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8.02 Electricity and Magnetism, Spring 2002
Transcript – Lecture 10

We have often talked about power supplies, which are devices which maintain a constant potential difference.

Here, we have such a power supply, potential difference V, this being the plus side, and this being the minus side.

I'm going to connect this, I have a resistor here, R, and as a result of this, current will start to flow in this direction, this direction, this direction, so in the power supply, the current flows in this direction.

Through the resistance, the current flows in this direction.

In what direction is the electric field?

The electric field always runs from plus to minus potential.

So right here, in this resistor, the electric field is in this direction, from plus to minus.

But inside the supply it must also go from plus to minus.

And so inside the supply, the electric field is in the direction that opposes the current.

So some kind of a pump mechanism must force the current to go inside the supply, against the electric field.

A boulder does not, all by itself, move up a hill.

And so something is needed to push it.

You remember, with the Van de Graaff, we were spraying charge onto a belt, and then we rotated the belt, and the belt forces the charge into the dome.

It had to overcome the repelling force of the dome.

So work had to be done.

So the energy must come from somewhere.

And in the case of the Van de Graaff, it was clearly the motor that kept the belt running.

In the case of the Windhurst it was I who turned the crank, so I did work.

In the case of common batteries, the ones that you buy in the store, it is chemical energy that provides the energy.

And I will discuss now with you and demonstrate a particular kind of chemical energy, which is one whereby we have a zinc and a copper plate in a solution.

So we have here, H2SO4, and we have here, zinc plate, and we have here a copper plate.

This side will become positive, and this side will become negative.

You will get a potential difference between these two plates.

To understand that really takes quantum mechanics, this goes beyond this course.

But the potential difference that you get is normally something around 1 volt.

The secret, really, is not necessarily in the solution, because if you take two conductors, two different conductors, and you touch them, metal on metal, there will also be a potential difference.

So let's look at his now in some more detail.

We have here a porous barrier that the ions can flow freely from one side to the other.

And we connect them here, with a resistor, and so a current is now flowing.

A current is flowing in this direction, through the resistor, from the plus side of the battery to the minus side, that means inside the battery, the current is flowing like this, and the electric field, here, is in this direction, from plus to minus, but also inside the battery, the electric field must be from plus to minus, so you see again, as we saw here, that the electric field is in the opposite direction of the current.

You will have here SO4 minus ions, and you have copper plus ions in this solution, and here you have zinc plus and you have SO4 minus.

And as current starts to run, SO4 minus ions, which are now the current-carrier inside this battery, is going from the right -- they're going from the right to the left.

Now why would SO4 minus ions travel through an electric field that opposes them?

That opposes their motion?

And they do that because, in doing so, they engage in a chemical reaction which yields more energy than it costs to climb the electric hill.

And while a current is flowing, while the SO4 minus is going from the right to the left, you get fewer SO4 minus ions here, this liquid here remains neutral, so copper plus must disappear.

And it precipitates onto this copper bar.

So it is like copper-plating.

On this side, you get an increase of SO4 minus, therefore you also must get an increase of zinc plus, because, again, this liquid there remains neutral, and that means that some of the zinc is being dissolved, so you get an increase in the concentration of the zinc.

So the charge carriers inside this battery, the SO4 minus ions, travel through this barrier, and they go from here to here, so they travel through an electric field that opposes their motion.

And this happens at the expense of chemical energy.

Now, when the copper solution becomes very dilute, because all the copper has been plated onto the copper, and when this becomes concentrated zinc plus, then the battery stops, and now what you can do, you can run a current in the opposite direction, so you can run a current, now, in this direction, you can force a current to run with another external power supply, and now the chemical reactions will reverse, so now, copper will go back into the solution, so it will dissolve, and now the zinc will be precipitated onto the zinc, and so now, if you do this long enough, you can run the battery again the way it is here.

A car battery is exactly this kind of battery, except that you have lead and lead oxide instead of zinc and copper, but you also have sulfuric acid, like you have here, and a nickel-cadmium battery is well-known, you can charge that, too, those are the ones that are readily available in the stores, you can run your flashlights with these nickel-cadmium batteries.

