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8.02 Electricity and Magnetism, Spring 2002
Transcript – Lecture 14

Well, we have a current going through a wire, like so.

And we look at the magnetic field in the vicinity of this wire , then we know from experiment that if you put pieces of magnetite around the wire that they line up in a circle.

Put around like this.

If that circle has a radius R, then the magnetic fields, that's an experimental fact, is proportional with the current I and is inversely proportional with the radius of that circle.

By convention, the direction of the magnetic field is given by the right-hand corkscrew, rotate this way, the current goes up.

You've seen before, with electric charges, when you have a wire which is uniformly distributed say with positive charge, you've also seen that electric fields in the vicinity of that straight wire falls off as 1 over R, whereas the direction is different than the magnetic field but it also falls off as 1 over R, and the reason is that electric monopoles, individual charges, the electric field falls off as 1 over R squared.

And so when you integrate that out over a straight wire you get the 1 over R field.

So by analogy, it would be very plausible that if you took magnetic monopoles that the magnetic field would also fall off as 1 over R squared, but magnetic monopoles as far as we know don't exist.

In principle they could exist, but we've never seen one, and if any one of you ever find one, that would certainly be a Nobel Prize.

It's by no means impossible.

And so the simple fact that the magnetic field around a current wire falls off as 1 over R, sort of suggests that if you carve this wire up in little elements dL, that each one of those elements contributes to the magnetic field in an inverse R-squared law, and by integrating out over the whole wire you'd then get the 1 over R fields.

And this behind the idea of the formalism by Biot and Savart, who introduced the idea that if you have a little current element dL, and the current is in this direction, and you want to know what the magnetic field is, This is small contribution dB to that little current element, and the distance is R, and the unit vector from the element dL to the point where you want to know the magnetic field is R roof.

Then the idea is that dB, it's a little bit of curr- little bit of magnetic fields.

In this case it would be in the blackboard because of the right-hand corkscrew rule.

The current is in this direction, so these little elements would contribute to magnetic fields in this direction perpendicular to the blackboard.

Is some constant, proportional to the current no doubt, and then is proportional to the length of that little element dL, if it's longer then the magnetic field is larger, and in order to get the direction right perpendicular to the blackboard you take the cross product with the unit vector R.

The unit vector R has length 1 so you only do that in order to get the direction right.

And this, and that inversely proportional to R squared.

That's of course key.

And this is, the formalism by Biot-Savart and you can do experiments and measure the magnetic field in the vicinity of wires and this formalism works, so you then calculate the individual contributions of all these little elements dL and then you do an integration and this formalism works.

You can then also measure what C is, in SI units, C is 10 to the -7.

But we write for C something quite peculiar.

We write for C mu 0 divided by 4 pi, and we call this mu 0 the permeability of free space.

You've seen earlier with Coulomb's law that this constant 9 times 10 to the 9th, we call that 1 over 4 pi epsilon 0.

What is in the name?

And so here we call this mu 0 divided by 4 pi.

So now you can apply Biot-Savart's Law and you can go to a straight wire and you have a current I, and suppose you want to know what the magnetic field at that location P is at a distance capital R, and so what you now have to do, is you carve this up, in an infinite number of small elements dL, and this distance is R, and the unit vector is then like so, and you calculate the small amount of magnetic field due to this little element and you integrate this over the whole wire.

It's mathematics.

You've done it.

You've done it before, where we had uniformly electric charge on the wire.

So I'm not going to do this again for you.

It's a very straightforward piece of mathematics.

The magnetic field by the way, in this case, would come out of the blackboard.

Because of the right-hand corkscrew rule.

And what you find when you do this, we will find that B equals mu 0 times I, divided by 2 pi R, this being R, and so you indeed see that the inverse 1 over R comes out.

And so if you, for instance, take a radius of 0.1 meters, 10 centimeters, and you have a current through the wire of about 100 amperes, then you would end up with a B field.

You use this equation, 2 times 10 to the -4 tesla.

That is about 2 gauss.

100 amperes.

10 centimeter distance is only 2 gauss.

Think about it.

The Earth's magnetic field is half a gauss.

So if you go 1 meter away from the wire, so we have a magnetic field which is 10 times lower, look, it goes with 1 over R, then the magnetic field of the Earth already dominates substantially.

So you need very high currents, actually, when you do these experiments.

It's nice to see that out of Biot-Savart's formalism the 1 over R pops out, but of course you must realize that Biot-Savart knew that the magnetic field falls off as 1 over R.

