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8.02 Electricity and Magnetism, Spring 2002
Transcript – Lecture 26

So today, I will start with a general discussion on waves, as an introduction to electromagnetic waves, which we will discuss next week.

We'll start with a very down-to-earth equation, Y equals one-third X.

And I'm going to plot that for you, so here is Y and here is X, and that's a straight line through the origin, Y equals one-third X.

Suppose, now, I want this line to move.

I want this line to move with a speed of 6 meters per second in the plus X direction.

All I will have to do now is to replace X in that equation by X - 6T.

Notice the minus sign.

I will go, then, in the plus X direction.

The equation then becomes Y equals one-third times X - 6T.

So look at it at T equals 1.

At T equals 0, you already have the line.

At T equals 1, you now have Y equals 1/3 X - 2.

That means, here it will intersect at - 2, and there it will intersect at + 6, and the line parallel to the first one, this line is now T = 1, and this is T = 0.

And it has moved in this direction, with a speed of 6 meters per second.

And so what this is telling us, that if we ever want something to move with a speed V in the plus X direction, then all we have to do in our equations to replace X by X - VT, and if we want it to move in the minus X direction, then we replace X by X + VT.

That's all we have to do.

So now, I'm going to change to something that is a real wave.

I now have Y = 2, times the sin 3X.

That's a wave.

It's not moving, not yet.

So I can make a plot of Y as a function of X, and that plot will be like this.

This is zero, so when the sine is zero, this is pi divided by 3, and this is 180 degrees, and it's again zero, this is 2 pi divided by 3, it's again zero.

And lambda, which we call the wavelength, lambda, in this case, is from here to here, that is 2 pi divided by 3, this goes also from here to there.

I will introduce a symbol K that you will often see, we call that the wave number, and K is simply defined as 2 pi divided by lambda.

So in our specific case, K is 3.

This here is K.

If you know this number, you can immediately tell what the wavelength is.

Now, I want to have this wave move.

I want to have a traveling wave.

And I want to have it move with 6 meters per second in the plus X direction.

So the recipe is now very simple, all I have to do replace this X by X - 6T.

So now I get Y equals 2 sin [3(X-6T)].

And if you now look at this curve, this equation, and you plot it a little bit later in time than T0 -- this is already T0 -- a little later in time, you will see that, indeed, it has moved in the plus X direction.

And it's moving with a speed of 6 meters per second.

So this equation, when you look at it, holds all the characteristics of the oscillation.

It holds the amplitude.

This 2 is the amplitude.

This is - 2, that's the amplitude.

This information, K, holds the information on the wavelength, and this information tells you what the speed is.

And the minus sign, which is important, tells you that it's going in the plus X direction, and not in the minus X direction.

Can we make such a traveling wave?

Yes, we can do that, actually, quite easily.

Suppose I have here a rotating wheel -- rotate with angular frequency omega, and let this has a radius R, and I give it 2 units, so that I get the same amplitude that I have here.

And I attach to this a string, and I put some tension on the string, so that I create a wave as I rotate it, and the string is attached here, and as it rotates, the wave is going to propagate into the string with a velocity, let's say, V.

So I can generate a traveling wave.

The period of one oscillation -- if you were here on the string, you're going up, you're going down, you're going up, you're going down, that's all you're doing, when the wave passes by -- the period of one whole oscillation is obviously 2 pi divided by this omega.

The wavelength lambda that you are creating -- from here to here is lambda -- well, if you know the speed with which it is traveling, and you know it has been traveling capital T seconds, one oscillation, that's a distance lambda.

So this is V times T.

But this is also V divided by F, if F is the frequency in Hertz.

And so the frequency F is then also given by the speed divided by lambda.

And so I can write down this equation now in a somewhat different form, Y equals 2 times the sine, and now I bring the 3 inside, so I get 3X-18T.

This 18 is now that omega.

This is omega T.

In here is all the timing information.

