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8.01 Physics I: Classical Mechanics, Fall 1999
Transcript – Lecture 31

So far, we analyzed...

We calculated the periods of lots of oscillators: pendulums, springs, rulers, hula hoops.

We gave them a kick, moved them off equilibrium, and then they were oscillating at their own preferred frequency.

Today, I want to discuss with you what happens if I force upon a system a frequency of my own.

So we call that forced oscillations.

I can take a spring system, as we have before.

This is x equals zero, this is x, and we have the spring force, very familiar, minus kx.

But now this object here, which is mass m, I'm going to add a force to it, F zero, which is the amplitude of the force, times the cosine of omega t.

So I'm going to force it in a sinusoidal fashion with a frequency that I choose.

This frequency is not the frequency with which the system wants to oscillate.

It is the one that I choose, and I can vary that.

And the question, now, is what will the object do? Well, we have Newton's Second Law--

ma equals minus kx plus that force, F zero cosine omega t.

a is x double dot, so I get x double dot, plus-- I bring this in--

k over m times x equals F zero divided by m times the cosine omega t.

Now, the question is what is the solution to this differential equation? It's very different from what we saw before, because before, we had a zero here.

Now we have here a driving force.

It's clear that if you wait long enough that sooner or later that system will have to start oscillating at that frequency.

In the beginning, it may be a little different.

In the beginning, it may want to do its own thing, but ultimately, if I take you by your arms and I shake you back and forth, in the beginning you may object, but sooner or later, you will have to go with the frequency that I force myself upon you.

And when we reach that stage, we call that the steady state as opposed to the beginning, when things are a little bit confused, which we call the transient phase.

So in the steady state, the object somehow must have a frequency which is the same as the driver, and it has some amplitude A.

And I want to evaluate with you that amplitude A.

So this is my trial function that I'm going to put into this differential equation.

x dot equals minus A omega sine omega t.

x double dot equals minus A omega squared cosine omega t.

And so now I'm going to substitute that in here, so I'm going to get minus A omega squared cosine omega t plus k over m times A cosine omega t, and that equals F zero divided by m times the cosine of omega t.

And that must always hold.

So therefore I can divide out my cosine omega t.

I can bring the A's together, so I get A times k over m minus omega squared equals F zero divided by m.

Now, this k over m is something that we are familiar with.

If we let the system do its own thing--

we bring it away from equilibrium and we don't drive it--

then we know that omega squared, which I will give the zero, equals k over m.

This is the frequency that we have dealt with before.

This is the driving frequency--

it's very different.

And so I'm going to substitute in here for k over m omega zero squared, and so I find, then, that the amplitude of this object here at the end of the spring will be F zero divided by m divided by omega zero squared minus omega squared.

And this amplitude has very remarkable characteristics.

First of all, if I drive the system at a very low frequency so that omega is much, much smaller than omega zero, we call omega zero often the natural frequency.

It is the one that it likes.

If you have omega much, much less than omega zero, this goes--

omega zero squared is k over m--

so you get an amplitude A which is F zero divided by k.

If you go omega way above the natural frequency or, let's say, omega goes to infinity--

it becomes very, very large--

then downstairs becomes very, very large, so A goes to zero.

But now, what happens when omega is exactly omega zero? Then the system goes wacky.

Look what happens.

The downstairs becomes zero and the amplitude goes to infinity.

And that's what we call resonance.

So if we drive it at that frequency, the system goes completely berserk.

I can make a plot of A as a function of frequency.

When I say "omega," you can obviously always change to hertz, if you prefer that, because omega is two pi times F, so you can do it either in hertz or you can do it in radians per second, of course.

So if I make a plot of the amplitude versus frequency omega, then at low values-- I have here F zero divided by k--

is the amplitude.

When I hit the resonant frequency, the natural frequency of the system, it goes out of hand, it goes to infinity.

The moment that omega is larger than omega zero, notice that the amplitude becomes negative.

A negative amplitude simply means that you get all of a sudden a phase change of 180 degrees, so the object is 180 degrees out of phase with the driver.

I will not expand on that too much today, but it is negative, and so it comes up here, and then it goes here to zero for very high frequencies of omega.

