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8.02 Electricity and Magnetism, Spring 2002
Transcript – Lecture 33

I'm very proud of you.

You did very well on the last exam.

Class average is a little bit above 70.

Congratulations.

There were 22 students who scored 100.

Many of you are interested in where the dividing line is between C and D.

If I take only the three exams into account, forget the quizzes, forget the homework, forget the motor, and you add up the three grades of your three exams, the dividing line between C and D will be somewhere in the region 135 to 138.

So you can use that for your calibration where you stand.

The controversy between Newton and Huygens about the nature of light was settled in 1801 when Young demonstrated convincingly that light shows all the characteristic of waves.

Now in the early twentieth century, the particle character of light surfaced again and this mysterious and very fascinating duality of being waves and particles at the same time is now beautifully merged in quantum mechanics.

But today I will focus on the wave character only.

Very characteristic for waves are interference patterns which are produced by two sources, which simultaneously produce traveling waves at exactly the same frequency.

Let this be source number one and let this be source number two.

And they each produce waves with the same frequency, therefore the same wavelength, and they go out let's say in all directions.

They could be spherical, in the case of water surface, going out like rings.

And suppose you were here at position P in space at a distance R1 from source number one and at a distance R2 from source number two.

Then it is possible that at the point P the two waves that arrive are in phase with each other.

That means the mountain from two arrives at the same time as a mountain from one, and the valley from two arrives at the same time as the valley from one.

So the mountains become higher and the valleys become lower.

We call that constructive interference.

It is also possible that the waves as they arrive at point P are exactly 180 degrees out of phase, so that means that the mountain from two arrives at the same time as the valley from one.

In which case they can kill each other, and that we call destructive interference.

You can have this with water waves, so it's on a two-dimensional surface.

You can also have it with sound, which would be three-dimensional.

So the waves go out on a sphere.

And you can have it with electromagnetic radiation as we will also see today, which is of course also three dimensions.

If particles oscillate then their energy is proportional to the square of their amplitudes.

So therefore since energy must be conserved, the amplitude of sound oscillations and also of the electric vector in the case of electromagnetic radiation, the amplitude must fall off as one over the distance, 1 / R.

Because you're talking about 3-D waves.

You're talking about spherical waves.

And the surface area of a sphere grows with R squared.

And so the amplitude must fall off as 1 / R.

Now if we look at the superposition of two waves, in this case at point P and we make the distance large, so that R1 and R2 are much, much larger than the separation between these two points, then this fact that the amplitude of the wave from two is slightly smaller than the amplitude from the wave from one can then be pretty much ignored.

Imagine that the path from here to here is one-half of a wavelength longer than the path from here to here.

That means that this wave from here to here will have traveled half a period of an oscillation longer than this one.

And that means they are exactly 180 degrees out of phase and so the two can kill each other.

And we call that destructive interference.

And so we're going to have destructive interference when R2 - R1 is for instance plus or minus one-half lambda, but it could also be plus or minus 3/2 lambda, 5/2 lambda, and so on.

And so in general you would have destructive interference if the difference between R2 and R1 is 2N + 1 times lambda divided by 2 whereby N is an integer, could be 0, or plus or minus 1, or plus or minus 2, and so on.

That's when you would have destructive interference.

We would have constructive interference if R2 - R1 is simply N times lambda.

So then the waves at point P are in phase and N is again, could be 0, plus or minus 1, plus or minus 2, and so on.

If the sum of the distance to two points is a constant you get an ellipse in mathematics.

If the difference is a constant, which is the case here, the difference to two points is a constant value, for instance one-half lambda, then the curve is a hyperbola.

It would be a hyperbola if we deal with a two-dimensional surface.

But if we think of this as three-dimensional, so you can rotate the whole thing about this axis, then you get hyperboloids, you get bowl-shaped surfaces.

And so if I'm now trying to tighten the nuts a little bit, suppose I have here two of these sources that produce waves and the separation between them is D, then it is obvious that the line right through the middle of them and perpendicular to them is always a maximum if the two sources are oscillating in phase.

