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8.02 Electricity and Magnetism, Spring 2002
Transcript – Lecture 6

Last time I mentioned to you that charge resides at the surface of solid conductors but that it's not uniformly distributed.

Perhaps you remember that, unless it happens to be a sphere.

And I want to pursue that today.

If I had a solid conductor which say had this shape and I'm going to convince you today that right here, the surface charge density will be higher than there.

Because the curvature is stronger than it is here.

And the way I want to approach that is as follows.

Suppose I have here a solid conductor A which has radius R of A and very very far away, maybe tens of meters away, I have a solid conductor B with radius R of B and they are connected through a conducting wire.

That's essential.

If they are connected through a conducting wire, then it's equipotential.

They all have the same potential.

I'm going to charge them up until I get a charge distribution QA here and I get QB there.

The potential of A is about the same that it would be if B were not there.

Because B is so far away that if I come with some charge from infinity in my pocket that the work that I have to do to reach A per unit charge is independent of whether B is there or not, because B is far away, tens of meters, if you can make it a mile if you want to.

And so the potential of A is then the charge on A divided by 4 pi epsilon 0 the radius of A.

But since it is an equipotential because it's all conducting, this must be also the potential of the sphere B, and that is the charge on B divided by 4 pi epsilon 0 R of B.

And so you see immediately that the Q, the charge on B, divided by the radius of B, is the charge on A divided by the radius on A.

And if the radius of B were for instance 5 times larger than the radius of A, there would be 5 times more charge on B than there would be on A.

But if B has a 5 times larger radius, then its surface area is 25 times larger and since surface charge density, sigma, is the charge on a sphere divided by the surface area of the sphere, it is now clear that if the radius of B is 5 times larger than A, it's true that the charge on B is 5 times the charge on A, but the surface charge density on B is now only one-fifth of the surface charge density of A because its area is 25 times larger and so you have this -- the highest surface charge density at A than you have at B.

5 times higher surface charge density here than there.

And I hope that convinces you that if we have a solid conductor like this, even though it's not ideal as we have here with these two spheres far apart, that the surface charge density here will be larger than there because it has a smaller radius.

It's basically the same idea.

And so you expect the highest surface charge density where the curvature is the highest, smallest radius, and that means that also the electric field will be stronger there.

That follows immediately from Gauss's law.

If this is the surface of a conductor, any conductor, a solid conductor, where the E field is 0 inside of the conductor, and there is surface charge here, what I'm going to do is I'm going to make a Gaussian pillbox, this surface is parallel to the conductor, I go in the conductor, and this now is my Gaussian surface, let this area be capital A, and let's assume that it is positive charge so that the electric field lines come out of the surface like so, perpendicular to the surface.

Always perpendicular to equipotential, so now if I apply Gauss's law which tells me that the surface integral of the electric flux throughout this whole surface, well, there's only flux coming out of this surface here, I can bring that surface as close to the surface as I want to.

I can almost make it touch the conductor.

So everything comes out only through this surface, and so what comes out is the surface area A times the electric field E.

The A and E are in the same direction, because remember E is perpendicular to the surface of the equipotentials.

And so this is all there is for the surface integral, and that is all the charge inside, well the charge inside is of course the surface charge density times the area A, divided by epsilon 0, this is Gauss's law.

And so you find immediately that the electric field is sigma divided by epsilon 0.

So whenever you have a conductor if you know the local surface charge density you always know the local electric field.

And since the surface charge density is going to be the highest here, even though the whole thing is an equipotential, the electric field will also be higher here than it will be there.

I can demonstrate this to you in a very simple way.

I have here a cooking pan and the cooking pan, I used to boil lobsters in there, it's a large pan.

The cooking pan I'm going to charge up and the cooking pan here has a radius, whatever it is, maybe 20 centimeters, but look here at the handle, how very small this radius is, so you could put charge on there and I'm going to convince you that I can scoop off more charge here where the radius is small than I can scoop off here.

I have here a small flat spoon and I'm going to put the spoon here on the surface here and on the surface there and we're going to see from where we can scoop off the most charge.

