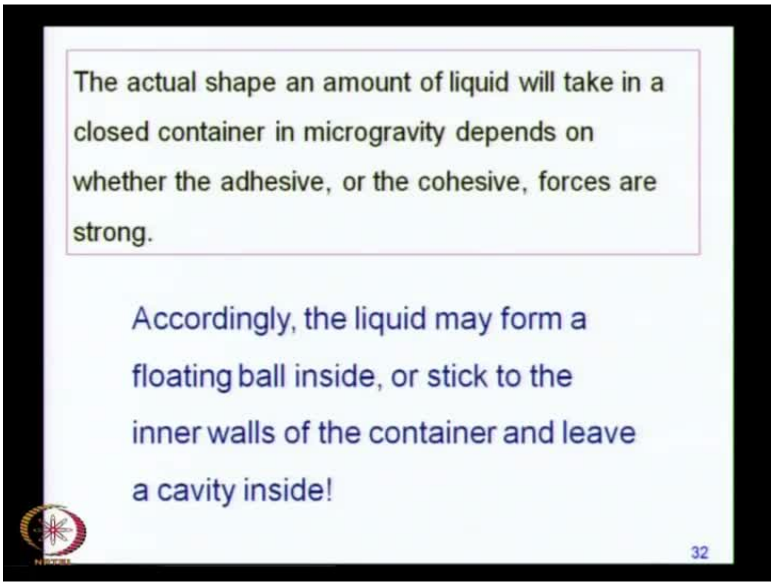

The actual shape depends on whether the adhesive or the cohesive forces are stronger and this is really a very fascinating example, because the liquid could either be like a floating ball inside or it could just stick to the inner walls of the container and leaves a cavity inside.

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You can enjoy state of weightlessness or zero gravity as it is called and you do not really have to become an astronaut for that because to become an astronaut you have to go through lots of rigorous training and before that the selection process is very tough which is part of the reason I did not become one.

If u do not become an astronaut you can still get the zero gravity experience, all you have to do is to go to this website go zerog dot com and you can book a flight for a 0 gravity experience it costs just a little over 5000 dollars but that does not include the taxes I have no idea what it is, you can go and have some fun.

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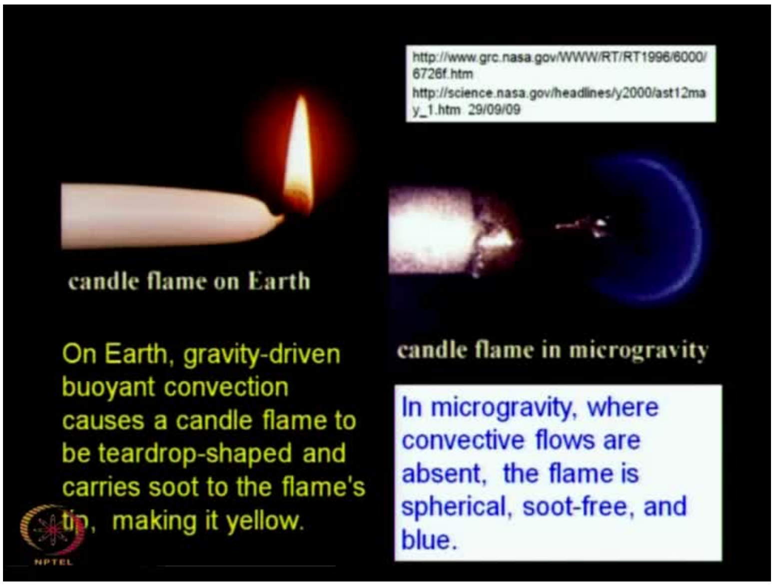

This is called the zero gravity experience and you can actually get it for yourself. There are other effects for example, the shape of a flame of a candle. If you light a candle in dark, this is how a candle would look and these pictures are from NASA's website you can get much more information from NASA website than what I am going to discuss over here.

Typically, on earth if you light the flame of the candle, it will look yellow and it will look like a tear drop shape as it is called and the reason it has got the shape is because, it is the convective currents which carry the soot to the top of the flame. The whole combustion process, the chemistry of combustion, the thermo dynamics is a fairly involved process and I am certainly not going to discuss all aspects of this. Just these one little aspect that this is the general shape of the flame and it is yellow and the reason for yellow is because these convective currents, they carry the soot to the top. Convective currents obviously take place against gravity, so gravity is important it is against gravity that convection raises these hotter molecules to the top.

So, gravity is essentially an integral element of the convective current process. If you do this in a state of weightlessness where gravity will not play a role then, the convective currents will be absent and the flame will be blue color because the soot will not be carried to the top. So, the experience in a satellite for astronauts is really quite different from what it is for as on earth because, that is in a state of a free fall whereas we are reasonably stable on earth.

