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Transcript – Lecture 4

We're going to talk about, again, some new concepts.

And that's the concept of electrostatic potential...

electrostatic potential energy.

For which we will use the symbol U and independently electric potential.

Which is very different, for which we will use the symbol V.

Imagine that I have a charge Q one here and that's plus, plus charge, and here I have a charge plus Q two and they have a distant, they're a distance R apart.

And that is point P.

It's very clear that in order to bring these charges at this distance from each other I had to do work to bring them there because they repel each other.

It's like pushing in a spring.

If you release the spring you get the energy back.

If they were -- they were connected with a little string, the string would be stretched, take scissors, cut the string they fly apart again.

So I have put work in there and that's what we call the electrostatic potential energy.

So let's work this out in some detail how much work I have to do.

Well, we first put Q one here, if space is empty, this doesn't take any work to place Q one here.

But now I come from very far away, we always think of it as infinitely far away, of course that's a little bit of exaggeration, and we bring this charge Q two from infinity to that point P.

And I, Walter Lewin, have to do work.

I have to push and push and push and the closer I get the harder I have to push and finally I reach that point P.

Suppose I am here and this separation is little R.

I've reached that point.

Then the force on me, the electric force, is outwards.

And so I have to overcome that force and so my force, F Walter Lewin, is in this direction.

And so you can see I do positive work, the force and the direction in which I'm moving are in the same direction.

I do positive work.

Now, the work that I do could be calculated.

The work that Walter Lewin is doing in going all the way from infinity to that location P is the integral going from in- infinity to radius R of the force of Walter Lewin dot dR.

But of course that work is exactly the same, either one is fine, to take the electric force in going from R to infinity dot dR.

Because the force, the electric force, and Walter Lewin's force are the same in magnitude but opposite direction, and so by flipping over, going from infinity to R, to R to infinity, this is the same.

This is one and the same thing.

Let's calculate this integral because that's a little easy.

We know what the electric force is, Coulomb's law, it's repelling, so the force and dR are now in the same direction, so the angle theta between them is zero, so the cosine of theta is one, so we can forget about all the vectors, and so we would get then that this equals Q one, Q two, divided by four pi epsilon zero.

And now I have downstairs here an R squared.

And so I have the integral now dR divided by R squared, from capital R to infinity.

And this integral is minus one over R.

Which I have to evaluate between R and infinity.

And when I do that that becomes plus one over capital R.

Right, the integral of dR over R squared I'm sure you can all do that is minus one over R.

I evaluate it between R and infinity and so you get plus one over R.

And so U, which is the energy that -- the work that I have to do to bring this charge at that position, that U is now Q one, times Q two divided by four pi epsilon zero.

Divided by that capital R.

And this of course this is scalar, that is work, it's a number of joules.

If Q one and Q two are both positive or both negative, I do positive work, you can see that, minus times minus is plus.

Because then they repel each other.

If one is positive and the other is negative, then I do negative work, and you see that that comes out as a sign sensitive, minus times plus is minus.

So I can do negative work.

If the two don't have the same polarity.

I want you to convince yourself that if I didn't come along a straight line from all the way from infinity, but I came in a very crooked way, finally ended up at point P, at that point, that the amount of work that I had to do is exactly the same.

You see the parallel with eight o one where we dealt with gravity.

Gravity is a conservative force and when you deal with conservative forces, the work that has to be done in going from one point to the other is independent of the path.

That is the definition of conservative force.

Electric forces are also conservative.

And so it doesn't make any difference whether I come along a straight line to this point or whether I do that in an extremely crooked way and finally end up here.

That's the same amount of work.

Now if we do have a collection of charges, so we have pluses and minus charges, some pluses, some minus, some pluses, minus, pluses, pluses, then you now can calculate the amount of work that I, Walter Lewin, have to do in assembling that.

You bring one from infinity to here, another one, another one, and you add up all that work, some work may be positive, some work may be negative.

Finally you arrive at the total amount of work that you have to do to assemble these charges.

And that is the meaning of capital U.

Now I turn to electric potential.

And for that I start off here with a charge which I now call plus capital Q.

It's located here.

And at a position P at a distance R away I place a test charge plus Q.

Make it positive for now, you can change it later to become a negative.

And so the electrostatic potential energy we -- we know already, we just calculated it, that would be Q times Q divided by four pi epsilon zero R.

That's exactly the same that we have.