Still charged from the previous lecture.

So here, we see the electroscope that we have seen before.

I'm going to charge this cooking pan with my favorite technique which is the electrophorus.

So we have the cat fur and we have the glass plate.

I'm going to rub this first with the cat fur, put it on, put my finger on, get a little shock, charge up the pan, put my finger on, get another shock, charge up the pan, and another one, charge up the pan, make sure that I get enough charge on there, rub the glass again, put it on top, put my finger on, charge, once more, and once more.

Let's assume we have enough charge on there now.

Here is my little spoon.

I touch here the outside here of the can -- of the pan.

And go to the electroscope and you see a little charge.

It's very clear.

What I want to show you now it's very qualitative is that when I touch here the handle, it's a very small radius, that I can take off more charge.

There we go.

Substantially more.

That's all I wanted to show you.

So you've seen now in front of your own eyes for the first time that even though this is a conductor that means that it is an equipotential, that the surface charge density right -- right here is higher than the surface charge density here.

Only if it is a sphere of course for circle symmetry reasons will the charge be uniformly distributed.

If the electric field becomes too high we get what we call electric breakdown.

We get a discharge into the air.

And the reason for that is actually quite simple.

If I have an electron here and this is an electric field, the electron will start to accelerate in this direction.

The electron will collide with nitrogen and oxygen molecules in the air and if the electron has enough kinetic energy to ionize that molecule then one electron will become two electrons.

The original electron plus the electron from the ion.

And if these now start to accelerate in this electric field, and if they collide with the molecules, and if they make an ion, then each one will become two electrons, and so you get an avalanche.

And this avalanche is an electric breakdown and you get a spark.

When the ions that are formed become neutral again they produce light and that's what you see.

That's the light that you see in the spark.

And so sparks will occur typically at the -- at sharp points -- at areas where the curvature is strong, whereby the radius is very small, that's where the electric fields are the highest.

How strong should the electric field be?

Well, we can make a back of the envelope calculation.

If you take air of 1 atmosphere, dry air, at room temperature, then the -- the electron on average, on average, will have to travel about 1 micron, which is 10 to the -6 meters, between the collisions with the molecules, it's just a given.

On average.

Sometimes a little more, sometimes a little less.

Because it's a random process of course.

To ionize nitrogen, to ionize oxygen, takes energy.

To ionize an oxygen molecule takes twelve-and-a-half electron volts.

And to ionize nitrogen takes about 15 electron volts.

What is an electron volt?

Well, an electron volt is a teeny weeny little amount of energy.

It's 1.6 times 10 to the -19 joules.

Electron volt is actually a very nice unit of energy.

Because once you have an electron and it moves over a potential difference of one volt, it gains in kinetic energy, that's the definition of an electron volt, it gains 1 electron volt.

It's the charge of the electron, which is 1.6 times 10 to the -19 coulombs, multiplied by 1 volt.

And that gives you then the energy, 1 electron volt.

And so what it means then -- let's assume that this number is 10 electron volts.

We only want a back of the envelope calculation.

So we want the electron to move over a potential difference delta V which is roughly 10 volts and we want it to do that over a distance delta X which is 10 to the -6 meters, that's your 1 micron.

And if that happens you'll get this enough kinetic energy in the electron to cause an ion.

So what electric field is required for that, that is delta V, the potential difference, divided by the delta X, so that is 10 divided by 10 to the -6, so that's about 10 to the 7 volts per meter.

That's a very strong electric field.

In reality when we measure the electric fields near breakdown, it is more like 3 million volts per meter.

But it's still very close.

This was only a back of the envelope calculation.

So very roughly at 1 atmosphere air, room temperature, when the air is dry, we get electric breakdown at about 3 million volts per meter.

When the ions neutralize you see light, that's why sparks can be seen.

They heat the air, they produce a little pressure wave, so you can also hear noise.

If you had two parallel plates and you would bring those plates closely together and suppose they had a potential difference of 300 volts, then you would reach an electric field of 3 million volts per meter when the distance D is about one tenth of a millimeter.