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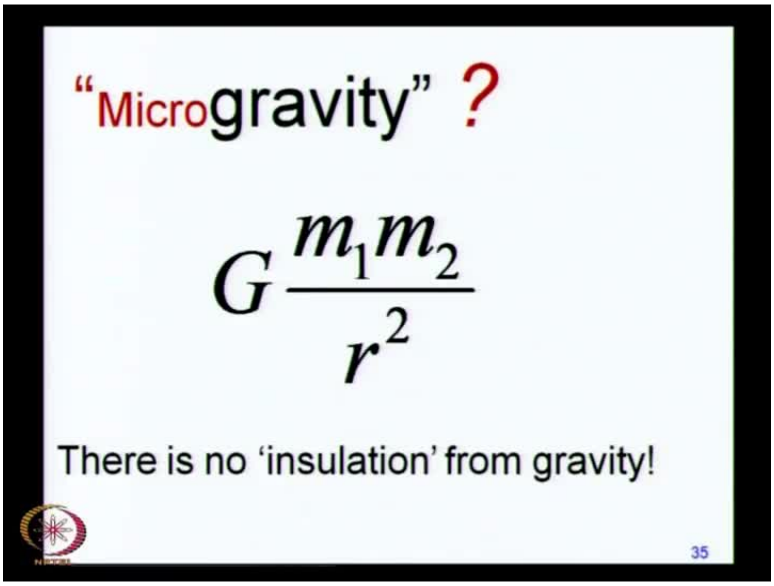

Now, we do use the terms microgravity which is used on at the NASA website, we also use this term weightlessness over here, know how many using it but one must remember that you really do not ever switch off gravity. You can insulate electromagnetic interaction for example, you can put insulators but you cannot take two masses and put anything in between and stop these two masses from attracting each other by a force which is exactly always is equal to G m 1 m 2 by r square, no matter what you put or do not put in between them.

So, you cannot switch off gravity, you cannot really have zero gravity, there is nothing like zero gravity. There may be points where various forces balance out and so on, the state of weightlessness has got a meaning of its own because all parts of the object are falling at the same, they undergo the same acceleration but that is the idea, that is what generates the state of weightlessness it is not the universal constant capital G - this is the upper case capital G - this does not have a go to 0, so you have to use these terms or with some degree of caution.

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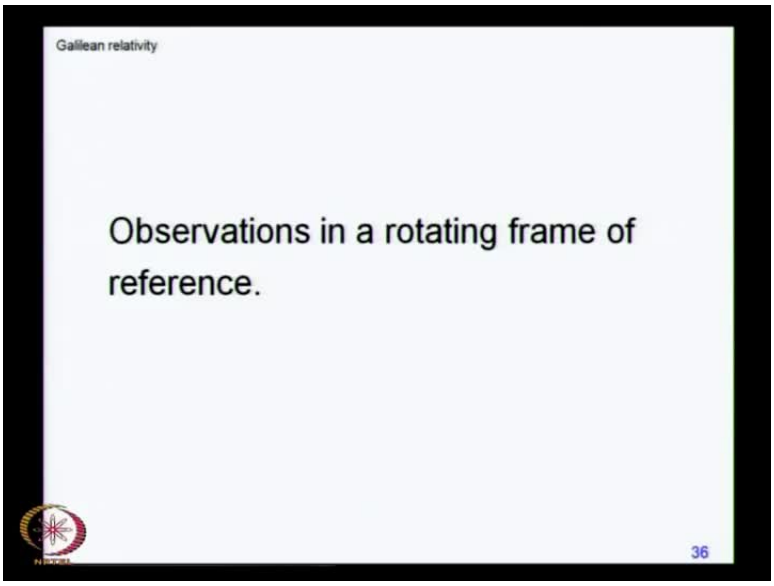

Now, having said this we will discuss observations in a rotating frame of reference. We considered a frame of reference which was moving away from an inertial frame of reference at a constant velocity first, then at a constant acceleration. Now, we will consider an inertial frame of reference with respect to which another frame of reference rotates and what will be the consequences in this frame of reference, thus causality survive, can this be modified and can we reintroduce causal relationships in such a frame of reference? These are the question that we are going to take up in today's class.

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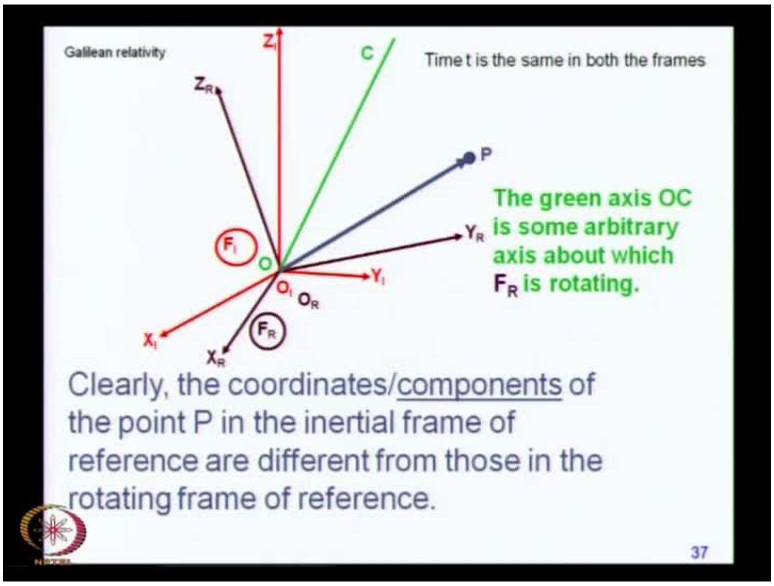

So, we consider a frame of reference F I and there is X axis, Y axis and Z axis and there is another frame of reference which will be the rotating frame of reference with the subscript R and t is equal to 0, let us say that the two frames of references are on top of each other, their origins coincide the axis are corresponding, the corresponding axis are parallel to each other. Then, at a certain instant of time one frame starts rotating with respect to the other about a certain axis.

So, OC is some arbitrary axis and about this axis you have the second frame of reference which rotates about this axis. So, you have the X axis will come here, the Y axis will go here, the Z axis will go here and there will be this rotation of this, what is this color? Purple is it, I would think so.

