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8.02 Electricity and Magnetism, Spring 2002  
Transcript – Lecture 1

I'm Walter Lewin.

My lectures will in general not be a repeat of your book but they will be complementary to the book.

The book will support my lectures.

My lectures will support the book.

You will not see any tedious derivations in my lectures.

For that we have the book.

But I will stress the concepts and I will make you see beyond the equations, beyond the concepts.

I will show you whether you like it or not that physics is beautiful.

And you may even start to like it.

I suggest you do not slip up, not even one day, eight o two is not easy.

We have new concepts every week and before you know you may be too far behind.

Electricity and magnetism is all around us.

We have electric lights, Electric clocks.

We have microphones, calculators, televisions, VCRs, radio, computers.

Light itself is an electromagnetic phenomenon as radio waves are.

The colors of the rainbow in the blue sky are there because of electricity.

And I will teach you about that in this course.

Cars, planes, trains can only run because of electricity.

Horses need electricity because muscle contractions require electricity.

Your nerve system is driven by electricity.

Atoms, molecule, all chemical reactions exist because of electricity.

You could not see without electricity.

Your heart would not beat without electricity.

And you could not even think without electricity, though I realize that even with electricity some of you may have a problem with that.

The modern picture of an atom is a nucleus, which is very small compared to the size of the atom.

The nucleus has protons, which are positively charged and it has neutrons, which have no charge.

The mass of the proton is approximately the same as the mass of the neutron.

It's about six point seven times ten to the minus twenty-seventh kilograms.

One point seven.

The positive charges here with the nucleons, with the neutrons, and then we have electrons in a cloud around it.

And if the atom is neutral, the number of electrons and the number of protons is the same.

If you take one electron off you get a positive ion.

If you add an electron then you get a negative ion.

The charge of the electron is the same as the charge of the proton.

That's why the number is the same for neutral atoms.

The mass of the electron is about eighteen hundred thirty times smaller than the mass of the proton.

It's therefore negligibly small in most cases.

All the mass of an atom is in the nucleus.

If I take six billion atoms lined up touching other, I take six billion because that's about about the number of people on earth.

Then you would only have a length of sixty centimeters.

Gives you an idea of how small the atoms are.

The nucleus has a size of about ten to the minus twelve centimeters.

And the atom itself is about ten thousand times larger.

The cloud of electrons, which is about ten to the minus eight centimeters.

And if you line six billion of those up you only get this much.

Already in six hundred BC, it was known that if you rub amber that it can attract pieces of dry leaves.

And the Greek word for amber is electron.

So that's where electricity got its name from.

In the sev- sixteenth century there were more substances known to do this.

For instance glass and sulfur.

And it was also known and written that when people were bored at parties that the women would rub their amber jewelry and would touch frogs, which then would start jumping of desperation, which people considered to be fun, not understanding what actually was happening to the amber nor what was happening to the frogs.

In the eighteenth century it was discovered that there are two types of electricity.

One if you rub glass and another if you rub rubber or amber for that matter.

Let's call one A and the other B.

It was known that A repels A and B repels B but A attracts B.

And it was Benjamin Franklin without any knowledge of electrons and protons who introduced the idea that all substances are penetrated with what he called electric fluid, electric fire.

And he stated if you get too much of the fire then you're positively charged and if you have a deficiency of that fire, then you're negatively charged.

He introduced the sign convention and he decided that if you rub glass that that is an excess of fire and he called that therefore positive.

You will see later in this course why this choice he had fifty percent chance is extremely unfortunate but we have to live with it.

So if you take this fluid according to Benjamin Franklin and bring it from one substance to the other, then the one that gets an excess becomes positively charged but automatically as a consequence of that the one from which you take the fluid becomes negatively charged.

And so that's the whole idea behind the conservation of charge.

You cannot create charge.

If you create plus then you automatically create minus.

Plus and plus repel each other.

Minus and minus repel each other.

And plus and minus attract.

And Benjamin Franklin who did experiments also noticed that the more fire you have the stronger the forces.

The closer these objects are to each other, the stronger the forces.

And there are some substances that he noticed, which conduct this fluid, which conduct this fire, and they are called conductors.