So this line is immediately clear that R2 - R1 is 0 here.

If the two are in phase.

And they always have to generate the same frequency, of course.

So this line would be always a maximum.

Constructive interference.

It's this 0, substitute there.

And in case that we're talking about three-dimensional, this is of course a plane.

Going perpendicular to the blackboard right through the middle.

The different R2 - R1 equals lambda would again give me constructive interference.

That would be a hyperbola then, R2 - R1 equals lambda, that would again be a maximum, and you can draw the same line on this side, and then R2 - R1 being 2 lambda again would be a maximum.

And again, if this is three-dimensional, you can rotate it about this line and you get bowls.

And so in between you're obviously going to get the minima, the destructive interference, lambda divided by two, and then here you would have R2 - R1 is 3/2 lambda.

We call these lines where you kill each other, destructive interference, we call them nodal lines or in case you have a surface it's a nodal surface.

And the maxima are sometimes also called antinodes, but I may also refer to them simply as maxima.

And so this is what we call an interference pattern.

If you look right here between -- on the line between the two points, then you should be able to convince yourself that the linear separation here between two lines of maxima is one-half lambda.

Figure that out at home.

That's very easy.

Also the distance between these two yellow lines here right in between is one-half lambda.

And so that tells you then that the number of lines or surfaces which are maxima is very roughly 2D divided by one-half lambda.

So this is the number of maxima, which is also the same roughly as the number of minima, is then approximately 2D divided by lambda.

And so if you want more maxima, if you want more of these surfaces, you have a choice, you can make D larger or you can make the wavelength shorter.

And if you make the wavelength shorter you can do that by increasing the frequency, if you had that control.

The first thing that I'm going to do is to make you see these nodal lines with a demonstration of water.

We have here two sources that we can tap on the water and the distance between those two tappers, D, is 10 centimeters, so we're talking about water here.

Uh, we will tap with a frequency of about 7 hertz and what you're going to see are very clear nodal lines, this is a two-dimensional surface, where the water doesn't move at all.

The mountains and the valleys arrive at the same time.

The water is never moving at all.

So let me make sure that you can see that well.

And so I have to change my -- my lights.

I'll first turn it on, that may be the easiest.

Starts tapping already.

I can see the nodal lines very well.

So here you see the two tappers and here you see a line whereby the water is not moving at all.

At all moments in time it's standing still.

Here's one.

Here is one.

And you even with a little bit of imagination can see that they are really not straight lines but they are hyperbolas.

If you're very close to one tapper, the zero can never be exactly zero, because the amplitude of the wave from this one then will always be larger than the amplitude from that one, because as you go away from the source the amplitude must fall off on a two-dimensional surface as 1 / the square root of R.

In a three-dimensional wave must fall of as 1 / R.

But if you're far enough away then the distance is approximately the same and so the amplitudes of the individual waves are very closely the same and you can then, like you see here, the water is absolutely standing still.

And here are then the areas whereby you see traveling waves, they are traveling waves, they're not standing waves, that here you see if you were sitting here in space the water would be up and down, bobbing up and down, and the amplitude that you would have is twice the amplitude that you get from one, because the mountains add to the mountains and the valleys add to the valleys.

But if you were here in space you would be sitting still.

You would not be bobbing up and down at all.

And that is very characteristic for waves.

If I were to tap them 180 degrees out of phase, which I didn't -- they were in phase -- then all nodal lines would become maxima and all maximum lines would become nodes, that goes without saying of course.

It is essential that you -- that the frequencies are the same, that is an absolute must.

They don't have to be in phase, the two tappers, if they're not in phase then the positions in space where you have maxima and minima will change but a must is that the frequency is the same.

Now I was hiking last year in Utah when I noticed a butterfly in the water of a pond which was fighting for its life.

And you see that butterfly here.

