Historical Perspective in Magnetism

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Here we show the experimental works on the magnetism which are historically important. These works can be collected from the web sites and standard textbooks of Electricity and Magnetism.

1. Time line

1600 **William Gilbert** (1540-1603, Great Britain) publishes On the Magnet.

1699 **Edmund Halley** (1656-1742, Great Britain) conducts the first magnetic survey.

1785 **Charles Augustin Coulomb** (1736-1806, France) announces his inverse square law of electrical attraction and repulsion.

1799 **Alessandro Volta** (1745-1827, Italy) invents the electric battery (announced in 1800).

1812 **Siméon Denis Poisson** (1781-1840, France) put the finishing touches on the mathematical apparatus of Coulomb's electrodynamics.

1813 **Hans Christian Oersted** (1777-1851, Denmark) suggests that the electricity ought to be convertible to magnetism.

1819 **Oersted** shows that an electric current is able to deflect a magnetic needle (published in 1820).
Dominique F.J. Arago (1786-1853, France) shows that a current can magnetize iron (the electromagnet).
André Marie Ampère (1775-1836, France) commences work on electromagnetism.

1821 **Michael Faraday** (1791-1867, Great Britain) shows that electrical forces can produce rotational motion of a needle.
Thomas Johann Seebeck (1770-1831, Germany) converts heat into electricity.

1824 **Poisson** publishes a mathematical treatment of magnetism to complement the one that he had published for electrostatics in 1812.

1825 **Ampère** deduces law for force between current-carrying conductors.
William Sturgeon (1783-1850, Great Britain), a British electrician, constructs an electromagnet.

1826 **Georg Simon Ohm** (1787-1854, Germany) proposes what is now called Ohm's law relating current and voltage.

1831 **Faraday** discovers electromagnetic induction and devices the first electrical generator. Begins work on electrolysis.
Joseph Henry (1797-1878, USA) independently obtains similar results in the United States.

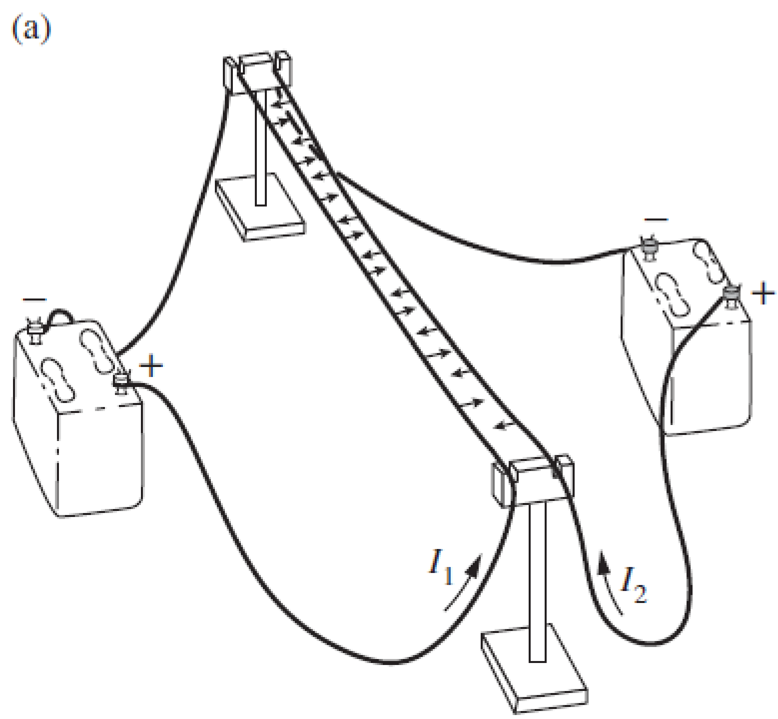
1834 **Heinrich F.E. Lenz** (1804-1865, Germany) finds the Lenz law.

1840 **J.P. Joule** (1818-1889, Great Britain) finds the Joule's law.

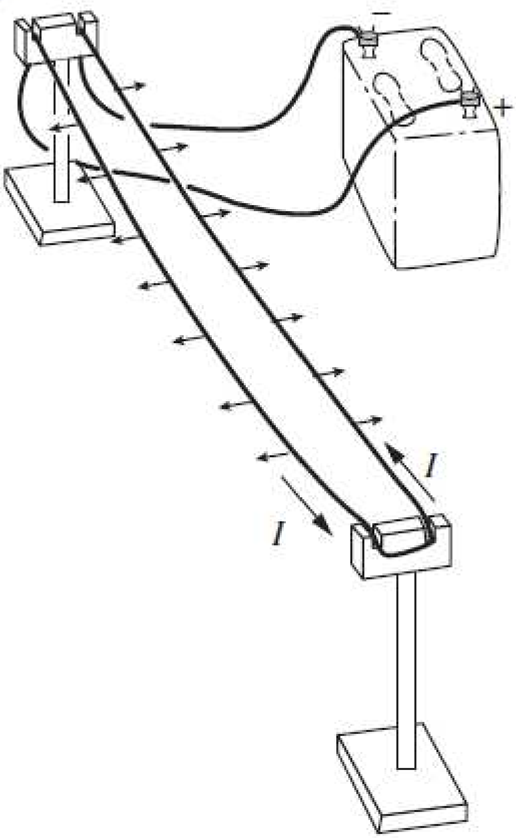
1845 **Faraday** discovers effect of magnetic field on polarized light (Faraday effect). Faraday finds the diamagnetism.

1864 **James C. Maxwell** (1831 – 1879, Great Britain) finds the Maxwell's equation and predicts the existence of electromagnetic wave which travels at the speed of light.

2. Magnetic force due to currents



(b)



(c)

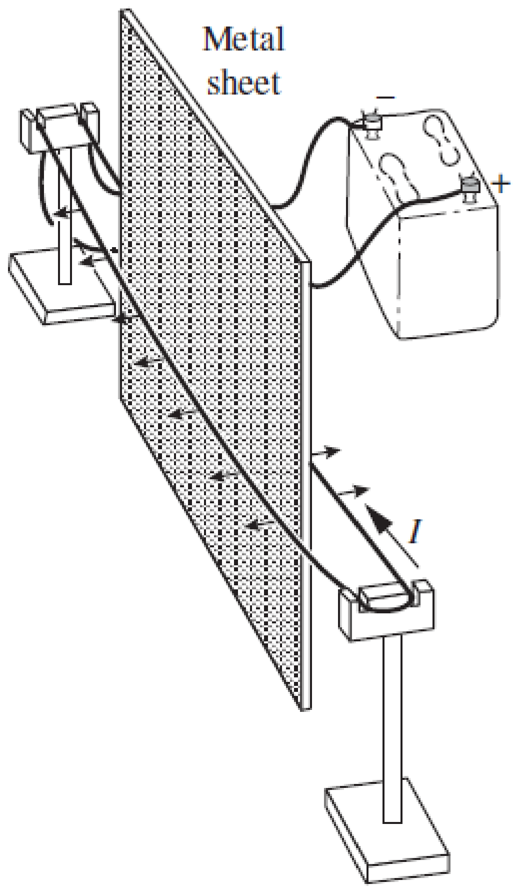


Fig. (a) Parallel wires carrying currents in the same direction are pulled together. (b) Parallel wires carrying currents in opposite directions are pushed apart. (c) These forces are not affected by putting a metal plate between the wires.

3. Experiment by Oersted

(a)

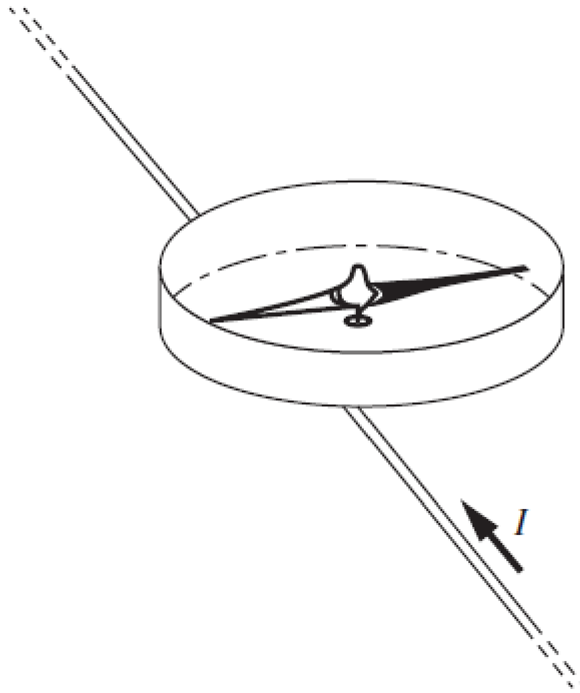


Fig. Oersted discovered that the needle of a compass was deflected by a current-carrying wire. This stimulated Faraday's work in electromagnetism.

(b)

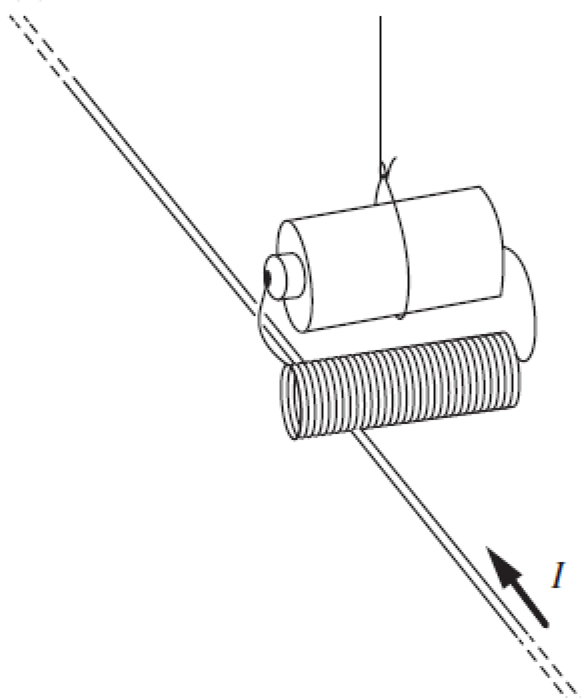


Fig. A compass needle (a) and a coil of wire carrying current (b) are similarly influenced by current in a nearby conductor. The direction of the current I is understood to be that in which positive ions would be moving if they were the carriers of the current. In the earth's magnetic field the black end of the compass would point north.

((**Explanation by Purcell**))

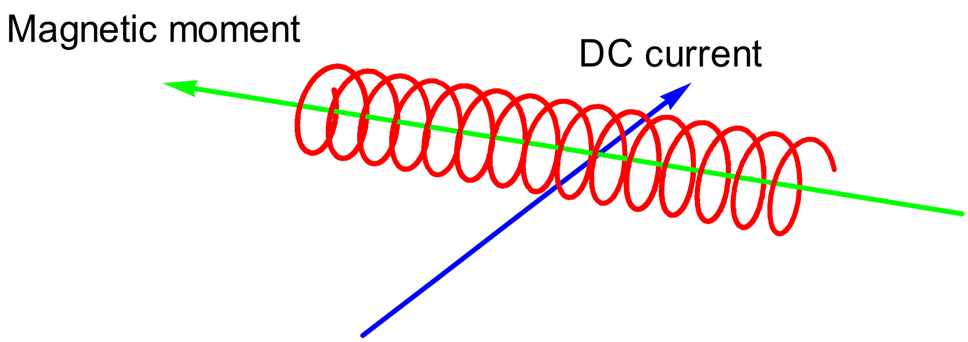


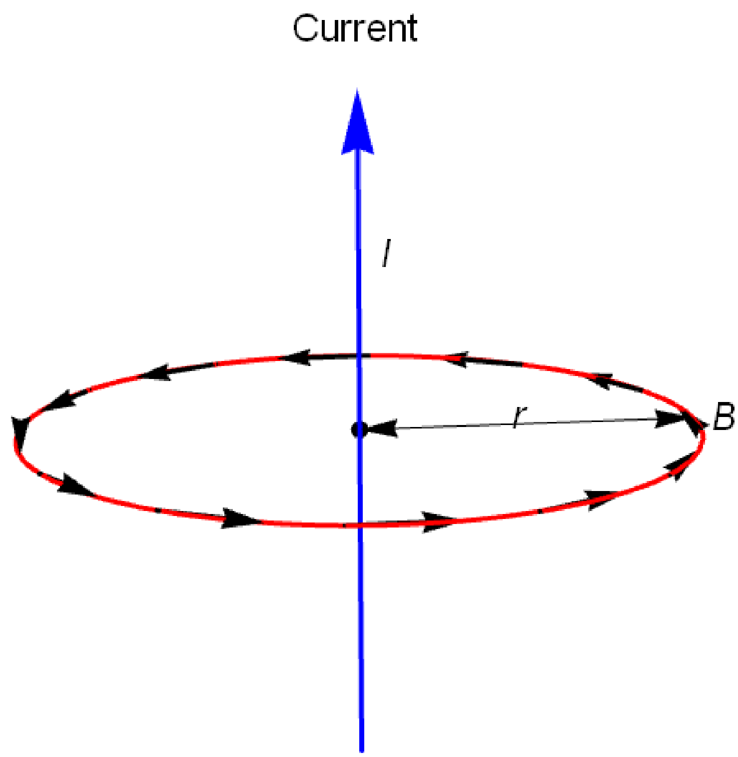
Fig. The compass (magnetic moment) is equivalent to the solenoid coil with a flowing current I_s. When the compass is perpendicular the DC current I, the current direction of I becomes parallel to the current direction of I_s, leading to the attractive force between them.

