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Transcript – Lecture 9

When positive charges move in this direction, then per definition, we say the current goes in this direction.

When negative charges go in this direction, we also say the current goes in that direction, that's just our convention.

If I apply a potential difference over a conductor, then I'm going to create an electric field in that conductor.

And the electrons -- there are free electrons in a conductor -- they can move, but the ions cannot move, because they are frozen into the solid, into the crystal.

And so when a current flows in a conductor, it's always the electrons that are responsible for the current.

The electrons fuel the electric fields, and then the electrons try to make the electric field 0, but they can't succeed, because we keep the potential difference over the conductor.

Often, there is a linear relationship between current and the potential, in which case, we talk about Ohm's Law.

Now, I will try to derive Ohm's Law in a very crude way, a poor man's version, and not really 100 percent kosher, it requires quantum mechanics, which is beyond the course -- beyond this course -- but I will do a job that still gives us some interesting insight into Ohm's Law.

If I start off with a conductor, for instance, copper, at room temperature, 300 degrees Kelvin, the free electrons in copper have a speed, an average speed of about a million meters per second.

So this is the average speed of those free electrons, about a million meters per second.

This in all directions.

It's a chaotic motion.

It's a thermal motion, it's due to the temperature.

The time between collisions -- time between the collisions -- and this is a collision of the free electron with the atoms -- is approximately -- I call it tau -- is about 3 times 10 to the -14 seconds.

No surprise, because the speed is enormously high.

And the number of free electrons in copper per cubic meter, I call that number N, is about 10 to the 29.

There's about one free electron for every atom.

So we get twen- 10 to the 29 free electrons per cubic meter.

So now imagine that I apply a potential difference -- piece of copper -- or any conductor, for that matter -- then the electrons will experience a force which is the charge of the electron, that's my little e times the electric field that I'm creating, because I apply a potential difference.

I realize that the force and the electric field are in opposite directions for electrons, but that's a detail, I'm interested in the magnitudes only.

And so now these electrons will experience an acceleration, which is the force divided by the mass of the electron, and so they will pick up, a speed, between these collisions, which we call the drift velocity, which is A times tau, it's just 8.01.

And so A equals F divided by Me.

F is e E, so we get e times E divided by the mass of the electrons, times tau.

And that is the the drift velocity.

When the electric field goes up, the drift velocity goes up, so the electrons move faster in the direction opposite to the current.

If the time between collisions gets larger, they -- the acceleration lasts longer, so also, they pick up a larger speed, so that's intuitively pleasing.

If we take a specific case, and I take, for instance, copper, and I apply over the -- over a wire -- let's say the wire has a length of 10 meters -- I apply a potential difference I call delta V, but I could have said just V -- I apply there a potential difference of 10 volts, then the electric field -- inside the conductor, now -- is about 1 volt per meter.

And so I can calculate, now, for that specific case, I can calculate what the drift velocity would be.

So the drift velocity of those free electrons would be the charge of the electron, which is 1.6 times 10 to the -19 Coulombs.

The E field is 1, so I can forget about that.

Tau is 3 times 10 to the -14, as long as I'm room temperature, and the mass of the electron is about 10 to the -30 kilograms.

And so, if I didn't slip up, I found that this is 5 times 10 to the -3 meters per second, which is half a centimeter per second.

So imagine, due to the thermal motion, these free electrons move with a million meters per second.

But due to this electric field, they only advance along the wire slowly, like a snail, with a speed on average of half a centimeter per second.

And that goes very much against your and my own intuition, but this is the way it is.

I mean, a turtle would go faster than these electrons.

To go along a 10-meter wire would take half hour.

Something that you never thought of.

That it would take a half hour for these electrons to go along the wire if you apply potential difference of 10 volts, copper 10 meters long.

Now, I want to massage this further, and see whether we can somehow squeeze out Ohm's Law, which is the linear relation between the potential and the current.

So let me start off with a wire which has a cross-section A, and it has a length L, and I put a potential difference over the wire, plus here, and minus there, potential V, so I would get a current in this direction, that's our definition of current, going from plus to minus.

The electrons, of course, are moving in this direction, with the drift velocity.

And so the electric field in here, which is in this direction, that electric field is approximately V divided by L, potential difference divided by distance.

In 1 second, these free electrons will move from left to right over a distance Vd meters.

So if I make any cross-section through this wire, anywhere, I can calculate how many electrons pass through that cross-section in 1 second.

