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8.01 Physics I: Classical Mechanics, Fall 1999
Transcript – Lecture 28

Today we're going to continue with playing with liquids.

If I have an object that floats, a simple cylinder that floats in some liquid, the area is A here, the mass of the cylinder is M.

The density of the cylinder is rho and its length is l and the surface area is A.

So this is l.

And let the liquid line be here, and the fluid has a density rho fluid.

I call this level y1, this level y2.

The separation is h, and right on top here, there is the atmospheric pressure P2, which is the same as it is here on the liquid.

And here we have a pressure P1 in the liquid.

For this object to float we need equilibrium between, on the one hand, the force Mg and the buoyant force.

There is a force up here which I call F1, and there is a force down here which I call F2--

barometric pressure.

The force is always perpendicular to the surface.

There couldn't be any tangential component because then the air starts to flow, and it's static.

And here we have F1, which contains the hydrostatic pressure.

So P1 minus P2--

as we learned last time from Pascal--

equals rho of the fluid g to the minus y2 minus y1, which is h.

So that's the difference between the pressure P1 and P2.

For this to be in equilibrium, F1 minus F2 minus Mg has to be zero, and this we call the buoyant force.

And "buoyant" is spelt in a very strange way: b-u-o-y-a-n-t.

I always have to think about that.

It's the buoyant force.

F1 equals the area times P1 and F2 is the area times P2, so it is the area times P1 minus P2, and that is rho fluids times g times h.

And when you look at this, this is exactly the weight of the displaced fluid.

The area times h is the volume of the fluid which is displaced by this cylinder, and you multiply it by its density, that gives it mass.

Multiply it by g, that gives it weight.

So this is the weight of the displaced fluids.

And this is a very special case of a general principle which is called Archimedes' principle.

Archimedes' principle is as follows: The buoyant force on an immersed body has the same magnitude as the weight of the fluid which is displaced by the body.

According to legend Archimedes thought about this while he was taking a bath, and I have a picture of that here--

I don't know from when that dates--

but you see him there in his bath, but what you also see are there are two crowns.

And there is a reason why those crowns are there.

Archimedes lived in the third century B.C.

Archimedes had been given the task to determine whether a crown that was made for King Hieron II was pure gold.

The problem for him was to determine the density of this crown--

which is a very irregular-shaped object--

without destroying it.

And the legend has it that as Archimedes was taking a bath, he found the solution.

He rushed naked through the streets of Syracuse and he shouted, "Eureka! Eureka! Eureka!" which means, "I found it! I found it!" What did he find? What did he think of? He had the great vision to do the following: You take the crown and you weigh it in a normal way.

So the weight of the crown--

I call it W1--

is the volume of the crown times the density of which it is made.

If it is gold, it should be 19.3, I believe, and so this is the mass of the crown and this is the weight of the crown.

Now he takes the crown and he immerses it in water.

And he has a spring balance, and he weighs it again.

And he finds that the weight is less and so now we have the weight immersed in water.

So what you get is the weight of the crown minus the buoyant force, which is the weight of the displaced fluid.

And the weight of the displaced fluid is the volume of the crown--

because the crown is where...

the water has been removed where the crown is--

times the density of the fluid--

which is water, which he knew very well--

times g.

And so this part here is weight loss.

That's the loss of weight.

You can see that, you can measure that with a spring.

It's lost weight, because of the buoyant force.

And so now what he does, he takes W1 and divides that by the weight loss and that gives you this term divided by this term, which immediately gives you rho of the crown divided by rho of the water.

And he knows rho of the water, so he can find rho of the crown.

It's an amazing idea; he was a genius.

I don't know how the story ended, whether it was gold or not.

It probably was, because chances are that if it hadn't been gold that the king would have killed him--

for no good reason, but that's the way these things worked in those days.

This method is also used to measure the percentage of fat in persons' bodies, so they immerse them in water and then they weigh them and they compare that with their regular weight.

Let's look at an iceberg.

Here is an iceberg.

Here is the water--

it's floating in water.