So, this purple colored frame of reference rotates about the green axis which is along OC. The purple frame of reference is now in a state of rotation about the axis OC. You have got an observer in the purple frame of reference carrying out observations which he will compare with the observations carried out by another observer who is in the red inertial frame of reference, so that is the comparison we are now going to discuss.

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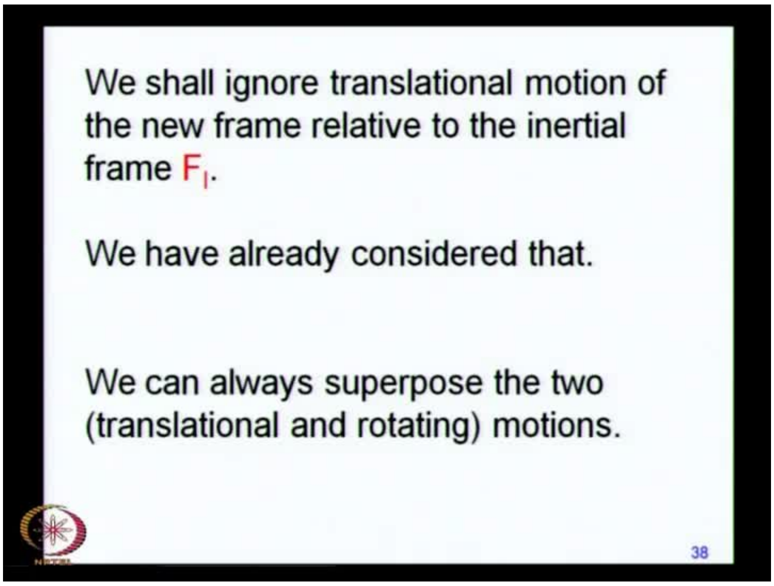

The components of any vector, so if OP is the position vector of a certain point P, does this vectors seem to be different to the two observers? The components of this position vector of course are different from the origin to the point. So, given that perception which both the observers have the X component, the Y component, the Z component they will of course change from time to time.

So, what we will do is for the time being ignore any translational motion between the two frames because we have already discussed that in our previous class, we can always superpose that and combine it with the rotational motion as well, but we will do one thing at a time and then, if necessary we can always superpose the two relative motions. For this discussion, I will ignore any translational motion of this purple frame of reference with respect to the red frame of reference, there is no relative translation. The two origins remain coincident throughout the event that we are talking about.

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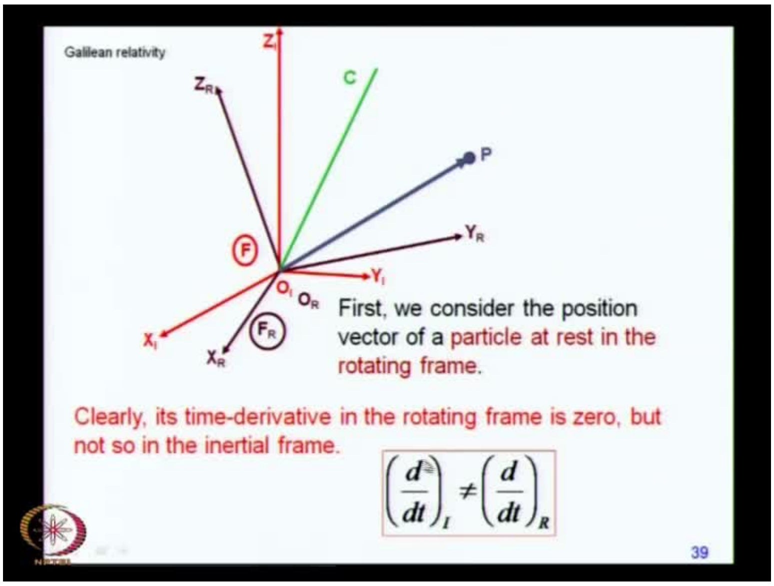

Now, what we are doing is this which is to observe a point P and we have this rotation about the green axis OC. We consider the position vector of a particle which is at rest in the rotating frame of reference - mind you it is at rest in the rotating frame of reference.

If the observer is somewhere on this rotating frame of reference, this frame of reference is rotating like this and an observer who is over here looks at this point and to him this point remains, where it was no matter how much time as a wall. To the observer who is in a rotating frame of reference this point is at fixed, but the same point will seem to be in a state of motion to an observer who is in the red inertial frame which is not rotating.

So, we consider the position vector of a particle which is at rest in the rotating frame and while it appears to be at rest in the rotating frame it does not appear to be at rest, so the time derivatives in the two frames are obviously different. This is the differential operator d by dt which takes the differentiation with respect to time in the inertial frame of reference. The effect of this operator is not going to be equal to the effect of taking the time derivative in the rotating frame of reference, so that is the first conclusion that we draw.