In 1 second, the volume that passes through here, the volume is Vd times A but the number of free electrons per cubic meter is called N, so this is now the number of free electrons that passes, per second, through any cross-section.

And each electron has a charge E, and so this is the current that will flow.

The current, of course, is in this direction, but that's a detail.

If I now substitute the drift velocity, which we have here, I substitute that in there, but then I find that the current -- I get a e squared, the charge squared, I get N, I get tau, I get downstairs, the mass of the electron, and then I get A times the electric field E.

Because I have here, is electric field E.

When you look at this here, that really depends only on the properties of my substance, for a given temperature.

And we give that a name.

We call this sigma, which is called conductivity.

Conductivity.

If I calculate, for copper, the conductivity, at room temperature, that's very easy, because I've given you what N is, on the blackboard there, 10 to the 29, you know what tau is at room temperature, 3 times 10 to the -14, so for copper, at room temperature, you will find about 10 to the 8.

You will see more values for sigma later on during this course.

This is in SI units.

I can massage this a little further, because E is V divided by L, and so I can write now that the current is that sigma times A times V divided by L.

I can write it down a little bit differently, I can say V, therefore, equals L divided by sigma A, times I.

And now, you're staring at Ohm's Law, whether you like it or not, because this is what we call the resistance, capital R.

We often write down rho for 1 over sigma, and rho is called the resistivity.

So either one will do.

So you can also write down -- you can write down V equals I R, and this R, then, is either L divided by sigma A, or L times rho -- let me make it a nicer rho -- divided by A.

That's the same thing.

The units for resistance R is volts per ampere, but we call that ohm.

And so the unit for R is ohm.

And so if you want to know what the unit for rho and sigma is, that follows immediately from the equations.

The unit for rho is then ohm-meters.

So we have derived the resistance here in terms of the dimensions -- namely, the length and the cross-section -- but also in terms of the physics on an atomic scale, which, all by itself, is interesting.

If you look at the resistance, you see it is proportional with the length of your wire through which you drive a current.

Think of this as water trying to go through a pipe.

If you make the pipe longer, the resistance goes up, so that's very intuitively pleasing.

Notice that you have A downstairs.

That means if the pipe is wider, larger cross-section, it's also easier for the current to flow, it's easier for the water to flow.

So that's also quite pleasing.

Ohm's Law, also, often holds for insulators, which are not conductors, even though I have derived it here for conductors, which have these free electrons.

And so now, I want to make a comparison between very good conductors, and very good insulators.

So I'll start off with a -- a chunk of material , cross-sectional area A -- let's take it 1 millimeter by 1 millimeter -- so A is 10 to the -6 square meters.

So here I have a chunk of material, and the length of that material, L, is 1 meter.

Put a potential difference over there, plus here, and minus here.

Current will start to flow in this direction, electrons will flow in this direction.

The question now is, what is the resistance of this chunk of material?

Well, very easy.

You take these equations, you know L and A, so if I tell you what sigma is, then you can immediately calculate what the resistance is.

So let's take, first, a good conductor.

Silver and gold and copper are very good conductors.

They would have values for sigma, 10 to the 8, we just calculated for copper, you've seen in front of your own eyes.

So that means rho would be 10 to the minus 8, it's 1 over sigma.

And so in this particular case, since A is 10 to the -6 the resistance R is simply 10 to the 6th times rho.

Because L is 1 meter.

So it's very easy -- resistance here, R, is 10 to the -2 ohms.

1/100 of an ohm.

For this material if it were copper.

Let's now take a very good insulator.

Glass is an example.

Quartz, porcelain, very good insulators.

Now, sigma, the conductivity, is extremely low.

They vary somewhere from 10 to the -12 through 10 to the -16.

So rho, now, the resistivity, is something like 10 to the 12 to 12 to the +16, and if I take 10 to the 14, just I grab -- I have to grab a number -- then you'll find that R, now, is 10 to the 20 ohms.

A 1 with 20 zeros.

That's an enormous resistance.

So you see the difference -- 22 orders of magnitude difference between a good conductor and a good insulator.

And if I make this potential difference over the wire, if I make that 1 volt, and if I apply Ohm's Law, V equals I R, then I can also calculate the current that is going to flow.

If I R is 1, then the current here is 100 amperes, and the current here is 10 to the -20 amperes, an insignificant current, 10 to the -20 amperes.

