Phys 100: The Physical World
Chapters 24 & 25

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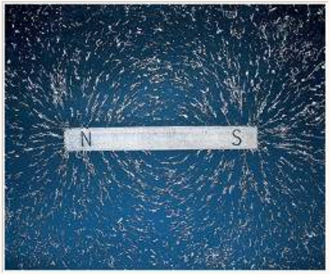
Magnetism

Around 500 BC, Greeks discovered magnetite, an iron ore with the unique property of attracting and repelling similar materials. Every magnet has two inseparable poles—one north and one south. Like poles repel, while unlike poles attract. Since magnetic forces act over a distance, we infer the existence of a magnetic field that fills the space around the poles.

Ferromagnets, such as iron oxide, are materials that exhibit permanent magnetism. No matter how many times a ferromagnet is divided, the pieces will always have both north and south poles. Even a single iron atom has both north and south magnetic poles!

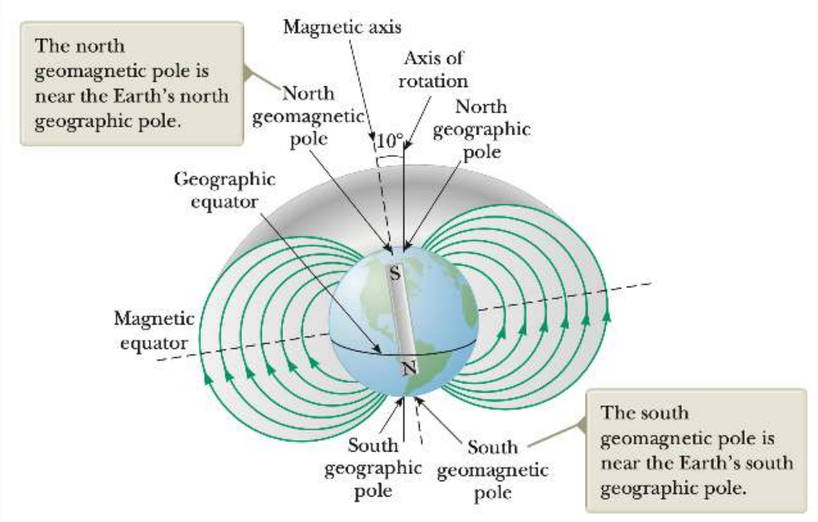


Earth's Magnetic Field

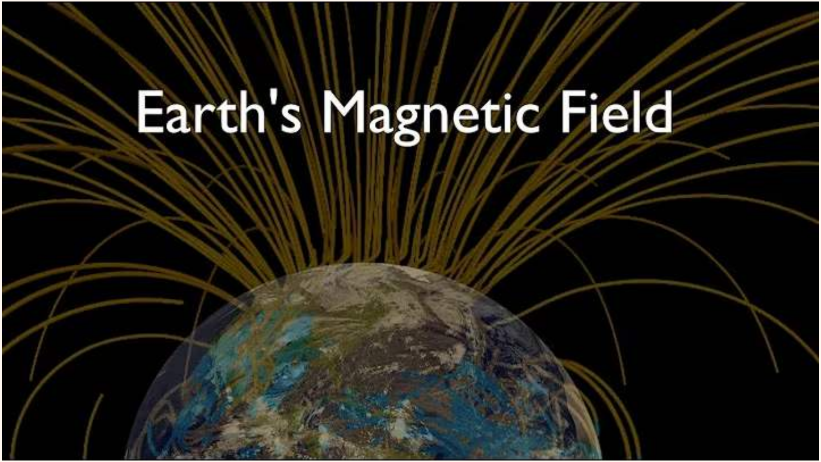
The Chinese were among the first to make practical use of magnetism. By the 2nd century BC, they had developed the first compasses using lodestones to align with Earth's magnetic field. In 1600, English scientist William Gilbert published *De Magnete*, in which he proposed that Earth itself behaves like a giant magnet, with a north and south magnetic pole.

Gilbert defined the magnetic field direction to be the direction in which the north pole of a compass needle points. This implies that Earth's geographic north pole is actually a south magnetic pole (although not exactly; as it turns out, the "magnetic axis" does not align with the "spin axis" of the Earth).