So that's when you expect spontaneous discharge between these two plates.

In practice however it probably will happen when the plates are further apart than one tenth of a millimeter.

And the reason for that is that there is no such thing as perfect plates.

The plates have imperfections.

That means there are always areas on the plate which are not flat, which are a little bit like what you see there, small radius, and that's of course where the electric field then will be larger and that's where the discharge will occur first.

However, if you touch the doorknob and you get a spark, you feel a spark, and you look at the spark and you see that when you're 3 millimeters away from the doorknob that the spark develops, you can s- pretty sure that the potential difference between you and the door was of the order of 10000 volts, several thousand volts, at least.

Because over 3 millimeters it requires 10000 volts to get the 3 million volts per meter.

When you comb your hair or when you take your shirt off you get little sparks, you can hear them and if it's dark you can see them, and you can be sure that at the sharp ends of this hair, of the fabric, that you have developed electric fields of the order of 3 million volts per meter.

And then you get the automatic breakdown.

Now of course high voltage alone doesn't necessarily kill you.

What -- what -- what matters is not so much the voltage to get killed but it's the current that goes through you.

And current is charge per unit time.

And so in SI units it would be coulombs per second.

For which we write a capital A which stands for Ampere, the man who did a tremendous amount of research in this area, A Frenchman.

And so if you touch the doorknob the instantaneous current may actually be quite high.

It may be an ampere even, but it may only last for 1 millisecond.

And so that's not going to kill you.

We all know that when you comb your hair that you don't die and you also know that when you take your shirt off even though you may hear the sparks that that's not lethal.

So maybe in a future lecture we can discuss in some more details what it does take to actually execute someone electrically which is very unpleasant but nevertheless we would have to evaluate how long the current should last, how strong the current should be and then also during which parts of the body the current would cause lethal reactions.

So I want to be a little bit more quantitative now uh and deepen our knowledge of the Van de Graaff.

Slowly we're going to understand how the Van de Graaff works.

And today I want to calculate with you how much charge we can put on the Van de Graaff and what the maximum potential is at the surface.

If we charge up the Van de Graaff, with charge Q, then the potential of the surface is an equipotential, is Q divided by 4 pi epsilon 0 R.

And the electric field right here at the surface would be Q divided by 4 pi epsilon 0 R squared.

So in this case of spherical symmetry we have that the potential V equals E times R.

But we know that E cannot exceed 3 million volts per meter.

And so that gives you now a limit on the potential that we can give the Van de Graaff.

So if you substitute in here 3 million volts per meter you can calculate what potential you can maximally reach for a given sphere with a given radius.

And if we here have the radius and we here have the voltage, then if the radius of the sphere were 3 millimeters then you could not exceed a voltage of 10 kilovolts.

If you did you would get this automatic electric breakdown.

You would get a spark.

If you have a sphere of 3 centimeters that would be 100 kilovolts and our Van de Graaff, which has a radius of 30 centimeters, would therefore be 1 million volts.

And you could not exceed that.

And in practice in fact this one doesn't even make it to 1 million volts.

The sphere is not perfect.

There are imperfections of the sphere.

There are areas which have so-to-speak sharp points and so we won't make it to 1 million volts.

We get a breakdown maybe at a few hundred thousand, maybe 300000 volts.

You can now also calculate what the maximum charge is on the Van de Graaff.

Because if the maximum potential is 300000 volts, you know the radius is .3 meters, so you can calculate now what the maximum charge is that you can put on the Van de Graaff using that equation, will give you 10 microcoulombs.

And so the maximum potential for our Van de Graaff is of the order of 300000 volts.

So this gives you now a feeling, a quantitative feeling, for numbers, for what the -- can I put this down?

So that gives you an idea of what our Van de Graaff can do, and later we will understand how the charge gets there.

But at least you have some feeling now for potentials, and for the charges that are involved.

If here's my Van de Graaff and I approach the Van de Graaff with a sphere which is connected to the earth and if this Van de Graaff had positive charge on it then the sphere will become negatively charged through induction and so you get field lines which go from the Van de Graaff to this object, always perpendicular to the equipotentials, so they go like this, and so the electric field here will probably be the strongest, and so the spark will then develop between this sphere and the Van de Graaff provided that you were close enough.

