home

Physics 2415 Lecture 19: Magnetic Induction I

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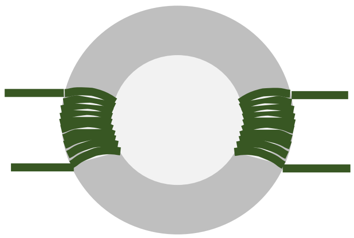
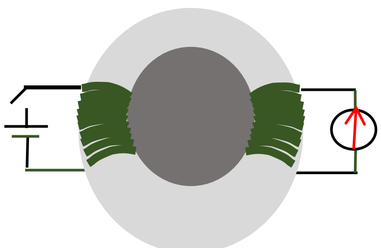
Faraday's Idea

Faraday theorized that since an electric current could generate a powerful magnetic field, maybe a magnetic field could generate a current?



He tested this theory by winding *two* solenoids around the same doughnut shape of soft iron.

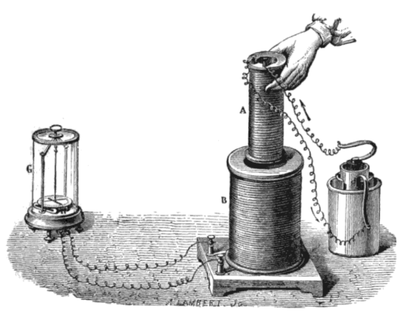
He ran a large current in one, looked for a current in the other—and didn't find it.



But he did find something!

He found a *transient* current appeared in the second coil *at the moment the current in the first coil was turned on*, then a transient *opposite* current when it was turned off.

Induced EMF



Faraday discovered that what he called "induced current" appeared in a coil whenever the external magnetic field through the coil was changing.

Here is one of Faraday's experiments as portrayed in an 1892 physics textbook "for advanced students". On the right is a battery, on the left a fancy galvanometer.

We say there is an induced *emf* driving this current, emf being short for "electromotive force", the "force" driving the current, the voltage. Other sources of emf are electric fields, and the chemical forces inside a battery.

Faraday's Experimental Findings about emf

For a coil of *N* loops close together, he found the induced emf to be *N* times that for one loop (meaning the current will be the same if there's negligible external resistance in the circuit).

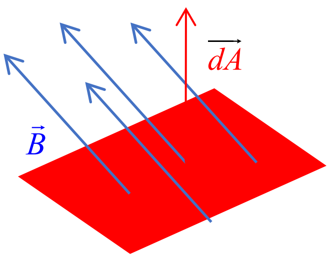
For a uniform magnetic field, the emf is proportional to the area of the loop.

It's proportional to the component of magnetic field perpendicular to the area.

It's proportional to the *rate of change* of field.

Faraday thought of the magnetic field lines as representing flow of some ethereal fluid, rather analogous to the electric field—but with one big difference. The electric field "fluid" flowed out of positive charges, into negative charges. In contrast, on looking at the magnetic field of a solenoid, for example, the north and south poles are *not* like positive and negative electric charge, they're illusions, the magnetic field lines do not end, they just circle around.

To quantify the interaction of the magnetic field with the loop, bearing this fluid picture in mind, a natural quantity to measure is what is the total magnetic flux (Latin for flow) through the loop, to be measured by putting a roof over the loop and measuring the total magnetic field through the area.

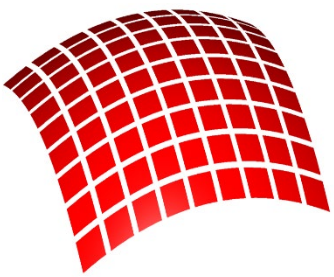


The flux through a small square with area $\overrightarrow{dA}$ is $\vec{B}\cdot\overrightarrow{dA}$.

The total magnetic flux through the surface bounded by the loop is written:

$$\Phi_B = \int \vec{B}\cdot\overrightarrow{dA},$$

summing the contributions from all the small squares.



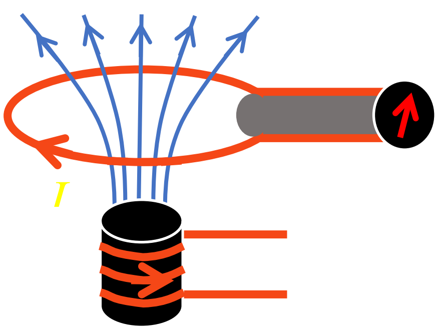
Recall now Faraday's first idea was to see if having a magnetic flux through a loop/coil generated a current, just as having a current generated a field.

It didn't—except when it changed.

Faraday's Induction Formula

He saw transient currents *when the flux through the loop changed*: the induced emf he measured as

$$\mathcal{E} = -\frac{d\Phi_B}{dt}.$$



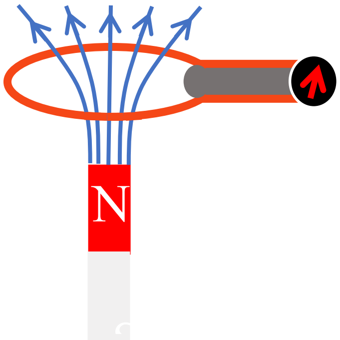
Lenz' Law

The sign of the induced emf is most simply found by applying *Lenz' law*, the induced current will generate a magnetic field opposing the change in field flux caused by the movement.

So if the current builds up from zero in the solenoid in the direction shown, a north pole is appearing at the top of the solenoid, so the current generated in the loop will have a north pole on its underside, to partially cancel the field from the solenoid.

Notice this also means there is a momentary *repulsive* force between the coil and the ring, if the ring is not attached, and the current is sufficient, the ring will jump. There are many YouTube demos, for example this.

We could of course get the same effect by physically moving a magnet towards the coil instead of turning on the solenoid. It's useful to consider this alternative, because it makes explicit that as the



response current builds up in the ring, it generates a repulsive force so it takes work to keep moving the magnet, this is the source of the energy needed to build up the current in the ring (which then dissipates as ohmic heat).

Exercise: Discuss the energy balance when turning on the solenoid.