Omega, the period T, everything is in here.

Here is all the spatial information.

This is K.

In here is the information about lambda.

And so if I know omega, and I know K, then I can also find the velocity, which is omega divided by K.

So everything is in here, omega divided by 3 gives me back my 6 meters per second.

So once you have the equation, I can ask you any question about that wave, and you should be able, then, to answer.

Wavelength, frequency, in hertz, in radians per second, speed, everything.

You may ask me now, "Why do you discuss this with us?" Well, we are coming up to electromagnetic waves next week, and electromagnetic waves, you're going to see lambdas, you're going to see omegas, you're going to see capital Ts, you're going to see frequency, you're going to see Ks, everything you see there you're going to see next week.

One exception, that Y, the displacement Y, will not be in centimeters or meters, but it will be an electric field, a traveling electric field, volts per meter.

Or a traveling magnetic field, tesla.

But other than that, all these quantities will return in exactly the same way.

Now I want to discuss with you a standing wave first, because standing waves are going to be important.

This is a traveling wave.

And now comes something even more intriguing, which is a standing wave.

Suppose I have a wave traveling in this direction, and I call that Y1, and Y0 is the amplitude, sine (K X - omega T).

And notice now, I have all the symbols that we are familiar with.

We have the K here, we have the omega here, and we have the amplitude here.

And the minus sign tells me, [wssshhht], it's going in the plus direction.

But I have another wave.

And the wave is exactly identical, in terms of amplitude, in terms of wavelength, in terms of frequency, identical, but it's traveling in this direction.

And so this is Y2, which is Y0 sine (KX + omega T).

This plus sign tells me it's going in this direction.

And so if this is a string, the net result is the sum of the two.

So I have to add them up.

So Y = Y1 + Y2.

So I have to do some trigono- trigonometric manipulation, and this is what I leave -- I'll leave you with that, that's high school stuff -- you add the two up and you'll find 2 Y0-- notice that the amplitude has doubled -- times the sine (K X) times cosine (omega T).

That's the sum of those two.

And this is very, very different from a traveling wave.

Nowhere will you see K X - omega T any more.

K X is here, separate under the sine, and omega T is separate under the cosine.

All the timing information is now separate from the spatial information.

And so what does a standing wave like this look like?

Well, let's -- a bracket here.

Let's make a drawing of such a standing wave.

So here we have Y, and here we have X.

Let's only look at the sine K X for now.

If X is 0, the sine is always 0, so this point will never move.

But if K X is 180 degrees, it's also 0, always.

So lambda over two will never move.

X is lambda, when this is 360 degrees, it will never move.

- lambda / 2, will never move.

So what will it look like?

Well, you're going to see something like this, let's take the moment when T equals 0, so when cosine omega T is plus 1.

So we're going to have a curve like this, so this goes up to 2Y0 like this -- and this here is then my 2Y0.

These points will never move, they will always stand still.

There's nothing like a traveling wave.

If it's a traveling wave, these points will see the wave go by, they will go up and down, they never do that.

They sit still.

They have a name.

We call them nodes.

Let's now look at little later.

Let's look at T equals one quarter of a period.

Now, the cosine is 0.

So there's not a single point on the string that is not 0.

So the string looks like this.

If you took a picture of the string, you wouldn't even know it's oscillating.

It would be just a straight line.

And now, if we do -- look a little later, and we look at T equals one-half the period, then the cosine is -1.

So now the curve will look like this.

And so what does it mean?

If we just look what's here happening, this is what's going to happen.

The string is just doing this, and there are points that stand still.

Nothing is going like this, nothing is going like this.

You see this point going up and down, up and down, up and down, and this will do the same, and these nodes will do nothing.

So that is what a standing wave will look like, and I think the name standing wave is a very appropriate name, very descriptive, because it's really standing, it's not -- it's not moving.

At least, not traveling along the X direction.

Can we make a standing wave?

Yes, we can, and I will do that today.

