DO PHYSICS ONLINE

MOTORS AND GENERATORS

9.3.2 THE RELATIVE MOTION BETWEEN A CONDUCTOR AND MAGNETIC FIELD IS USED TO GENERATE AN ELECTRICAL VOLTAGE

view **1 Magnetic field strength or magnetic flux density or**
B-field B [tesla T]
Magnetic flux Φ_B [T.m^2]

view **2 Michael Faraday: conductor moving in a magnetic field induces an *emf* across conductor which generates a current in a closed circuit**

view **3 Lenz's Law (conservation of energy statement)**

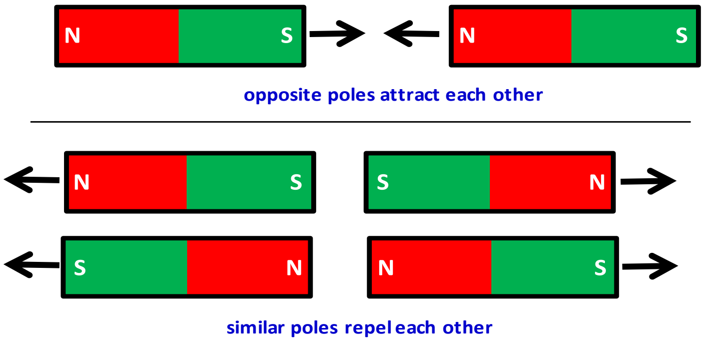
view **4 Induced *emf* (potential difference) equals the time rate of change of magnetic flux Φ_B**

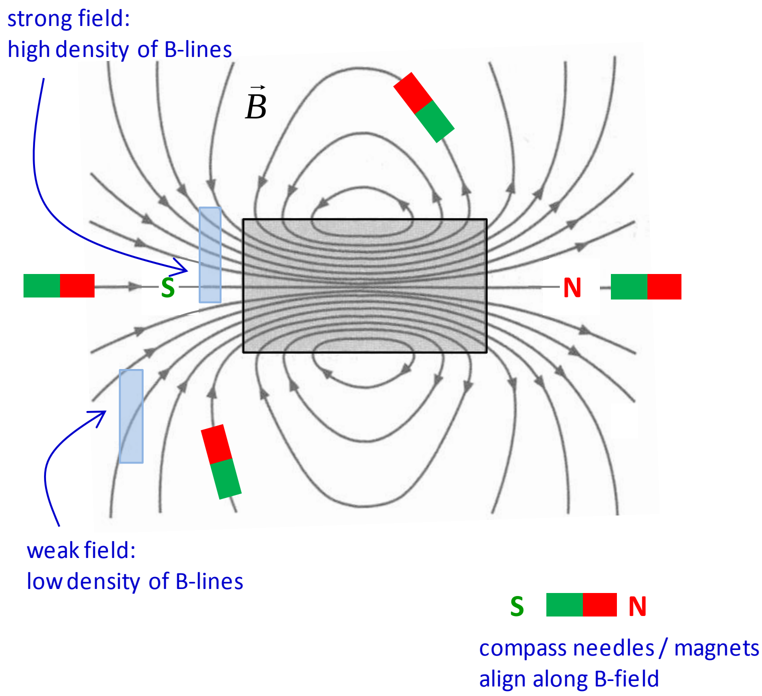
view **5 Electric motors and back *emf* in motors**

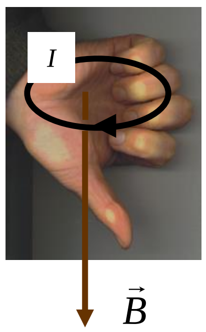
view **6 Lenz's Law: eddy currents – induction electric cooktops and electromagnetic braking**

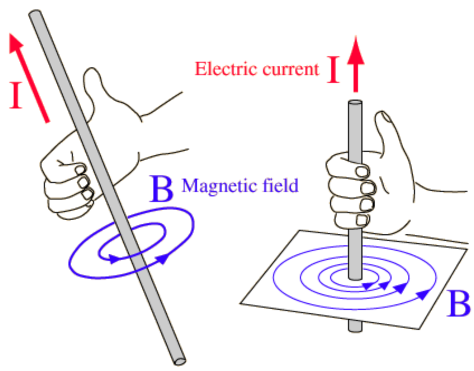
1 Magnetic field strength or magnetic flux density or B-field B [tesla T]
Magnetic flux Φ_B [T.m^2]

- Region in space in which a moving charges or currents experience forces









$$B = \frac{\mu_0 I}{2\pi R}$$

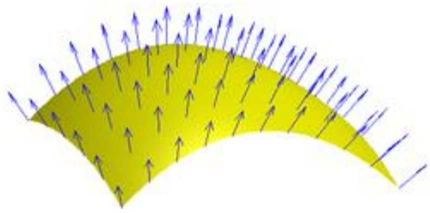
MAGNETIC FLUX Φ_B [T.m^{-2} weber Wb]

