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8.02 Electricity and Magnetism, Spring 2002
Transcript – Lecture 11

So far, we have only discussed in this course, electricity.

Calm down.

But this course is about electricity and magnetism.

Today, I'm going to talk about magnetism.

In the fifth century B.C, the Greeks already knew that there are some rocks that attract bits of iron.

And they are very plentiful in the district of Magnesia, and so that's where the name "magnet" and "magnetism" comes from.

The rocks contain iron oxide, which we will call, uh, magnetite.

In 1100 A.D., the Chinese used these needles of magnetite to make compasses, and in the thirteenth century, it was discovered that magnetites have two places of maximum attraction, which we call poles.

So if you take one piece of magnetite, it always has two poles.

Let's call one pole A, and the other B.

A and A repel each other, B and B repel each other, but A and B attract each other.

There is a huge difference between electricity and magnetism.

With electricity, you also have two polarities, but you are free to choose a plus or a minus pole.

With magnetism, you don't have that choice.

The poles always come in pairs.

Isolated magnetic poles do not exist -- or, as a physicist would say, magnetic monopoles do not exist, as far as we know.

If anyone finds a magnetic monopole -- and don't think that people are not looking -- that would certainly be worth a Nobel Prize.

In principle, they could exist, but as far as we know, they don't exist, they have never been seen.

Electric monopoles do exist.

If you have a plus charge, that's an electric monopole.

You have a minus charge, electric charge, that is an electric monopole.

If you have a plus and a minus of equal strength, that is an electric dipole.

Whenever you have a magnet, you always have a magnetic dipole.

There is no such thing as a magnetic monopole.

In the sixteenth century, Gilbert discovered that the Earth is really a giant magnet, and he experimented with compasses, and he was, effectively, the first person to map out the elec- the magnetic field of the Earth.

And if you take one of those magnetite needles, and the needle is pointing in this direction, which is the direction of Northern Canada, then, by convention, we call this side of the needle plus -- uh, not plus -- north, and we call this side of the needle south.

Since A repels A, and B repels B, but A and B attract each other, in north Canada is the magnetic South Pole of the Earth, not the magnetic North Pole.

That's a detail, now, of course.

So this is the way that we define the direction, north and south, of these magnetite needles.

A crucial discovery was made in 1819 by the Danish physicist Oersted.

And he discovered that a magnetic needle responds to a current in a wire.

And this linked magnetism with electricity.

And this is arguably, perhaps, the most important experiment ever done.

Oersted concluded that the current in the wire produces a magnetic field, and that the magnetic needle moves in response to that magnetic field which is produced by the wire.

And this magnificent discovery caused an explosion of activity in the nineteenth century -- notably by Ampere, by Faraday, and by Henry -- and it culminated into the brilliant work of the Scottish theoretician Maxwell.

Maxwell composed a universal field theory, which connects electricity with magnetism.

And that is at the heart of this course.

Maxwell's equations.

You will see them, all fier -- all four, by the end of this course.

If I have a current, a wire, let's say the wire is perpendicular to the blackboard, and the current goes into the blackboard, I put a cross in there.

If the current comes out of the blackboard, I put a dot there.

And there is a historical reason for that.

You're always talked about vectors, in 18.01, and in other courses, but you're never seen a vector.

And I'm going to show you a vector.

This is a vector.

And this is where it comes to you.

That's when you see a dot.

And this is where it goes away from you.

That's when you see a cross.

So this current, when it's going into the blackboard, I can put these magnetite needles in its vicinity, and they will then do this.

And when I put it here, it will go like this.

And they follow the tangents of a circle, and this is the way that we define magnetic fields, and the direction of the magnetic field, namely, that the magnetic field -- for which we always write the symbol B, magnetic fields -- is now in the clockwise direction.

By convention, current goes into the blackboard.

And, if you ever forget that, use what we call the right-hand corkscrew rule.

If you take a corkscrew, and you turn it clockwise, the corkscrew goes in the board.

That connects the B with the current.

If you take a corkscrew and you rotate it counterclockwise, then the corkscrew would come to you, comes out of the cork.