So the electric potential, electrostatic potential energy, is the work that I have to do to bring this charge here.

Now I'm going to introduce electric potential.

Electric potential.

And that is the work per unit charge that I have to do to go from infinity to that position.

So Q doesn't enter into it anymore.

It is the work per unit charge to go from infinity to that location P.

And so if it is the work per unit charge, that means little Q disappears.

And so now we write down that V at that location P.

The potential, electric potential at that location P, is now only Q divided four pi epsilon zero R.

Little Q has disappeared.

It is also a scalar.

This has unit joules.

The units here is joules per coulombs.

I have divided out one charge.

It's work per unit charge.

No one would ever call this joules per coulombs.

We call this volts, called after the great Volta, who did a lot of research on this.

So we call this volts.

But it's the same as joules per coulombs.

If we have a very simple situation like we have here, that we only have one charge, then this is the potential anywhere, at any distance you want, from this charge.

If R goes up, if you're further away, the potential will become lower.

If this Q is positive, the potential is everywhere in space positive for a single charge.

If this Q is negative, everywhere in space the potential is negative.

Electro- electric static potential can be negative.

The work that I do per unit charge coming from infinity would be negative, if that's a negative charge.

And the potential when I'm infinitely far away, when this R becomes infinitely large, is zero.

So that's the way we define our zero.

So you can have positive potentials, near positive charge, negative potentials, near negative charge, and if you're very very far away, then potential is zero.

Let's now turn to our Vandegraaff.

It's a hollow sphere, has a radius R.

About thirty centimeters.

And I'm going to put on here plus ten microcoulombs.

It will distribute itself uniformly.

We will discuss that next time in detail.

Because it's a conductor.

We already discussed last lecture that the electric field inside the sphere is zero.

And that the electric field outside is not zero but that we can think of all the charge being at this point here, the plus ten microcoulombs is all here, as long as we want to know what the electric field outside is.

So you can forget the fact that it is a -- a sphere.

And so now I want to know what the electric potential is at any point in space.

I want to know what it is here and I want to know what it is here at point P, which is now a distance R from the center.

And I want to know what it is here.

At a distance little R from the center.

So let's first do the potential here.

The potential at point P is an integral going from R to infinity if I take the electric force divided by my test charge Q dot dR.

But this is the electric field, see, this force times distance is work, but it is work per unit charge, so I take my test charge out.

And so this is the integral in R to infinity of E dot dL -- dR, sorry.

And that's a very easy integral.

Because we know what E is.

The electric field we have done several times.

Follows immediately from Coulomb's law and so when you calculate this integral you get Q divided by four pi epsilon zero R which is no surprise because we already had that for a point charge.

So this is the situation if r, little r, is larger than capital R.

Precisely what we had before.

We can put in some numbers.

If you put in R equals R, which is ho point three meters, and you put in here the ten microcoulombs, and here the -- the thirty centimeters, then you'll find three hundred thousand volts.

So you get three times ten to the fifth volts.

If you take r equals sixty centimeters, you double it, if you double the distance, the potential goes down by a factor of two, it's one over R, so it would be a hundred and fifty kilovolts.

And if you go to three meters, then it is ten times smaller, then it is thirty kilovolts.

And if you go to infinity which for all practical purposes would be Lobby seven, if you go to Lobby seven, then the potential for all practical purposes is about zero.

Because R is so large that there is no potential left.

So if I, if I, Walter Lewin, march from infinity to this surface of the Vandegraaff, and I put a charge Q in my pocket, and I march to the Vandegraaff, by the time I reach that point I have done work, I multiply the charge now back to the potential, that gives you the work again, because potential was work per unit charge, and so the work that I have done then is the charge that I have in my pocket times the potential, in this case the potential of the Vandegraaff.

If I go all the way to this surface, which is three hundred thousand volts.

If I were a strong man then I would put one coulomb in my pocket.

That's a lot of charge.

Then I would have done three hundred thousand joules of work.

By just carrying the one coulomb from Lobby seven to the Vandegraaff.

That's about the same work I have to do to climb up the Empire State Building.

The famous MGH, my mass times G times the height that I have to climb.

So I know how the electric potential goes with distance.

It's a one over R relationship.

Now I have arrived at the Vandegraaff, I am at the surface, with my test charge, and now I go inside.

And I slosh around inside, I feel no force anymore.

There is no electric field inside.

So as I move around inside, I experience no force.

That means I do no work.