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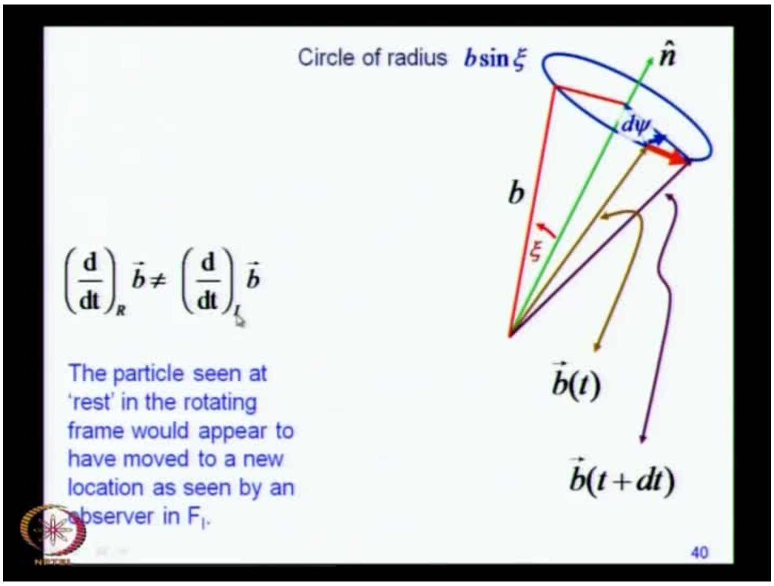

Now, let us see how this particle which is at rest in the rotating frame will appear to an observer, who is in the inertial frame. Let us say that we do not talk any more about just the position vector but any vector, let it be b t, it can be the position vector but this is some arbitrary vector b, this is the axis about which the rotation is being considered. This point will be taken to a new point here in the rotating frame, it will appear to be static to an observer in the rotating frame, but to the observer in the inertial frame it would have seem to move through this red displacement vector.

This is the position b at a later time t plus dt, when this was the position at an earlier time t and as time continues this point will seem to go, it will seem to traverse on the surface of this perimeter of a cone whose vertex is over here.

This distance from any point on the rim of this cone to the vertex is b. In the time dt or a differential time increment delta t the angle which is swept is - let us say - d psi and this cone will subtend an angle at the vertex. If you look at any of this radial lines whether this or this or this, this will have a cylindrical symmetry about this green axis. So, you can take any radial line and they will all subtend the same angle which is the angle I indicate over here, which is xi, so that is the geometry that we are talking about.

The rate of change with respect to time of the vector b in the rotating frame is actually 0, as we know it that is by our choice. This is obviously not equal to the rate of change with respect to time in the inertial frame of the vector b; our question is what the difference is?

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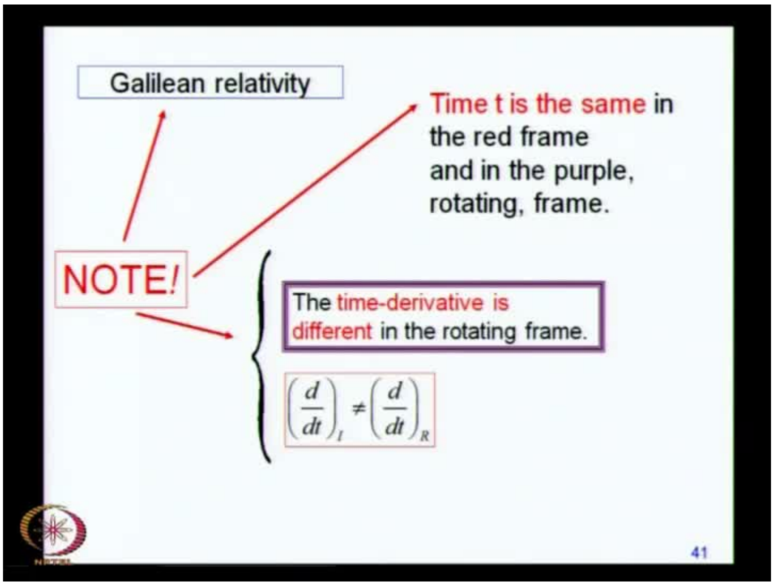

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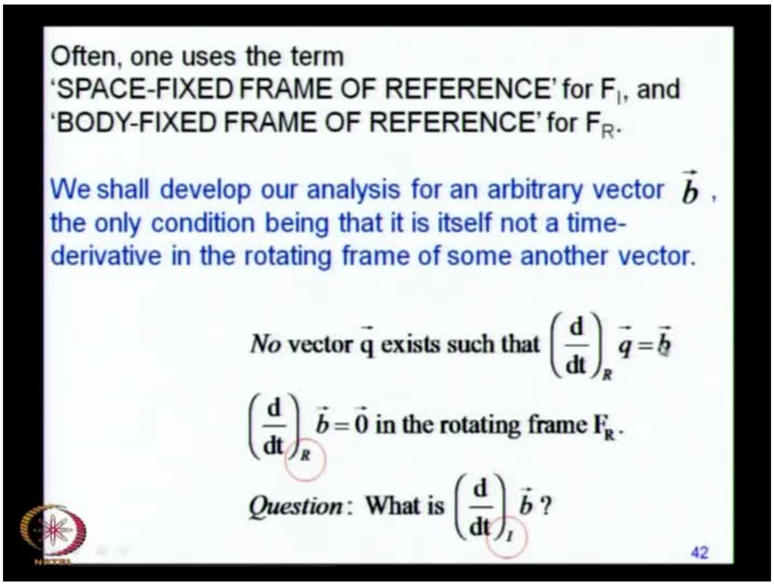

You must remember that we continue to work within the domain of Galilean relativity; this is not of great significance till we really meet fluorine's relativity. We shall be doing that only in the next unit, but in anticipation of that, let me remind you that we are working within the domain of Galilean relativity. Time has got the same meaning but the time derivative in the two frames is different, the time derivative in the rotating frame is 0, the time derivative in the inertial frame is not 0. There is a certain relationship between these two and we have to discover what that relation is.

So, sometimes the inertial frame is called as the space fixed frame of reference and the rotating frame is called as the body fixed frame of reference that these terms are almost self-explanatory, so I need not elaborate the meaning.

