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8.01 Physics I: Classical Mechanics, Fall 1999
Transcript – Lecture 30

Okay, you did have some problems with physical pendulums, and I want to talk a little bit more about physical pendulums.

Let's first look at the picture in very general terms.

I have here a solid object, which is rotating about point P about an axis vertical to the blackboard, and here at C is the center of mass.

The object has a mass M, and so there is here a force Mg, and let the separation be here b.

I'm going to offset it over an angle theta, and I'm going to oscillate it.

Clearly, there has to be a force at the pin.

If there were no force at the pin, this object would be accelerated down with acceleration g, and that's not what's going to happen.

But I don't care about that force because I'm going to take the torque about point P.

Remember when we had a spring, just a one-dimensional case, we had F equals ma, and that, for the spring, became minus kx, and the minus sign indicates that it's a restoring force.

So we now get something very similar.

In rotation, force becomes torque, mass becomes moment of inertia, and acceleration becomes angular acceleration.

So now we have minus r cross F, and the minus sign indicates that it is restoring.

So if I take the torque relative to point P, then I have...

This is the position vector, which has magnitude b.

The force is Mg, and I have to multiply by the sine of theta.

So I have b times Mg times the sine of theta and that now equals minus...

I can bring the minus here--

minus the moment of inertia about point P times alpha, and alpha is the angular acceleration, which is theta double dot.

I bring them together, and I use the small-angle approximation, small angles.

Then the sine of theta is approximately theta if theta is in radians.

And so I bring this all on one side, so I get theta double dot plus bMg divided by the moment of inertia about that point P times theta--

now this is my small-angle approximation--

equals zero.

And this is a well-known equation.

It is clearly a simple harmonic oscillation in theta because this is a constant.

And so we're going to get as a solution that theta equals theta maximum--

you can call that the angular amplitude--

times cosine omega t plus phi.

This omega is the angular frequency It is a constant.

Omega here, theta dot, is the angular velocity, which is not a constant.

The two are completely different.

That is the angular frequency.

So we know that the solution to this differential equation gives me omega is the square root of this constant.

So it is bMg divided by the moment of inertia about that point P.

And so the period of oscillation is two pi divided by omega, and so that is two pi times the square root of I relative to point P divided by bMg.

And let's hang on to this for a large part of this lecture because I'm going to apply this to various geometries.

Make sure that I have it correct--

yes, I do.

This is independent of the mass of the object.

Even though you will say there is an M here, you will see that in all cases when we calculate the moment of inertia about point P that there is always a mass up here.

So the mass will disappear, as you will see very shortly.

I have four objects here, and they all have different moments of inertia.

They're all going to rotate about an axis perpendicular to the blackboard, so to speak, and we're going to massage each one of them to predict their periods.

Let's first go to the rod.

So we first do the rod.

We have the rod here.

This is point P, and here is the center of the rod.

The rod has mass M and it has length L.

So we have here Mg.

I don't have to worry about this anymore.

I simply go to this equation, and I want to know what the period is of this rod, of this oscillating rod.

All I have to know now is what is the moment of inertia about P.

And I know already that b in that equation equals one-half L.

So, what is the moment of inertia of oscillation about point P? I have to apply now the parallel axis theorem--

which you also had to do during the exam--

which says it is the moment of inertia of rotation about the center of mass, which, in our case, is C--

the axes have to be parallel, so there is this axis perpendicular to the blackboard, and this axis perpendicular to the blackboard--

plus the mass of the rod times the distance between P and c squared--

plus M times this distance squared--

so that is b squared, and b squared is one-quarter L squared.

What is the moment of inertia for rotation of a rod about this axis? I looked it up in a table.

I happen to remember it now, because I am lecturing 801.

Two months from now, I will have forgotten.

So I remember now that it is 1/12 ML squared plus one-quarter ML squared.

That becomes one-third ML squared.

And so the period T becomes two pi times the square root of this moment of inertia, which is the one-third ML squared, divided by bMg, and b is one-half L for this geometry.