A standing wave can be made by shaking -- or rotating, in that fashion -- a string.

So here I have a string, I -- say I attach the string to the wall there, and I move it up and down here.

So a wave goes in -- I do just this, like the rotating disc -- the wave travels, but the wave is reflected, and so I have a wave going in and I have a wave coming back, so I have now two waves going through each other.

And if the conditions are just right, then these reflective waves -- this one will reflect, when it arrives here, it will reflect again, it goes back again, and it will continue to reflect -- so if the conditions are just right, then these reflective waves will support each other, and they will generate a large amplitude -- as I will demonstrate to you -- but that's only the case for very specific frequencies, and we call those resonance frequencies.

The lowest possible frequency for which this happens -- which we call the fundamental -- will make the string vibrate like this.

So the whole thing goes.

[wssshhht], [wssshhht], [wssshhht], and we call that the fundamental.

We call that also the first harmonic.

If now I increase the frequencies, then I get a second resonant frequency, and a node jumps in the middle -- there is already a node here, and there is a node here, because this motion of my hand here is very small, as I will demonstrate to you, for all practical purpose you can think of this being a node -- and so now the string in the second harmonic will oscillate like this.

[Wssshhht], [wssshhht], [wssshhht], [wssshhht], so this is the second harmonic.

And if we go up in frequencies, then -- this should be right in the middle, by the way -- and if I go up in frequency one step more, then I get another resonance whereby we get an extra node, and so we get the third harmonic, and you just can go on like that.

You get a whole series of resonance frequencies.

And so, for the fundamental, lambda 1 -- the 1 refers to the first harmonic -- is 2L, if L is the length of my string.

This is L.

You only have half a wavelength here, so L is 2L.

But we know that the frequency is the velocity divided by the wavelength -- we see that there, frequency is velocity divided by the wavelength -- so the frequency F1 is the velocity divided by lambda 1, so that's divided by 2L.

So that's the frequency in the fundamental for which this resonance phenomenon occurs.

For the second harmonic, lambda 2 equals L.

You can tell, you see a complete wavelength here.

And F2, that frequency, is going to be twice F1.

And F3 is going to be 3 F1.

And if you want to know, for the Nth harmonic, N being Nancy, then lambda of N equals N -- 2L/N.

Substitute in N1, and you find the wavelength for the first harmonic.

Substitute for N2, and you find the wavelength for the second harmonic.

And so on.

And the frequency for the Nth harmonic -- N stands for Nancy -- is N times V divided by 2L.

So here you see the entire series of frequencies and wavelengths for which we have resonance.

Unlike in our LRC system that we discussed last time, where you had one resonance frequency, now you have an infinite number of resonance frequencies, and they are at very discrete values, equally spaced.

I want to demonstrate this to you with a violin string, it's a very special violin string, it's here on the floor, it's a biggie, and I need some help from someone.

You helped me before, would you mind helping me again?

So here is, uh, one end of the string, which you're going to hold, you're going to be a node, believe it or not.

Hold it better, two hands -- no, much better.

You will see shortly, why -- no, no, no, much better.

That's it.

And walk back a little, walk further.

Yes, that's good, hold it.

I will put on a white glove, and there is a reason for that, because I want you to be able to see my hand when we're going to make it dark, so that you will convince yourself that my hand, which is generating the wave, is hardly moving at all.

For practical purposes, it's a node, and yet we get these wonderful resonance phenomenon.

So I'm going to make it very dark so that the UV will do its job, and you can see the string better, that's the only way we can make you see the string well.

All right.

Don't let go, er- under any circumstances, you will hurt me if you do that.

Of course, if I let go first, then [pfft], I will hurt you, but that's not my plan.

OK, so let's try to go a little bit further back.

Let's try to, uh, find, first the -- the fundamental.

And I'll try to find it by exciting just the right frequency with my hand.

There it is.

I think I got it.

That's the fundamental.