If I have a glass rod as I have here and I rub it then it gets this positive charge that we just discussed.

So here is this rod and I rub it with some silk and it will get positively charged.

What happens now to an object that I bring close to this rod and I will start off with taking a conductor.

And the reason why I choose a conductor is that conductors have a small fraction of their electrons, which are not bound to atoms but which can freely move around in the conductor.

That's characteristic for a conductor, for metals.

That's not the case with nonconductors.

There the all electrons are fixed to individual atoms.

So here we have a certain fraction of electrons that can wander around.

What's going to happen that electrons want to be attracted by these positive charges.

Plus and minus attract each other.

And so some of these electrons, which can freely move will move in this direction and so the plus stay behind.

This process we call induction.

You get sort of a polarization.

You get a charge division.

It's a very small effect, perhaps only one in ten to the thirteen electrons that was originally here will end up here but that's all it takes.

So we get a polarization and we get a little bit more negative charge on the right side than we have on the left side.

And so what's going to happen is, since the attraction between these two will be stronger than the repelling force between these two because the distance is smaller and Franklin had already noticed the shorter the distance the stronger the force.

What will happen is that if this object is free to move it will move towards this rod.

And this is the first thing that I would like you to see.

I have here a conductor that is a balloon, helium-filled balloon.

And I will rub this rod with silk.

And as I approach that balloon you will see that the balloon comes to the rod.

I will then try to rub with that rod several times on that balloon.

It will take a while perhaps because the rod itself is a very good nonconductor.

It's not so easy to get charge exchange between the two.

But if I do it long enough I can certainly make that balloon positive.

Then they're both positive.

And then they will repel each other.

But first, the induction part, whereby you will see the balloon come to the glass rod.

These experiments work best when it is dry, in the winter.

They don't work so well when it is humid so it's a good time to teach eight or two in the winter.

OK there we go this should be positively charged now.

And the balloon wants to come to the glass.

You see that?

Very clearly.

Come on baby.

OK.

So now I will try to get this balloon charged a little so there is a change of electrons that go from the balloon to the glass.

And the glass doesn't, it's not a conductor itself so it is not always so easy to get charge exchanges.

OK let's see whether I have succeeded now in making the balloon positively charged as well as the glass rod.

If that's the case then the balloon is not going to like me.

The balloon will now be repelled.

And you see that very clearly.

To show you now that there are indeed two different kinds of electricity.

If I now rub with cat fur by tradition we do that with cat fur, I don't know why by tradition we use silk for the glass.

So if we do this with cat fur now then this becomes negatively charged.

Remember there were two types of electricity.

And since that balloon is positively charged now the balloon will come to me.

And there it is.

Now it comes to me.

So you've seen for the first time now clearly that there are two different kinds of electricity.

The positive charge is chosen by Franklin on the glass rod and the negative charge on the rubber.

So now you may think that if I approach a nonconducting balloon with a glass rod and I have a nonconducting balloon here you may think now that this balloon will not come to the glass rod because there are no free electrons.

So these electrons cannot freely move and so you don't get this polarization.

You don't get this induction.

But that is not the case.

And this is actually quite subtle.

You have to look now at the atomic scale.

If I take an atom like you have here.

You have positive charge and you have the electrons here in a cloud around the positive nucleus.

If I bring a glass rod positively charged nearby, then these electrons which are stuck to the atoms, they cannot freely move like in conductors, however will spend a little bit more time on the side where the glass rod is because they feel attracted by the glass rod, whereas the nuclei if anything want to go away from the glass rod.

So what you're going to see is that in a way if I started off with a spherical atom let's suppose this were a spherical atom or a spherical molecule then what will happen is that you get sort of a shape like this and the electrons spend a little bit more time here than they spend here and that means that I have actually polarized that atom.

If the electrons spend more time on this side of the atom than on this side I have also created the phenomenon of induction and I therefore expect that this side becomes more negative than that side.

And I can show you that in a nice way with a transparency, whereby I have plus and minus signs and I have equal number of plus and minus signs.

So they represent neutral atoms.

There you see them.

Boy.

It's a little dirty but maybe see I can clean it a little.

OK.

OK.

So here we go.