So one-half LMg, and notice, indeed, as I anticipated, you always lose your M, you also lose one L here, and so you get two pi times the square root of two-thirds L divided by g.

So that is the period that we predict for the rod.

So let's write that under here, because we are going to compare them shortly.

So this is two pi times the square root of two-thirds L divided by g.

The rod that we have here is designed in such a way that the period is very close to one second.

That was our goal.

So T is as close as we can get it to 1.00 seconds.

And so if you substitute in this equation T equals one, you will find that the length of this rod, if it is really pivoting at the very end, should be about 37.2 centimeters.

So we did the best we can when we made this rod.

There is always an uncertainty, of course--

how you drill the holes and where you drill the holes--

so I would say the value that we actually achieved is 37.2, probably with an uncertainty of about three millimeters, so 0.3 centimeters.

That's what we have.

That is an error of one part in 370.

Let's make that...

round that off.

That's a one-percent error in the length.

Since the length is under the square root, the one-percent error becomes half a percent error, so the period that I then would predict is about 1.000 plus half a percent, so that is 0.005 seconds.

So that, then, has a one-half-percent error.

So this is my predicted period.

And so we're going to make ten oscillations of the observed oscillations.

We're going to get a number.

My reaction time is not much better than a tenth of a second.

So we're going to get a number there.

We divide this number by ten.

And so we can always calculate the period, then, and then we get a much improved error of a hundredth of a second, because we will divide this number by ten, so this also is going to be divided by ten.

And let's see how close we were able to get this to the 1.0 seconds.

So, here is the rod.

Turn this on, the timer.

We'll offset the rod, and I will start it when it stops somewhere.

Now--

one, two, three, four, five, six, seven, eight, nine, ten... not bad.

9.92--

well within the prediction.

9.92, and so this becomes 0.992 plus or minus .01, and you see that is well within the prediction that I made.

Now, all these four objects were designed in such a way that they have exactly the same period of one second.

And now comes the question, how do the dimensions relate to each other in order to get them a period of one second? So let's now calculate the period for the other three objects: for the ring, for the disk and for the pendulum.

Let's start with the pendulum.

For the pendulum, center of mass is here.

Here is point P.

I give the pendulum length little l--

you see that on the right blackboard there.

So b equals l--

that's the separation between P and C.

The moment of inertia about point P is very easy now.

This has no mass--

the mass is all here, mass capital M, so that must be M times l squared.

So I go to this equation, and so I ask, what is the period of a pendulum? And you're not surprised that you find two pi times the square root of l over g.

We've seen that before, but, of course, it also comes out if you do it in this more complicated way.

So here we get two pi times the square root of l over g.

Let's now do the ring.

This is the ring.

Pivot about point P here.

Here is the center of mass right in the middle, in the middle of nowhere.

Right here is the center of mass.

And so the distance b is the radius of the ring, so we have to calculate the moment of inertia about point P.

Again, we have to use now the parallel axis theorem.

It is the moment of inertia for rotation about this axis through point C, through a center of mass.

That is MR squared, if R is the radius of the ring.

All the mass is at the circumference, all at a distance R from the center of mass.

And then we have to add to that--

according to the parallel axis theorem--

the mass times this distance squared, and this distance is R, so you get MR squared.

So it is 2MR squared.

So what is the period of an oscillation? I of P, that is 2MR squared, divided by bMg--

b is R--

RMg.

I lose one R, I lose an M, and we have seen this before.

I derived this in lecture number 21.

I remember everything by lecture number, believe it or not.

So the period, now, is the same as a pendulum with length two R.

This is the ring.

And so here we have two pi times the square root of 2R divided by g.

I'll make a comparison very shortly.

I just want to finish them all.

And I now would like to do the disk, last but not least.

For the disk, all we have to do now is calculate the moment of inertia.

This was very close to your...

the problem you had on the exam.

So, here you have the disk, a solid disk.