Tom, perhaps you can turn off that overhead.

You see the butterfly here, and you see here projected on the bottom the beautiful rings dark and bright, because these rings on the water act like lenses, and what you see very dramatically is indeed what I said, that the amplitude of the wave must go down with distance, because energy must be conserved of course in the wave, and since the circumference grows linearly with R, the amplitude must go down as 1 / the square root of R because the energy in the wave is proportional to the amplitude squared.

So when I saw this it occurred to me that it would be a good idea to catch another butterfly, put it next to it, and then photograph -- make a fantastic photograph of an interference pattern.

But I realized of course immediately, having taken 8.02, that the frequencies of the two butterflies would have to be exactly the same and so I gave up the idea and I decided not to be cruel.

So no other butterfly was sacrificed.

If we look at the directions where we expect the maxima as seen from the location of the sources, then I want to remind you of what a hyperbola looks like.

If here are these two sources and here is the center, I can draw a line here, then a hyperbola would look like this.

Let me re- remove the part on the left, doesn't look too good, but it's the same on the left of course.

And what you remember from your high school math, that it approaches that line.

And therefore you can define angle theta as seen from the center between these two, which are the directions where you have maxima and where you have minima.

And that's what I am going to work out for you now on this blackboard here.

So here are now the two sources that oscillate, there's one here and there's one here and here is the center in between them, and let this separation be D.

And I am looking very far away so that I'm approaching this line where the hyperbolas merge, so to speak, with the straight line.

And so I look very far away without being -- committing myself how far, I'm looking in the direction theta away.

This is theta.

And so this is theta.

And I want to know in which directions of theta I expect to see maxima, and in which direction I expect to see minima.

So this is what we called earlier R1 and we called this earlier R2, it is the distance to that point very far away.

If I want to know what R2 - R1 is that's very easy now.

I draw a line from here perpendicular to this line and you see immediately that this distance here is R2 - R1.

But that distance is also -- you realize that this angle is theta -- it's the same one as that one, so that distance here is also D sine theta.

And so now I'm in business, I can predict in what directions we will see constructive interference.

Because all we are demanding now, requesting, that R2 - R1 is N times lambda.

And so we need that D sine theta and I'll give it a subindex N, as in Nancy, equals N times lambda.

In others words that the sine of theta N is simply N lambda divided by D.

And that uniquely defines all those directions, the whole zoo of directions N equals 0, that is the center line, N equals 1, N equals 2, N equals 3, and so on.

And then I have the whole family of destructive interference.

Which would require that lambda R2 - R1 which is D sine theta must now be 2N +1 times lambda/2.

Just as we had it on the blackboard there.

We discussed that earlier.

And so that requires then that the sine of theta N for the destructive interference is going to be 2N+1 times lambda / 2D.

So this indicates the directions where we expect maxima and where we expect minima as seen from the center between the two sources.

But now I would like to know what the linear distance is if I project this onto a screen which is very far away.

And so let us have a screen at a distance capital L which has to be very far away, so here are now the two sources.

It's a different scale.

And here is a screen.

And the distance b- from the two sources to the screen is capital L.

And here is one of those direction theta.

And you see immediately that if I call this the direction X, X being 0 here, that the tangent of theta is X/L.

If but only if I deal with small angles, the tangent of theta is the same as the sine of theta.

And therefore I can now tell you where the maxima will lie on that screen, away from the center line, which I call 0, that is now when X of N is L times the sine of theta, in small angle approximation.

So this is approximately L times N lambda divided by D, and for the same reason you will get here c- destructive interference when X of N is going to be L times 2N+ 1 times lambda / 2D.

That is simple geometry.

So now we have all the ingredients here on the blackboard and I'm going to leave it there for the rest of the lecture.

Whenever we're going to do an experiment with two sources which are in phase, at the same frequency, you can predict the directions of maxima and minima and you can even predict the separation, the linear separation, if you know how far away you are from these sources.

And the first demonstration that I'm going to do is with sound.

