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8.01 Physics I: Classical Mechanics, Fall 1999
Transcript – Lecture 5

Today we will discuss what we call "uniform circular motion." What is uniform circular motion? An object goes around in a circle, has radius r and the object is here.

This is the velocity.

It's a vector, perpendicular.

And later in time when the object is here the velocity has changed, but the speed has not changed.

We introduce T, what we call the period--

of course it's in seconds--

which is the time to go around once.

We introduce the frequency, f, which we call the frequency which is the number of rotations per second.

And so the units are either seconds minus one
or, as most physicists will call it, "hertz" and so frequency is one divided by T.

We also introduce angular velocity, omega which we call angular velocity.

Angular velocity means not how many meters per second
but how many radians per second.

So since there are two pi radians in one circumference--

in one full circle--

and it takes T seconds to go around once it is immediately obvious that omega equals two pi divided by T.

This is something that I would like you to remember.

Omega equals two pi divided by T--

two pi radians in capital T seconds.

The speed, v, is, of course, the circumference two pi r divided by the time to go around once but since two pi divided by T is omega you can also write for this "omega r." And this is also something that I want you to remember.

These two things you really want to remember.

The speed is not changing, but the velocity vector is changing.

Therefore there must be an acceleration.

That is non-negotiable.

You can derive what that acceleration must be in terms of magnitude and in terms of direction.

It's about a five, six minutes derivation.

You'll find it in your book.

I have decided to give you the results so that you read up on the book so that we can more talk about the physics rather than on the derivation.

This acceleration that is necessary to make the change in the velocity vector is always pointing towards the center of the circle.

We call it "centripetal acceleration."   Centripetal, pointing towards the center.

And here, also pointing towards the center.

It's a vector.

And the magnitude of the centripetal acceleration equals v squared divided by r, which is this v and therefore it's also omega squared r.

And so now we have three equations and those are the only three you really would like to remember.

We can have a simple example.

Let's have a vacuum cleaner, which has a rotor inside which scoops the air out or in, whichever way you look at it.

And let's assume that the vacuum cleaner these scoops have a radius r of about ten centimeters and that it goes around 600 revolutions per minute, 600 rpm.

600 rpm would translate into a frequency, f, of 10 Hz so it would translate into a period going around in one-tenth of a second.

So omega, angular velocity, which is two pi divided by T is then approximately 63 radians per second and the speed, v, equals omega r is then roughly 6.3 meters per second.

The centripetal acceleration--

and that's really my goal--

the centripetal acceleration would be omega squared r or if you prefer, you can take v squared over r.

You will get the same answer, of course, and you will find that that is about 400 meters per second squared.

And that is huge.

That is 40 times the acceleration due to gravity.

It's a phenomenal acceleration, the simple vacuum cleaner.

Notice that the acceleration, the centripetal acceleration is linear in r.

Don't think that it is inversely proportional with r.

That's a mistake, because v itself is a function of r.

If you were sitting here then your velocity would be lower.

Since omega is the same for the entire motion you really have to look at this equation and you see that the centripetal acceleration is proportional with r.

Therefore, if you were...

if this were a disc which was rotating and you were at the center of the disc the centripetal acceleration would be zero.

And as you were to walk out, further out, it would increase.

Now, the acceleration must be caused by something.

There is no such thing as a free lunch.

There is something that must be responsible for the change in this velocity and that something I will call either a pull or I will call it a push.

In our next lecture, when we deal with Newton's laws we will introduce the word "force." Today we will only deal with the words "pull" and "push." So there must be a pull or a push.

Imagine that this is a turntable and you are sitting here on the turntable on a chair.

It's going around with angular velocity omega and your distance to the center, let's say, is little r.

You're sitting on this chair and you must experience--

that is non-negotiable--

centripetal acceleration A of c, which is omega squared times r.

Where do you get it from? Well, if your seat is bolted to the turntable then you will feel a push in your back so you're sitting on this thing, you're going around and you will feel that the seat is pushing you in your back and so you feel a push, and that gives the push out.