This is point P, this is the center of mass, but now it's solid, so again, b is R, the separation between c and b.

And the moment of inertia for rotation about point P is now the moment of inertia for rotation about the center of mass, which you look up in a table--

in the case of your exam, it was given on the front cover--

one-half MR squared.

That's the moment of inertia for rotation about the center of mass.

And now we have to add Mb squared, and b equals R, so we have to add MR squared.

So we find three-halves MR squared.

So what is the period of oscillation? Two pi times three-halves MR squared divided by bMg--

b is R--

RMg, and that equals two pi times the square root...

I lose my M as always, I lose an R.

I get here three-halves R divided by g.

And so let's write that down here, so we have two pi times the square root of three-halves R divided by g.

So we have them all four there, and so we can now make a meaningful comparison.

We want the periods to be the same, so we can hang on to those numbers, so we don't need this anymore.

We want the periods to be the same.

We already have established that the period of the rod is close to the one second, so we're not going to measure them anymore.

We just want to compare them--

whether, indeed, they have the same period of oscillation--

by making them oscillate in unison.

But we want to know what the relative ratios are of these dimensions the way we designed it.

So let's first go to the rod, then, and make a comparison between the rod and the pendulum.

So if you look at the rod--

and we use the pendulum as our standard, with length little l--

then you see the period will be the same if 1Ω R is little l...

Oh, sorry, the rod.

If two-thirds capital L is little l.

So, for the rod, two-thirds L equals little l, so capital L is 1Ω l.

It has to be exactly 1Ω times the length of the pendulum, so this length has to be exactly 1Ω times this length to the center of mass, which is the center of that billiard ball.

And that's what we tried, to the best that we could.

So let's now go to the ring.

For the ring to have the same period, one second, 2R has to be the same as the length of the pendulum.

So 2R equals l, so we can put in here for L, this has to be 1Ω times l, and here, this now, which is 2R, has to be l.

Very nonintuitive, that this length here is the same as the diameter of the ring.

Not at all obvious.

And so now we go for the disk.

So now we require that three-halves R, 1Ω R...

We want that to be l, so we want R to be 2l divided by three.

So we want the diameter 2R to be 4l divided by three.

And when you look at the disk, it's hard to see that it is exactly four-thirds, but you can see that it is longer than the pendulum--

it should be one-third longer--

but it is not as long as the rod because the rod is 1Ω times the length of the pendulum, and so we can now complete that picture.

And we have now that the diameter here--

2R--

is now four-thirds times l.

And so what we can do now, we can play with them.

We can oscillate them simultaneously and just see how well they track each other.

There's no sense in giving you the dimensions.

The rod was 37.2 centimeters.

Let me write that down, because we calculated that.

So this was 37.2 centimeters, and I think that translates into--

for the pendulum--

24.8 centimeters.

But for the others I leave it up to you to calculate the dimensions.

Yes, 25... 24.8 is correct.

So timing is not useful anymore.

Let's just see how these two go together.

So we offset them, and then we let them go.

And they go pretty much in unison.

If you wait long enough, of course, you will see there is a difference.

You can never make them exactly the same, but they track each other nicely.

We can now also use the rod and the disk.

They track each other beautifully.

They're both very close to 1.00 seconds.

And we can have the disk versus the pendulum.

And you see they track each other very nicely.

But wait long enough and you will see that, of course, the periods will be different.

So, this is my last word on physical pendulums, but you may see it again on the final.

Not maybe--

you can almost count on that, I'm telling you.

Okay, I want to discuss now some other interesting oscillation--

again, simple harmonic--

and that is liquid in a u-tube, which you see there.

If I have here a tube, which has everywhere...

it's open on both sides and everywhere the same cross-section, and I put a liquid in here, in equilibrium, just like that, and the liquid has mass M.

It has density rho.

The area of the tube is A, and the length of the liquid is l.

So this is l.