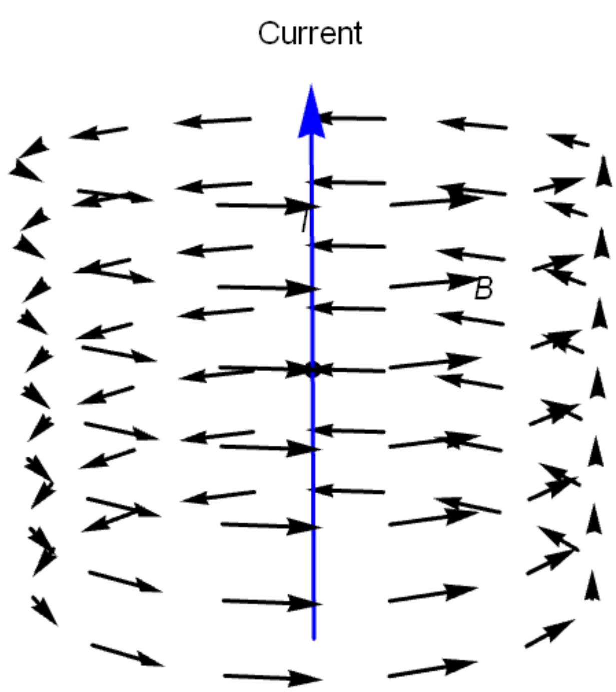
A compass needle (a) and a coil of wire carrying current (b) are similarly influenced by current in a nearby conductor. The direction of the current I is understood to be that in which positive ions would be moving if they were the carriers of the current. In the earth's magnetic field the black end of the compass would point north.

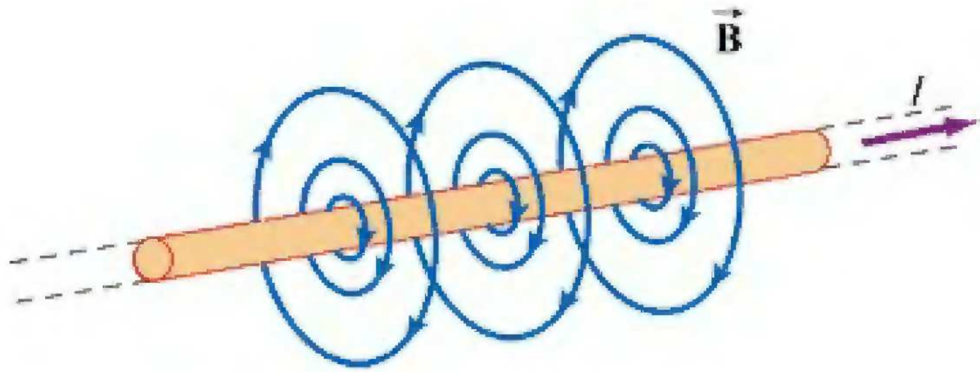
REFERENCES

E.M. Purcell and D.J. Morin, Electricity and Magnetism, 3rd edition (Cambridge, 2013).

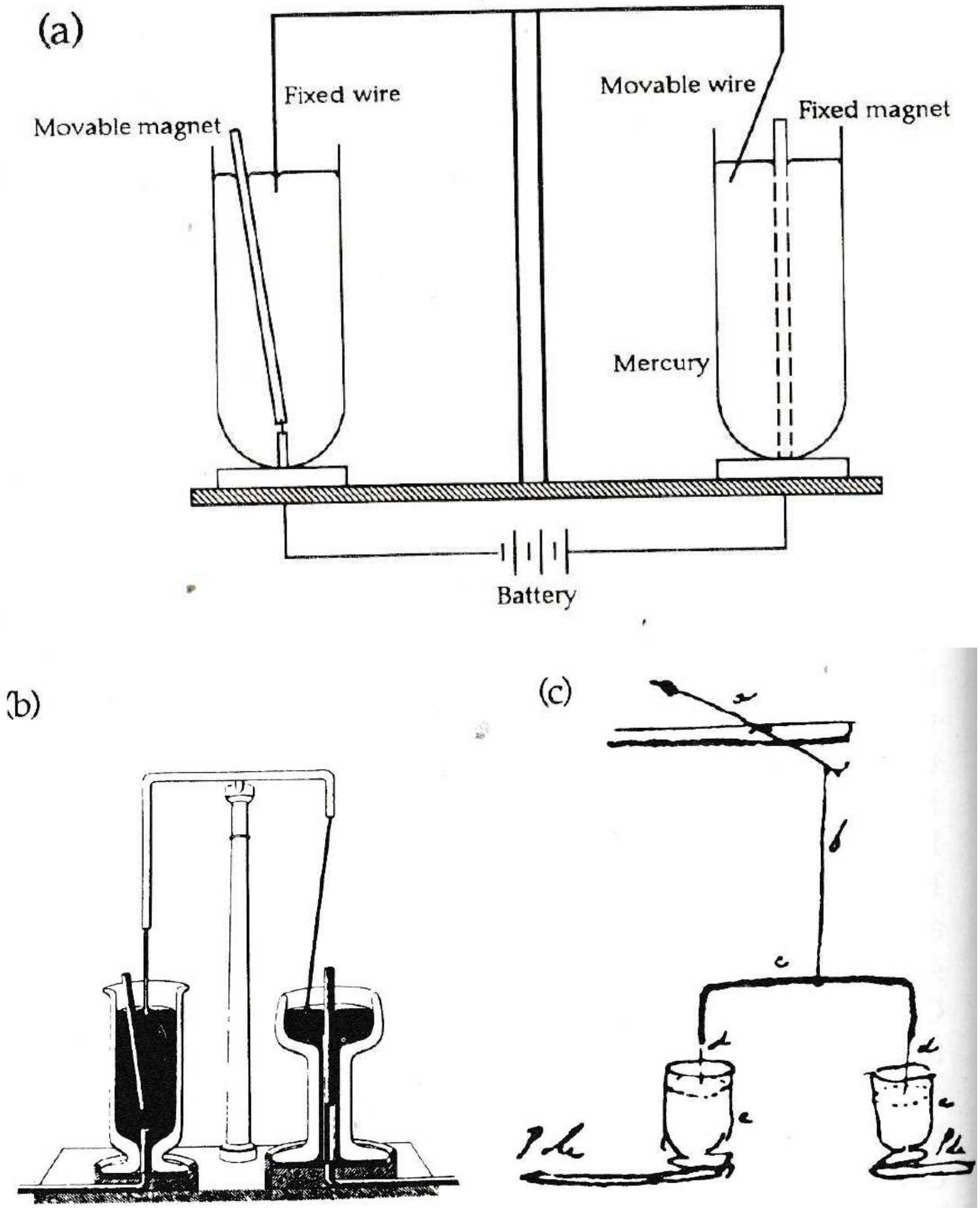
4. Ampere's law

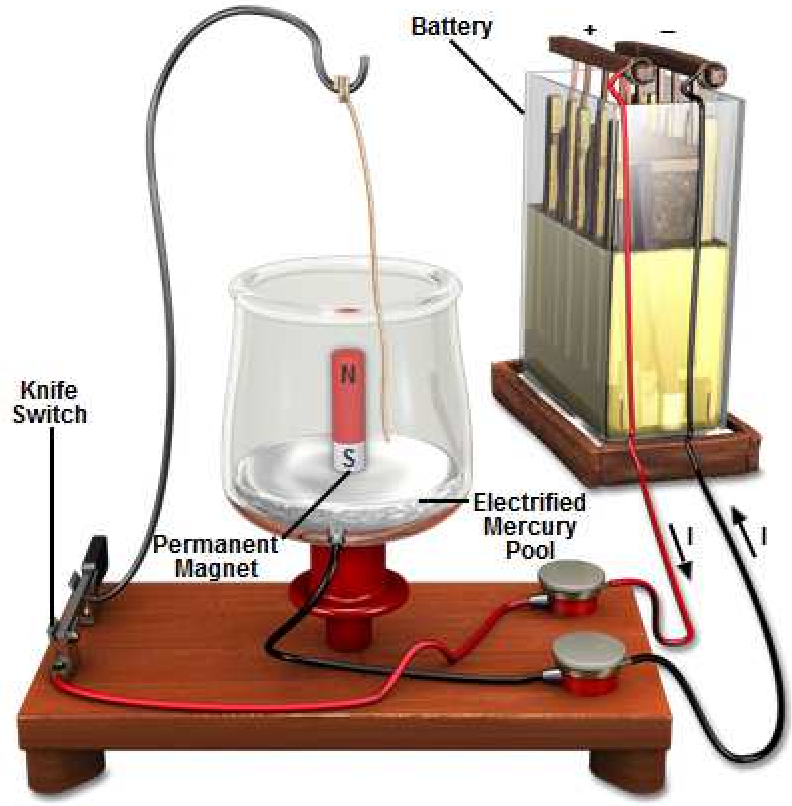

Current
I
r
B


Current
I
B



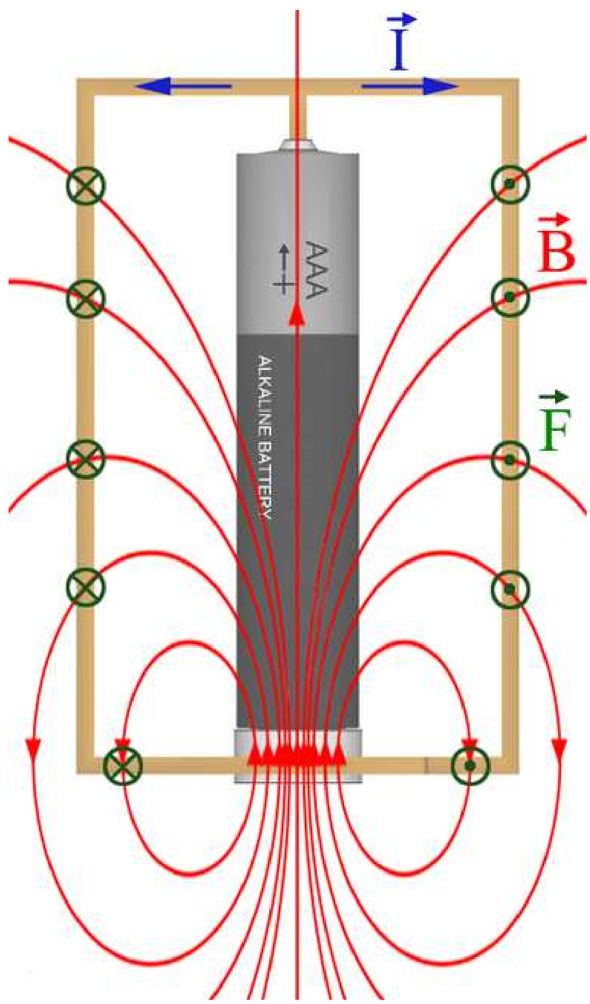
5. Faraday's motor


(a)
Fixed wire
Movable magnet
Movable wire
Fixed magnet
Mercury
Battery
(b)
(c)



A homopolar generator is a DC electrical generator comprising an electrically conductive disc or cylinder rotating in a plane perpendicular to a uniform static magnetic field. A potential difference is created between the center of the disc and the rim (or ends of the cylinder) with an electrical polarity that depends on the direction of rotation and the orientation of the field. It is also known as a unipolar generator, acyclic generator, disk dynamo, or Faraday disc. The voltage is typically low, on the order of a few volts in the case of small demonstration models, but large research generators can produce hundreds of volts, and some systems have multiple generators in series to produce an even larger voltage. They are unusual in that they can source tremendous electric current, some more than a million amperes, because the homopolar generator can be made to have very low internal resistance. Also, the homopolar generator is unique in that no other rotary electric machine can produce DC without using rectifiers or commutators.
https://en.wikipedia.org/wiki/Homopolar_generator


AAA
ALKALINE BATTERY


$\vec{I}$
$\vec{B}$
$\vec{F}$
AAA
ALKALINE BATTERY

The homopolar motor was the first electrical motor to be built. Its operation was demonstrated by Michael Faraday in 1821 at the Royal Institution in London.
In 1821, soon after the Danish physicist and chemist Hans Christian Ørsted discovered the phenomenon of electromagnetism, Humphry Davy and British scientist William Hyde Wollaston tried, but failed, to design an electric motor.[5] Faraday, having been challenged by Humphry as a joke, went on to build two devices to produce what he called "electromagnetic rotation". One of these, now known as the *homopolar motor*, caused a continuous circular motion that was engendered by the circular magnetic force around a wire that extended into a pool of mercury wherein was placed a magnet. The wire would then rotate around the magnet if supplied with current from a chemical battery. These experiments and inventions formed the foundation of modern electromagnetic technology. In his excitement, Faraday published results. This strained his mentor relationship with Davy, due to his mentor's jealousy of Faraday's achievement, and is the reason for Faraday's assignment to other activities, which consequently prevented his involvement in electromagnetic research for several years.

