Induction - An Introduction: Crash Course Physics #34

Crash Course: Physics
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Physicists learned a lot about electricity and magnetism in the 19th century. We've already talked about one of the biggest discoveries – that electric currents can create magnetic fields. And once scientists had figured that out, they wondered if the opposite was also true.

Could magnetic fields create – or induce – an electric current? Many physicists designed experiments to detect electric currents induced by magnetic fields, but they kept coming up empty. That is, until two physicists, Joseph Henry and Michael Faraday, both on their own, figured out what was happening: It turns out that magnetic fields do induce electric currents, but only under certain circumstances – when the magnetic field is changing with time. And this discovery is what eventually led to the invention of hard drives.

[Theme Music]

When Faraday discovered that magnetic fields induce electric currents, he got kind of lucky. He set up a current flowing through a coil of wire so that it would generate a magnetic field, and then he watched to see if that magnetic field induced a current in a second coil of wire.

And it didn't, which was probably pretty disappointing at first. But then, Faraday noticed something weird: When he turned the current on and off in the first coil, there was a brief spike of current in the second coil – but only while the current was changing from off to on and back again. He realized that he'd been looking for the wrong thing: a constant magnetic field didn't cause an electric current in a loop of wire. Only a changing magnetic field did!

These days, we call this idea Faraday's Law of Induction: It says that a changing magnetic field will induce an emf in a loop of wire. And emf, you'll recall, stands for electromotive force, which is what causes electrons to move and form a current.

So now Faraday knew that when a magnetic field changed over time, it induced an emf in a loop of wire. But a couple of other things induced emf, too, even if the strength of the magnetic field stayed the same. Changing the area of the loop of wire induced a current, too, and so did changing the angle between the loop and the magnetic field.

That's because of a property that most directly induces emf – the property known as magnetic flux, represented by Phi B. Magnetic flux is essentially a measure of the magnetic field running through a loop of wire. And when that field changes, that's what induces an emf. And there are three factors that affect the magnetic field, and therefore the magnetic flux through the loop:

First, there's the strength of the magnetic field, which we label as B. Next, there the area of the loop, A. If the loop is bigger, there'll be a larger magnetic field running through it, and vice versa. And finally, there's the angle, theta, between the magnetic field and a line perpendicular to the face of the loop. Combining all these factors, we find that the magnetic flux is equal to the strength of the magnetic field times the area of the loop, times the cosine of the angle between the magnetic field and that perpendicular line. And if the magnetic field and the loop are perpendicular, then the magnetic flux will just be equal to the strength of the magnetic field times the area of the loop.

Magnetic flux is measured in units of Tm^2, also known as webers. But when it comes to inducing emf, what really matters is how the flux is changing over time. If the magnetic flux through a loop of wire decreases over time, the emf increases accordingly. And if the flux increases over time, the emf decreases. In maths terms, we'd say that the emf is equal to the negative of the change in flux, over the change in time.

This equation works well for the change in flux through one loop of wire. But often, you'll be inducing emf in a coil of wire – like what Faraday was doing in his experiment – so it helps to know how a change in the magnetic flux will induce emf in a coil. And the key here is that a change in the magnetic flux through a coil induces the same emf in each loop of the coil.

So if you want to know the total emf in the coil, you calculate the emf for one loop of wire, then multiply it by the number of loops in the coil, or N. Which means that the induced emf in a coil of wire is equal to the number of coils, times the change in magnetic flux over the change in time, all multiplied by a negative sign. So, having two loops in the coil would mean double the emf that would be induced in one loop, while 10 loops would mean 10 times the emf.

So! Faraday's law of induction lets us calculate how much emf – and therefore, how much current – will be induced in a loop of wire by a change in magnetic flux. But in what direction will the induced current flow?