The symbol for battery that we will be using in our circuits is this, this is the positive side, and this is the negative side, this is a symbol that symbolizes that we are dealing with a -- with a battery.

So let this point be B, and let this point be A, and here, we have a resistor R.

So we have a current going, the current is going in this direction, a current I.

This could be a light bulb, could be your laptop, could be a hair dryer, whatever, that you supply.

If this R is not there, that means that the resistance is infinitely large, that means that the current that is running is 0, then the voltage that we would measure over this battery, which is VB minus VA -- for which I will simply write down, V of the battery -- that voltage we call a curled E, which stands for EMF, which is electromotive force.

I will show you that later.

If I put a resistance R in here, which is not infinitely large, then a current will start to flow, but now, we should never forget, that between the points A and B, invisible to the human eye, there is always an internal resistance which I call little R of I, and so if a current starts to flow, it goes, not only through capital R, but it will also go through this little R, and so, according to Ohm's Law, the EMF is now I times the external resistance plus the internal one.

The voltage that you would measure between point B and A is now going to change.

That voltage, according to Ohm's Law, is I R, and so it's also the EMF minus I times R of I.

And you see it's a little lower than the EMF.

And the reason is this internal resistance here.

If I shorted out this battery -- stupid thing to do -- but if I make R equal 0 -- so I take the battery and I just short it out -- then, the maximum current that I can draw, then -- so R is now 0, so you can see that the maximum I that you can get is E divided by R of I -- and V of B, the voltage that you would measure now, between point B and A goes to 0.

It doesn't mean that there is no current running, but it means that between these points, your potential difference goes down to 0.

Shorting out a battery, of course, is not a very smart thing to do.

You can put batteries in series, and thereby getting a higher potential difference -- this is the negative side, and this is the positive, I have an independent one, negative positive, and an independent one, negative, positive, each one, with an EMF E, and I can connect the positive side of one with the negative side of the other, just a conducting wire, and the positive side of this with the negative side of the other, and now the potential difference between these two points is now 3E, open circuit, if I don't draw any current.

If I draw a current, then, of course, I have to deal again with the internal resistance.

I'm going to build with you a copper-zinc battery of the kind that we just discussed.

You see it here.

Here's the copper -- copper sulfate solution, which is H2SO4, and here are my plates, this is my zinc plate, and this is my copper plate, and you are going to see the voltage displayed, I think, over there, that is correct -- there's no potential difference now, because they're not in place yet, and so here comes my zinc, and here comes my copper, and they go into the solution, and you see about 1 volt.

In general these potential difference are of that order of 1 volt.

0.95.

So now what I will do, I'm going to create a double one, so I have two independent batteries, I have here one whereby I have copper and zinc, and I have another one whereby I have copper and zinc, and I'm going to connect this one, and you will see now that the EMF will double.

If we're ready for that -- this is my second one, it's going to be completely independent, so here comes the other two plates, make sure that I have the copper and the zinc not confused -- there we go -- and now you should see twice the potential.

And you do see that.

It's open circuit, there is no current running.

Well, there is a minute little small current running through the volt meter that you see.

But that's so small that that's -- can always be ignored.

And you see you get double the EMF.

Now what I will do -- so I have, now, about 2 volts between these two plates, two batteries in series, I now have a little light bulb here, and I'm going to turn on the light bulb.

And now what you will see is that the voltage that you measure right here -- that's all you can do, you can only measure the voltage at the plates of the battery -- that now this voltage will drop, because of the internal resistance of the battery, in addition you will see some light, but that's really not my objective.

For those of you who are sitting close, you can see this light bulb going to be lit.

So I do this now, I can see the light bulb, a little bit of light, and notice that the voltage goes down.

And so this value that you measure now, V of B, is now lower than the 1.9 volts because of this term.

You lose inside the battery through the internal resistance, you lose there potential difference.

All right?

So let's take this out, because this produces a lot of a lot of smelly fumes.

OK.

That's fine.