And that's how you find the magnetic field going around current wires.

It's just a convention.

I want to show you how a magnetic needle responds to a current.

I have here a wire through which I'm going to run a fabulous amount of current, something like 300 amperes, and you're going to see that wire there -- I'm going to get my lights right, see how I want it to go, this is the way I want it to go, get you optimum light there.

When I draw a current -- here, you see the the magnetite, the -- we call it a compass, nowadays -- and it's lined up in the direction of the magnetic fields of the Earth.

We're going to run 300 amperes through here, and it will change the direction, it will change the direction which is -- there's going to be a magnetic field around the wire, like this.

So it will go like this.

The current that I run is so high that things begin to smell and smoke within seconds.

The battery is not going to like it when I draw such a high current.

I can, therefore, do it only for a few seconds.

So this compass will swing in this direction, and it starts to oscillate, I can't keep the current so long that it stops the oscillation.

So I will stop it by hand, and convince you that that's really the equilibrium position.

So if you're ready for that -- so we get, now, connection, watch it three, two, one, zero.

There it goes.

Now I'll stop it -- the current is still going.

You see, that's the -- that is the equilibrium position.

And I will stop the current.

And now I will reverse the current, in the opposite direction, now you will see that it swings backwards.

It -- 180 degrees in a different direction.

Three, two, one, zero.

There it goes, I will stop it, [sniffs], few seconds, that's the equilibrium position, and I'll let it go.

So you've seen that, indeed, the magnetic needle responded to the magnetic field that was produced by the wire, this was the great discovery by Erstadt, the discovery -- this demonstration, all by itself, may not be very spectacular for you, but, historically, it is of enormous importance.

I would argue, perhaps, the most important demonstration, the most important research ever done in physics, because it connects electricity with magnetism.

It was the foundation of the creation of the whole concept of a field theory.

Actually, it was magnet's reaction, and that means that if a wire that runs a current has a force on a magnet, then, of course, the magnet must also exert a force on the wire.

And I'm going to demonstrate that to you, too, but now, I have a much more potent magnet, for which I will use this one, and the magnet will not move, it's so heavy that it can't move -- so now you will only see the wire move.

And the basic idea is then as follows, here is that magnet.

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This is the north pole of the magnet, and this is the south pole -- I don't remember which is which, to be frank with you -- so the magnetic field would run, then, like so, and I have, here, a current wire, a wire that runs a current through it -- the wire is perpendicular to the blackboard.

If, when I turn the current on, if the current is coming out of the blackboard -- and I have fifty percent chance, because I really don't remember whether this is north or south -- but let's assume that this is the configuration, that the current is coming out of the blackboard, then you will see this wire experience a force up.

It is an experimental effect that the force on the wire is always in the direction of I cross B.

These are unit vectors.

And since I is coming out of the blackboard, if I cross I with B, I get a force in this direction.

And so if I reverse, now, the current -- if the current goes like this -- then, of course, the wire wants to go down.

And I will show you both.

But I don't know which one will come first, because I didn't mark the poles.

Ahh -- uhh.

So you see it, now, slightly different from the way I have drawn it.

I've drawn you the magnet looking this way, but it's, of course, much nicer for you to see it this way.

So you see the wire, and there is the magnet, and now I'm going to run a few hundred amperes through that wire, and then it either will jump up, or it will jump down, and then I will reverse the current, and then the opposite thing will happen.

OK.

We ready for this?

Three, two, one, zero.

Notice, there was a distinct force down, the force was so high that it even pulled down the supports.

So now I can predict that if I reverse the current from this experiment, that now the wire will jump up.

Here we go -- I know now, exactly, because I switched it this way, so now I will switch it this way, and the wire will jump up.

That's the first drawing you see.

Three, two, one, zero.

Very clear.

You saw it come out.

OK.

Let me take this down.

All right.

If I have a wire, through which I run a current -- let's say I run a current I1 through this wire -- it will produce a magnetic field, right-hand corkscrew, right here, that magnetic field will be in the blackboard -- I'll call it B1 -- right here, it will be out of the blackboard.

But that's irrelevant right now.