So that you do achieve a electric field close to this sphere of about 3 million volts per meter.

And I will show you that later, you will see more sparks today than you've ever seen before in your life, but I want you to appreciate a little bit more about the sparks about lightning before uh I demonstrate that.

So you get a little bit more out of it.

If I approach the Van de Graaff not with the sphere but I would walk to the Van de Graaff being very courageous like this, I'm also a pretty good conductor, I'm also connected with the earth, then the chances are that the spark would develop first between my nose and the Van de Graaff, because that is the smallest curve, the sharpest curvature, the smallest radius, or certainly my head, would be a good candidate for being hit first.

If I approach the Van de Graaff like this with my hand stretched, then chances are of course that the sparks will first develop between my fingertips.

Because it's a very small radius and they're very close to the VandeGraaff, and so that's where the discharge will occur.

So before we will enjoy some of this, you will enjoy it, I will enjoy it less, um I want to talk a little bit about lightning with you first.

Because what you're going to see in a way is a form of lightning.

There are 400000 thunderstorms every day on average on earth.

400000 thunderstorms.

There are about 100 lightning flashes every second.

The top of a thundercloud becomes positive and the bottom becomes negative.

The physics of that is not so easy, and probably incomplete, and I will not go into the details of the physics, but it does have to do with the flow of water drops.

They become elongated, they can become charged because of friction, and they can break off, and they can transport charge.

I will simply give you some facts.

And so I will accept the fact that the cloud is going to be charged.

This is the cloud.

Positive at the top, negative at the bottom.

And here is the earth.

Because of induction, the earth of course will therefore become positively charged here, and so we're going to see field lines, electric field lines, which go from the earth to the cloud, always perpendicular to the equipotentials, something like this.

I'll give you some dimensions, uh this may be something like 5 kilometers, this vertical distance D is about 1 kilometer.

These are typical numbers, of course, it can vary enormously from thunderstorm to thunderstorm.

And this height is something typically like 10 kilometers.

And this allows us now to make some very interesting calculations to get some feeling for the potential difference between the cloud and the earth.

That's the first thing we can do.

If we make the simplifying assumption that the electric field is more or less constant here, it's like having two parallel plates, where the electric field is constant between them, then the potential difference delta V between the bottom of the cloud and the earth, is simply the electric field times the distance D.

So this becomes E times D.

But if the breakdown occurs at 3 million volts per meter -- by the way that's dry air, when it -- when there is a thunderstorm it's probably not so dry, but let's take the 3 million volts per meter, so we get 3 times 10 to the 6, that is for E, and the distance between the cloud and the earth let's take 1 kilometers.

So that's 10 to the 3rd meters, so we get of the order of 3 billion volts between the earth and the clouds.

And the values that are typically measured are several hundred million to 1 billion volts, so it is not all that different.

You expect that the potential is probably less than what we have calculated because clearly uh these are not flat surfaces, there are trees, here on the ground, there are buildings on the ground, which are like sharp points, where the electric field will be locally higher, and so you will get a discharge at these sharp points first.

And that means the potential difference between the cloud and the earth could then be less than the 3 billion that we have calculated here.

It's only a back of the envelope calculation.

The details of the physics of the discharge very complicated.

But I want to share with you some facts without giving detailed explanations.

The start of the lightning begins when electrons begin to flow from the cloud to the earth.

They form a funnel, which is about 1 to 10 meters in diameter and we call that the step leader.

The step leader moves about 100 miles per second and so it comes down in about 5 milliseconds.

5 milliseconds from here to here and it takes about half a coulomb to the earth.

Half a coulomb, for about 5 milliseconds, that means the current is about 100 amperes.

The step leader creates a channel of ionized air, full of ions and full of electrons, which is an extremely good conductor.

And with -- when this step leader reaches the ground there is this highly conductive channel and the electrons can now very quickly flow from this channel to the ground.

And that starts first right here at the surface of the earth.

