Revision Guide for Chapter 15

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I can show my understanding of effects, ideas and relationships by describing and explaining cases involving:

transformers: where an induced emf is produced by changing the magnetic flux linking one coil and another Revision Notes: transformer, electromagnetic induction, Lenz's law Summary Diagrams: How a transformer works, Faraday's law of induction	
generators: where an induced emf is produced by conductors and flux moving relative to one another, either by moving flux or moving a conductor Revision Notes: generator Summary Diagrams: Transformer into generator, Large high-power generator, Motors and generators	
electric motors: where motion is produced when a force acts on a current-carrying conductor placed in a magnetic field, including the induction motor in which the current is induced in the conductor Revision Notes: electric motor Summary Diagrams: Motors and generators, Alternating fields can make rotating fields, A rotating field motor, Flux and forces	
linked electric and magnetic circuits: flux produced by current turns, qualitative need for large conductance and permeance, and effects of dimensions of circuit and of iron and air gap Revision Notes: magnetic field, magnetic flux Summary Diagrams: Flux and flux density, Electric circuits and magnetic flux, Electric and magnetic circuits	
electromagnetic forces: qualitatively as arising from tendency of flux lines to shorten or from interaction of induced poles; quantitative ideas restricted to force on a straight current-carrying wire in a uniform field Revision Notes: magnetic field, magnetic flux, force on a current-carrying conductor Summary Diagrams: Flux and forces, Force on a current-carrying conductor	

I can use the following words and phrases accurately when describing effects and observations:

magnetic *B*-field, magnetic flux, flux linkage Revision Notes: magnetic field, magnetic flux Summary Diagrams: Electric circuits and magnetic flux, Flux and flux density, Changing the flux linked to a coil	
induced emf (electromotive force), eddy currents Revision Notes: electromagnetic induction, Lenz's law Summary Diagrams: Faraday's law of induction	

I can sketch and interpret:

diagrams showing lines of flux in magnetic circuits Summary Diagrams: Electric circuits and magnetic flux, Flux and flux density, Flux and forces	
graphs showing variations of current, induced emf and flux with time Summary Diagrams: Graphs of changing flux and emf	

I can make calculations and estimates involving:

magnetic flux $\phi = BA$ induced emf $\varepsilon = -\frac{d(N\phi)}{dt}$ Revision Notes: magnetic field, magnetic flux, electromagnetic induction, Lenz's law Summary Diagrams: Flux and flux density, Faraday's law of induction	
forces acting on current-carrying conductors $F = ILB$ where current, force and uniform magnetic field are at right angles Revision Notes: force on a current-carrying conductor Summary Diagrams: Flux and forces, Force on a current-carrying conductor	
voltages, currents and turns in an ideal transformer: voltage ratio $\frac{V_1}{V_2} = \frac{N_1}{N_2}$ power $I_1V_1 = I_2V_2$ Revision Notes: transformer Summary Diagrams: How a transformer works	

Revision Notes

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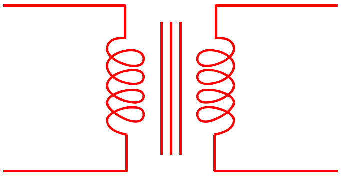
Transformer

A transformer changes the peak voltage of an alternating potential difference. The symbol for a transformer is:

Transformer symbol



A transformer has two electric circuits, generally with different numbers of turns, wound over a common magnetic circuit, generally a closed iron core.

The transformer turns rule:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

relates the peak p.d.s across the primary and secondary coils V_p and V_s to the number of turns of the primary coil N_p and of the secondary coil N_s. The rule is an idealisation, assuming that all the flux in the magnetic circuit passes through both coils, and that there are negligible drops in p.d. across the resistances of the two coils.

The efficiency of a typical transformer can be quite close to 100% so the current ratio I_s / I_p is equal to V_p / V_s. Conservation of energy requires that because power is potential difference × current, if the potential difference is stepped up, the current must be stepped down and vice versa.

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Electromagnetic induction

Electromagnetic induction is the generation of an emf due to changing magnetic flux in a circuit. The magnetic flux ϕ through a surface of area A which is perpendicular to the lines of a uniform magnetic field is $B A$, where B is the magnetic flux density.

The magnetic flux linkage through a coil of N turns and area A in a uniform magnetic field is $B A N$, where B is the component of the magnetic field at right angles to the plane of the coil.

The SI unit of magnetic flux is the weber (Wb). The SI unit of magnetic flux density is the tesla (T), equal to 1 weber per square metre (Wb m^{-2}).

The SI unit of rate of change of magnetic flux, the weber per second, is the same as the unit of emf, the volt.

The induced emf in a coil is proportional to the rate of change of magnetic flux linkage through the coil. This is Faraday's law of electromagnetic induction.

The induced emf acts in a direction so as to oppose the change. This is Lenz's law and is a consequence of the conservation of energy.

Faraday's law may be written as

$$\varepsilon = -\frac{\mathrm{d}(N\phi)}{\mathrm{d}t}$$

where ε is the induced emf and $\mathrm{d}(N\phi) / \mathrm{d}t$ is the rate of change of flux linking the circuit. The minus sign shows that the induced emf acts against the change that causes it, in accordance with Lenz's law

Faraday's and Lenz's laws apply to all situations where an emf is induced due to changing magnetic flux. Such a change can be due to movement of a conductor in a magnetic field or due to changing the magnetic flux density through a coil.

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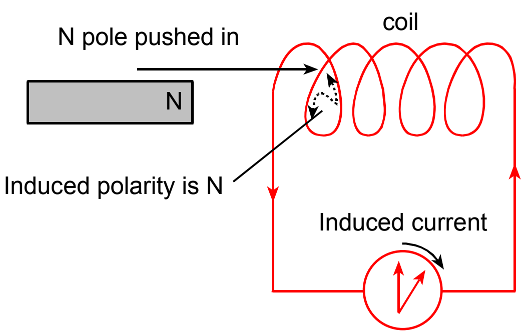
Lenz's law

Lenz's law states that the direction of an induced emf is always such as to act against the change that causes the induced emf.

To understand Lenz's law, consider an open coil connected to a centre-reading meter. The meter pointer deflects in a certain direction when a bar magnet is pushed into the coil. This occurs because an emf is induced in the coil by the changing magnetic flux and the coil is in a complete circuit so a current is generated during the time the magnet is moving into the coil.

The current is in such a direction as to create a magnetic field which acts against the incoming bar magnet. The magnetic polarity of the coil due to the current is opposite to the polarity of the leading pole of the incoming bar magnet. This opposition means that work must be done on the magnet to keep it moving into the coil and this is the source of the electrical energy produced. If the induced current was in the opposite direction, the incoming pole would be attracted into the coil, increasing both its kinetic energy and the electrical energy produced, in violation of the principle of conservation of energy.

Lenz's law



If the same magnet is moved out of the coil, the meter deflects in the opposite direction. The current is reversed compared with its previous direction because the magnetic field it creates opposes the change by attracting the outgoing magnet. The work done to keep the magnet moving appears as electrical energy.

Induced currents due to changing magnetic flux in armature and transformer cores cause inefficiency in electromagnetic machines. These induced currents are referred to as **eddy currents**. These eddy currents cause resistance heating in the conductors and they act against the changes causing them, thus requiring work to be done to keep the changes occurring. Armature cores and transformer cores are laminated to minimise eddy currents.