So that means that the potential must remain constant.

So the absence of an electric field here implies that the electric potential everywhere is exactly the same inside is the same as on the sphere.

Because no further work is needed in marching around with a test charge.

And so for this special case, I could make a graph of the electric potential versus R and this is then the radius of the Vandegraaff and that would be a constant all the way up to this point and then it would fall off as one over R here.

And in for the numbers that we have chosen, the potential at the maximum here would be three hundred thousand volts.

Just as when you look at maps, where you see contours of equal height of mountains, which we call equal altitudes, here we have surfaces of equipotential.

And if you had a point charge or if you had the Vandegraaff, these surfaces would be concentric spheres.

The further out you go, if the charge is positive, the lower the potential would be.

They would be nicely spherical surfaces.

Suppose now we had more than one charge, we had a plus Q one charge, and we had a minus Q two charge, for instance.

And you're being asked now what is the potential at point P.

Well, now the electric potential at point P, VP, is the potential that you would have measured if Q one had been there alone.

And you have to add the potential that you would have seen if Q two had been there alone.

Just adding work per unit charge for one with work per unit charge of the other.

And if this is negative, then this quantity is negative, and this is positive.

So when you have configurations of positive and negative charges then of course depending upon where you are in space, if you're close to the plus charge, the potential is almost certainly positive, because the one over R is huge.

If you're very close to the negative charge, again the one over R of this little charge will dominate and so you get a negative potential.

And so you have surfaces of positive potential and you have equipotential surfaces of negative potentials and so there are surfaces which have zero potential.

And they're not always very easy to envision.

But what I want to show you is some work that Maxwell himself did in figuring out these equipotentials.

And so I have here a transparency of publication by Maxwell.

You see a charge, let's assume it is plus four and plus one-- it could be minus four and minus one, but let's assume they're plus.

And you see the green lines, which we have seen before, which are the field lines.

Don't pay any attention to the green field lines now.

The red lines are equipotentials.

And you have to rotate them about the vertical, because they're of course surfaces, this is three-dimensional.

I have not drawn all the equipotential surfaces in red because they become too cluttered here.

But I've tried to put most of them in red.

Since this charge is positive and that charge is positive, everywhere in space, no matter where you are, the potential has to be positive.

There is not a single point where it could be negative.

If you are very far away from the plus four and the plus one, then you expect that the equipotential surfaces are spheres, because it's almost as if you were looking at a plus five charge.

So it doesn't surprise you that when you go far out that you ultimately get spherical shapes.

When you're very close to the plus four they are perfect spheres, when you're very close to the plus one, they are perfect spheres.

But then when you're sort of in between, neither close to the plus four nor to the plus one, they have this very funny shape.

It reminds me the shape of this balloon a little bit.

Sort of like this.

You see.

And there is one surface which is most unusual equipotential surface which here has a point where the electric field is zero.

It's sort of like twisting the neck of a goose, you get something like this, and so you have here a surface which has a point here and it is exactly at that point where the electric field is zero.

That does not mean that the potential is zero, of course not, the potential is positive here.

If you come with a positive charge from the Lobby seven and you have to march up to that point, you have to do positive work.

You have to overcome both the repelling force from the plus four and the repelling force from the plus one.

But finally when you reach that point you can rest because there is no force on you at that point.

That's what it means that the electric field is zero.

It does not mean that you haven't done any work.

So never confuse electric fields with potentials.

I want to draw your attention to the fact that the green lines, the field lines, are everywhere perpendicular to the equipotentials.

I will get back to that during my next lecture.

That is not an accident.

That is always the case.

Now, Maxwell shows you something that is a little bit more complicated.

Here, he calculated for us the equipotential surfaces, the red ones are the surfaces.

Again you have to rotate them about the vertical to make it three-dimensional.

And now we have a minus one charge and a plus four.

And so whenever it is red, the surface, the potential is positive, and whenever I have drawn it blue, the potential is negative.

First, if we were very far away from both the plus four and the minus one, you expect to be looking at a charge which is effectively plus three.

And so if you go very far away for sure the potential is everywhere positive and you expect them to be spherical again.

If you look here you're very far away from the plus four and the minus one, indeed this has already the shape of a sphere.

So that's clear that the plus four and the minus one far away behave like a plus three.

If you're very close to the plus four, you get nice spheres around the plus four, positive potential, if you're very close to the minus one, notice that the blue surfaces are almost nice spheres, but now they're all negative because you're very close to the minus one.