But it is out of the blackboard.

Here, it's in the blackboard.

And here, I have another wire, I'm going to run a current I2.

There will be a force now, on this wire, in the direction I cross B.

Take your hands, I cross B [krrk], that force is up.

So this wire will experience a force up.

But of course, if this wire experiences a force up, since action equals minus reaction, this wire will experience a force down.

So they will go towards each other.

They will be attracted by each other.

You can in an independent way confirm that the force here is down.

That this is the force.

For me, it would be enough to say action equals minus reaction, Newton's Third Law.

But if you want to put in here, the magnetic field B2, which is the result of this current, which is, of course, out of the blackboard -- remember the right-hand corkscrew rule -- then you will see that this force, now, here, must be in the direction of I1, crossed with B2.

And that's down, which is exactly what I predicted.

So the two wires will go towards each other.

However, if I leave everything the same, but I reverse the direction of I2 -- so now the two currents are in opposite direction -- then the forces will flip over, and so now the two wires repel each other.

And I will demonstrate that to you.

I have those two wires here, and you will see them there on the screen.

I will explain what you're looking at in some detail.

The two wires run vertically -- this is one wire, and this is the other wire -- and when I run a current in the same direction, then they will attract each other.

And you will see that shortly.

Three, two, one, zero.

See?

They go towards each other.

I will do it again, now.

If I run the current in opposite directions, they will repel each other.

Now I run them in opposite directions.

They repel each other.

I'll do it again, three, two, one, zero.

They repel each other.

The reason why I showed you this demonstration is a different one.

What I want you to appreciate that if I have this conducting plate of aluminum -- it's a conductor -- and I put that in between the two wires, and I repeat the experiment, that exactly the same thing will happen.

And that tells you that magnetic fields are really very difference from electric fields, because electric fields would be heavily affected by a conducting sheet like this.

Magnetic fields are not.

So what I'm going to do now is I'm going to put this plate in between, and then I'm going to again put the currents in opposite directions, and so we will see the wires repel each other as if the plate were not there.

Three, two, one, zero.

There you go.

So magnetic fields have a very interesting story to tell.

However, electricity and magnetism are connected.

How do we define the strength of a magnetic field?

With electricity, we defined the strengths of electric fields in the following way -- we measured the force, the electric force, on a charge, on an electric charge, and then the electric force is the charge times the electric field.

That determines the strength of the electric field.

Wouldn't it be nice if we could now say, "OK, the magnetic force is a magnetic charge times the B field." So that would then define the magnitude of the B field.

That would be nice.

But as long as we haven't found a magnetic monopole, we can't do it.

If you come with a magnetic monopole tomorrow, I can do this.

But we have no magnetic monopoles, and so it cannot be done this way.

How is magnetic field then defined?

Well, it is defined in the following way.

I take an electric charge, and the electric charge is Q.

And if that electric charge moves with a velocity V, and there is a magnetic field where the electric charge is moving, then it is an experimental fact that the force is always perpendicular to V.

If you want to call that B, with a magnetic indication, that's fine.

So there is a magnetic field, the charge is moving with this velocity, and there is a force on that charge which is always perpendicular to V.

The magnitude of that force is proportional to the speed of the particle, and it is also proportional to the charge itself.

If I double the charge, then the force doubles.

If I double the speed, then the force doubles.

And so the way that we define, now, magnetic field strength, is this way.

The force -- and I give it a B to remind you -- magnetic, is Q, is the electric charge, V is the velocity of the electric charge, the cross-product with B.

And you see that the force is always perpendicular to V, and that it is linearly proportional with the speed, and linearly proportional with the charge Q.

And this is often called the Lorentz force after the Dutch physicist.

This equation is completely sign-sensitive.

If you change from a positive charge to a negative charge, then the force flips over, 180 degrees.

You change the direction of V, force flips over.

Change the direction of B, force flips over.

So it's a completely sign-sensitive equation.

The unit for magnetic field strength follows from this equation, this is newtons, Q is coulombs, and V is meters per second.

So this would be the unit for magnetic field strength, but no one would ever say that.