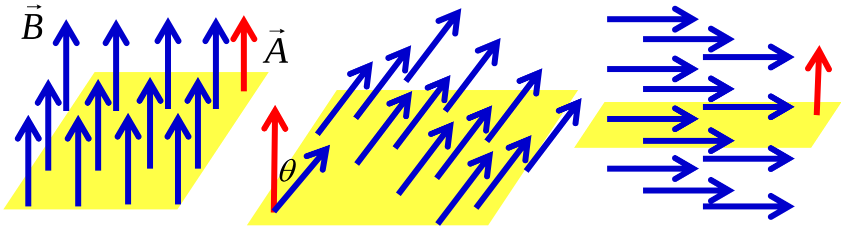
Number of magnetic field lines crossing an area $\rightarrow$ concept: magnetic flux

Magnetic flux for constant B-field

$$\boxed{\Phi_B = B\,A\cos\theta}$$

Each point on a surface is associated with a direction, called the surface normal; the magnetic flux through a point is then the component of the magnetic field along this direction





$\theta = 90^o$

$\cos\theta = 1$

$\Phi_B = B\,A$

$$\Phi_B = B\,A\cos\theta$$

$\theta = 0^o$

$\cos\theta = 0$

$\Phi_B = 0$

Magnetic flux when the magnetic field B is uniform over an area A.

top

2 Michael Faraday: conductor moving in a magnetic field induces an *emf* across conductor which generates a current in a closed circuit

FARADAY'S LAW – ELECTROMAGNETIC INDUCTION

- A changing magnetic flux induces a changing electric field
- The changing electric field induces an emf in a conductor.
- In a conductor loop, the changing emf induces a current.

English Michael Faraday (1791 – 1867) experimented with electric and magnetic phenomena discovered that a changing magnetic field produces an induced emf (voltage – source of electrical energy).

Faraday's law of electromagnetic induction is one of the great laws of physics. This phenomenon is the basis for many practical devices such as transformers, reading computer memory, electronic devises, alternators and generators. Without generators we could not produce large quantities of electrical energy required for our modern society to function.

top

3 Lenz's Law (conservation of energy statement)

Lenz's law: the induced emf and induced current are in such a direction as to oppose the change that produces them.

Lenz's law is a consequence of the law of conservation of energy.

Consider what would happen when a permanent magnet is pushed towards a conductive coil.

According to Lenz's law a current is induced in the coil which induces a magnetic field that interacts with the B-field of the magnet to oppose the motion towards it.

What happens if Lenz's law was **not true**?

The induced current would create a magnetic field to attract the magnet $\rightarrow$ attractive force between magnet and coil would accelerate and increase the speed and kinetic energy of the magnet. But, the greater the speed, the greater the change in magnetic flux and hence the induced current would increase and the greater the attractive force. The current would continually grow indefinitely and the kinetic energy of the magnet would also increase indefinitely – this would be a violation of the law of conservation of energy.

top

4 Induced *emf* (potential difference) equals the time rate of change of magnetic flux density Φ_B

Faraday's law

$$\varepsilon = -\frac{\Delta\Phi_B}{\Delta t}$$

induced emf	ε	[V]
magnetic flux	Φ_B	[weber Wb or T.m^{-2}]
change in magnetic flux	$\Delta\Phi_B$	[Wb or T.m^{-2}]
small time interval	Δt	[s]

The negative sign gives the direction of the induced emf (**Lenz's Law**)

More formally, Faraday's law is

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

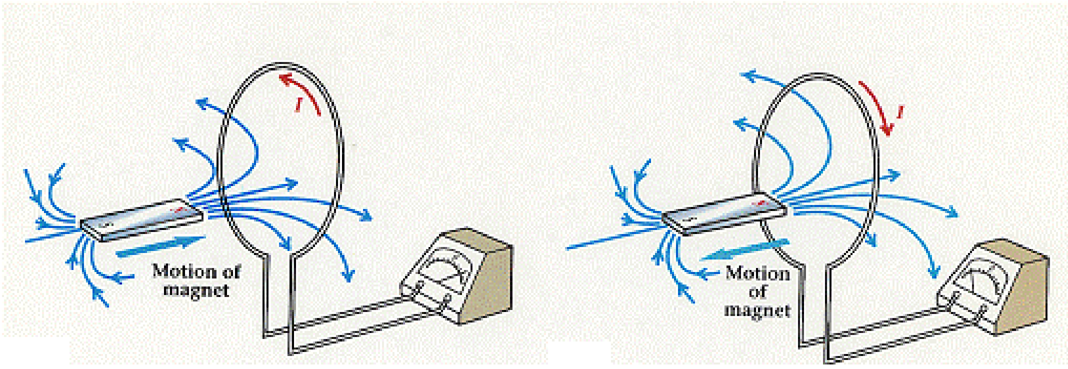
Induced emf is equal to the negative of the time rate of change of the magnetic flux