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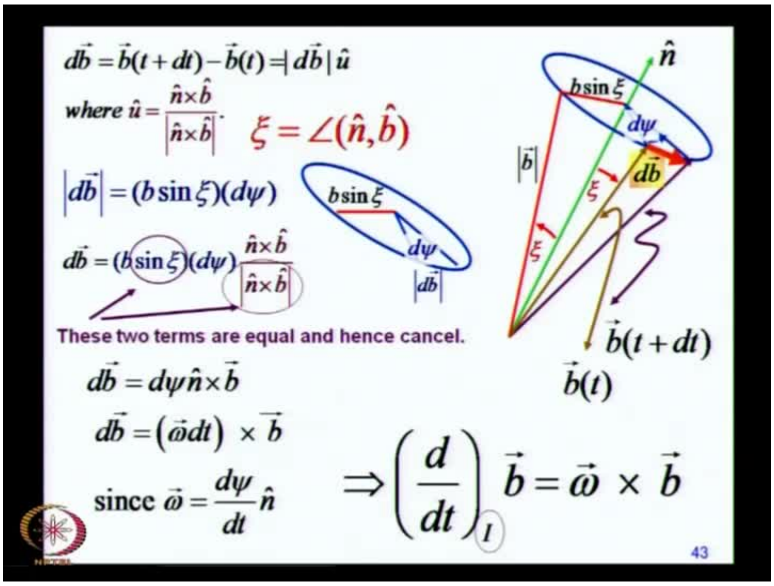

Again, let me remind you because this of importance that we are dealing with the vector b and this itself is not the time derivative of some other vector in the rotating frame. In the rotating frame it remains in varied, so that is the situation that we are dealing with.

So, no vector q exists such that d by dt of q is equal to b, so b in the rotating frame is a constant vector, it is not going to change. So, this is our geometry and now, what is the angle xi? xi is the angle between this direction n which is a unit vector along this axis shown along the green line and b is the instantaneous position of this vector which remains static in the rotating frame. In the inertial frame it moves as time progresses and the tip of this vector will sweep along the rim of a cone whose vertex is at this point, which I am showing here in this figure.

From this geometry you can easily see that this distance is b; this is the magnitude of the vector b. Therefore, the radius of this circle which is the phase of this cone, this is b sin xi, so that part of the geometry is simple enough. So, this is b sine xi, this angle which is swept is d psi which means that if you want the exact vector db which is this red displacement vector, this displacement vector is the difference between the vector b at a later time t plus dt from which you subtract the position the vector b at the time t which is the magnitude of the db times a unit vector. You can easily see direct from this diagram that the direction of this red vector here will be orthogonal to both n and b because, it is the change in b. So, the change in any unit vector is always orthogonal to it, it must be orthogonal to b and also to n.

It is actually along n cross b, so the unit vector will be given as n cross b divided by the magnitude of n cross b, because that is what will you give the unit vector in that direction. The magnitude of this vector db is this, which is this arc length, which is b sine xi times the angular displacement, which is d xi. So, this is the magnitude of db, which is the arc length of this, which is b sine xi times this angular displacement d xi, so b sine xi these d xi is this magnitude db is that clear.

We can write an expression for the displacement vector db itself which is the magnitude, which is b sine xi d xi times the direction unit vector, which is n cross b over the magnitude of n cross b, but what is the magnitude of the n cross b? That is sine xi. The cross product of the 2 vector has got a magnitude which is equal to the product of magnitudes of the 2 unit vectors which is always equal to 1 times the sign of the angle between.

So, sine xi n cross b also has got a sine xi sitting in it, so these terms will cancel each other. This sine xi in the numerator and this sine xi which is implicit in the cross product of n cross b will cancel each other and you get a relatively simple expression for the displacement vector db which is this d xi times n cross this vector - which is a unit vector - times this magnitude b which will make the vector b itself.

So, I have included the magnitude of this vector b and this direction of that vector together in this vector b. So db, the displacement vector becomes d xi times n cross the vector b itself and d psi we know because, if omega is the angle of velocity then, it is nothing but d xi by dt times the unit vector. So, you can write d xi times n as omega dt; this is the rather straight forward algebra.

This gives us db equal to omega dt cross b which means that if you divide both sides, you consider these to be like small increments delta b over a time evolution delta t and write this as delta b equal to omega delta t cross b, divide both sides by delta t and take the limit delta t going to 0, you will get the rate of change of b with respect to time in the inertial frame of reference. This is exactly what we were looking for, because we knew that the rate of change of b in the rotating frame of reference was 0 whereas, in the inertial frame of reference - we wanted to find out what it was and what we discovered is that this - is rate of change of with respect to time of the vector b is given by the cross product of the angle of velocity vector omega with the vector b itself.

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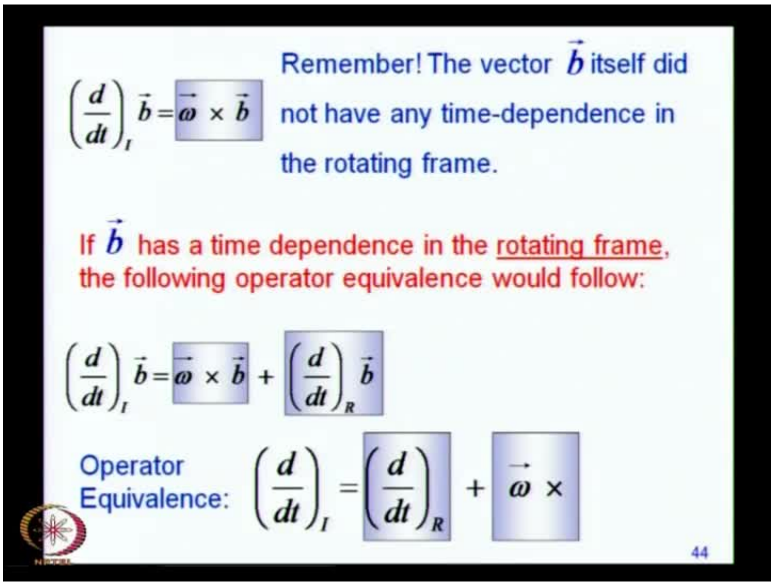

