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8.02 Electricity and Magnetism, Spring 2002
Transcript – Lecture 8

Electric fields can induce dipoles in insulators.

Electrons in insulators are bound to the atoms and to the molecules, unlike conductors, where they can freely move, and when I apply an external field -- for instance, a field in this direction, then even though the molecules or the atoms may be completely spherical, they will become a little bit elongated in the sense that the electrons will spend a little bit more time there than they used to, and so this part becomes negatively charged and this part becomes positively charged, and that creates a dipole.

I discussed that with you, already, during the first lecture, because there's something quite remarkable about this, that if you have an insulator -- notice the pluses and the minuses indicate neutral atoms -- and if now, I apply an electric field, which comes down from the top, then, you see a slight shift of the electrons, they spend a little bit more time up than down, and what you see now is, you see a layer of negative charge being created at the top, and a layer of positive charge being created at the bottom.

That's the result of induction, we call that also, sometimes, polarization.

You are polarizing, in a way, the electric charge.

Uh, substances that do this, we call them dielectrics, and today, we will talk quite a bit about dielectrics.

The first part of my lecture is on the web, uh, if you go to 8.02 web, you will see there a document which describes, in great detail, what I'm going to tell you right now.

Suppose we have a plane capacitor -- two planes which I charge with a certain potential, and I have on here, say, a charge plus sigma and here I have a charge minus sigma.

I'm going to call this free -- you will see, very shortly why I call this free -- and this is minus free.

So there's a potential difference between the plate, charge flows on there, it has an area A, and sigma free is the charge density, how much charge per unit area.

So we're going to get an electric field, which runs in this direction, and I call that E free.

And the distance between the plates, say, is D.

So this is given.

I now remove the power supply that I used to give it a certain potential difference.

I completely take it away.

So that means that this charge here is trapped, can not change.

But now I move in a dielectric.

I move in one of those substances.

And what you're going to see here, now, at the top, you're going to see a negative-induced layer, and at the bottom, you're going to see a positive-induced layer.

I called it plus sigma induced, and I call this minus sigma induced.

And the only reason why I call the other free, is to distinguish them from the induced charge.

This induced charge, which I have in green, will produce an electric field which is in the opposite I- direction, and I call that E-induced.

And clearly, E free is, of course, the surface charge density divided by epsilon 0, and E induced is the induced surface charge density, divided by epsilon 0.

And so the net E field is the vectorial sum of the two, so E net -- I gave it a vector -- is E free plus E induced, vectorially added.

Since I'm interested -- I know the direction already -- since I'm interested in magnitudes, therefore the strength of the net E field is going to be the strength of the E fields created by the so-called free charge, minus the strength of the E fields created by the induced charge, minus -- because this E vector is down, and this one is in the up direction.

And so, if I now make the assumption that a certain fraction of the free charge is induced, so I make the assumption that sigma induced is some fraction B times sigma free, I just write, now, and I for induced and an F for free.

B is smaller than 1.

If B were .1, it means that sigma-induced would be 10% of sigma free, that's the meaning of B.

So clearly, if this is the case, then, also, E of I must also be B times E of F.

You can tell immediately, they are connected.

And so now I can write down, for E net, I can also write down E free times 1 minus B, and that 1 minus B, now, we call 1 over kappa.

I call it 1 over kappa, our book calls it 1 over K.

But I'm so used to kappa that I decided to still hold on to kappa.

And that K, or that kappa, whichever you want to call it, is called the dielectric constant.

It's a dimensionless number.

And so I can write down, now, in general, that E -- and I drop the word net, now, from now on, whenever I write E, throughout this lecture, it's always the net electric field, takes both into account.

So you can write down, now, that E equals the free electric fields, divided by kappa, because 1 minus B is 1 over kappa.

And so you see, in this experiment that I did in my head, first, bringing charge on the plate, certain potential difference, removing the power supply, shoving in the dielectric that an E field will go down by a factor kappa.

Kappa, for glass, is about 5.

That will be a major reduction, I will show you that later.

If the electric field goes down, in this particular experiment, it is clear that the potential difference between the plates will also go down, because the potential difference between the plates, V is always the electric field between the plates times D.

And so, if this one goes down, by a factor of kappa, if I just shove in the dielectric, not changing D, then, of course, the potential between the plates is also going down.

None of this is so intuitive, but I will demonstrate that later.

The question now arises, does Gauss's Law still hold?