So notice there are equal amount of pluses and minuses, so think of the plus and the minuses as one neutral atom.

Just a representation.

Now I'm holding a glass rod on this side which is positively charged.

And so each atom the electrons want to go a little bit to this side and so the nucleus stays behind.

And if each atom does that this is what's going to happen.

And now notice what you end up with.

In the middle of the substance plus and minuses cancel each other out again.

But on the right side you have created a negatively charged layer and on the left side you have created a positively charged layer.

And so in a way you have again induction.

So even in the nonconducting objects this side will turn negative and this side will turn positive and therefore, if I approach a nonconducting balloon with a glass rod, I will also see the balloon come to me.

And so I can easily show you that.

It doesn't make any difference whether I choose glass or whether I choose rubber.

I can do it with both.

Nonconducting balloons always have a potential problem.

The potential problem is that they can be charged by themselves just like the metal balloons can be charged by themselves.

However, if I touch the metal balloon then any charges there will immediately flow through me to the earth.

We will understand that later.

Because this is a conductor.

That remember the electric fluid is conducted by a metal but not by a nonconductor.

So with this it's more difficult.

Even if I kiss it and touch it it's not clear that I can take all the charge off.

In fact by doing that I may even make it worse.

Let's hope that it is not charged too much and let's approach it with this glass rod and see whether I can convince you that indeed it's coming to the rod not because of the free electrons but because of that process.

Oh boy.

Ho.

And it should also do the same with rubber I hope.

If it were negatively charged it'd go away.

Ha it does go away so it is negatively charged you see that.

By touching it I actually probably charged it and there's not much I can do about it.

Very difficult to get charge off.

I already had a suspicion when I approached it with the glass it was too eager to come to the glass.

Still negatively charged.

That's the way it goes.

It's not because the demonstration failed but it's because the balloon is charged and doesn't want to give it up because it's a, it is a nonconductor.

Friction can cause electric charge and that's exactly what happened when I touched this balloon and tried to discharge it.

Through friction I may actually have charged it.

If I take these party balloons that all of you may have seen and you just rub them on your shirt, on your trousers, they stick to my hand.

They have charge on them.

Whether it's positive or negative I don't know, I don't even remember.

It's not important.

And so when I bring them to my hand, my hand is not a good conductor but you get induction, this phenomenon that we just discussed and so the two attract each other.

The positive and the negative side attract each other.

And you can stick them on the ceiling.

Or you can stick them on the board.

You can decorate your room that way.

Very pretty isn't it.

All that you can do now because of eight o two.

Now these heavy balloons may be a little bit more difficult.

Also I'm wearing cotton.

If you wear nylon or polyester it's much better.

It's much easier to get, oh that's good, that's a nice one.

I think we need a blue one.

There we go.

So you see friction causes electricity.

That's of course why the silk when we rubbed the glass and the cat fur we rub the rubber then we create charge on one.

Of course if you make the glass positively charged your silk will be automatically negatively charged.

When you comb your hair you may have noticed with dry weather that you hear some cracking noise.

Cracking noise means sparks.

And you will learn all about sparks in this course though not today.

But you can hear it if you're very quiet.

And as you do that you charge the comb.

I can hear the cracking.

Interesting.

So the comb is now charged.

Probably so am I and there it comes.

See.

It's not as good as the glass but same idea.

If you take your shirt off and you make it, and you make it dark in your dormitory and you stand in front of a mirror.

An amazing experience.

And I'd be happy to do it for you because, but I told you I already wear cotton and it doesn't work with cotton so well.

You really have to do it with a nylon shirt.

And when you take that nylon shirt off, not only do you hear the cracking, but you actually see the glow of these teeny weeny little sparks.

You actually are like a light bulb.

It is an experiment that you cannot miss.

And I would suggest you try that this weekend.

Do it with a friend.

That's even more fun.

We'll all perhaps remember when you just walk around.

Do your normal things during the day.

There are rugs in rooms and you want to leave the room and you touch the doorknob and you get a shock.

It's a spark that flies over.

It's electricity.

Even when you touch a person you sometimes feel this shock.

When you cook and you take saran wrap off these rolls the damn stuff just doesn't want to come off because as you roll it off, there is friction and it gets charged and it often gets crumpled up and it's very bad, very difficult to handle it.