A practical use of Lenz's law is electromagnetic braking in vehicles. A generator driven by the motion of the vehicle brakes the vehicle by taking energy from the energy of motion. The induced current acts in such a direction as to provide a torque due to the motor effect acting against the vehicle's motion. The energy of motion of the vehicle can be fed back into the supply. Lenz's law also relates to the back emf in a motor when it is spinning, thus keeping the current smaller than it would be if the motor armature was stationary.

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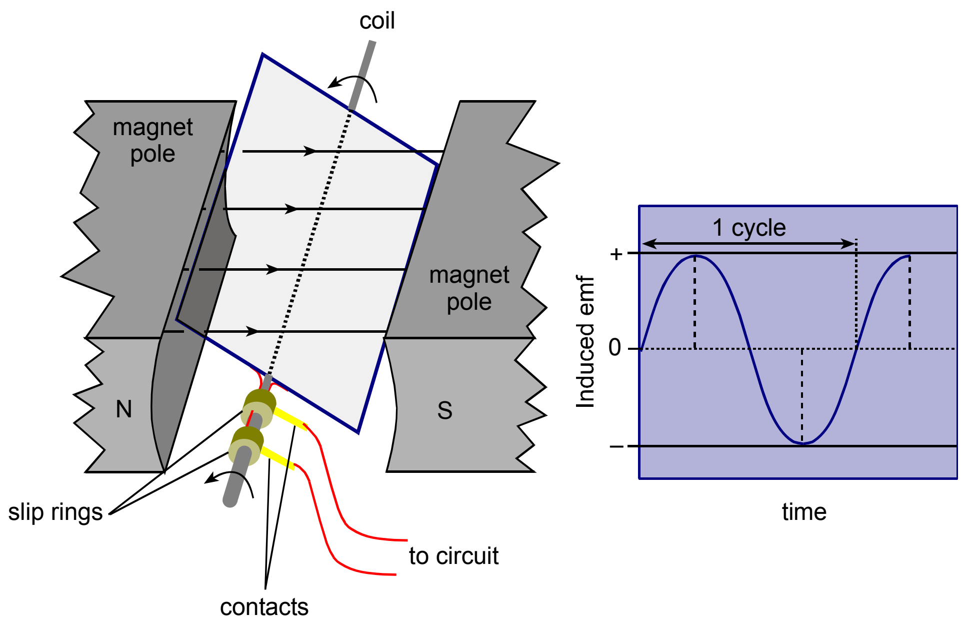
Generator

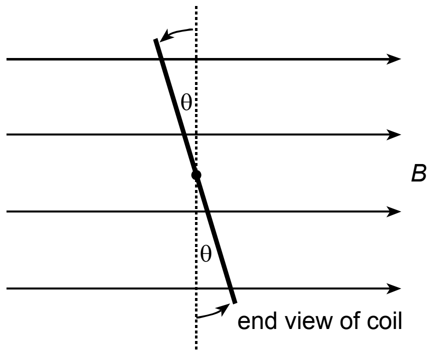
A generator produces an emf as a result of relative motion between a magnetic flux and an electrical conductor.

The diagram below shows a very simple model dynamo in which a rectangular coil spins at a constant rate in a uniform magnetic field. An alternating emf is generated by the spinning coil because the magnetic flux through the coil changes sinusoidally. A graphite brush presses on each slip ring to maintain continuous contact so that the coil is part of a complete circuit when a load is connected to the brushes.

The a.c. dynamo



Changing flux



At the instant when the coil plane has turned through angle θ from the position of maximum flux linkage, the flux linkage

$$N\phi = BAN\cos\theta$$

where *A* is the area of the coil. This may be written as

$$N\phi = BAN\cos\omega t$$

where ω is the angular speed of the coil and *t* is the time taken to reach this position after passing through the position of maximum flux linkage. Faraday's law of electromagnetic induction gives the induced emf as

$$\text{emf} = -\frac{\mathrm{d}(N\phi)}{\mathrm{d}t}.$$

Since

$$\frac{\mathrm{d}(\cos\omega t)}{\mathrm{d}t} = -\omega\sin\omega t$$

then the induced emf = $B\,A\,N\,\omega\sin\omega\,t$. Thus the peak emf (when $\sin\omega t = 1$)

$$\varepsilon_0 = BAN\omega.$$

An **alternator** is a generator which produces an alternating emf by rotating a magnetised rotor inside coils wound on a stationary stator. The coils are at rest, and the magnetic flux rotates. See Summary Diagram: Large high-powered generator.

When a generator is operating the induced current in the coils has a magnetic flux associated with it, causing a motor effect. The motor effect will oppose the spinning of the generator, by Lenz's law. A noticeable increase in torque is needed to keep a generator spinning at constant frequency when a current is drawn from it.

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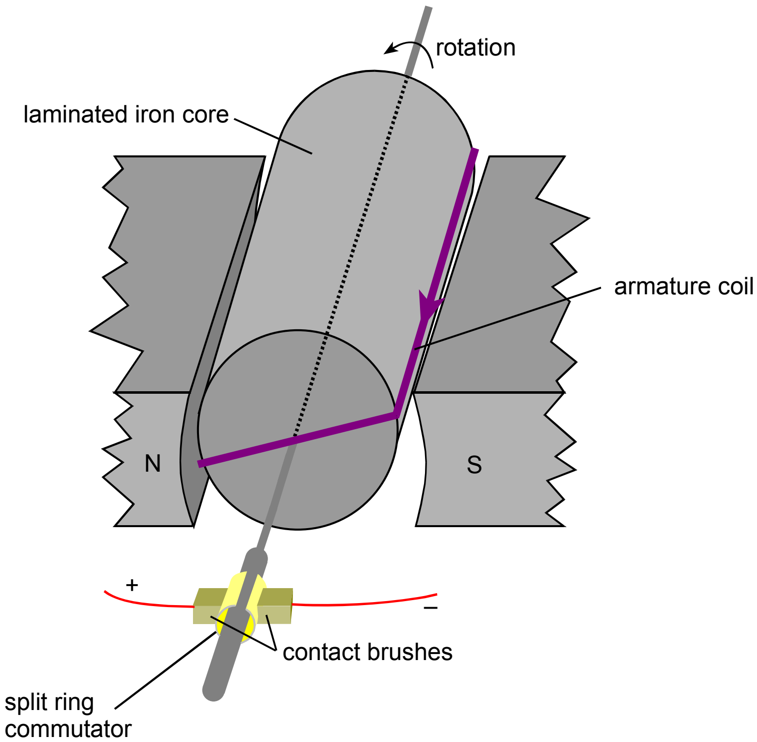
Electric motor

A motor consists of an electric circuit and a magnetic circuit. A simple **moving coil motor** has a rectangular coil on a spindle between opposite magnetic poles. Two fixed brushes provide continuous electrical contact with the coil via a split-ring commutator. When a direct current is passed through the coil, forces are exerted on the coil due to the interaction between the current-carrying wires and the magnetic field. These forces cause the coil to turn about the spindle.