That's where the electrons will first go to the earth.

And then successively electrons which are higher up in the channel will make it down to the earth.

And so you're going to see electrons going through the channel to the earth but first the electrons are closer to the earth than the electrons farther away and then even farther away.

And this is actually where most of the action occurs.

The current is now enormously high, 10000 to some 100000 amperes, and you heat the air, get a tremendous amount of light, the ions recombine and you get pressure, heat can produces pressure, and there comes your thunder.

And so most of the action is not in the step leader but is in the second phenomenon, which we call the return stroke.

Which is from the earth to the cloud.

And the speed of that return stroke is about 10 to 20 percent of the speed of light.

During the return stroke there is about 5 coulombs exchange between the cloud and the earth, and 5 coulombs is a sizable fraction of the total charge that was on the cloud -- on the cloud the first place -- to start with.

After a return stroke, maybe 20 milliseconds later, this whole process can start again.

You can get a step leader.

And you can get the return stroke.

However, the step leader will now follow exactly the same path that was made before because that's where the air is ionized so that's where the conductivity is very high, so that's the easiest way to go.

And this process can recur 5, 10, maybe 15 times.

So what a- appears to you as one lightning bolt in fact could be 10 flashes back and forth between the cloud and the earth.

And the -- the real light is not in the step leader, that's very little light, but the real light is in the return strokes.

So 10 return strokes, which may be 20, 30, 40 milliseconds apart, appear to you and to me only as one flash, which would take place maybe in as little as a tenth of a second.

And during these 5 or 10 return strokes you exchange between the cloud and the earth maybe a total of 25 to 50 coulombs, and that of course will lower the potential difference.

And if the potential difference becomes too low then the process stops.

You have to wait now for the clouds to charge up again.

And then lightning will strike again.

And that can take anywhere from maybe 4, 5, 10, 20 seconds.

And then you get another lightning bolt.

The study of these -- of this process, of the step leader and of the return stroke, can be done with a camera, which is called the Boys camera.

Let me first explain to you in detail -- in principle how it works.

If this is the area on the film that is exposed by your lens suppose that I move the film at a very high speed to the left and suppose the step leader comes down and it sees some light from the step leader, then I may see on the film this.

Some light.

And from here to here would then be the 5 milliseconds which it takes the step leader to go from the cloud to the earth.

Now the return stroke takes place with way higher speed and so I see a tremendous amount of light because there's a lot of light in the return stroke.

And of course this is very steep.

Because it goes 100 times faster up than the step leader came down.

And so you can measure these times and so you can get the speed of the return stroke.

And then later in time, maybe 30, 40 seconds later, on the film, you may see another return stroke.

And you may see another one.

And so you can see then how long the time was between the return strokes and you can also calculate their speeds.

With a real camera it's not really the film that is moving but it is the -- the lens that is moving, and the way these pictures are taken, and I will show you one, is if this is photographic plate, then it is the camera that moves over the plate with a um very high speed, about 3000 revolutions per minute, and so you would get these -- this information then not horizontally but you get it spread out over the film.

But you get the same information, you can calculate speeds and times.

During the past decade, new forms of lightning have been discovered which occur way above the clouds.

Way higher up.

Red colors have been seen.

Red sprites they are called.

And also blue jets.

The light is very faint and it occurs only for a very short amount of time.

It's very difficult to photograph.

I have not been able to get good slides for today.

However, I did see some pictures on the Web.

And when you log into the Web, when you visit the Web 8.02 which you should, then I give you directions how to access slides pictures of the red sprites and of the blue jets.

The physics of that is not very well understood.

It's being researched very heavily.

But it's way above the clouds.

There are also other forms of electric breakdown, of discharge.

They are different in the sense that it's not an individual spark.

But there is a continuous flow of -- of -- of charge.

It occurs always from very sharp points.

So there is a continuous current actually going on.

And some of that you may have seen but you may not remember when we used a carbon arc here.

We had two carbon arcs, two carbon rods, and we had a potential difference between them and we got a discharge between them which caused a tremendous amount of light, which we used for projection purposes.

