

Workshop Tutorials for Introductory Physics

Solutions to EI8: Electromagnetism

A. Review of Basic Ideas:

Currents and fields

There is a relationship between **electricity** and magnetism, which was discovered by Hans Christian Oersted in 1819. During a lecture demonstration he noticed that a wire carrying an electric current deflected the needle in a nearby compass. Not only are magnetic fields produced by permanent magnets, but they are also produced by moving charges, or **currents**.

For example, the magnetic field lines produced by a current I in a long straight wire form **circles** around the wire and the magnitude of the field at a distance r from the axis of the wire is given by $B = \frac{\mu_0 I}{2\pi r}$. The constant μ_0

is the permeability of free space, and is equal to $4\pi \times 10^7 \text{ N}\cdot\text{A}^{-2}$. You can use your **right** hand to find the direction of the field. Point your **thumb** in the direction of the current and your fingers curl in the direction of the field. The field is **perpendicular** to the current that produced it.

It turns out that not only do currents produce a magnetic field, but a **changing** magnetic field produces a current. This effect is called electromagnetic **induction**, because the changing magnetic field *induces* an electric field which can cause a current in a conductor. Such an induced current also produces a magnetic field whose net effect is to oppose the change that produced the current in the first place. This is Lenz's law.

The induced electric field exists even if there is no conductor and no induced current. Such induced electric fields are often described in terms of an associated quantity called *emf*. In a closed conducting loop such as a coil of wire with resistance R the induced *emf* and the induced current are related by $emf = IR$. We can find the *emf* induced in a closed loop of area A , using **Faraday's law** : $emf = -\frac{d\Phi}{dt}$, where Φ is the magnetic flux through the loop. In the simple case of a uniform field perpendicular to the plane of the loop, the flux is given by $\Phi = BA$.

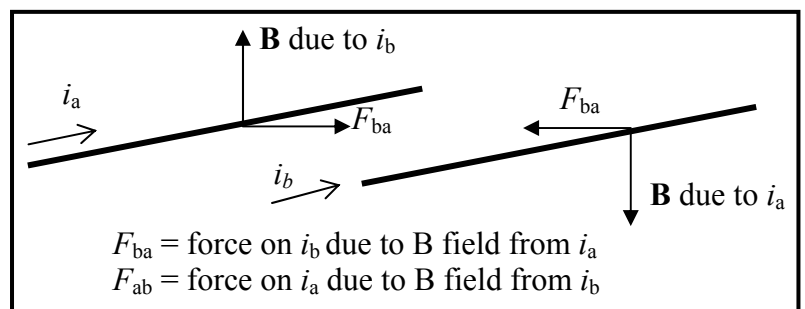
Discussion Question:

The induced *emf* is equal to the rate of change of the flux through the loop. You can change the flux to induce an *emf* either by changing the field, or by changing the size or orientation of the loop.

B. Activity Questions:

1. The magnetic force – pinch effect

Both currents produce a magnetic field. A current carrying wire in a magnetic field experiences a force proportional to the current and the external field, $F \propto i \times B$. This force will be towards the other wire when the currents are parallel, and away from it when the currents are anti-parallel.



2. Electromagnetic Induction – two coils of wire and a magnet

The direction of the current depends on the motion of the magnet relative to the loop and changes when the magnet is reversed. The magnitude of the current depends on the speed of the motion, number of turns of wire and the 'angle' between the loop and the magnet. It doesn't matter whether the coil or the magnet is moved, only the relative motion of the two is important.

A current carrying coil of wire has a magnetic field so there will be an induced current in a closed loop of wire which is moving relative to a current carrying coil.

3. Magnetic braking I – damped pendulums

In all cases currents are induced in sheets and loops without slits and not in sheets or loops with slits. The induced currents experience a force due to the magnetic field from the magnets, which produces a force on the pendulum opposing the motion that causes them, braking the pendulums without slits.