View an animation: electromagnetic induction

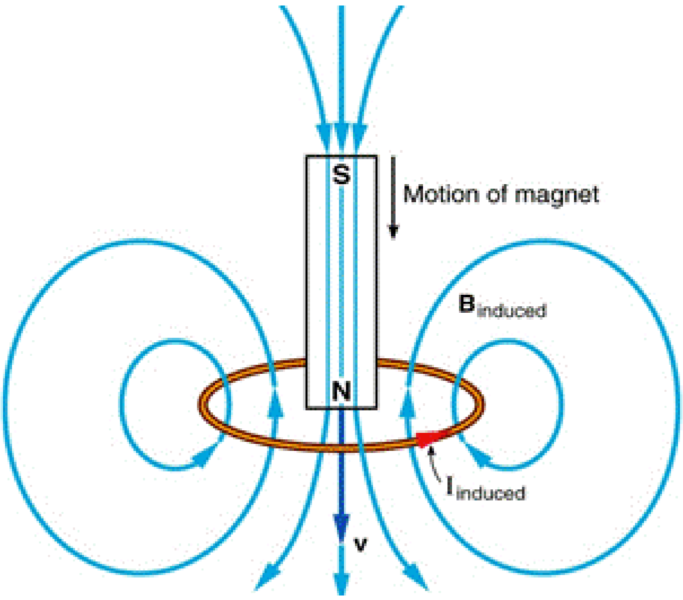
An induced an emf and induced current in a coil is generated by a changing magnetic flux threading the coil:

- Increasing magnetic field strength and hence magnetic flux threading the coils.
- A permanent magnetic maybe moved toward or away from the coil or the coil moved toward or away from a magnet.
- The orientation of a coil in the magnetic field can be changed.

Changing magnetic flux through a coil



if magnet stationary – no deflection of galvanometer needle (no induced emf)



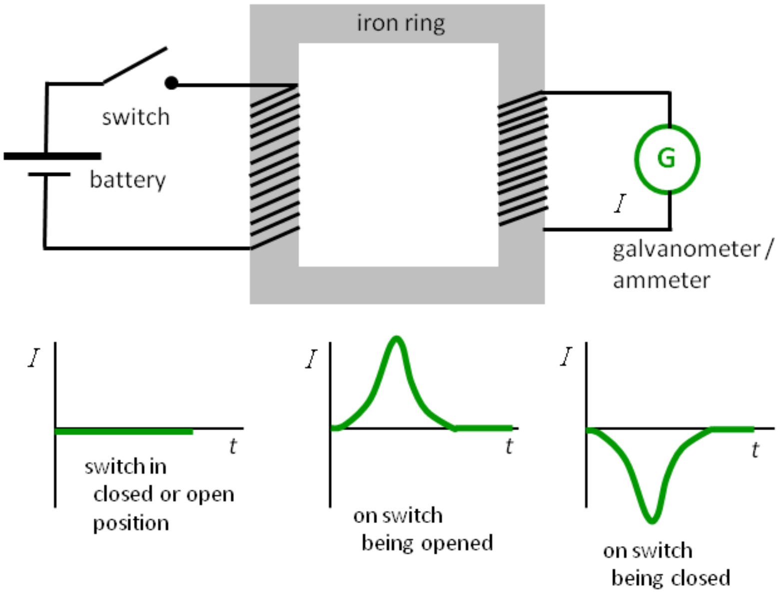
When the magnetic field through a conductive loop is increasing, an electric field is induced which produces an induced emf and a resulting induced current.

The emf is distributed throughout the loop (there is no positive or negative terminals to drive the current as in the emf of a battery).

The direction of the electric field, induced emf and induced current are determined by using **Lenz's law** and the **right hand screw rule**

Curl of fingers $\rightarrow$ current
Thumb $\rightarrow$ direction of induced magnetic field