You've all experienced that.

Also cellophane around boxes with chocolate, the same thing happens.

As you take it off you charge it, whether you like it or not.

I now want to do an experiment and I need a volunteer.

I need a student who actually is wearing preferably not all cotton but I think Simon you have a beautiful wonderful nylon parka.

So if you are willing to sacrifice a little bit for the sake of science and come over here and sit down here.

Just relax.

Make sure that your feet are off the ground.

OK.

So what I'm going to do now Simon I'm going to beat you with cat fur.

And as I beat you with cat fur you will get charged and since I don't want you to be the only person who suffers under this experiment, I will also stand on an insulated stool so if you become for instance positively charged, I don't know whether it's positive or negative, I would get the other amount of charge.

So we share in the charge.

And as I beat you, you will charge up more and more and I will charge up more and more, and then we will have to convince the class that, that we are both charged.

And we will do that in a way that will be hopefully rather convincing.

I, let me just start beating you a little bit.

To make you feel at home.

We know each other right.

OK.

Now of course as I mentioned to you these experiments work well when it is dry and so if you are too wet it won't work.

But let's see if you sweat a little bit too much then it doesn't work too well.

So we ready?

I have here in my hand a neon flash tube.

And although we don't know yet what voltage is, because we will learn about that in this course, to get a good flash out of these you need about a few thousand volts.

And so we will see and we'll make it dark shortly and I will hold the flashlight, the flashlight in one hand, the neon discharge tube, and then Simon will touch it on the other side.

And if we've succeeded then you may see some light.

So Simon look at me first, don't touch it yet, because we're going to make it all the way dark.

You know where it is, it's there, OK, make it darker Marcos.

Touch it.

Touch it.

OK, try it again, touch it again.

OK.

Thank you.

Can we have some light.

[applause] Thank you very much.

Equal charges repel each other.

I've shown that, the demonstration with the balloons.

Here we have an instrument, which is called the Van de Graaff.

It's named after Professor Vandegraaff, who invented it.

It was an MIT professor.

And this instrument, which I will not discuss in any detail though but you will understand it later on in the course.

I'll tell you all about it later.

Just think of this instrument as a super amber rod.

And although we don't know yet what voltage is, I mentioned already the twenty thousand volts between Simon and me, in this instrument you have to think in terms of several hundred thousand volts.

So this instrument is not without danger.

But that of course makes it more exciting to work with it.

So it's a super amber rod and what I will do first now is to put some confetti on top and when we turn on the Vandegraaff the confetti may at first go to the charged dome, it is already on top of it, and when it picks up some of the charge it will then spread out because it, it will repel.

So let's get some some light on there, which will make it a little bit better to see.

Let me put some of this on top.

It's just regular confetti.

Pieces of paper.

All right, now all I have to remember is how to start the.

Most of the action has already occurred.

I will put a little bit more on.

[laughter] If you see sparks don't worry yet.

[laughter] Put some more on.

More and nothing left for the second class.

[laughter] Make it perhaps a little darker.

Ah that's too dark.

[laughter] OK.

We'll try it once more.

Give it a zap.

So look at the confetti on top.

And I think it's quite convincing.

Some of the confetti will stay there.

Well that's the reason that it's not a good conductor and so it get it first sucked in and if it doesn't get charge of the Vandegraaff then it will not spread out.

All right.

So now let's try for the first time to be a little bit more quantitative.

If I take two charges and we use in general we use for charge the symbol  $Q$ .

So here we have  $Q$  one.

And here we have  $Q$  two.

And let's say they're separated by a distance  $R$ .

And the unit vector in the direction from one to two I call that  $\hat{R}_{1-2}$ .

The  $\hat{R}$  stands for unit vector.

If these charges are equal, both minus or both plus, then they will repel each other and so here there is a force  $F$  which I call  $F_{1-2}$ .

It is the force on two due to number one and since action equals minus reaction force here is to one equal in magnitude but a hundred eighty degrees in opposite direction.

Coulomb, the French physicist, who did a lot of research on this in the nineteenth, eighteenth century actually.

Coulomb found the following relationship, that the force is proportional to the product of the two charges.