So a negative potential.

There is here one surface which now has zero potential.

It has to be because if you're negative potential close to the minus one and you have positive potential very far out, you got to go through a surface where it's zero.

And so there is here a surface, I still have put it in blue, which is actually everywhere on this surface the potential is zero.

Is the electric field zero there?

Absolutely not.

Electric field should not be confused with potential.

What it means is that if you take a test charge in your pocket and you come from infinity and you walk to that surface, that by the time you have reached that surface, you've done zero work.

That's what it means.

That the potential is zero.

There is here one point which we discussed earlier in my lectures where the electric field is zero.

The potential is not zero there.

The potential is definitely positive here.

Because here was the zero surface.

Here is already positive surface, and this is a positive surface.

So the potential is positive.

However, if you reach that point there's no force on your charge.

So that means electric field is zero.

And it's not so easy of course to calculate these surfaces.

Maxwell was capable of doing that a hundred ten years ago.

And nowadays we can do that very easily with computers.

Equipotential surfaces which have different values can never intersect.

Plus five volt surface can never intersect with a plus three or a minus one.

And you think about why that is.

Why that is, that would be a total violation of the conservation of energy.

So equipotential surfaces, different values, can never intersect.

All right.

So you've seen that for the various charge configurations, the equipotential surfaces have very complicated shapes and cannot always be calculated in a very easy way.

Now comes the question why do we introduce electric potentials, who needs them?

And who needs equipotential surfaces?

Isn't it true that if we know the electric field vectors everywhere in space that, that determines uniquely how charges will move, what acceleration they will obtain, that means how their kinetic energy will change.

And the answer is yeah, if you know the electric field everywhere in space sure.

Then you can predict everything that happens with a charge in that field.

But there are examples where the electric fields are so incredibly complicated that it is easier to work with equipotentials because the change in kinetic energy as I will discuss now really depends only on the change in the potential when you go from one point to another.

So you will see very shortly that sometimes if you're only interested in change of kinetic energy and not necessarily interested in the details of the trajectory, then equipotentials come in very handy.

Never confuse U which is electrostatic potential energy with V which is electric potential.

This has unit joules.

And this has unit joules per coulombs, which we call volts.

If I have a collection of charges, pluses and minuses, U has only one value.

It is the work that I have to do to put all these crazy charges exactly where they are.

But the electric potential is different here from there from there to there to there to there.

If you're very close to a plus charge, you can be sure that the potential is positive.

If you're very close to a -- a negative charge, you can be sure that the potential is negative.

But U has only one number.

It's only one value.

They're both scalars.

Don't confuse one with the other.

In a gravitational field, matter, like a piece of chalk, wants to go from high potential to low potential.

If I just release it with zero speed, there it goes, high potential to low potential.

In analogy, positive charges will also go from a high electric potential to a low electric potential.

And of course this is unique for electricity, negative charges will go from a low potential to a high electric potential.

Suppose I had a position A in space and I had another position B and I specify the potentials.

So here we have A, potential is VA, and here we have point B where the potential is VB.

By definition, the potential of VA as we discussed before is the integral -- by the way if these are separated by some random distance R, whatever you want.

So the potential of A is defined as the integral going from A to infinity of E dot dR.

That is the definition of the potential of A.

There is an E here which is force per unit charge.

So it is not work.

If there were force DR it would be work but it is force per unit charge that makes it E.

So the potential of B, for definition, is the integral from B to infinity of E dot dR.

And so therefore the potential difference between point A and B, VA minus VB, equals the integral from A to B of E dot dR, and for reasons that I still don't understand after having been in this business for a long time, books will always tell you they reverse VA and B so they give you VB, VB minus VA.

And then they say well we have to put a minus sign in front of the integral.

It's the same thing.

So books always give it to you in this form.

But it is exactly the same.

Hope you realize that.

This is the two equations that I have here are the same.

VA minus VB is the integral from A to B of E dot dR.

If I flip this over then all I have to do is put a minus sign here and the two are identical.

Notice that if there is no electric field between A and B they have the same potential, of course.

Because when you march from A to B with a charge in your pocket no work is done.

So the potential remains the same.

I will change this dR to a different symbol, which I call dL.

dR would mean that we go from A to infinity along this straight line and then we go from B to infinity along the straight line but it makes no difference how you go.