In SI units -- this would be SI units -- we call that 1 tesla, for which we write 1 capital T.

A tesla is an extremely strong magnetic field.

The magnetic field of this magnet is only 2/10 of a tesla.

And that's a very strong magnet.

We often use, therefore, a unit, which is the gauss, which is not an SI unit, but you will see it often in books, and 1 t- gauss is 10 to the -4 tesla.

The Earth's magnetic field is roughly half a gauss.

And so this magnet is about 2 kilogauss.

But the SI unit is tesla.

If you look at a television, or the screen of your computer, you have a fluorescent screen -- and in a television, there are electron guns that raster scan this fluorescent screen -- on a television screen, you have 525 lines, and the electron guns scan that it one-thirtieth of a second.

And the intensity changes of these electron beams create images.

So if you look at the tube from the side, then there are electrons -- one moment in time, they may move like this, another moment, they may be here, in the raster scan -- and so it's clear that if you bring a strong magnet in the vicinity of your television screen, that you will distort the image, because you are now affecting the motion of these currents, of these electrons.

And there is a very famous artist, Nam June Paik who used this for his art, and almost every major museum in this world has a work by Nam

June Paik, with distorted images using magnets and using television screens.

I don't want to compete with Nam June Paik, but I do want to show this to you.

I have there, television sets, and I have a very strong magnet, and I will try to distort that image and give you the best lights that we know how to.

And I suggest we try to find a program that we hate.

So here is my magnet -- oh, man -- this is an extremely strong magnet, and let's turn on the television, and let's see what we can get first.

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Oh, I turned it off instead of on.

Ah, I hate commercials.

Now, watch it closely.

Here comes my magnet, there's the image.

[background] You see that?

So you've seen that we can, with a magnet and a moving charge, that we can change the direction of the moving charge.

Force on the moving charges.

If you have an electric field as well as a magnetic field, then, of course, you have also the electric force.

And so the total force on a moving charged particle would then be Q times the electric field vector, plus V cross B.

And this, of course, we've seen before.

An electric field can do work on a charge.

Remember, Q delta V.

Can be positive, can be negative, but it can do work.

It can change the kinetic energy of the charge.

Magnetic fields can never do work on a moving charge.

And the reason is that the force is always perpendicular to the velocity V.

And so if the force is always perpendicular to the motion, you can change the direction of the motion, but you can't change the kinetic energy.

So that's a fundamental difference between the electric force and the magnetic force.

So now I want to calculate, with you, the force on a current that runs a wire I through it, and we have a magnetic field B.

So we're going to be slowly -- we're going to be more and more quantitative.

This, by the way, is often -- also called the Lorentz force, just a combination of the two.

That one certainly is.

So let us start with a -- a wire, and a wire that runs a current through, here is the wire, and the current is I.

And let's say, at this point here, we have a magnetic field B.

And the magnetic field could be difference along the wire, in principle.

Here, I have a charge, plus dQ, and this charge is running through the wire with a drift velocity Vd.

Let's first think about what happens if the current is 0.

If the current is 0, at room temperature, the free electrons in these wires have huge speeds.

3 million meters per second.

Way larger than the drift velocity.

But they are in all chaotic directions.

Random motion, it's a thermal motion.

And so on each individual charge, there will be a force.

But they average out to be 0.

It's not until I run a current that these charges are going to walk through with a very slow drift velocity, and now, of course, the net force is not 0.

So let's have this charge dQ that moves in this direction, and so that gives me a current.

And let this angle be theta between them.

Say, that's going to be important, because it's a cross-product between velocity and B.

That means the sine of this theta comes in later.

You will say -- I hope you will say, "Well, listen, man, this is ridiculous.

Uh, positive charges don't move through wires.

It is the electrons that move through wires.

They are responsible for the current.

And electrons have a negative charge, and they go in this direction." You're right.

Perfectly fine.

However, a negative charge going in this direction is mathematically exactly the same as a positive charge going in that direction.

In both cases, do we agree that the current is in this direction.

So I have preferred, for mathematical reasons, to take a plus dQ charge going in this direction rather than taking a minus dQ charge that goes with the drift velocity in that direction.