And look how little my hand is moving here.

And you will see a very large amplitude in the middle.

And so these reflected waves, one runs to him, it runs back at me, it runs back at him, keeps reflecting many times, they support each other in a constructive way, that's what resonance is all about.

And now I'll try to find the second harmonic -- so you'll see another node coming in at the middle.

It's easier for you to see than for me, actually.

And it's not always easy to find the -- no, no, no, I'm too low frequency, I have to go up.

I think I got it now.

Is this it?

Yes, one extra node in the middle?

Speak out up, please.

[chorus of agreement] Ah, that's better.

Now I can hear you, thank you.

Um, there are three nodes now.

My friend there is a node, I'm a node, and then there is one in the middle.

If you subtract 1, the 3-1 is 2, then it's the second harmonic.

And so now I will try to generate a very high frequency, in resonance, and then you count the number of nodes, subtract one, and then you know which harmonic I was able to generate.

But I will try to -- not so easy to get a resonance in there.

No, I'm off resonance.

No.

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Yeah! Yeah! Yeah! Yeah! Yeah! Yeah! Yeah! [laughter] Got it, got it, got it! Got it! You keep counting.

Keep counting.

Oh, that's a super-high harmonic! [crowd responds] How many did you count?

[crowd responds] 10, do I hear 10?

[crowd responds] Do I hear 20?

[laughter] Actually, I counted about 27, but that's OK.

[laughter].

All right, thank you very much, it was great that you helped me.

[applause].

So that's, uh, standing waves.

And you see the shapes, and you saw the, the mode of operation, very characteristic for standing waves.

When I pluck a string, of a violin, or I strike it with a bow, or with a hammer, on a piano, just a hammer comes down, that is exposing the string to a whole set of frequencies.

And so the string, now, decides which frequencies it like to oscillate in.

And so it selects these resonance frequencies.

And so if the string has a fundamental of 400 hertz, then it would start to resonate at 400, but simultaneously, it will be very happy with 800 hertz, and with 1200 hertz.

And so the string will simultaneously -- if I bang it, or strike it, or pluck it -- simultaneously oscillate, often at more than one frequency.

Fundamental, and several of the higher harmonics.

And all the others that are present, all the other frequencies in this striking with the bow, I ignore, they're off resonance.

So if you design a string instrument, then this is really a key equation.

If you want a particular fundamental -- say your fundamental is 440 and this is a given number.

And so N is 1.

You can now manipulate V, because V depends on the tension on the string, and it depends on what kind of string you have.

The speed in the string is the square root of the tension -- if you take 8.03, you will even see a proof for that -- divided by the mass of the string per unit length of the string.

So you take four strings for a violin -- six for a guitar -- and you make them out of very different material -- different mass per unit length --

and so that gives you, then, difference velocities -- you can also fool around with the tension -- and so the four strings, then, have all four different fundamental.

In the violin, they may have the same length.

What are going to do now to play the violin?

All that is left over is L, that's the only thing you can change, and that's what a violinist is doing.

Goes with the finger, back and forth over the strings, make them shorter, pitch goes up, frequency goes up, makes them longer, frequency goes down.

And you do the same with a guitar, and you do the same with a bass and a cello.

So when you're playing, what you're doing all the time is changing L so that you get all these frequencies that you want to produce.

If you take your instrument out of the closet, you may have noticed that it's really not in tune anymore, it's slightly off-tune.

Well, what you can do now, you can change V a little bit -- uh, these little knobs -- and you can change the tension in the strings.

And that's what violinists do when they tune their violin, they change the tension on the string to get just the right frequency.

But the playing means you change L.

A piano is different, that's really a luxury.

A piano has 88 keys, and the length of each set of strings is fixed, so you don't have to worry about that.

It's a great luxury, you may think, therefore, that it is much easier to play the piano that to play a violin, because you don't have to do this all the time, and be exactly at the right length.

