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Transcript – Lecture 7

...assemble charges, I have to do work, we discussed that earlier.

And we call that electrostatic potential energy.

Today, I will look at this energy concept in a different way, and I will evaluate the energy in terms of the electric field.

Suppose I have two parallel plates, and I charge this one with positive charge, which is the surface charge density times the area of the plate, and this one, negative charge, which is the surface charge density negative times the area of the plate.

And let's assume that the separation between these two is h, and so we have an electric field, which is approximately constant, and the electric field here is sigma divided by epsilon 0.

And now, I'm going to take the upper plate, and I'm going to move it up.

And so as I do that, I have to apply a force, because these two plates attract each other, so I have to do work.

And as I move this up, and I will move it up over distance X, I am creating here, electric field that wasn't there before.

And the electric field that I'm creating has exactly the same strength as this, because the charge on the plates is not changing when I am moving, the surface charge density is not changing, all I do is, I increase the distance.

And so I am creating electric field in here.

And for that, I have to do work, that's another way of looking at it.

How much work do I have to do?

What is the work that Walter Lewin has to do in moving this plate over the distance X?

Well, that is the force that I have to apply over the distance X.

The force is constant, and so I can simply multiply the force times the distance, that will give me work.

And so the question now is, what is the force that I have to apply to move this plate up?

And your first guess would be that the force would be the charge on the plate times the electric field strength, a completely reasonable guess, because, you would argue, "Well, if we have an electric field E, and we bring a charge Q in there, then the electric force is Q times E, I have to overcome that force, so my force is Q times E." Yes, that holds most of the time.

But not in this case.

It's a little bit more subtle.

Let me take this plate here, and enlarge that plate.

So here is the plate.

So you see the thickness of the plate, now, this is one plate.

We all agree that the plus charge is at the surface, well, but, of course, it has to be in the plate.

And so there is here this layer of charge Q, which is at the bottom of the plate.

And the thickness of that layer may only be one atomic thickness.

But it's not 0.

And on this side of the plate, is that electric field, which is sigma divided by epsilon 0.

But inside the plate, which is a conductor, the electric field is 0.

And therefore, the electric field is, in this charge Q, is the average between the two.

And so the force on this charge, in this layer, is not Q times E, but is one-half Q times E.

So I take the average between these E fields, and this E field is then this value.

And so now I can calculate the work that I have to do, the work that I have to do is now my force, which is one-half Q times E, and I move that over a distance X.

And so what I can do now is replace Q by sigma A, so I get one-half sigma A times E times X, and I multiply upstairs and downstairs by epsilon 0, so that's multiplied by 1.

And the reason why I do that is, because then I get another sigma divided by epsilon 0 here -- divided by epsilon 0, and that is E, and therefore, I now have that the total work that I, Walter Lewin have to do -- has to do is one-half epsilon 0 E-squared times A times X.

And look at this.

A X is the new volume that I have created, it is the new volume in which I have created electric field.

And this, now, calls for a work done by Walter Lewin.

Per unit volume, and that, now, equals one-half epsilon 0 times E squared.

This is the work that I have done per unit volume.

And since this work created electric field, we called it "field energy density".

And it is in joules per cubic meter.

And it can be shown that, in general, the electric field energy density is one-half epsilon 0 E squared, not only for this particular charge configuration, but for any charge configuration.

And so, now, we have a new way of looking at the energy that it takes to assemble charges.

Earlier, we calculated the work that we have to do to put the charges in place, now, if it is more convenient, we could calculate that the electrostatic potential energy, is the integral of one-half epsilon 0 E-squared, over all space -- if necessary, you have to go all the way down to infinity -- and here, I have now, dV, this is volume.

This has nothing to do with potential, this V, in physics, we often run out of symbols, V is sometimes potential, in this case, it is volume.

And the only reason why I chose H there is I already have a D here, so I didn't want 2 Ds.

Normally, we take D as the separation between plates.

And so this, now, is another way of looking at electrostatic potential energy.