If you go from A to B this potential difference and you go in this way then VA minus VB is not going to change.

And so if now I introduce here a element dL, which is a small vector, and if the local E vector here is like so, at this point here, then VA minus VB is then the integral of E dot dL.

In other words I can replace the R by an L and you may choose any path that you prefer.

And that's the way that we will show you this equation most of the time.

So it makes no difference how you march because we are dealing here with conservative fields.

So let's now make the assumption that VA is hundred fifty volts.

And that VB for instance is fifty volts.

So it's a very specific example.

What does it mean now?

It means that if I put plus Q charge in my pocket and I come all the way from Lobby seven and I walk up to point B.

So Walter Lewin, plus Q charge in his pocket, goes from Lobby seven to point B, I have to do work and the work I have to do is the product of my charge Q with the potential.

So that is Q the work I have to do is Q times VB.

So in this case it's fifty times Q, whatever that charge is that I have in my pocket.

This is in joules.

Now, I go from Lobby seven to point A.

I have to do more work.

I have to do hundred fifty Q joules of work.

You can think of it I first come to A to B, I'm already exhausted, I have to put in another work to get all the way to point A.

So you can imagine if I have this plus Q charge at point A, where there it's-- it's a higher potential, it wants to go back all by itself to B.

It wants to go from a higher potential to a lower potential.

Look, the E vector is in this direction.

Positive charge will go to a lower potential.

And as it moves from A to B energy is released.

How much energy?

Well, this is the amount of work I have done to get to A, this is the amount of work I did to get to B, and so if now the charge goes back from A to B, it's the difference that becomes available in terms of kinetic energy.

It's a change in potential energy.

And that change in potential energy, so the change in potential energy...

when the plus Q charge goes from A to B, that change is Q times VA minus VB.

QVB at point B and QVA at point A.

So this is the potential energy that is in principle available if the charge moves from A to B.

And you remember from eight oh one the work energy theorem.

If we deal with conservative forces, then the sum of potential energy and kinetic energy of an object is the same.

That's also true for gravitational forces.

In other words, this difference in potential energy that becomes available like potential energy becomes available when I drop my chalk from a high potential to a low potential, that's converted to kinetic energy.

So this difference now is also converted into kinetic energy of that moving charge.

And so that would be the kinetic energy at point B minus the kinetic energy at point A.

Which is really the work energy theorem.

It's the conservation of energy.

Now any piece of metal, no matter how crumby or dented it is, is an equipotential.

As long as there is no charge moving inside the metal.

And that's obvious that it's an equipotential.

Because these charges inside the metal, these electrons, when they experience an electric field, they begin to move immediately in the electric field, and they will move until there is no force on them anymore, and that means they have effectively made the electric field zero.

So charges inside the conductor always move automatically in such a way that they kill the electric field inside.

If the electric field hadn't been zero yet, they would still be moving.

And so each metal that you have, no matter where you bring it, as long as there are no electric currents inside, will always be an equipotential.

So I can take a trash can and bring it into an external field and then very shortly after I've brought it in when things have calmed down, the trash can will be an equipotential and the electric field inside the metal will everywhere will everywhere be zero.

So I could for instance attach point A to a trash can, metal trash can, so the whole trash can would be at a hundred fifty volts, and I could put point B, make it part of my -- of my soda, which is also made of metal.

And so the whole soda would be at fifty volts and the entire trash can would be at a hundred fifty volts.

I place the whole thing in vacuum and now I release an electron at point B.

An electron.

An electron wants to go to higher potential.

A proton would go from A to B, electron wants to go from B to A.

And so now energy is available.

The electric potential energy is available and the electron will start to pick up speed and finally end up at A.

Now how it will travel I don't know.

The electric field configuration is enormously complicated.

Between the can and this trash can.

Amazingly complicated.

If you were to see the field lines it would be weird.

But if we all we want to know is what the kinetic energy is, what the speed is, with which this electron reaches the can, so what?

Then we can use the work energy theorem and find out immediately what that kinetic energy is.

Because the available potential energy is the charge of the electron times the potential difference between these two objects.

Well the charge of the electron is one point six times ten to the minus nineteen coulombs.

The potential difference is a hundred volts.

And that is the difference in kinetic energy.

If I assume that I release the electron at zero speed, then I have immediately the kinetic energy that it has at point A which is one-half M of the electron times the speed at A squared.