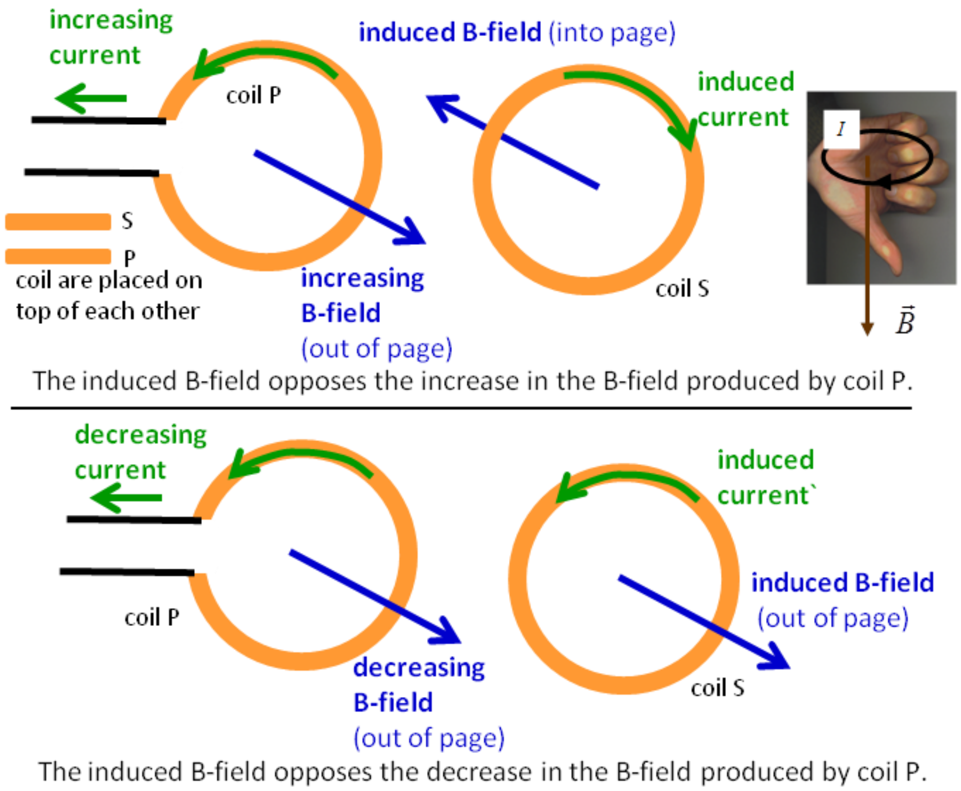
Faraday's ring



Faraday experimented with a Faraday ring.

- A changing magnetic flux in the iron ring induced a current in the galvanometer coil.
- The changing magnetic flux is produced only when the switch is opened or closed.
- There is no deflection of the galvanometer pointer when a steady current is flowing in the coil on the left.

Coils placed on top of each other



The lower coil (P) has a changing current through it. The upper coil (S) has a current induced in it because of the changing magnetic flux produced by the changing current in coil P. The direction of the induced magnetic field and induced current for coil S is determined by **Lenz's law** and the **right hand screw rule**.

Why do you often observe sparks when a plug is pulled out of a power point?
When the plug is pulled quickly away from a powerpoint socket when turned on, the current abruptly drops to zero and the magnetic field due to the current collapses. This changing magnetic flux produces an *emf* that tries to maintain the original current, resulting in a spark at the terminals of the plug and socket.

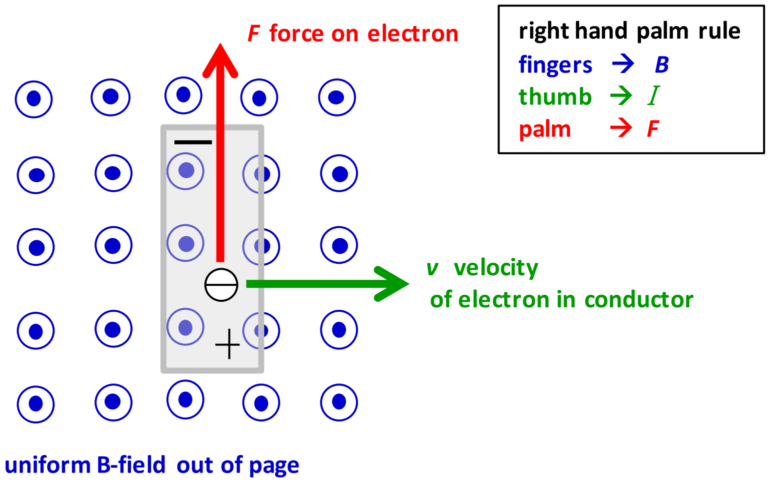
emf INDUCED IN A CONDUCTOR MOVING IN A UNIFORM MAGNETIC FIELD

Consider a straight conductor of length *L* moving through a uniform magnetic field *B* as shown. The conductor is moving with a speed v and travels a distance $\Delta x = v\Delta t$ in the time interval Δt. The area swept out by the conductor in transgressing the B-field is $\Delta A = L(v\Delta t)$. Therefore, there will be a changing magnetic flux and an emf induced in the conductor. This is often referred to as a motional emf. By Faraday's law, the magnitude of the induced emf ε across the end of the conductor is given by

$$\varepsilon = \left|\frac{\Delta\Phi_B}{\Delta t}\right| = \frac{B\Delta A}{\Delta t} = (BLv)\left(\frac{\Delta t}{\Delta t}\right) = BLv$$