We look at it now only from the point of view of all the energy being in the electric field, and we no longer think of it, perhaps, as the work that you have done to assemble these charges.

I will demonstrate later today that as I separate the two plates from these charged planes, that indeed, I have to do work.

I will convince you that by creating electric fields that, indeed, I will be doing work.

So, from now on, uh, we have the choice.

If you want to calculate what the electrostatic potential energy is, you either calculate the work that you have to do to bring all these charges in place, or, if it is easier, you can take the electric field everywhere in space, if you know that, and do an integration over all space.

We could do that, for instance, for these two parallel plates now, and we can ask what is now the total energy in these plates -- uh, in the field.

And at home, I would advise you, to do that the way that it's done in your book, whereby you actually assemble the charges minus Q at the bottom and plus Q at the top, and you calculate how much work you have to do.

That's one approach.

I will now choose the other approach, and that is, by simply saying that the total energy in the field of these plane-parallel plates, is the integral of one-half epsilon 0 E-squared, over the entire volume of these two plates.

And since the electric field is outside 0, everywhere, it's a very easy integral, because I know the volume.

The volume that I have, if the separation is H -- so we still have them H apart -- this volume that I have is simply A times H, and the electric field is constant, and so I get here that this is one-half epsilon 0.

For E, if I want to, I can write sigma divided by epsilon 0, I can square that, and dV, in doing the integral over all space, means simply I get A times H, it is the volume of that box.

So I get A times H.

And so this is now the total energy that I have, I lose one epsilon here, I have an epsilon 0 squared and I have an epsilon.

I also remember that the charge Q on the plate is A times sigma, and that the potential difference V, this now is not volume, it's the potential difference between the plates, is the electric field times H.

The electric field is constant, it can go from one plate to the other, the integral E dot dL in going from one plate to the other, gives me the potential difference.

And so I can substitute that now in here, I can take for A, sigma, I can put in the Q, and you can also show that this is one-half Q V.

V being, now, the potential difference between the plates.

And so this is a rather fast way that you can calculate what the total energy is in the field, or, say, the same thing, the total work you have to do to assemble these charges.

Or, to say it differently, the total work you have to do to create electric fields.

You have created electric fields that were not there before.

I now will introduce something that we haven't had before, that is the word "capacitance".

I will define the capacitance of an object to be the charge of that object divided by the potential of that object.

And so the unit is coulombs per volt, this V is volt, now, it's potential.

Uh, but we never say that it is coulombs per volt in physics, we write for that a capital F, which is Farad, we call that, 1 farad is the unit of capacitance, undoubtedly called after the great maestro Faraday, we will learn more about Faraday later in this course.

So let us go to, um, a sphere which has a radius R, and let us calculate what the capacitance is of this sphere.

Think of it as being a conductor, and we bring a certain charge Q on this conductor, it will then get a potential V, which we know is Q divided by 4 pi epsilon 0 R.

We've seen this many times, and so, by definition, the capacitance now is Q divided by the potential, and therefore, this becomes 4 pi epsilon 0 R.

So that is the capacitance of a single sphere.

And so we can now look at the values as a function of R.

I have here some numbers, I calculated it for the Van de Graaff, and I calculated it for the Earth.

If you want 1 Farad capacitance, that's a real biggie, you need a radius of 9 times 10 to the 9 meters, that's the 4 pi epsilon 0 that comes in there.

That's huge, that's 25 times the distance from the Earth to the moon, that's a big sphere to have a capacitance of 1 Farad.

The Earth itself, with a radius of 6400 kilometers, would have 700 microfarad, the Van de Graaff, 30 centimeters radius would be 30 picofarad, the pico is 10 to the -12.

And if you take a sphere with a radius of 1 centimeter, then you have, uh, roughly, 1 picofarad, 10 to the -12 Farad.

So this gives you a rough idea about the size of objects, and how they connect to their capacitance.

