

Magnetism, Faraday's Law, and Transformers

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The idea of this handout is to get more understanding of how transformers harness the properties of magnetic fields to change voltages from one level to another. Every wall bug you own (to charge a cellphone, laptop, etc.) has a transformer in it as its most important component.

The Magnetic Field and Magnetic Flux

Suppose you have a butterfly net, but you are not waving it around. Instead, you are holding the hoop up, pointing it in some direction and hoping that some butterflies moving downwind with a breeze will happen to come through the hoop from the direction you have it pointed and end up in the net.

Or you could imagine a net strung across a stream and depending how the net is oriented, more or less water will pour through the net.

Between 1831 and 1865, scientists—starting with Michael Faraday and culminating with James Clerk Maxwell—created the modern idea of the electric and magnetic field. The electric field is created by the presence of charge and can be thought as emanating from it. The magnetic field is created by the presence of current and can be thought of as circulating around current-carrying wires.

Mathematically, the electric and magnetic fields are remarkably like the breeze carrying the butterflies or the current passing through the net.

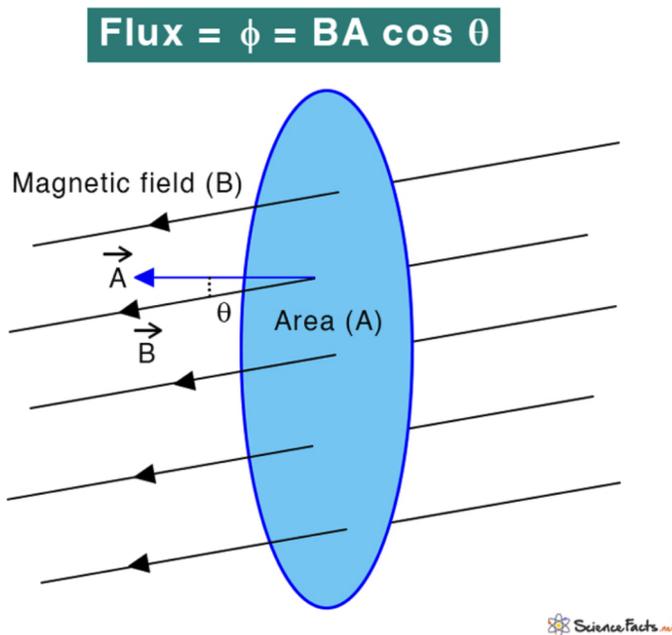
In the case of the current passing through the net, mathematically, we can ask and answer how much water passes through the net every second, provided we know the direction and speed of the current, and the orientation and area of the net.

The people that invented this area of physics were surely informed by the concurrent work going on in fluid mechanics. There are remarkable similarities between the finalized Maxwell's Equations for electricity and magnetism and the Navier-Stokes equations for fluid motion.

For us, it is enough to visualize the magnetic field as permeating space like wind or water in motion.

Magnetic flux is the amount of magnetic field that passes through a surface.

Flux is usually denoted with the capital Greek letter, Φ . Here is a picture I lifted from sciencefacts.net:



Changing Magnetic Flux

In the diagram in the previous section was the formula $\Phi = BA \cos \theta$. This formula is only valid for a magnetic field that has a constant direction, and only for a flat area, and I will spare you the generalization, which requires multivariable calculus.

The area drawn is imaginary! We only imagine how much magnetic field passes through it. We might often ask when doing the calculation, how much field the area “catches,” but of course, since it is imaginary, it actually does no catching.

The $\cos \theta$ in the formula is plausible. It says that if the area isn’t oriented across the field, then it won’t catch as much of the field going through it. If you turned the area completely sideways (by 90°), the area wouldn’t catch any field and this comports with $\cos 90^\circ = 0$. If the angle shown in the diagram is 0° , the area is catching as much field as it can, and this comports with $\cos 0^\circ = 1$ (because 1 is the maximum value of the cosine).

It turns out that flux has little effect, unless it is changing! There are lots of ways to make flux change. We could imagine that the area is rotating so that sometimes $\theta = 0^\circ$, a little later it is 90° , then 180° , and then 270° , before getting back to 360° which is equivalent to 0° .

Another way to change the flux is to have the magnetic field increase and decrease in strength. Mims set up a crude version of changing flux by changing the strength of a magnetic field this by having you press a switch that connected and disconnected a current going to the transformer windings. We'll see more about what Mims did shortly.

The Effect of Changing Magnetic Flux — Faraday's Law

Remarkably a voltage is generated when magnetic flux changes. Imagine putting a wire with resistance, R , around the area, A , and causing the flux through the area to change at a rate $\frac{d\Phi}{dt}$. Then a current will be generated in the wire:

$$I = -\frac{1}{R} \frac{d\Phi}{dt}$$

I'll spare you the reason for the minus sign for a moment, and instead concentrate on the fact that if we multiply through by R , we have:

$$IR = -\frac{d\Phi}{dt}$$

This suggests that there is a voltage in the wire going around a circle, and that makes a mockery of Kirchoff's loop rule which said that the sum of the voltages around any loop is zero.

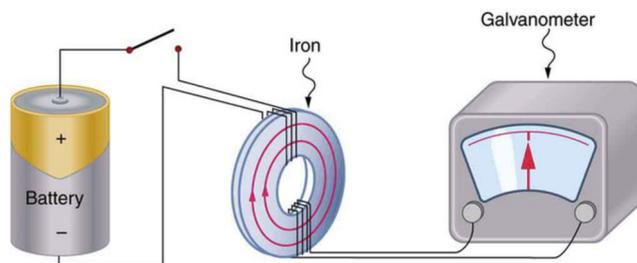
We'll still use Kirchoff's loop rule unchanged but we will have to incorporate transformers and inductors into it quite carefully. So you usually see:

$$\mathcal{E} = -\frac{d\Phi}{dt}$$

where \mathcal{E} is the voltage in the loop. This is Faraday's Law of Induction.

Faraday's Apparatus

Remarkably, Faraday's apparatus is pretty much the same as the one Mims had you build to illustrate the effect of a transformer, and you are not far from understanding it. Here is the apparatus:



The galvanometer shown is set up to measure current, or it could measure voltage if it had a resistor of known size in series with it. The drawing is from phys.libretexts.org.

The experiment is to open and close the switch connected to the battery. When the switch is closed, current flows through the coil it is connected to. *A current generates a magnetic field.* The iron loop channels the magnetic field around and through the other coil.

So that coil has a changing magnetic flux through it! So it generates a voltage that registers on the galvanometer.

We need some names for some of the things in the drawing! The upper coil where the current voltage and current are applied by the battery is known as “the primary winding, or just “the primary.” This is the winding that generates the magnetic field. Where the voltage and current are produced by the changing magnetic flux is “the secondary winding” or just “the secondary.”

Connecting them is the transformer “core” which is metal chosen to guide the magnetic field generated by the primary to the secondary. No current flows in the core! The wires in the windings are insulated. Transformers short out and burn up if the winding insulation gets too hot or is physically damaged.

Transformers

In the drawing in the previous section, the artist put about the same number of coils on the primary and the secondary. The idea was just to show the effect. But now there is another idea!

If we put lots and lots of windings in the secondary, each wrap around the magnetic field generates the same voltage as the magnetic field changes, and so the total voltage in the secondary including that effect is:

$$\mathcal{E} = -N \frac{d\Phi}{dt}$$

where N is the number of windings in the secondary. By adjusting the number of windings in the primary and the secondary, and the resistance of the primary and the secondary which are also proportional to the number of their respective windings, you can create a large voltage in the secondary compared the primary, or vice versa.