It has mass M, it has a total volume V total, and the density of the ice is rho ice, which is 0.92 in grams per cubic centimeter.

It's less than water.

This is floating, and so there's equilibrium between Mg and the buoyant force.

So Mg must be equal to the buoyant force.

Now, Mg is the total volume times rho ice times g, just like the crown.

The buoyant force is the volume underwater, which is this part, times the density of water, rho water, times g.

You lose your g, and so you find that the volume underwater divided by the total volume equals rho ice divided by rho of water, which is 0.92.

That means 92% of the iceberg is underwater, and this explains something about the tragedy on April 15, 1912, when the Titanic hit an iceberg.

When you encounter an iceberg, you literally only see the tip of the iceberg.

That's where the expression comes from.

92% is underwater.

I want to return now to my cylinder, and I want to ask myself the question, when does that cylinder float? What is the condition for floating? Well, clearly, for that cylinder to float the buoyant force must be Mg, and the buoyant force is the area times h--

that's the volume underwater--

multiplied by the density of the fluid times g must be the total volume of the cylinder, which is the area times l, because that was the length of the cylinder, times the density of the object itself times g.

I lose my A, I lose my g, but I know that h must be less than l; otherwise it wouldn't be floating, right? The part below the water has to be smaller than the length of the cylinder.

And if h is less than l, that means that the density of the fluid must be larger than the density of the object, and this is a necessary condition for floating.

And therefore, if an object sinks then the density of the object is larger than the density of the fluid.

And the amazing thing is that this is completely independent of the dimensions of the object.

The only thing that matters is the density.

If you take a pebble and you throw it in the water, it sinks, because the density of a pebble is higher than water.

If you take a piece of wood, which has a density lower than water, and you throw it on water, it floats independent of its shape.

Whether it sinks or whether it floats, the buoyant force is always identical to the weight of the displaced fluid.

And this brings up one of my favorite questions that I have for you that I want you to think about.

And if you have a full understanding now of Archimedes' principle, you will be able to answer it, so concentrate on what I am going to present you with.

I am in a swimming pool, and I'm in a boat.

Here is the swimming pool and here is the boat, and I am sitting in the boat and I have a rock here in my boat.

I'm sitting in the swimming pool, nice rock in my boat.

I mark the waterline of the swimming pool very carefully.

I take the rock and I throw it overboard.

Will the waterline go up, or will the waterline go down, or maybe the waterline will stay the same? Now, use your intuition--

don't mind being wrong.

At home you have some time to think about it, and I am sure you will come up with the right answer.

Who thinks that the waterline will go up the swimming pool? Who thinks that the waterline will go down? Who thinks that it will make no difference, that the waterline stays the same? Amazing--

okay.

Well, the waterline will change, but you figure it out.

Okay, you apply Archimedes' principle and you'll get the answer.

I want to talk about stability, particularly stability of ships, which is a very important thing--

they float.

Suppose I have an object here which is floating in water.

Here is the waterline, and let here be the center of mass of that object.

Could be way off center.

It could be an iceberg, it could be boulders, it could be rocks in there, right? It doesn't have to be uniform density.

The center of mass could be off the center...

of the geometric center.

So if this object has a certain mass, then this is the gravitational force.

But now look at the center of mass fluid that is displaced.

That's clearly more here, somewhere here, the displaced fluid.

That is where the buoyant force acts.

And so now what you have...

You have a torque on this object relative to any point that you choose.

It doesn't matter where you pick a point, you have a torque.

And so what's going to happen, this object is clearly going to rotate in this direction.

And the torque will only be zero when the buoyant force and the gravitational force are on one line.

Then the torque becomes zero, and then it is completely happy.

Now, there are two ways that you can get them on one line.

We discussed that earlier in a different context.

You can either have the center of mass of the object below the center of mass of the displaced fluid or above.

In both cases would they be on one line.

However, in one case, there would be stable equilibrium.

In the other, there would not be a stable equilibrium.

I have here an object which has its center of mass very low.

You can't tell that--

no way of knowing.