So a carbon arc discharge is such a form of discharge whereby you have a continuous current.

It's not just sparks.

If you take grass or trees or brushes for that matter, with thunderstorm activity, they can go into this discharge at their sharp tips.

And we call this brush discharge, we call it St.

Elmo's fire, it's all the same thing, it's also called corona discharge.

I normally call it corona discharge.

It produces light because the ions when they neutralize produce light.

Heat makes sound, pressure, and so you can hear this cracking noise of the corona discharges.

An airplane that flies or a car that drives, there is friction with the air, and any form of friction can charge things up.

And so it's not uncommon at night that you can see this corona discharge from the tip of the wings of an airplane.

I've also seen it from cars.

Corona discharge from cars.

Which charge themselves up simply by driving through the air.

The air flow would charge them up.

You can hear it, cracking, and you can see it sometimes if it's dark enough, you see some light.

In general it's bluish light.

Something completely on the side, going back to the lightning bolts, lightning bolts, the discharge, the moving electrons, can cause radio waves.

And these radio waves you can receive on your car radio.

And all of you have experienced this.

Driving around, lightning very far away, you can hear it on the radio.

So that's telling you that there is lightning going on somewhere.

After a thunderstorm, something that many of you may not have experienced because in the cities there is always -- always exhaust from cars, that spoils everything, but when you're out in the country after a thunderstorm there's a very special smell in the air.

I love it.

And that's ozone.

O2, O2 in lightning becomes O3.

And O3 has a wonderful smell, and you can really smell that.

It's very typical.

I hope that most of you sooner or later in life will have that experience.

Go to the country after a thunderstorm and you can really smell this ozone.

Let's now look at some slides.

The first slide that you will see is one very classic slide made by Gary Ladd, at Kitt Peak Observatory in Arizona, uh what I like about this is that uh these are the observatories, the telescopes, in the domes, and of course when you're an astronomer, this is the kind of weather that you can do without.

But nevertheless it happens.

Uh you see here return strokes, the light is definitely due to the return strokes, it's very bright.

These are step l- leaders that never made it to the earth, and if a step leader doesn't make it to the earth you don't get a return stroke and so the light as you can see here is much less.

And what you think here is only one bolt is probably at least 10, 5 to 10, maybe 15, flashes.

Return strokes.

All right next slide please.

Here you see the result of a Boys camera exposure.

For those of you who are sitting in front you can recognize maybe the Empire State Building here.

And the Empire State Building is hit here by lightning at the very tip, that's the sharp edge, that's where you expect it to be hit.

This is not taken when the camera was rotating.

This is just the exposure the way you and I would see it.

Not moving camera but here you see the result of the rotating Boys camera.

And this is the same flash.

So here you see the return stroke, the -- the light from the step leader is too faint.

You can't see that.

So here is the return stroke and then this time separation may be 30 or 40 milliseconds, see another stroke, you see another one, and another one, so there's 6 here, looks like you see a double one here.

And so you have 6 or 7 of these return strokes.

And this is the way that you can study speeds and how much charge actually is exchanged between these uh between the clouds and in this case the Empire State Building.

Uh the next slide shows you a corona discharge in the laboratory this is a high voltage supply with a very sharp tip -- tip here at the end, the sharp point, and here you see not individual sparks, you don't call this lightning but this is what you would call the St.

Elmo's fire, the corona discharge is bluish light.

And in fact when you are close to this power supply you can also smell the ozone.

It also produces locally ozone.

And you can see it.

If you make it dark in the laboratory you can see some bluish light.

Uh when I was a graduate student I had to build power supplies, high voltage power supplies, and I remember when my soldering job was not a very good job that means when I take the solder ironing off then I could draw a little sharp point, the solder, and that would then later cause me problems with corona discharge, that means I would have to redo the soldering so that the radius of the solder joint would become larger, so no sharp points.

That's enough for the slides right now.

Benjamin Franklin invented the lightning rod.

His idea was that through the lightning rod you would get a continuous discharge, corona discharge, between the cloud and the building.

And therefore you would keep the potential difference low.