So now you see that accepting the fact that we know the equipotentials, we can very quickly calculate the kinetic energy and therefore the speed of the electron, as they arrive at A, without any knowledge of the complicated electric field.

If you put in the numbers for the mass of the electron, then, which is nine times ten to the minus thirty-one kilograms, then you'll find that this speed is about two percent of the speed of light.

A substantial speed.

All our potentials, electric potentials, are defined relative to infinity.

That means at infinity they are zero.

That is because of the one over R relationship.

That's very nice and dandy and it works.

However, there are situations whereby it really doesn't matter where you think of your zero.

Remember with gravity we had a similar situation.

With gravity we always worried about difference in potential energy but sometimes we call this zero and this plus.

Sometimes you call this plus and this minus.

It doesn't really matter because the change in kinetic energy is dictated only by the difference in potentials.

So it is very nice and dandy to call that hundred fifty and to call that fifty but you wouldn't have found any different answer for the electron if you called this potential one hundred volts and you called this one zero or you called this one zero and this one minus one hundred or you called this one fifty and this one minus fifty.

So the behavior of the electrons of the charges would of course not change.

And of course electrical engineers would always per definition call the potential of the earth zero when they built their circuits.

So now I would like to demonstrate to you with the Vandegraaff that if you get a strong electric field from the radially outwards from the Vandegraaff that you get a huge potential difference between this point here and this point there.

If I have my numbers still there, I hope I do.

There they are.

At the surface of the Vandegraaff which takes about ten microcoulombs, it will be three hundred thousand volts right here, here it would be a hundred fifty thousand volts, and here three meters from the center, it's about thirty kilovolts.

So that means that if I place this fluorescent tube into that electric field that there would be a gigantic potential difference between here and there provided that I hold it radially.

If I hold it like this then the potential difference between here and there would be zero of course, if I hold it tangentially, they would be both at the same electric potential.

But when I hold them radially you will see perhaps that this fluorescent tube will show a little bit of light.

Once you see light it means that electrons are moving through that gas.

It means charge is moving.

We haven't discussed current yet, but that's what it means.

A current is flowing.

And this current has to be delivered by the Vandegraaff and the Vandegraaff is only capable of providing very modest currents.

So you're not going to see a lot of light.

But I want to show you that you will see some light.

No wires attached.

Just here.

And then I will rotate it tangentially and you will see no light at all.

So if we can make it a little darker as a start and I'll start the Vandegraaff and then if Marcos comes to make it completely dark when necessary, because the light is so little that we really have to make it completely dark.

I will put on a glove for safety reasons although I don't think it will do me much good.

Notice I have here a piece of glass to well, to be well-insulated from the glass so that I don't mess up the demonstration by if I hold my fingers here it will be very different than holding my hands here.

So let's go first close without -- with the lights still on and then OK why don't you turn the lights off now all the way off.

OK I -- I think you can see a glow.

It's radially outwards now.

And Marcos can you give a little light?

OK I will now go tangential, can you turn the lights off?

And now you see nothing, very little.

And now I go radial again.

And there you go.

Now if I -- if I'm crazy, if I were crazy, then I would touch the end of this tube with my finger thereby allowing this current to go straight through my body to the earth which may increase the light.

Let me try that.

So -- so I'm going to touch the -- the -- the -- this -- this fluorescent tube on your right side.

Ah.

Ah.

Ah.

Every time I -- I touch it ah.

But that's not ah.

But you see every time I touch it I make it easier for the current to flow and you see very clearly that it lights up.

Now I want to do the same demonstration with a neon flash tube and the neon flash tube I will place at the end of a fishing rod.

This neon flash tube we used during the first lecture when I was beating up students but I've learned not to do that anymore.

This takes several kilovolts to get a little bit of light out of it from one side to the other, oh, that's duck soup for the Vandegraaff, you know you're talking about hundreds and thousands of volts, and so here I will actually start spinning it and then when it is radially inwards maybe you will see light and when it is tangential you won't see much light and then if I feel very good I will do that again.

OK so Marcos if you make it dark I'll give it a twist.

OK, radial, radial, radial, radial, radial, radial, radial, radial, radial, OK.

Now I, ah.

OK I touched it now I touch it again.

And I touch it again.

And again.

And again.

Ah.

You see every time I touch it it likes me.

And it gives a nice flash of light.

So you see here in front of your eyes without any wires attached that the potential difference created by the electric field that those potential differences make these lights work.

All right, see you Friday.