I first want to demonstrate to you that Ohm's Law sometimes holds, I will do a demonstration, whereby you have a voltage supply -- put a V in here -- and we change the voltage in a matter of a few seconds from 0 to 4 volts.

This is the plus side, this is the minus side, I have connected it here to a resistor which is 50 ohms -- we use this symbol for a resistor -- and here is a current meter.

And the current meter has negligible resistance, so you can ignore that.

And I'm going to show you on an oscilloscope -- we've never discussed an oscilloscope, but maybe we will in the future -- I'm going to show you, they are projected -- the voltage is go from 0 to 4, versus the current.

And so it will start here, and by the time we reach 4 volts, then we would have reached a current of 4 divided by 50, according to Ohm's Law, I will write down just 4 divided by 50 amperes, which is 0.08 amperes.

And if Ohm's Law holds, then you would find a straight line.

That's the whole idea about Ohm's Law, that the potential difference, linearly proportional to the current.

You double the potential difference, your current doubles.

So let's do that, let's take a look at that, you're going to see that there -- and I have to change my lights so that you get a good shot at it -- oh, it's already going.

So you see, horizontally, we have the current, and vertically, we have the voltage.

And so it takes about a second to go from 0 to 4 -- so this goes from 0 to 4 volts -- and you'll see that the current is beautifully linear.

Yes, I'm blocking it -- oh, no, it's my reflection, that's interesting.

Ohm's Law doesn't allow for that.

So you see how beautifully linear it is.

So now, you may have great confidence in Ohm's Law.

Don't have any confidence in Ohm's Law.

The conductivity sigma is a strong function of the temperature.

If you increase the temperature, then the time tau between collisions goes down, because the speed of these free electrons goes up.

It's a very strong function of temperature.

And so if tau goes down, then clearly, what will happen is that the conductivity will go down.

And that means rho will go up.

And so you get more resistance.

And so when you heat up a substance, the resistance goes up.

A higher temperature, higher resistance.

So the moment that the resistance R becomes a function of the temperature, I call that a total breakdown of V equals I R, a total breakdown of Ohm's Law.

If you look in your book, they say, "Oh, no, no, no, that's not a breakdown.

You just have to adjust the re- the resistance for a different temperature." Well, yes, that's an incredible poor man's way of saving a law that is a very bad law.

Because the temperature itself is a function of current, the higher the current the higher the temperature.

And so now, you get a ratio, V divided by I, which is no longer constant.

It becomes a function of the current.

That's the end of Ohm's Law.

And so I want to show you that if I do the same experiment that I did here, but if I replace this by a light bulb of 50 ohms -- it's a very small light bulb, resistance when it is hot is 50 ohms, when it is cold, it is 7 ohms.

So R cold of the light bulb is roughly 7 ohms, I believe, but I know that when it is hot, it's very close to the 50 ohms.

Think it's a little lower.

What do you expect now?

Well, you expect now, that when the resistance is low in the beginning, you get this, and then when the resistance goes up, you're going to get this.

I may end up a little higher current, because I think the resistance is a little lower than 50 ohms.

And if you see a curve like this, that's not linear anymore.

So that's the end of Ohm's Law.

And that's what I want to show you now.

So, all I do is, here I have this little light bulb -- for those of you who sit close, they can actually see that light bulb start glowing, but that's not important, I really want you to see that V versus I is no longer linear, there you go.

And you see, every time you see this light bulb go on, it heats up, and during the heating up, it, um, the resistance increases.

And it's the end of Ohm's Law, for this light bulb, at least.

It was fine for the other resistor, but it was not fine for this light bulb.

There is another way that I can show you that Ohm's Law is not always doing so well.

I have a 125 volt power supply, so V is 125 volts -- this is the potential difference -- and I have a light bulb, you see it here, that's the light bulb -- the resistance of the light bulb, cold, I believe, is 25 ohms, and hot, is about 250 ohms.

A huge difference.

So if the resistance -- if I take the cold resistance, then I would get 5 amperes, but by the time that the bulb is hot, I would only get half an ampere.

It's a huge difference.

And what I want to show you, again with the oscilloscope, is the current as a function of time.

When you switch on a light bulb, you would expect, if Ohm's Law holds, that when you switch on the current -- or switch on the voltage, I should say -- that you see this.

This is then your 5 amperes.

And that it would stay there.

That's the whole idea.

Namely, that the voltage divided by the current remains a constant.

However, what you're going to see is like this.

Current goes up, but then the resistance goes down, then the resistance goes up, when the current goes up, the resistance goes up, and then therefore the current will go down, and will level off at a level which is substantially below this.