That was an experimental fact.

So the fact that it falls out is logical, because it was cooked into that formalism.

If you think about it, it all goes back to Newton.

Newton was the one who first suggested that the gravitational field falls off as 1 over R squared.

And then later a logical ex10sion was that the electric fields would fall off as 1 over R squared and out of that came the idea that the fields of magnetic monopole, if they only existed, would fall off as 1 over R squared, and that's all behind this and so the person who really deserves most of the credit for all this in my book is Newton.

Using Biot-Savart, we can calculate now quite easily the magnetic field at the center of a current loop.

Let this be a wire circle and let the current go in this direction, and I would ask you what is the magnetic field right at the center.

Well, the magnetic field right at the center of course is pointing upwards.

Each little element along the line here, dL, each little element will contribute a little bit magnetic field at that point right in this direction.

And if this radius is R, with Biot-Savart now, we can calculate quite easily the total field that you would get at this location, because that total field is then the integral of dB vectorially over the entire wire so the entire loop...

So if you go there, so you would get your mu 0, divided by 4 pi, you get your current and you get your 1 over R squared, and now you have to do an integral over that dL cross R.

Well, R is of course always perpendicular to dL.

Any element dL that you choose, the unit vector R is exactly perpendicular to the element dL, because that's characteristic of a circle.

And so the sine of the angle between dL and R is 1, and so all we have to do is do an integral over dL, which is the integral of the circle, which is the circumference of the circle, and that is 2 pi R.

And so now you find, you lose a pi, you lose an R, so you find mu 0 times I divided by 2R.

Just to show you an example, how in this case how easy it is to use Biot-Savart and calculate the magnetic field right at the center.

If you were asked what the magnetic field was here or there, that would be also relatively easy.

You've done that.

I've given you a problem earlier where we had point charges uniformly distributed on a wire and I asked you what the electric field was here.

So that can also be done now with magnetic fields.

If I ever asked you what the magnetic fields would be here, that of course is an impossibility to do that with Biot-Savart, practically an impossibility.

I wouldn't know how to do that.

But in principle it could be done and certainly with a computer you can do it.

So we can go to our same situation, we can take 100 amperes for I and you can take R 0.1 meters and then the B field, the strength of the B field right at the center of this loop that I found is then 6 times 10 to the -4 tesla.

And that would be 6 gauss.

It's clear that if you want to put in some field lines, magnetic field lines, as a result of this current going around in a circle, that the- through the center there would be a field line like so.

If you're very close to the wire here, which goes into the blackboard, I want you to see this three-dimensionally, then the magnetic field would go like this, clockwise.

Here the current comes to you, so it would be counterclockwise.

If the magnetic field line is here like so, and here it is curled up, then clearly I expect them to be here, sort of like so, and like so, and like so.

This is the kind of magnetic field line configuration that I would expect, then, in the vicinity of such a current loop.

And I want to show this to you in a little bit more detail.

I have here a transparency, and you see there on the right side, current goes into the paper and here it comes out of the paper.

That is a circular loop.

And you see here the field line configuration.

It's not too different from what I have on the blackboard there.

Very close to the wires, of course, you get circles because the 1 over R dominates there.

It's so close to the wire that the 1 over R relationship makes it come out like circles and here too, but then if you're farther away you get configurations like I have there.

When you're very far away from a current loop, the magnetic field configuration is very similar to that of an electric dipole.

I can show you that in the following way.

Let's first look at the electric dipole that you see up there.

This is a positive charge, this is a negative charge.

Don't look anywhere near the charges.

Don't look in between the charges.

Look far away.

Here you see electric field lines and you see them here.

Now look at your current loop here.

The current is going into the paper here, coming out of the paper.

There is a loop.

And look, you see the same configuration, field lines, field lines.

This goes like so.

This one goes like so.

Here, the electric field lines coming in, magnetic field lines are coming in.

Electric field lines are going out.

Magnetic field lines are going out.

They look very similar.

Gauss's Law tells me that the closed surface integral of the electric flux is the charge inside the box divided by epsilon 0, and so if you have a closed surface here, it looks like a line but I meant it to be a surface, then that closed surface integral of the electric flux is not 0 because there's a charge inside the box.

No matter where in the magnetic field you make a closed surface there is never any magnetic flux going through that surface.

Never, unless you come into 26-100 and show me a magnetic monopole.

Only then will there be magnetic flux coming out of a closed surface, if we put a magnetic monopole inside.