We have here two loudspeakers.

And the distance between those two loudspeakers, we're going to do it with sound, D, is 1.5 meters.

That's a given.

And the frequency is 3000 hertz.

The wavelength, therefore, lambda, equals V divided by the frequency, the speed of sound is about 340 meters per second, divided by 3000, is about 0.113 meters.

So the wavelength is about 11.3 centimeters.

I can now calculate everyone who is sitting here [fweet] right in the middle through this whole plane will have a maximum of sound, and then when we go away at angle theta, some will again have maxima, and we go further away theta, again maxima, and in between will be the minima.

And I'm going to calculate where they fall in the lecture hall.

The first thing that I'm going to do is I'm going to give you N as in Nancy and calculate that angle theta of N and I will do it for the maxima.

In other words, I'm going to use constructive interference and you see there, the sine of theta N is lambda divided by D.

That's the equation I use.

When N is 0 the angle is 0.

That is 0 angle.

Everyone here will hear a maximum.

When N is 1, and you may want to check that at home, I find an angle of 4.3 degrees, and when N is 2, the angle is about double that, is about 8.7 degrees, and when N is 3, it should be close to 13 degrees, 13.1.

In case you take N is 10, so I skip a few, you get about 49 degrees.

This is where the maximum fall.

And so there's going to be a maximum here and then 4.3 degrees away is again a maximum.

But surely we would like to know how far you in the audience will have to move in order to go from a maximum to a minimum.

And so the way you have to think of this is that if I make here a picture of the lecture hall, if here are these two sources, you are at a distance L away from here.

Some of you are 5 meters away.

Some are 10 meters away.

Some are 15 meters away, all the way in the back of the audience.

And you want to know where you're going to hear the maxima.

I call this X1, I call this X2, and I call this X3, and this is 0.

So this is the meaning of theta 1.

And this is the meaning of theta 3, and this angle here would be theta 2.

That's the meaning of these angles.

And so I can calculate now how far you have to move depending upon what capital L is to hear, to go from one maximum in sound to another maximum.

And we raise the a little more.

And so I will show you now s- some of the results for maxima.

So I only go now for constructive interference.

And I have done this for three different distances.

Those of you who are 5 meters away from me, 10 meters away from me, and 15 meters away from me.

And what you see on the left side is going to be X, that is the linear separation, and these, so these were in meters, forgive me but I will do these in centimeters.

And this is X1, if you are 5 meters away from me, you will have -- I will put X1 a little lower than I have it now, you will see shortly why I put it a little lower -- X1, this is about 38 centimeters.

So the linear separation from one to the next is 38 centimeters.

And you're 10 meters away, it's double that, that's no surprise, 76 centimeters.

And if you're 15 meters away it is 113 centimeters.

And then X2, which is the position where you have another maximum, would be at 76 centimeters and it would be at 152 centimeters, and it would be at 228 centimeters if you're 15 meters away from me.

So the minima will fall almost exactly in between, and so the minima where, in an ideal case there is no sound at all, sound plus sound gives silence, think about it, sound plus sound will give silence, will be when you are roughly at 19 centimeters, half of this, this will be 38 centimeters.

Half of this, and here will be something like 57 centimeters.

And you can calculate what these values are, they are exactly in between.

And so the conclusion is that if you're 5 meters away from me and you're near the center line, but you can also be a little bit in this direction, that the separation between bright sound, loud sound, which is always at zero of course in the middle, to silence is 19 centimeters.

And then you move another 19 centimeters and then you hear loud sound.

If you are however 10 meters away from me, just past the cameras, then you have to move 38 centimeters to go from loud sound to silence.

And if you're all the way in the audience, in the back of the audience, it's more like 60 centimeters.

And this is what we're going to do now together.

I want you all to stand up and I'm going to make you listen to 3000 hertz.

And what I want you to do when I turn on the two loudspeakers, I want you to move your head very slowly and try to find locations where you hear silence.