All you know is that the weight of the displaced fluid that you see here is the same as the weight of the object.

That's all you know.

If I took this object and I tilt it a little with the center of mass very low--

so here is Mg and here is somewhere the waterline--

so the center of mass of the displaced fluid is somewhere here, so Fb is here, the buoyant force, you can see what's going to happen.

It's going to rotate towards the right--

it's a restoring torque, and so it's completely stable.

I can wobble it back and forth and it is stable.

If I would turn it over, then it's not stable, because now I would have the center of mass somewhere here, high up, so now I have Mg.

And the center of the buoyant force, the displaced water, is about here, so now I have the buoyant force up, and now you see what's going to happen.

I tilt it to the side, and it will rotate even further.

This torque will drive it away from the vertical.

And that's very important, therefore, with ships, that you always build the ship such that the center of mass of the ship is as low as you can get it.

That gives you the most stable configuration.

If you bring the center of mass of ships very high--

in the 17th century, they had these very massive cannons which were very high on the deck--

then the ship can capsize, and it has happened many times because the center of mass was just too high.

So here... the center of mass is somewhere here.

Very heavy, this part.

And so now, if I lower it in the water notice it goes into the water to the same depth, because the buoyant force is, of course, the same, so the amount of displaced water is the same in both cases.

But now the center of mass is high and this is very unstable.

When I let it go, it flips over.

So the center of mass of the object was higher than the center of mass of the displaced fluid.

And so with ships, you have to be very careful about that.

Let's talk a little bit about balloons.

If I have a balloon, the situation is not too dissimilar from having an object floating in a liquid.

Let the balloon have a mass M.

That is the mass of the gas in the balloon plus all the rest, and what I mean by "all the rest"...

That is the material of the balloon and the string--

everything else that makes up the mass.

It has a certain volume v, and so there is a certain rho of the gas inside and there is rho of air outside.

And I want to evaluate what the criterion is for this balloon to rise.

Well, for it to rise, the buoyant force will have to be larger than Mg.

What is the buoyant force? That is the weight of the displaced fluid.

The fluid, in this case, is air.

So the weight of the displaced fluid is the volume times the density of the air--

that's the fluid in which it is now--

times g, that is the buoyant force.

That's... the weight of the displaced fluid has to be larger than Mg.

Now, Mg is the mass of the gas, which is the volume of the gas times the density of the gas.

That's the mass times g--

because we have to convert it to a force--

plus all the rest, times g.

I lose my g, and what you see...

that this, of course, is always larger than zero.

There's always some mass associated with the skin and in this case with the string.

But you see, the only way that this balloon can rise is that the density of the gas must be smaller than the density of air.

Density of the gas must be less than the density of the air.

This is a necessary condition for this to hold.

It is not a sufficient condition, because I can take a balloon, put a little bit of helium in there--

so the density of the gas is lower than the density of air--

but it may not rise, and that's because of this term.

But it is a necessary condition but not a sufficient condition.

Now I'm going to make you see a demonstration which is extremely nonintuitive, and I will try, step by step, to explain to you why you see what you see.

What you're going to see, very nonintuitive, so try to follow closely why you see what you will see.

I have here a pendulum with an apple, and here I have a balloon filled with helium.

I cut this string and I cut this string.

Gravity is in this direction.

The apple will fall, the balloon will rise.

The balloon goes in the opposite direction than the gravitational acceleration.

If there were no gravity, this balloon would not rise and the apple would not fall.

Do we agree so far? Without gravity, apple would not fall, balloon would not rise.

Now we go in outer space.

Here is a compartment and here is an apple.

I'm here as well.

None of us have weight, there's no gravity, and here is a helium-filled object, a balloon, and there's air inside.

We're in outer space, there's no gravity.

Nothing has any weight.

We're all floating.

Now I'm going to accelerate.

I have a rocket--

I'm going to accelerate it in this direction with acceleration a.

We all perceive, now, a perceived gravity in this direction.

I call it g.

So the apple will fall.

I'm standing there, I see this apple fall.

I'm in this compartment, closed compartment.