So you're looking there -- you're staring at the breakdown of Ohm's Law.

And so that's what I want to show you now.

So, here we need 125 volts -- and there is the light bulb, and when I throw this switch, you will see the pattern of the current versus time -- you will only see it once, and then we freeze it with the oscilloscope -- turn this off -- so look closely, now.

There it is.

Forget these little ripples that you see on it, it has to do with the way that we produce the 125 volts.

And so you see here, horizontally, time, the time between two adjacent vertical lines is 20 milliseconds.

And so, indeed, very early on, the current surged toward -- to a very high value, and then the filament heats up, and so the resistance goes up, the light bulb, and the current just goes back again.

From the far left to the far right on the screen is about 200 milliseconds.

That's about 2/10 of a second.

And here you get a current level which is way lower than what you get there.

That's a breakdown of Ohm's Law.

It is actually very nice that resistances go up with light bulbs when the temperature goes up.

Because, suppose it were the other way around.

Suppose you turn on a light bulb, and the resistance would go down.

Light bulb got hot, resistance goes down, that means the current goes up.

Instead of down, the current goes up.

That means it gets hotter.

That means the resistance goes even further down.

That means the current goes even further up.

And so what it would mean is that every time you turn on a light bulb, it would, right in front of your eyes, destruct itself.

That's not happening.

It's the other way around.

So, in a way, it's fortunate that the resistance goes up when the light bulbs get hot.

All right.

Let's now be a little bit more qualitative on some networks of resistors, and we'll have you do a few problems like that, whereby we just will assume, naively, that Ohm's Law holds.

In other words, we will always assume that the values for the resistances that we give you will not change.

So we will assume that the heat that is produced will not play any important role.

So we will just use Ohm's Law, for now, and if you can't use it, we will be very specific about that.

So suppose I have here, between point A and point B, suppose I have two resistors, R1 and R2.

And suppose I apply a potential difference between A and B, that this be plus, and this be minus, and the potential difference is V.

And you know V, this is known, I give you V, I give you this resistance, and I give you that one.

So I could ask you now, what is the current that is going to flow?

I could also ask you, then, what is the potential difference over this resistor alone -- which I will call V1 -- and what is the potential difference over the second resistor, which I call V2?

Very straightforward question.

Well, you apply, now, Ohm's Law, and so between A and B, there are two resistors, in series.

So the current has to go through both, and so the potential difference V, in Ohm's Law, is now the total current times R1 plus R2.

Suppose these two resistors were the same, they had the same length, same cross-sectional area.

If you put two in series, you have twice the length.

Well, so, twice the length, remember, resistance is linearly proportional with the length of a wire, and so you add them up.

So now you know R1 and you know R2, you know V, so you already know the current, very simple.

You can also apply Ohm's Law, as long as it holds, for this resistor alone.

So then you get that V1 equals I times R1, so now you have the voltage over this resistor, and of course, V2 must be the current I times R2.

And so you have solved your problem.

All the questions that I asked you, you have the answers to.

We could now have a slightly different problem, whereby point A is here, but now we have a resistor here, which is R1, and we have here, R2.

This is point B, and this is R2.

And the potential difference is V, that is, again, given, and now I could ask you, what, now, is the current that will flow here?

And then I can also ask you, what is the current that would go through one -- resistor one, and what is the current that could go through resistor two?

And I would allow you to use Ohm's Law.

So now you say, "Aha! The potential difference from A to B going this route, that potential difference, is V, that's a given." So V must now be I1 times R1.

That's Ohm's Law, for this upper branch.

But, of course, you can also go the lower branch.

So the same V is also I2 times R2.

But whatever current comes in here must split up between these two, think of it as water.

You cannot get rid of charges.

The number of charges per second that flow into this juncture continue on, and so I, the total current, is I1 plus I2.

And so now, you see, you have all the ingredients that you need to solve for the current I -- for the current I1, and for the current I2.

And you can turn this into an industry, you can make extremely complicated networks of resistors -- and if you were in course 6, you should love it -- I don't like it at all, so you don't have to worry about it, you're not going to get very complicated resistor networks from me -- but in course 6, you're going to see a lot of them.

They're going to throw them -- stuff them down your throat.

The conductivity of a substan- substance goes up if I can increase the number of charge carriers.