And so there would be no danger of lightning.

And so he advised King George the Third to put these sharp points on the royal palace and on uh powder houses, ammunition, storage places for ammunition.

There was a lot of opposition against Franklin.

Uh they argued that uh a lightning rod will only attract lightning.

And that the effect of the discharge, lowering the potential difference, would be insignificant.

But nevertheless the King followed Franklin's advice and after the sharp rods, the lightning rods, were placed, there was a lightning bolt that hit one of the ammunition places at Pearl Fleet, but there was very little damage.

And so we now know that on the one hand the discharge is indeed insignificant.

And so the opposition was correct.

And in fact you do attract lightning, unlike what Franklin had hoped for.

However, if your lightning rod is thick enough that it can handle the high current, which is 10000 or 100000 amperes, then the current will go through the lightning rod and therefore there will not be an explosion.

So it will not hit the building.

So it will be confined to the lightning rod.

And so it worked but for different reasons than Franklin had in mind, but he had the right intuition.

Was a very great scientist, and great statesman.

And so his lightning rod survived up to today.

So now I want to return to the Van de Graaff and show you some of the things that we have discussed.

And the first thing that I would want to do is create some sparks.

Lightning.

I run the Van de Graaff and I will approach it with this small sphere, small radius, and as I come closer and closer, the electric field will build up here and then I would predict that if sparks fly over, that they would go between the Van de Graaff and this uh this sphere.

This sphere is grounded.

And so any current that will flow will flow not through Walter Lewin but will go through the ground, so there's no danger that anything will happen to me.

At least not yet.

You already hear some cracking noise.

That means there are already sparks flying around inside there.

It's very hard to avoid, there are always some sharp edges in there that we cannot remove.

This is not an ideal instrument.

But I still think I will be able to show you some lightning.

By coming closer.

There we go.

So what you think is only one spark may well be several like these return strokes, the way I described with lightning.

So what you're seeing here now is that the electric field locally has become larger than 3 million volts per meter and then you're going to this discharge phenomenon that we described, and that gives you then -- that gives you the lightning.

What I will do now is I would like you to experience -- although it may not be so fascinating for you -- to experience a corona discharge between a very sharp point that I have here, extremely sharp, and the Van de Graaff.

And the only way that I can convince you that there is indeed going to be a discharge between this point and the Van de Graaff is by approaching the Van de Graaff and this cracking noise that you hear now will disappear.

And the reason why it will disappear is that if I get a corona discharge between the tip and the Van de Graaff it will drain current, it will lower the potential and so that cracking noise will disappear.

So the sparks which are now flying over will not fly over anymore.

You will not be able to see the light.

It's -- there's too much light here.

Although I can probably see at the tip here this blue light.

So I'm going to approach the Van de Graaff now.

It's almost as if I had a lightning rod and I'm not worried at all because if any current starts flowing it goes through this rod, which is like a lightning rod to the earth.

So I'm not worried at all.

I just am very brave, very courageous, approaching the V- the Van de Graaff, and I want you to listen to that cracking noise.

That cracking noise will disappear when I'm going to be -- draw a current through this sharp point.

Oh, boy, there I go.

And the cracking stops.

And I can actually see here some glowing discharge, bluish.

Will be impossible for you to see.

I can come closer, I'm not worried.

And so I'm draining charge now off the Van de Graaff thereby lowering the potential of the Van de Graaff and so these crazy sparks that occur here can no longer occur.

But now they will.

Can you hear them?

And now you can't.

If I were crazy then I would develop a corona discharge between the Van de Graaff and myself.

One way I could do that is by approach it with my fingertips as I mentioned earlier, but that may be a little bit too dangerous because I may draw a spark, I may be hit by lightning, which is the last thing that I would want today.

However, a corona discharge using these tinsels may be less dangerous.

So I get a continuous flow of current which now unfortunately doesn't go through the lightning rod but now it goes straight through my body.

And I can assure you that I can feel that.

It's probably a very low current.

It may be only a few microamperes.

But it's not funny.

It's not pleasant.

But anything for my students, what the hell.