And the answer is, yes, of course, Gauss's Law will still hold.

Gauss's Law tells me that the closed loop -- closed surface, I should say, not closed loop -- the closed surface integral of E dot dA is 1 over epsilon times the sum of all the charges inside my box.

All the charges! The net charges, that must take into account both the induced charge, as well as the free charge.

And so let me write down here, net, to remind you that.

But Q net is, of course, Q free plus Q induced.

And I want to remind you that this is minus, and this was plus.

The free charge, positive there, is plus, and at that same plate, if you have your Gaussian surface at the top, you have the negative charged Q induced.

And so therefore, Gauss's Law simply means that you have to take both into account, and so, therefore, you can write down 1 over epsilon 0, times the sum of Q free, but now you have to make sure that you take the induced charge into account, and therefore, you divide the whole thing by kappa.

Then you have automatically taken the induced charge into account.

So you can amend Gauss's Law very easily by this factor of kappa.

Dielectric constant is dimensionless, as I mentioned already, it is 1, in vacuum, by definition.

1 atmosphere gases typically have dielectric constant just a hair larger than 1.

We will, most of the time, assume that it is 1.

Plastic has a dielectric constant of 3, and glass, which is an extremely good insulator, has a dielectric constant of 5.

If you have an external field, that can induce dipoles in molecules -- but there are substances, however, which themselves are already dipoles, even in the absence of an electric field.

If you apply, now, an external field, these dipoles will start to align along the electric field, we did an experiment once, with some grass seeds, perhaps you remember that.

And as they align in the direction of the electric field, they will strengthen the electric field.

On the other hand, because of the temperature of the substance, these dipoles, these molecules which are now dipoles by themselves, through chaotic motion, will try to disalign, temperature is trying to disalign them.

So it is going to be a competition, on the one hand, between the electric field which tries to align them and the temperature which tries to disalign them.

But if the electric field is strong, you can get a substantial amount of alignment.

Uh, permanent dipoles, as a rule, are way stronger than any dipole that you can induce by ordinary means in a laboratory, and so the substances which are natural dipoles, they have a much higher value for kappa, a much higher dielectric constant that the substances that I just discussed, which themselves, do not have dipoles.

Water is an example, extremely good example.

The electrons spend a little bit more time near the oxygen than near the hydrogen, and water has a dielectric constant of 80.

That's enormous.

And if you go down to lower temperature, if you take ice of minus 40 degrees, it is even higher, then the dielectric constant is 100.

I'm now going to massage you through four demonstrations, four experiments.

One of them, you have already seen.

And try to follow them as closely as you can, because if you miss one small step, then you miss, perhaps, a lot.

I have two parallel plates which are on this table, as you have seen last time, and I have, here, a current meter, I put it -- an A on there, that means amp meter.

And the plates have a certain separation D.

I'm going to charge this capacitor up by connecting these ends to a power supply, and I'm going to connect them to 1500 volts.

I'm -- I'm already going to set my light, because that's where you're going to see it very shortly.

I'm going to start off with a distance D -- so this is going to be my experiment one -- with a distance D of 1 millimeter.

And the voltage V always means the voltage the -- the -- the potential difference between the plates is going to be 1500 volts.

Forgive me for the two Vs, I can't help that.

This means, here, the potential difference, and this is the unit in volts.

Once I have charged them, I disconnect -- this is very important -- I disconnect the power supply, for which I write PS.

That's it.

So the charge is now trapped.

As I charge it, as you saw last time, you will see that the amp meter shows a short surge of current, because, as I put charge on the plates, the charge has to go from the power supply to the plates, and you will see a short surge of current which will make the handle -- the hand of the power su- of the amp meter, as you will see on the -- on the wall there -- go to the right side, just briefly, and then come back.

This indicates that you are charging the plates.

Now, I'm going to open up the gap -- so this is my initial condition, there is no dielectric -- and now I'm going to go D to 7 millimeters.

And this is what I did last time.

The reason why I do it again, because I need this for my next demonstration.

If I make the distance 7 millimeters, then the charge, which I call now, Q free, but it is really the charge on the plates, is not going to be -- is not going to change, it is trapped.

So there can be no change when I open up the gap.

That means the amp meter will do nothing, you will not see any charge flow.

The electric field E is unchanged, because E is sigma divided by epsilon 0.

If sig- if Q free is not changing, sigma cannot change.

So, no change in the electric field.