If a charge moves from point A to point B, and here the potential is VA, and here the potential is VB, and a charge dQ moves -- and let's suppose, for simplicity, that VB minus VA -- yes, let's make the A larger than V B, that's just a little bit easier to think in that -- in those terms.

It's not necessary, of course.

So let's make VA large than VB.

So the electric field is from A to B.

And I move charge from A to B, then the electric field is doing work.

And the work that the electric field is doing, dW, is the charge times the potential difference, which is VA minus VB.

This work can be positive, if the charge is positive, it can be negative if the charge is negative, because we have assumed that this is positive, in this case.

I can now do something that you shouldn't tell your math teachers, but physicists do it all the time, we divide by dT, and now we say, "Aha! What we have on the left side is now work per unit time.

That's power.

Joules per second." So this, now, is power.

dQ dT is current, how many Coulombs per second flow.

So this is current, I.

And the potential difference, I simply call -- I use that symbol, V.

So you see down here that the power delivered by a power supply is the current that it produces times the potential difference.

And this is independent of Ohm's Law, this always holds.

If you also include Ohm's Law, if you can use it -- last time, we discussed the limitations of Ohm's Law -- but if you can use it, and V equals I R, then of course, you can also write down for the power, that it is I squared R, and it is also V squared divided by R.

Power is joules per second, but we write, for that, joules per second, we write for that, watts, just a capital W, but it's named after the physicist Watt.

So we always express the power in terms of watts.

So suppose we have a resistance R, and we run a current through it -- this is the resistance -- we run a current I through it, and let us take an example, that the current I is 1 ampere, and that the resistance is 100 ohm.

Then the power which is dissipated in this resistor has to be provided by your battery, that power P is now 100 watts.

I squared R, if you want to use this.

If it is 2 amperes, and you don't change the resistance, then it becomes 400 watts.

Because it's I squared R.

I doubles, the power, and four times higher.

Now, this energy is dissipated in the form of heat, and if it gets hot enough, then maybe you can produce light, that's the idea behind a light bulb.

The filament into -- in a tungsten incandescent light bulb becomes very high, 2500 degrees Centigrade, maybe even 3000 -- not so high, of course, that the tungsten melts -- and so, you begin to see light.

So, for instance, a 100 watt light bulb -- oh, there's work up here -- so if we have a 100 watt light bulb in your dormitory, and the voltage is 110 volts, you just plug it into the wall, then the current that will run is about 0.9 amperes.

P equals V I.

This product must be 100.

And then the resistance that you have is about 120 ohms.

V equals I R.

So even though it's quite hot -- a light bulb -- the amount of light that it produces is, in general, not more than 20% of this power.

It's not a very efficient thing, an incandescent light bulb.

A fluorescent tube is much better.

So if you have a 40 watt fluorescent tube, you can much more light that you get out of a 40 watt incandescent bulb.

If we take your heaters that you have in your dormitories - typically 2 kilowatts, but let's make it 2200 watts, because that divides nicely through 110 volts -- so then you would have 20 amperes -- that's a lot of amperes.

If the dormitory is very old, chances are that your fuses will go.

20 amperes is more than many houses can handle.

But nowadays, I think most outlets are good for 25 amperes or so.

But not for much more.

And so, now you have a resistor in your heater which is about 5.5 ohms.

Just to give you a feeling for some numbers.

Now, you want heat out of your heater, and you want light out of your light bulb, so you want to keep the temperature of your heater modest, not so high that you get a lot of light.

If you make it 2000 or 2500 degrees, then you would get a lot of light out of your heater.

And so suppose that half of that power would come out in terms of light, and you turn on your heater it night, would be like having a 1000-watt light bulb in your dormitory, you don't want that.

So how do you do -- what do you do now?

Well, you simply keep the temperature about, maybe, 1000 degrees Centigrade, it gets a little red-hot, very little light is produced, and how do you keep the temperature low?

Well, you could cool it with air, some of these heaters have fans that cool them.

Or you just make the resistance, you do both, very large, huge surface area of the resistance, not small, but large, and so now they have a large surface area so they can radiate their heat, and so the temperature remains low.