There we go.

Ya ya ya ya ya.

You see tinsels, I'm now in a corona discharge and I feel the current through my fingers, it's a continuous discharge now.

This is St.

Elmo's fire.

You can't h- ah, there was lightning.

Boy, you got something for your 27000 dollars.

Oh, man.

OK.

So you saw both corona discharge and you saw lightning.

Boy, you were luckier than the -- than the first class by the way.

Clearly lightning can be dangerous, lightning can cause a fire, it can excite, it can explode fumes, if you gas your car just the flow of gasoline can charge up the nozzle, friction can charge things up, that's why the nozzle is always grounded, because a spark could cause a major explosion.

If you fill a balloon with hydrogen then the flow of hydrogen is friction, can charge up the balloon and a spark can then ignite the hydrogen.

And this has led to a classic tragic accident, it's a long time ago.

But it's so classic that I really have to show this to you.

Hitler was very proud of his large airships.

They're named after Graf Zeppelin the Germans called them the Zeppelins, we call them dirigibles or blimps.

And one of the largest ones that Hitler's Germany ever built was the Hindenburg, 803 feet long and 7 million cubic feet of hydrogen.

And the Germans couldn't fill their Zeppelins with helium because they didn't have helium.

And the Americans were not going to sell them helium, for very good reason.

And so they had to fill them with hydrogen.

And so the Hindenburg which was the name of this Zeppelin came over in May, 1937 and when it arrived at Lakehurst in New Jersey it started a gigantic fire.

It came over in 35 hours trans-Atlantic and you see here the explosion.

May 6 at 7:25 in the afternoon.

There were 45 passengers on board and 35 died in this fire.

The speculation was that this may have been sabotage.

It's still quite possible.

Although the official inquiry board concluded that it was St.

Elmo's fire, that as the uh ship moored on this mast here, that a spark flew over and that that caused the uh the explosion, the fire.

And it was the end of the dirigibles for Germany.

Napoleon, also not the nicest man on earth, uh had the suspicion when many of his soldiers got sick in Egypt that this was the result of marsh gas.

And they suspected that this bad air that they could smell when they were near marshes that that was the cause of the disease, bad air in French is mal air, and so they called the disease malaria.

And so the way that they tested the air to make sure that the soldiers wouldn't get malaria was to build a small gun which was like so, this was a conducting barrel.

And they would let some of this marsh gas in the gun and put a cork on here, close it off, and here was a sharp pin, this pin was completely insulated from the barrel, the conducting barrel, and then they would put some charge on here, so that the spark would fly over there.

This is really the precursor of the spark plug that we have in our cars.

It's no different.

And so if indeed there was then this marsh gas in there, there might be an explosion and that was a warning then that um there may be danger for the soldiers.

Well, this morning I was walking through the building and I was in Lobby 7 and I smelled some funny, it was a funny smell, and I was just wondering whether perhaps, who knows, at MIT anything can happen, whether uh there was some uh some uh gas there that shouldn't be there.

And so I brought my uh my special gun which is here, which is uh built after Napoleon and uh you see here this uh little sphere and I opened up the cork here and I let some of that air in, Building 7, and then I decided that we, you and I would do the test and see whether perhaps there was some uh some gas there that uh may cause some danger.

So I would have to cause a discharge then inside the -- the barrel here.

I can try to do that by combing my hair uh but that may not be sufficient amount of charge so I can always make sure that there will be a spark inside that gun and use this -- this disk.

Which has a little bit more charge on it.

So here is then this uh Lobby 7 gas inside.

Now of course there's one possibility that there was nothing wrong with the air, in which case you will see nothing.

And there is another possibility that the air wasn't kosher enough and that you may see here small bloop and since it's going to be very small at best you have to be very quiet otherwise you won't hear anything.

And so let's first try now with my comb.

I have my comb here.

To see whether I can generate a spark inside this barrel and that may not work because I'm not sure that I get enough charge on this comb.

No, that doesn't work at all.

Well, let's see whether we can use this instrument.

I sure hope that we won't get malaria.

See you tomorrow.