The position of silence is extremely well-defined, so don't go too fast, you miss it, also keep in mind that there are reflections of the sound from the walls, and from the blackboard, and so the pattern that I have calculated here is not perfect.

But you will see that there will be locations where sound plus sound will give you silence.

[tone] [tone] You are a couple of lousy scientists.

[tone] You are a couple of lousy scientists.

If the separation between a lot of sound and silence is 19 centimeters, that's about the separation of your ears, you dummies, so one ear could be at a maximum, the other ear could be at a minimum, so at least close one ear.

[laughter] [tone] Go very slowly.

[tone] Who has found clear location where [tone] the sound is nearly zero [tone] or practically zero?

[tone] Most of you.

And you certainly can hear if you move that there's an enormous difference [tone] in sound intensity.

[tone] [tone] So again, who has found locations [tone] whereby you clearly say this is practically silence?

[tone] Ah, you see them all the way in the back, [tone] [tone] and the separation, how far you have to move, depends on how far you are away from me.

Sit down again.

[audience noise] Young was a sound engineer and as a sound engineer he was very familiar with the interference of sound.

He knew that sound and sound can make silence.

And so in 1801 he demonstrated in a convincing way that light plus light can create darkness.

That would be the nail in the coffin that would demonstrate uniquely that light are indeed waves, and there was still this controversy between Huygens and Newton as you perhaps remember.

Newton wanted light to be particles but Huygens wanted them to be waves.

And the way that Young did his experiment is as follows.

He had a screen, don't think of it as this big, you're talking now about extraordinarily small dimensions, you will understand shortly how small, and in this screen are two openings, two pinholes, and light is coming from the left and think of light as being plane waves.

They reach these two openings and these two openings according to Huygens will produce circular waves, spherical waves of course, three-dimensionally.

These openings become Huygens sources and spherical waves will propagate out in this direction.

And so now we have exactly the situation that we had with our sound.

Now if all works well there should be directions theta away from this line where you see darkness and other directions where you see bright light.

And we are going to do it in a way, we have the luxury of laser beams, so we have very strong light sources, which Young did not have.

The way we are going to do it, we have a -- a slide, which is completely black, but with a razor blade two lines have been drawn on it.

And so I will draw these lines as white lines.

But they're really openings.

And there is another one here.

And the separation between these lines D is 0.088 millimeters, less than a tenth of a millimeter.

When you look at them you cannot even see that they are two lines.

Our laser beam has a diameter of about 3 millimeters, which is 30 times larger than this distance, 30 times larger.

So what I'm going to show you now that this is our laser beam, is not to scale, the laser beam is much larger than that.

And so the light will go through some parts of these slots, as far as our laser beam reaches, and we are now capable of predicting when we're going to project it there, here are the two slots which are like so, and so you're going to get interference patterns in these directions theta, and we can calculate what the position X is going to be there between the maxima.

And so if that is the screen and if this is X equals 0, and if this is X1 and this is X2, and of course the whole thing is symmetric, you can always go in the opposite direction, you can now calculate, and you have all the tools, I did it for you in great detail using sound, but you have all the tools to do it now, you know D, I'm going to tell you what lambda is, it's 6328 Angstroms, and one Angstrom is 10 to the -10 meters, so you can calculate all the direction theta for which there are maxima and for which there are minima.

Minima means light plus light gives darkness, an amazing concept.

And you can then if you know the distance from here to the screen, which is capital L, you can calculate what the separation is as we see it on the screen, and L is roughly 10 meters, maybe 11, but that's not so important.

And so I calculated, and you can confirm that -- and you should confirm that, that the angle theta 1, I will only calculate theta 1, which is the angle then to this point, theta 0 is of course always 0, right, that's the easiest, I find that theta 1 is 0.41 degrees, that is for maximum, and that means that X1 given the distance of 10 meters then becomes 7.2 centimeters.