But the potential V is now going to go up by a factor of 7, because V equals E times D.

E remains constant, D goes up, V has to go up.

And this is what I want to show you first, even though you have already seen this.

And I need the new conditions for my demonstration that comes afterwards.

I'm going from 1500 volts to about 10000 volts, it goes up by a factor of 7.

And you're going to see that there.

There you see your amp meter.

I'm going to -- you see the, um, this is this propeller volt meter that we discussed last time, and here you see the -- the plates.

They're 1 millimeter apart now, very close.

And I'm going to charge the plates, I will count down, so you keep your eye on the amp meter, three, two, one, zero, and you saw a current surge.

So I charged the capacitor.

It is charged now.

The volt meter doesn't show very much, 1500 volts.

Maybe it went up a little, but not very much, but now I'm going to increase the gap to 10 -- to 7 millimeters, and look that the amp meter is not doing anything, the charge is trapped, so there is no charge going to the plates, but look what the volt meter is doing.

It's increasing the voltage, it's not approaching almost 10000 volts, although this is not very quantitative, and now I have a gap of about 7 millimeters, and that's what I wanted.

We've seen that the plates on the left side here are now farther apart than they were before.

So that is my demonstration number one, a repeat of what we did last time.

So now comes number two.

So now my initial conditions are that V is now 10 kilovolts, so that's the potential difference between the plates that I have now, and D is now 7 millimeters, and I'm not going to change that.

At this moment, kappa is 1.

But now, I'm going to insert the dielectric.

So I take a piece of glass, and I'll just put it into that gap.

Q free cannot go anywhere, because I have disconnected the power supply.

So Q free, no change.

If there is no chee- no change in the free charge, the amp meter will do nothing.

So as I plunge in this dielectric, you will not see any reading on the amp meter.

But, as we discussed at length now, the electric field, which is the net electric field, will go down by that factor kappa.

That's what the whole discussion was all about.

That's going to be a factor of 5.

And since the potential equals electric field times D -- but I keep D at 7 millimeters, I'm not going to change it -- if E goes down by a factor kappa, then clearly, the potential will also go down by a factor kappa.

So now you're going to see the second part, and that is I'm going -- as it is now, I'm going to plunge in this glass, the 7 millimeters thick, I put it in there, you expect to see no change on the amp meter, but you expect the voltage difference over the plates to go down by a factor of 5, so you will see that -- that the propeller volt meter will have a smaller deflection.

You ready for this?

There we go.

Now you have a smaller potential difference, but there was no current flowing to the plates or from the plates.

When I take it out again, the potential difference comes back to the 10000 volts.

So that's demonstration number two.

Now we go to number three.

But before we go to number three, I want to ask myself the question, what actually happened with the capacitance when I bring the dielectric between those plates?

Well, the capacitance is defined as the free charge divided by the potential difference over the plates.

That's the definition of capacitance.

And since, in this experiment, as you have seen, the voltage went down by a factor of kappa, the capacitance goes up by a factor of kappa, because Q free was not changing.

And so, since the capacitance, as we derived this last time for plane -- plate capacitors, I still remember, it was the area times epsilon 0 divided by the separation D -- since we now know that with the glass in place, that's -- the capacitance is higher by a factor of kappa, this is now the amendment we have to make.

To calculate capacitance, we simply have to multiply, now, by the dielectric constant of the thin layer that separates the two conductors, the layer that has thickness D that is in between the two plates.

In our case, I brought in glass.

I could write down a few equations now that you can always hold on to in your life, and you can also use them in the two demonstrations that follow.

And one is that E -- which is always the net E, when I write E it's always the net one -- equals sigma free divided by epsilon 0 times kappa.

There comes that kappa that we discussed today.

Let's call that equation number one.

The second one is that the potential difference over the plates is always the electric field between the plates times D, because the integral of E dot dL over a certain pass, is the potential difference.

That's not going to change.

And then the third one that may come in handy is the one that I have already there, C equals Q free divided by the potential difference, which, in terms of the plate area, is A times epsilon 0, divided by D, times kappa.

Let's call this equation number three.

Now comes my third experiment.

In the third demonstration, I am not going to disconnect my power supply.

So now, in number three, I start out with 1500 volts, just like we did with number one, but the power supply will stay in there throughout, never take it off.

We start with D equals 1 millimeter, just like we did in experiment one.

No glass.

I'm going to charge it up, just like I did with number one, and, of course, I will see that the amp meter will show this charge.