So something very spectacular is going to happen at the resonant frequency of the system.

In practice, of course, the amplitude will not go to infinity, and the reason for that is that there is always friction of some kind.

There is always damping, but you get a very high amplitude but not infinitely high.

So if I make you a more realistic plot of the amplitude, and I will take now the absolute value, the magnitude, so we don't have to worry about it getting negative--

we don't have to worry about the 180-degree phase shift--

then you would get a curve that looks like this.

And here, then, if this is frequency F, then here you would get the natural frequency when things go out of hand.

And depending upon how much damping there is, this curve would look either very narrow and very spiky--

it goes very, very high, then there is very little damping--

or if there is a lot of damping in the system, it's more like this.

So the narrower this...

We call this the resonance curve.

The narrower that is, the less damping there is.

I have here a system on the air track which is an object that I can drive with a frequency that I can choose.

Here is a spring...

object mass m, and here is another spring.

It's fixed on this side, right there, and here I'm going to drive it, so I have here this variable force that you see there.

And what I want to show you now is that first I will drive it at a frequency which is way below the resonant frequency.

Then you will see an amplitude, not very large.

I will then drive it way above the resonant frequency.

Again, you will see an amplitude which is very low.

If I can go very high frequency, you will see that it almost stands still, and then I will try to hit the resonant frequency, and that will be...

It's about one hertz, the resonant frequency, if I just let this object do its own thing, just this.

Now you see the natural frequency--

it's about one hertz--

but now I'm going to drive it here with a system, and we are going to pull on this spring with a frequency that we control.

So let me start.

You see here the frequency.

You see an indicator, very low, way lower than one hertz.

And when you look at the way that the system responds, if you wait long enough when the transients are died out, you will see that they go hand in hand, that the amplitude is in phase with the driver.

That's why we have plus amplitude here.

But the phase is not so important today.

See, they go hand in hand.

Very small amplitude, roughly at zero divided by k, which is the spring constant of the spring.

Now I'll go way above resonance, and this system will slip here, so don't pay attention to the arrow anymore.

Way above resonance.

You see, it starts to slip.

Look at the amplitude--

very modest, very small.

But we went over this curve, so first we probed it here and now we're probing it here.

Look, it's almost not moving at all, almost standing still, and I'm driving it at a high frequency now.

And now I'm going to find you this resonance, which is near one hertz...

which is somewhere here.

And look-- very high amplitude.

If we're not careful, then we can actually break the system.

Very high amplitude--

I'm trying to scan over it now, go a little bit off resonance.

Now I'm back on resonance.

See what a huge amplitude! Better turn it off.

So you see here the response when I drive a system.

When my system is a little bit more complicated--

for instance, if I had two masses here so I would add one here, spring constant k, spring constant k--

I could repeat this experiment, and if I did that, I would find two resonant frequencies.

And if I do it with three objects,

I would find three resonant frequencies.

If I did it with five, I would find five resonant frequencies.

And when I make, then, this curve of A amplitude as a function of frequency--

either hertz or in radians per second, whichever you prefer--

then if I had three objects there in a row, you would see something like this.

And depending upon how many of these objects you have, you get more and more resonances.

And these resonances can all be found by driving the system and searching for them.

If I go to a system whereby I have an infinite number of these masses...

We call them coupled oscillators; these oscillators are coupled through the springs.

An infinite number of coupled oscillators would be a violin string.

Here's a violin string.

And the reason why I call it "infinitely" number of oscillators is that I can think of each atom or each molecule as being driven, as being connected by springs to the neighbor.

And so it's an infinite number of coupled oscillators.

And so when I start to shake this system, I would expect a lot of resonances, and that's what I want to explore with you now.

In the case here, that the objects move in the same direction of the spring...

I call this the y direction and I call this the x direction, so the spring is in the x direction, the objects, the beats are in the x direction, and the oscillations are in the x direction.

We call those longitudinal oscillations.

There is also a way that you can have transverse oscillations, transverse...

whereby the motion is in the y direction, whereas the beats are in the x direction.

I could even do that with this system--

I could make them oscillate like this, because the springs will obviously also work if I do this with the system.