Yeah, I can give this a red color for now.

So you feel a push in your back.

That push, apparently, is necessary for the acceleration.

Alternatively, suppose you had in front of you a stick.

You're not sitting on a chair.

You don't get a push from your back.

But you hold onto the stick and now you can go around by holding onto the stick.

Now the stick is pulling on you in this same direction.

So now you would say, aha, someone is pulling on you.

Whether it is the pull or whether it is the push one of... either one of the two is necessary for you to go around in that circle on that turntable with that constant speed.

Now, the classic question comes up, which we often ask to people who have no scientific background.

If you were to go around like this and something is either pushing on you or is pulling on you to make this possible suppose you took that push out, all of a sudden.

The pull is gone.

[makes whooshing sound]

What is now the motion of the person who is sitting on the turntable? And many non-scientists say, "Well, it will do like this." That's sort of what your intuition says.

You go around in a circle, and all of a sudden you no longer have the pull or the push and you go around in a spiral and obviously, that is not the case.

What will happen is, if you have, at this moment in time a velocity in this direction and you take the pull or the push out you will start flying off in that direction and depending upon whether there is gravity or no gravity there may be a change, but if this were...

if there were no gravity you would just continue to go along that line and you would not make this crazy spiral motion.

I have here a disc, which we will rotate and at the end...

the edge of the disc here we have a little ball.

And the ball is attached to that disc with string.

So now this is vertical, and so this is going to go around with angular velocity omega.

And we have a string here and the string is attached to this ball and the whole thing is going around and so at one moment in time this has a velocity, like so.

And therefore there must be non-negotiable centripetal acceleration which in magnitude is omega squared r or, if you want to, v squared divided by r.

Now I cut it and that's like taking away the push and the pull.

The string that you have here is providing the pull on this ball.

This ball is feeling a pull from the string and that provides it with the centripetal acceleration.

Cut the string and the pull is gone and the object will take off.

And if there were gravity here, as there is in 26.100 it would become a parabola and it would end up here.

If, however, I cut the ball exactly when it is here--

not the ball, but I cut the string--

then, of course, it would fly straight up gravity would act on it, it would come to a halt and it would come back.

So it really would then go along a straight line.

But you would clearly see, then that it's not going to do what many people think--

that it would start to swirl around.

It would just go...

[makes whooshing sound]

and comes back.

Let's look at that.

We have that here.

So here is that ball.

The string is behind here; you cannot see the string.

I will rotate it, wait for it to pick up a little speed and the knife, that you can't see either, is behind here and when I push the knife in, I do it exactly here.

It cuts the string and it goes up.

You ready for this? You sure you're ready? Three, two, one, zero.

Wow! That was very high.

So you see, it's nothing like this.

It simply continued on in the direction that it was going.

It wasn't going into a parabola because I was shooting it straight up.

The string forms the connection between the rotating disc and the ball and therefore, the pull is responsible for the centripetal acceleration.

Let's now think about planets.

Planets go around the sun.

There's no string, so who is pushing? Who is pulling? Well, it's clear that it must be gravity.

It must be the sun that is pulling on the planets.

Now, I realize that the orbits of planets are not nicely circular so it's not really a uniform circular motion.

We will deal with orbits in great detail in a few weeks--

circular orbits and elliptical orbits.

Let us just assume for simplicity now that the orbits are roughly circular just to get a little bit of feeling for it.

And you can look up now in your book--

which I did for you--

even in your preliminary version you can look up what the mean distance of the planets is to the sun and you can look up what the period is the time to go around the sun.

The time to go around the sun is not the same for all planets.

The planets are not attached to a turntable.

Anywhere, any person on a turntable would go around in the same amount of time.

We know that that's not true for planets.

It takes the Earth a year to go around the sun.

It takes Jupiter 12 years to go around so don't make the mistake to think that omega is the same for all planets.

That's not true.

So I look up the distance--

the mean distance to these various planets--

and you see that here in millions of kilometers.

Notice that Mercury is about 100 times closer than Pluto.