[clk].

See a surge of current.

Now I'm going to increase D to 7 millimeters.

Now something very different will happen from what we saw in the first experiment.

The reason is that the potential difference is going to be fixed, because the power supply is not disconnected, the power supply stays in place.

Look, now, at equation number two.

If that V cannot change, and if I increase D by a factor of 7, now the electric field must come down by a factor of 7.

And so now the electric field will come down by that factor of 7, because I go from 1 millimeter to 7 millimeters.

So now the electric field changes, because D goes up.

In case you were interested in the capacitance, the capacitance will also go down by a factor of 7, because, if you look at this equation, kappa is 1.

If I make D go up by a factor of 7, C goes down by a factor of 7.

Just look at this, simple as that.

So C must also go down by a factor of 7.

Nothing to do with dielectric.

Nothing.

And so Q free must now also go down by a factor of 7, because if the potential difference doesn't change, but if Q free goes down a factor of 7 -- or by -- if C goes down by a factor of 7, Q free must go down by a factor of 7.

This goes down by a factor of 7, this doesn't change.

So the free charge goes down by a factor of 7.

And what does that mean?

That means charge will flow from the plates, away from the plates, and so my amp meter will now -- will tell me that charge is flowing from the plates, and so that handle -- that hand there will go [wssshhht] to the left.

And so, as I open up, depending upon how fast I can do that, charge will flow from the plates, in the other direction, it -- the charge will flow off the plates, and that current meter will show you, every time that I open it a little bit [klk], it will go to this direction.

So let's do that first, no dielectric involved, simply keeping the power supply connected.

So I have to go back, first, to 1 millimeter, which is what I'm doing now, I have here this thin sheet to make sure that I don't short them out, it's about 1 millimeter, and I am going to now connect the 1500 volts, and keep it on, and as I charge it, you will see the current meter surge to the right, right?

That always means we charge the plates.

So there we go, did you see it?

I didn't see it because I had to concentrate.

Did it go like this?

Good.

So now it's charged.

We don't take this connection off, it's connected with the power supply all the time.

And now I'm going to open up, and as I'm going to open up, the potential remains the same, so this volt meter doesn't give a damn, it will stay exactly where it is, because 1500 volts remains 1500 volts, but now, we go -- as we open up, we're going to take charge off the plates and so this, I expect to go to the left.

Every time that I give it a little jerk, I do it now, it went to the left.

I go it now, again, I go to 2 millimeters, go to 3 millimeters, go to 4 millimeters, make it 5 millimeters, 5 millimeters, 6 millimeters, and I finally end up at 7 millimeters.

And every time that I made it larger, you saw the hand go to the left.

Every time I took some charge off.

So that is demonstration number three.

Why did I go to 7 millimeters?

You've guessed it! Now I want to plunge in the dielectric.

So my experiment number four, I start with 1500 volts, I start with D equals 7 millimeters, and I'm not going to change that.

There's no dielectric in place, but now, I put a dielectric in.

So kappa goes in.

What now is going to happen?

Well, for sure, V is unchanged, because it's connected with the power supply, so that cannot change.

What happens with Q free?

Look at this equation.

When I put in the dielectric, I know that the capacitance goes up by a factor of kappa.

C will go up by a factor of kappa.

If C goes up with a factor of kappa, and if V is not changing, then Q free must go up by a factor of kappa.

Follows immediately from equation three.

So this must go up by a factor of kappa.

What does that mean?

That the charge will flow through the plates.

I increase the charge on the plates, and so my amp meter will tell me that.

And so my amp meter will say, "Aha! I have to put charge on the plates," and so my amp meter will now do this.

And that's what I want to show you.

The remarkable thing, now, is that the electric field E, the net electric field E, will not change.

And you may say, "But you put in a dielectric!" Sure, I put in a dielectric.

But I kept the potential difference constant, and I kept the D constant.

And since V is always E times D, if I keep this at 1500 volts, and I keep the 7 millimeter 7 millimeters, then the net electric field cannot change, it's exactly what it was before.

That is the reason why Q free has to change, think about that.

Because you do introduce -- induce charges on the dielectric, and you have to compensate for that to keep the E field constant, and the only way that nature can com- compensate for that is to increase the charge on the plates, the free charge.

And so that's what I want to show you now, which is the last part.

So I'm going now to put in the dielectric, and what you will see, then, is that current will flow onto the plates, so the propeller will do nothing, will sit there, and you will see this one go klunk when I bring in the glass.