Earth’s Magnetic Field



Earth's Magnetic Field



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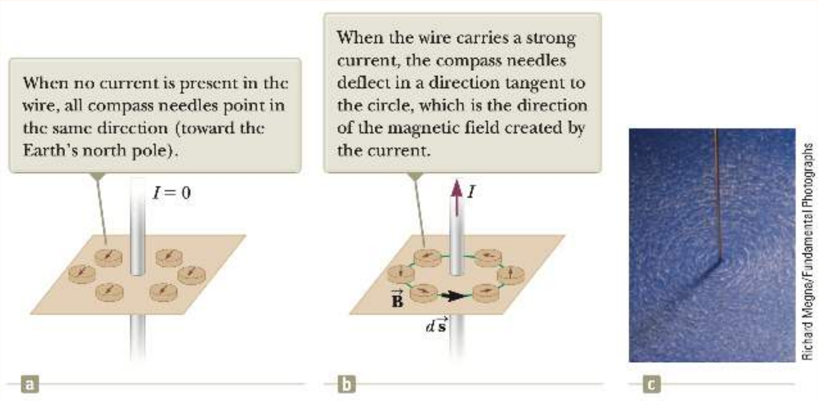
Oersted's Discovery

Until 1820, electricity and magnetism were believed to be completely unrelated phenomena. Danish physicist and chemist Hans Christian Oersted suspected there might be a hidden connection. During a lecture at the University of Copenhagen, he made a groundbreaking discovery: when a compass needle is placed near a current-carrying wire, it may deflect, revealing a link between electricity and magnetism after all.

Interestingly, no deflection occurs if the current flows perpendicular to the needle. But when the current wire runs parallel to the needle, the needle rotates until it aligns perpendicular to the wire. The direction of the current matters. Placing small compasses or iron filings around a current-carrying wire reveals the existence of a circular magnetic field, and flipping the direction of the current flips the direction of the magnetic field.

Oersted's Discovery

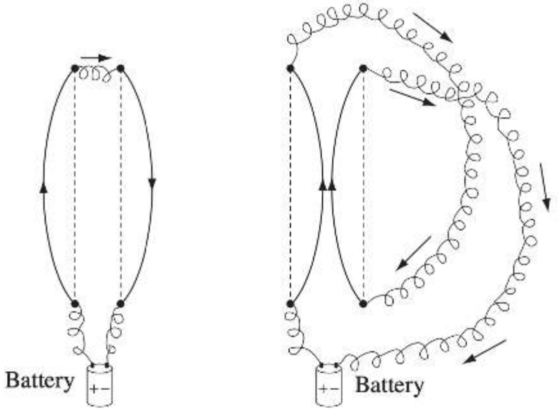


Ampère's Discovery

Soon after Oersted's discovery, André Ampère found that two parallel wires carrying electric current experience a force between them; they attract each other if the currents flow in the same direction and repel if they flow in opposite directions.

In summary, current carrying wires produce magnetic fields and experience magnetic forces. While a compass needle may not look anything like a current-carrying wire, we now know, as Ampère was the first to suspect, that magnetized iron is full of perpetually moving charges-electric currents on an atomic scale. Magnetic fields are produced by and act upon moving charges.

Ampère's Discovery



(a) Currents in opposite directions repel.

(b) Currents in same directions attract.

Magnetic Field

The magnetic field is measured in units of teslas (T) where one telsa is equal to one newton per coulomb per m/s.

$$\text{tesla} = \frac{\text{newton}}{\text{coulomb} \cdot \text{m/s}}$$

A moving charge in a magnetic field experiences a force that

(i) is always perpendicular to the velocity and magnetic field

(ii) is proportional to its speed and magnitude of charge

(iii) depends on the direction of its velocity relative to the field:

The force is

- greatest when it moves perpendicular to the field
- zero when it moves parallel to the field

Conceptual Question 1

The reason that an electron moving in a magnetic field doesn't pick up speed is

(a) the charge of the electron is very small.

(b) the magnetic force opposes the electric force.