B. G. Lamme described in 1913 a homopolar machine rated 2,000 kW, 260 V, 7,700 A and 1,200 rpm with 16 slip rings operating at a peripheral velocity of 67 m/s. A unipolar generator rated 1,125 kW, 7.5 V 150,000 A, 514 rpm built in 1934 was installed in a U.S. steel mill for pipe welding purposes.
https://en.wikipedia.org/wiki/Homopolar_motor

6. Faraday's Dynamo

((Experimental demonstration))
https://www.youtube.com/watch?v=vW5pEq7ZuEM

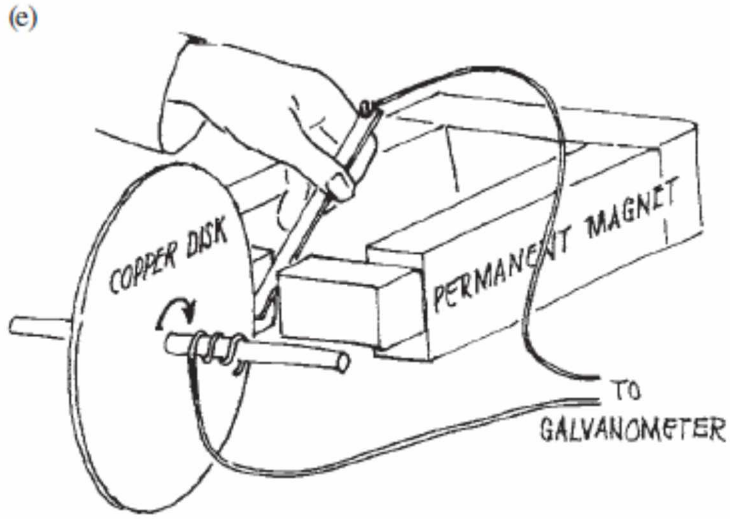
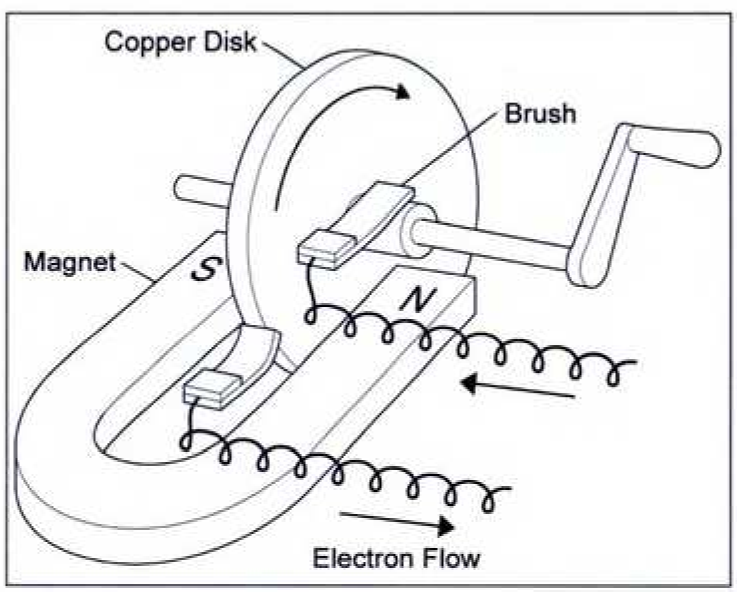


Figure 7.1.
(Continued)



However, within a few days he (Michael Faraday) hit upon a possible method. He proposed to rotate a copper disk (like the one Arago used) between the poles of a magnet and see if a current could be detected in a circuit connected to the disk. After a few disappointments he (Michael Faraday) made a simple arrangement with one end of the circuit connected to the brass axle on which the disk rotated, and the other touching the edge of the moving wheel. In Faraday's own words, he had obtained “production of a permanent current of electricity by ordinary magnets.” He had invented the dynamo.

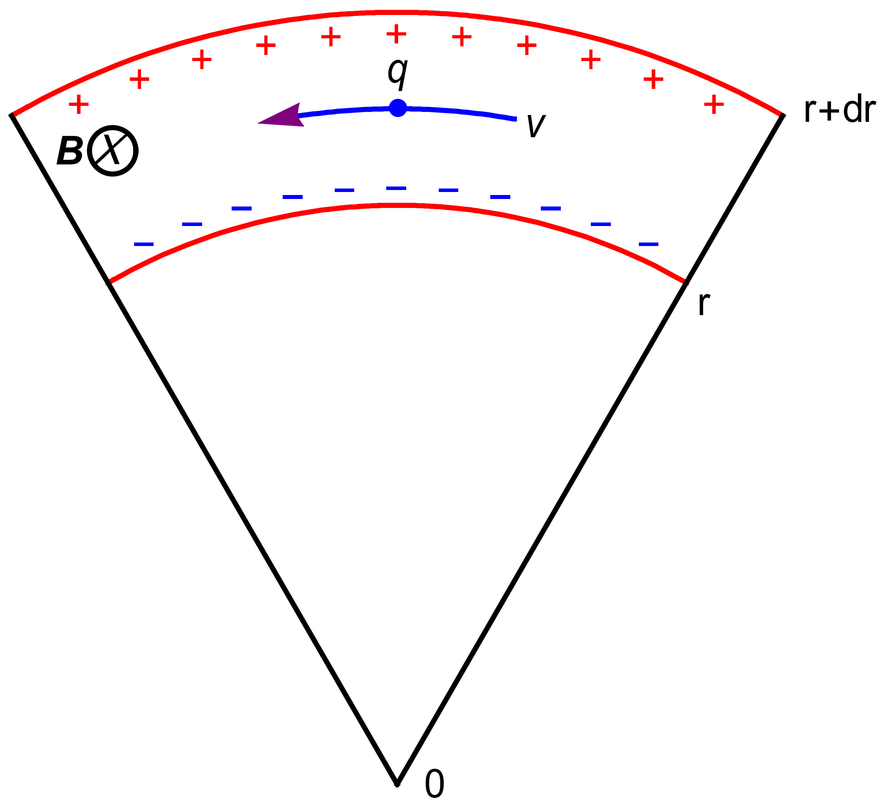


Fig. Principle of dynamo. q is the charge. q>0. The angular velocity is $v = \omega r$. w is the angular velocity.

The electric field:

$$E = vB$$

where B is the magnitude of magnetic field whose direction is into the page and v is the velocity. $v = \omega r$. The electric potential generated is

$$\begin{aligned} dV &= Edr \\ &= vBdr \\ &= (\omega r)Bdr \end{aligned}$$

or

$$V = \int_0^R E dr = \omega B \int_0^R r dr = \frac{\omega B R^2}{2}$$

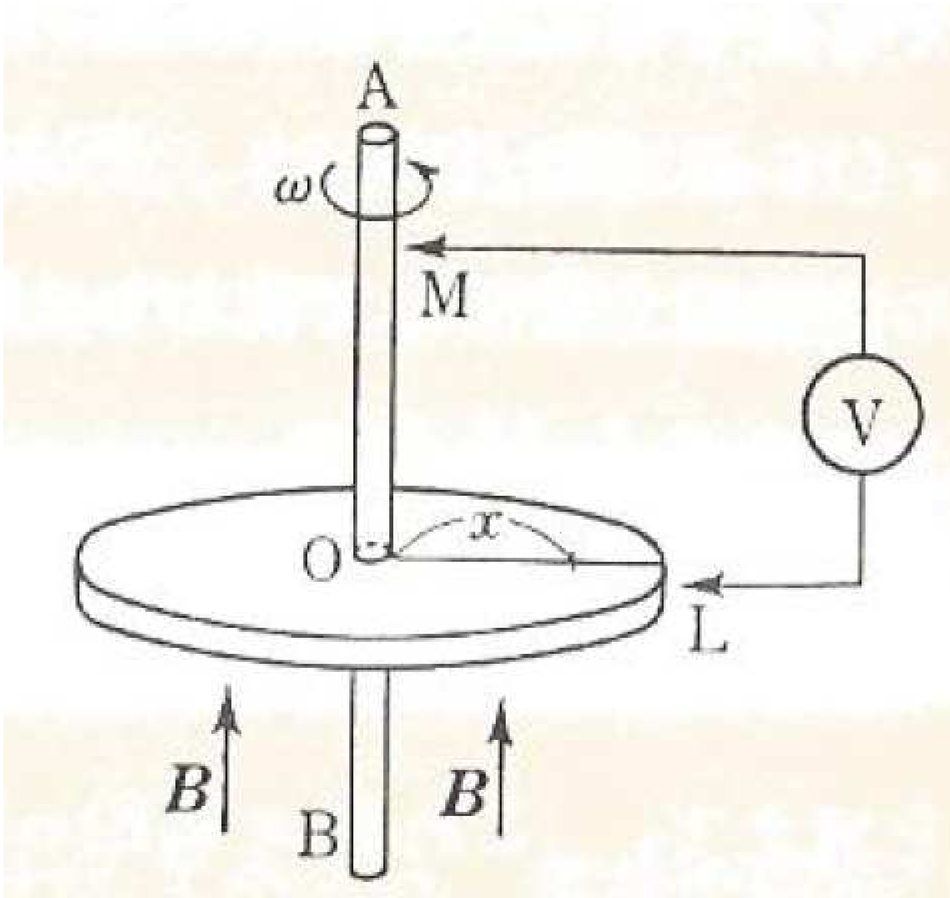
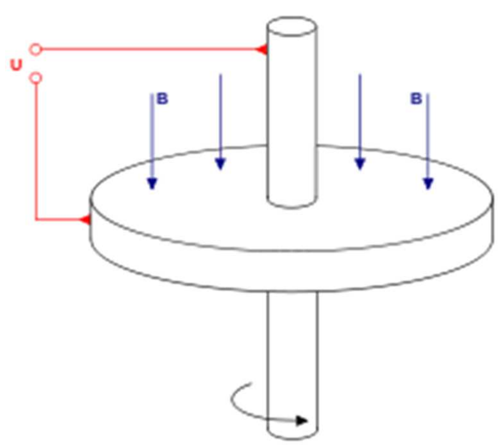
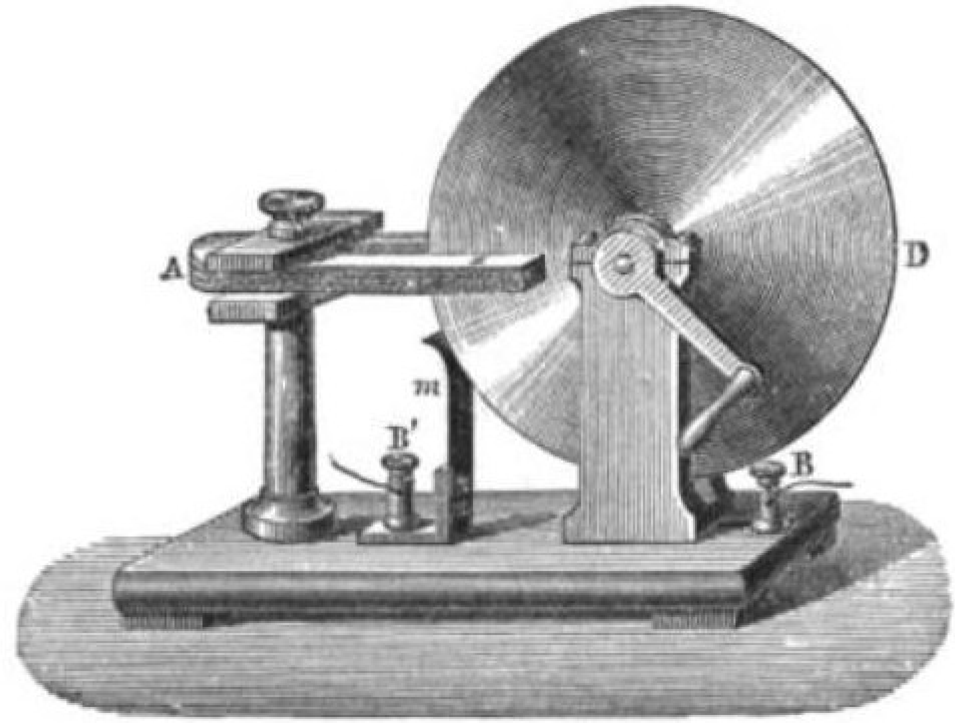