But there is no difference at all in the outcome that you will see.

So on this charge, there is a force, dF -- that's this -- this magnetic force, and that is the charge dQ, that equation, times V cross B.

Well, V was that drift velocity, and here is the magnetic field, at this location.

The current through the wire, everywhere on the wire, must be dQ dT.

Because that's the definition of current, how many coulombs per second.

Current is always dQ dT.

So I can also write this as I dT times Vd cross B.

But I remember 8.01, that Vd times dT, that is speed times a time is a distance.

And I call that distance dL.

It's a distance along the wire.

I will put a distance in here now, because I don't want to clutter up my -- my drawing.

So this charge, in time dT, moves over that distance, that's a vector.

8.01.

So I can write down for this product, I can write down dL.

So I can also write down that dF of B equals I times dL cross B.

What is this telling you?

This is the force of a wire over a small segment of the wire which has length dL, I is the current through the wire, and B is the local magnetic field at that location dL, that's what it means.

And if you want to know the entire force on the wire, you have to do the integral along the whole wire.

And so you have to do an integral along the entire wire, and at every portion dL, you have to determine what B is, and you get, then, a force, which is a vector, and you have to add those vectors vectorially.

Could be a pain in the neck, but that's the basic idea.

So now, I want to calculate what the force was on this wire, roughly, when we ran 300 amperes through there.

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And I make a geometry so simple that we can execute that integral.

This was the wire, and we had a current running through here which was 300 amperes, roughly.

And we have a magnetic field, which was right in the gap there, that magnetic field B, and that was 2/10 of a Tesla.

2 kilogauss.

And that magnetic field was only operating here.

It wasn't operating there.

And I make the assumption -- which is a simplifying assumption -- that that magnetic field was constant over the portion of the wire which was, say, only 10 centimeters.

And so I assume here that I have a length which is 0.1 meters, and that in -- during -- in this range here, the magnetic field is constant.

I just want to get a rough number for the force on that wire.

So now I can integrate that equation very easily, because I have assumed that the magnetic field is perpendicular to the direction dL -- dL is now in this direction -- so the sine of theta is 1, so I don't have to worry about that -- and so I simply get that the force on this section F -- on this section L, that force -- call it F of B if you want to -- is the current I, which we have there, we get the length L, which is this length, multiplied by the magnetic field.

There is no sine I anywhere because the angles are 90 degrees.

And so I find that that force is 300 times 0.1 times 0.2, so it is 30 times 0.2, that is about 6 Newton.

6 Newton is more that the weight of 1 pound.

And so it is not so surprising that when I turn this current on, that something, all of a sudden, that something all of a sudden pulls that wire down with a weight that is equivalent of a little more than a pound, almost a pound and a half, actually.

And so it's not so surprising that these supports fell over.

So you see that you can turn this quantitatively, provided that you make some simplifying assumptions about the uniformity of the magnetic field, and about where the magnetic field is present.

Now, I want to talk about the great 8.02 motor contest.

We are about to start on this great 8.02 motor contest, you got an envelope today, and I'm going to start to tell you, slowly, about the physics.

The goal is, ultimately, to build a motor.

If I have a current loop -- here is a current loop.

Current comes in at A, and I'll try to make it -- make you look at it three-dimensionally, which is not so easy.

This is -- current goes out here, at D.

This is a current loop.

Current go through here, go through here, go through here, and we turn here.

And we have a magnetic field, we will assume that the magnetic field is constant throughout, in this direction.

There is a force right here on this wire, in the direction I cross B.

That force is up.

There is a force here, on this wire, which is, of course, down.

Magnetic field is in the same direction, the current is in the opposite direction, so the force is down.

If this wire has a length A, this wire has a length A, that force -- the magnitude of that force is the current through the wire times the length of the wire times the B field.

We just derived that.

There's that integral, we just assume that the magnetic field is constant everywhere here, they're at 90 degree angles, so the sine of theta is 1, and so that's the force.

What is the force here and what is the force here?

Well, it's 0.

0 here, and it is 0 here.

Why is that?

Because the cross-product is 0.