So if you look at your -- things that you have at home, you have light bulbs, 40 to 200 watts, your toaster, maybe 300 watts.

Your cooking plates and your heaters, something like 2 kilowatts, TV, a few hundred watts, your electric toothbrush probably only 4 watts, very modest.

Your own body produces about 100 watts heat -- of course that's -- energy.

You have a very large surface area, so you don't get nearly as hot as a 100-watt light bulb, because your surface area is large, so you only have a modest 98 degrees Fahrenheit, unless you're running a fever.

So you don't produce any light, because you're not hot enough for that, so you produce infrared radiation, and that's very noticeable.

You hold someone in your arms, the good feeling is, you feel the body heat.

That's the infrared radiation.

That radiates at about 100 joules per second.

100 watts.

An electric blanket is only 50 watts.

So a partner is about twice as effective as an electric blanket.

Maybe also more fun.

The power delivered by a battery is the current that the battery delivers times E, which is this EMF.

And so when a current is running, it is I squared times the sum of the two resistances.

The external one plus the internal one.

We can never bypass that.

The heat that is produced in the external one is I squared capital R, but the heat that is produced inside the battery is I squared little R, you can't avoid that.

And so if you make R 0, by shorting out the battery, then you get a current which is the maximum current that you can get, which is the EMF divided by R of I -- so you've killed the capital R, it's 0 now -- and so -- so you get a power which is the maximum power, which is now E squared divided by R of I.

I maximum squared times R of I.

It's the same thing, it is the maximum current squared times R of I, and all of that comes out inside the battery.

Nothing comes out outside it.

If you have a 9-volt Duracell battery, the ones that we're all so familiar with, so then E is about 9 volts, the EMF, the internal resistance of such a battery is about 2 ohms, and so the maximum current that you can ever get out of a Duracell battery would be about 4.5 amperes, that is I Max, would be about 4.5 amperes, and so P Max would be about 40 watts.

So if you take a 9-volt battery, and you short it out, then the battery should get warm, because all that heat, all that 40 watts is generated inside your battery.

The value for V of B that you measured would go down to 0, if you really could short it out, with a resistor which has 0 resistance.

Now it's, of course, a pretty stupid thing to do, to short out a battery, but it's not dangerous.

40 watts, the thing gets a little warm, big deal.

So let's do it.

So I have, here, the voltage, that you can see, that we measure a 9-volt Duracell battery, I have the battery here.

And you can read it here.

I hope the decimal point is in there, but it's about 9.6 volts.

And now I am going to do something stupid, but, again, it's not dangerous -- I'm going to take my car keys and I'm going to short out the battery.

So simply connect point A with point B, and so the voltage that you're going to see is going -- maybe not go to 0, exactly, because my key may not have 0 resistance, but it goes very low -- and what you cannot experience is something that I can, that this battery will get hot.

These 40 watts will be generated inside here.

It is possible, though, that when the battery gets hot, that the internal resistance may even go up a little because, remember that resistance goes up when temperature goes up, in which case, the power will go down, so it may not be the full 40 watts.

But I can assure you that I can feel this thing getting warm.

So let me short it out, now.

I'm doing this now.

And you read the voltage, I can see it, too here -- oh, it's always not so easy with a key to do that -- here, it's very low, hey, look at that.

It's about a 10th of a volt, and I feel this thing getting hot.

It's really warming up, now.

And so I'm ruining this battery.

This is a terrible thing to do, batteries don't like that.

But, when I take off the external resistance, some of that may come back.

It may not be permanently damaged, and you see, it's already 8.5 volts.

So there's no way that you can start a car with a 9-volt Duracell battery, because you just can't get the current that you need for your starter engine.

Your starter motor needs a few hundred amperes.

If you take a car battery, that's about twelve volts.

It has a very low internal resistance, of about 1/50 of an ohm.

So that means that the maximum current that you can draw, if you short-circuit it, would be something like 600 amperes.