Fig. Faraday disk, the first homopolar generator (T. Kinbara; Electricity and Magnetism (Shokabo, in Japanese).





https://upload.wikimedia.org/wikipedia/commons/1/19/Faraday_disk_generator.jpg

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C.A. Russell, Michael Faraday, Physics and Faiths (Oxford, 2000).
J.M. Thomas, Michael Faraday and the Royal Institution (Adam Hilger, 1991)

7. Faraday's Scientific Contribution

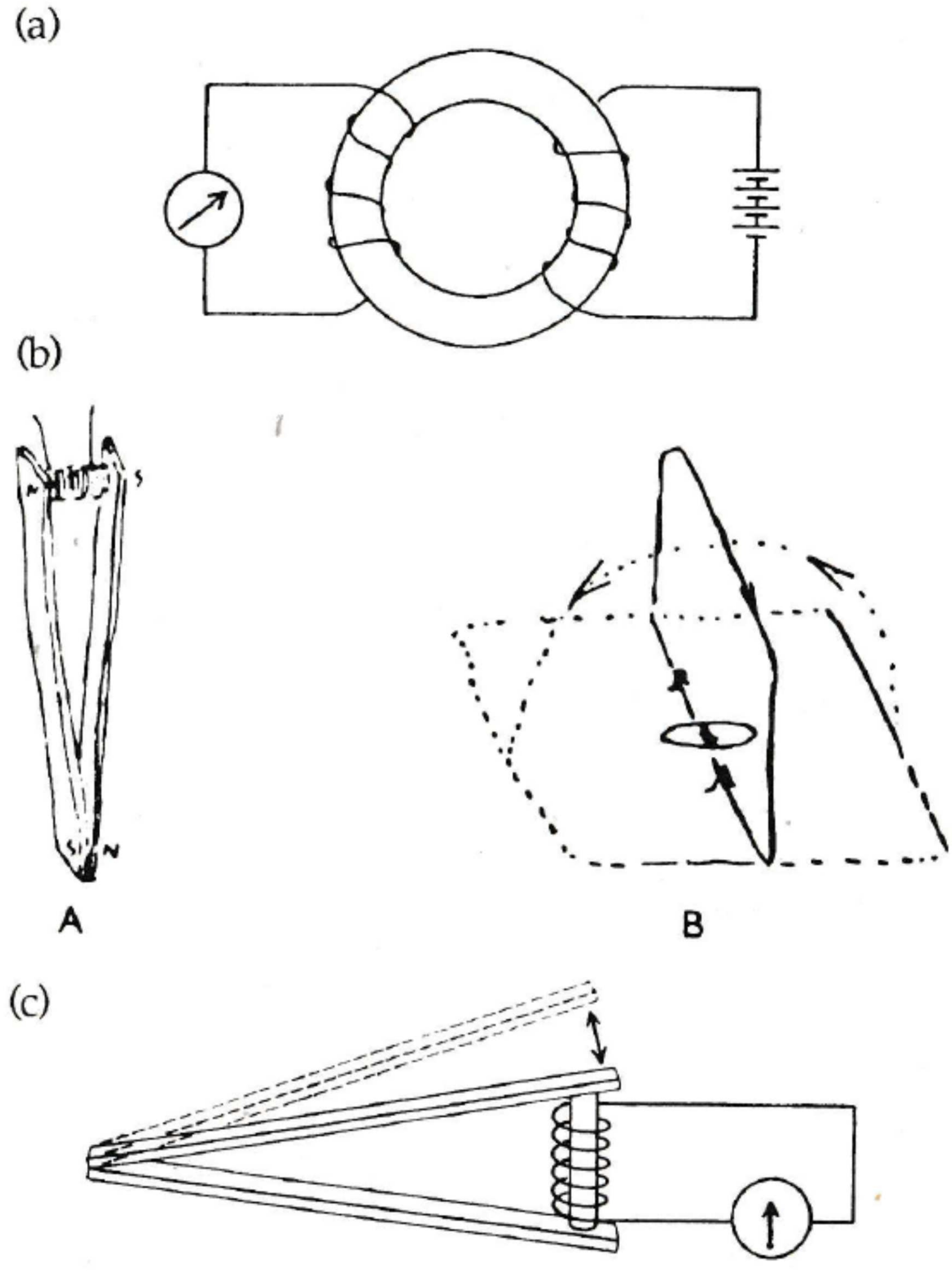


Fig.16 (a) Schematic illustration of Faraday's 'electromagnetic rotations' apparatus with which he showed that a wire carrying a current could be made to rotate around a stationary magnet, and a magnet to rotate around a stationary wire. (b) Published

version of the apparatus made by Newman to Faraday's instructions. (c) Faraday's sketch of the apparatus from his diary entry of 22 December 1821.

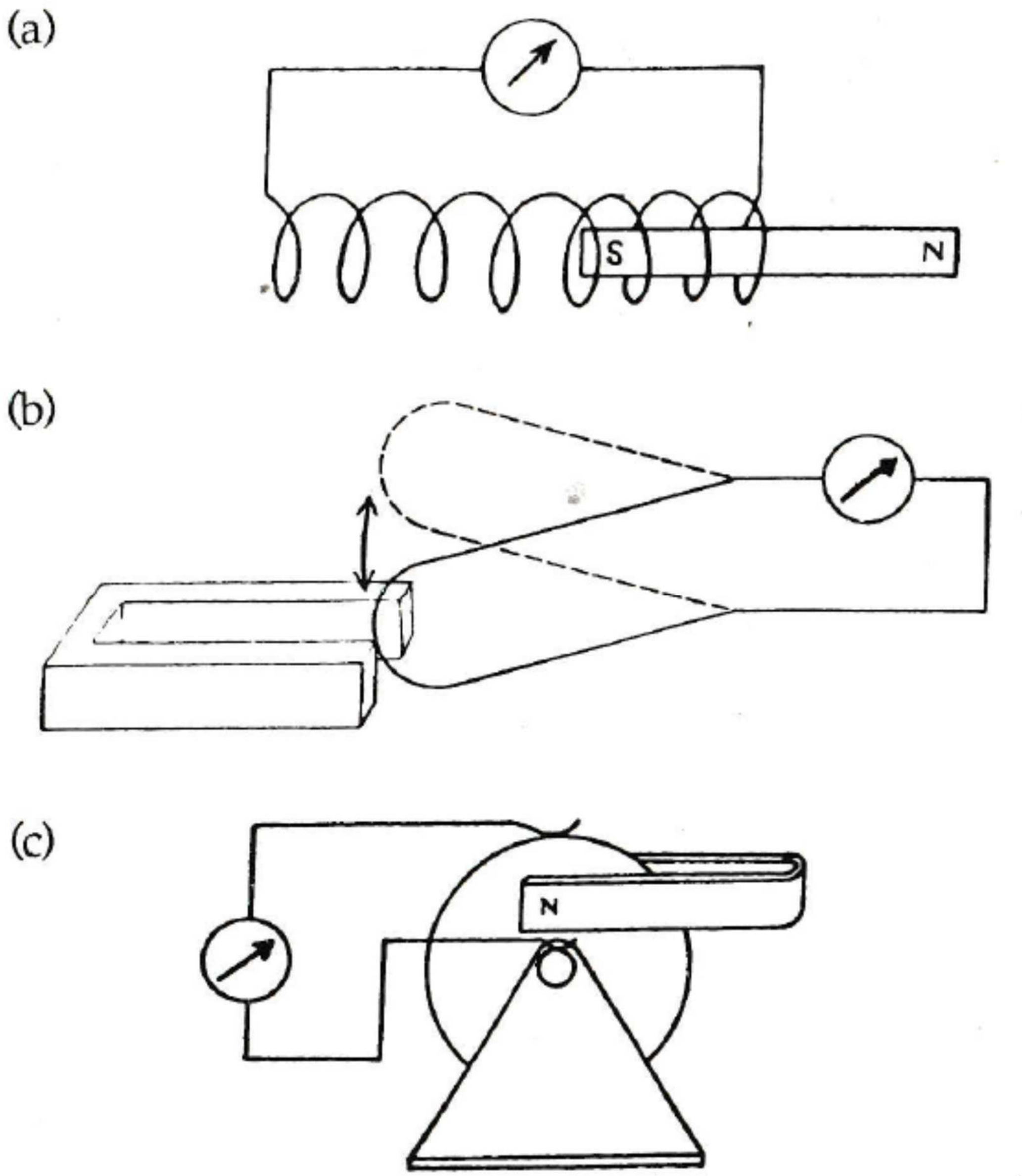
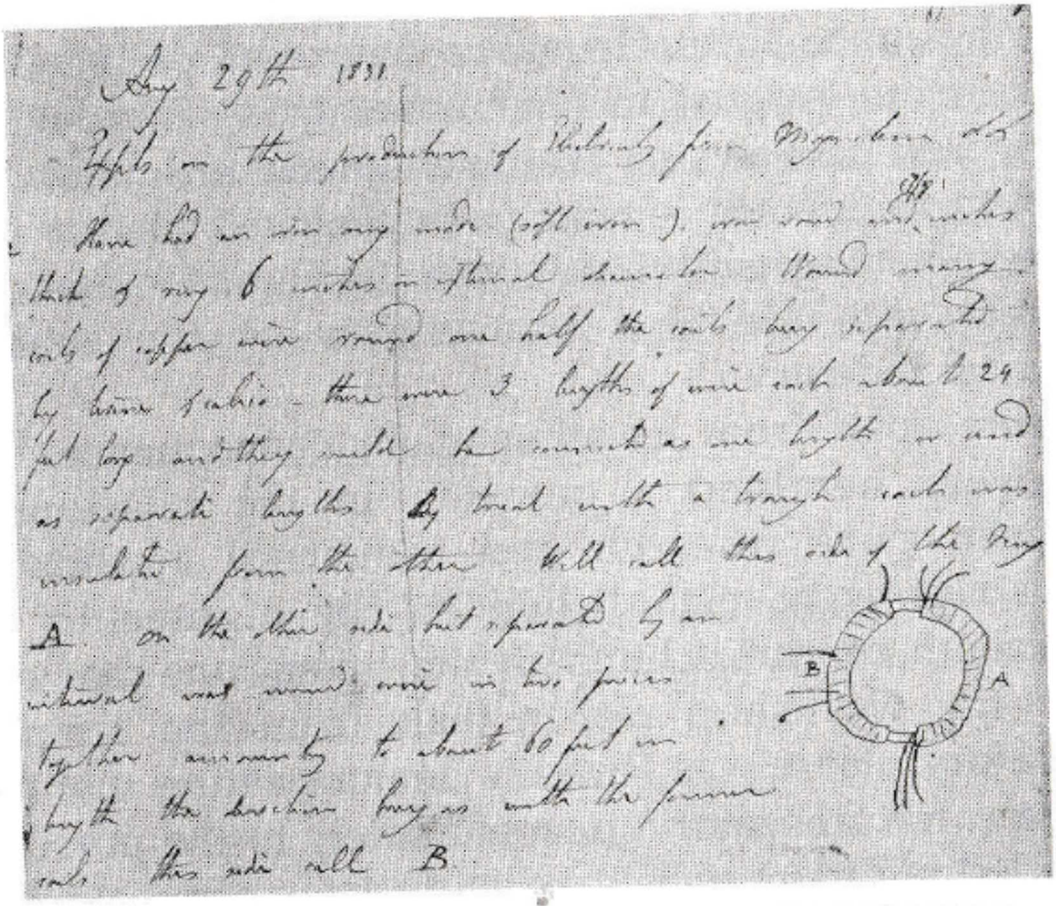


Fig.20 Faraday subsequently showed that an electric current was also produced by thrusting a magnet into a coil of wire or by withdrawing it (a), or by moving a loop of wire up and down in a magnetic field (b). He later showed that, by rotating a copper disk between the poles of a powerful magnet a steady current was induced across the disk (c).