And that's the way I want this violin string or piano string to oscillate now, because that's the only meaningful way that I can make it oscillate.

And so I wonder--

if I'm going to drive it here by shaking it up and down, searching for the resonant frequencies--

what I will be seeing.

If I go with very low frequencies, the string laughs at me, the string does nothing.

It's just bored, doesn't respond to me.

I am somewhere here in the resonance curve.

But then when I increase the frequency slowly, I hit the very first frequency at which it likes to oscillate.

I call that f1.

And when I look at the string, and you will see that shortly, the string will oscillate like so.

It will go up here, and it will go down here.

And all it will do is this.

[makes swishing sounds]

That's its first resonance.

And I call this n equals one, often called the first harmonic.

And then I go to higher frequencies, and it will not do very much.

It's very unhappy.

And then all of a sudden, I hit a second resonance.

I call that f2.

And the second resonance will show up like this.

This point of the string will not move at all.

When this part is up, this part will be down.

I call that s... n equals two.

And it oscillates like so.

[makes swishing sounds]

And this point which is not moving at all, we call that a node.

I go a little bit beyond that second resonance, and nothing happens-- the string will be quite unhappy, sort of flutters a little bit until I hit another resonance, f3, and then is the next resonance.

I will see two nodes appear, one here and one here, and the string will oscillate like so.

This goes up and down, 180 degrees out of phase, and these two ends are in phase.

This is n equals three.

And I can go on like that and add nodes, and I will show you some of that very shortly.

The frequency that I generate--

I call that f of n, n is an integer;
it could be one, two, three or four-- is linear in f1.

In other words, if f1 were 100 hertz, then f2 would be 200 hertz and f3 would be 300 hertz.

We call n equals one-- we call that the first harmonic.

Some books also call it the fundamental.

I will call it the first harmonic.

And we call n equals two the second harmonic.

And so on-- n equals three is the third harmonic.

So we're going to get a series of discrete frequencies which were equally spaced.

f1 depends on the length of the string, on the tension--

I will write "tension"; don't confuse this with period--

and it depends on the mass of the string.

Without going into the detail how the dependence is, these are the parameters that determine the first harmonic.

I have here a very special violin string or piano string, whatever you want to call this.

And we can generate these resonant frequencies by searching for them, and I would need assistance from a student.

Would you be willing to help me? So, you hold one end of the piano string in your hand.

Don't let it go, please, don't let it go.

I promise you I won't let it go either.

Okay, so I put a certain tension on it, and I start to shake at a very low frequency.

Look how low, and look how happy this string is-- nothing.

It just laughs at me, ignores me, it doesn't like me.

Now I'm going to increase the frequency.

And now I'm hitting the first resonance-- it's coming up.

There it is, and that's exactly the shape that you see on the blackboard-- very clear.

I shake it here.

I have exactly the resonance at one.

Let me now try to hit the second harmonic.

If I go up a little over the f1, then nothing much happens.

It's hard for me to see.

Is this... is this the second harmonic, or is this already the third?

[chuckling]: It's already the third.

Let me see whether I can get the second.

I think I got it now; do I?

Okay, so here you see the second harmonic.

You see, indeed, that node, that point standing still, and the amplitude is enormous.

That's a characteristic for a resonant frequency.

We call it also a normal mode frequency or a natural frequency.

It's all the same thing.

Let me now try to generate one that is very high, as high as I possibly can, and you tell me which harmonic it is.

All you have to do is count how many nodes there are, not counting my hand and his hand, and you add one, and that is the harmonic that I generate.

The system is not too happy.

You see, you feel it sort of when it comes...

[yells].

No, no, no, no, no.

See, now I'm off resonance.

It's very hard for me to hit resonance, but I will get it.

There it comes, there it comes, there's no question now! I got it, I'm on resonance now! Look at it! Clearly I'm on resonance! So, how many did you count? STUDENT: Six.

LEWIN: Six harmonic? Looked 12 to me, but okay, you count better than I can.

Okay, thank you very much.

So, you see here how the system responds to a driver, and a complicated system like a string has many, many of these resonant frequencies, which we call the normal modes.