And so the maximum power, if you were so stupid to short-circuit it, that would all be generated inside the battery, would be something like 7 kilowatts.

If you ever work on your car, make sure that you never drop accidentally the wrench that you're using onto the battery.

Because if you did, then inside the battery, about 6 kilowatts, 7000 joules per second, are going to be produced in terms of heat, and the sulfuric acid is going to boil, the case may melt, and that's no good.

Not only is that stupid, but it's also very dangerous.

So let's do it.

I have, here, this battery, and I have here, the wrench.

Just in case.

I'm going to short out that battery, and as I do that, you will clearly see that the battery doesn't like it.

I will be very careful not to hold on to this wrench too long, because it would weld onto it, actually, it can weld on to it and stay there, the current is so high, it can go up to 600 amperes, that it can weld onto it, and then you can't get it off any more.

In case that happens, I will walk out of here.

And I advise you to do the same.

You ready?

OK.

I go now.

You see?

That's what happens.

A very high current, and when you do this too often to batteries, they're not going to live very long, they don't like it.

But I wasn't joking when I said, when you work on the car, that you should avoid this, because I have seen it happen, that wrenches actually welded onto the terminals.

Your electric company charges you for energy, they don't care about the power, how many joules you use per second, but they care about how much energy you're using.

So they will charge you, then, for joules, you think.

That's energy.

However, if you look at your bill, you're being charged for kilowatt-hours.

Well, a kilo is thousands, and an hour is 3600 seconds, so the units of energy for which they charge you is this in joules.

2000 watt cooking plates, you run for 2 hours, that is 4 kilowatt-hours.

They will probably charge you 10 cents per kilowatt-hour -- for that same amount of money, you could run your 100-watt light bulb for 40 hours.

Again, that would be the same 4 kilowatt hours -- or, you could brush your teeth with your electric toothbrush for about 1000 hours.

Now I want to take a look with you at a network which consists of resistors and batteries.

And this is the kind of stuff that you see on homework assignments, and, perhaps, on exams.

And so now, we start out with a very modest circuit, here we have a resistance R1, here we have a resistor R2, and here R3, and then we put a battery in here, and we put the plus side, say, on the left, this the plus side, and minus side, and let the potential difference of this one be V2.

It's really the EMF, but I will ignore any kind of internal resistance of the batteries, it's completely negligible in this problem.

And here I put also a battery, let this be the negative side, and this be the positive side, and let the potential difference be V1.

And so, imagine that you know V1, V2, R1, R2, and R3.

But what I'm going to ask you is, what is I1, what is I2, and what is I3?

I want the magnitude, and I want the direction.

When you look at this, it's by no means obvious that the current in this resistor will be to the right or to the left, it's by no means obvious, it depends on the -- on the values V1 and V2, and on the resistances.

The basic idea behind solving these problems are in what we call Kirchoff's rules.

Kirchoff's first rule is that the closed loop integral over a closed loop of E dot dL is 0.

We've seen that before.

I don't know why Kirchoff gets the credit for this.

0:34:41.6650 This always is the case when we're dealing with conservative fields.

When you start at a particular point, you go around E dot dL, you're back at the same potential where you were before, so this must be 0, as long as you deal with conservative fields.

So that's his first rule.

And you can do this closed loop anywhere.

You can even do it here.

It would still be 0.

You can do it here.

Also 0.

You can do it there.

No matter where you do it, that closed loop integral must be 0.

And then there is the second Kirchoff's rule, and that is what we call charge conservation.

If it is a steady-state situation, then, independent of which junction you go to, the current that flows in must flow out.

Can't have a pile-up of charge.

That's the second rule.

And I gave you a problem, 3-7, to work out, and you can look in the book how that is done.

However, I'm going to work on this with you in a slightly different way than the book is doing it, which I, personally, like better.

But it may confuse you.

So I warn you in advance, you may not want to use my method at all.

What I do is the following.

I say, OK, I assume that there is a closed loop current here, I1.

And that there is a closed loop current here, I2.

Whether I make them clockwise, or counterclockwise, unimportant.

I could have chosen one clockwise, the other counterclockwise, unimportant.