By the way, this is on the Web, so don't copy this.

You will find this on the 801 home page.

Then I looked up how many years it takes to go around the sun--

12 years for Jupiter, one year for the Earth--

and I looked up all the other values.

Then, since I know the periods, I can calculate omega.

Omega is two pi divided by T, so I know omega.

And then I take omega squared times the mean distance to the sun and this is, of course, the centripetal acceleration.

So the planets experience this centripetal acceleration in some crazy units, but who cares about the units here? And notice that Mercury, which is 100 times closer than Pluto has a centripetal acceleration which is 10,000 times larger than Pluto.

100 times closer has a 10,000 times larger centripetal acceleration.

So what I did was I plotted this data, the centripetal acceleration versus the mean distance to the sun and I did that on log paper.

And what immediately strikes...

is very striking is that all these points--

I've done them for all the planets--

they fall on a straight line.

And so what is the slope of that line? Well, I tried various slopes and I found that the slope is very, very close to minus two.

Here is the slope of minus two, and I can overlay this and notice that the fit is absolutely stunning.

Therefore, you cannot escape the conclusion that the centripetal acceleration which is the result of gravity, falls off as one over R squared.

We refer to this, often, in physics as the "one over R square" law.

And therefore, the effect of gravity itself must go down with R squared.

So if you are 100 times further away like Pluto compared to Mercury then the gravitational...

the centripetal acceleration which is due to gravity is 10,000 times smaller.

And we will learn a lot about gravity in the future.

We will just leave it for now.

If you took the sun away, it would be like cutting the string that provides the pull and in that case what you would see is that the planets would just take off along a straight line.

They would continue to go.

They wouldn't have anything to pull on them anymore.

Now let's look at an object that we're going to rotate.

I have a glass tube that I want to rotate and in the glass tube, I have a marble.

The glass tube is very smooth.

I have here the glass tube.

Here's a marble.

I'm going to rotate it in this direction say, with some angular velocity omega about an axis perpendicular to the blackboard.

So the marble here has a velocity like so, at this moment in time but it's a very smooth glass tube and the marble is very smooth.

The glass cannot push on the marble nor can the glass pull on the marble.

Now, the marble gets desperate because the marble needs a centripetal acceleration in this direction in order to go around like this.

But there is nothing to provide that centripetal acceleration.

So the marble is doing exactly the same that the planets would do if you take the sun away.

The marble continues to go in the direction that it was going.

So by the time that the tube is here, the marble is here and by the time that the tube is here the marble is there.

So the marble finds its way to the edge and that's, of course the basic idea behind a centrifuge.

My grandmother had always...

She was a great lady and she had such fantastic ideas, I remember.

And when she made lettuce we had no good way of drying the lettuce and I would take the lettuce and go like this... paper towel.

She had a method of her own.

She took a colander and, of course, first of all we would wash the lettuce, that goes without saying.

I would wash it once.

My grandmother would wash it three times but that's what you have grandmothers for.

So there comes the lettuce.

We were also very fond of spinach, so add some spinach.

We would wash it...

there goes the spinach.

Then she would take something to cover it up--

maybe some Saran wrap, or something else--

put it over it and put a rubber band around it to hold it.

And now what she's going to do, she's going to swing it around.

And now the water is like these marbles.

The water will work its way to the edge but there are holes, so the water will come out.

Isn't she clever? Okay, I'll give you a demonstration.

Be careful or you may get some water on your lecture notes.

But I want to show you the basic idea behind it is very interesting.

She would go out... she would do this outside, by the way.

But I have no choice, so I will do it here.

So there we go.

[class laughs]

You see? This is the way you dry...

Oh, I lost my magnetic strawberry--

that's a detail in the process.

So you end up with...

you end up with dry and clean and nice lettuce.

This is 801 at work and this is clearly an early version of a centrifuge.

Now, my grandmother's method, very tragically has been replaced lately with something that you can buy at Crate and Barrel.

We have it here.

Um, it is very boring.

It's very decadent.