I see the apple go down.

A little later, the apple will be here.

I myself fall; a little later, I'm there.

I can put a bathroom scale here and weigh myself on the bathroom scale.

My weight will be M times this a, M being my mass, a being this acceleration.

I really think that it is gravity in this direction.

The air wants to fall, but the balloon wants to go against gravity.

The balloon will rise.

The air wants to fall, so inside here you create a differential pressure between the bottom, P1, and the top of the air, P2, inside here.

Just like the atmosphere on earth--

the atmosphere is pushing down on us--

the pressure is here higher than there.

So you get P1 is higher than P2.

So you create yourself an atmosphere, and the balloon will rise.

The balloon goes in the opposite direction of gravity.

If there were no air in there, then clearly all of us would fall: The apple would fall, I would fall, and the helium balloon would fall.

The only reason why the helium balloon rises is because the air is there and because you build up this differential pressure.

Now comes my question to you: Instead of accelerating it upwards and creating perceived gravity down, I'm now going to accelerate it in this direction, something that I'm going to do shortly in the classroom.

I'm going to accelerate all of us in this direction a.

In which direction will the apple go? In which direction will the balloon go? What do you think? The apple will go in the direction that it perceives gravity.

The apple will go like this.

I will go like this.

The air wants to go like this.

But helium--

balloon--

goes in the opposite direction of gravity, so helium goes in this direction.

In fact, what you're doing, you're building here an atmosphere where pressure P1 here will be higher than the pressure P2 there.

The air wants to go in this direction.

The pressure here is higher than the pressure there--

larger than zero.

If there's no air in there, we would all fall.

Helium would fall...
helium balloon would fall, apple would fall, and I would fall.

I have here an apple on a string in a closed compartment, not unlike what we have there except I can't take you out to an area where we have no gravity.

So here is that closed compartment, and here is the apple.

There is gravity in this direction.

It wants to fall in that direction of gravity if I cut the wire.

Now I'm going to accelerate it in this direction, and when I do that, I add a perceived component of gravity in the opposite direction.

So I add a perceived component of gravity in this direction.

So this apple wants to fall down because of the gravity that I cannot avoid, and it wants to fall in this direction.

So what will the string do? It's very clear, very intuitive, no one has any problem with that--

the string will do this.

Now I have a balloon here.

Helium.

There is gravity in this direction.

That's why the balloon wants to go up.

It opposes gravity.

I'm going to accelerate the car in this direction.

I introduce perceived gravity in this direction.

What does the balloon want to do? It wants to go against gravity.

I build up in here, and it must be a closed compartment...

I must build up there a pressure differential.

The air wants to fall in this direction.

I build up a pressure here which is larger than the pressure there.

That's why it has to be a closed compartment.

What will the helium balloon do? It will go like that.

That is very nonintuitive.

So I accelerate this car.

As I will do, the apple will go back, which is completely consistent with all our intuition, but the helium balloon will go forward.

Let's first do it with the apple, which is totally consistent with anyone's intuition.

I'm going to make sure that the apple is not swinging too much.

Now, it only happens during the acceleration, so it's only during the very short portion that I accelerate that you see the apple go back, and then of course it starts to swing--

forget that part.

So watch closely--

only the moment that I accelerate the apple will come this way.

It goes in the direction of the extra component of perceived gravity.

Ready?
Boy, it almost hit this glass here.

Everyone could see that, right? Okay.

Now we're going to do it with the balloon.

We're going to take this one off.

And now let's take one of our beautiful balloons.

We're going to put a balloon in here.

Has to be a closed compartment so that the air can build up the pressure differential.

There's always problems with static charges on these systems.

Okay.

Only as long as I accelerate will the balloon go in a forward direction, so I accelerate in this direction, and what you're going to see is really very nonintuitive.

Every time I see it, I say to myself, "I can reason it, but do I understand it?" I don't know, what is the difference between reasoning and understanding? There we go.

The balloon went this way.

You can do this in your car with your parents.

It's really fun to do it.

Have a string with an apple or something else and have a helium balloon.