(c) the magnetic force is always perpendicular to its motion.

(d) all of the above.

Conceptual Question 2

The magnetic force on a moving charged particle can change the particle's

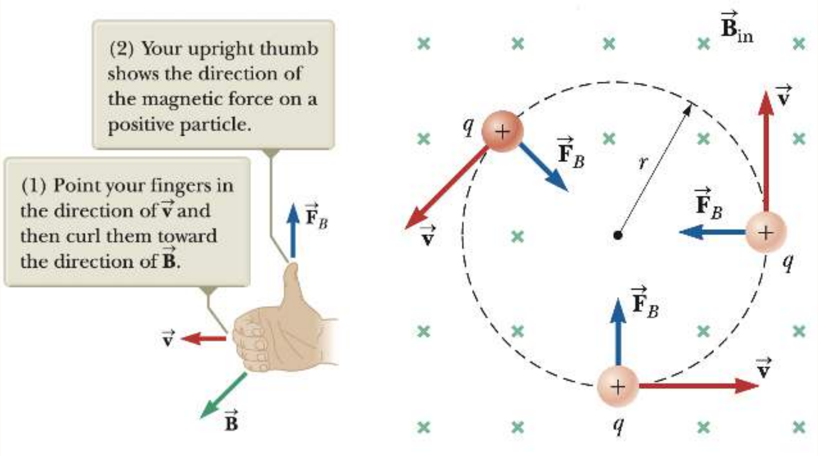
(a) speed

(b) direction

(c) both (a) and (b)

(d) neither (a) nor (b)

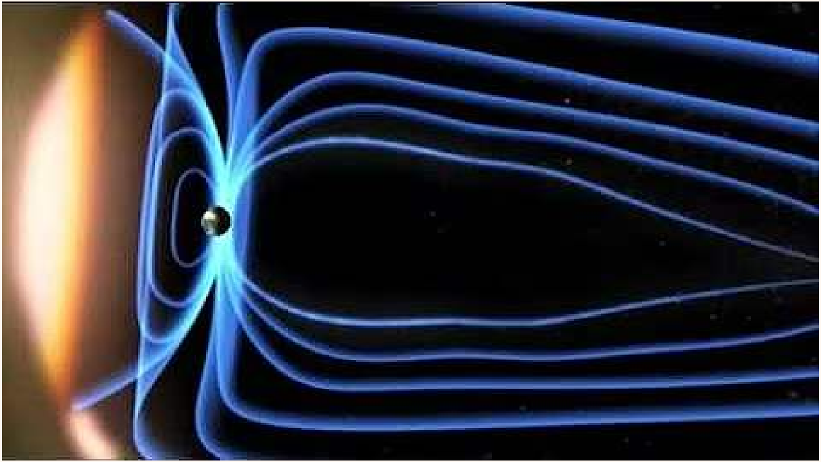
Direction of the Magnetic Force



Magnetic Force on Charged Particles

Click here to watch video (1:59)

Earth's Magnetic Shield



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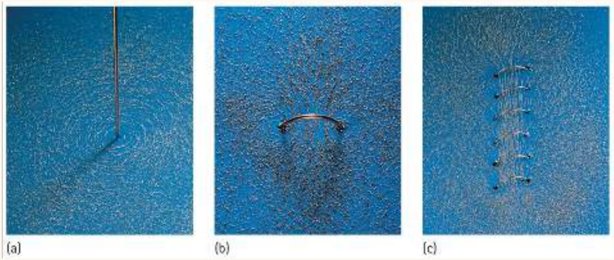
Biot-Savart Law

In 1820, Jean-Baptiste Biot and Félix Savart discovered the magnetic field strength of long straight current-carrying wire is proportional to the current and inversely proportional to the perpendicular distance from the wire.

The magnetic field of a wire is enhanced by winding it into a coil, and especially when the coil wraps around a ferromagnetic core like an iron rod. Current-carrying coils are called electromagnets, and they are especially useful because we can engineer their magnetic properties.