Put the salad in here and all you do is you rotate and it dries.

It's a centrifuge.

This is actually a high-tech version of the much more sophisticated invention of my grandmother.

And it's nowhere nearly as exciting.

The days of romance are really over but that's the way it goes.

I'm now going to make a connection between rotation on the one hand and centripetal acceleration on the other.

I'm going to make a connection between centripetal acceleration and perceived gravity.

The way that you perceive gravity.

I'm going to put you in various positions and then ask you what is the direction of gravity.

I'm going to create artificial gravity for you.

And let's first do it as follows.

I first hang you on a string.

There you are, like this.

And I ask you, do you feel a push or a pull? And you say, "Yeah, I feel a pull." And you feel a pull in this direction.

So now I ask you "Ah, in what direction do you perceive gravity?" and you think I'm crazy.

You're right in that case, but nevertheless you say "Gravity is in this direction." The other direction is the pull.

Okay, so far, so good.

So now I'm going to put you just standing on the floor and I say to you, "Do you feel a push or a pull?" And you say, "Yeah, I feel a push.

I feel a push from the floor up." So I say, "In what direction do you perceive gravity?" You say, "Well, come on, don't be boring.

Gravity is in this direction." Notice in both cases you tell me that gravity is always in the opposite direction of either your pull or your push.

Okay, now I'm going to be a little rough on you.

Now I'm going to swing you around on a string just as if you were an apple and I'm going to do this with you.

And you're at the end of the apple.

You are the apple, not at the end.

You're at the end of the string.

You are the apple.

So there you are.

Here... poor you.

[class laughs]

And I say, "Do you feel a push or a pull?" And you say, "Yeah, I do, I feel a pull." Fine, in what direction? "I feel a pull in this direction." Okay, so now I say to you "In what direction do you perceive gravity?" And you say, "Well, in the opposite direction as pull." So now you perceive gravity in this direction which is very real for you.

Now, in this particular case since the direction changes all the time--

since I swirl you around--

you will, of course, get dizzy like hell, but that's a detail.

You will perceive gravity in this direction when you're here and when you're here you will perceive gravity in that direction.

So you perceive gravity in the direction which is opposing the pull and the faster I rotate you, the stronger will be the pull and therefore the stronger will be your perceived gravity.

A carpenter would use a plumb line and the carpenter would just hold the plumb line like this.

The pull is in this direction and so the carpenter says "Okay, perceived gravity is in that direction." The carpenter happens to be right in this case.

Gravity is in this direction, but it's the same idea.

The plumb line is being used to find the direction of gravity.

Think of this as being a plumb line to find...

used to find the direction of gravity.

Now you're in outer space.

You're going to play Captain Kirk and you're in a space station and there is no gravity.

So we're going to make some gravity for you.

We're going to create some artificial gravity.

So let this be your space station; it's a big wheel, a radius of about 100 meters and we'll make it very fancy for you.

We'll make some corridors around, like here.

We'll make it a very interesting space station like so... and like so.

And this is rotating around with angular velocity omega.

You're here--

there you are.

You go around.

Therefore, non-negotiable you're going around with a certain velocity v.

This v equals omega r and therefore, you require centripetal acceleration towards the center--

that is non-negotiable.

Where do you get it from? Well, the floor--

this is your floor--

is pushing on you.

Simple as that, just like the floor is pushing on me now.

This floor is pushing.

There's nothing wrong with that; I don't fall over.

And so I say to you, "In what direction do you perceive gravity?" And you say, "This is the direction of gravity" which is as real for you as it can be.

Someone else is standing here.

What do you think that person will think if I ask that person "What is the direction of gravity?" Exactly, radially outwards, opposing the push from the floor.

So we could now calculate how fast we have to rotate this space ship to mimic the gravitational acceleration on Earth--

which is 9.8 meters per second squared.

Let's call that 10, just to round it off a little.

So we want the people who walk around in this corridor to have an acceleration omega squared R which is about 10 so omega squared is about 0.1 so omega is about 0.3 radians per second.