And then it goes back, of course.

There's only a little charge that comes off, and then it will go back.

So as I plunge it in, you will see charge flowing onto the plates.

There we go, you're ready for it?

Three, two, one, zero.

And you saw a charge flowing onto the plates.

When I remove the glass, of course, then the charge goes off the plates again, and you see that now.

I've shown you four demonstrations.

None of this is intuitive.

Not for you, and not for me.

Whenever I do these things, I have to very carefully sit down and think, what actually is changing and what is not changing?

I have no gut feeling for that.

There is not something in me that says, "Oh yes, of course that's going to happen.

Not at all.

And I don't expect that from you, either.

Then only advice I have for you, when you're dealing with these cases whereby dielectric goes in, dielectric goes in, plates separate, plates not separate, power supply connected, power supply not connected, approach it in a very cold-blooded way, a real classic MIT way, very cold-blooded.

Think about what is not changing, and then pick it up from there, and see what the consequences would be.

How can I build a very large capacitor, one that has a very large capacitance?

Well, capacitance, C, is the area, times epsilon 0, divided by D, times kappa, which your book calls K.

So give K -- make K large, make A large, and make D as small as you possibly can.

Ah, but you have a limit for D.

If you make D too small, you may get sparks between the conductors, because you may exceed the electric field, the breakdown electric field.

So you must always stay below that breakdown field, which in air, it would be 3 million volts per meter.

If you want a very large kappa, you would say, "Well, why don't you make the layer water, in between, that has a kappa of 80." Ah, the problem is that water has a very low breakdown electric field, so you don't want water.

If you take polyethylene -- I'll just call it poly here, just as abbreviation -- polyethylene has a breakdown electric field of 18 million volts per meter, and it has a kappa, I believe of 3.

Many capacitors are made whereby the layer in between is polyethylene, although mica would be really superior.

Be that as it may, I want to evaluate, now, with you, two capacitors, which each have the same capacitance of 100 microfarads.

But one of them, the manufacturer says, that you could put a maximum potential difference of 4000 volts over it, that's this baby.

And the other, I go to Radio Shack, and it says you cannot exceed the potential difference, not more than 40 volts.

Well, if I have polyethylene in between the layers of the conductors, then I can calculate what the thickness D should be before I get breakdown.

That's very easy, because V equals E D, and so I put in here, 18 million volts per meter, and I go to 4000 volts, and then I see what I am for D.

And it turns out that the minimum value for D, you cannot go any thinner, is then 220 microns, and so for this one, it is only 2.2 microns.

You can make it much thinner, because the potential difference is 100 times lower.

So you can make the layer 100 times thinner before you get electric breakdown.

I want the two capacitors to have the same capacitance.

That means, since they have the same kappa, and they have the same epsilon 0, it means that A over D has to be the same for both capacitors.

So A divided by D, for this one, must be the same as A divided by D for that one.

But if D here is 100 times larger than this one, then this A must also be 100 times larger, because A over D is constant.

So if A here is 100, then A is here 1.

But now, think about it.

What determines the volume of a capacitor?

That's really the area of the plates, times the thickness.

And if I ignore, for now, the thickness of the conducting plates, then the volume of a capacitor clearly is the product between the area and the thickness, and so it tells me, then, that this capacitor, which has 100 times larger area, is 100 times thicker, will have a 10000 times larger volume than this capacitor.

And this baby is 4000 volts, 100 microfarads, it has a length of about 30 centimeters, 10 centimeters like this, 20 centimeters high, that is about 10000 cubic centimeters.

10000 cubic centimeters.

You go to Radio Shack, and you buy yourself a 40 volt capacitor, 100 microfarads, which will be 10000 times smaller in volume.

It will be only 1 cubic centimeter.

And if I had one of them behind my ear, you wouldn't even notice that, would you?

Could you tell me what it says here?

100 microfarad.

How many volts?

40.

40 volts.

That's small.

Compared to this one, which can handle 4000 volts.

But the capacitance is the same.

So you see now, the connection with area and with thickness, by no means trivial.

All this has been very rough on you.

I realize that.

It takes time to digest it, and you have to go over your notes.

And therefore, for the remaining time -- we have quite some time left -- I will try to entertain you with something which is a little bit easier.

A little nicer to digest.

Professor Musschenbroek in the Netherlands, invented -- yes, you can say he invented the -- the capacitor.