Now, when you have a violin, you have four strings.

They all have the same length.

There are musical instruments like a piano, whereby the length is different.

Violin-- four strings, all the same length.

You can set the tension so you have something to play with.

The tension is changed, normally, when you tune the instrument before you start playing, but these four strings all have a different mass, and that gives them a very different frequency.

Now, if you play the violin, you cannot change the tension, of course, during the playing.

That would be a little difficult, although there are instruments that exist where actually the playing depends on the tension of the string.

With the violin, that's not the case, so with the violin, the only option you have while you are playing it is to make the string length shorter, and you do that by moving your finger along the string.

By making it shorter, the frequency goes up, and by making it longer, the frequency goes down.

Now, how do you excite a musical instrument like a piano string or a violin string? There is nothing that is driving it exactly at that resonant frequency, so if you want to get a 440 hertz out of a violin string, then you are not driving it exactly at the 440 hertz, like we are doing.

Well, that's true, but if you take a bow and you rub the string with a bow, then in a way what you're doing is you're exposing that string to a lot of possible frequencies, not just one.

But it is a rubbing action.

I could also rub it with my finger, or I could pluck it, or I could kick it, and what it does is it ignores all the frequencies which are not at resonance, but it picks out the ones which are at resonance.

So striking it with a bow is effectively exposing it to a whole large spectrum of frequencies, and it picks out the ones that it likes.

In fact, if you strike a violin string with a bow, you may excite it simultaneously in the first harmonic and in the second, and even in the third harmonic, or even higher harmonics.

And that makes the difference between the various instruments.

That gives it the special tone quality.

Depends upon the cocktail, the combination of the various harmonics that you excite.

Now, if you go to woodwind instruments, then the situation is quite different.

I have here a sound cavity.

It's a box that has length l, and there is air inside here.

And I want to see whether this system has resonant frequencies.

So I put in here a little loudspeaker to generate sound with different frequencies and search for resonances, and there are.

The resonances of this system, however, are different from the string in that sense.

It's not the box that will resonate here, but it is the air itself that starts to resonate.

Air acts like a spring.

In fact, in that sense, it is very parallel to our spring system.

It is also a longitudinal oscillation, whereas that is a transverse oscillation.

So you make pressure waves inside, and if you do that at the right frequency, the air acts like a spring and then you get strong reactions, which are the resonances.

In this case, the nth mode, the nth harmonic, is given by n times the velocity of sound divided by 2L.

And v is about 340 meters per second at room temperature, so it is the sound speed.

Notice it's again linear in n.

In other words, if an instrument produces a certain frequency--

let us say that L equals 25 centimeters--

then you can calculate the frequency f1.

You know what the speed of sound is, 340, so we take n equals one, so the frequency that we would get equals 340 divided by 2L, which is 0.5 in meters, and so that gives me 680 hertz.

So that would be this big, it would give you 680 hertz, but the second harmonic, f2, will be double that.

So it will be 1,360 hertz, and so on.

Now, this system which is closed on both sides wouldn't be a very good musical instrument because your sound would not come out.

So what people do, they make them open, a sound cavity which is just open on both sides.

Like this, for instance--

this is open on both sides.

And even though it may surprise you, if we put a little loudspeaker here, we can excite the air column, even in this open system, in a complete similar way than we do it here in this closed system, and we get exactly the same series of frequencies that I put here on the blackboard.

There are also musical instruments which are open on one side and closed on the other.

So this is called an open-open system, and this would be called a closed-open.

A clarinet is closed-open.

Here I can also get a series of resonant frequencies, even though here, the series wouldn't be exactly like this;
it's a little different.

It doesn't matter now how different, but it is a little different.

But you get, again, a whole series of resonant frequencies.

So, again, you see that if I make the system longer, then I get lower frequencies.

So if I make the length one meter, yay big, then I would get a frequency f1, which is about four times lower than the one that I have there, which is 170 hertz.

And if the second harmonic were, then, 340 hertz, and so on...

So when you see an organ in a church, you see all these organ pipes, different lengths.

The long ones have the very low tones, and the short ones have the very high tones.