Close the windows.

They don't have to be totally closed, but more or less, and ask your dad or your mom to slam the brakes.

If you slam the brakes, what will happen? The apple will go...
what do you think? If you slam the brakes, the apple will go forwards, balloon will go backward.

If you accelerate the car all of a sudden, the apple will go backwards and the balloon will go forward.

You can do that at home.

You can enjoy... entertain your parents at Thanksgiving.

They'll get some of their $25,000 tuition back.

[class laughs]

When fluids are moving, situations are way more complicated than when they are static.

And this leads to, again, very nonintuitive behavior of fluids.

I will derive in a short-cut way a very famous equation which is called Bernoulli's equation, which relates kinetic energy with potential energy and pressure.

Suppose I have a fluid, noncompressible, like so.

This cross-sectional area is A2 and the pressure here is P2.

And I have a velocity of that liquid which is v2 and this level is y2.

Here I have a cross-sectional area A1.

I have a pressure P1.

My level is y1; this is increasing y.

And I have a much larger velocity because the cross-section is substantially smaller there.

Now, if this fluid were completely static, if it were not moving--

so forget about the v1 and forget about the v2; it's just sitting still--

then P1 minus P2 would be rho g times y2 minus y1 if rho is the density of the fluid.

That's Pascal's Law.

So it would just be sitting still, and we know that the pressure here would be lower than the pressure there.

This is also, if you want to, rho gh if you call this distance h.

Rho gh--

that reminds me of mgh, and mgh is gravitational potential energy.

When I divide m by volume, I get density.

So this is really a term which is gravitational potential energy per unit volume.

That makes the m divided by volume become density.

Therefore, pressure itself must also have the dimension of energy per unit volume.

And if we now set this whole machine in motion, then there are three players: There is, on the one hand, kinetic energy--

of motion--

kinetic energy...
I take it, per unit volume.

There is gravitational potential energy...

I will take it, per unit volume.

And then there is pressure.

They're equal partners.

And if I apply the conservation of energy, the sum of these three should remain constant.

That's the idea behind Bernoulli's law, Bernoulli's equation.

When I take a fluid element and I move it from one position in the tube to another position, it trades speed for either height or for pressure.

What is the kinetic energy per unit volume? Well, the kinetic energy is one-half mv squared.

I divide by volume, I get one-half rho v squared.

What is gravitational potential energy? That is mgy.

I divide by volume, and so I get rho gy plus the pressure at that location y, and that must be a constant.

And this, now, is Bernoulli's equation.

It is a conservation of energy equation.

And as I will show you, it has very remarkable consequences.

First I will show you an example whereby I keep y constant.

So I have a tube which changes diameter, but the tube is not changing with level y, as I do there.

So I come in here, cross-sectional area A1.

I widen it, cross-sectional area A2.

This is y--

it's the same for both.

I have here inside pressure P1 and here inside I have pressure P2 and this is the density of the fluid.

There is here a velocity v2, and there is here a velocity v1.

And clearly v1 is way larger than v2 because A1 times v1 must be A2 times v2 because the fluid is incompressible.

So the same amount of matter that flows through here in one second must flow through here in one second.

And so these have to be the same, and since A1 is much smaller than A2, this velocity is much larger than v2.

Now I'm going to apply Bernoulli's equation.

So the first term tells me that one-half rho v1 squared...

I can forget the second term because I get the same term here as I get there because I measure the pressure here and I measure the pressure there.

They have the same level of y.

So I can ignore the second term.

Plus P1 must be one-half rho v2 squared plus P2.

That's what Bernoulli's equation tells me.

Now, v1 is larger than v2.

The only way that this can be correct, then, is that P1 must be less than P2.

So you will say, "Big deal." Well, it's a big deal, because I would have guessed exactly the other way around, and so would you, because here is where the highest velocity is, and all our instincts would say, "Oh, if the velocity is high, there's a lot of pressure." It's exactly the other way around.

Here is the low pressure, and here is the high pressure, which is one quite bizarre consequence of Bernoulli's equation.