And this, now, brings us to the second of four Maxwell's equations, the first one being Gauss's Law, the second one is that the closed surface-closed surface integral of B dot dA is always 0, unless you come with a magnetic monopole.

So we now have two of Maxwell's four equations in place.

Historic day.

I want to show you the magnetic field in the vicinity of a wire like this.

I have to use a few hundred amperes through that wire.

I told you why, because magnetic field falls off quite rapidly, and I do that with iron file which I will sprinkle around the wire and these magnetites will orient themselves in that magnetic field and then I will try to also make you see this field configuration by having one wire going into the paper and one coming out of the paper.

So let's first look at the single current wire.

It's coming towards you and it goes into of course.

It is a wire that goes like this and the reason why you see it here is of course we have to get the current in somehow.

But it really is a wire like this, and this platform I'm going to show you.

I'm going to put some iron file around this.

These are magnetites and when they see magnetic field, they will try to orient themselves in the direction of the magnetic field, so you're going to see these circles.

But appreciate the fact that you need huge currents for this.

Hundreds of amperes we do.

That's why we have a car battery here, remember, that was capable of delivering many hundreds of amperes.

So I close the current now.

I tap, you can see these circular configurations.

I hope you can see that.

Looks like circles.

I want to do the same now.

This is a little bit more exciting, perhaps, with one wire going into the plane and the other one coming out.

Even though it's not a circle, the idea is that you get a field configuration very much like you see there.

Boy, it's already hot.

These cables are already hot.

They don't like the few hundred amperes.

OK, let's do it this way.

So you're going to see a field configuration similar to what I have on the blackboard, similar to what you have here.

Oh, no, not this one.

Similar to this.

Yeah, actually, it was also the one that I have, but this is nicer way to look at it.

So we have one wire going in and one wire coming out of the plane.

All right, so let's first put some iron file on.

All right, and now a few hundred amperes through it, tap it, and you can see close to the wire that goes in here and here, you see circles.

Those are the 1 over R relationship.

They dominate the magnetic fields, but look in between here.

With a little bit of imagination you can see these field lines going like this, just like I have today on the blackboard.

All right.

We don't need it anymore, and we don't need that anymore.

So this gives you a little bit of insight into the magnetic field configurations that we have about these wires when we run a current through.

I will return to magnetic fields next lecture and we will expand on it.

We will learn techniques to calculate magnetic fields in a way which is highly superior to Biot-Savart's law.

In fact, that will get us to the third Maxwell equation, almost.

But I now want you to relax a little bit because this may already have been a little rough on you, so now I want to discuss something entirely different, something very practical, and it has to do with the transport of electric energy.

So we have a power station somewhere at location A, and they deliver electric power, electric energy to Boston.

Here is Boston, location B.

And A is the location of the power station.

This could be 1000 miles, the distance.

There's a cable going from the power station to us, and the potential here in this line, say, is B, a V of B.

Here's a cable for the return current, so the current goes like this, and the return current is in this direction, and, and here you use this energy.

You hook up your computer, you hook up your hairdryer, your heaters, you electric toothbrush and what have you, your TV station, everything.

And so you are the consumer here.

You take the energy that is provided by this power station.

I will call the potential of this line 0 and so this is V of A higher than this line here.

Well, according to Ohm's Law, VA minus VB is the current times capital R which is now not radius, but that is resistance in the wire, this wire.

This cable, however thick it may be, has a finite resistance.

And so VB, that is the potential that we receive in Boston, equals VA minus IR.

So if there's no current going through the wire, no one is using any electric energy, then VB is the same as VA.

Now I want to know if we consume energy, so we're dealing now with power, so the power that we take off at Boston is I times V of B.

That's the number of joules per second that we are consuming.

So that then equals VA times I minus I square R.

That's fine.

What is this?

This is the energy per second that we are consuming.

What is this?

This is the energy per second that the power station is delivering to us.

What is this?

That's lost energy.

It's the I square R that is the heat produced in this cable that goes into the universe.

It's gone.

So the economy demands that we try to make this as small as possible.

See, this is the power that is available but you get a loss of power in terms of heat, the minus sign here, so you get less in Boston.

And so how can you make this I square R low?

Well, what is the resistance of a wire?

That is rho, which is the resistivity, times the length of the wire divided by the cross-section of the wire.

So we have several options.

You could make A very large, a very thick copper wire, that's expensive.

You could also make the wires out of gold, which has a lower resistivity than copper.

That's also expensive.

People are thinking of making these transmission wires of superconducting material.