So it's  $Q_1$  times  $Q_2$ .

Times a constant, which nowadays we call Coulomb's constant,  $K$ .

Divided by the distance between these charges squared.

And it is in direction of the unit vector that goes from one to two.

This is the force on number two due to one.

And notice that this equation is sign sensitive.

Because if  $Q_1$  and  $Q_2$  are both negative the force is in the, the force is in this direction and if they are both positive it's also in this direction as I have it.

However if one is positive and one is negative you get minus this direction so this force flips over and that one then obviously also flips over.

In the SI units in this course we will use for the unit of charge the coulomb named after this great man.

One coulomb charge is a horrendous amount of charge.

More than you will ever see in your lifetime.

We normally work with microcoulombs, sometimes even less than that.

The charge of one proton, which is exactly the same as the charge of one electron, is approximately one point six times ten to the minus nineteen coulomb.

So one coulomb is something like six times ten to the eighteen protons or electrons if the charge is negative.

This constant  $K$  in SI units is nine times ten to the ninth.

And the unit you can find out because you know that this is newtons, this is coulomb squared and this is square meters.

So the unit is newton square meters, newtons square meters divided by square coulombs.

But that's not so important.

No one ever thinks of it that way.

For historical reasons, which may at times be a pain in the neck for you, we write for  $K$  one divided by four pi epsilon zero.

There is nothing magic about that.

It's just a historical reason.

And so one divided by four pi epsilon zero is nine times ten to the ninth.

That's all that matters.

This epsilon zero has a name it's called the permittivity of free space.

But you can forget about that.

It's not important the name.

Notice that there is a clear parallel with gravity.

Newton's law of gravity that the force, which in that case is always attracting, gravity never repels, is the product of two masses and then you have here the gravitational constant and again you have the distance squared.

So there is an enormous parallel between the two.

There's a great beauty that electricity acts in a way that is very parallel to the way that gravity works.

If I added a third charge, for instance here,  $Q_3$ , and if now I want to know what the force is on  $Q_2$ , then I use the superposition principle which we've used many times in eight o one, and we say OK the net force on number two is the force due to number one plus the force from number three.

If number three, if this is positive and this is positive and this were negative, then this force would be in this direction,  $F_1$ ,  $F_3$ , two and then the net force on number two would be the vectorial sum of these two.

Is it obvious that the superposition principle works?

Not at all.

It's not at all obvious.

Do we believe in it?

Yes we do.

Why do we believe in it?

Because it's consistent with all experiments that we have done.

But the superposition principle which is very powerful is really not a matter of course.

But it works.

We can always use it.

And we will.

If you compare eight o one with eight o two, thereby comparing electricity with gravity, you will see that electric forces are way more powerful than gravitational forces.

And the way I can best show you that is by taking two protons which are a distance  $D$  apart.

Here is a proton and here is a proton and they are separated by a distance  $D$ .

They repel each other.

And the force by which they repel each other is of course extremely easy to calculate.

We know Coulomb's law.

That law is called after Coulomb.

And so the force, the electric force with which they repel each other, this is just the magnitude now of the force, is the charge of the proton which is one point six times ten to the minus nineteen but I have to square that.

I have to multiply it by Coulomb's constant, which is nine times ten to the ninth, and I divide it by D squared.

That's the electric force.

If I want to know the gravitational force, which is the force with which they attract each other, these are repelling forces, but I just want magnitudes here, then I have to take the mass of the proton, which is one point seven times ten to the minus twenty-seven.

I have to square that.

Remember M one times M two times the gravitational constant.

The gravitational constant in SI units is six point seven times ten to the minus eleven and I divide that by D squared.

If now I compare the electric force with the gravitational force, so I divide one by the other, notice that the D cancels.

They both have D squared downstairs.

And so you will easily be able to show that this ratio is roughly ten to the thirty-six.

So the electric force is thirty-six orders of magnitude more potent than the gravitational attraction.

This teaches you some respect perhaps for eight o two.

If these were the only forces that acted on the protons and you bring them in the nucleus, which has a size of only ten to the minus twelfth centimeters, then the acceleration that the proton will experience is the electric force divided by the mass of the proton.