However, once I choose a direction, it has consequences, as you will see.

And that's all that's running.

One current like this, and one current independently like that.

If I assume that, then I have automatically -- automatically, I am obeying the second rule, because a current that goes around is -- charge conservation, right?

There's no charge piling up.

So the second rule of Kirchoff is already obeyed.

So now I go to the first one, and I can start, now, at any point in that circuit, and go around -- I can go around clockwise, I can go around counterclockwise, it makes no difference as long as I return to the same point, that integral E dot dL must be 0.

I'm returning at the same potential.

What is the integral of E dot dL in going from point one to point two?

Well, that's the potential difference between point one and point two.

And so let us start here, and let us go around, and we have to adopt a certain convention, namely, if we go up in potential, and we go down in potential.

Again, you're free to choose the sign convention.

But I would say, when I go up in potential, I give that a plus sign, when I go down in potential, I give that a minus sign.

So I start here.

I could have started there, I could have started there, makes no difference, as long as I don't start here, that makes no sense.

So I start here, and I go around like this.

So right here, I go down in potential, V1.

So I get minus V1.

Now I go with current I1 in the direction, from left to right, so that means that the potential here must be higher than there.

V equals I R.

Potential here must be higher than there.

So I go down in potential, so I get minus I1, R1.

Now I go through R3.

This current, I1, is going down, so this has a higher potential than here, so I go down in potential, so I get minus I1 times R3.

But I have, independently, a current I2 which is now coming towards me when I go down.

And so if it comes towards me, that current would give me an increase in potential.

This would have to have a higher potential than this, for this current to do this.

So now I climb up the potential hill, so I get now plus I2 times R3 [recording slows down.] [normal speed] Uh-oh, look what I did, I wrote down I1 R, there is no capital R in the whole problem.

I clearly meant I1 R1.

Sorry for that, you should read this as minus I1 R1.

[recording starts slow, speeds up to normal] I'm back where I was, because these wires have no resistance.

And so I'm back where I am, so this is 0.

One equation with two unknowns, I1 and I2.

So now, let's go around this one.

We can go clockwise, we can go counterclockwise, makes no difference.

Let's start here, and I go in this direction, once around.

So now, I go through R3, and this current I2 is running in this direction, so I go down in potential.

So I get minus I2 times R3.

But current I1 is coming towards me.

See, if I go in this direction, I1 is coming towards me, so I climb up the potential hill.

So I got plus I1 times R3.

Now I go through R3 in this direction, current I2 is also in this direction, and so this must have a higher potential than this, so I go downhill in potential, so I have minus I2 times R2.

I come down here -- ah, here's a battery.

And it goes up in potential.

So I get plus V2, and that's 0.

Two equations with two unknowns.

I can solve for I1, and I can solve for I2.

So I1 and I2 pop out.

Let us assume that I1 is positive, I find a positive value.

It means, it's really in this direction.

Let's suppose that I1 is negative.

I find -3 amperes.

Well, it means that I1 is in this direction, big deal.

And so the whole operation is sign-sensitive.

And the same is true here.

If I2 is positive, it means it's in this direction.

If I2 is negative, then it's in that direction.

How about I3 now?

Well, let us assume that I1 is plus 3 amperes, and that you find that I2 is plus 1 ampere.

That's possible, right?

You have two equations, two unknowns, and these are the answers.

So 3 amperes goes like this [wssshhht], down, and 1 ampere comes up.

Well, it's clear, then, that I3 is 3-1, is +2.

Another way of looking at it is, 3 amperes come in at this juncture, I2 is 1 ampere, so 1 ampere goes through, so 2 must go down.

That's really Kirchoff's second rule.

If I1 were plus 1 ampere, and I2 was also plus 1 ampere, then I3 will be 0.

No current would flow through I3.

But my method would still work.

I find 1 ampere going down, and 1 ampere going up, so there's no -- no current going through R th- there's only current going in this direction, 1 ampere.

And so, you have to recognize, then, that I3 is I1 minus I2, which is really application, then, of Kirchoff's second rule.