They have to cool them at very low temperatures.

That's outrageously expensive but that's a way you could get the resistance down.

Let's now look at the current.

What can we do with the current?

Suppose we consume 100 megawatts.

Not an unreasonable number, so we are consuming 100 megawatts, and just for the sake of the argument, suppose at VB the potential is 100 volts, so V of B is 100 volts.

What now is the current?

Well, current times potential gives me power, and so my current is now a million amperes.

Alternatively, suppose that the potential at B in the wire is 100000 volts, 1000 times higher.

Now the current is only 1000 amperes, gives me the same power.

In both cases, am I consuming at a rate of a hundred million joules per second.

But I square R, the heat loss on the way from the power station to me, is a million times lower in this case than in that case, because I is 1000 times lower, and the heat loss goes with I squared, and so now you understand why electricity, when it is transported from one place to another, why this is done at the highest voltage possible.

When you get to Boston, you've obviously got to do something about this enormous potential, because if you were to deliver a 100000 potential difference there, then half the population in Boston would electrocute itself, so now you've got to come down in voltage, which you do with transformers.

We will talk about that later in the course.

And so you bring it down to a comfortable voltage, which is in the United States about 110 volts.

In Europe it's 220.

Now comes the question, how high can you make V of A.

The higher you could make it, the less loss there would be along the way.

Well, you've got to stay away from the breakdown electric field, which is the 3 million volts per meter.

If at the surface of these cables you get 3 million volts per meter, you get corona discharge.

That's a big loss and you want to stay away from that, and so typical cables have about a radius R.

This is now, R is the radius of the cable of about 2 centimeters; that gives him a cross-sectional area I think of about 10 to the -3 meters squared, that's correct.

And the potential V at A is roughly 300 kilovolts, and with that configuration you stay comfortably below the electric field of 3 million volts per meter, but you don't get the corona discharge.

If the length of that cable, L, if that were something like 1000 kilometers, not an unreasonable number, 1000 kilometer distance from if we get our electricity from Niagara Falls to Boston, not an unreasonable number, you can calculate now what the resistance of that cable would be, because that resistance R equals rho times L divided by A.

If you take copper, that has a resistivity of 2 times 10 to the -8 SI units.

We have a length of 10 to the 6th meters of the cable and we have a cross-sectional area of 10 to the -3 square meters so that 1000 kilometer cable would only have a resistance of 20 ohms.

And to make the numbers a little easy, if we have a current, say, of 300 amperes, then the power that the power station produces, if you take the 300 kilovolts for now, that power would be the 300 kilovolts times the 300 amperes and that is about 90 megawatts.

That's close to my 100 that I had in mind earlier.

So you can calculate now what the loss is.

The loss is I squared R.

You know R is 20 ohms, you know I, 300 amperes, and so you'll find now that you have about 2 megawatt loss.

That's not bad.

2 out of 90.

So we have about 2 percent energy loss in transportation.

You can also calculate now what the difference is in potential between the power station and Boston, VA minus VB is IR.

You know that I is 300 amperes and you know that R is 20 ohms, so VA minus VB is about 6 kilovolts.

In other words, if the power station puts it on the line at 300 kilovolts, then you would get it here with only four six kilovolts less.

So it's not a very unreasonable situation.

I told you that these power lines have to stay away from the 3 million volts per meter electric field because then you get corona discharge and when there is thunderstorms in the area it can actually push up the electric field on the wire and you can get corona discharge.

I have seen that several times, not only seen it at night, with my naked eyes that you see the power lines glow, but I've also heard it, because you can hear this cracking noise of corona discharge.

It's very fascinating, actually.

I have a slide here which shows that.

So here you see a high voltage power line, transmission line, and you clearly see the glowing of the corona discharge.

They compare that with what's called a Romas kite string.

Kite strings at night when you fly them near thunderstorms can also produce corona discharge and light.

That's why they are called Romas kite string candles.

Benjamin Franklin did quite a bit of experiments at night with, uh, kites near thunderstorms.

Dangerous business by the way.

So you see that these high-voltage power lines can go into a corona discharge.

I now want to revisit our Leyden jar.

We had a truly absurd situation whereby we did an experiment with a jar which you still see here, and I will redo the demonstration, but it's crying for an explanation because it looked like there was something wrong with physics, and I want to refresh your memory of what we have seen before and what this Leyden jar is all about.

The Leyden jar is nothing but a capacitor, with a dielectric between two conductors in the form, in the shape of a- of a bottle, a jar.