So if I bring all these spheres, uh, at the same potential, so I charge them all up to the same potential, then the one with the largest capacitance, uh, will have the most charge.

And that, of course, is where the word "capacitance" comes from, it is the capability of holding charge for a given, uh, electric potential.

Don't confuse that with electric fields, because if you bring all these spheres at the same potential, then the one with the strongest electric field, that's the one which has the short -- smallest radius, we discussed that last time.

Now, I will look at the situation a little bit differently.

I have, here, a sphere, B, positively charged, and I place it close to another sphere, A, which is negatively charged.

And so, by my definition, I can say that the capacitance of B is the charge that I have on B divided by the potential of B.

That will be my definition.

But, there is here, this object which charged negative.

And how did we define potential?

Potential was work per unit charge.

I go to infinity, I put plus Q in my pocket, I approach B, and the work I have to do per unit charge is the potential of B, that's the definition of potential.

But B is repelling me.

So I have to do positive work.

But A is now attracting me.

And so the work I have to do is less the work per unit charge.

And so, because of the presence of A, the potential of B goes down, and therefore, the capacitance of B goes up.

And so now, you see that that the presence of this charged sphere here has an influence, an important impact, on the capacitance of B, and, therefore, it is really unclear to call this the capacitance of B.

We think of it as the capacitance of B in the presence of A.

So it's no longer just B alone.

And so I'm now going to change the definition of capacitance.

And I'm going to change it in the following way.

I have two conductors.

And these two conductors have the same charge, but different polarities.

And now the capacitance of this combination of two conductors is the charge on one of them -- which is the same, of course, on the charge of the other, except different polarity -- divided by the potential difference.

So that, now, is my new definition of capacitance.

So we always deal with two objects, not with one in isolation, if you have the charge on one of the two, and you divide it by the potential difference between the two.

Uh, you may say, "Well, it's a little artificial to have two conductors and one is positively charged, and the other has exactly the same amount of negatively charge." Well, it is not so artificial as you may think.

Uh, remember, then, we have this Windhurst machine, which I was cranking, and I was charging one plate positive and the other one negative.

And without my doing anything, if one becomes positive, the other one becomes negative by exactly the same amount, because you cannot create charge out of nothing.

So if you charge one thing positive, chances are that something else is charged negative by the same amount, but with opposite polarity.

So it's not so artificial, that you have two conductors with the same charge but opposite polarities.

So, now, we have two conductors there, so if we go to this -- these two parallel plates, the question, now, is what is now the capacitance, then, according to our new definition of these parallel plates?

Well, that capacitance C, is the charge on one plate divided by the potential difference between the two plates.

And the charge on one plate is sigma A.

And the potential difference between the plates is the integral of E dot dL, they are separated there by a -- a distance H.

I will change that, now, to a D, because that's more commonly done, that the separation between plates is D.

There was a reason why I didn't want to put a D there, because I didn't want to get you confused, but now, there is no confusion.

And so the potential difference is the electric field between the plates times the distance D.

But E itself is sigma divided by epsilon 0, so we get here, sigma divided by epsilon 0, divided by D, I lose my sigma, and so, two parallel plates have this as the capacitance.

It's linearly proportional with the area of the plates, that's intuitively pleasing.

The larger the plate, the more charge you can put on there.

And it's inversely proportional with the distance between the plates.

The smaller you make the distance, the larger is the capacitance.

Well, that goes back to this idea, that the closer A is to B, the larger effect that will have on the capacitance.

And if you bring them very close together, this potential will go down, and so the capacitance will go up.

So it's not too surprising that you see D here downstairs.

The closer you bring the plates together, the higher, uh, the capacitance will be.

Let us look at at some numbers.

Suppose I have a plate, It's very large, 25 meters long, and 5 centimeters wide -- 25 meters long, and 5 centimeters wide.

I have two of them.

Called a plate capacitor.

And let the distance between them, D, let D be -- oh, let's make it very small, because we want a real big capacitor, .01 millimeters.

Very small gap between them.