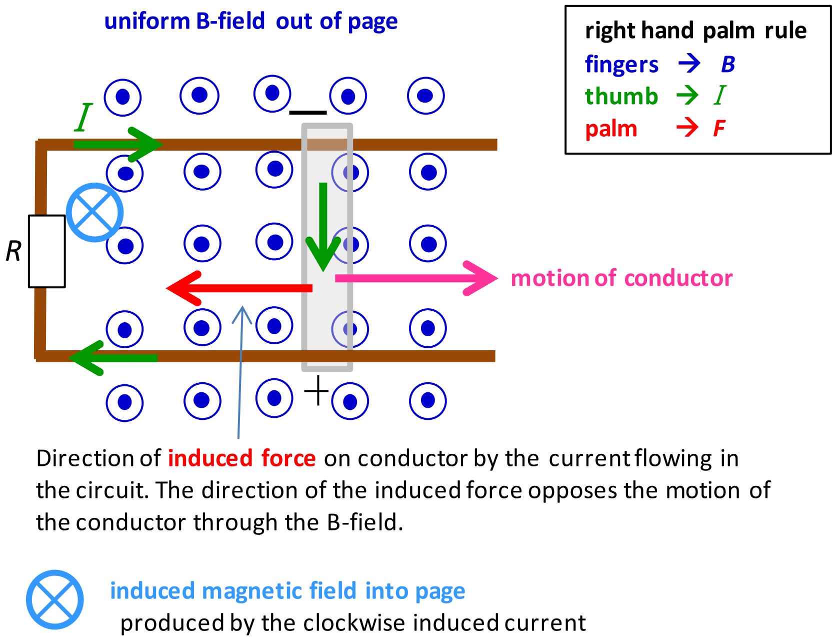
This equation is valid provided B is constant and B, L and v are mutually perpendicular.

The direction of the induced emf is determined by **Lenz's rule** and the right hand palm rule. The force on the electrons in the moving conductor is up which causes a charge separation – the top of the conductor becomes negative while the bottom of the conductor becomes positive.



When there is a complete circuit, the induced *emf* will give rise to a current. For the arrangement shown, the direction of the induced current is clockwise.

The conductor carrying the current in the magnetic field will experience a force to oppose its motion (right hand palm rule). As the conductor moves to the right, the area swept out increase, so the magnetic flux increases. By Lenz's law, the induced current must produce a magnetic field to oppose the change, so the induced magnetic field must be into the page, therefore, the current must be in a clockwise direction.



Thus, when a conductor moves in a magnetic field it acts as a source of electrical energy. This is the basis of a **generator**.

top

5 Electric motors and the back *emf* in motors

An electric motors operates by a current from some energy source (emf) passing through an external magnetic field. A current in a magnetic field experiences a force. The conductor carrying the current is wound into a coil (armature) so that it will experience a torque to cause the rotation.

However, by **Faraday's law**, a coil rotating in the magnetic field produces a continually changing magnetic flux. Hence, an emf is induced in the rotating coil.

By **Lenz's law** this emf must be in the opposite sense to the supply emf, otherwise the voltage would continually increase leading to an ever increasing current through the coil.

This induced emf is known as the **back emf.** It has opposite polarity to the supply emf.

Consider an ideal motor with no friction or drag forces acting. The net voltage V_{coil} across the coil of the motor is equal to the supply emf $\varepsilon_{\text{supply}}$ minus the back emf ε_{back}

$$V_{coil} = \varepsilon_{\text{supply}} - \varepsilon_{back}$$

If there is no load attached to the motor, the coil (armature) will spin faster and faster until the supply emf is equal to back emf. Then, the net voltage across the coil is zero, resulting in the coil current and hence torque acting on the coil to be both zero and so the coil will rotate at a constant angular speed.

$$\varepsilon_{\text{supply}} = \varepsilon_{back} \quad \Rightarrow \quad V_{coil} = 0 \quad \Rightarrow$$
$$I_{coil} = 0 \quad \Rightarrow \quad \tau_{coil} = 0 \quad \Rightarrow \quad \text{armature spins at a constant rate}$$

When the load on the motor increases:

→ the armature spins more slowly

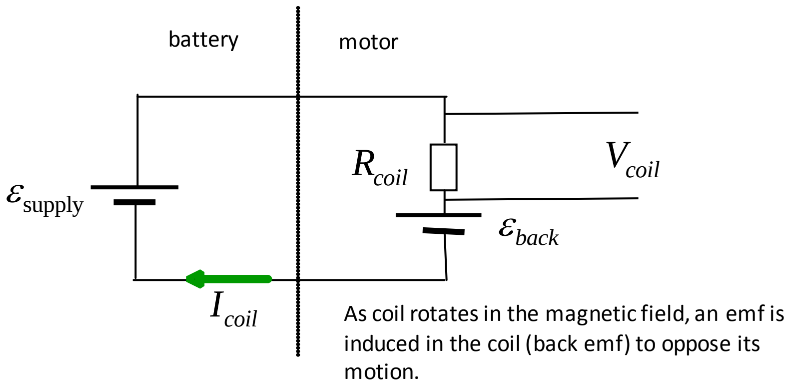
→ the rate of change of the magnetic flux deceases