And so the inner portion, which is glass, say has this shape.

You see it there, you're going to see it shortly there, and then we have conductors, the conducting beaker around it here, and we have a conducting beaker on the inside.

And we charge these up with the Windhurst.

This is the Windhurst machine.

And when we do that, we get free charge on the conductor, and so you get sigma free right here and you get it here, opposite signs of course, and you get sigma induced on the dielectric.

Why do you get it?

Because the dielectric sees an external field due to this sigma free, so it begins to polarize, and so you get here induced charge and you get there induced charge.

If this side is positive, then the induced charge here will be negative, and vice-versa.

We have here a metal hook, so that we can lift out the inner portion.

And so what we did, we charged it up with the Windhurst, and then there is a certain amount of energy.

The electrostatic potential energy of this configuration is one-half Q free times the potential difference, and the Q free is the charge which is on the outer conductor.

And what I then did, I disassembled it very carefully after we had charged it up, took the inner portion out, took the glass out, the outer portion, and I took all the free charge off.

I touched the conductors and discharged them, so there is no Q free left.

It's gone.

The moment that that is gone, the induced charge must also go away because the induced charge is only there because of the free charge.

Remember the induced charge density is 1 - 1 over kappa times sigma free.

So if glass has a kappa of 5, then the induced surface charge density is about 0.8 times the free surface charge density.

The moment that the free one goes, the induced one goes.

And then I assembled it again, and much to our surprise when I short out the inner portion with the outer portion, we saw a huge spark.

That means there was energy left and that is very puzzling.

There cannot be any energy left unless there is something wrong with physics.

So I first want to show that again, to remind you of what you have seen before, and then I will make a proposal for a- for an explanation.

Let me check my light configuration.

Ah, we're going to make it all dark.

I can charge it up while you're seeing it, actually.

Yeah.

Make it dark now.

And now I will disassemble it.

I take the inner portion out.

The glass is a good insulator, so I don't mind touching that with my hand.

OK, and so now I take the inner conductor, touch it, lick it, kiss it, take all the charge off.

There it is.

Do the same with the outer conductor, have it in my hand.

For sure, there is no Q free left on anymore, on that anymore.

I put the glass back in again, and then I put the inner [inaudible] again, and now I'll make it a little darker for you because I want you to see that when I short this out that you're going to see a spark, so I'm going to turn the lights down, so look very closely.

I'll tell you when I'm going to do it.

Three, two, one, I'm approaching it now, 0.

And there's a huge spark.

That means energy, and that's crazy.

There shouldn't be any.

And so some of you must have had sleepless nights not being able to explain this.

Some of uh- some of you actually wrote me e-mail.

Uh, you didn't have sleepless nights, I can tell that.

So what's going on?

There's only one possibility and that is there must be free charge on the glass.

How did it get there?

Well, corona discharge.

That's the only way it can get there.

Keep in mind that the electric field in air, E in air, can be no larger than 3 times 10 to the 6 volts per meter.

If it gets larger, you get corona discharge.

In glass, by the way, it's a bit higher.

It's 10 to the 7th volts per meter.

I will now make some calculations based on certain assumptions.

And those assumptions may not be exactly accurate because I don't know the exact dimensions of this system, but the exact dimensions don't matter.

What matters is the idea behind it, why it does such crazy things.

So first of all, I will assume that this capacitor is just two parallel plane plates.

That's a simplifying situation because it has the shape of a bottle.

I will assume that the Windhurst produces about 30 kilovolts.

I know that it's approximately right, but it may be 25.

It may be 35.

I will assume that the air gap between the outer conductor and the glass is 1 millimeter, that both are 1 millimeter, and I would assume that the glass thickness is 3 millimeters, and I take kappa equals 5 for the glass.

So that is the basis of my calculations.

So now I have here the conductor on the outside.

This is the glass, and this is the conductor on the inside, so this is 1 millimeter thick, this is 3 millimeters thick, and this is 1 millimeter thick, and the potential difference over the whole thing is going to be 30 kilovolts.

But I know that the potential difference is always E times D.

That holds for this gap, the local E times this D, the local E times this D, and the local E times that D.

I also know that E glass is the same as E in the air divided by that kappa, which is 5.

And I know that the total potential difference between here and here must be 30000 volts.

And so this allows me now to calculate in a very straightforward way the electric field here in the air, the electric field here in the air, and the electric field in the glass because I get simple equation with one unknown and that's the following.

I first go over this gap and so I get E in the air times the distance D, which is 1 millimeter.