Now, this relation is valid when the vector b itself was fixed, it was not changing with respect to time in the rotating frame of reference. This is an assumption that we made to begin with, I had emphasized it. Now, if we accommodate the fact that we might consider a vector b which actually has got time dependence in the rotating frame. If that is the case, then that velocity - that rate of change with respect to time - in the rotating frame will have to be added to this, because earlier we had ignored. We had ignored in the sense, we had considered the vector which was static over the rotating frame of reference, so now we accommodate that possibility as well.

Having accommodated the possibility, the rate of change of b with respect to time in the rotating frame of reference is not 0. Then, this will have to be added to omega cross b to get the net rate of change with respect to time of the vector b, so this is the simple additive expression. We can use this to generate a operator equivalence because the vector b was completely arbitrary.

The corresponding operator equivalence is given by this; the time derivative operator in the inertial frame of reference is completely equivalent to the time derivative operator in the rotating frame of reference plus a cross product involving the angle of velocity.

The left hand side is an operator, the right hand side is also an operator and this operator either one on the left or on the right would operate on an operand to give the corresponding equivalence, the operand could be any arbitrary vector and this is our operator equivalence.

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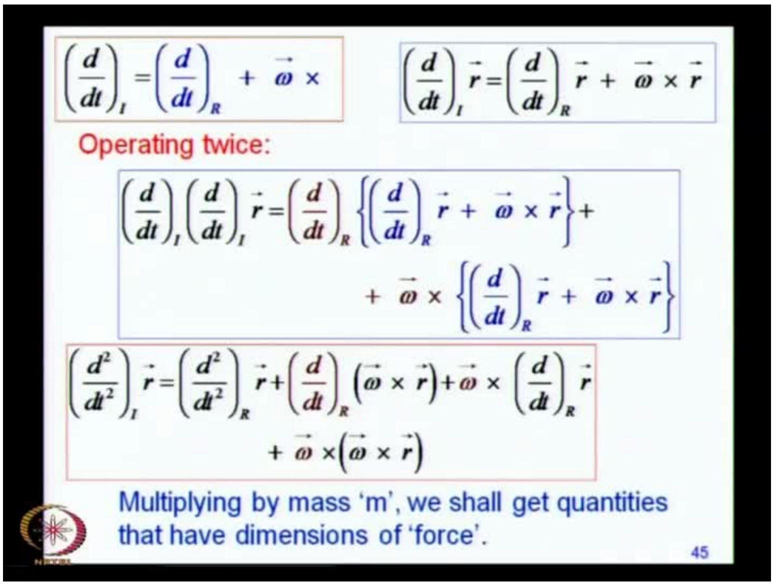

If it operates on the position vector, we get this relation that the velocity in the inertial frame of reference is equal to the velocity in the rotating frame of reference plus the cross product of the position vector with omega which is omega cross r. This is what happens when you take the first derivative.

When you take the second derivative again, you are taking differentiation with respect to time, but differentiation with respect to time must always have this operator equivalence, the d by dt in the inertial frame will be given by d by dt in the rotating frame plus this cross product operation. Suppose, we carry out this operation twice then, d by dt of the position vector r and you operate on this one more time by the same operator d by dt which means, you have to carry out this process twice.

From the first term you have got two terms over here; one is, involving the differentiation to time in the rotating frame and the second is, the cross product with omega. This is the differentiation with respect to time in the rotating frame operating on the result of the first time derivative operation plus the second term coming from the cross product with omega of the result of the first time, you did the time derivative operation - is it clear everybody.

This is your operation equivalence and you can simplify the terms, because here you have to take the time derivative of this velocity plus this. So, from the time derivative in the rotating frame of the velocity, you will get the acceleration in the rotating frame and then, you must take the time derivative with respect the rotating frame of this cross product. So, whenever you take d by dt of omega cross r, you will get d omega by dt cross r plus omega cross d r by dt. So, you just have to take it term by term construct, it as the product of two vectors, the cross product of two vectors and do the time differentiation.

Let us do it term by term, so this is the second derivative in a inertial frame. So, these two terms will give you the second derivative in the rotating frame of the position vector then, you have the time derivative in the rotating frame of this cross product omega cross r which is coming here. Then from here you have the omega cross this term which is the time derivative in the rotating frame, the subscript capital R tells us that. Then, from the last term you have got the cross product with omega, omega cross of this last term which is omega cross r, so it comes as omega cross omega cross r. This is the vector triple product you can expand it with the back tab role which you know very well.