(a)



Aug 29th 1831.

Expts on the production of Electricity from Magnetism &c &c

Have had an iron ring made (soft iron), iron round and 7/8 inches thick & ring 6 inches in external diameter. Wound many coils of copper wire round one half the coils being separated by twine & calico - there were 3 lengths of wire each about 24 feet long and they could be connected as one length or used as separate lengths. By trial with a trough each was insulated from the other. Will call this side of the ring A. On the other side but separated by an interval was wound wire in two pieces together amounting to about 60 feet in length the direction being as with the former coils. this side call B.

(b)

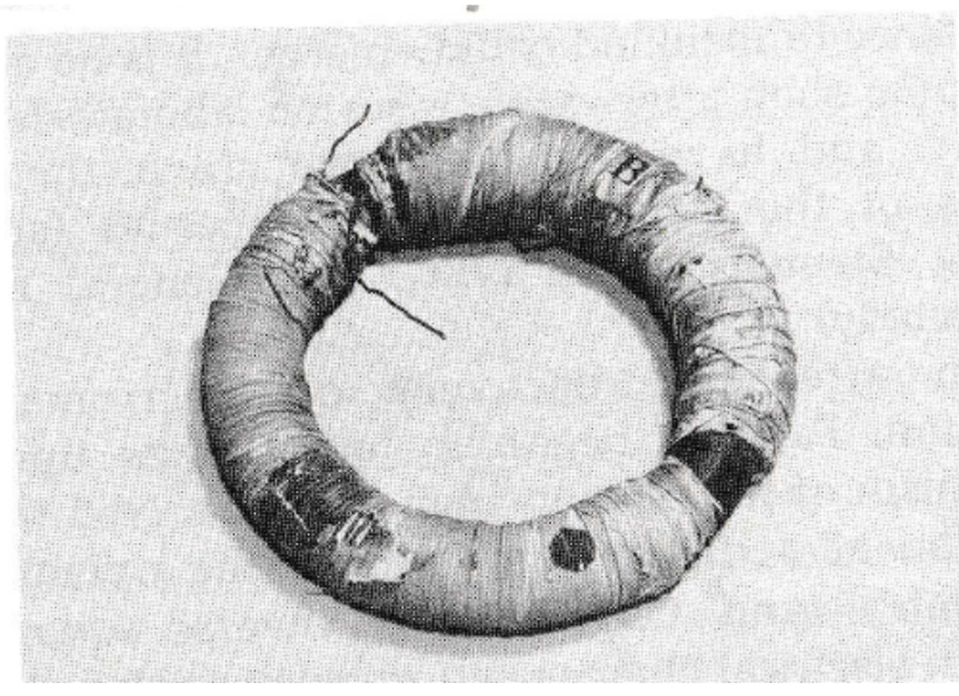


Fig.21 (a) Faraday's diary entry for 29 August 1831 (b) The actual soft-iron ring used by Faraday.

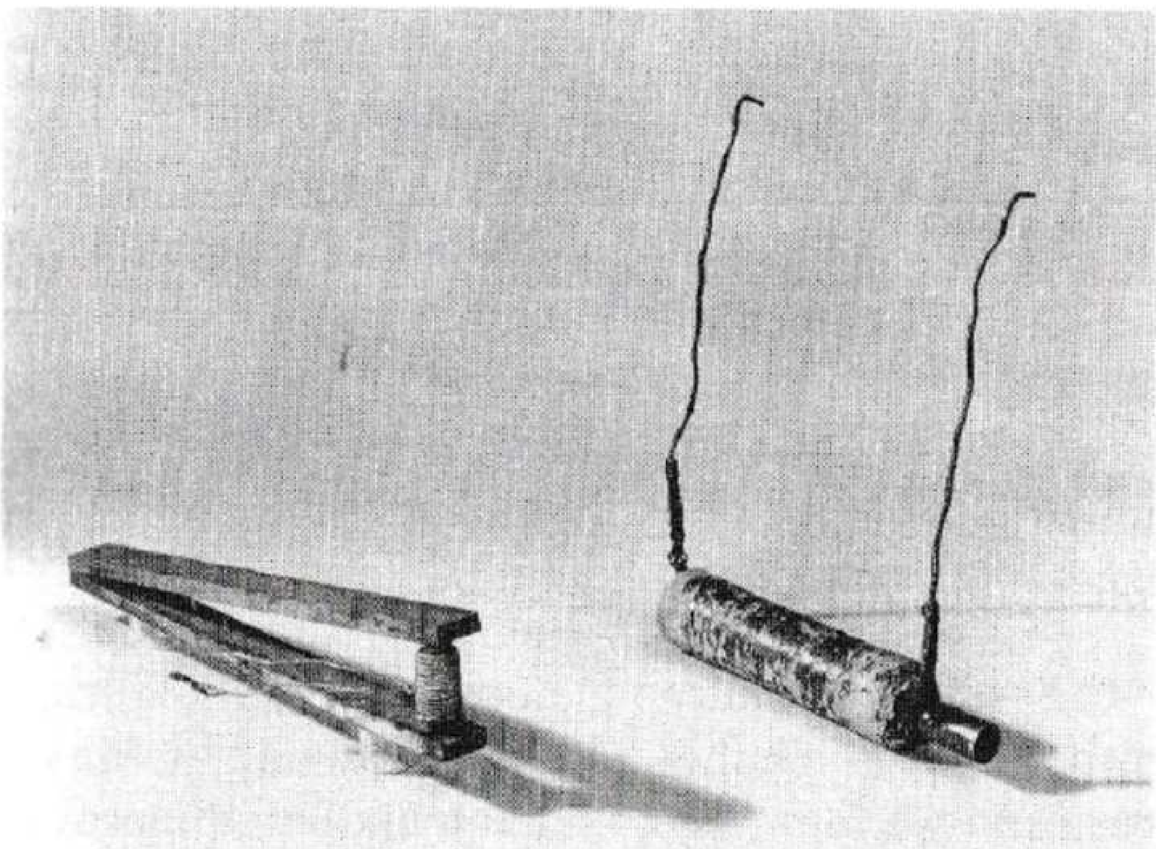
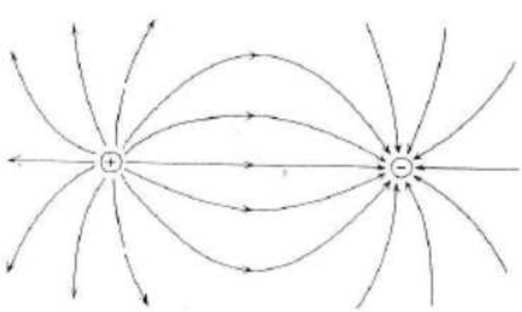
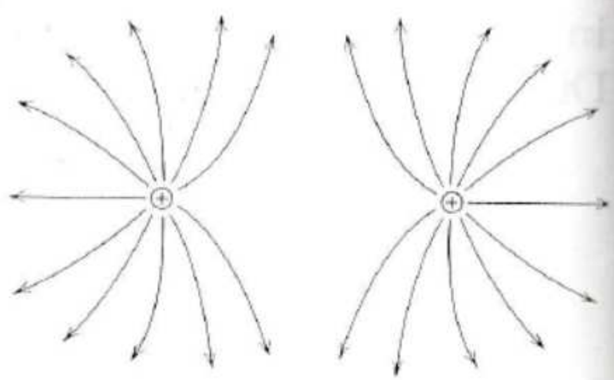


Fig.22 Photographs of original apparatus used by Faraday for the experiments schematized in Figs.19 and 20

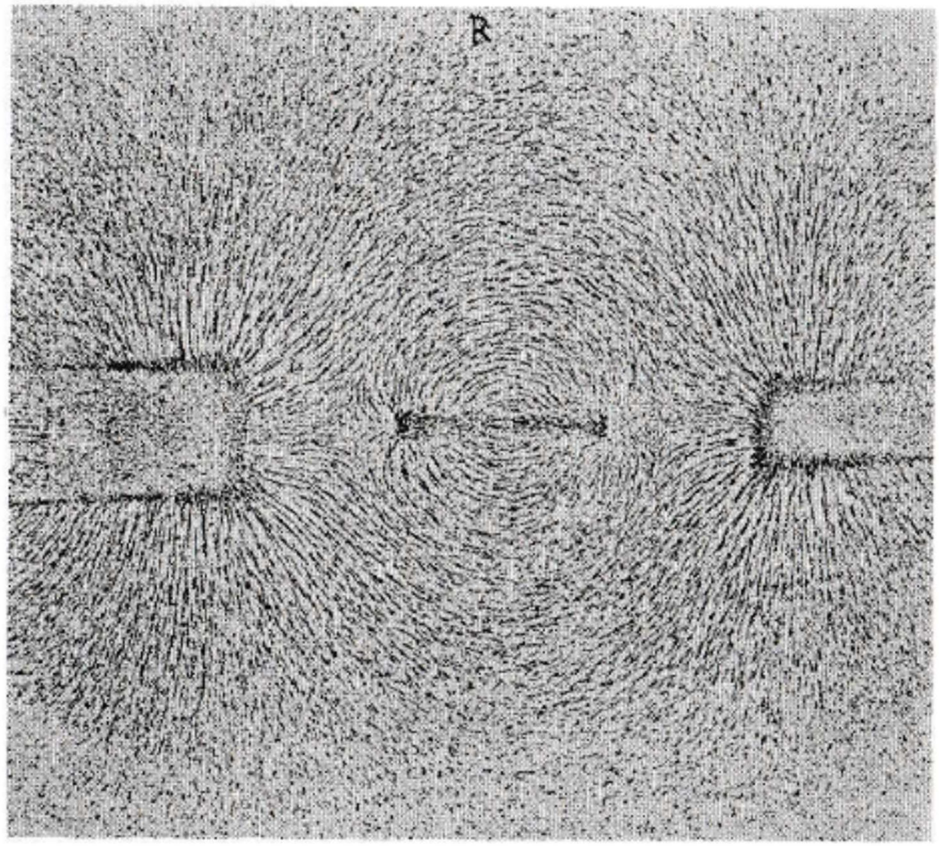


Electric field lines for a pair of unlike charges.



Electric field lines for a pair of positive charges.