I'm going to offset it, the liquid, and I wanted to see it oscillate, and I wanted to see whether I could calculate the period of the oscillation.

The total mass of the liquid that I have...

the total mass is the volume, which is the area times the length times rho.

I'm going to offset it so that this is higher over a distance y.

So this, then, is lower over a distance y.

So this distance is also y, same as that.

So the liquid now is here, and then I release it, and it will start to oscillate.

Well, when it starts to oscillate, there comes a time that the liquid, the whole liquid is going to slosh back and forth and so everywhere in the tube, the velocity at any moment in time will be the same because the cross-section is not changing--

it's the same everywhere.

See, if there is a certain velocity here v, then it's the same as the velocity here, as the velocity there, as the velocity there.

And that, of course, is y dot.

That's the first derivative of that position here.

I'm going to write down the conservation of total energy, mechanical energy.

I assume that there is no energy loss, although there probably is some.

Friction inside the liquid will probably generate some heat and that will cause some damping.

You will see that when we do the experiment.

For now, I will assume that that's not the case.

So what, now, is then the total energy of the system--

that is, the sum of the kinetic energy plus the potential energy? And if we assume that that's constant, we will be able to find the period of the oscillation very shortly, as you will see.

The kinetic energy of the liquid is easy.

That is one-half M times the velocity squared, and the velocity, we agreed, is y dot squared.

Now the potential energy.

I call the potential energy here, I call that u equals zero.

When the liquid is standing here and the liquid is standing here, I call that potential energy zero.

The mass that is now above this level here, I call that delta M, and delta M is the area times y times rho.

This is how much mass there is here.

It was taken away from here and was put here.

How much work do you have to do to take this liquid and put it there? Well, that's the same when you take this liquid and put it here.

And when you bring this liquid which was there here, then you have moved it up over a distance y, and so the gravitational potential energy increases by delta M--

this is the amount of mass here--

times g times h, and h is y.

Mgh, remember? That's the increase in potential energy.

And so I move an amount of mass which is delta M...

I move it over a distance y.

I bring it here, but that makes no difference, of course.

And so this is the total energy, and this is now a constant.

So I'm going to substitute in there the A, I and rho, so I get one-half Al rho velocity squared plus A rho g.

And I get a y squared equals a constant, because I have a y here and I have a y there.

We've done this before--

this is the conservation of energy, and in order to find the period of the simple harmonic oscillation, we take the time derivative.

By the way, before we do that, this is... this was delta M and this is an A, right? Yeah.

A, rho--

yeah, that's it.

So we lose A, we lose rho, and we continue with what we have.

And so we're going to take the derivative versus time of this equation.

That gives me one-half I.

The two pops out, and the two becomes a one, so I get 2y dot, then I apply the chain rule, so I get y double dot.

Here I get plus g.

The two pops out, becomes 2y, and then I get the chain rule, y dot, and that equals zero.

I lose my y dot, because I have y dot in both terms.

This two eats up this two.

And so I find that y double dot plus 2g divided by l times y equals zero, and that was my goal, because this is clearly a simple harmonic oscillation, because this is a constant.

And it'll oscillate in the following way: y equals y max times the cosine of omega t plus phi, then this is the angular frequency, which is directly related to the period.

Omega, angular frequency equals the square root of 2g over l, and so the period will be two pi times the square root of l over 2g.

So this is the period for an oscillating liquid.

Notice that it is the period that you would have had...

would have obtained from a pendulum if the length of the pendulum were l... l over two--

not at all obvious, not at all intuitive.

You see our setup here.

I have to know what l is, and that is not so easy.

Because of this radius here, if I measure l on the outside, it's substantially larger than on the inside.

You may not think it's a big difference, but it's huge--

it's a nine-centimeter difference between the outside and the inside.

If I take the average value between the two...

if I take the average, I find 72 centimeters, and I could be off by one.

If I use this number for l and I substitute it in this equation, then I find my predicted period, which is 1.204, and because of this error that I have of one, that would give me an uncertainty of about 0.01 seconds.