So, now I substitute the numbers in there, I can calculate the area, I have to calculate the area here for the plates in square meters, of course, multiplied by epsilon 0, and divided by D in meters, and when you do that, you find that the capacitance of this big monster is only 1 microfarad.

It's not very much.

And when you go to Radio Shack, and you buy yourself a 1 microfarad capacitor, you don't by something that is 25 meters long, and yea big.

Well, you may actually have -- you may actually buy that without you realizing that.

Because these large plates, these very long ribbons of conductors, two very close together, separated by some insulating material, very thin, they're rolled up often.

And you don't notice that, but they are rolled up, and they are put in a little canister, and that then gives you a parallel plate capacitor.

Uh, I brought one with me, that is one that I have used for several years, but, today I decided to cut it open for you so that you can look inside, and then you actually will see the, um, you're going to see, there, this is the canister in which it was, and so I cut the canister open, and when you look here, you see, there is this conductor -- looks like aluminum foil -- and then there is insulating material, and then you find more conductor, on the other side.

And so you -- and it's rolled up.

Here, if I unroll it here -- I'm breaking it, but that's OK -- so you see the idea of a parallel plate capacitor, how it can be rolled up nicely, and you not realizing that you're really talking often about meters, many meters of material.

Now, through chemical techniques, the distance D can easily be made 1000 times smaller than this.

And if the distance is 1000 times smaller, then you would get a capacitance of 1000 microfarads.

Compare that with the Earth, which is only 700 microfarads.

So a capacitor like this is 1000 microfarads.

If we bring the potential difference over here, then we get a tremendous amount of charge on here.

In fact, if I hold this in my hands, and if I assume that the potential difference between my left hand and my right hand is 10 millivolts, then I would bring on this capacitor, 10 microcoulombs.

That is a tremendous amount of charge.

In fact, 10 microcoulombs is the maximum charge we can ever put on the big Van de Graaff, we calculated it last time.

If we put more on the Van de Graaff, it goes into discharge.

And by simply holding this in my hands, I could put 10 microcoulombs here on this capacitor.

Now, you may say, "Well, yes, but, uh, potential difference would be your right hand and your left hand, 10 millivolts, isn't that funny?

No, not really.

Uh, in the future, I will give a lecture and then discuss electrocardiograms.

And you will see, then, that there is a potential difference between the left side of your body and the right side which is several millivolts.

So it is not as artificial as you may think.

Actually, we'll take a cardiogram in -- in class, so you can see it really working.

How much energy can I store in a capacitor?

Well, we already calculated that.

Uh, we had the energy, is it, uh this was the plate capacitor, one-half Q V, and we can now substitute for, we can substitute in there the capacitance C, and the C is Q divided by V, and so this is also one-half C V-squared, that's one and the same thing.

So either you take the charge on the capacitor, multiply it by V, or you take the capacitance and multiply it by V-squared.

The capacitance is never a function of the charge that is on the object.

V- if you look here, the capacitance is only a matter of geometry.

And when you look there, the plate capacitor, it's only a matter of geometry, never does the charge show up in there.

So I mentioned that I can bring 10 microcoulombs on this capacitor, and yet, on the Van de Graaff, I can also only bring 10 microcoulombs, that's the maximum I can do before it goes into breakdown.

We can think of a capacitor as a device that can store, uh, electric energy.

I will now return to my promise that I was going to demonstrate to you that I have to do positive work when I create electric fields.

In other words, when I take these two charged plates, and I bring them further away from each other, that I do positive work.

And how am I going to show that to you?

I have two parallel plates.

They're on the table there, you're going to see them shortly, projected there.

And we have, here, a current meter -- I put an A in there for amperes, symbolic for current meter -- and I'm going to have a power supply and put a potential difference over here, this is the capacitance C -- we normally use for capacitor the symbol of two parallel lines -- I'm going to put a potential difference V over the capacitor of 1000 volts.

So let me put a delta here to remind you that it's the difference between the two plates.