Fig.23 Faraday believed that lines of force, schematized here, occupied the space separating magnetic or electric charges.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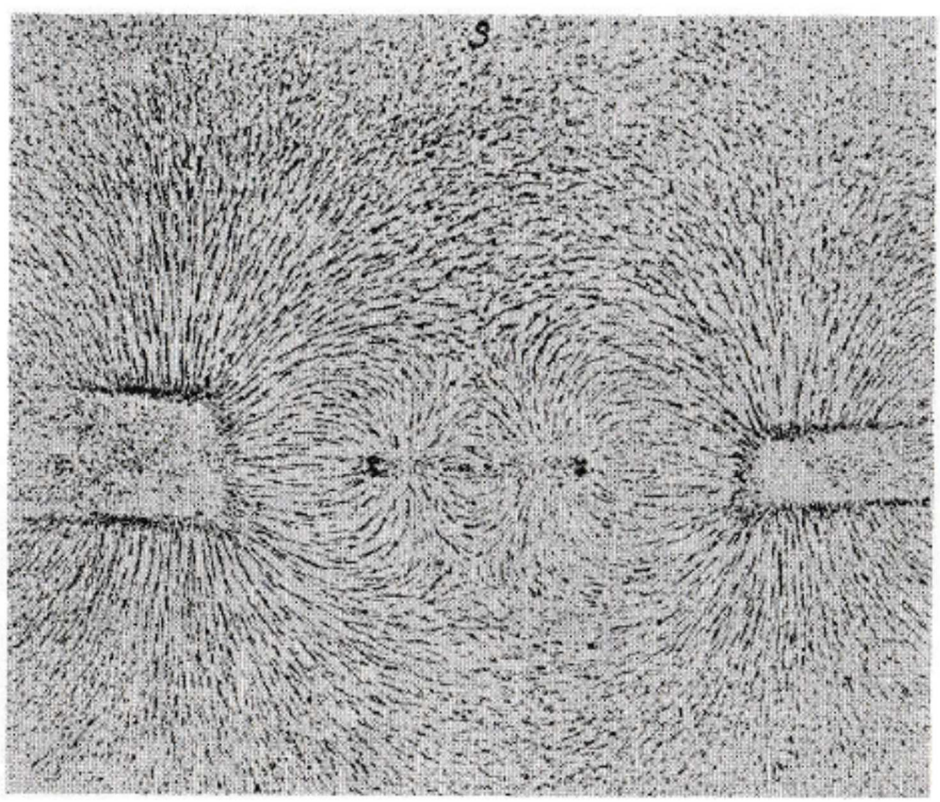
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Fig. A favorite experiment of Faraday's to illustrate the reality of lines of force was to sprinkle iron powder on a sheet of paper beneath which there was placed a magnet. On gently tapping the paper the particles of iron revealed the lines of force.

REFERENCES

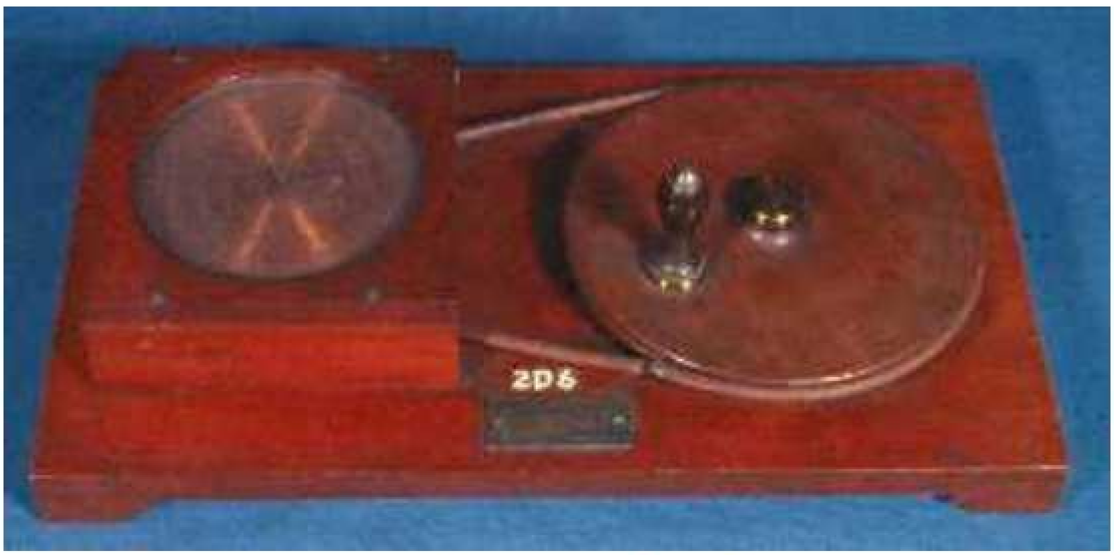
J.M. Thomas, Michael Faraday and the Royal Institution (Adam Hilger, 1991)

8. Arago's disk-I

In 1824, Arago [**Dominique F.J. Arago** (1786-1853, France)] designed an experiment known as Arago's disk which showed that a needle suspended on a pivot held above a spinning copper disk will follow the rotation of the copper disk. What was impressive about Arago's apparatus was its utilization of copper, a nonmagnetic substance; that is, the experiment seemed to show that motion could induce magnetism in a metal object. Arago's copper disk caused a commotion. Arago found that the other metals exhibited similar effects. Silver showed a greater effect than copper, whereas lead, mercury, and bismuth were less effective.

[**Brian Baigrie, Electricity and Magnetism: A Historical Perspective (Greenwood Press, 2007). p.81**].

St. Patrick's College, Maynooth, Ireland



Smithsonian Institution

Vanderbilt University

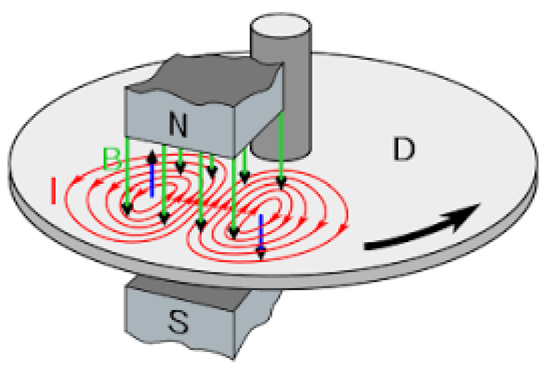
In this device, a copper disk is rotated rapidly with a hand crank and a step-up pulley system. Balanced on a pivot above the center of the disk is a compass needle. The motion of the needle relative to the highly conducting copper disk induces eddy currents in the disk. In turn, these eddy currents produce a torque on the magnetic needle, which starts to rotate. The presence of eddy currents may be inferred from the fact that a copper disk with radial slots cut in it produces little effect; the slots interrupt the eddy currents. The inverse effect also occurs: a spinning bar magnet will cause a suspended copper disk to rotate.

The French physicist, Dominique Arago (1786-1853) discovered this effect in 1825 while studying the observation that the proximity of a piece of copper to a compass needle reduces the effect of the earth's magnetic field on the needle. The Maynooth apparatus is by Yeates & Son of Dublin, and is ca. 1877. The Smithsonian apparatus is by Queen and cost $16.50 in 1889. The example at the right of Arago's Wheel from the Garland Collection of Classical Physics Apparatus at Vanderbilt University is unmarked. The copper disk is 22 cm in diameter and the compass needle is 15 cm long. The base is made of walnut.
http://physics.kenyon.edu/EarlyApparatus/Electricity/Aragos_Disk/Aragos_Disk.html

9. Arago disk (II)

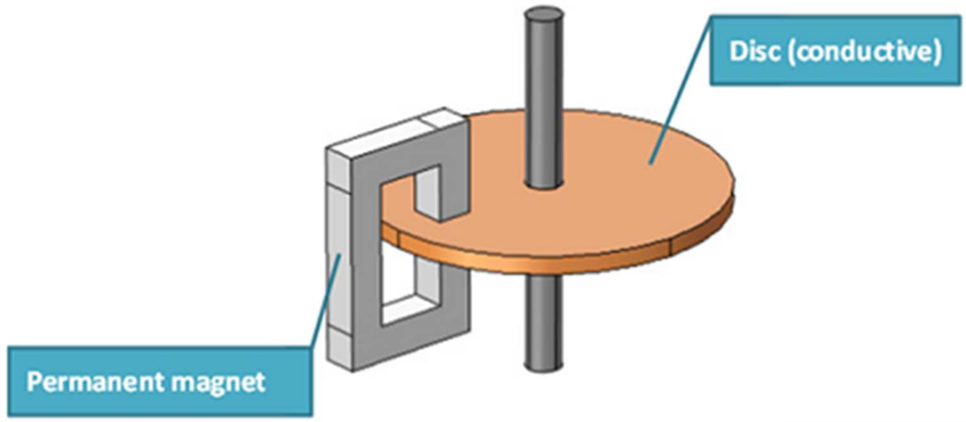
PH EM IN DEMO 70018A V0240 Arago Disk Interaction between Magnets and Conductors
https://www.youtube.com/watch?v=vghaAcoVaAU

Magnetic Damping - Spinning Wheel Generator
https://www.youtube.com/watch?v=1m2r8fh8JMA

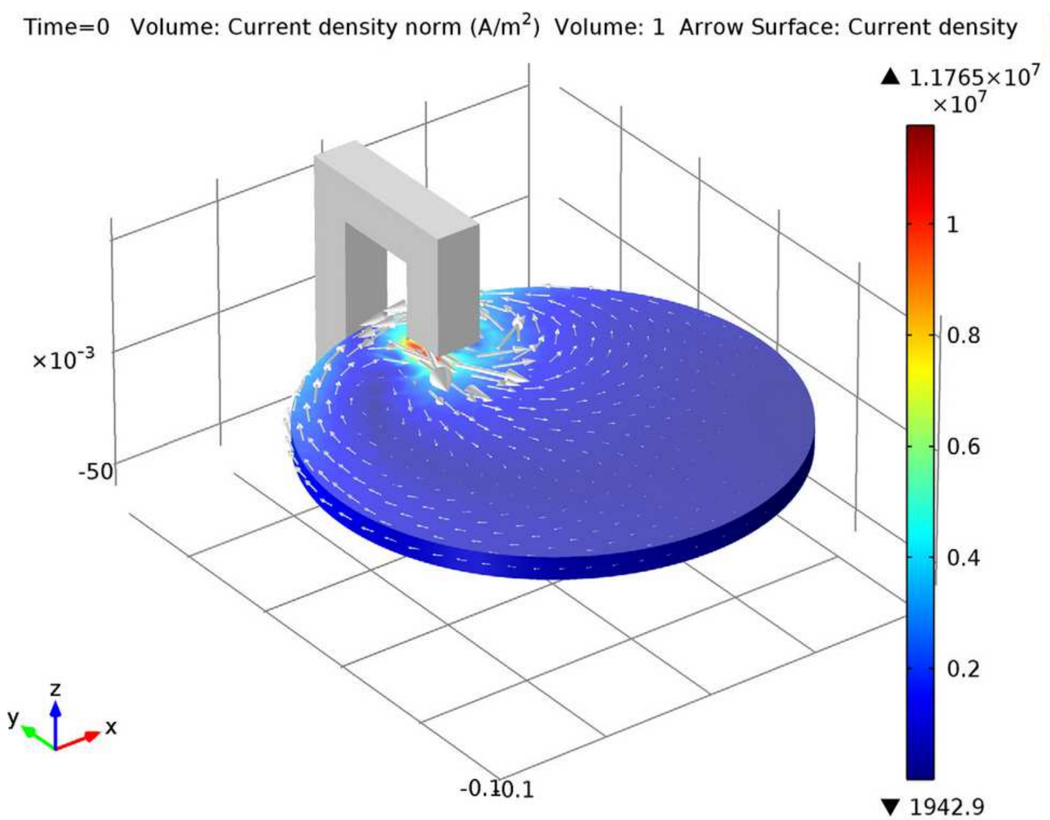


Simulating eddy current brakes
https://www.comsol.com/blogs/simulating-eddy-current-brakes/