You must all have encountered in your life what we call a siphon.

They were used in the medieval and they're still used today.

You have here...

A bucket in general is used with water--

lakes.

We have water here, but it could be any liquid.

And I stick in here a tube which is small in diameter, substantially smaller than this area here.

And there will be water in here up to this level--

this level P2, y2.

This is y1, increasing value of y.

This height difference is h.

P2 is one atmosphere.

I put a one there--

it's atmosphere.

And here, if it's open, then P1 is also one atmosphere.

So there's air in here and there's liquid in here.

I take this open end in my mouth and I suck the water in so that it's filled with this water, full with this water.

And strange as it may be, it's like making a hole in this tank.

If I take my finger off here, the water will start to run out, and I will show you that.

And you have here a velocity v1.

The water will stream down into this here and the velocity here is approximately zero, because this area is so much larger than this cross-sectional area that to a good approximation this water is going down extremely slowly.

Let's call this height difference d.

I apply Bernoulli's law.

So now we have a situation where the y's are different but the pressure is the same, because right here at this point of the liquid I have one atmosphere, which is barometric pressure, and since this is open with the outside world, P1 is also one atmosphere.

So now I lose my P term.

There I lost my y term; now I lose my P term.

So now I have that one-half rho... rho--

this is rho of the liquid--

v1 squared plus rho g times y1 must be one-half rho v2 squared, but we agreed that that was zero, so I don't have that term.

So I only have rho gy2.

I lose my g's...
no, I don't lose my g's.

One-half rho v squared--

no, that's fine.

And so... I lose my rho.

This is one-half.

I lose my rho.

And so you get that one-half v1 squared equals g times y2 minus y1, which is h.

And so what do you find? That the speed with which this water is running out here, v1, is the square root of 2gh.

And you've seen that before.

If you take a pebble and you release a pebble from this level and you let it fall, it will reach this point here, this level with the speed the square root of 2gh.

We've seen that many times.

So what is happening here--

since the pressure terms are the same here and there, now there's only a conversion.

Gravitational potential energy--

which is higher here than there--

is now converted to kinetic energy.

This siphon would only work if d is less than ten meters.

Because of the barometric pressure you can never suck up this water--

no one can; a vacuum pump can't either--

to a level that is higher than ten meters.

When I did the experiment there with the cranberry juice, I was able to get it up to five meters, but ten meters would have been the theoretical maximum.

So this has to be less than ten meters that you go up.

If I would have made a hole in this tank here, just like this, down to exactly this level, and I would have asked you to calculate with what speed the water is running out, you would have found exactly the same if you had applied Bernoulli's equation.

This is a way that people...

I've seen people steal other people's gasoline in the time that gasoline was very scarce and that there were no locks yet on the gasoline caps.

You would put a hose in the gasoline tank and you would have to suck on it a little--

you have to sacrifice a little bit--

you get a little bit of gasoline in your mouth, and then you can just empty someone's gasoline tank by having a canister or by having a jerrican and fill it with gasoline.

And I'm going to show that now to you by emptying...

That's still cranberry juice, by the way, from our last lecture.

So let's put this up on a stool.

So there is the hose--

it's that thing--

and I'm going to transfer this liquid from here to here.

So first I have to fill it with cranberry juice.

And there it goes.

And as long as this level is below that level, it keeps running.

Not so intuitive.

I remember, I was at a summer camp when I was maybe six or seven years old.

I couldn't believe it when I saw this for the first time.

We had these outdoor sinks where we washed ourselves and brushed our teeth, and the sink was clogged, it was full with water.

And one of the camp leaders took a hose, sucked up and it emptied itself.

And I really thought, you know, you'd have to take spoonfuls of water or maybe buckets and scoop it out.

This is the way you do it.

Very nonintuitive.

The nonintuitive part is that it runs up against gravity there.

So we can let it sit there and we have a transfer, mass transfer of cranberry juice.

Last time I was testing my lungs to see how strong I was.

I wasn't very good, right? I could only blow up one meter of water and only suck one meter water.