As I do that, as I connect the power supply to these two ends, charge will flow on here, and so you will see a very short surge of current.

So the amp meter will give you, only for the short amount of time that I am charging [wssshhht], will see you -- will show you that there is charge flowing.

And you will see that.

But that's not really the goal of my demonstration.

What I'm now going to do is, I'm now going to increase the separation, the distance D of these two plates.

And remember that the potential difference over the capac- over the plates, which I call now a capacitor, is the electric field times the distance, and the electric field is constant.

If I charge the capacitor up with a certain charge, there is plus Q here, there's minus Q there, and then I remove the power supply, it's no longer there, that charge is trapped, that charge can never change.

And so if the charge doesn't change, the charge surface density doesn't change, and so the electric field inside remains constant.

So exactly what we did there.

And now I'm going to move them further apart, therefore I'm going to make D larger, and that can only happen if the potential difference between the plates increases.

And I will start off with 1000 volts, whereby D is 1 millimeter, and then I will open up this gap up to 10 millimeters.

And then I have a potential difference of 10000 volts.

But since the energy in the capacitor is one-half Q times the potential difference V -- this V is the same as this delta V -- and if Q is not changing, but if I go from V from 1000 volts to 10000 volts, it's very clear that I have done work, I have increased the electrostatic potential energy.

And this is what I want to show you, we're going to have that there -- so I've changed my television, and I will have to change the lights a little bit so that you can see that -- well, turn this one off, this one off, and all them -- let's wait for the light to settle, and we want also the the current meter.

So the one on the right there is the, uh -- the amp meter, the current meter, and you see here these two plates, they are separated now by about 1 millimeter.

I have here a very thin sheet, transparency which I can move in between to make sure that they don't make contact -- and here is my power supply, and I have there, this, uh, propeller-type thing which is some kind of a volt meter.

And if it's going to move in this direction, that means that the voltage between the plates increases.

And so I'm going to charge it now, with a potential difference of 1000 volts, and as I do that, you will see a very short surge here on this amp meter.

That's not very spectacular, but at least you can see, for the first time in your life, that charge is actually flowing from my power supply onto the plates.

Then you will see, [pssshhht], and that's it.

There will only be a current as long as the charge is flowing.

So let me first do that, look at the amp meter there, three, two, one, zero.

That's all it took to charge these plates.

It's now fully charged, 1000-volt difference, and now, as I'm going to increase the gap, there's no reason for any charge to go away from the plates, so the amp meter will not do much, probably nothing, but you're going to see this propeller which indicates the potential difference between the plates, you're going to see it move, because I'm doing all this work, I'm going from 1 millimeter to 10 millimeters, I'm creating all this electric field, and this hard work pays off in terms of increasing the potential from 1000 volts to 10000 volts.

So there I go, I'm 2 millimeters now, look at the volt meter, there's going -- aargh, 3 millimeters, I'm doing all this hard work while you're doing nothing -- 4 millimeters, I'm creating electric fields -- you should be proud of me, I'm creating electric field, look at that.

The electric field remains constant between the plates, because the charge is trapped, the charge can't go anywhere.

I'm now at 7 millimeters, 7000 volts, 8000 volts, I'm at 9 millimeters, 9000 volts -- notice that the amp meter does nothing, no charge is flowing to the plates, no charge is flowing from the plates, I'm now at 10 millimeters, and now I have created a huge volume electric field, and the potential difference is 10 times larger than it was before, and so, you see that I, indeed, have done work.

You see it here in front of your own eyes.

All right, let's get this down, and I'll take the -- bring the lights back up, and we go back to normal.

I have here a 100 microfarad capacitor -- it's a dangerous baby -- and we can charge that up to 3000 volts, and when we do that, we get 3/10 of a Coulomb of charge on that capacitor.

So the, um, I'll give you some numbers -- so it is 100 microfarads, I'm going to put a potential difference over it of 3000 volts, that gives it a charge Q of 0.3 Coulombs, and that means that one-half C V squared, which is the energy that is stored, then, in the capacitor, is 450 joules.