Moving coil motor

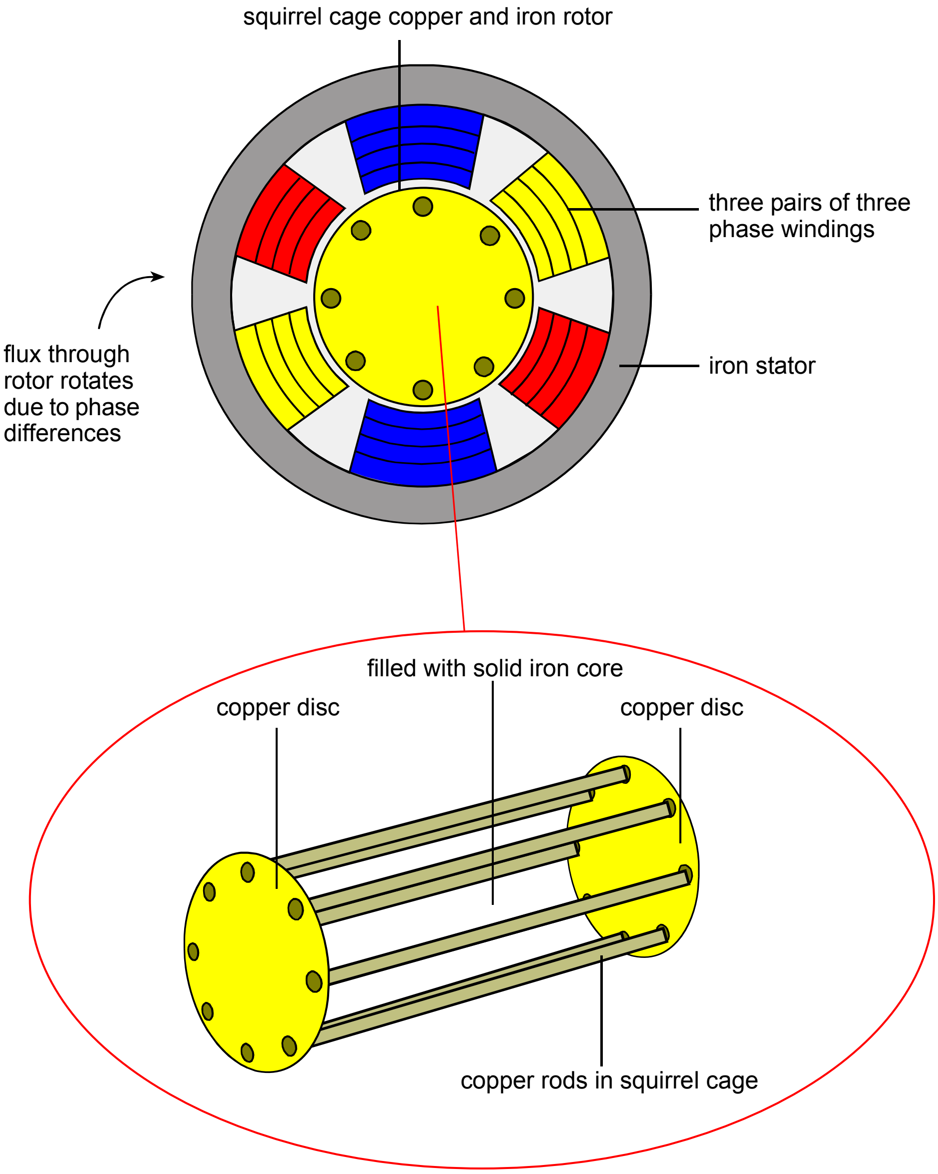


The split-ring commutator reverses the direction of the current round the coil each time the coil rotates through 180°, so that the forces on the coil continue to make the coil turn in the same direction.

The dynamo effect of the spinning motion of the coil in a magnetic field causes an induced emf, referred to as a back emf, in the coil, acting against the motor supply.

Most motors used in industrial applications are **induction motors**. In an induction motor, the currents in the rotor are not fed directly from the supply but are induced by an alternating magnetic flux through the rotor. The rotor is in the form of a 'squirrel cage' of copper conductors embedded in an iron cylinder. The flux through the rotor is made to rotate by creating it from coils around the rotor which carry currents with a phase difference between them. In large industrial motors the phase differences derive from the three phases of the national grid supply.

The squirrel cage



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Magnetic field

The strength of a magnetic field or **magnetic flux density** *B* can be measured by the force per unit current per unit length acting on a current-carrying conductor placed perpendicular to the lines of a uniform magnetic field.

The SI unit of magnetic flux density *B* is the tesla (T), equal to 1 N A^{-1} m^{-1}.

The force *F* on a length *L* of wire carrying current I, when at an angle θ to a uniform field *B* is given by $F = ILB \sin\theta$. Thus one way to measure the flux density is to measure this force, using some form of current balance.

Alternatively, magnetic flux $N\phi$ over an area *A* can be measured by the induced emf ε in a search coil with *N* turns, using

$$\varepsilon = -\frac{d(N\phi)}{dt}$$

and the magnetic field calculated as the flux density ϕ / A.

A further practical way to measure flux densities is to use a calibrated Hall probe.

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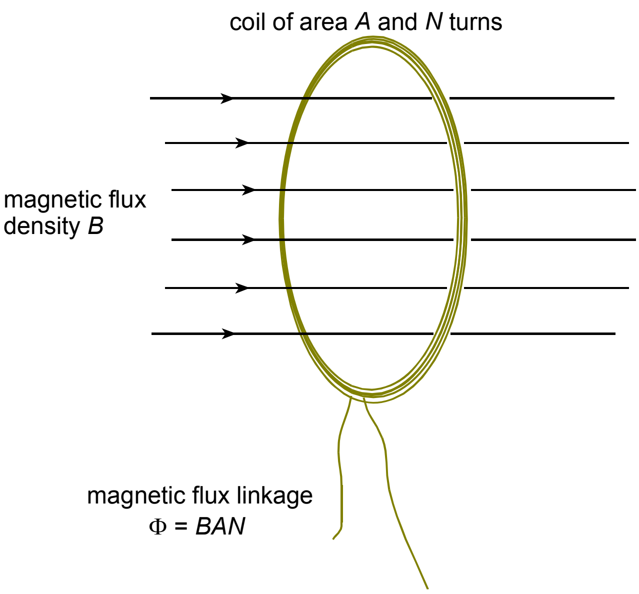
Magnetic flux

The **magnetic flux** ϕ through a surface of area *A* which is perpendicular to the lines of a uniform magnetic field is *B A*, where *B* is the magnetic flux density.

The magnetic **flux linkage** $\Phi = N\phi$ through a coil of *N* turns and area *A* in a uniform magnetic field is *B A N*, where *B* is the component of the magnetic field at right angles to the plane of the coil.

The SI unit of magnetic flux is the weber (Wb). The SI unit of magnetic flux density is the tesla (T), equal to 1 weber per square metre (Wb m^{-2}).

Flux linkage



The design of many electromagnetic machines in which magnetic flux is created by electric currents needs to make the magnetic flux as large as possible. This is achieved by using iron and by reducing or eliminating air gaps.

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Force on a current-carrying conductor

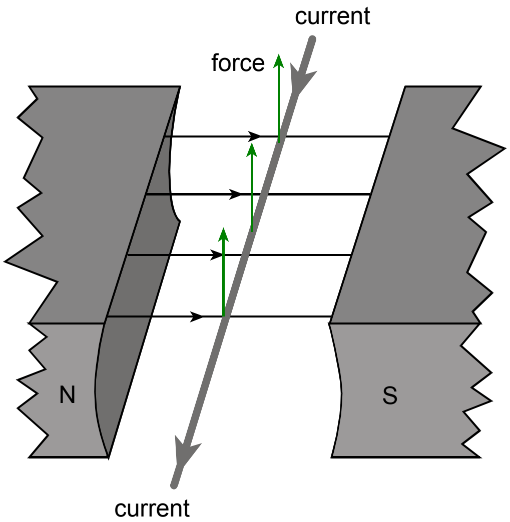
The force F on a current-carrying conductor perpendicular to a uniform magnetic field is proportional to:

1. the current I
2. the length L of the conductor
3. the magnetic flux density B

The force is given by $F = I L B$. When the conductor is at angle θ to the field, $F = I L B \sin \theta$.