And so the period to go around is about two pi divided by omega and that is about 20 seconds.

And the tangential speed--

that value for v, which is omega R--

would then be 0.3 times 100 would be about 30 meters per second just to give you an idea for these numbers which are by no means so ridiculous.

What is interesting, that the perceived gravity--

and therefore the centripetal acceleration--

is zero here.

There is nothing; there is no gravity there.

And so that may be a good place for you to have your sleeping quarters.

Now comes an interesting question.

You can walk around here without any problem.

Could you walk into these spokes? So when you were here, could you then walk towards your sleeping quarters? When you were standing here and I first ask you "In what direction is gravity?" And you will say, "Well, gravity is in this direction." Can you now walk to your sleeping quarters? And what's the answer? You cannot.

You cannot walk up against gravity.

It would be like asking you to walk to the ceiling.

How do you do that? An elevator or a staircase, that's fine because then you get the push from the stairs when you step on the stairs.

So you could have the staircase here and that's the way this person could go here.

But you cannot simply walk here because gravity is always in this direction.

Now let's suppose you are at your sleeping quarters and you wake up in the morning and you decide to go back either in this direction or this direction or this direction or that direction--

it doesn't matter.

Could you do that, just by...

just going into this corridor and slowly, carefully starting moving? What would happen? Yeah? STUDENT: You would fly out.

LEWIN: You would fly out.

It would be suicide, because the moment that you are here already, you have maybe not a very large gravitational experience but already it's beginning to grow on you.

The farther out you are, the stronger it will be.

By the time you're here, it's 10 meters per second squared.

Remember? We had 10 meters per second squared because we wanted to mimic the Earth and so you literally crash.

It's like falling into a shaft, jumping into a shaft.

It's not quite the same because you start off with no pull on you.

The moment you start going, however the situation gets out of hand and indeed you will slam.

So you can use the same elevator.

You can use the same staircase.

There's nothing wrong with that.

Suppose I have a liquid which has very, very fine, small particles in it--

extremely small, so small and so light that they will not sink to the bottom.

So you will always see some colored milky-type liquid.

And here is that tube which has these fine particles.

And the tube is sitting there and the line of the liquid is obviously like this.

Why? Well, that's obvious.

Because gravity is in this direction.

And so the surface of the liquid is always perpendicular to gravity.

You see here two glasses with water.

The surface is perpendicular to gravity.

Now I'm going to rotate this about this axis--

it's going around like this--

and I'm going to rotate it with an angular velocity omega and this is at a distance, R.

Therefore, there is now a centripetal acceleration in this direction, and so the particles now say "Aha! Gravity is in this direction." The side of the glass and the liquid is pushing in this direction to provide this centripetal acceleration.

So if you ask them, "Where is gravity?" they will say "Gravity is there." And this gravitational effect can be so much stronger than this one that you can forget this one--

you will see that in a minute.

You can completely forget this one.

And so the liquid will say "I'm going to be perpendicular to gravity." And so the liquid will go like this, clunk.

While it rotates around the liquid in this tilted tube will be vertical.

But not only that, the particles that are here experience now way stronger gravity than they did before so I have made them heavier.

They are no longer light particles.

They are heavy particles, and what do heavy particles do? They have no problems in making it to the side.

The reason why the light particles couldn't fall in the first place has to do with the fact that the molecules of the liquid due to their temperature, have a chaotic motion.

We call that the "thermal agitation." And these molecules would interact with these very small and light particles and so the light particles would never make it to the bottom.

The thermal agitation now of the liquid is the same--

the temperature doesn't change--

but the particles have become way, way heavier and so the particles now go in the direction of gravity which is here.

And what you will see, if these particles are white you will see white precipitation there and the liquid will become clear.

And that is something that I would like to demonstrate to you.

But before I do that, I want to give you some numbers.

Here we have a household, simple, nothing-special centrifuge that is used in any laboratory.

The centrifuge that we have has an rpm which is 3600 rpm.

So 3600 rpm translates into a frequency of 60 Hz.