And this will take fifteen minutes.

And so th- I'm going to charge it now, because at the end of the lecture, I need a charged capacitor for a demonstration.

And so I can show you there the potential difference over the capacitor, which will slowly change, and we'll keep an eye on it during the lecture, and then, by the time it's fully charged, we will have reached the end of the lecture and then we can continue.

So here is, then, this monster, the 100 microfarad -- I call it a monster because the amount of energy that you can pump in there is frightening, it's 450 joules.

And my power supply is here, that will deliver, comfortably, the 3000 volts.

In fact, this is the voltage of the power supply, this is about 3800 volts.

And so, now, the idea is that I'm going to charge this capacitor -- always have to be very slow and careful that I don't make mistakes, because this is really a device that could be lethal if you are not careful.

So I think we're OK.

Uh, the moment that I'm going to charge this capacitor, the reading there will show you the potential difference over these plates, and it will take a long time for that to go up to 3000 volts.

And so I think I'm ready to go, and I'm going to charge it now.

So you see now that the potential difference over the plates is very low, it's near 0, but if you wait just a -- a few seconds, you will see, very slowly, that, um, it is charging up, and 15 minutes from now, we will be very close to the 3000 volt mark, and then we will return to this.

So we'll leave it on just for now, while it is charging.

The idea of a photo flash is that you charge up a capacitor, and that you discharge it over a light source.

So the idea being that you have a capacitor -- let me erase some of this -- and that we charge the capacitor up, put a certain amount of energy in there, and then we dump all that energy in a bulb.

So here is the capacitor, we're going to charge it up, we have a switch here, and here is a light bulb, and when we throw the switch, then all the energy will be going to the light bulb, if this is positively charged and this is negatively charged, a current will start to flow, and you will see a flash of light.

I have, here, a capacitance of 1000 microfarad.

So C equals 1000 microfarad, I'm going to put a potential difference over that capacitor of 100 volts, which then gives me a energy of one-half C V squared, which is 5 joules.

In fact, this is not just one capacitor, but these are 12 capacitors which I hooked up in such a way that the 12 capacitors of 80 microfarad each are a combined capacitor of 1000 microfarads.

And so I'm going to charge it up, and then I'm going to discharge the capacitor through the light, and then you will be able to see some lights, perhaps, depending on how much energy we dump through there.

So concentrate now on this light bulb.

The 100 volts -- you should see here, do you see it?

-- so it's set at 100 volts now, and I'm now going to charge it, and the moment that I charge, you will see the voltage over the capacitor, and so it takes a while for it to charge up, so it goes [unintelligible] down to 0 and then slowly comes back to 100, it may take 5 or 10 seconds.

So if you're ready, then there we go.

Took only 5 or 6 seconds.

And so now we have 100 volts, so we have 5 joules stored in there, and I'm going to discharge that now over this light bulb, if you're ready, three, two, one, zero.

A little bit of light.

I can tell that you're disappointed.

It's not very exciting.

It's not really my style, is it?

Well, what we can do, we can increase the voltage a little bit.

Uh, we could go to 250 volts, in which case, since it goes with V-squared, we would have 6 times more energy, so then we have 30 joules, so let's see whether that's a little bit more exciting.

So now I have to jack up the voltage to 250 volts -- now you see the power supply again -- 250 volts -- we've getting there, we don't have -- oh, boy, huh, am I lucky, on the button.

So 250 volts, and now I can charge up again, and it will take a little longer, so you'll see the voltage over the capacitor, 140, 170, 200, 250, there we are.

And now we can see whether we get a little bit more light.

So you go from 5 joules now, to 30 joules.

Three, two, one, zero.

Waahaa, now we're getting somewhere.

Now you really see how a photo flash works.

Now, we all, of course, have destructive instincts.

And so you wonder, right?

You- you're thinking the same thing that I do.