Well, that is true, of course, but given the fact that you have 88 keys, you can imagine you can hit occasionally the wrong key, and that's not what you want.

If a string is vibrating, it is pushing on the air, and it's pulling on the air, and it's producing thereby what we call pressure waves.

If I have a string that oscillates 400 hertz, it makes pressure waves -- pressure goes up, down, up, down, up, down -- 400 times per second it goes up, it reaches your eardrum, and your eardrum starts to shake 400 times per second, it goes back and forth, and your brain say, "I hear sound." That's the way it works.

So it is the string, then you get the air, pressure waves, and then you get your eardrum, and then you get to brains, if there are any.

Now, I want to discuss with you before I demonstrate some of this, I want to discuss with you instruments which don't have strings, and I will call them all woodwind instruments, although that's perhaps not an appropriate name for all of them.

But I'll just call them woodwinds for now.

And suppose I have, here, a box which is filled with air.

Completely closed box, and it has a length L.

And I put in here a loudspeaker, and I generate a particular frequency of sound.

Then pressure waves are going to run, they're going to bounce off, and they come back, and I get reflected traveling waves.

And what I get inside the -- the box, now, I get standing waves of air.

It's not the box that goes into a standing resonance, but it's the air itself.

And the frequencies that are produced, at which the system is in resonance, is given exactly by the same equation.

Except, now, that V is non-negotiable -- V is now the speed of sound, which, at room temperature, is about 340 meters per second.

So whenever you design an -- wi- we- woodwind instruments, that is non-negotiable.

You cannot change V, which you can do when you are an instrument builder of strings.

You will say, "Gee, if I have an instrument whereby the sound is inside a closed box, you're not going to hear very much." Well, that's true.

You must let the sound go out somehow.

And what is surprising, that if you take this end out -- off -- and you take this end off, that this box, which is now open on both sides, will still resonate at exactly those frequencies.

And you've got to take 8.03 to get to the bottom of this.

There are also resonant frequencies in case that the sound cavity -- if I call this a sound cavity -- is closed on one end and open on one end.

The series of resonant frequencies is different from this one, though.

It's not so important, but it is different.

But you also get a whole series of resonance frequencies.

The velocity of sound in a gas, V, is the square root of the temperature -- so it's a little temperature-dependent -- divided by the molecular weight.

Well, you can't do much about the temperature in a room -- in general, it's room temperature -- and with air, you are stuck with the molecular weight, oxygen and nitrogen is about 30, there is not much you can do about that.

But every one of you who plays woodwind instruments know that if you go from a cold room to a warm room that your instrument is no longer in tune.

And that's because of this, the temperature change.

So V changes, so your fundamentals change.

And what do you do know?

These people know what they do.

They have a way of making the cavity a little shorter or a little longer.

It's not very much, but they have a little bit to play with.

And when they do that, so they compensate L for the slight difference in V to get back to the same fundamental that they need.

So now you have a woodwind instrument.

Low-frequency woodwind instruments will be big.

And high-frequency woodwind instruments will be small, because in L lies the secret, you can't fool around with V, V is a God-given.

And so how do you play an instrument now?

Well, you have to change L, that's all you can do.

And if you have a trombone, you're doing this, it's clear that you're changing L, you make the cavity shorter and longer.

So that's easy.

If you have a flute, you have holes in the flute.

And if all the holes are closed, the flute is this long.

But if you take your fingers off the holes, it gets shorter.

And so when you take all your fingers off the holes, then you have a high frequency -- flute is only this long, if you put all your fingers on it, it's this long, and so the frequency is lower.

And a trumpet is the same idea.

You have valves that open holes and close holes.

If you blow air in an instrument, it is like plucking a string, it's like exciting a string with a bow, you are dumping a whole spectrum of frequencies onto that air cavity.

And you let the air cavity decide where it wants to resonate.

And it will pick out the ones that it likes, it will pick out the fundamental, and maybe the second and the third harmonic.