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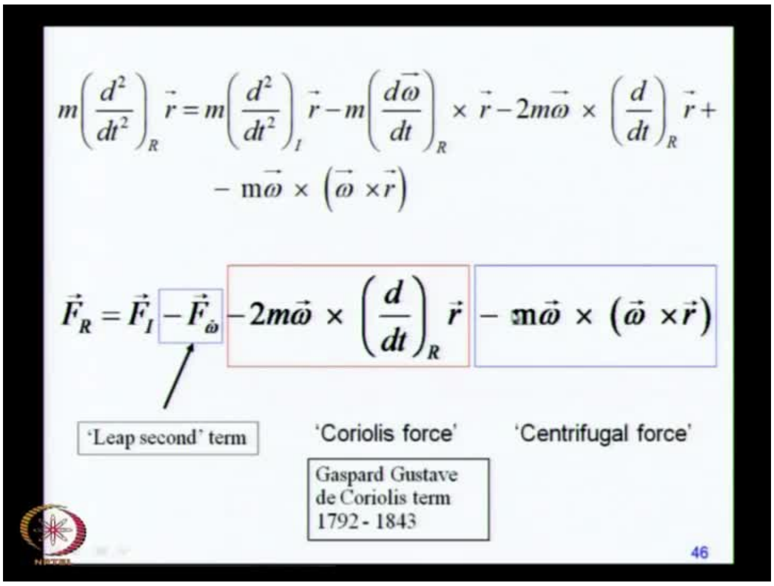

Here is an expression for acceleration, if you multiply each term by mass, you will get a term which will have the dimensions of force. Now, what is the interpretation of each force term is a different question, we will discuss that. It is obvious that if you multiply each term by mass you will get new quantities which will have the dimensions of force, so here I have multiplied each term by mass. This is mass times acceleration in the inertial frame of reference, this we know what it is, this is the force which we have used in Newton's dynamics.

Mass times acceleration in an inertial frame of reference is our idea of what are real forces that is the physical interaction that is, electromagnetic gravity nuclear strong or weak none of the other terms is the fundamental force that is the only real force. Every other term is a pseudo force it is a fictitious term. It is a result of the fact that it is coming from carrying out observations in a rotating frame of reference. So, we have got a term in d omega by dt then, we have got two of these terms. So, there is minus twice m omega cross d r by dt and then, there is a vector triple product omega cross omega cross r.

These terms have got specific names and I have put these terms which I have got dimensions in force, so the left hand term is what an observer in the rotating frame will call as a force in his frame of reference because it is the product of inertia and the acceleration that he measures that acceleration is a real result for him, so in his mind that is the force and that is made up of all of these terms here which is 1, 2, 3 then a 4th term over here which is coming from the vector triple product.

There is one term coming from here and another coming from here and this is the only term which we have accommodated in Newtonian dynamics as the physical interaction. So, the force that an observer in the rotating frame of reference will invoke to explain the acceleration that he measures is F of r. It will not only be the force which is recognized in the inertial frame of reference which is FI, but it will include this term which will depend on the rate of change of this angle of velocity d omega by dt which is written with an omega dot. So, I have put a dot on top of this omega to remind me that it is coming from the rate at which the angle of velocity itself is changing which may change this is called as the leap second term.

Then, there is a term which is coming from the cross product with omega scaled by the factor 2 m, but mind you there is a minus sign that you have to keep track of. So, this minus sign is included in this rectangular box and this is coming from the velocity seen in the rotating frame d by dt in the rotating frame of r is the velocity.

So, this is the origin of this term and this term is called as the Coriolis force, it is this French mathematician and physicists who was the first one to explain this term to us and the last term which is mass times this vector triple product is called as centrifugal term which is again a fictitious force is a pseudo force. This is the net equation that we get to represent a force in a rotating frame of reference, it includes the real physical interactions only in the first term and everything else is a pseudo force. The force seem in the rotating frame which is the left hand side, since it is made up of a real physical force and a contribution from these three pseudo forces, then net result is again a pseudo force.

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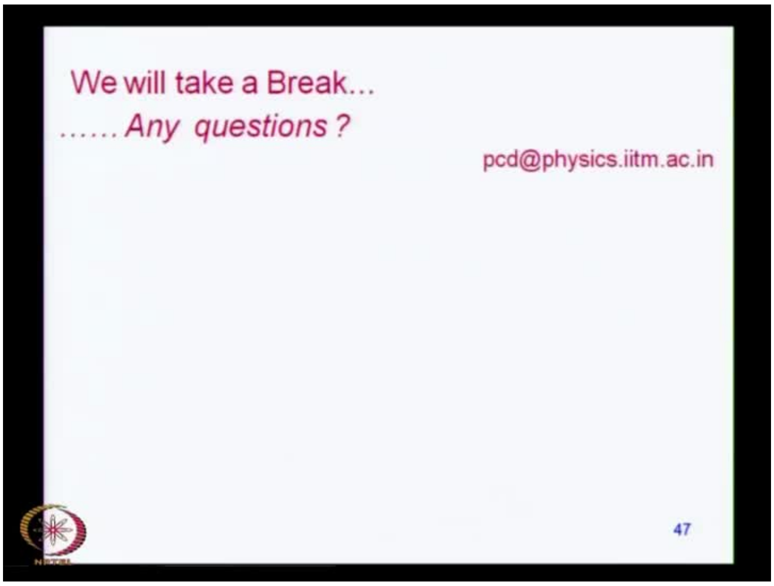

So, at this point we will take a break I will be happy to take some questions and we will continue from this point we will deal with some interesting and important questions because for you and I, we are always in the rotating frame of reference.

When you wake up in the morning the sun is in the east when you well not necessarily because some of you may be sleeping through the day, but for most people or at least that is what your parents want you to do. So, if you wake up in the morning the sun is in the east and then by the end of the day the sun sets in the west and it is not because the sun is going from anywhere to anywhere but only because the earth is spinning about its axis. So, if the sun is here and you are here, so as the day progresses you go from here to here and then when you go on this side you are in the middle of the night.

