AmpÃ¨re's Law: Crash Course Physics #33

Crash Course: Physics
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===== Introduction (0:02) =====

It was the autumn of 1820. Hans Christian Oersted had just discovered the connection between electricity and magnetism. Meanwhile, a French physicist named André-Marie Ampère was experimenting with some wires, trying to learn more about the connection between currents and the magnetic fields they create.

He took two parallel wires and ran a current through both of them in the same direction, and the wires attracted each other. And when he ran a current through both wires in the opposite directions, the wires repelled each other.

Studying this strange force between the wires led Ampere to discover one of the most fundamental laws of electromagnetism: what we now call "Ampère's Law."

And that's not the only weird thing that current-carrying wires do. If you wrap a current-carrying wire into a coil, the inside of the coil acts like a magnet. There's a north pole at one end of the coil, and a south pole at the other, and if you put the loop of current-carrying wire in a magnetic field, it'll turn.

Ampère's Law lets you calculate the strength of the currents and magnetic fields in all these situations. This also helps to explain how motors work.

===== Main Episode (1:14) =====

So first, those two parallel wires: why do they attract and repel each other? It's easier to see why the two wires act the way they do if you look at one wire first.

Like we talked about in our last episode, the current running through a wire generates a magnetic field. So let's say you have a long, straight wire with a current running through it. The current will create a magnetic field circling the wire.

That magnetic field decreases the further you are from the wire. If you draw a circle, say, a centimeter from the wire, the magnetic field along the circle will have a set strength.

Ampère realized that the stronger the current is that's running through the wire, the stronger the magnetic field will be along that circle. That's the basic logic behind Ampère's Law.

But this is physics, and in physics we tend to express relationships in terms of equations. The equation for Ampère's Law applies to any kind of loop, not just a circle surrounding a current, no matter how many wires there are or how they're arranged or shaped. The law is valid as long as the current is constant.

The equation itself says that the integral of the magnetic field "B" along the loop times the cosine of theta with respect to distance is equal to a constant called mu-zero multiplied by the current running through the loop. This equation just means that the total magnetic field along the loop is equal to the current running through the loop times a constant number.

The constant, mu-zero, is sometimes called "the magnetic constant." And it's equal to four times pi times ten to the negative seven Newtons per Ampère-squared.

Now you may have noticed there's an integral on the left-hand side of the equation for Ampère's Law. And you might remember that we use integrals when we need to add up lots of infinitely tiny values. Well, in Ampère's Law, we're adding up all the little bits of magnetic field along the loop.

We're saying that all those bits of magnetic field added together are equal to the enclosed current times the magnetic constant. "B" is the strength of the magnetic field at each point along the loop, "theta" is the angle between the magnetic field on each point along the loop, and "ds" is referring to each infinitely tiny section of the loop.

The mathematics of Ampère's Law can get very complicated very quickly. But to get a basic sense of how it works, let's return to our scenario: a circle around one long, straight wire.

We're trying to find the magnetic field at each point on the circle (that's B) in terms of the enclosed current and the radius of the circle. So first let's solve the integral in Ampère's Law to get the total magnetic field along the circle.

According to the law, we're solving the integral of the magnetic field, times the cosine of theta with respect to the points along the circle. But we can simplify this integral pretty easily.

First you'll notice that the magnetic field coming from our wire is parallel to the circle at every point. So the angle, theta, is zero, and the cosine of zero is one. Anything times one is equal to itself. So we can just knock the cosine-of-theta term out of the integral.

Now we're left with the integral of the magnetic field, B, with respect to the points along the circle. But every part of the circle is the exact same distance from the wire, so the magnetic field will be the same at every point. In other words, B is constant, so we can move it in front of the integral sign.

Now all we have to do is figure out the integral of all the points along the circle, which is equal to the circumference of the circle (so two times pi times the radius).

Putting that all together we find that when we apply Ampère's Law to a long, straight wire, the total magnetic field along a circle surrounding a wire is equal to B times two times pi times the radius. And that total magnetic field is equal to the magnetic constant times the enclosed current.

So for a long, straight wire, B is equal to the magnetic constant times the enclosed current divided by two-pi-r.

The equation for the magnetic field along a circle surrounding one wire turned out to be really important for Ampere when he was trying to figure out what was going on with two wires. When both wires had current running through them in the same direction, they attracted each other. And when the current was going in opposite directions, they repelled each other.

It's easy to see why if you apply the first right-hand rule. That's the one that says if you point your right thumb in the direction of the current and curl your fingers, the magnetic field points in the same direction as your fingers.

So first, let's look at the wires with currents running in the same direction. For this example, we'll say that they're vertical wires with the current flowing upwards. If you point your right thumb in the direction of the current in each wire, your fingers will curl in the direction of the magnetic field.

The magnetic field from the wire on the left will be pointing to the right, and the magnetic field from the wire on the right will be pointing to the left, so the wires will attract each other.

For the case where the current is flowing in opposite directions, the

reverse is true, so they'll repel each other.

Now Ampère also wanted to find the force from the magnetic field on the wires. Like we talked about last time, the force depends on the angle between the current and the magnetic field, the strength of the current, the length of the wire, and the strength of the magnetic field.

Calculating that magnetic field, B, was the tricky part. With the equation he came up with, the one that we now call Ampère's Law, allowed him and future physicists to figure out what B was in a lot of situations, including the case of the two parallel wires.

So the two parallel wires attracted and repelled each other because of the magnetic field created by the currents. What about the coil of wire that turned into a magnet? Well you can probably guess that its behavior also has to do with the magnetic field produced by currents.

See that coil of wire is a special shape called a "solenoid." And when a solenoid has a current running through it, it produces a magnetic field, basically all of which goes through the inside of the coils.

If you curled your right hand around the solenoid so that your fingers pointed in the direction of the current running through the loops, your thumb will point in the direction of the magnetic field.

Ampère's Law is useful for solenoids too. It says that the magnetic field inside the coils (B) is equal to the magnetic constant times the current running through the coils times the number of coils.

So that's what happens when loops of wire create a magnetic field. When you stick a loop of wire in a magnetic field, something a little stranger happens: the loop of wire turns. That's because the magnetic field creates a torque on the wire.

Take a look at this loop of wire. The horizontal parts of the loop are parallel to the magnetic field, so it won't exert a force on them. But the vertical parts of the loop are perpendicular to the magnetic field, so it will exert a force on them: a force that turns the loop.

From the last episode, we know that the force from the magnetic field on the wire will be equal to the current times the length of that part of the coil times the magnetic field. And we can use the second right-hand rule to figure out the direction of that force.

If you point your hand in the direction of the current, then bend your fingers in the direction of the magnetic field, your thumb will point in the direction of the force. Which turns out to be away from you for the left-hand side of the coil, and toward you for the right-hand side. So the coil turns clockwise.

This is how electric motors work. They have an electric current that continuously flips directions, making loops of wire spin. Those moving loops of wire can be used to do mechanical work, like turning the drum in your washing machine, or your power drill, or the fan that probably cools your computer.

There are electric motors all over the place. So the next time you wash your clothes, or put together some furniture, or use your computer without it overheating, or do anything else that involves an electric motor, you have Ampère to thank.

===== Summary (7:54) =====

Today you learned about Ampère's Law and how it applies to a long, straight wire. We also talked about the forces between two parallel wires, and the magnetic field created by a solenoid. Finally we described the torque on a current loop.

===== Credits (8:05) =====

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