4. Magnetic braking II – magnets in pipes

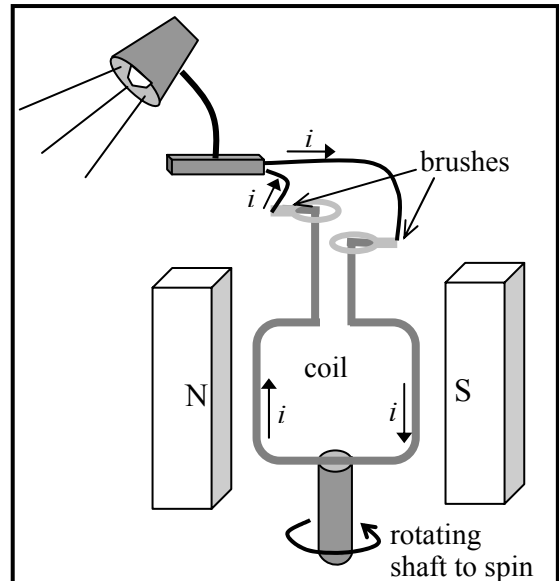
The movement of the magnet creates currents in the copper pipe, which produce magnetic fields, which act to oppose the motion which causes them, slowing the fall of the magnet. The plastic pipe is an insulator, no current is created and hence the magnet is not braked. In the pipe with the slit there are still currents produced in vertical loops, but not around the pipe as the slit prevents this. So the fall is slowed, but not as much as in the complete pipe.

C. Qualitative Questions:

1. Almost all electricity production uses a generator.

a. See diagram opposite.

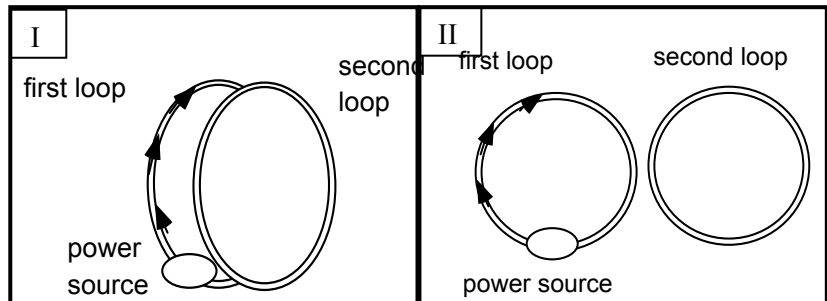
b. The shaft at the bottom of the generator is mechanically driven. This can be done by a turbine which has water falling over it (hydro-electric) to make it spin or by steam pushing it (coal, nuclear, geothermal). Wind vanes in wind farms can also be used to drive the shaft. The shaft is attached to the coil and rotates it in the magnetic field produced by the magnets. The magnetic flux through the coil changes as the coil rotates, it is a maximum when the coil is perpendicular to the field and zero when the coil is parallel to the field. The changing magnetic flux through the coil induces an *emf* causing a current to flow.



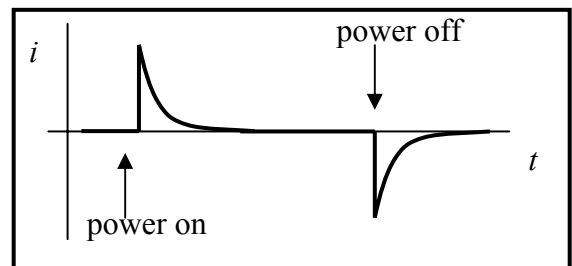
c. According to Lenz's law the current flows to counteract the change in magnetic flux. As the coil turns from parallel to the field to perpendicular the magnetic flux increases. As it continues to turn the magnetic flux decreases again. While the flux is increasing the current flows in one direction and while the flux decreases the current flows the opposite way. Hence an alternating current is produced.

2. Induced currents in loops.

a. The induced currents in the two arrangements are different because the magnetic field, B , through the area of the loop in arrangement II is smaller than that in arrangement I. Thus changes in the magnetic field $\frac{dB}{dt}$ and the rate of change of flux $\frac{d\Phi}{dt}$ will also be smaller. So any induced *emfs* and currents will be smaller.



b. When the power supply is switched on the current will begin to flow producing an increasing magnetic field which causes a current in the other wire. When the magnetic field is constant there will be no current induced in the other coil. When the magnetic field decreases after the power supply is turned off a current will briefly flow in the other direction.



D. Quantitative Question:

a. The changing magnetic field will induce a current. Metal jewellery or zips etc have low resistance so large currents could be induced in them.

b. According to Faraday's law the induced $emf = -\frac{d\Phi_B}{dt}$, which is the rate of change of magnetic flux.

$\Phi_B = BA\cos\theta$ for a uniform field. So now we have

$emf = -\frac{d\Phi_B}{dt} = \frac{d(BA\cos\theta)}{dt} = \frac{d(BA)}{dt} = A \left(\frac{dB}{dt}\right) = A\left(\frac{B_{\max}}{T}\right)$ for a steadily changing field with B perpendicular to A , which reaches its maximum value at time T . We want the maximum value of the *emf* to be 0.01 V, and we are finding T : $T = \frac{B \cdot A}{emf} = \frac{1.5 \text{ T} \times 0.04 \text{ m}^2}{0.01 \text{ V}} = 6 \text{ s}$.

It must take at least 6 s for the machine to reduce the field to zero.