However, before we start measuring it--

and I will do ten oscillations to get a reasonable, accurate result--

I want to warn you.

I make a prediction--

that the period that we will measure will probably be larger than this, and I can think of two reasons.

The first is that the damping of this liquid will be huge.

You will see how quickly it damps.

In the past, we have never taken damping into account, and we won't do that in 801.

But the damping has the effect on making the period longer.

We've always ignored that, and in most of the demonstrations that we did--

like just now--

that was acceptable.

It may not be acceptable for the liquid.

But now there is a second point that I want you to think about.

Is it correct that I take the average length, namely the average value between the outer length and the inner length? I don't think it is.

I want you to think about why that is not correct.

Look carefully where that I comes into my differential equation and you will probably come up with the right answer.

And I claim that the actual I that we should have taken is a little bit larger--

I don't know how much larger, but it's a little bit larger--

and so that will also make the observed period become larger than the predicted one.

So I'm not too optimistic that we will go and hit this the way we want to hit it, but that's good, because that's where the physics lies--

that you see that there are other factors that have to be taken into account.

I'll turn this one on.

Is it on now? Is it zeroed? I'll make it completely dark in the classroom, because you're going to see...

otherwise, you can't see the liquids.

So you see the liquid now.

Oh, you see these equations, too.

Okay, it's zeroed.

So, let me try to give this a swing, a large swing.

It damps so enormously that I really want to get a very large swing.

That's nice.

Now--

one... two... three...

four... five... six...

seven... eight... nine...

Ten! Ah, not bad.

12.18--

not bad.

We'll get a little bit of light.

12.18.

So observed...

Ten T observed... is it 12.18? Okay, my reaction time is 0.1.

So T observed is 1.2...

let's make it two plus or minus 0.01 seconds.

Oh, that's not bad.

It actually...

there is an overlap.

If you add this one here, you get one-to-one, and if you subtract it here, you get also one-to-one.

So it's not bad.

I expected it to be a little higher, but it's close enough to be happy.

Think about why I should have been taken a little larger.

Now one more very interesting oscillation--

a torsional pendulum.

There's a wire there, 2Ω-meter steel wire, and there's hanging something on the bottom, which we're going to offset, and then it's going to oscillate back and forth.

That's called a torsional pendulum.

And we're going to calculate the period of oscillation of the torsional pendulum, and they have wonderful properties.

They are in a way like a spring, like a one-dimensional spring.

Remember the one-dimensional spring that we had a period which was independent of the amplitude? Well, within reason, of course.

If you make the amplitude too large, then you get permanent deformation of the spring.

But you never had to make any small-angle approximation with the spring as we had to do with the pendulum.

Here is the pendulum, the torsional pendulum.

Here's a bar, and there is a weight here and there's a weight here--

I'll tell you more about that later.

It's hanging here from the ceiling.

It has a certain length l.

This is point P.

And we're going to twist it and then we are going to let it oscillate--

this bar--

in a horizontal plane.

So when you look from above, you will see the bar here--

see point P here--

and then we can offset it over an angle theta, and then it will oscillate back and forth.

The torque relative to point P is now very similar to what we had with a spring.

We have a minus sign; again, that illustrates that it is restoring.

Instead of a k now, we have kappa, which is what we call the torsional spring constant, and now we have an angle which we call theta.

So we generate a torque which is proportional to the angle, very similar to the linear spring whereby we generate a force which is proportional to the linear displacement.

Now you generate a torque which is linearly proportional to the angle.

And this is the moment of inertia about point P times alpha, and alpha is theta double dot.

So we're going to get that theta double dot plus kappa times theta divided by I of P equals zero.

Kappa, by the way, is the torsional constant.

So we have a differential equation.

It's clear that you're going to see a simple harmonic oscillation.

This is a constant, and so you're going to get theta equals theta maximum times the cosine omega t plus phi.

It's getting boring.

This is the angular frequency, angular frequency...