And that is the way that these instruments work.

I have here a wind organ which I have demonstrated to you before.

It is open on both sides, and because it is corrugated in a very special way, when I blow wind past this, it will go into resonance.

That's to say, wind here is like a spectrum of all possible frequencies.

It's like the bow on the violin.

And then it picks out the frequencies that it likes.

However, if I increase the speed of the wind, I can try to force it into higher frequencies.

So at low wind speeds, I am more likely to hit the lower harmonics.

At high wind speeds, I am more likely to hit the higher harmonics.

This one is 75 centimeters long, it's open-open;
and if I were able to hit the first harmonic, that would be a frequency of about 240 hertz.

I may not be able to excite the lowest harmonic, the first harmonic, but I'll try.

But certainly the higher harmonics are very easy to excite, and I can make you even listen simultaneously to more than one frequency, just like the violin string, when you strike it, can simultaneously oscillate in a combination of these modes.

So let me swirl this around.

I'll first start low.

[tube hums medium tone]

This may be 240.

[tube hums higher tone]

This is definitely way higher.

[tube hums even higher]

[tube hums higher, then starts going back down]

[tube returns to first tone]

I think this is the 240.

This is the lowest, this is the first harmonic.

Were there times that you heard two simultaneously?

[tube hums two tones]

I hear two.

[tube hums two tones]

If you play a flute, that... you do the following: You make holes in here, and when you take your fingers off both holes, then the effective length of the flute is this long and you get a high tone.

If you put your finger on this one, then the effective length of the flute is this long and you get a lower tone.

When you put your finger on both, the effective length of the flute is this long and you get an even lower tone.

I have here a very special flute, open on both sides, and here you see the two holes.

We will first close the two.

That gives us the lowest frequency...

[plays low tone, then up and down triad]

[plays short tune on low tones]

...that you play the flute.

So it's simply a matter of making the instrument longer or shorter.

I have another example here of an instrument which is open here and here is closed.

This is my version of a trombone.

There's a piston here.

So this is a system that is like this, but I can move this in and out, and so when I have it far in, the frequency would be high...

[plays high tone]

and when I have it here...

[plays low tone]

[tones gradually get higher]

So you see, it's directly related to the length of this trombone.

And if you learn how to play, you can try to play a tune.

I'll try.

[plays "Jingle Bells"]

[class laughs quietly]

[tune continues]

[tune ends]

[class applauds]

LEWIN: Thank you.

Resonances are all around us.

When you drive your car, you may have noticed that all of a sudden, you hear some crazy rattle somewhere.

It could be your mirror, or it could be something else, it could be an ashtray, because you are driving it, and you are exciting it with the frequency with which the wheels go around and you may hit a resonant frequency.

You go a little slower and the rattle stops, but something else may start to rattle.

The reason why the first rattle stopped, because you go off resonance, but you may go on resonance of another object.

All objects that you have in your room have preferred resonant frequencies.

Whether they are the pots or the pans or whether it is your refrigerator, or anything you can think of, everything has resonant frequencies.

Your body has resonant frequencies.

If I took you in my hands and I would start to shake you, then if I do it at low frequency, not much would happen, but there would be one frequency that your arms begin to move like this, like they're physical pendulums, right? And if I hit that frequency, then indeed there would be a strong response, and so your body has many resonant frequencies: your arms, your legs, your head, everything.

We also experience, all of us, emotional resonances--

a small input, a huge output.

Falling in love is an emotional resonance.

If someone touches a sensitive nerve, that is a resonance.

Someone could say something to you and it could be a very sensitive issue for you, and you go nonlinear! Your response is unbelievably strong! That, in my view, is also a form of an emotional resonance.

I have here two tuning forks.

And these tuning forks are designed in such a way that all I would have to do is just bang them and they will pick out their own resonant frequencies.

The tuning fork is very simple, like this.

I give it a kick, and the kick is like dumping a whole spectrum of frequencies on it, and it picks out the ones that it likes, which is this one, and that's the one at which it will resonate.

It's possible that I can excite it at higher frequencies, at higher harmonics, but that's a little hard, even, with a tuning fork.