But of course later on I have to go through this gap again so I'll multiply it by two now.

And now I have to add the electric field in the glass, which is the same as air divided by 5, times its distance which is 3 millimeters, and that must now be 30000, because that's the potential difference between here and there.

That's one equation with one unknown.

And I can calculate the electric field in the air gap.

And the electric field in the air gap turns out to be 11.5 times 10 to the 6 volts per meter.

It's here the same, of course, 11.5 times 10 to the 6th, and here it is 5 times smaller, so I find here 2.3 times 10 to the 6th.

To show you that I did my homework correctly, the potential difference here is now 11.5 kilovolts.

I put it here in kilovolts.

The potential difference here is now about 7 kilovolts and the potential difference here is the same, is 11.5 kilovolts.

And if you add them up, you get 30.

If you look at this, this can not be, because a field of 11.5 times 10 to the 6th is way above the breakdown electric field.

And so what are you going to- what's going to happen, you're going to get corona discharge from the conductor to the glass, and so what you're doing is you're spraying charge on the glass, and that's the key to the solution of this bizarre behavior.

And so when you later disassemble it and you take the free charge of the conductors.

There is still this free charge which you have sprayed on the glass.

I never remove that.

It's very hard to remove because the glass is an insulator.

It's very difficult to take charge off an insulator.

It's easy to take it off a conductor but I've never even attempted that because I made you believe, as I believed myself for years, that once you take the Q free off the conductor that there can be no charge on the glass.

That is wrong, because there's corona discharge.

So now comes the question, before we disassemble, what now is the configuration of the electric fields and the potentials.

I'll make a drawing here and so now I draw again the conductor, the glass, and the conductor.

I assume now that after the corona discharge this field here is 3 times 10 to the 6th.

Maybe a little lower, but that's the maximum that it can be, and so the field here in the air will be also 3 times 10 to the 6th volts per meter.

But since I know that the potential difference between here and here must be 30 kilovolts, I can now immediately conclude that the electric field here is now 8 times 10 to the 6th volts per meter.

That is the only way that it adds up to 30 kilovolts, because the 3 million volts per meter gives me here 3 kilovolts.

This here gives me 3 kilovolts.

So now I need a potential difference here of 24 kilovolts, and that over 3 millimeters requires this field.

Look, this field is stronger than that field, whereas earlier we made the assumption that this field was 5 times lower than that field.

Yah, why is it now higher?

Because we have sprayed right here on this surface, we have sprayed free charge.

It's no longer the field that is dictated by the external field and then the induced charges.

That's no longer the case.

It carries now itself free charge.

You now have all the tools, maybe not the courage, to calculate how much free charge there is right here on the glass to get this field.

It's a very straightforward calculation.

And you will find that there is twelve times more free charge here on the glass than there is here on the conductor, twelve times more, and so if I disassemble and remove the free charge on the conductors, I have almost done nothing because most of the free charge is on the glass, and I have not touched that.

So now, if I reassemble, I have almost all energy left.

I have not lost much.

Lost some, but not much.

And so what I should have really have done, I should also have discharged the inner glass.

That's not easy, but I will try that today.

It's not easy because it's very hard to take that charge off, but I will try that.

And then there shouldn't be much energy left if we reassemble it again and try to get a spark out.

So I go through the same routine and I'm going to charge it up now.

OK, take this cable off, take that cable off.

I take it apart, do everything that I did before the same way, gone, all charge gone, whatever there was.

All charge gone.

Now, this is more difficult.

This is not enough if I do this.

I have to get in there.

Ooh, I could actually feel it.

It's really, it's a great feeling.

I can feel a sort of corona discharge with my -- I have to really get all everything out and that's not easy.

It's not.

In fact, when I rub in with my shirt, I may even make it worse.

I may be charging it up through friction.

But I'll do the best I can.

It's very indecent, what I'm doing.

OK.

So I'll try to get a charge now, something that we ignored completely before.

This is really where the energy was, and I'm trying to kill that now, and so now I'm going to reassemble it, and I'll go through the same routine [clink] [whoop].

Good thing I didn't break it.

Put it back in again.

I'll make it dark, so that you can see whether perhaps there may be a little bit of spark, if I didn't succeed to remove all the charges from the glass.

So I'm going to short it out again, three, two, one, zero, and I saw a teeny-weeny little spark.

You may not even have seen it, so we have to conclude now that the physics behind this lies in the glass and physics works even when it sometimes surprises us.

See you Wednesday.