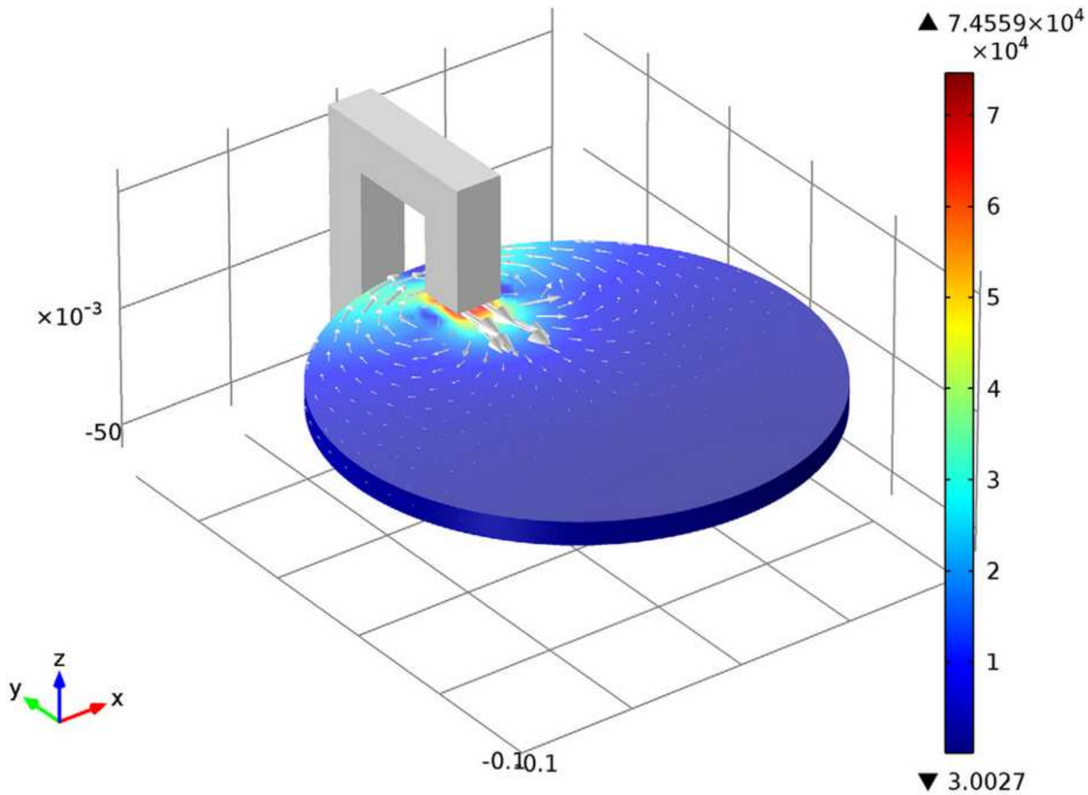
Fanny Griesmer



Disc (conductive)
Permanent magnet

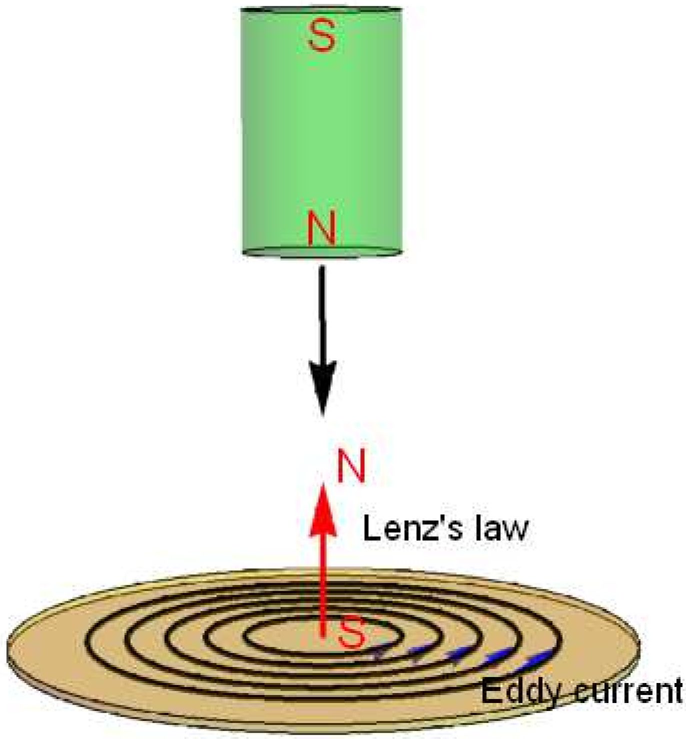


Time=0 Volume: Current density norm (A/m²) Volume: 1 Arrow Surface: Current density
▲ 1.1765×10⁷
×10⁷
1
0.8
0.6
0.4
0.2
▼ 1942.9
×10⁻³
-50
-0.10.1
z
y
x

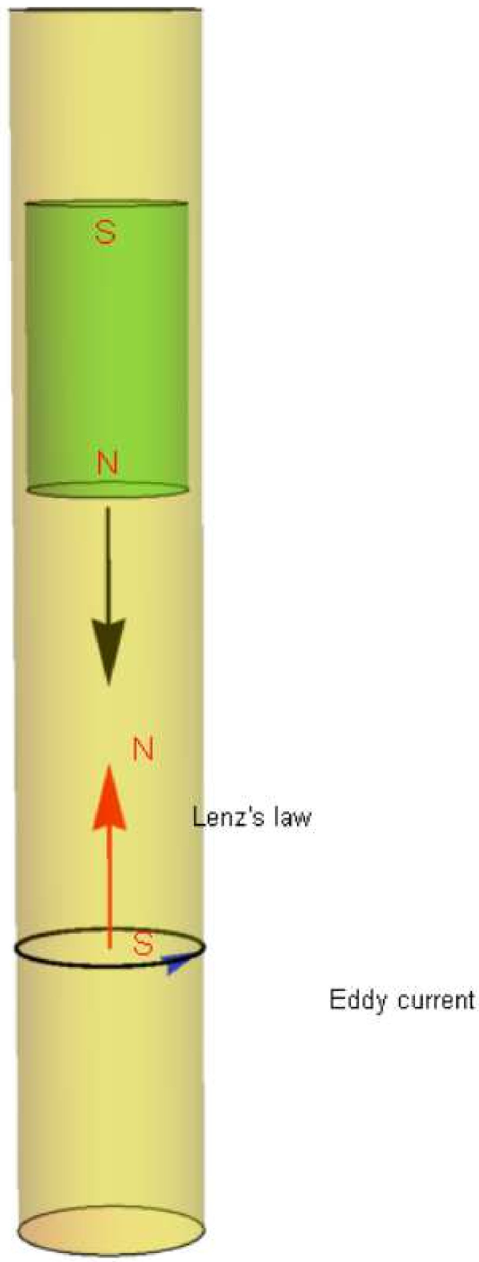


10. Eddy current (II): The falling of a bar magnet well above the metal disk on the floor
((**Eddy current**))
Copper's Surprising Reaction to Strong Magnets | Force Field Motion Dampening
https://www.youtube.com/watch?v=sENgdSF8ppA

Experiment using bar magnet and metal plate.



Suppose that a bar magnet undergoes a free fall and is supposed to hit the conducting metal on the floor. Because of the Lenz's law, the eddy current is generated in the surface of metal, leading to the generation of magnetic moment upward. The falling bar magnet and the generated magnetic moment repel each other. For metal such as copper, there may occurs a Joule heating produced by eddy current. In this case, the bar magnet slowly falls down on the floor. On the other hand, for the superconductor such as $YBa_2Cu_3O_7$ (with no Joule heating), the bar magnet does not fall on the metal, but levitates on the air well above the floor.



Suppose that a bar magnet falls down inside the empty metal tube, under the gravity. Because of the Lenz's law, an eddy current flows in the metal tube in counter clock-wise. In this case the bar magnet and the resulting magnetic moment due to the eddy current repel each other. Consequently, the bar magnet slowly falls down inside the metal tube.

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11. Eddy current from the book of Feynman (III)

R.P. Feynman, R.B. Leighton, and M. Sands, The Feynman Lectures on Physics II (Basic Books, 2010).

In **Fig. 1**, a square sheet of copper is suspended on the end of a rod to make a pendulum. The copper swings back and forth between the poles of an electromagnet. When the magnet is turned on, the pendulum motion is suddenly arrested. As the metal plate enters the gap of the magnet, there is a current induced in the plate which acts to oppose the change in flux through the plate. If the sheet were a perfect conductor, the currents would be so great that they would push the plate out again—it would bounce back. With a copper plate there is some resistance in the plate, so the currents at first bring the plate almost to a dead stop as it starts to enter the field. Then, as the currents die down, the plate slowly settles to rest in the magnetic field.

The nature of the eddy currents in the copper pendulum is shown in **Fig. 2**. The strength and geometry of the currents are quite sensitive to the shape of the plate. If, for instance, the copper plate is replaced by one which has several narrow slots cut in it, as shown in **Fig. 3**, the eddy-current effects are drastically reduced. The pendulum swings through the magnetic field with only a small retarding force. The reason is that the currents in each section of the copper have less flux to drive them, so the effects of the resistance of each loop are greater. The currents are smaller and the drag is less. The viscous character of the force is seen even more clearly if a sheet of copper is placed between the poles of the magnet of Fig. 1 and then released. It doesn't fall; it just sinks slowly downward. The eddy currents exert a strong resistance to the motion—just like the viscous drag in honey. If, instead of dragging a conductor past a magnet, we try to rotate it in a magnetic field, there will be a resistive torque from the same effects. Alternatively, if we rotate a magnet—end over end—near a conducting plate or ring, the ring is dragged around; currents in the ring will create a torque that tends to rotate the ring with the magnet.

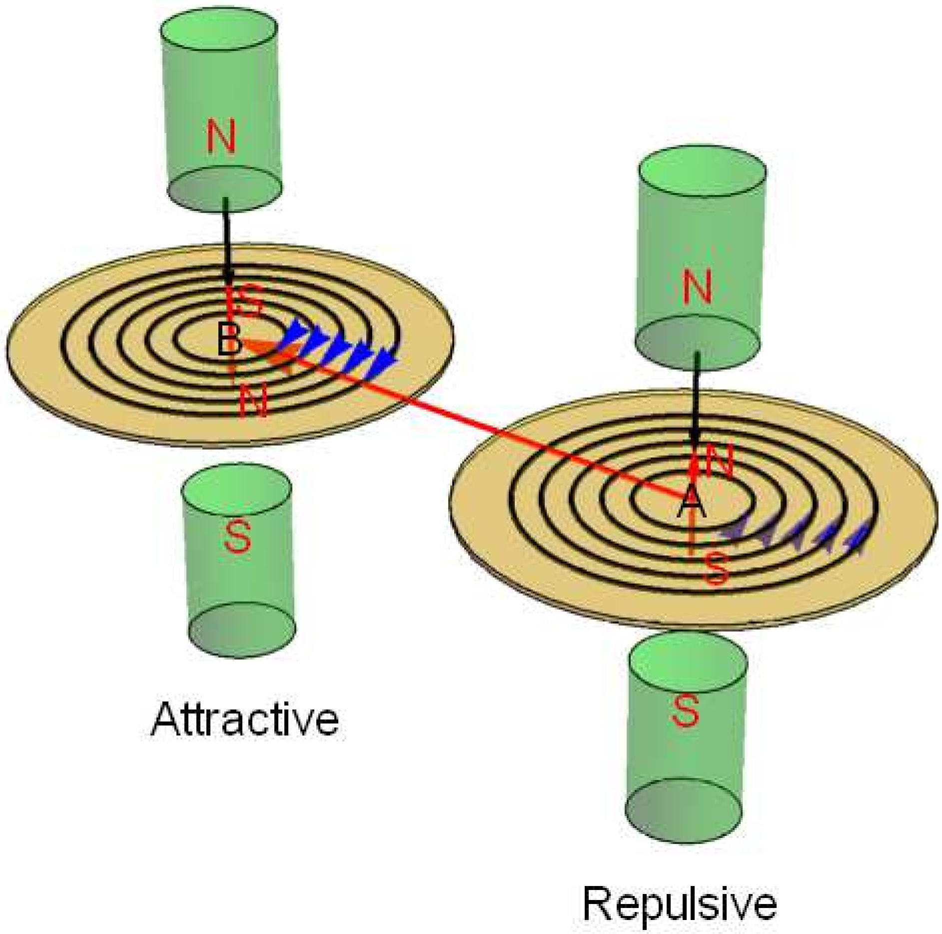


Fig. Explanation of the eddy current effect for the simple pendulum (metal plate) in the presence of horse-shoe magnet. When the metal pendulum enters into the magnetic field region (point A), the eddy current is produced in the metal plate. Because of the Lenz law, the direction of the magnetic moment due to the eddy current is antiparallel to the direction of the magnetic field, leading to the repulsive interaction. When the metal pendulum goes out from the magnetic field region (point B), the eddy current is again produced in the metal plate. Because of the Lenz law, the direction of the magnetic moment due to the eddy current is parallel to the direction of magnetic field, leading to the attractive interaction.