So this one is 256 hertz.

[plays low tone]

So the prongs move 256 times per second, and this one is 440 hertz.

[plays higher tone]

And you hear no overtones--

you don't hear higher harmonics.

If I take something as simple as a wineglass like this, it has many, many normal-mode frequencies, many resonant frequencies.

The lowest one is very easy to excite, and I will do that.

I will rub it with my finger.

Rubbing is like striking a string with a bow.

It's all the same-- I expose it to lots of frequencies, it ignores them all, it picks out the one that it likes, the resonant frequency, the normal mode, the natural frequency.

And what the glass will do, in its lowest harmonic--

in its first harmonic--

it will sort of oscillate, like this, and I will show that to you later in this lecture in slow motion.

But let me first make you listen to the frequency.

It's around 430... 470 hertz.

I have to wash my hands because I have chalk on my fingers and because of the chalk, I will not be able to excite it.

I have to really rub it with some liquid, and therefore my hands have to be chalk-free.

Chalk is just too greasy--

let me try.

[plays high tone]

Very clear.

I remember when I was a student, we had after-dinner speakers.

If we got bored, we would all do this.

Let me tell you, that makes a lot of noise.

So, again, I'm not exciting it with the 470 hertz.

I'm dumping the whole frequency...

the whole spectrum of frequencies on it, and it picks out the one that it likes, which, in this case, is the 470 hertz.

Resonances can be destructive, and rumor has it that there are singers, women who take a wineglass and they do exactly what I did.

They do this.

[plays high tone]

They listen carefully, they generate that frequency with their voice, they increase the volume of the voice, and then the rumor has it that bang, the glass goes.

In other words, the amplitude of the glass becomes so large that you get so high so close to resonance and so much power goes into it because of the volume of the voice that the glass breaks.

I'm going to try to break a glass with you, and you'll see that it is not easy.

I have here a wineglass.

It's almost the same as the one I have there.

And we can illuminate that glass with a strobe light, which you see here.

And I'm going to show you there the display of that strobe light.

And the reason why we strobe it is that we want you to see, as we excite the exact frequency of the glass, we want you to see the motion of the glass.

And the way we can make you see the motion is by strobing it not exactly at the frequency of the sound but a little bit different frequency.

So you will see the stroboscopic motion, then, of the glass.

So I can... already I will make it darker shortly, but I want you to see at least most of this.

I can generate, then, the 470 hertz, which is very close to the resonant frequency.

[plays high tone]

This is the tone that we will use.

We will increase the volume, and then we will try to hit that resonance just right.

We may be off by a few hertz.

We have to be right on within a hertz, and then we'll see whether we can make the glass break.

Now, I want to warn you, the sound is going to be very strong, so you may... as the time goes on, as we go to higher volume, you may want to turn, you may want to close your ears.

In fact, I will use this to protect my ears, and I will even use this to protect my eyes in case the glass might break, which I doubt whether it will, but who knows?

All right, so let's make it very dark.

[tone continues]

So, you see here the glass.

It's not doing very much.

And I'm now going to increase the volume of the sound.

[high tone gets louder]

I'm going to cover my ears now.

We already begin to see some motion.

I'm not sure that I am on resonance.

[high tone continues, becomes louder]

We increase the volume.

[high tone continues, louder]

[tone continues]

[tone continues]

I'm now changing the frequency.

[similar tone playing]

Getting very close.

[tone continues, getting slightly louder]

Getting very close.

[shatters loudly]

[tone continues]

[tone fades away]

[lower tone plays as slow-motion replay begins]

[shatters slowly]

I mentioned that resonances can be very destructive, and there are some striking examples in history.

In fact, you may have...

When there's a storm, you may have seen the traffic signs, which... just a sign on a pole, that the traffic sign starts doing this.

This is strange, because there's a wind.

Wind is like a spectrum of all kinds of frequencies.

It's like blowing air into a musical instrument.

And then this traffic sign just picks out the frequency that it likes, and then, if the wind is strong enough, it could be very destructive.

And the most striking example of destruction is that of a bridge which was built.

And that is the Tacoma Bridge, on the West Coast, which is very dramatic, and, of course, I will have to show you that movie.