So from here to here on the screen, from maximum to maximum, will be about 7.2 centimeters, and from here to here will then of course also be about 7.2 centimeters, and in between you will see darkness.

The light from the two sources, 180 degrees out of phase, and that will give you darkness.

Let me turn on the laser.

And turn off the lights.

Make sure I have my -- OK.

And there you see it.

There you see a maximum, darkness, a maximum, darkness, a maximum, darkness, and so on.

And the separation if I didn't make a mistake between the maxima is indeed about 7 centimeters.

Imagine what an incredible moment this is in your life, that you actually see that light plus light can make darkness.

So the waves go simultaneously through both openings, and each opening acts like a Huygens source, and the net result is that these two waves arrive there on the screen 180 degrees out of phase at the locations of darkness.

The censor is of course that they have exactly the same frequency which is what they do, because we have one laser gun going in and so the wave goes through both slots.

So we're guaranteed, and that was the secret, that Young understood you're guaranteed that the waves are not only the same frequency but they're even in phase because they both go through to both slots.

Now if you look very carefully here you will see of course that these maxima don't have the same strength.

We will understand next lecture why that's the case.

They would have very closely the same strength if the opening where we scratched out the black on the slide was much, much smaller than the separation between the two slots, so to speak.

And that separation is 0.088 millimeter.

If we make the openings much narrower, indeed, the light intensities would be more uniform, each maximum would be approximately the same strength, but then very little light will go through.

And so it's a trade-off.

And the moment you make these two openings, these two slots, larger and larger, you will understand Friday why then the light intensities are not the same, why the light intensity is a maximum at the center and then falls off near the edge.

As you see.

It's a maximum here, and then the light intensities become smaller.

I've shown you now the interference pattern with sound and for red laser light, but imagine now that I did the same with white light.

The situation would be very different, and maybe even disappointing for you.

Let this be the location on the screen.

So we -- we have X here, and here X is 0.

And I want to know where the maxima are in the red, well that's very easy, there will be a maximum here when this position is L times lambda divided by D.

This is when Nancy is 1.

And there will also be a maximum here when we have 2L times lambda divided by D.

And of course there will be one on this side, same distance.

And there will be one here, this is when N is 0.

N is 1.

N is 2.

The red light will have maxima.

How about the blue light?

The blue light will have maxima here, where L lambda divided by D, but lambda is different, lambda for blue light is smaller.

Substantially smaller than red light, so the maximum of the blue will fall here, the maximum of the blue will always fall at N equals 0 together with red, and then Nancy equals 2 the blue will fall here, so this is Nancy 2, Nancy 1, Nancy 0.

And here Nancy 0, Nancy 1, Nancy 2.

And so the red and the blue and therefore all the other colors live a life of their own.

They don't talk to each other.

They come in with their own separation in terms of angles and in terms of locations X.

That's the reason why I chose one and only one frequency with the sound.

Because if I had exposed you to many different frequencies, many different wavelengths, then the location of silence for one wavelength is not the location of silence for the other wavelength.

And so the experiment would not have worked.

And that's why it worked so well with the laser, the red laser, which is practically one wavelength, and so the minima and the maxima are extremely well-defined.

If we had done the experiment with white light, it wouldn't have been so impressive, and on the next slide I show you what you w- would have seen then.

This is what white light would have done, this is a two-slit interference pattern.

This is what red light would have done.

Red light is a narrow bandwidth of wavelengths, well-defined black lines, light plus light give darkness, well-defined maxima, and the blue -- notice that the separation between the dark lines and therefore also the separation between the bright lines is substantially smaller.

Because blue light has a wavelength of about 4500 Angstroms and red light roughly 6500.

So there's a big difference.

And so white light would then give you the superposition of all these colors, and so you don't really get a very nice interference pattern of dark areas and bright areas, because all the colors begin to overlap and each live a life of their own.

What I can do with sound and what I did with water and what I have done with laser light I can also do with radio electromagnetic waves.

With radar -- we have a 10-gigahertz transmitter here that we have used earlier in this course.