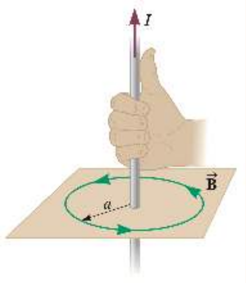


Magnetic Field of a Long Straight Wire

The magnetic field strength of a long straight wire is

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

where the field circulates around the wire in a direction given by a right-hand rule as shown on the right.



The constant μ_0 is called the "permeability of free space" but we'll just call it the magnetic constant and it has the value

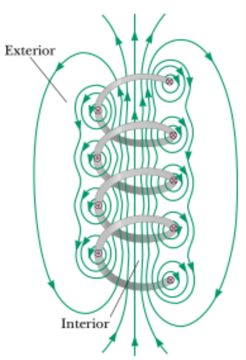
$$\mu_0 \approx 4\pi \times 10^{-7}\ \mathrm{T \cdot m/A}$$

Magnetic Field of a Solenoid (Electromagnet)

The magnetic field strength inside a long coil of current-carrying wires is

$$B = \mu_0 \frac{N}{\ell} I$$

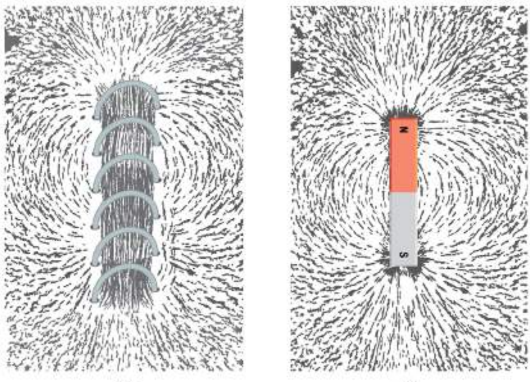
where N is the number of loops, ℓ is the length of the coil, and I is the current running through the coil. The direction of the magnetic field is given by a right-hand rule as illustrated on the right.



Curl the fingers of your right hand in the direction of the current in the coil, and your outstretched thumb will point in the direction of the magnetic field.

Electromagnets

Electromagnets are employed for everything from a wrecking yard crane that lifts scrapped cars to controlling the beam of a 90-km-circumference particle accelerator to the magnets in medical imaging machines. The magnetic field around an electromagnet is similar to that of a bar magnet.



(a) (b)

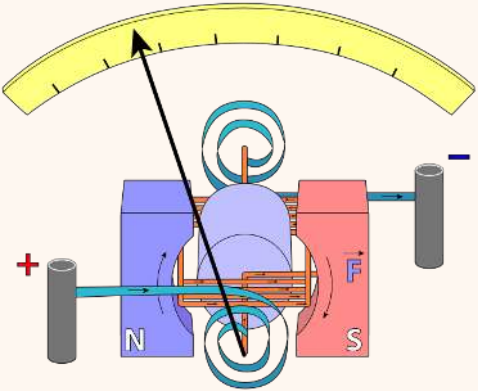
Conceptual Question 3

An electromagnet can be made stronger by

(a) increasing the number of turns of wire.
(b) increasing the current in the coil.
(c) Both A and B are correct.
(d) None of the above is correct.

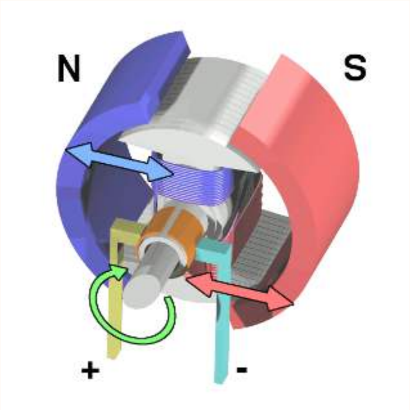
Galvanometer

Current-indicating device named after Luigi Galvani that can act as an ammeter when it reads current directly, a voltmeter when calibrated to measure volts, and as an ohmmeter when calibrated to measure resistance.



Electric Motors

An electric motor is a device that transforms electrical energy into mechanical energy. The most basic design is similar to a galvanometer, except each time the coil makes a half rotation, the direction of the current changes in a cyclic fashion to produce continuous rotation.