It was an accidental discovery.

He called them a Leyden jar, because he worked in Leyden.

And a Leyden jar is the following.

This is a glass bottle, so all this is glass, that's an insulator, and he has outside the insulator, he has two conducting plates, so that's a beaker outside, and there's a beaker inside, conducting.

That's a capacitor.

Although he didn't call it a capacitor.

And so he charged these up, and so you can have plus charge here, and minus Q on the inside, and he did experiments with that.

The, um, the energy stored in a capacitor -- we discussed that last time -- equals one-half times the free charge times the potential difference, if you prefer one-half C V squared, that's the same thing, I have no problem with that, because the C is Q free divided by V, so it's the same thing.

What I'm going to do, I'm going to put a certain potential difference over a Leyden jar, I will show you the Leyden jar that we have -- you'll see there -- and once I have put in -- put on some potential difference, put on some charge on the outer surface and on the inner surface -- you can see the outer surface there, the inner one is harder to see, but I will show that later to you.

So here you see the glass, and here you see the outer conductor, and there's an inner one, too, which you can't see very well.

Once I have done that, I will disassemble it.

So I first charge it up so there is energy in there, this much energy.

And then I will take the glass out, I will put the, um, the outside conductor here the inside conductor here, I will discharge them completely.

I will hold them in my hands, I will touch them with my face, I will lick them, I will do anything to get all the charge off.

And then I will reassemble them.

Well, if I get all the charge off, all this Q free [wssshhh] goes away, there's no longer any potential difference.

When I reassemble that baby, then, clearly, there couldn't be any energy left.

And the best way to demonstrate that, then, to you, is, to take these prongs, which I have here, conducting prongs, and see whether I can still draw a spark by connecting the inner part with the outer part.

And you would not expect to see anything.

So it is something that is not going to be too exciting.

But let's do it anyhow.

So here is this Leyden jar, and I'm turning the Windhurst to charge it up.

I'm going to remove this connection, remove this connection, take this out, take this out, come on -- believe me, no charge on it any more.

This one.

It's all gone.

Believe me.

There we go.

And now let's see what happens when I short out the outer conductor with the inner conductor.

Watch it.

That is amazing.

There shouldn't be any energy on that capacitor.

Nothing.

And I saw a huge spark, not even a small one.

When I saw this first, and I'm not joking, I was totally baffled.

And I was thinking about it, and I couldn't sleep all night.

I couldn't think of any reasonable explanation.

And so my charter for you is, to also have a few sleepless nights, and to try to come up, why this is happening.

How is it possible that I first bring charge on these two plates, disassemble them, totally take all the charge off, and nevertheless, when I reassembled them again, there is a huge potential difference between the two plates, otherwise, you wouldn't have seen the spark.

So give that some thought, and later in the course, I will make an attempt to explain this.

At least, that's the explanation that I came up with, it may not be the best one, but it's the only one that I could come up with.

In the remaining 8 minutes, I want to tell you the last secret, which I owe you, of the Van de Graaff.

And that has to do with the potential that we can achieve.

Remember the large Van de Graaff?

We could get it up to about 300000 volts.

How do we charge a conducting sphere?

Well, let's start off with a -- with this hollow sphere, which is what the con- the Van de Graaff is -- and suppose I have here a voltage supply, with a few kilovolts.

I can buy that.

And I have a sphere, and I touch with this sphere, with an insulating rod, I touch the output of the kilo- the few kilovolt supply, and I bring this -- so there's positive charge on here, say -- and I bring it close to the Van de Graaff, there will be an electric field between this charged object and the Van de Graaff, and the closer I get, the stronger that electric field will be.

And when I touch the outer shell, then the charge will flow in the Van de Graaff.

I go back to my power supply, I touch again the few thousand volts, and I keep spooning charge on the Van de Graaff.

Will I be able to get the Van de Graaff up to 300000 volts?

No way, because there comes a time that the potential of this object -- which comes from my power supply -- is the same electric potential as the Van de Graaff, and then you can no longer exchange charge.

What it comes down to is that when you come with this conductor and you approach the Van de Graaff, there will be no longer any electric fields between the two.

So there will be no longer any potential difference.

So you can't transfer any more charge.

So you run very quickly into a situation which will freeze.

You cannot get it above a few thousand volts.

So now what do you do?

And here comes the breakthrough by Professor Van de Graaff from MIT, who now said, "Ah.