I like this idea, of a closed loop current, I know that some of you don't like it, that's fine.

The reason why I like it is, I always end up, in this case, with two equations with two unknowns, I solve for I1, I solve for I2, and then the third one comes out in natural way by just thinking, "Ah! One current goes in this direction and the other goes in that direction." But if you prefer the method that the book will present to you, you get three equations with three unknowns, and you get I1, I2, and I3, right at the start, you get an I3.

You see, I don't even start off with an I3, it's not there, it comes in later.

So the choice is yours.

Now I want to entertain you for the last 6 minutes with something amazing, something that is truly amazing.

And it is a form of a battery that is mind-boggling.

And the battery is right here, on my -- my left, on your right.

It is a battery that produces an enormous potential difference, 10, 20 kilovolts -- you see a schematic here on the transparency, you have a bucket of water, here on the top, and you have glass, and the bucket of water is hiding behind here -- it's not that because we hide it from you, but that's the best place to be -- and you see plastic tubing coming down, and the water can run out on the right, and it can run out on the left.

It runs out here, there is a, uh -- some paint can, no top and no bottom.

And you see this paint can here, it's completely open.

There's a letter A.

And there's another paint can on the right, there's a letter B.

It's a conducting can.

And this is also a conducting can.

And this water runs into another conducting trash can, and this water also runs into a conducting trash can.

And now comes the key point, that this conductor here, A, is connected through a conducting wire with C, and the conductor B, the paint can, is connected with a conducting wire to this trash can D.

You let the water run for a while, and you will see, between there two points here, sparks.

Even when the points are as far apart as, say, 5 millimeters, when you're talking about at least a potential difference of something like 10, 15000 volts, [poit], you will see the sparks.

And you wait, see another spark.

And you wait, and you see another spark.

So this is a power supply.

And there must be energy coming from somewhere.

And so, problem 4-1, which you haven't seen yet, on your fourth assignment, is asking you how this works.

I will demonstrate it today, and I will come back to it later.

The way it works is actually quite subtle, but I want you to think about it.

It's a remarkable battery, a remarkable power supply.

As the water starts running, I want to draw your attention to the fact that you can almost anticipate when the start -- when the spark occurs, because the water, at the very last, is beginning to spread.

It doesn't come out any more, just like a narrow cylinder, but it begins to spread.

And then comes the spark.

And then it goes back to running normally, and then slowly, in time, it will spread, and then comes the spark.

So let us get it going, have some light here, Marcus and Bill spent a lot of time getting this going -- Marcus, do we have -- are my lights the way you want them?

You're happy with that.

There, you see the two balls, which are really here and let's first look at the sparks, so I will start the water running now.

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Let's just be patient a little bit.

And let's see when we see a spark.

Keep -- ah! Did you see one?

Did you see the spark?

Oh, you were not looking.

Man, you're paying for this.

Look at the, uh, look at the two balls.

Give it some time again.

I have to charge up.

Oh, I can already anticipate, it's coming up, it's coming up, dah! Did you see it?

10, 15000 volts.

Let's give it a little bit more time, and then we'll take a look at the water flow, which I can see, I'm close, but we can make you see the water flow.

Look again.

Ah, it's coming up -- ah! Did you see?

I could see it coming up.

I can make you listen by having my microphone near the water, and you can hear this water running, familiar sound to all of us.

And now, the sound changes, you hear change?

And there's the spark! Once more.

It's running, spreading, coming up! Yah! Amazing, isn't it?

I can make you see this water.

Just stay there, we have one and a half minutes left.

So now you can see the water.

You happy with the light, Marcus?

You can improve on it.

So look at the water.

Ah! It was just spreading already, you can't see the spark and the water at the same time.

See, the water's running, now, normally?

It's going to spread slowly -- I will tell you when I see the spark here, but it's already -- I can almost predict when it happens.

The water is spreading now , coming up shortly -- yah! I saw the spark.

And you immediately see the water go like this.

I want you to think about it and explain this.

This is one of the most remarkable things I've ever seen in my life.