So in that sense, blowing air is like striking it with a bow, in the case of a string instrument.

But blowing air is not always as easy as you may think it is.

Have you ever tried to blow air into a trumpet?

Nothing happens.

You just blow, [pffff], and you hear nothing.

You have to do this.

[ppppppp].

Something like that.

A bizarre sound you have to make, you have to know how to spit in the instrument just the right way to get a sound out of it.

I've tried it many times, it's really not easy.

So blowing air is just said in a simple way, but in order to get it exc- to resonate, you've got to really know how to hold your lips, and how to excite that cavity.

I can show you the easy relation between the frequency of the fundamental and the length of woodwind instruments.

That's a one-to-one correlation -- this is on the web, you can download it, you don't have to copy this -- and you see there that, uh, this is only for an open open system, this is not for a closed open system.

The number would be different.

So if you are interested in very high frequencies, then an open open system which is only one centimeter long would give you a fundamental of 17000 Hertz, which most of you can hear, because you're still young, you can hear up to 20 kilohertz, probably.

The second harmonic you would not be able to hear, that is too high for you.

An instrument which is 10 centimeters long, open open, you would here the fundamental easily, 1700 hertz, second harmonic, 3400 hertz, no problem, third harmonic, fourth harmonic, no problem.

And then when you go to the very low frequencies, uh, organ pipes that produce fundamentals in the range 20 and 30 hertz, are huge in size.

And you -- in general, that holds.

When you have a woodwind instrument which is tunes for low frequencies, it's big.

And for high frequencies, like a flute, it's small.

In a way, that's also true for string instruments.

A bass which generates low frequencies, it's a big instrument.

But the violin, which generates high frequencies, is a much shorter instrument.

So in that sense, the reason is, they have both an L here.

And it's the L, of course, that is crucial in terms of the fundamental.

So I can now ge- uh, demonstrate to you the basic idea of a flute -- this is a flute.

Now, the flute is this long.

[plays flute].

Low frequency.

[plays flute].

Higher frequency, because it's shorter.

[plays flute].

Even higher frequency, because it's shorter.

[plays flute].

That's all it takes.

[applause] Trombone.

That speaks for itself, right?

Make it longer, you make it shorter.

I'll try it.

[plays trombone] [applause] Trombone.

[applause].

Wind organ.

80 centimeters long.

Open and open, on both sides.

80 centimeters, it would give me a fundamental a little higher than 170.

And then it will give me a second harmonic, and a third harmonic, it all depends on how fast the air is flowing by, and there will be moments that you will hear more than one harmonic.

I'll try to swing it around.

It's not easy for me to hit the fundamental, but I'll try that, too.

This is the second harmonic.

[plays wind organ].

Third harmonic.

[wind organ] Fourth harmonic.

[wind organ] Fifth harmonic.

[wind organ] Fourth.

[wind organ] Furdamen-, this is fundamental.

[wind organ] This is the fundamental, 212 Hertz.

[wind organ] 425 Hertz.

[wind organ] 637, 637.

[wind organ] [applause] Thank you, thank you, thank you.

If you bang on a tuning fork, or you pluck on a string, in isolation, you hear nothing, almost nothing.

I have here a tuning fork, and if I bang on it, you hear nothing, and I hear nothing -- almost nothing.

Unless I heel- hold it very close to my ear.

What we do now, with string instruments, we mount the strings on a box with air.

A sound cavity.

Sound- sounding board, it's called.

And now the air inside can s- oscillate with it -- it doesn't always have to be precisely at resonance -- and also, the surface itself of the box can start to vibrate.

So you're displacing more air, and the sound becomes loud and clear.

You don't gain energy, but you drain the energy out of the oscillating string faster, and so for that short amount of time, you get louder sound.

And I will demonstrate that, first, with the tuning fork.

I hear it now very well, it's harder for you because it's farther away.

Now you hear nothing.