→ induced emf decreases (back emf decreases)

→ coil voltage increases

→ coil current increases

If the load becomes too large causing the armature to rotate slowly or stop, then large currents through the coil will cause unwanted heating effects and damage the motor. When motors are turned on, there will be large coil currents unless there is some protection mechanism.



$$I_{coil} = \frac{V_{coil}}{R_{coil}} = \frac{\varepsilon_{supply} - \varepsilon_{back}}{R_{coil}}$$

Electric circuit for a DC motor

Example

The armature windings of a DC motor has a resistance of 5.0 Ω. The motor is connected to a 240 V power supply. When the motor reaches its full rotation speed the back emf is 188 V. (a) When the motor is just starting, what the motor current? (b) What is the current when the motor is operating at its maximum rotation speed?

Solution

R = 5.0 Ω ε = 240 V ε_{back} = 188 V

Motor starting

ε_{back} = 0 V I = ? A $I = \varepsilon / R$ = (240 / 5) A = 48 A

Motor max speed

ε_{back} = 188 V   I = ? A

$I = (\varepsilon - \varepsilon_{back}) / R$ = (240 - 188) / 5 A = 10 A

Faster the rotation speed the greater the induced back emf. Currents can be very high on starting. When a motor is jammed → rotation speed much reduced → reduced emf → increased current → motor heats up → motor maybe damaged.

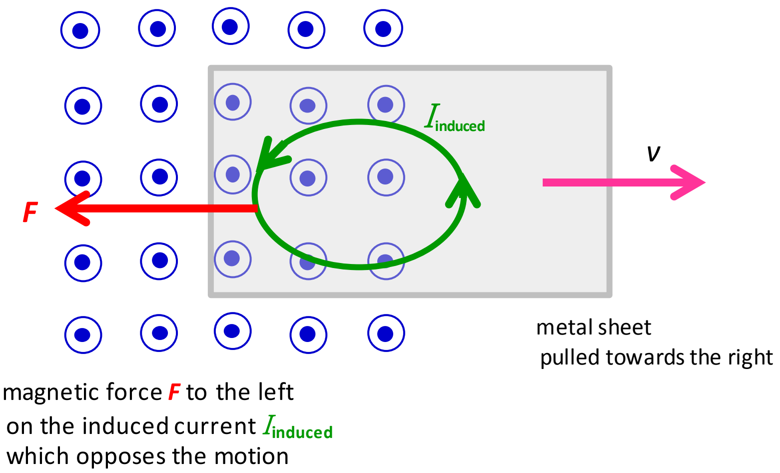
top

6 Lenz's Law: eddy currents
– induction electric cooktops and electromagnetic braking

A changing magnetic flux can induce a current in a conductor. Sometimes the changing magnetic flux induces circulating current known as **eddy currents**.

Eddy currents have a heating effect upon the conductor (ohmic heating: $P = I^2 R$). This heating effect is put to good use in induction cooktops, but this heating effect contributes to an energy loss in transformers.

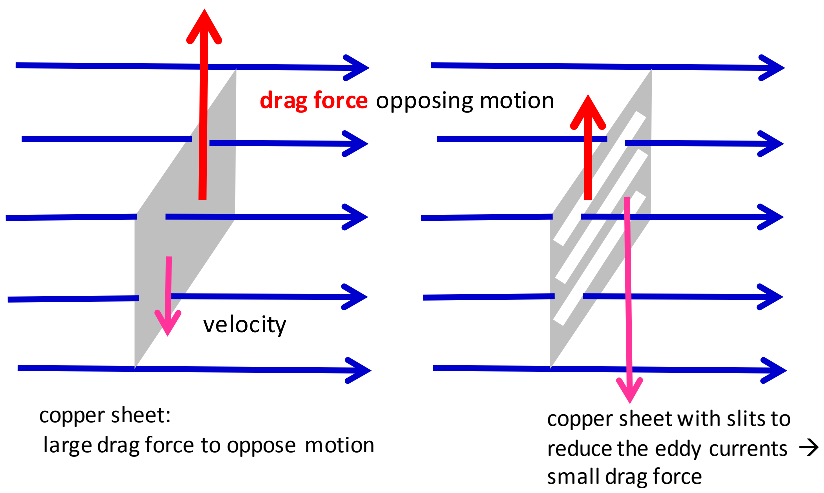
When you try to pull a strip of copper or aluminium through the poles of a magnet, you feel a retarding force. As you move the conductor through the magnetic field of the magnet, a changing flux is produced. This results in circulating eddy currents in the metal strip. The induced force on the metal strip opposes its motion (Lenz's law).