The direction of the force is perpendicular to the conductor and to the field lines.

Force on a conductor in a magnetic field



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Summary Diagrams

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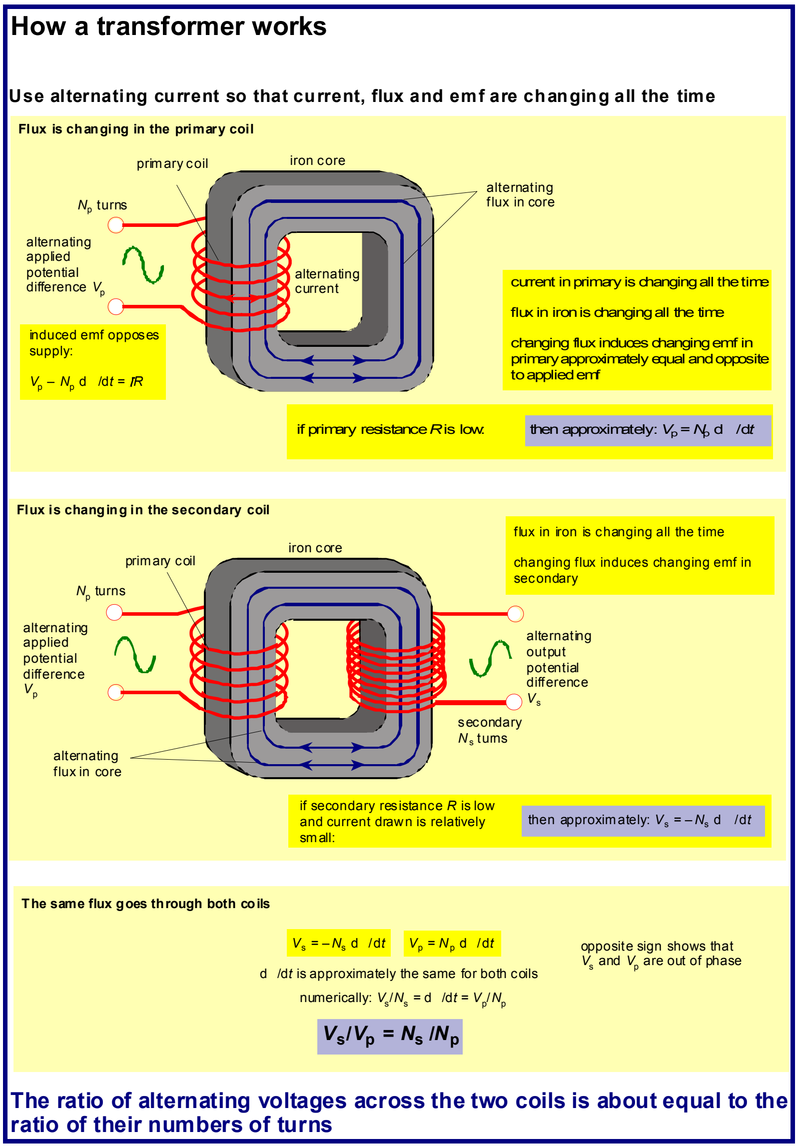
How a transformer works

This diagram shows how the transformer works and the relationships between the primary current, flux produced and emf induced. Approximations then lead to the ideal transformer relationship.



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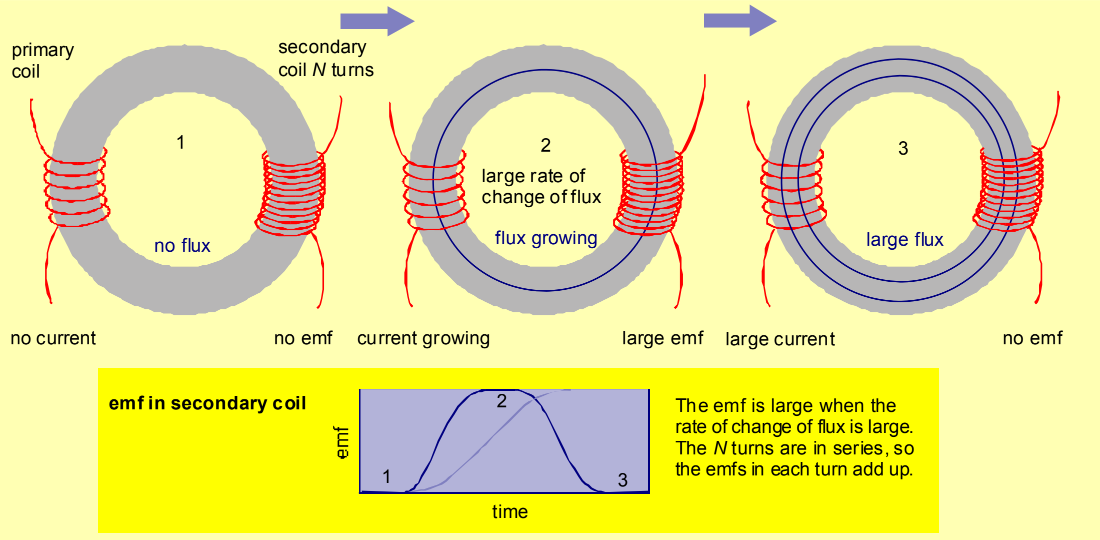
Faraday's law of induction

Faraday's law of induction



Flux linkage *N*
The emf per turn is proportional to d /d*t*. The *N* turns are in series so the emfs in each turn add up.
The emf across the coil is proportional to *N*d /d*t*. The quantity *N* is called the flux linkage.

Faraday's law: emf is proportional to rate of change of flux linkage *N*d /d*t*
Lenz's law: the induced emf opposes the change of flux producing it

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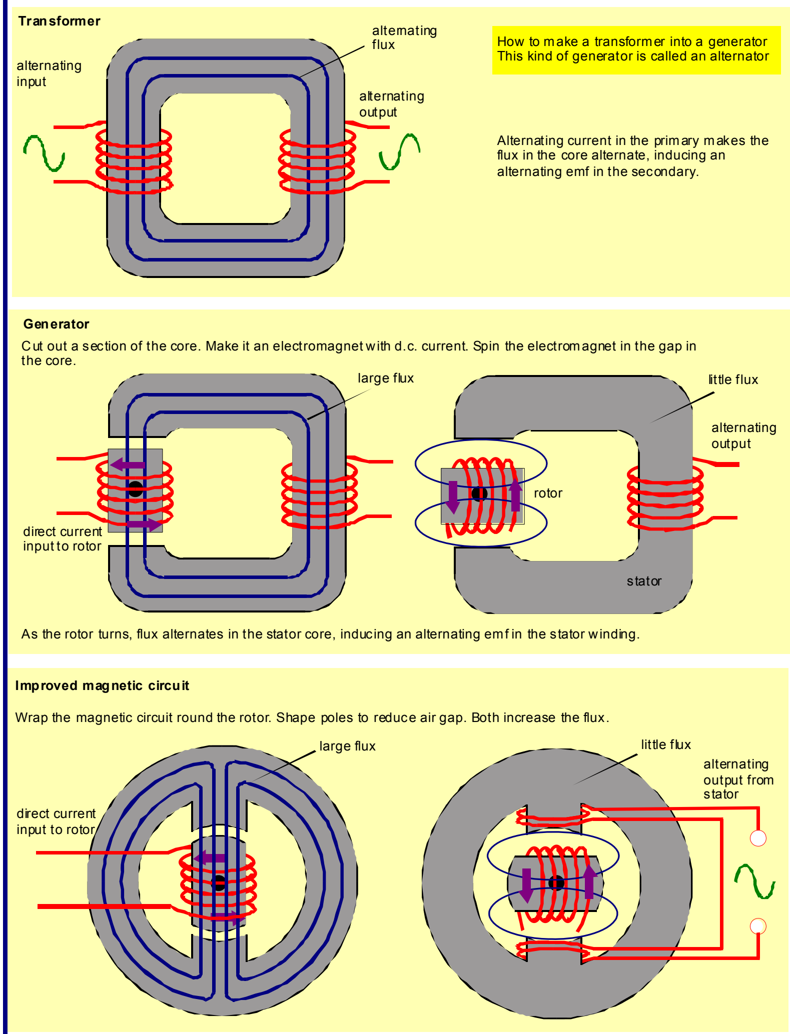
Transformer into generator