I don't have to bring the charge on this way, but I can bring the charge in this way." So now you go to your power supply, a few thousand volt, and you bring it inside this sphere, where there was no electric field to start with.

When you charge the outside, there's going to be an electric field from this object, and there's going to be an electric field from this object, the net result will be 0 in between.

There was no electric field inside.

If I now bring the positively charged sphere there, I'm going to get E field lines like this, problem 2-1, and so now there is a potential difference between this object and the sphere.

What I have done by moving it from here to the inside, I have done positive work without having realized it, and therefore, I have brought this potential higher than the sphere.

Now I touch the inside of the Van de Graaff, and now the charge will run on the outer shell.

And I can keep doing that.

Inside, touch.

Inside, touch.

Inside, touch.

And every time I come in here, there is no electric field in there.

So I can do that until I'm green in the face.

Well, there comes a time that I can no longer increase the potential of the Van de Graaff, and that is when the Van de Graaff goes into electric breakdown.

When I reach my 300000 volts, it's all over.

I can try to bring the potential up, but it's going to lose charge to the air.

And so that is the -- ultimately the limit of the potential of the Van de Graaff.

So how does the Van de Graaff work?

Uh, we have a belt, which is run by a motor -- here is the Van de Graaff -- and right here, through corona discharge, we put charge on the belt.

They're very sharp points, and we get a corona discharge at a relatively low potential difference, it goes on the belt, the belt goes here, and right here, there are two sharp points, which through corona discharge take the charge off.

On the inside, that's the key.

And then it goes through the dome, and then it charges up, up to the point that you begin to hear the sparks, and that you have breakdown.

And I can demonstrate that to you.

I built my own Van de Graaff.

And the Van de Graaff that I built to you is this paint can.

I'm going to charge that paint can by touching it repeatedly with a conductor, and the conductor has a -- is going to be -- yes, I'm going to touch the conductor with a few thousand volt power supply every time -- this is the power supply, turning it on now -- and you're going to see the potential of the Van de Graaff there.

Uh, that is a very crude measure for the potential on the Van de Graaff, but very crudely, when it reads 1, I have about 10000 volts -- this is the probe that I'm using for that -- 2, it's 20000 volts.

My power supply is only a few thousand volts.

But that's not very good.

Well, I will first start charging it on the outside to demonstrate to you that I very quickly run into the wall that I just described.

That if they have the same potential, then I can no longer transfer a charge.

But then I'm going to change my tactics and then I go inside.

And then you will see that it will go up further.

So let's first see what happens if I now bring charge on the outside.

There it goes.

It's about 1000 volts, about 2000 volts, 2000 volts, keep an eye on it, 3000 volts, it's heading for 3000 volts, 3000 volts, 3000 volts, 3000 volts, 3000 volts, not getting anywhere, I'm beginning to reach the saturation, maybe 3500 volts, 3.5, it's slowly going to 4, let's see whether we can get it much higher than 4, I don't think we can.

So this is the end of the story before Professor Van de Graaff.

But then came Professor Van de Graaff.

And he said, "Look, man, you've got to go inside.

Now watch it.

Now I have to concentrate on this scooping, so I would like you to tell me when we reach 5000, you just scream.

Oh, man, we already passed the 5000, you dummies! 10000, scream when you see 10000.

[crowd roars].

Scream when you see 15000.

Scream when you see 15000.

[crowd roars].

Very good, keep an eye on it, tell me when you see 20000.

[noise] I don't hear anything! [crowd roars] Now I want you tell me every 1000, because I think we're going to run into the wall very quickly.

21?

I want to hear 22.

[crowd roars].

Already at 23.

So I expect that very s- very quickly now -- [crowd roars] -- the can will go into discharge, you won't see that, but you get corona discharge, and then, no matter how hard I work, I will not be able to bring the potential up.

But let's keep going.

Are we already at 2500?

25000, sorry, 25000?

25000 volts.

25 - 6.

27.

27.

28.

28.

It looks like we are beginning to get into the corona discharge.

28! Boy, 28! That's a record.

28, keep an eye on it.

29?

29?

Whew.

You realize I'm doing all this work.

Well, I get paid for it, I -- I think I've reached the limit.

I've reached my own limit and I've reached the limit of the charging.

Now, we have 30000 volts, and we started off with only a few thousand volts.

Originally, it wasn't a very dangerous object.

But now, 30000 volts -- shall I?

OK, see you next week.