If we have dry air, and it is cold, then the resistivity of cold, dry air at 1 atmosphere -- so rho for air, cold, dry, 1 atmosphere -- cold means temperature that we have outside -- it's about 4 times 10 to the 13.

That is the resistivity of air.

It is about what it is in this room, maybe a little lower, because the temperature is a little higher.

If I heat it up -- the air -- then the conductivity will go up.

Resistivity will go down, because now, I create oxygen and nitrogen ions by heating up the air.

Remember when we had this lightning, the step leader came down, and we created a channel full of ions and electrons, that had a very low resistivity, a very high conductivity.

And so what I want to demonstrate to you, that when I create ions in this room, that I can actually make the conductivity of air go up tremendously.

Not only will the electrons move, but also the ions, now, will start to move.

And the way I'm going to do that is, I'm going to put charge on the electroscope -- oh, that is not so good -- no harm done.

I'm going to put charge on the electroscope, and you will see that the conductivity of air is so poor that it will stay there for hours.

And then what I will do, I will create ions in the vicinity of the electroscope.

But let's first put some charge on the electroscope.

I have here a glass rod and I'll put some charge on it.

OK, that's a lot of charge.

And, uh, the r- the air is quite dry, conductivity is very, very small, and so the charge cannot go off through the air to the surroundings, to the earth.

But now I'm going to create ions there by heating it up, and I decided to do that with a candle, because a candle is very romantic, as we all know.

So here I have this candle -- look how well the charge is holding, eh?

-- and here's my candle.

And I will bring the candle -- oh, maybe 20 centimeters from the electroscope.

Look at it, look at it, already going.

It's about fifteen centimeters away.

I'll take my candle away, and it stops again.

So it's all due to the fact that I'm ionizing the air there, creating free electrons as well as ions, and they both participate now in the current, and the charge can flow away from the electroscope through the earth, because the conductivity now is so much higher.

I stop again, and it stops.

You see in front of your eyes how important the temperature is, in this case, the presence of the ions in the air.

If I have clean, distilled water -- I mean, clean water.

I don't mean the stuff that you get in Cambridge, let alone did I mean the stuff that is in the Charles River, I mean clean water, that has a pH of 7.

That means 1 out of 10 to the 7 of the water molecules is ionized, H+ and OH-.

The conductivity, by the way, is not the result of the free electrons, but is really the result of these H+ and OH- ions.

It's one of the cases whereby not the -- the electrons are maj- the major responsibility for the current.

If I have add 3% of salt, in terms of weight, then all that salt will ionize, so you get sodium plus and Cl- ions, you increase the number of ions by an enormous factor.

And so the conductivity will soar up by a factor of 300000, or up to a million, because you increase the ions by that amount.

And so it's no surprise then, for you, that the conductivity of seawater is a million times higher -- think about it, a million times higher -- than the conductivity of distilled water.

And I would like to give you the number for water -- so this is distilled water -- that is about 2 times 10 to the 5 ohm-meters.

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That is the resistivity, 2 times 10 to the 5 ohm-meters.

I have here, a bucket of distilled water.

I'll make a drawing for you on the blackboard there.

So here is a bucket of distilled water, and in there, is a copper plate, and another copper plate, and here is a light bulb, and this will go straight to the outlet [wssshhht], stick it in, 110 volts.

This light bulb has 800 ohm resistance when it is hot.

You see the light bulb here.

You can calculate what this resistance is between the two plates, that's easy, you have all the tools now.

If you know the distance, it's about 20 centimeters, and you know the surface area of the plates, because remember, the resistance is inversely proportional with A, so you have to take that into account -- and you take the resistivity of water into account, it's a trivial calculation, you can calculate what the resistance is of this portion here.

And I found that this resistance here is about 2 megaohms.

2 million ohms.

So, when I plug this into the wall, the current that will flow is extremely low, because it has to go through the 800 ohms, and through the 2 megaohms.

So you won't see anything, the light bulb will not show any light.

But now, if I put salt in here, if I really manage to put 3% in weight salt in here, then this 2 megaohm will go down to 2 ohms, a million times less.

So now, the light bulb will be happy like a clam at high tide, because 2 ohms here, plus the 800, the 2 is insignificant.

And this is what I want to -- to demonstrate to you now, the enormous importance of increasing ions.

I increased ions here by heating the air, now I'm going to increase the ions by adding salt.

And so the first thing that I will do is, I will stick this in here.

There's the light bulb.

And I make a daring prediction that you will see nothing.

There we go.

Nothing.