Transformer into generator



Alternating flux in the core generates an alternating output. Flux in the core alternates because:
in the transformer, current in the primary coil alternates; and in the generator, a magnetised section of the core rotates.

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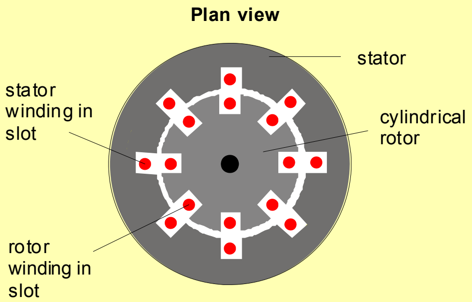
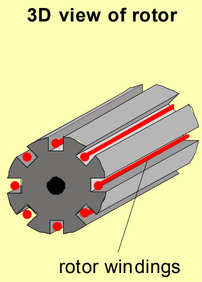
Large high-powered generator

Large high-power cylindrical rotor machine

Slotted rotor and stator
Both rotor and stator are slotted. The coil windings go in the slots. Only a few slots and coils are shown.

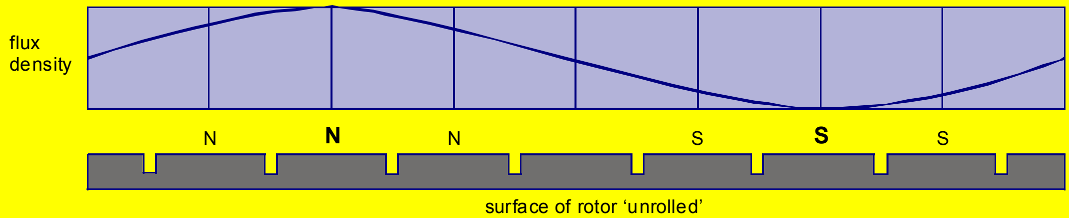




Action
As the rotor spins, the magnetic flux pattern turns with it. Thus flux through the stator coils is continually rising and falling. This induces an alternating emf in the stator coils.

Coil windings
The rotor is wound with coils producing a N pole on one face of the rotor and a S pole on the opposite face.

Rotor coils are arranged so that flux density varies sinusoidally around the surface of the rotor.



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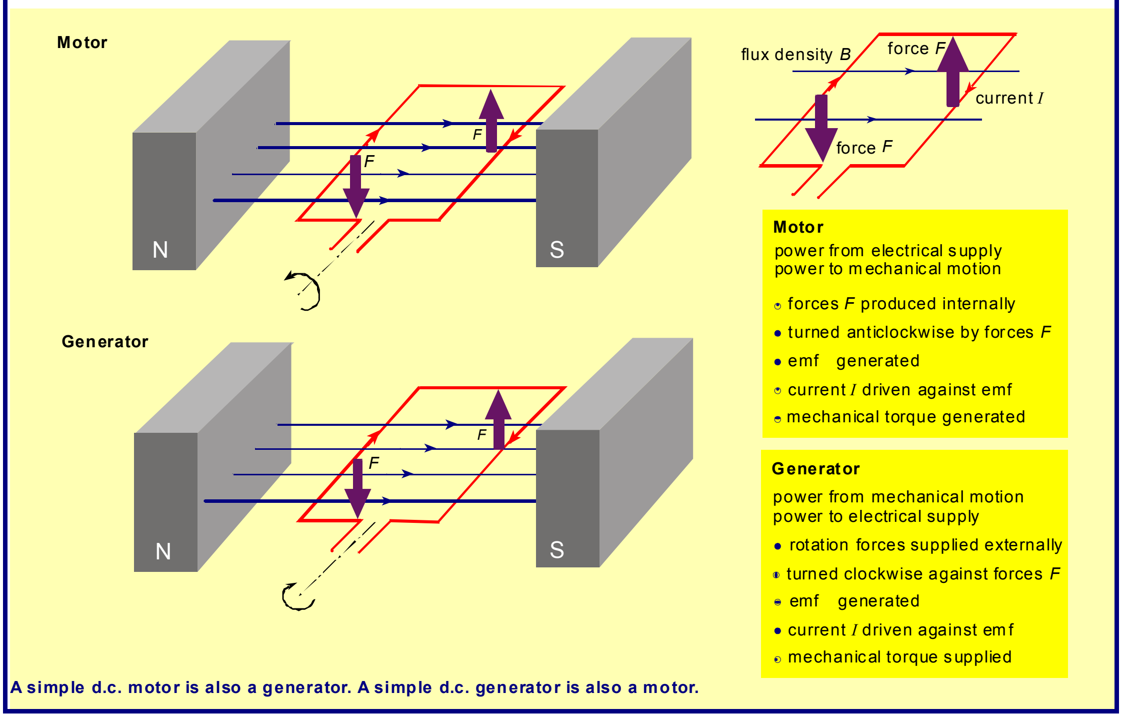
Motors and generators

This diagram compares and contrasts motors and generators.

Motor and generator



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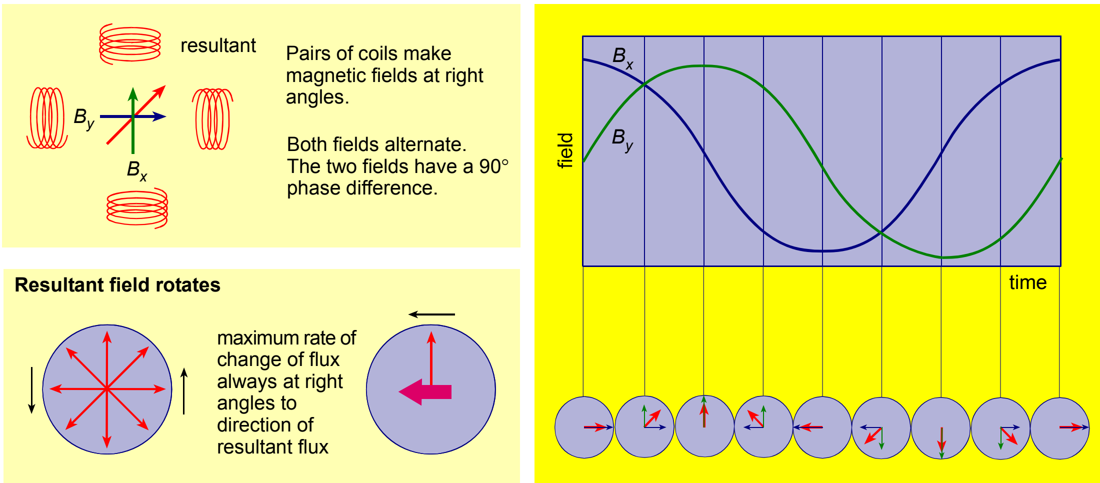
Alternating fields can make rotating fields

Alternating fields can make rotating fields



Two or more alternating fields at different angles with different phases can make a rotating field

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A rotating field motor

This diagram shows how alignment forces drive a rotating flux motor.