So it goes around once in one-sixtieth of a second.

Omega is two pi times f is therefore roughly 360 radians per second.

360 radians per second.

If we assume that the radius is...

maybe it's 10, 15 centimeters.

Whatever, let's take a radius of 15 centimeters.

And we can calculate now what the centripetal acceleration is.

And the centripetal acceleration a of c which is omega squared R is then roughly about 20,000 meters per second squared.

20,000 meters per second squared.

And that is 2,000 times the gravitational acceleration.

It means that these particles experience gravity which is 2,000 times stronger than if I don't rotate them.

And so they will go to the side here.

But the glass itself is also 2,000 times heavier and therefore the glass can easily break so when you design a centrifuge like that you have to really think that through very carefully--

that the pieces that are in there don't fly apart.

I have here water in which I have dissolved some table salt--

the same table salt that you use in the kitchen when you prepare your food, table salt in here.

Here I have water in which I dissolved some silver nitrate.

It's nasty stuff, I warn you for it, you have to be very careful because if you get the stuff on your hands it burns through your hands very quickly without your realizing it and you end up with a very black spot.

It really eats away, burns out your skin.

People put it on warts and then the warts, they think, fall off.

They probably do after a while but your finger may also fall off.

So I have here silver nitrate and there I have sodium chloride and I mix the two.

So I get table salt--

sodium chloride--

plus silver nitrate gives sodium nitrate plus silver chloride and this, very small white particles, and you will see that the liquid turns milky instantaneously.

It almost becomes like, like yogurt, as you will see.

And so I want to show that to you.

I have here these two glasses.

This is the table salt and this is the silver nitrate.

I'm going to mix them.

I hope you can see this.

Here are the two glasses, and when I mix them...

[whistles]

instantaneously you get milk.

[class laughs]

Yeah.

I'm not asking you to taste it but look at it, right? Just milk.

You can leave this for hours and hours and hours and it will just stay like that.

Very small particles of silver chloride are in here.

So now we are going to put this in the centrifuge.

I have to put it in a very small tube.

I'll show you this small tube.

There's no way that I can pour that in without making a mess.

Here's this small tube and so what I will do is I will first put it in a small beaker and then from this small beaker I will transfer it, some of it, to this tube.

When you put this in a centrifuge your force on this glass is so high that you must always make sure that you balance it with another tube that you fill with water on the other side.

Otherwise the thing begins to shake like crazy.

It's like your centrifuge when you dry your towels.

If they are not equally distributed it begins to make very obscene sounds and starts to move.

[class laughs]

And the same thing will happen here.

So you just have to take my word for it that we have put on the other side just some water to balance it out.

So here is now the yogurt and on the other side is plain water and we will just let it sit there for a while and we will return to that shortly.

I mentioned already your centrifuge for your clothes.

That is the way that you can dry your clothes.

That is the same way that my grandmother dried the lettuce.

The water will go to the circumference.

A household centrifuge for your clothes would easily rotate 1,200 revolutions per minute have a radius maybe of 15 centimeters which would give you a centripetal acceleration of 200 times g, 200 times the gravitational acceleration.

So your clothes experience gravity which is 200 times stronger and therefore your clothes are 200 times heavier and therefore your clothes can tear apart and we have all seen that.

We have all put in stuff in a centrifuge and when you take it out you're disappointed because it's torn.

That's because of the tremendous gravity that you have exposed them to.

Many times when I take my shirts out, half my buttons are gone.

That's because the force--

I shouldn't use that word...

the gravitational effect on the buttons is enormous and they just get ripped off.

Now I want to revisit the situation that you are on the end of my string and I'm going to swirl you around.

Earlier, I swirled you around like this and you didn't like it and I don't blame you because you got dizzy.

Now I'm going to rotate you like this.

You may like that better.

Maybe not.

[chuckles]

And so, whether you like it or not I'm going to twirl you around and here you are.

This is the circle.

There's a string--

you're here.

Here's the string and there you are.

You have a certain velocity.