You will see what the wind can do to a bridge.

So we'll start this movie, and then we'll make it dark.

FILM ANNOUNCER: On the first of July, 1940, a delegation of citizens met in Washington State.

The weather was beautiful, the occasion historic, and the speechmaking and fanfare altogether appropriate.

This was the grand opening of the Tacoma Narrows Bridge.

From the beginning, the bridge, which spanned Puget Sound between Seattle and Tacoma, was traveled in style, as well it should have been.

The Tacoma Narrows Bridge was one of the longer suspension bridges on earth.

And if somebody hadn't overlooked something, it probably would have remained one of the longer suspension bridges on earth.

The problem wasn't that right from the beginning, a lot of people didn't pay a lot of attention to details-- they did.

But somewhere along the line, and this was obvious in the end, it looks as if someone forgot the significance of resonance.

[low rumbling as wind blows]

Among other things, the Tacoma Narrows Bridge was the most spectacular Aeolian harp in history.

Unfortunately, its first performance was destined to run only about four months.

[sirens wailing]

In the meantime, she was a beautiful bridge...

beautiful, but a little strange.

Even before construction was completed, people observed its peculiar behavior.

That was because even in a light breeze, ripples ran along the bridge.

After a while,

one of the local humorists called her "Galloping Gertie." And for fairly obvious reasons, the name stuck, at least until the seventh of November, 1940.

Then as now, Seattle and Tacoma were sports-minded cities.

For four months, a regional sport was to drive across the bridge on a windy day.

While some claimed it was like riding a roller coaster, others found it a little disconcerting to see the car in front disappear.

How popular this bridge sport was, or to what extent it might have spread across the country, is anybody's guess.

On November 7, 1940, the winds were relatively moderate, about 40 miles per hour.

A new mode appeared.

Rather than ripple, the bridge began to twist.

[wind blowing]

A wind of 40 miles per hour is not too strong, but it was strong enough to start the bridge twisting violently.

And at 11:00 a.m., it fell.

[low roaring]

[loud crashing]

[rumbling as wind blows]

[rumbling continues]

LEWIN: Amazing-- amazing what resonance can do.

With musical instruments, we have...

we're stuck to the speed of sound in air, which is 340 meters per second.

And when I speak to you, I have here a sound cavity which has a certain size, a certain shape.

And while I speak, this size and this shape changes all the time.

And that gives my voice a very characteristic sound that makes it possible for me to make a low sound.

It makes it possible for me to make a high sound.

And no matter how I speak, you will say, "Yeah, there's no question.

That's Walter Lewin--

that's clear." It's very recognizable.

Each one of you and I have a very well recognizable voice.

The situation would change if I could change the speed of sound in my system.

And helium, which has a very different molecular weight from air, has a way higher speed than the speed of sound in air.

It's about 2.7 times higher, 2.7 times 340 meters per second.

So if I fill my system with helium--

apart from the fact that there's no oxygen in helium, so I wouldn't survive very long; that's a detail...

[class laughs]

LEWIN: If I fill my system with helium, then, of course, my vocal cords and my sound cavity here, they don't know that.

So they do the same thing that they normally do when they speak to you.

However, since the speed of sound is much higher here in my sound cavity, the frequency that it will produce is way higher, and I sound very differently.

The problem, however, is, as I mentioned, there is no oxygen in helium, and yet if I only take a little bit of helium, it doesn't work very well and you don't hear much difference, so I have to really take a lot of helium, and I will try that.

But for that I pay a small price, and the small price is that you can faint.

I'll try just to stay away from the fainting level.

So, here is helium, and I have to let my air out first and then get helium in and maybe let the helium out again and let the helium in again.

And during that time I can't speak, but then, when I think I'm full enough with helium, I will say a few words to you.

So, let's get the pressure up to the level that I like.

[exhaling]

[helium hissing from hose]

[inhales]

[helium hissing again]

[inhales again]

[in very high voice]: I told you it would sound very differently.

[class laughs and applauds]

LEWIN: Well, I hope you enjoyed this, and I'll see you Wednesday.

Thank you.

[class laughs]