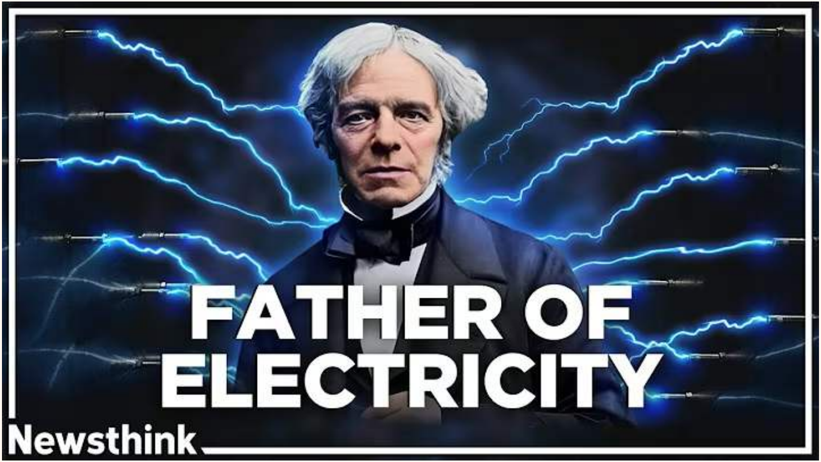


Electromagnetic Induction

By the 1830's it was well established that an electric current creates a magnetic field. In 1831, Michael Faraday demonstrated the reverse was also true–a magnetic field could create an electric current under the right circumstances. Faraday's law is a mathematical description of electromagnetic induction–the generation of electricity using magnetic fields.

Faraday's law revolutionized our understanding of electromagnetism and led to the development of electrical generators and transformers, making practical electricity generation and transmission possible. As the apocryphal tale goes, Faraday was once asked by an inquiring politician about the usefulness of his discoveries, to which he replied "I know not, but I wager that one day your government will tax it."

The Scientist Who Sucked at Math



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Faraday’s Law

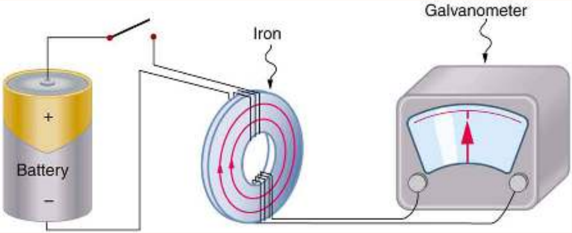
The induced voltage in a conducting coil is the product of

(i) the number of loops,

(ii) the area enclosed by the loops,

(iii) and the rate at which the magnetic field changes within the loops. The magnetic field can change by

- moving a bar magnet near the coil,
- moving the coil near a bar magnet,
- or changing the current in a nearby loop.



Lenz's Law

Lenz's law (technically a corollary of Faraday's law) says the induced current in a coil will always flow in a direction that opposes the change that caused it. In simple terms: the induced current creates a magnetic field that fights back. If you push a magnet toward a coil, the coil creates a magnetic field that pushes it away. That means you have to do work to keep the magnet moving, and that mechanical energy is what gets converted into electrical energy. If the coil didn't resist, you could get induced current without effort, which would violate conservation of energy. Lenz's law (really Faraday's law) prevents that–it guarantees you only get out the energy you put in.

Faraday's Law Demonstration

Click here to watch video (3:15)

Jumping Ring Demonstration

Click here to watch video (6:50)

Conceptual Question 4

The resistance you feel when pushing a piece of magnetized iron into a coil involves

(a) repulsion by the magnetic field produced by the current you induce.

(b) energy transfer between the iron and coil.

(c) Newton's third law.

(d) resistance to domain alignment in the iron.

Conceptual Question 5

More voltage is induced when a magnet is thrust into a coil

(a) more quickly.

(b) more slowly.

(c) Both A and B are correct.

(d) Neither A nor B is correct.

Conceptual Question 6

A coil of wire has its ends connected by a resistor. A current will flow through the resistor if

(a) a magnet is held stationary inside the coil.

(b) the coil is moved in the vicinity of a magnet.

(c) the coil is moved next to an identical coil.

(d) All of the above are correct.