Shall we try 340 volts and see whether the bulb [ptchee], maybe explodes?

I don't know how high this voltage supply can go, let's see.

Let's - let's go all the way.

337 volts.

OK.

So that would mean that we have 50 joules, roughly.

It goes as the voltage squared.

Well, let's charge again, so we're charging now.

200, 280, 300, there we go, 337 volts.

Now let's see -- AAAAH, we did it! It broke! I have a photo flash, and I have the photo flash here, and this photo flash has a capacitor of about 5000 microfarads, a real biggie, and we can charge that up to a potential difference of 100 volts, even though the batteries in there are only 6 volts, there is a circuit in there -- we'll learn about that later -- which converts the 6 volts to 100 volts, and so we can charge up this capacitor to 100 volts.

And that means that the one-half C V squared, the energy stored, then, in that capacitor, will be 25 joules.

And I can dump that energy over the light bulb, and then we see a bright flash of light, because this discharge can occur in something, like, only a millisecond.

So you get a tremendous amount of light, only for that millisecond.

And I want to demonstrate that to you.

And the only way I can demonstrate that to you is by aiming this flashlight at you -- I don't want to damage your eyes, so I warn you in advance -- so I am charging up, now, my capacitor, it will take a while, and I'm going to take your picture.

I might as well.

But, um, it's going to be very dark in the back, there, and so I've asked Marcos and Bill to also have some flashlights, which go off at the same time that my flashlight goes off.

Now, you may say, "Well, how can you do that, because if this flash only lasts a millisecond, how can you synchronize that?" Well, the way that's done is that those flashlights are waiting for my light signal to reach them, and that goes with the speed of light.

Takes way less than a millisecond to get there, and they go at the same time that they receive my light flash.

And so we call them flash-assists.

And so let's, uh, let's see whether we can do this.

I, uh, I have a green light here, that means I can take my picture, and, uh, yes, you can -- oh, you don't have to comb your hair, but -- you're looking good.

OK, let me -- let me, let me focus, because that's important -- so make sure you see the flash.

You ready for this?

Did you see the flash?

Did it flash?

Oh, it did.

Oh, you can say yes.

So, um, did the -- did the light-assists also flash?

OK, but you haven't seen that, yet, right?

Because you were looking at them.

You should have looked -- you really should have looked at me.

So why don't we take a picture, Marcos, Bill, aim the fli- li- the flash-assists at the students here, and then we'll try it again.

You ready?

OK.

Oh, boy.

Why don't you say cheese for a change?

OK, look at me -- oh, boy, you're looking great, you're really out of focus.

Uh, one person's sleeping there, oh, we'll let him sleep, that's OK.

Did that work?

Did you see the flash?

You did, eh?

25 - 25 joules.

But those haven't seen it yet.

So Marcos, Bill, make sure that we go this way, and give them a chance to see this light flash.

So we get a little bit of assistance there with the lights, and let's see how this works, make sure that you see the flash, very good, you can -- going to see another 25 joules going through this light bulb -- very good -- oh, oh, oh, yes, yes, uh, yes, your hand is in front of your mouth, sir, yes, that's OK, thank you.

Very good.

Did you see the flash?

Did the f- did the -- did the assist go?

So that's the idea of, um, of photo flashes.

So you dump a lot of energy in a very short amount of time, and you get a very bright flash.

Professor Edgerton at MIT became very famous for his flashlights.

He invented flashes that can handle way more energy than this flash, and they can dump that energy in less that 1 microsecond.

And so this opened up the road to high-speed photography, and that made it possible to study the motion of objects on time scales of microseconds, and even shorter than that.

And I'd like to show you some of the pictures that were taken with Doc Edgerton's flashes.

The first slide -- you see a bullet coming from the right going for a light bulb.

The exposure of this, uh, picture, is only one-third of a microsecond, during which the bullet probably moved only a third of a millimeter, so it looks like it's completely standing still.

And the bulb is heading for disaster, but it doesn't know that yet.