And angular frequency is the square root of kappa divided by the moment of inertia about point P.

And therefore the period--

which is two pi divided by omega--

equals two pi times the square root moment of inertia about point P divided by kappa.

Well... how about kappa? Kappa is a function of the cross-sectional area here A and the length l.

And it's also a function of what kind of material you have.

Whether you have steel or nylon makes a big difference.

That's very intuitive, of course.

Remember that in an earlier lecture when we stressed a wire to the point that it was breaking.

We dealt with Young's modulus.

We had a wire and we had a mass hanging at the end of the wire.

And we discussed the vertical oscillation.

We could stress it and let it go, and then we would get an oscillation, like a spring, and that spring constant that we found, then, was Young's modulus times the cross-sectional area here divided by the length.

And that was kind of pleasing.

The thicker the bar, the stiffer it is; the longer the wire, the less stiff it is.

Well, there is something very similar here, but I don't want to go into the details of exactly how you derive here kappa.

It's a little bit more complicated.

But indeed, the same is true.

If you make the wire thicker, then kappa will go up, and if you make the wire longer, kappa will go down.

That's immediately obvious.

If you have a very short rod and you try to twist that rod...

It's clamped at the top, and you twist it and it's very short, you would need a tremendous torque for ten degrees.

If you make the wire a hundred meters long and you want to twist it ten degrees, it takes nothing.

So you can immediately see that, of course, the value for kappa--

the torsional constant--

is a function of the length.

It will go down when the length goes up.

We have a wire here which is 2Ω meters long, and the thickness of the wire, the diameter--

according to the manufacturer, it's a piano string--

the thickness is 25/1,000 of an inch.

And if I calculate kappa to the best of my ability, well, I find that kappa should be very close to four times ten to the minus four newton-meters per radian.

And so all we have to do now is to calculate the moment of inertia of the system, and then we can predict what the period of this pendulum is going to be--

which is not my goal.

You will see, my goal is going to be a different one.

Look at the bar and look at the wire.

The wire is so thin that the moment of inertia relative to point P of the wire is very close to zero.

Remember, it is proportional to our square.

But you can forget about that.

Almost all moment of inertia is in this system.

I'll blow up that system for you--

here it is.

You'll see it there, and it has on both sides...

it has 200 grams.

It has 0.2 kilograms and it has here 0.2 kilograms.

And this mass is almost negligible.

And this distance here is 30 centimeters and this distance is 30 centimeters.

So to a very good approximation the moment of inertia for rotation about that point P--

this rotation--

will be this mass times radius squared plus this mass times radius squared.

So that will be twice, because I have two masses, times the mass times the radius squared, and that is about 0.036 kilogram meters squared.

And so when I use that into our equation--

so I know now what kappa is, at least I have a reasonable idea what kappa is--

and I know what I of P is--

that's really almost exclusively determined by that cross-bar--

I will find, then, using that equation that the period is very close to 60 seconds.

My goal is not to prove to you that it is close to 60 seconds.

My goal is to show you that for this dimension, which is very thin and very long, that we can make that angle theta maximum--

this angle--

amazingly large.

You're not talking about ten degrees or 30 degrees.

We can go much further.

And what I want to test with you is how far we can go.

This is one of the great things in life for you and for me--

a challenge: How far can you go and get away with it? There comes a time that if we make the angle too large that we permanently deform the wire--

it will not come back to its original position.

The same happens with a spring.

If you take a spring, it is true that the period of oscillation is independent of the amplitude but only up to a point.

If you go too far, that Hooke's Law no longer holds--

that you deform it permanently--

then, of course, the period will become a function of the extension, and the same is true here.

So if we twist it too much up, then, of course, we will permanently deform it, and then the period will not be independent of theta maximum.

Having said that, I would like to start asking you for advice.

What kind of angle in this direction shall we start with? What do you think is reasonable without total torture for the wire? And then we'll write down the times.