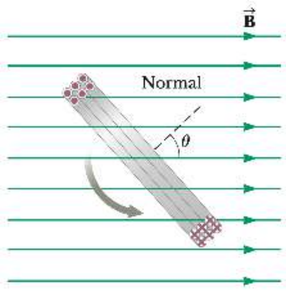
Magnetic Flux

When working with Faraday's law, it is convenient to use the concept of magnetic flux, defined as the product of the area enclosed by the loops and the magnetic field within the loops. Faraday's law then says the induced voltage depends on the rate of change of magnetic flux. If the magnetic field is held constant, the flux can change by simply rotating the coil, thereby changing the effective area of the magnetic field in the loops.

Imagine you're trying to catch fish that are all swimming downstream using a big net enclosed by a circular hoop. You'll catch the most fish by orienting the hoop perpendicular to the path of the fish, and no fish whatsoever by aligning the hoop with the path of the fish. Similarly, the maximum magnetic flux occurs when the loops are oriented to allow the largest number of magnetic field lines to pass through them.

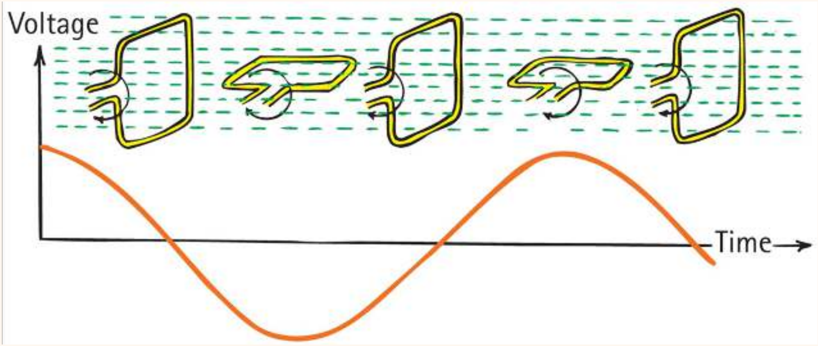
Electrical Generators

An electric generator is a device that converts mechanical or chemical energy into electrical energy. It is like an electric motor run "in reverse." The simplest mechanical generators consist of conducting coils rotated by some external means in a magnetic field. As the coil rotates, the magnetic flux changes with time, and this change induces a voltage in the loop.



AC Generators

The frequency of alternating voltage induced in a loop is equal to the frequency of the changing magnetic field within the loop.



Conceptual Question 7

In an AC generator, a coil with N turns of wire spins in a magnetic field. Of the following choices, which does not cause an increase in the emf generated in the coil?

(a) replacing the coil wire with one of lower resistance
(b) spinning the coil faster
(c) increasing the magnetic field
(d) increasing the number of turns of wire on the coil

Power Stations

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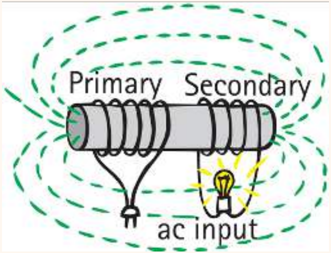
Transformer



A transformer consists of two components:

(i) The primary input coil is powered by an ac voltage source.
(ii) The secondary output coil connected to an external circuit.

Both coils are wound on a common iron core so that the magnetic field created by the primary passes through the secondary.

Transformer Relations

The ratio of the secondary voltage to the primary voltage is equal to the ratio of the number of secondary loops to the number of primary loops:

$$\frac{\text{secondary voltage}}{\text{primary voltage}} = \frac{\text{number of secondary loops}}{\text{number of primary loops}}$$

Many transformers move electrical energy from the primary to the secondary with efficiencies at or above 90%. Assuming the energy is transferred with 100% efficiency,

$$\text{primary power} = \text{secondary power}$$

$$I_P \times V_P = I_S \times V_S$$

Step-Up and Step-Down Transformers

(i) In a step-up transformer, the secondary voltage exceeds the primary voltage. The secondary coil has more loops than the primary and lower current.

(ii) In a step-down transformer, the secondary voltage is less than the primary voltage. The secondary coil has less loops than the primary and more current.