No matter how you look at it, you can say dL and B are either in the same direction or in opposite directions.

You can also say the drift velocity and B are either in the same or the opposite direction, it is all the same thing.

There is no force here, and there is no force here.

Because that equation that we had that gives us the magnetic force becomes 0.

The sine of that angle is 0.

So what's going to happen with this thing?

Well, there is a torque on this system.

There is no net force, because this force up is the same as this force down, but there is a torque which wants to rotate it in counterclockwise direction.

And the magnitude of that torque is, of course, this force -- you remember from 8.01 -- times the perpendicular distance between these two forces, and so the magnitude of that torque is I times a b times B at this moment in time, when the forces are this far apart.

Now, this is going to rotate, and so as they rotate, these forces come closer, and so the torque will become less.

Still, it wants to rotate counterclockwise.

And there comes a time, 90 degrees later, that the torque is 0.

And I will try to make you see that, again, in a three-dimensional way, it's not so easy for me.

Now, this is D, this has become D, a current always leaves at D.

I'll try to make you see this three-dimensionally.

It goes like this, current comes in here, at A, so we get this, and we get this.

It doesn't look so bad.

And the magnetic field B has not changed, uniform B in the same direction.

So the current now comes in through A, it has not changed, the only thing is that the loop has rotated 90 degrees.

If, now I ask you what the forces are, you have to go I cross B.

I cross B.

If you do I cross B here, I cross B, you get a force which is towards you.

Here, you get forces which are in the blackboard.

Here you get forces which are up, and here you get forces which are down.

At home, you will have some time to use your right hand, and do the I cross B, and you will see, then, that, indeed, all these forces are in the direction that I put them.

So now, there is, again, no net force on the system.

There was no net force here, either.

But now, there is no torque either.

So now, the torque has become 0.

If we rotate it a little further, it is possible, then we start this motor, starts to rotate counter clockwise, comes to this position, torque goes to 0, but it has enough inertia so it rotates a little further.

And now the torque will reverse.

And this is something that I leave you alone with, I don't want to make another drawing and convince you that it reverses.

But it's easy to see, because, take this thing, and just flip it over 180 degrees.

The magnetic field hasn't changed, but the currents in these two sides have changed direction now, because whatever is D is here and A is here.

And so the torque reverses, and so it goes like this, [wssshhht], and then [wsshht] it comes back.

And that's not much of a motor.

Current meters are very frequently used, they are in your cars, many more than you think, your, um, your fuel gauge and your temperature, of the cooling water, are current meters.

And a current meter works as follows.

We attach to this loop a needle, a handle, and we calibrate it here.

And you can read how many amperes are going through this meter.

It wants to go counterclockwise.

Here, we attach a spring, and the spring produces a counter-torque, and so the needle will start to deflect, but come to a halt.

But if you double the current, it will go further.

That's the way that a current meter works.

And your fuel gauge in your car is a current meter, except that the level of the fuel is somehow converted into an electric signal, and then it's sent through a current meter, and that's what you're reading.

And it is, of course, calibrated in terms of how much fuel you have.

And your temperature gauge is calibrated in terms of degrees, whatever, Fahrenheit or whatever.

So these current meters are very common, even when we're dealing with something that has nothing to do with current.

How do you build, now, a motor that works?

How do you get over this torque reversal?

Well, it's not only the torque reversal that is a problem, but there is also the problem that if you could keep this going around, that these two wires would intertwine, and they would break.

You roll it around 100 times, you can see what happens at A and D, it will break.

So you have to think of a design whereby you have slipping contacts -- we call them brushes.

Suppose I have, here, a conductor which is connected with A, physically soldered to the wire at A.

And here, I have a conductor which is D.

So the -- the loop is where you are.

Soldered wires coming out the loop is here.

But now the battery -- plus side of the battery is here, and the minus side of the battery of here, and this is a slipping contact.

In practice, we call them brushes.

So that immediately takes care of the problem, that the wires wind up.

But there is something else which is very clever about this design.

If the gap between A and D is an insulator, then, what's going to happen when this rotates 180 degrees?

A, which now is on the positive side of the battery -- this is negative, of course, heh?