To figure that out, we use a rule called Lenz's Law. You know how currents generate magnetic fields? Well, Lenz's law says that the magnetic field generated by the induced current will be in the direction opposite the change magnetic flux. So if you know the direction of the change in magnetic flux, you can figure out the direction of the magnetic field generated by the current. And from there, you can use our old friend the right-hand rule to figure out the direction of the current.

To get a better feel for how to apply Lenz's law, let's look at two scenarios involving a bar magnet below a loop of wire, with the north pole of the magnet facing the loop.

In the first scenario, you move the north pole of the bar magnet closer to the loop, which increases the magnetic field flowing through the loop. This therefore creates a change in magnetic flux and induces a current in the loop. And the current generates a magnetic field that opposes this change in magnetic flux.

Now, the north pole of the magnet points in the same direction as the magnetic field. So by moving the magnet closer to the loop, you essentially made the magnetic field from the bar magnet point more strongly upward. And according to Lenz's law, the magnetic field created by the induced current will oppose this – so it'll point downward.

In the second scenario, the north pole of the magnet is again facing the wire. But this time, you move the magnet away from the loop. In this case, you're basically making the magnetic field from the magnet point less strongly upward – and more strongly downward.

So the magnetic field created by the induced current will point upward to counteract this change. And once you know the direction of the magnetic field generated by the induced current, you can figure out the direction of the current from there.

This is where the right-hand rule comes in. Make a "stop" sign with your right hand, then point your thumb in the direction of the magnetic field being generated by the induced current. The direction that your fingers are pointing? That's the direction of the current.

Let's try it: In our first scenario, where we moved the north pole of the magnet closer to the loop of wire, the generated magnetic field was pointing upward. So the current will be moving clockwise along the loop. In the second scenario, where we moved the north pole of

the magnet away from the loop, the generated magnetic field was pointing downward.

So the current will be moving counterclockwise along the loop. Now, another way to use magnetic flux to induce a current in a loop is by changing how much of the loop is within the magnetic field. Say you have a horizontal magnetic field, and a loop of wire.

You arrange the loop so it's perpendicular to the magnetic field, then drag it out of the magnetic field, which decreases the amount of magnetic field within the loop. The magnetic flux through the loop changes, which induces an emf. The strength of the emf is equal to negative of the change in the magnetic flux, over the change in time.

The flux, you'll recall, is equal to the magnetic field times the area, times the cosine of the angle between the magnetic field and a line perpendicular to the loop. Since the magnetic field is perpendicular to the loop, the cosine of the angle is 1, so that term drops out of the equation. Which means that in this case, the change in flux is equal to the magnetic field times the change in the area of the loop within the magnetic field.

And the area of the loop is equal to its length, which we'll call L, times the width of the loop that's in the magnetic field, which we'll call x. As you move the loop out of the magnetic field, the amount of its width within the field, x, changes.

So! The change in magnetic flux is equal to the strength of the magnetic field, times the length of the loop, times the change in its width within the magnetic field. So the strength of the induced emf will be equal to all of that, divided by the change in time. Thankfully, there's a way to simplify all of this: The change in x over the change in time should look familiar – it's just equal to the velocity of the loop as you move it out of the magnetic field! So when you move a loop of wire in or out of a magnetic field, the strength of the induced emf is equal to the strength of the magnetic field, times the length of the loop, times the velocity of the loop.

Using a magnetic field to induce a current is useful for all kinds of reasons – we'll talk about some of the main ones next time. It's also how hard drives work – at least, the ones that use a rotating disk. Your computer stores information on your hard drive by magnetizing small sections of the disk.

To read that information, your computer rotates sections of the disk past the head, which is a small electromagnet that has a coil of wire. The changing magnetic field induces a current in the coil in the head, and computers processes that signal as the zeroes and ones we use to store digital information! Digital information like this episode of Crash Course!

Today, you learned about magnetic flux, and how a change in magnetic flux can induce an emf in a loop or coil of wire. We also talked about how to calculate that emf both when the magnetic field is changing and when the area of the loop in the magnetic field is changing. Finally, we described how induction works in hard drives.

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