And so I will now show you that with radar you can also show interference patterns and the calculation that you see there are absolutely identical.

The only thing I want to remind you of, that the approximation when you know capital L that the tangent theta is roughly the same as the sine of theta is only true for small angles.

5 degrees is fine, 10 degrees is fine, but by the time that you reach 50, 60 or 70 degrees that approximation is not true.

So then you really have to take the tangent of theta.

That's no problem because you first calculate what theta is, because that equation is correct, and then you can calculate always where X is, but then you use the tangent and not the sine.

So these are approximations which hold for small angles.

And so if now we look at a 10-gigahertz transmitter, that means we have two transmitters, one here and one here.

And their separation D is 23 centimeters.

You see them here.

This is where they are.

Here's one and here's the other, 23 centimeters apart.

At 10 gigahertz the wavelength is 3 centimeters.

You can confirm that.

The speed is speed of light.

Lambda is the speed of light divided by frequency.

That gives you the wavelength.

And we have here at a distance L which is 120 centimeters, we have here a receiver and a track, so this is X equals 0 and here we can move it along X and so you can calculate now at what angles seen from this point there will be a maximum there.

Theta 0 is obvious.

Right here there will be a maximum.

The two waves, the distance between them is zero, R2 - R1 is 0.

So they will constructively interfere.

But there is another angle, theta 1, for which again there will be constructive interference.

And you can confirm that I found for these numbers that theta 1 is about 7.5 degrees.

This is now for maxima.

And so roughly at an angle which is half that value you will find silence.

Silence means that the two radio waves will kill each other.

Essential for the maximum to be here is of course that the two transmitters are in phase.

We could have rigged it up so that they were 180 degrees out of phase in which case there would be silence here.

Silence in this case means that the radar would kill the radar.

But I do use the word silence for a good reason, because the way we rigged this up is the same way we did it before.

We modulate this 10-gigahertz signal with a 1000-hertz audio signal.

We call that amplitude modulation.

And the receiver which is here receives the 10-gigahertz radiation which is modulated at 1000 hertz.

We feed it to an amplifier.

We demodulate it and you will hear the 1000 hertz.

And so we can also move it along this track here and find the location X1 whereby we have our first maximum apart from the 0.

And I found that that is very roughly at 15.5 centimeters.

And you should confirm that using those equations.

Equations are the same.

Whether you deal with sound or with red laser light or with gigahertz, makes no difference.

And so let's turn now to this demonstration.

I will turn on the -- the two transmitters and here is the receiver which is exactly at angle theta 0.

So there's a maximum.

I'm now going to close one transmitter, [tone] put my hand in front.

[tone] And you think about what will be the reduction of intensity of the sound here.

[tone] If I close one, it's substantially down.

You may think that it is down by a factor of two.

Because we have only one transmitter instead of two.

You're wrong.

If you think that, you do not understand interference.

It is 4 times lower when I hold my hands over one.

Figure it out for yourself.

I'll test you on the final to see whether you really understood that.

So now the sound is 4 times larger than when I cover one up.

I'll cover the other one up.

It's down by a factor of 4.

[tone] I can cover this one up and then you hear nothing of course.

[tone] Now I will move this one [tone] to the location [tone] where there is destructive interference, [tone] which should be about half of 15.6 centimeters.

[tone] Maybe you have good ears but I hear nothing anymore.

Now I go through it and find the maximum, which is about 15.6 centimeters.

[tone] Here it is.

[tone] And the other side, [tone] here's the maximum at center, so here should be a minimum, there it is, and I go to the other side, there should be a maximum.

[tone] And there it is.

[tone] So what I have shown you today is I've shown you the interference pattern of sound, of water, of red laser light, of radar, and at the very least I hope I've convinced you as Young convinced the world in 1801 that light are waves.

And that means that Huygens was right and Newton was wrong.

Now that should perhaps not surprise you because Huygens was Dutch.