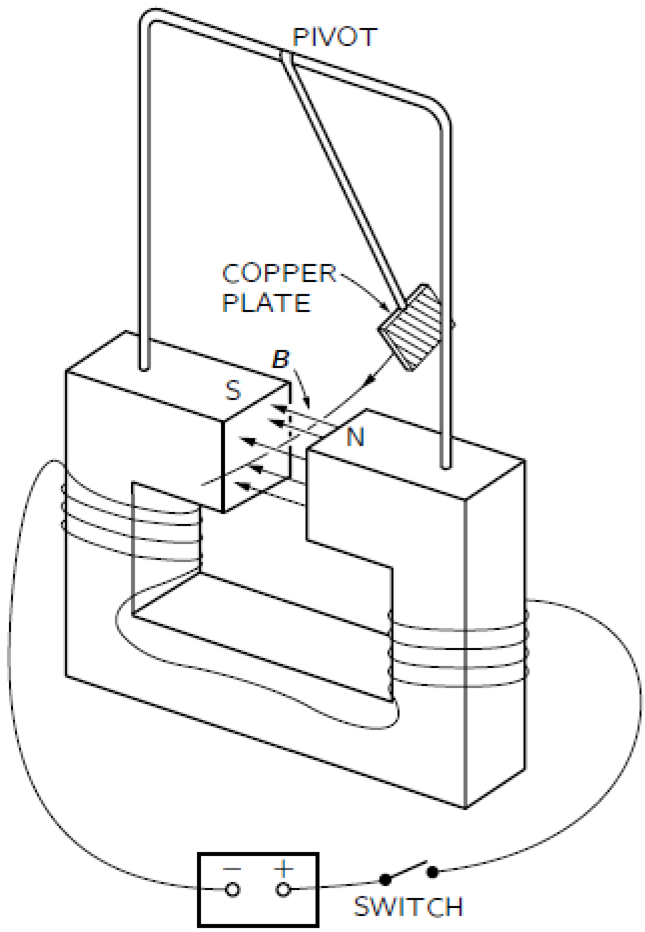


Fig.1 The braking of the pendulum shows the forces due to eddy currents.

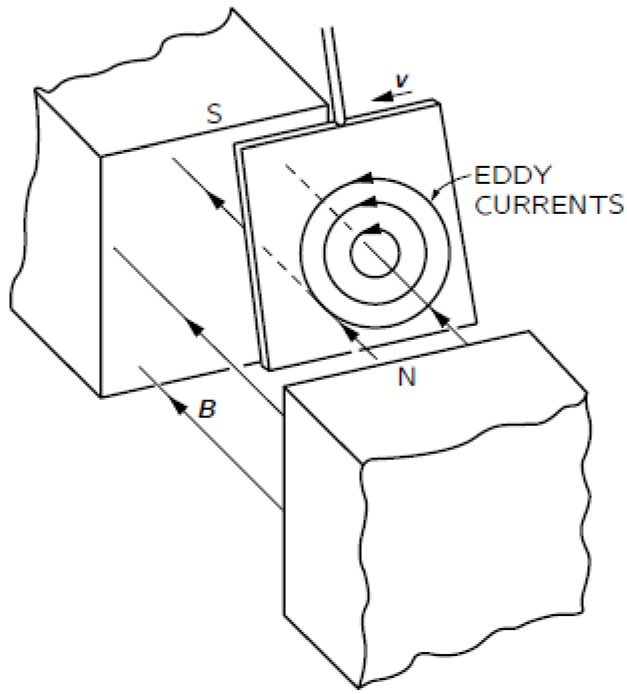


Fig.2 The eddy currents in the copper pendulum.

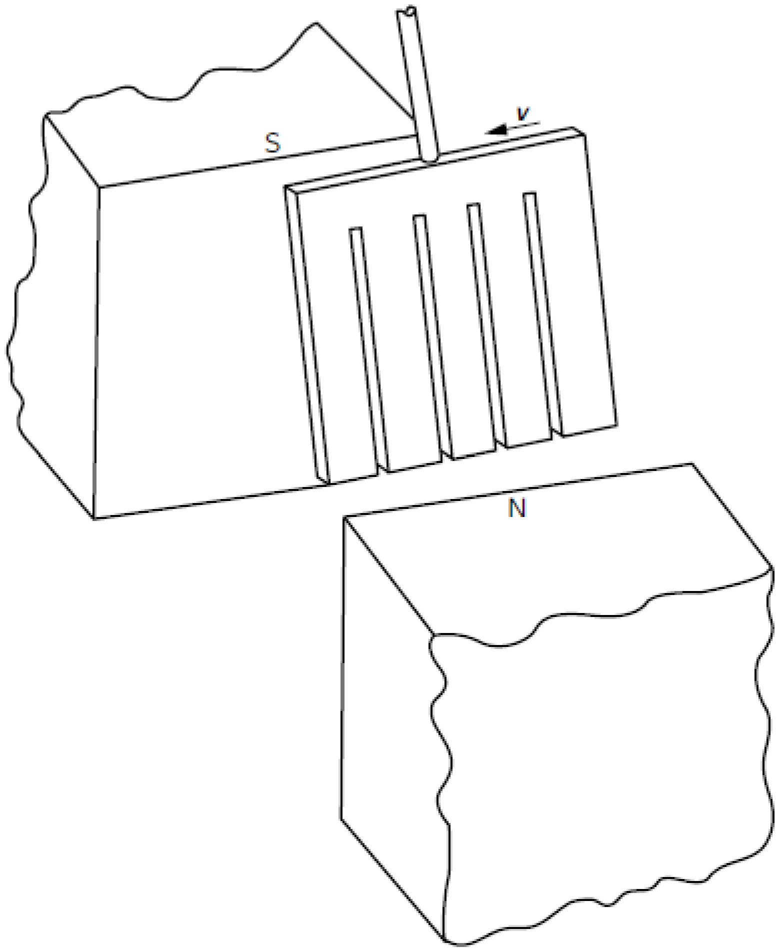


Fig.3 Eddy-current effects are drastically reduced by cutting slots in the plate.

((**Eddy current demonstration**))
https://www.youtube.com/watch?v=MzAPu_p2wI4

12. Eddy Currents (II)

We have seen that when a conducting loop moves through a magnetic field, current is induced as the result of changing magnetic flux. If a solid conductor were used instead of a loop, as shown in **Fig.1**, current can also be induced. The induced current appears to be circulating and is called an *eddy current*.

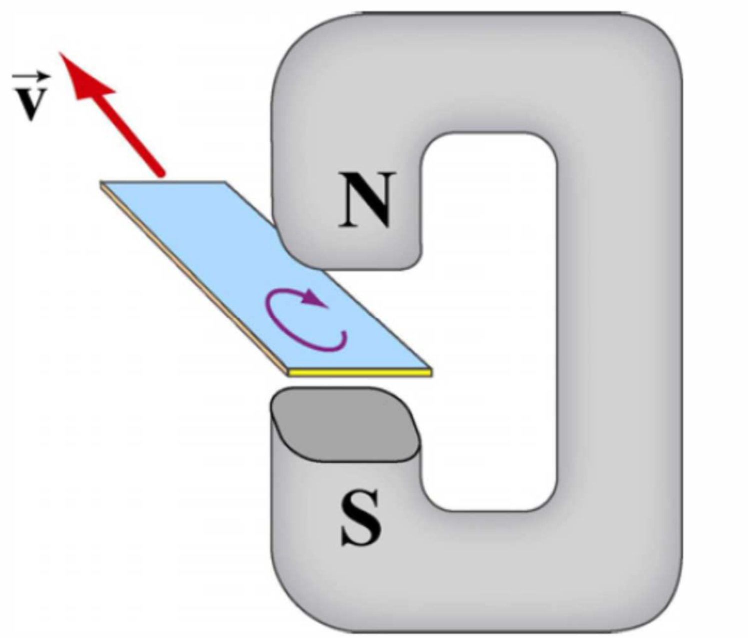


Fig.1 Appearance of an eddy current when a solid conductor moves through a magnetic field.

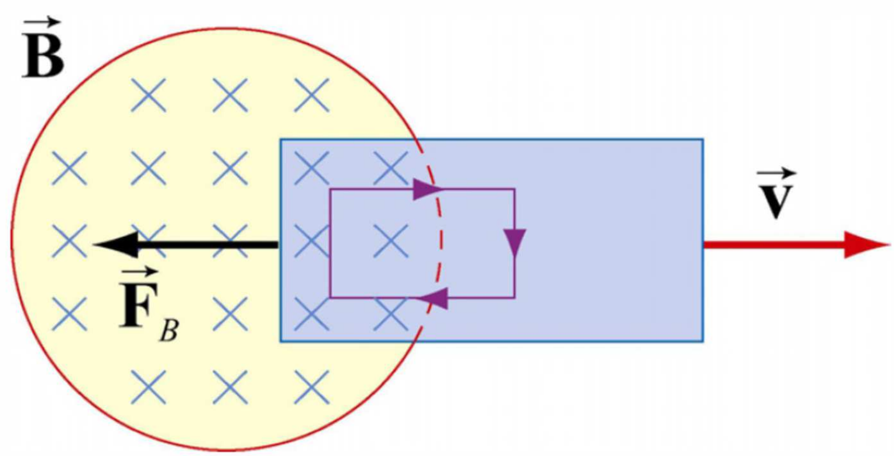


Fig.2 Magnetic force arising from the eddy current that opposes the motion of the conducting slab.

The induced eddy currents also generate a magnetic force that opposes the motion, making it more difficult to move the conductor across the magnetic field (**Fig.2**). Since the conductor has non-vanishing resistance R , Joule heating causes a loss of power by an amount $P = \varepsilon^2 / R$. Therefore, by increasing the value of R, the power loss can be reduced. One way to increase R is to laminate the conducting slab, or construct the slab by using gluing together thin strips that are insulated from one another (**Fig.3a**). Another way is to make cuts in the slab, thereby disrupting the conducting path (**Fig.3b**).

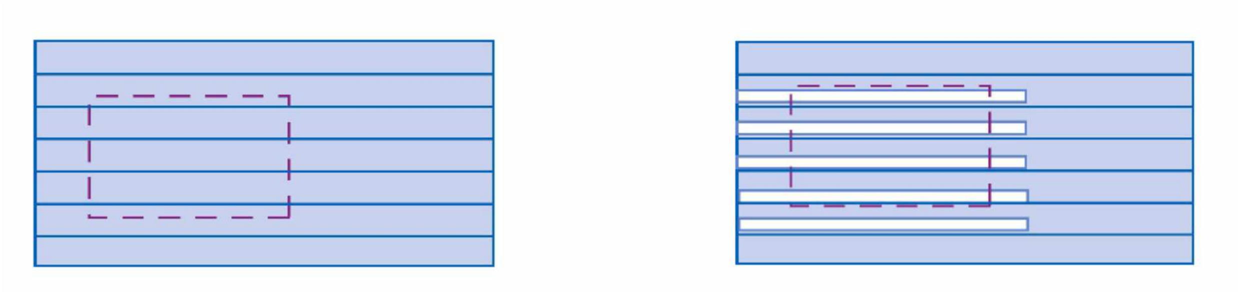
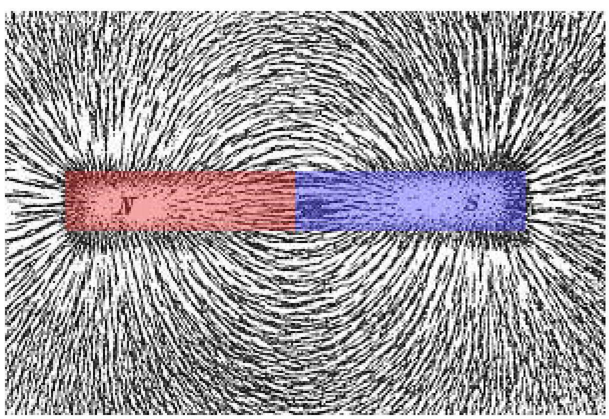


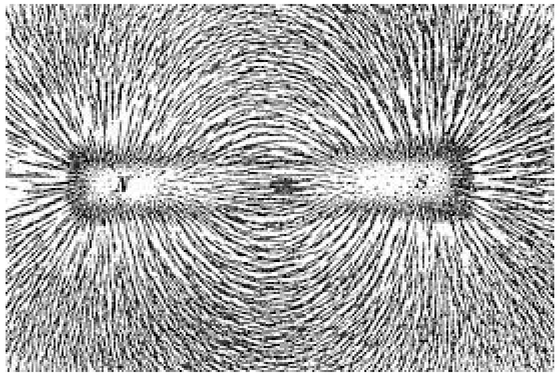
Fig.3 Eddy currents can be reduced by (a) laminating the slab, or (b) making cuts on the slab.

There are important applications of eddy currents. For example, the currents can be used to suppress unwanted mechanical oscillations. Another application is the magnetic braking systems in high-speed transit cars.

13. Magnetic field distribution of magnet with the use of Fe particles.

https://cdn4.explainthatstuff.com/magneticfield.jpg





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