Differential pressure only one-tenth of an atmosphere.

Today I would like to test one of the students who, no doubt, is more powerful than I am.

And I have here a funnel...

with a Ping-Pong ball here, very lightweight, and we're going to have a contest to see who can blow it the highest.

I have two funnels, so it's very hygienic.

I will try it with this one.

They're clean, they just...

We just got them from the chemistry department.

And so I would like to see a volunteer--

woman or man, it doesn't matter.

You want to try it, see whether you can reach the ceiling? You don't want to try it? Come on! You want to try it? You're shy? You don't want to? Can I persuade you? I can.

Okay, come along.

Come right here.

You think you can make it to the ceiling? It's only a very light Ping-Pong ball.

So, you go like this, blow as hard as you can.

STUDENT: Okay.

LEWIN: Try it, don't be nervous.

STUDENT: All right.

LEWIN: Straight up.

STUDENT: No...

LEWIN: Blow as hard as you can--

get it out.

Amazing! Do it again.

Come on, there must have been something wrong.

[class laughs]

LEWIN: You're not sick today, are you? Blow.

Harder! STUDENT: Is this a trick? LEWIN: No, there's nothing, there's no trick in here.

I mean, my goodness--

this is a Ping-Pong ball, I'm not a magician.

[class laughs]

LEWIN: Come on, blow it up! Hey, it doesn't work.

It's amazing.

Why don't you sit down?

[class laughs]

LEWIN: Why doesn't it work? Why doesn't it work? The harder you blow, the least it will work.

Air is flowing here...

and right here, where there is very little room, the air will have very high speed, way higher than it has where it has lots of room.

And so at the highest speed, you get the lowest pressure.

And so the Ping-Pong ball is sucked in while you're blowing it.

And to give you the conclusive proof of that I will do it this way.

I will put the Ping-Pong ball like so, and I'm going to blow like this, and if I blow hard enough, the Ping-Pong ball will stay in there because I generate a lower pressure right here where the passage is the smallest, but I have to blow quite hard.

[inhales deeply, blowing hard]

You see that? Isn't that amazing? That's the reason why she couldn't get it up.

[inhales deeply, blowing hard]

That's what Bernoulli does for you.

Not so intuitive, is it?
I have here an air flow, a hose with air coming out, and I can show you there something that is equally nonintuitive.

Let's start the air flow.

[air hissing]

It's coming out.

I take a Ping-Pong ball.

It stays there.

Is that due to Mr. Bernoulli? No.

No, that's more complicated physics, because it has to do with turbulence.

It has to do with vortices, which is very difficult.

What is happening here is that as the air flows, you get turbulence above here and the turbulence creates a lower pressure.

So the vortices, which are the turbulence, are keeping this up, because there's a lower pressure here and there.

But why is it so stable? I can see that I have...

because of this turbulence, that it's held up.

Why is it so stable? If I give it a little push it doesn't...
it's sucked back in again.

It's very stable--

that is Bernoulli.

Because if I blow air, like so...

then the velocity here is the highest, because it's diverging the air as it's coming out, but in the center, it is the highest, and so when this Ping-Pong ball goes to this side, it clearly has a lower pressure here than there and so it's being sucked back in again.

So the stability is due to Bernoulli, but the fact that it is held up is more difficult physics.

It is so stable that I can even tilt this...

and it will still stay there.

Now I have something that I want you to show your parents on Thanksgiving.

It's a little present for them, and that is something that you can very easily do at home.

You take a glass and you fill it with cranberry juice--

not all the way, up to here.

Take a thin piece of cardboard, the kind of stuff that you have on the back of pads.

You put it on top.

The table is beautifully set--

turkey, everything is there--

and you suggest to your parents that you turn this over.

Your mother will scream bloody murder, because she would think that the cranberry juice will fall out.

In fact, it may actually fall out.

I can't guarantee you that it won't.

[class laughs]

LEWIN: But it may not, in which case you now have all the tools to explain that.

Please do invite me to your Thanksgiving dinner and I'll show it to your parents.