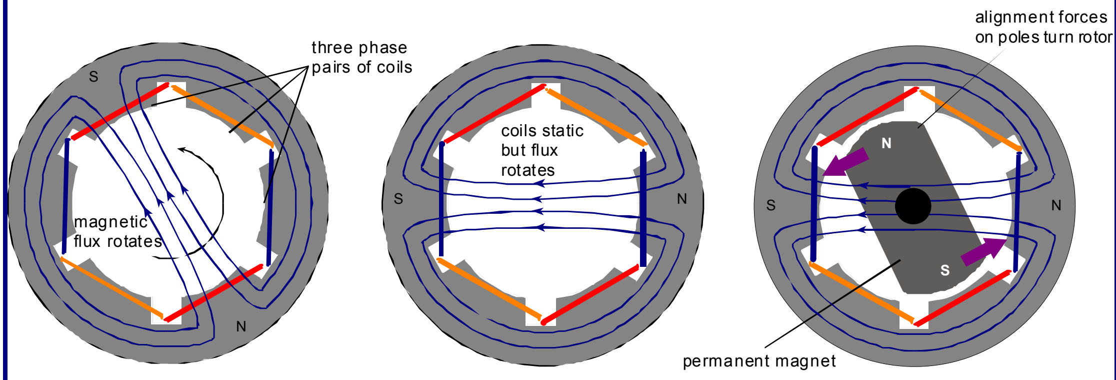
A rotating field motor

Rotating flux

A permanent magnet rotor turns with the field

The poles of a permanent magnet rotor are pulled round by the poles of the rotating field. The rotor turns at the frequency of rotation of the field.

Used in low power applications.



Motors are driven by alignment forces

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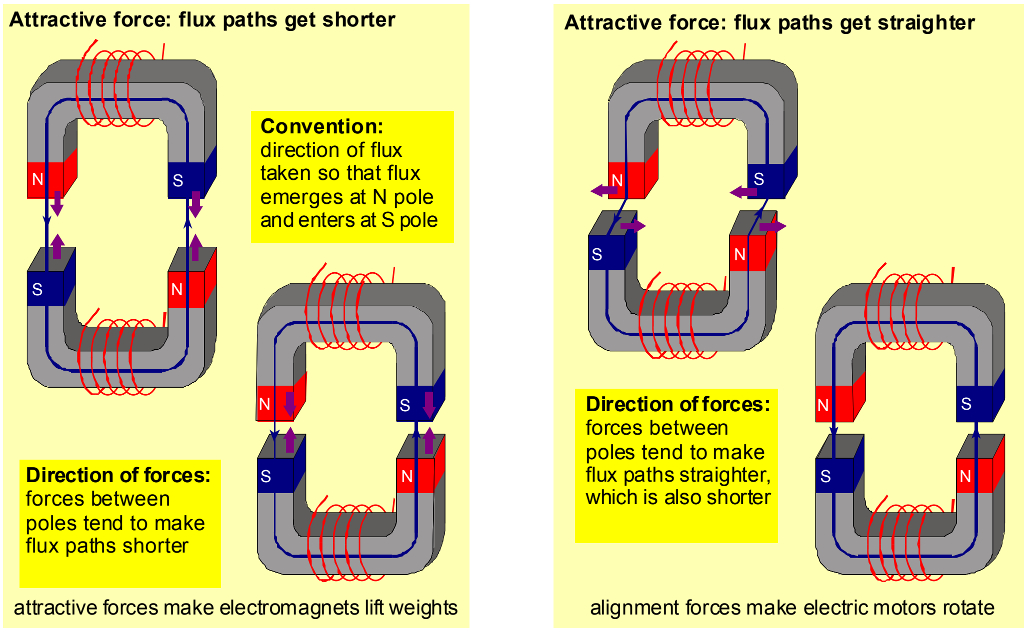
Flux and forces

These diagrams show two ways in which fluxes can give rise to forces. Forces between poles are such as to tend to make flux paths shorter and straighter. The flux behaves like an elastic string.

Flux and forces



Forces between poles tend to make flux paths shorter and straighter. The flux behaves like an elastic string.

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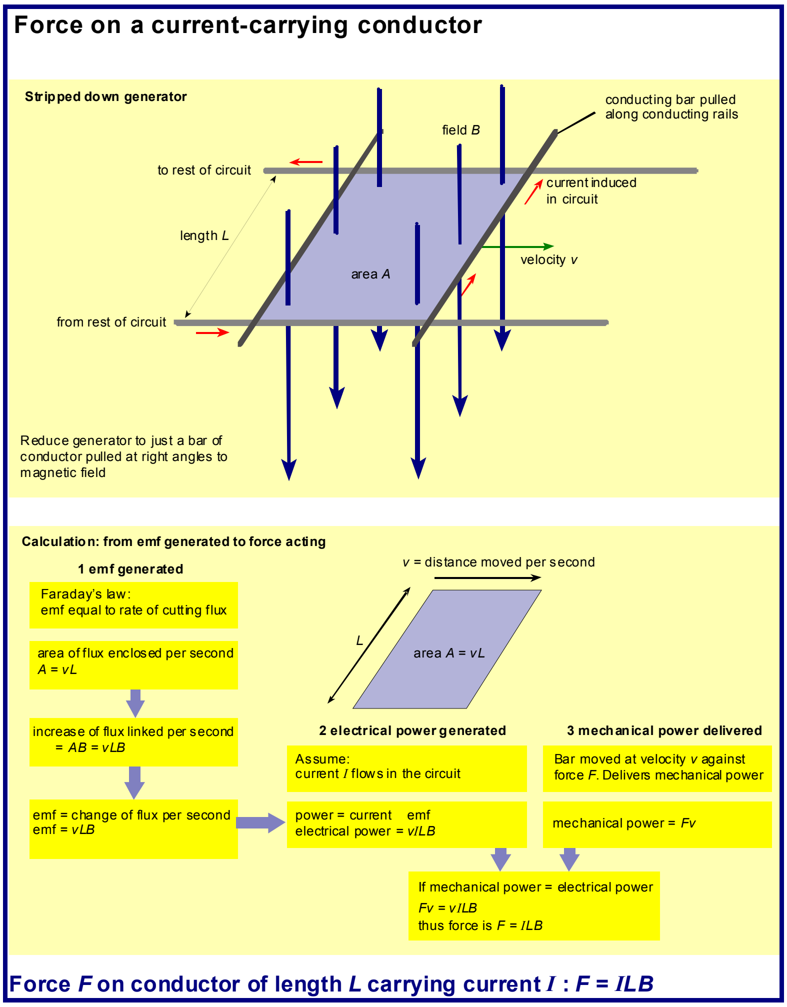
Force on a current-carrying conductor