$F$  equals  $MA$ .

Basis of eight o one.

And if you take this electric force when you make  $D$  ten to the minus twelfth centimeters, which is ten to the minus fourteen meters, and you calculate this ratio you will find that it is twenty-six orders of magnitude higher than the gravitational acceleration on earth.

Twenty-six orders of magnitude higher.

So you wonder what the hell holds the nucleus together.

If there is such a tremendous force on these protons.

Well, what is holding them together are the nuclear forces, which we do not fully understand, but thank goodness the nuclear forces are not part of eight o two so I will leave that alone for now.

So what holds our world together?

Well on the nuclear scale, ten to the minus twelve centimeters, very important are the nuclear forces.

On an atomic scale up to thousands of kilometers, it's really electric forces that hold our world together.

But on a much larger scale, planets and stars and the galaxy, it is gravity that holds our world together.

And now you may say, ah that's very inconsistent with what you just told us because didn't you tell us that  $D$  cancels if you compare gravity with electricity.

Yes, however, most objects are neutral or very close to neutral and so if you take the earth it is very unlikely even that the earth as a whole would have a charge of more than ten coulombs.

That probably is already an exaggeration.

So if I take the earth and I take the moon and I put on both a charge of ten coulombs, here's the earth and here's the moon, and I put say just arbitrarily ten coulombs here and that is put on here either minus, minus ten coulombs, so they will attract each other, but given their distance, it's almost nothing.

The force is negligibly small.

But of course the force of gravity, which is proportional to their masses, wins and in this particular case if you take the earth and the moon, the gravitational force wins over the electric force by twenty-five orders of magnitude.

So even though our immediate surroundings are dominated by electric forces, including your own body for that matter, the behavior of the universe on a large scale is dictated by gravity.

We will use various instruments to measure charge in a quantitative way and one of the instruments that you will see we will use it often in the lectures that are to come, is called an electroscope.

It's a very simple instrument.

In general it is just a conducting rod.

It could be aluminum, metal, and at the end are two pieces of tinsel, two pieces of aluminum foil.

And often there is a nice knob here.

And if I touch this with a charged object, then because this can conduct electricity, this can conduct the fire, as defined by Benjamin Franklin.

If I touch it with an object which is positively charged, then this object will become positively charged.

If I touch it with an object which is negatively charged it will become negatively charged.

And you see now here these two very light pieces of aluminum foil will repel each other.

And so you will see that this shows a certain angle, and the more charge there is the larger that angle.

Sort of gives us a way of doing some quantitative measurements.

There are other electroscopes which are not too different.

There's one central rod and they would have one leaf hanging there and when you charge that one up then this leaf will go out and if the charge is more it will go out even further.

I don't have an electroscope now here, but what I want you to see that if I charge myself up and I hold in my hands these Christmas tree tinsels, that in a way if I get enough charge on me, then these tinsels will spread out.

It's an idea that immediately follows from the fact that you get a certain amount of charge, whether it's negative charge from me, or whether I'm positively charged, that doesn't make any difference, these tinsels will spread out.

And of course the best way I can do that is if I charge myself with the Vandegraaff.

And as I said earlier experiments of this nature are not entirely without risk.

And so there's always the possibility of course that I don't survive this demonstration.

[laughter] But don't worry because in that case there will be someone else who will lecture eight o two, except he is not likely to show this demonstration again.

[laughter] So you might as well take a close look because this may be the only time you will ever see it.

So I will give you some nice light on the Vandegraaff.

And it's always a scary moment for me.

Sleepless nights about the Vandegraaff.

Am I going to turn it on, Marcos, or you have the courage to turn it on?

You will turn it on?

OK, hold it Marcos, this is too close for comfort.

You ready?

Are you nervous?

Feel.

[laughter] So look at the tinsels and try not to look at me please.

Go ahead.

I am now a living electroscope.

[laughter] If the, if the weather is cooperating today and if I had long hair you might even see that my hair would start to act like an electroscope.

We can try that too.

Why don't you throw it.

[laughter] [applause] Is it working?

OK, well, this weekend make sure you take this nylon shirt off in front of the mirror and enjoy your, enjoy the experiment at home.

Don't try this ever.

See you Friday.