Metal sheet pulled through a magnetic field experiences a drag force. This drag force opposes the motion of the metal through the B-field. The direction of the induced current can be determined using the right hand palm rule.

Copper sheets falling through the poles of a magnet

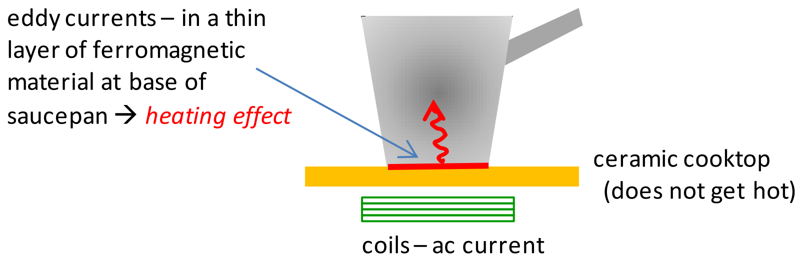
If the conductor has cuts made in it, again the eddy currents are weaker reducing the heating effect and also reducing the magnetic drag force acting on the conductor.



Induction cooktops are becoming more popular. The cooktop does not get hot. No heat is transferred from the cooktop to the saucepan. Induction cooktops are more energy efficient and quicker than traditional cooktops.

A coil in the cooktop induces eddy currents in the base of a saucepan. The eddy currents in the metal base produce the heating effect ($P = I^2 R$).

The magnetic properties of a steel vessel concentrate the induced current in a thin layer near its surface. This makes the heating effect stronger. In non-magnetic materials like aluminium, the B-field field penetrates too far, and the induced current encounters little resistance in the metal. Practical induction cookers are designed for ferromagnetic saucepans or frypans that will stick to a magnet.



Induction heating of a saucepan.

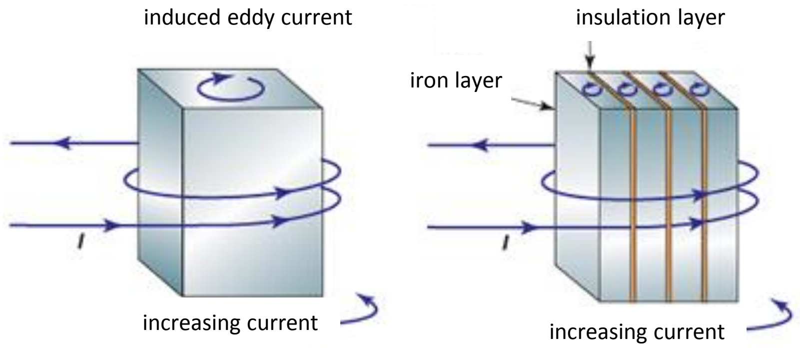
Eddy currents are used to dampen unwanted oscillations

Sensitive mechanical balances would oscillate up and down about its equilibrium position when a mass was placed on the scales if not for the damping produced by eddy currents.

Eddy currents are usually unwanted because of their heating

Eddy currents induced in the armature of a motor, generator or transformer can produce a considerable heating effect (ohmic heating: $P = I^2 R$). This degrades their performance because energy is lost as thermal energy.

Theses thermal energy losses can be reduced by using conductive slabs that are laminated (small strips glued together). This separates the conductive strips by an insulator, hence, the eddy currents are confined to individual strips which dramatically reduces the heating effect.