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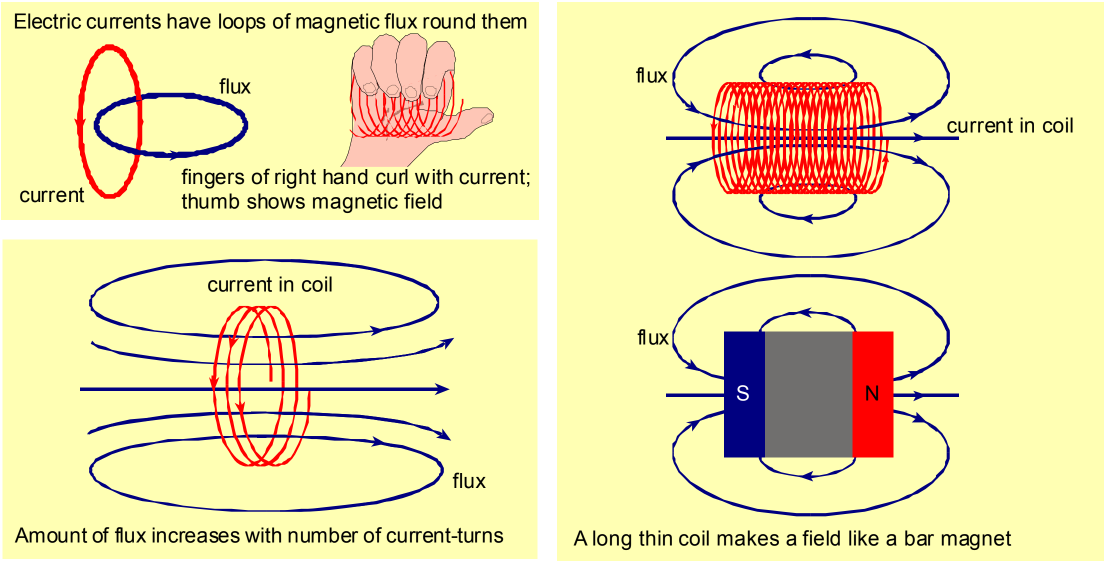
Electric circuits and magnetic flux

This diagram shows how the current in a circuit is related to the magnetic flux produced.

Electric circuits and magnetic flux



Flux loops around current. Current loops around flux. Current-turns drive flux.

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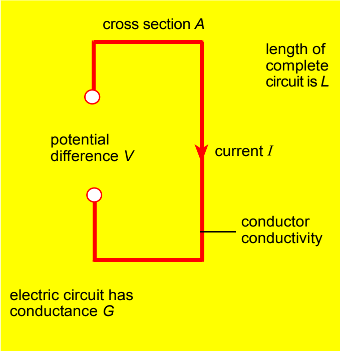
Electric and magnetic circuits

This diagram shows analogies between electric and magnetic circuits.

Electric and magnetic circuits

Electric circuit



Electric circuit:

require current, apply a potential difference

$$\text{conductance} = \frac{\text{current}}{\text{“driving” potential difference}}$$

conductance $G = \frac{I}{V}$

Units:

unit of current is ampere A

unit of conductance is siemens S

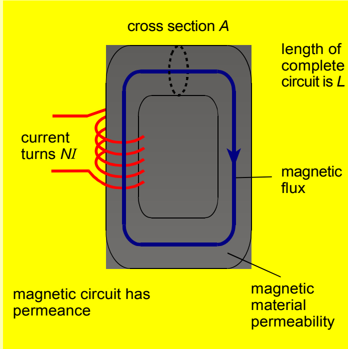
“amperes per volt” A V^{-1}

Length *L* and cross section *A*

conductivity has units S m^{-1}

conductance $G = \frac{A}{L}$

Magnetic circuit



Magnetic circuit:

require flux, apply current-turns

$$\text{permeance} = \frac{\text{magnetic flux}}{\text{“driving” current-turns}}$$

permeance $\frac{}{NI}$

Units:

unit of flux is weber Wb

unit of permeance is Wb A^{-1}

“webers per ampere-turn”

Length *L* and cross section *A*

permeability has units Wb A^{-1} m^{-1}

permeance $= \frac{A}{L}$

Shorter and thicker is better for both electric and magnetic circuits

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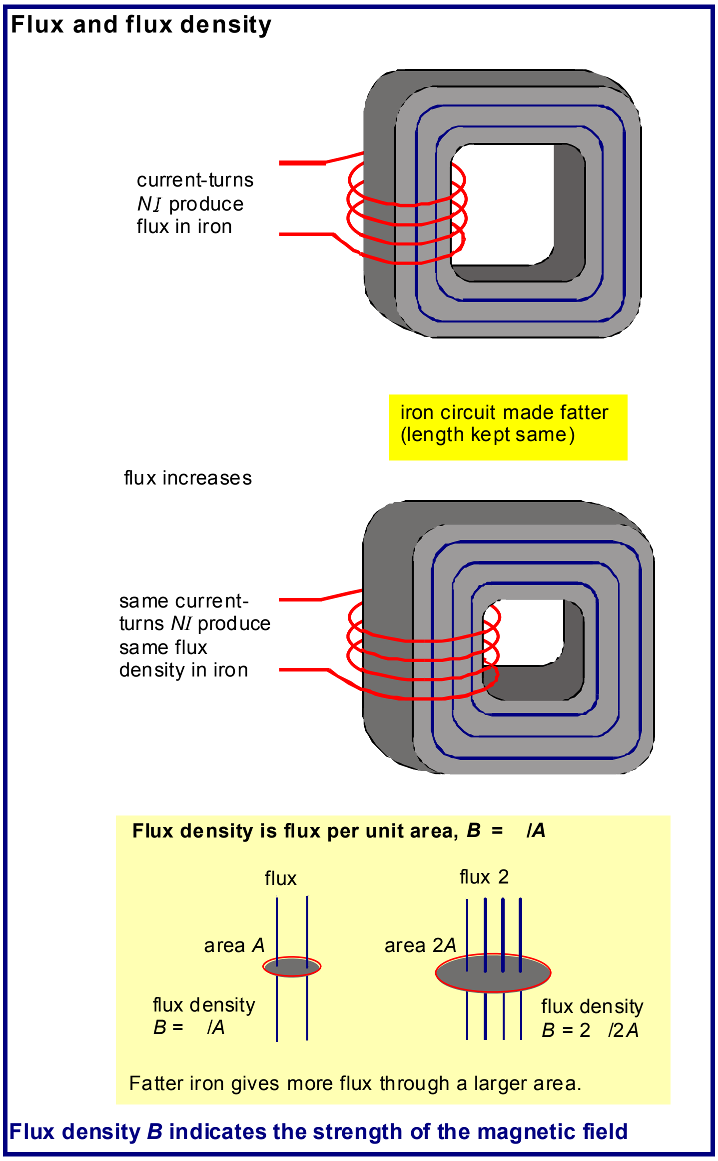
Flux and flux density

This diagram shows how flux can be related to flux density, and how this in turn shows the strength of the magnetic field.