A step-up transformer is used to lower the current before passing it through a transmission line, where the rate at which energy is dissipated depends on the square of the current. Reducing the current to half of its value in the primary reduces the rate of energy dissipation by one-fourth.

Conceptual Question 8

A step-up transformer in an electrical circuit can step up

(a) voltage.

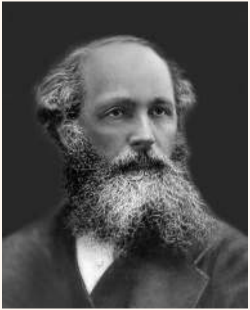
(b) power.

(c) Both (a) and (b) are correct.

(d) Neither (a) nor (b) is correct.

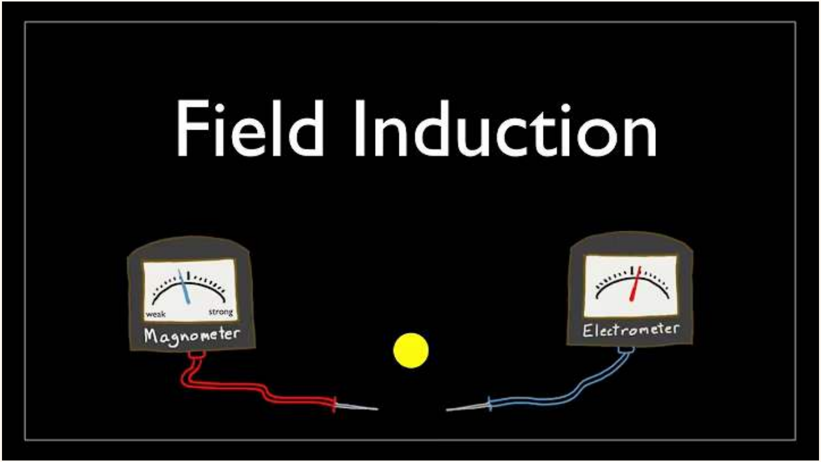
James Clerk Maxwell (1831-1879)

Scottish physicist responsible for synthesizing the entire theory of classical electromagnetism. Born the same year Faraday discovered that changing magnetic fields create electric fields, it is fitting Maxwell established that changing electric fields can create magnetic fields. It's a two-way street!



Maxwell demonstrated that the known laws of magnetism in his time conflicted with conservation of charge in certain situations. By introducing a correction term, Maxwell was able to create a consistent set of equations describing all electromagnetic phenomena and even predict electromagnetic waves in the process!

Field Induction



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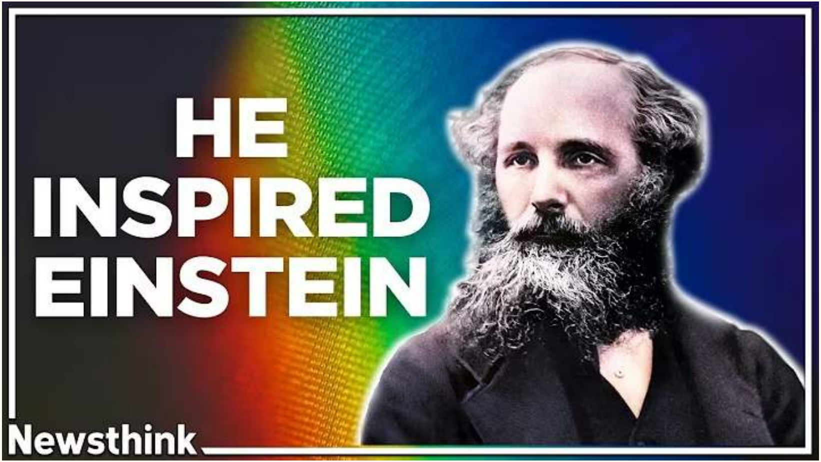
The Scientist Who Inspired Einstein



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Conceptual Question 9

The strength of an induced electric or magnetic field depends on the

(a) strength of magnetic poles.

(b) alignment of magnetic domains.

(c) rate of change of the induced field.

(d) all of the above

(e) none of the above