Your velocity is in this direction and there is a certain distance to the center, R.

And so you need a certain centripetal acceleration to go around in that curve.

So you need a centripetal acceleration a of c--

which is...

you can take the v squared divided by r, if you like that.

This is the magnitude of that v.

Now follow me very closely.

Just imagine that this number happens to be exactly 9.8.

I can always do that.

Where is this person going to get the push or the pull from for this centripetal acceleration? Does the string have to pull on it? No, because there's always gravity and gravity gives you an acceleration of 9.8 meters per second squared.

So the string says, "Tough luck, I don't have to do anything.

"Gravity provides me with the 9.8 meters per second squared that I required." Now I'm going to swing you faster, so the v will go up and so the centripetal acceleration will go up.

The string will say "Aha! I'm going to pull now on this person "because the gravitational acceleration alone is not enough--

I need some extra pull." So the string is going to tighten and pull on you.

And I say, "Hello, there, in what direction is gravity?" And you say, "Gravity is in this direction." Why? Because you feel the string is pulling on you in this direction, so you experience gravity there.

Now comes the question, how real is this? This is very, very real.

It is so real that if I took a bucket of water instead of you...

and here is the bucket of water.

I attached to the bucket a rope.

I swing it around, and I swing it around such that the centripetal acceleration is substantially larger than 9.8 so the string is definitely going to pull so if you were the water, and I asked you, "Where is gravity?" you would say the gravitational direction is in this direction and so the water will say, "Okay, fine, then this will be my surface and I want to go in this direction." But the water can't go in that direction so it will just stay there.

So I could swing this thing around if I do it fast enough--

so fast that the acceleration at this point here must be larger than 9.8--

the water will stay up while the bucket is upside down.

How fast should I rotate it? Well, let's put in some simple numbers.

I have here this bucket and let's say that this is about one meter.

Let's round some numbers off.

So R is about one meter.

And I want v squared over R I want that to be larger than 9.8--

let's just call it 10.

So that means v has to be larger than about 3.2 meters per second.

The time to go around is two pi R divided by this velocity so this time to go around, then, has to be six...

has to be less than two seconds.

So if I swing this around in less than two seconds I will be okay.

Now, I realize that the speed when I move this thing around is not constant everywhere.

That's very difficult to do that, because of gravity.

But it's close enough to get an idea.

So if I rotate this faster than in two seconds when the bucket is upside-down if physics works, the water should not fall out.

So let us fill this with water.

There we go.

I'm always nervous about this.

Um, let's first look at the centrifuge.

We have to see whether the centrifuge has done its job.

So let's look at what this tube...

I think it was tube number four.

Oh, yeah! Very clear is now the liquid and you see the white stuff here on the side.

It's not too easy for you to see, really.

I put my hand under here.

Maybe some of you can see some white stuff but it's no longer milk--

really a clear liquid.

Here you see some white stuff here but it's also on the side.

You can actually see it here.

You see the white stuff because this was the direction of gravity so it ended up here and there's some here.

It is completely clear.

You see the white stuff? So that's the way that you can separate the silver chloride.

So now we come to this daredevil, daredevil experiment.

And we're going to see whether we can fool the water and make the water think that gravity is not in this direction but in this direction.

Now, you're doing the right thing, there.

[class laughs]

I don't blame you at all.

[Lewin chuckling]

Okay...

There we go! You see the water is completely fooled and notice that I go around substantially faster than in two seconds.

And the water, when it's up there just thinks that gravity is towards the ceiling.

Physics works.

Now, who is going to do this for me, too?

[class laughs]

Please, someone should try this.

You think you can do it? Come on, try it.

In the worst case, it will be a disaster.

[class laughs]

Okay, get some feel for it, but before you do it make sure that I'm out of the way.

But first swing it a little and don't hold it too close to you because I don't want you to get hurt.

Larger swing, larger, larger.

Now you get some feel for it.

Go for it, now! Yeah, faster!

[class laughs]

That was very good.

[class laughs and applauds]

See you Friday.

[applause]