So we're not really interested in testing the 60 seconds, but we would rather like to compare the various angles that we give it.

So what is the first one we will try? Any idea?

[echoing class]: 30 degrees? What? STUDENT: Six pi.

LEWIN: The first try?! You are cruel! Man! The first one, you want six pi?! You're out of your mind.

[class laughs]

LEWIN: I'm willing to go one rotation, okay? You think that's nothing--

it's peanuts for you, right? Okay, I would like to go theta maximum of 360 degrees--

so two pi--

and measure the period.

In fact, to measure the period takes a minute, and it's not necessary.

We can measure half a period.

Namely, we wait until the pendulum stops, and we measure the time until it stops again; that's half a period.

Like with the spring--

if it stops here and it stops there, that's half a period.

So we'll measure half a period.

Now, I don't know what my reaction time is going to be, It may be another tenth of a second, because the moment that it stops is not so well defined, you will see.

I'm just guessing--

probably a little larger than one-tenth of a second.

Let's give it a shot.

Let's try first 360 degrees.

You see, this is black and this is a little red, so we will rotate it one rotation.

This is back here where it was.

Yeah, have you seen that? 360 degrees.

Okay, now, I will first let it go and wait until it stops.

I always do that, and then I start the time.

And then when it stops again, I'll stop the time, and then we have half a period.

So let it first do its own thing...

very slowly, very gently.

It should take roughly 30 seconds for half a rotation.

so you'll see now that it...

it's now at equilibrium again, because we wound it up one rotation and so back to equilibrium.

And now it's going to stop very shortly, and when it stops, I want to start the timer.

Now! Okay, so now it goes back, and we'll wait until it stops again.

That gives us half a period.

Okay.

Now! 28.75.

28.8.

What are we going to do now?

Three rotations? Five rotations? Three.

Are we in favor of three? Who is responsible for permanent damage to the wire? Do you accept responsibility in life? Three is a lot.

Three is six pi, man, six.

9I can start it, because it will take a while before it stops.

Three rotations--

first we have to be sure that it is more or less back at equilibrium, which is always a difficult thing, because it's so slow.

Yeah, close enough.

Okay, three--

shall we go clockwise or counterclockwise? It should make no difference.

I went this way first; shall we go back? Yeah? You can sleep with that? Okay? Okay.

One... two... three.

Six pi.

The piano wire.

Okay, let's go.

I will start the timer when it stops.

We have some time.

Six pi.

If we rotate it six...

three times, then it will rotate six times back before it stops.

I hope you realize that.

[student speaks up  in background]

LEWIN: Was I too late? Thank you for pointing that out.

So if you rotate it three times and then let it go, it goes first three times back, then it's at equilibrium, and then it winds three times up again before it stops.

Notice it's going much faster now, but the time--

that's the whole thing--

should be very close to that number again.

28.5.

Oh! Not bad.

Shall we now go all the way? What do you want to do now? Break the wire or...

Ten rotations?

You'd love to see that, right? It will go like mad, ten rotations.

Isn't it amazing how much faster it goes?

[imitates whirring]

It's still 30 seconds.

I must make sure that I have my equilibrium.

This was not equilibrium.

I know it's somewhere here.

No, it wasn't equilibrium.

I think this is it.

Okay--

ten, right? Ready? One... two... three... four...

five... six... seven...

eight... nine...

Ten--

poor wire.

We'll let it go and we'll see what happens.

When it stops, I'll start the time.

[student speaks up  in background]

LEWIN: Excuse me?

[student repeats]

LEWIN: Thank you.

Thank you for pointing that out.

Look how fast it's going.

I mean, it's really going wacko.

It has to do all that in 30 seconds.

Now!

So now it has to go back to its stopping.

It has to make 20 rotations now, 20 rotations in 30 seconds--

ten back to equilibrium and then ten to come to a halt.

This is going to be your Thanksgiving farewell demonstration.

Now! 29.2--

fantastic.

Okay, have a good Thanksgiving.