Uh, the bullet, uh, moves, uh, in 100 microseconds about 8 centimeters, and then next picture is taken 100 microseconds later, again one-third of a microseconds exposure.

So if we can look at that -- there, you see, so the bullet now just penetrates the light bulb, and then the next picture is another 100 microseconds later, and there you see the bullet emerging from the light bulb.

And, uh, this, uh, light bulb has hardly realized that it is broken.

But it's beginning to dawn on it, and and then the next slide is one wonderful picture of a boy who is popping a balloon, and you see half the balloon doesn't even know yet, that it is broken.

Doc Edgerton also -- that's enough for these slides -- he also developed a lot of, um, strobes.

A strobe -- I have one here -- is an instrument that repeatedly discharges, um, energy over a -- over the light bulb, and so you get repeated flashes, and that, then, gives you instrument like this.

Uh, you've seen them in use -- uh, they are being used at airplanes, just for warning signals, and you've also seen them on tall towers in the airports, also warning signals, but there are lot of more things you can do with strobes.

And later in 8.02, uh, I will show you, for instance, that you can measure the rotation rate of motors with flash lights, with these, uh, stroboscopes, and the motors are going to play a more important role in 8.02 than, uh, than you may have guessed before you took this course.

You can also measure with strobes the rotation, the speed of your record player, if you still have one, and then you can adjust it so that it just has the right speed that is required.

So there are a lot of things you can do with strobes, and some of which we will see also in 8.02.

So, now, I return to my capacitor there.

And let's see how it is doing.

Oh, boy, we are close to the 3000, which was my goal.

It takes a -- you see, a good 15 minutes, to actually reach the 3000 volts on this huge capacitor, and to get in there, the energy, the 450 joules that I wanted.

And why is it that I want to show you this?

Well, I want you to appreciate the idea of a fuse.

You have lots of fuses at home.

A fuse is a safety device.

A fuse is something that melts, something that breaks if the current that you are using is too high.

Suppose you have a short, electric short without realizing it, in your desk lamp, and a very high current could start to flow, then the fuse will say, "Sorry, you can't do that, the fuse will melt, and then that prevents you from a disaster, which, actually, might give you a fire.

And we already showed, in a way, the idea of a fuse, because when we broke this light bulb, that was, in a way, a fuse.

We dumped too much energy through that light bulb, and so, the light bulb itself [klk] was already like a fuse.

This is really more like a fuse that we are used to, it is a -- we have a wire there, which is an iron wire, which is 12 inches long, and it has a thickness of 30 thousandths of an inch.

And we're going to dump the 450 joules through that wire.

So the idea is very much like we had the -- the photo flash, we, um, have all this energy in the capacitor, and instead of dumping it through the light bulb, which was this system, we now have here, a wire, and when I throw this switch, the energy will go through the wire.

And chances are that you may see the wire glowing a little bit, and then it would melt, and that would then give you the idea of a fuse.

And it's also possible that, after we have done that, that there may still be energy left on this capacitor, and I can show that to you too, then, because I can short out the two ends of the capacitor and see whether we still see some -- some sparks, which would indicate that there's still some energy left.

So if you are ready -- I'm always a little bit scared with this demonstration -- not so much about what's going happen, that thing will probably just melt, and maybe we'll see a little bit of light, that's not the issue -- but I'm afraid of this baby, because that has, now, a tremendous amount of energy.

So I stop the charging -- so let's do that -- and if you're ready, then I will try to dump all that energy through this wire.

Three, two, one, zero.

[bang] [hum] [bang].

This is the way a fuse works.

This is very effective, as you see.

And if you hear this happening in your basement, then, well, maybe that's a fuse.

We can now check whether there is energy left on that capacitor.

Maybe not very much, but it's unlikely that everything was dumped in the iron, so let's see whether there is some left, if I'm going to be able to short it out with this conducting bar, and see whether we can get a spark.

And we can.

So there's still some energy left.

OK, see you Friday.