And now you hear it.

It can actually be much better demonstrated with this little music box that I bought years ago in Switzerland.

If I rotate this music box, it has a very romantic tune, you hear nothing.

I hear a little bit.

And now I put it on this box, unmistakable.

So that's the idea of sounding boards.

You have them violins, you have them on pianos, and, of course, the design of these sounding boards is top-secret, the manufacturer is not going to tell you how they built them, because the quality of the sound, of course, is partly in the design of the sounding board.

I can make you hear, and I can make you see sound.

And my goal for the remaining time is to make you see and hear at the same time.

I have here a microphone, which is like your eardrum, and suppose I generate 440 Hertz, and I can do that with the tuning fork.

So here is the amplitude of the oscillation of the membrane in the microphone, which is your eardrum, say, we amplify that, and we show you on an oscilloscope, the current after amplification.

And so you're going to see a signal like this.

And if this is 440 Hertz, so this is time, and this is the displacement of your eardrum -- in our case, it's a microphone, it's really a current after amplification -- and if this is 440 Hertz, then this time T will be about 2.3 milliseconds.

One divided by 440.

That's no problem for an oscilloscope.

We can do much better than that.

So the time resolution is not a problem.

And so I will show you there the output of our microphone, I will show you this signal as a function of time.

For 440 Hertz, you see a boring signal.

And I can make a boring signal with a tuning fork, it's almost a pure sinusoid.

But now, it just so happens, we have in our audie- in our audience, someone who can play the violin.

And that person is going to produce a 440 Hertz.

But at the same time, he's going to produce a second harmonic, and maybe a third harmonic, and maybe a fourth harmonic.

And so, imagine now, that at th- simultaneously, your eardrum is going to do this, but at the same time, your eardrum is going to do this, because this is some higher harmonic.

Then the net result is that your eardrum is going to do this.

And that is what I'm going to show you.

And so when you see the various instruments, you will recognize that on top of the fundamental, you will see these very characteristic harmonics, each instrument having its own cocktail, its own unique cocktail, and when you hear that cocktail, you say, "Oh, yes, that's a saxophone." Or you say, "No, that's a violin." You would never mistaken a saxophone for a violin.

And that's because of the combination of the higher harmonics.

And so we are so fortunate that we have four musicians in our audience.

Tom, who is the violinist -- where is Tom?

There's Tom.

[applause].

I hope you brought your violin [laughs].

Oh, you got it there.

And then we have Emily -- I saw her already, with the clarinet -- so if you come this way, Emily [applause].

And we have Aaron -- Aaron has a bassoon.

You may never have a bassoon.

A bassoon is an instrument that produces a very low tone.

So the instrument is going to be very big.

Bigger than -- bigger than Aaron.

Just wait and see.

It's a beauty, it's a really beautiful instrument.

A flute is only this big.

Ah, look at that, beautiful, big, bassoon.

And then we have Fabian, with a saxophone.

[applause].

So if you stand here, then I will first do the boring part, and what I will do is I will show you, then, 440 hertz signal looks like, produced with a tuning fork -- and we'll see it there, and so I have to change the light situation substantially.

The musicians will get a little bit into the dark, but you will still be able to see them.

And so I'm going to turn on, now, the microphone, and that's where you're going to see the signal, and when you make noise, you can hear -- hear and see yourself.

440.

Boring, and no signs of higher harmonics.

Now Tom will try to produce 440 in his violin -- or close to 440 -- and then look for the higher harmonics, which makes the violin characteristic.

[plays violin].

Notice that the average spacing, the repetition, is, indeed, the same as it was with the 440, but you saw this incredible richness of harmonics.

Tom happens to be, also, an excellent violin player, and so he insisted that he demonstrate that.

[laughter] All right, Tom?

Student: All right.

OK.

Go ahead.

[plays violin].

Terrific, Tom.

[applause].

Emily, would you mind producing something that comes close to 440 Hertz?