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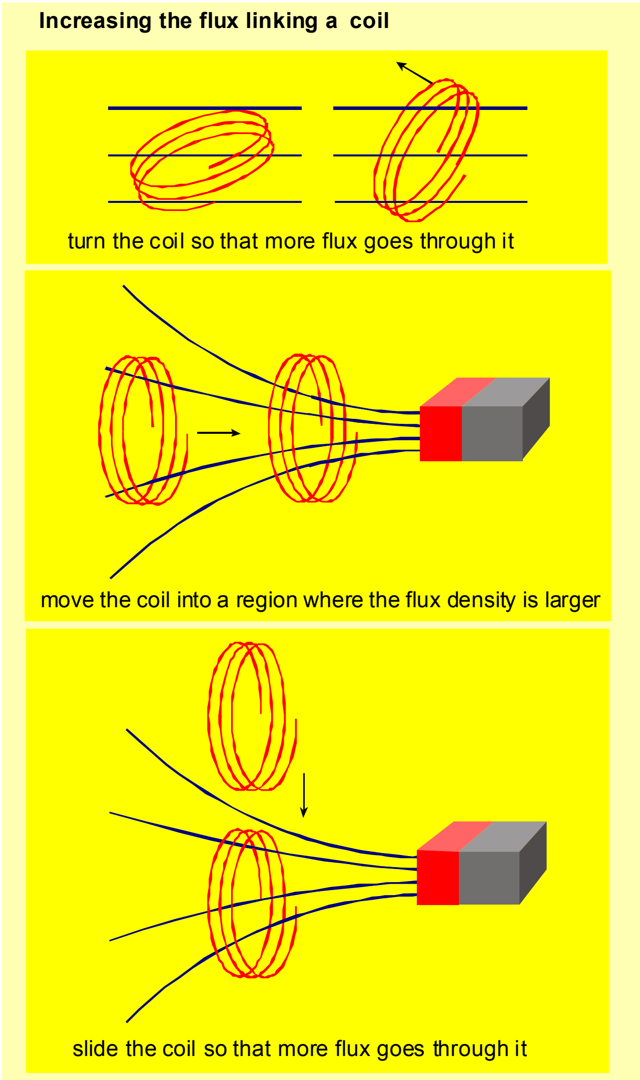
Changing the flux linked to a coil

Here are three ways of increasing the flux linked to a coil.

Flux cutting and flux changing



Cutting flux = change of flux linked
Lines cut = change in lines linking

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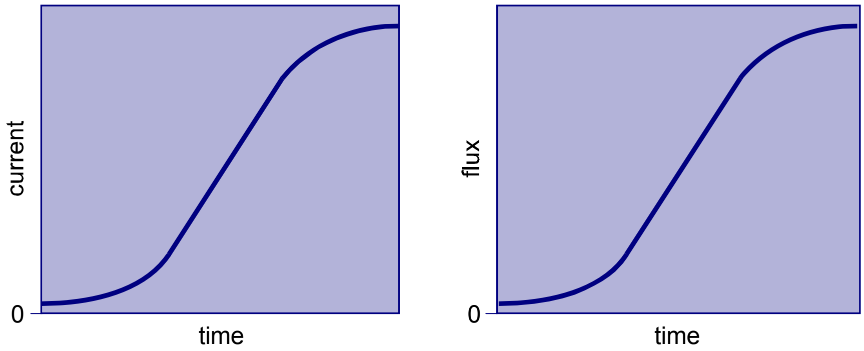
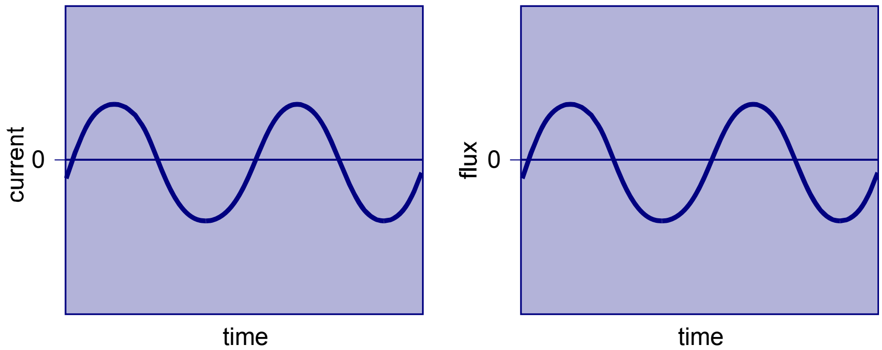
Graphs of changing flux and emf

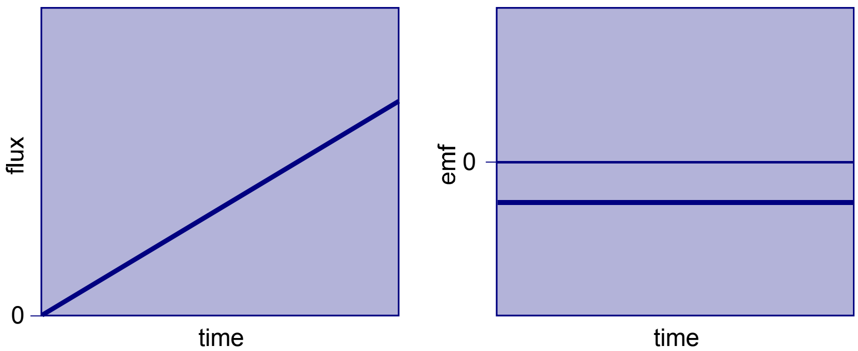
Flux produced by a current



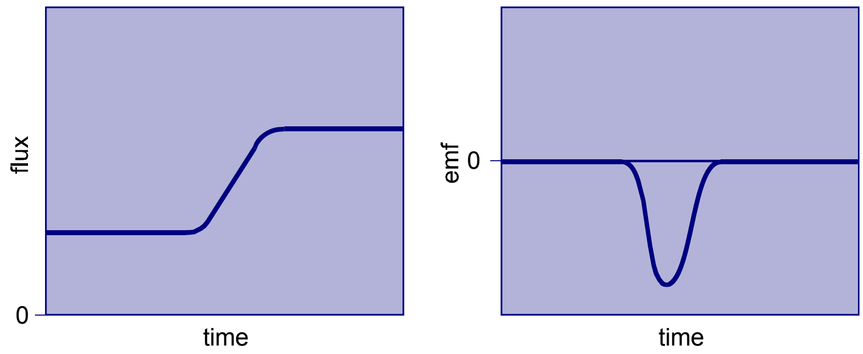


If the flux is proportional to the current, the graphs of changing flux and changing current have the same form.

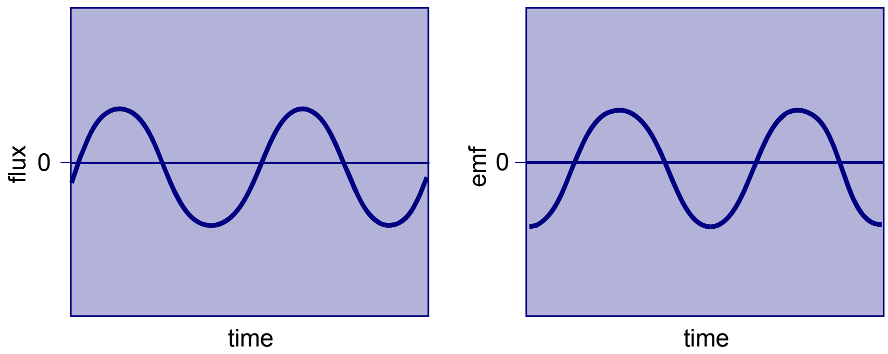
Emf induced by changing flux



A steadily increasing flux produces a constant emf, acting so as to oppose the change of flux producing it.



A sharp increase of flux produces a pulse of emf, acting so as to oppose the change of flux producing it.



A sinusoidally varying flux produces a sinusoidally varying emf, with a 90° phase difference.

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