Isn't that amazing?

You didn't expect that, right?

Physics works.

You see nothing.

If I take the plates out, and touch them with each other, what will happen?

There you go.

But this water has such a huge resistance that the current is too low.

Well, let's add some -- not pepper -- add some salt.

Yes, there's salt in there.

It's about as much as I would put on my eggs in the morning -- stir a little -- ah, hey, look at that.

Isn't that amazing?

And when I bring them closer together, it will become even brighter, because L is now smaller, the distance is smaller.

I bring them farther apart, it's amazing.

Just a teeny, weeny little bit of salt, about as much as I use on my egg, let alone -- what the hell, let's put everything in there -- that's a [unintelligible] I put everything, then, of course, you go almost down to the 2 ohms, and the light bulb will be just burning normally.

But even with that little bit of salt, you saw the huge difference.

My body is a fairly good conductor -- yours too, we all came out of the sea -- so we are almost all water -- and therefore, when we do experiments with little charge, like the Van de Graaff, being a student, then we have to insulate ourselves very carefully, putting glass plates under us, or plastic stools, to prevent that the charge runs down to the earth.

In fact, the resistance, my resistance between my body and the earth is largely dictated by the soles of my shoe, not by my body, not by my skin.

But if you look at my soles, then you get something like this, and it has a certain thickness, and this, maybe 1 centimeter.

This, now, is L in my calculation for the resistance, because current may flow in this direction, so that's L.

Well, how large is my foot?

Let's say it's 1 foot long -- no pun implied -- and let's say it's about 10 centimeters wide.

So you can calculate what the surface area A is, you know what L is, and if you know, now what the resistivity is for my sole, I can make a rough guess, I looked up the material, and I found that the resistivity is about 10 to the 10.

So I can now calculate what the resistance is in this direction.

And I found that that resistance then, putting in the numbers, is about 10 billion ohm.

And you will say, "Wow!" Oh, it's 4, actually.

Well, big deal.

4 billion ohm.

So you will say, "That's enormous resistance!" Well, first of all, I'm walking on two feet, not on one, so if I would be standing one the whole lecture, it would probably be 4 billion, but if I have two feet on the ground, it's really 2 billion, you will say, "Well, that's still extremely large!" Well, it may look large, but it really isn't, because all the experiments that we are doing here in 26-100, you're dealing with very small amounts of charge.

Even if you take the Van de Graaff -- the Van de Graaff, say, has 200,000 volts -- and let's assume that my resistance is 2 times 10 to the 9 ohms, two feet on the ground.

So when I touch the Van de Graaff, the current that would flow, according to Ohm's Law, would be 100 microamperes.

That means, in 1 second, I can take 100 microcoulombs of the Van de Graaff, but the Van de Graaff has only 10 microcoulombs on it.

So the resistance of 4 billion or 2 billion ohms is way too low for these experiments that we have been doing in 26-100, and that's why we use these plastic stools, and we use these glass plates in order to make sure that the current is not draining off the charge that we need for the experiments.

I want to demonstrate that to you, that, indeed, even with my shoes on -- that means, even with my 2 billion ohm resistance to the ground -- that it will be very difficult for me, for instance, to keep charge on an electroscope.

I'm going to put charge on this electroscope by scuffing my feet.

But, since I keep my -- I have my shoes on, I'm not standing on the glass plate, the charge will flow through me.

You can apply Ohm's Law.

And you will see that as I do this -- I'm scuffing my feet now -- that I can only keep that electroscope charged as long as I keep scuffing.

But the moment that I stop scuffing, it's gone.

Start scuffing again, that's fine, but the moment that I stop scuffing, it goes off again.

Even though this resistance is something like 2 billion ohms.

Let alone if I take my shoes off.

I apologize for that.

If now I scuff, I can't even get any charge on the electroscope, because now, the resistance is so ridiculously low, I don't even have the 2 billion ohms, I can't even put any charge on the electroscope.

It's always very difficult for us to do these experiments unless we insulate ourselves very well.

And if, somehow, the weather is a little damp, we can very thin films of water onto our tools, and then the current can flow off just through these very thin layers of water.

That's why we always like to do these experiments in winter, so that the conductivity of the air is very low, no water anywhere.

Here you see a slide of a robbery.

I have scuffed my feet across the rug, and I am armed with a static charge.

Hand over all your money, or I'll touch your nose.

This person either never took 8.02 or he is wearing very, very special shoes.

See you on Wednesday.