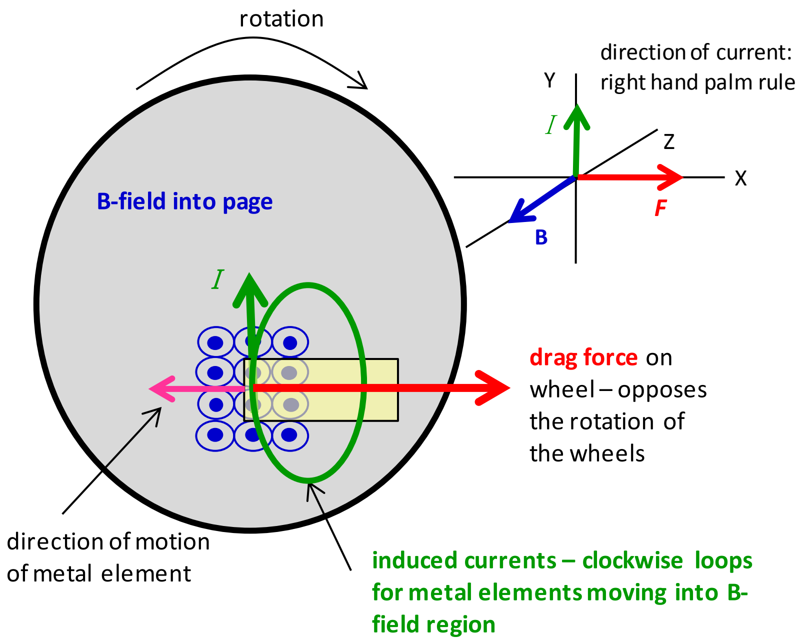


eddy current cause a heating effect

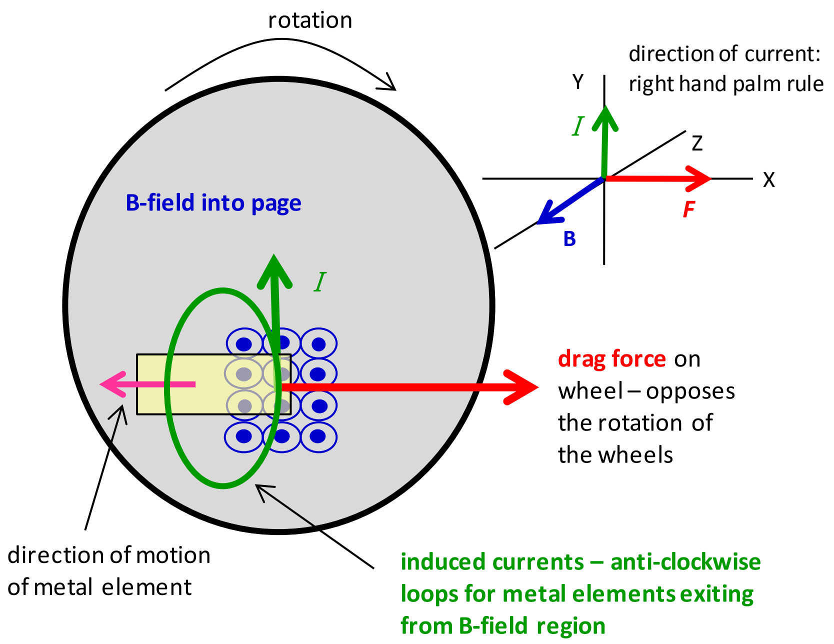
laminations reduce magnitude of eddy currents
$\Rightarrow$ less ohmic heating ($I^2 R$)

Electromagnetic breaking

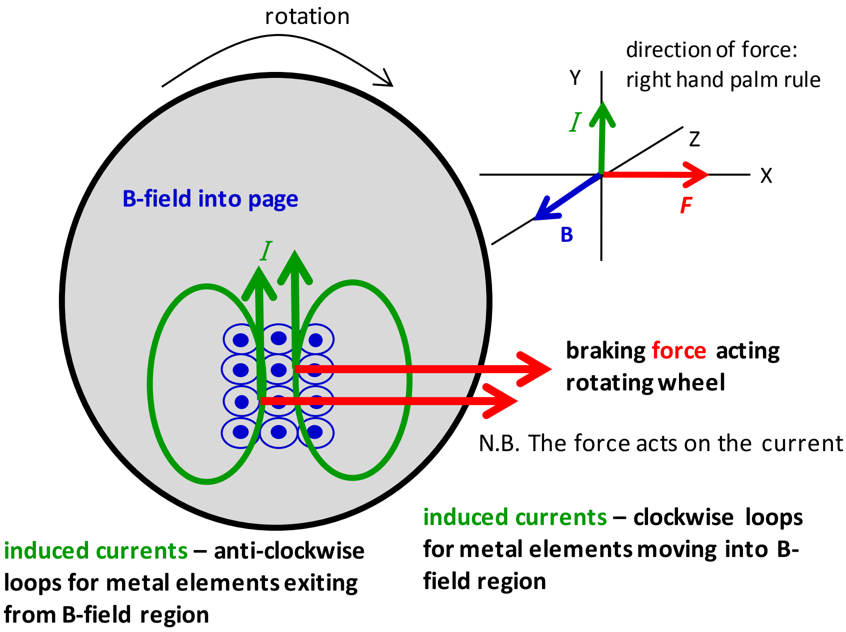
Eddy currents can be used in **electromagnetic breaking**. A large electromagnet is located over the wheels of a vehicle. When the electromagnet is switched on, large eddy currents are induced in the metal wheels and the magnetic force provides a drag force on wheels to stop the vehicle.



As an element of the metal enters the magnetic field, circular current loops are induced. The force on these current loops in such that it opposes the motion of the metal.



As an element of the metal exits from the magnetic field, circular current loops are induced. The force on these current loops in such that it opposes the motion of the metal.



As the metal wheel rotates, the section of the wheel within the B-field region will experience a drag force that can be used to stop the rotation. This is the mechanism used for brakes in vehicles using an electromagnetic induction braking system.

top