Come a little closer to the microphone.

[plays clarinet].

Notice the big difference with the violin.

Violin has many, many higher harmonics.

Her instrument, maybe only one, maybe only the fundamental and the second harmonic.

Can you try again?

[plays clarinet].

Now we have more, now we have more.

[plays clarinet].

Now, Emily did not insist that she wanted to play, but I did.

So Emily, would you please?

[plays clarinet].

Impressive.

[applause].

Aaron, with his bassoon.

He ordered a special chair, because he says, "Look, with an instrument so big, L is so large, it's heavy." Clearly, a bass, which produces low frequencies, is heavier than a violin, and the same is true with woodwind instruments.

Aaron, could you try something close to 440?

[plays bassoon].

Bizarre instrument, isn't it, eh?

You see a weird combination of probably fundamental and second harmonic.

Aaron, would you mind showing some of your expertise?

This is a wonderful instrument.

You don't see them too often, do you?

[plays bassoon].

Terrific.

[applause].

Last, but -- but not least, we have a saxophone, Fabian.

Now, you may have to stand a long distance from this microphone, because these instruments make a hell of a lot of noise, don't they?

So give it a shot, and try 440, or come close to that.

It doesn't have to be exact.

[plays saxophone].

Interesting.

Also, you see several higher harmonics, it's hard to s- hard to tell which.

Would you mind, uh, playing something real hot?

[laughter] [plays saxophone] [unintelligible] [laughter] [noise] If you think we're interested in hearing it, you're wrong, we want to see it! [laughter] [plays saxophone].

[unintelligible] [laughter] [unintelligible].

[plays saxophone].

[applause].

Thank all of them.

[applause] Thank you very much.

[applause] So during the last three minutes, I would like to discuss with you the speed of sound in a little bit more detail.

Uh, you notice that the speed of sound is the -- proportional with the temperature and the molecular weight.

In fact there are a few other things upstairs here.

But these are the -- these are the major contributors.

So I should really say it's proportional.

If you take air -- as we discussed earlier, molecular weight is 30, that's a God-given, there's not much you can do about it.

I would like to demonstrate to you, the dependence on molecular weight.

And one way I could do that, I could take all the air out of 26-100 and replace it with helium.

And then I would ask the same musicians to come, and I would ask them, then, to play their wind instruments.

The Ls are fixed, there's nothing you can do about it.

So their instruments don't know that I put helium in the audience, so the only thing that changes is V.

The speed would go up by almost a factor of three, and so the fundamental would be free -- three times higher.

And the harmonics would be three times higher.

So you would hear much higher frequencies.

And you wouldn't even recognize these instruments.

This wouldn't be very practical.

I cannot take the air out of 26-100, and replace it with helium.

But what I can do, as I have done so often here in 26-100, I can suffer myself -- I can suffer, and put helium in my system.

I have, here -- I have, here, my own sound cavity.

I am, in a way, like a wind instrument.

And, um, if I swallow helium, my sound cavity doesn't know that I'm producing helium.

And you will say, when I talk to you as I do right now, "Yes, that's typical, that's Walter Lewin." You recognize my fundamentals, you recognize my harmonics, and it's unique for my voice.

And so you will recognize me.

But the moment that I fill my system with helium, nothing is changing in my system except for V.

And so the frequency will go up.

And that will be noticeable.

And, in fact, chances are that you will say, "Hm, that's really not Walter Lewin any more." There's only one problem with helium.

And that is there is no oxygen in helium.

And that is also very noticeable for me.

And yet, I really have to fill my lungs with helium all the way, and so I will be, for a while, without oxygen, and, um, so you may catch two birds with one stone.

You may hear a strange frequency, and you see me on the floor.

So I'll really try not to fall on the floor, then.

OK, there we go.

[laughter].

And it really doesn't sound like Walter Lewin any more, does it?

I will see you Friday.

All the best.

[applause].

Whew.