-- A is now on the positive side of the battery, if you -- if you rotate 180 degrees, A will be on the negative side of the battery.

So now every rotation, the current will, all by itself, change direction.

And we call that a commutator.

And so now, what's going to happen is, now the torque reversal will not occur.

If, at the right moment, the current switches direction, the torque will always want to rotate the loop in exactly the same direction.

That's the idea behind a commutator.

The great 8.02 motor contest.

You have an envelope, when you open it up -- don't do it now -- you will find in there a copper wire, 2 meters insulated copper wire, 2 magnets, 2 paper clips, and some wood.

And the idea is that you try to build a motor that runs as fast as possible.

For every 100 RPM -- an RPM is a rotation per minute -- for every 100 RPM, I'll give you one credit point, with a maximum of 20 credit points.

So if your motor runs 2000 RPM or more, you get 20 credit points.

That is equivalent to two homework assignments.

And these credit points count over and above your course grade.

You have my word for that.

I'll give you a final course grade, the way that you've seen in the ground rules, in the first handout, and we add your motor contest, what you deserved.

For every 100 RPM, you get one point plus, with a maximum of, uh, of 20.

And we're going to test these motors on the second of April, and I gave you a handout in which I give you some hints, some ideas.

There is one idea that I gave you which you may ignore, and that is to overcome the torque reversal, you can build a commutator.

But that's, uh, that's really not easy.

Not only is it not easy, but when you build a commutator, your system may get a lot of friction, and you may lose more than you gain.

There is an alternative solution, which I mentioned in my handout that you picked up today, and that is that you design your motor in such a way that when the reversal, when the torque reversal occurs, that there is no current running any more.

And when it is half a rotation further, the torque is there again, the current is there again.

So for half the time, you stop the current, you will see that's very easy, I give you some hints how you do that.

So you have to weigh that against the possibility of building a commutator.

The bottom line is, the maximum is 20 credit points.

That's an equivalent of two homework assignments.

You get it over and above your course grade.

And it's also great, fun, believe me.

What more do you want?

To do physics, get credit, and have fun.

That's what I do every day, that's the great thing about physics.

We have 5 minutes left, and in those 5 minutes, I'm going to demonstrate to you a motor.

What you see there is a current loop -- I'll try to make you see it three-dimensionally -- this is the current loop, and we're going to run a current in this direction, and we, here, have a magnet, north, south, magnetic field is in this direction.

And we, here, have a magnet, north, south, magnetic field is also in this direction.

I'm going to run a current through here, and if the current is in the blackboard, I cross B -- I is in, cross B, force is up.

This side wants to go up.

If this side wants to go up, since the magnetic field is the same direction here, but the current is 180 degrees in opposite direction, this force will be down.

And so there's a torque on this motor.

And you will see that.

You will see that go like this.

However, when it's 180 degrees and it swings here, by, it wants to go back, because of the torque reversal.

That's the first thing that I want to show you.

And I think I don't need any changes in the light.

So here, we have this loop, and here we have the two magnets -- the magnetic field is, by no means, uniform, by the way, it's very strong here, and it's very strong there.

And now I have to power that.

Hmm, there we go.

I can't -- yes, I think I know that this one will come up this side, I'm fairly sure that I have the directions right.

Let's first take a look at it.

There it goes.

So when it's here, notice, it goes up.

But now, if I power it here again, wants to go back.

To here, wants to go up, and here, it wants to go back.

So we've got to do something.

And that something is a commutator.

So if we can somehow reverse the current when it's here, then it wants to go down again.

I'll show you that.

So now it's here.

And I'll drive the current in the other direction.

You ready for that?

Did you notice?

It now wants to go down.

Now it wants to go down.

But when it's here, I have to reverse the current, it wants to go up.

And if I do that with my hands, I can see whether I can keep this rotating.

It may take me a while, but I'll do my best I can.

There it goes.

Switch, switch, switch, switch, switch, switch, switch, switch, switch.

Yes, got it, yes I got it.

I'm a commutator! This motor is going at least 60 RPM, that's one credit point for me for this course.

Thank you.