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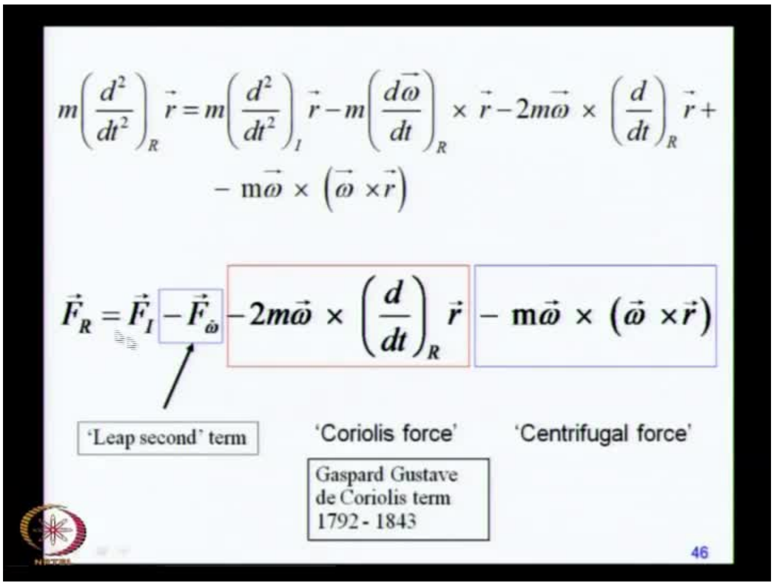

What causes the day and the night is the rotation of the earth about its own axis, so we are always in a state of rotation. We are in a rotating frame of reference whatever observations we are making will be explained only in these terms. Whatever acceleration of any object that we see will therefore, not governed by the fundamental forces alone, but by a combination of the fundamental force. This is the equation, the fundamental interaction is only this but then, we are going to take into our account the this term which is called as the leap second term then, the Coriolis term and the centrifugal term and in the next class, I will discuss the meaning and the implications of these three pseudo forces.

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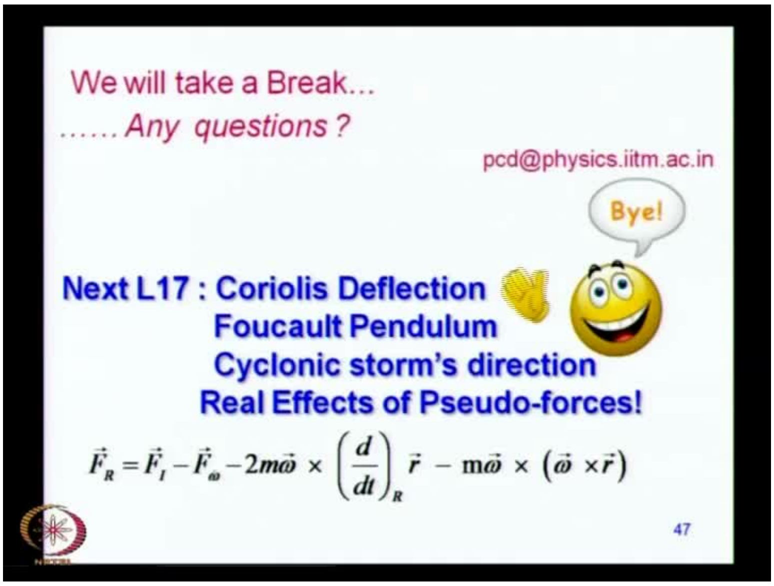

So, that will be the subject for the next class and if there is any question I will take it otherwise, we will continue from this point in the next class and then we will talk about Coriolis deflection and then we will understand Foucault pendulum, we will understand many other real effects of the pseudo forces.

Joby has a question.

Sir, actually this pseudo forces it can be rearranged in some other frame of references,

The pseudo forces like we termed it pseudo because we considered we put some frame of references,

No, we have called them as pseudo forces because these are distinguished with reference to what we have agreed to call as the fundamental force and with reference to those fundamental forces these will always remain pseudo forces.

But, if he stands in the frame of reference of this particle which is rotating then can we term that centrifugal force or pseudo force or something.

It will always be pseudo force, actually I am going to discuss this in some detail in the next class, but let me toss a question which I will discuss at length in the next class. I will give you three definitions of a vertical line, I consider the earth to be a perfect sphere, so

I will not worry about the oblique nature of the earth and all it always reminds me of my so let me not do that. So, we will not worry about the oblique shape and with reference to this shape, we consider three definitions of a vertical definition one, vertical is that direction or that space curve which is an extension of the radial line from the stomach from the center of the earth's stomach to a point on the surface and if you extend this line you get the definition of a vertical.

Second definition and may be Vivek you can help me construct a plumb line which I can show in my next class and you know what plumb liners are. The second definition is a plumb line you know what a plumb line is I just take a piece of thread and attach a mass to it and hold it in my hands and Vivek is going to construct a plumb line for us which I will show in the next class. I define the vertical in terms of this plumb line that the vertical is that line along which the plumb line orients itself.

I take a third definition that I take an object and let go I hold it and let go. I define the vertical as the line along which this object falls, the question to you is these three definitions equivalent do they define the same space craft and with that question I will take a break. I will discuss this question in the next class which we will not only answer this particular question but also your question as to does a pseudo force remain the same or does it become real in some other frame of reference to which I have already given the answer that it is a pseudo force because it has been defined with respect to what has been accepted as the physical interaction in an inertial frame of reference. So, I will discuss this in some further detail and in the meantime there is some food for thought till the next class thank you all very much.