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magnet and magnetism

In ancient times men knew of a special kind of rock that could pull other rocks of the same kind and pieces of iron toward itself. Such rocks were called lodestones. In modern times man uses the same force exerted by the ancient lodestones to generate electric power, to store information in computers, and to study the secrets of the universe. The force is called **magnetism**, and objects that exert it are known as magnets. By the end of the 19th century, all the elements were known to have some magnetic property.

The peoples of the ancient world could discover the magnetic force because certain rocks and minerals are magnetic in their natural state. Materials which retain their **magnetism** independently of their surroundings are called hard, or permanent, magnets. Magnetic forces always exist between permanent magnets. In addition, permanent magnets exert forces on certain other materials, such as iron, which by themselves do not act magnetic.

Most materials—for example, wood, copper, air, and water—do not seem to respond to permanent magnets. Actually, all materials, even the so-called nonmagnetic ones, can respond to the magnetic force. However, most materials are so weakly magnetic that the force they exert is not noticed in everyday life.

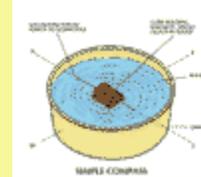
Materials which can be attracted to magnets but which are not themselves permanent magnets are called soft, or temporary, magnets. This distinguishes them from nonmagnetic substances such as wood. Soft magnets can be magnetic and can act like magnets only when they are in the presence of a permanent **magnet**. Some soft magnets such as iron can be made into hard magnets. One way is to roll or hammer a hot piece of the soft **magnet** into a needle shape and then to place it next to a hard **magnet** as it cools.

Magnetic Poles

Magnetic needles have a special property that links them with astronomy, the most highly developed science of the ancient world. If a magnetic needle is placed in a hollow reed and floated on water or freely suspended on a string or wire, it always seems to point in a fixed direction relative to the stars. This discovery was the basis for the development of the compass (see [Compass, Magnetic](#)).

Centuries passed before men understood why the compass needle always pointed in a north-south direction. In 1600 the English scientist William Gilbert published a monumental work that suggested that the Earth itself is a giant **magnet** that exerts a force on all the magnets on its surface.

It has since been established that the Earth is, indeed, a large but weak **magnet**. The force it exerts is strong enough to orient small permanent magnets like iron needles but not strong enough to affect



**A magnetized steel
needle stuck through a
float...**

A magnetized steel
needle stuck through a
floating cork makes a
compass. The needle is
magnetized by stroking it
in one direction about 20
times with one end of a
permanent magnet.

soft magnets perceptibly. The Earth's **magnetism** is strongest at two points—one near the geographic North Pole, the other near the geographic South Pole. At one end of all magnets is a pole that points north; at the other end, a pole that points south. The north-seeking pole of a **magnet** is commonly called the north pole, and the south-seeking pole, the south pole.

If a long bar **magnet** is cut in half, each half becomes a complete **magnet**. Each half has a north pole and a south pole. Since all magnets have two poles and no **magnet** has been discovered that has only one pole, magnets are called dipoles.



A basic law of magnetism is that like poles rep...

A basic law of magnetism is that like poles repel each other.

If two magnets are brought near to each other, one of the fundamental laws of **magnetism** can be experienced. Like poles (north and north, or south and south) repel each other, and unlike poles (north and south) attract each other.

If a permanent **magnet** is brought near a bar of soft magnetic material such as iron, poles are induced at the ends of the soft bar. If the north-seeking pole is near one end of the soft magnetic iron bar, that end of the iron bar becomes a south pole, the other end a north pole. If the permanent **magnet** is turned

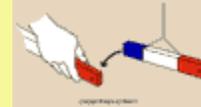
around so that a south pole come near the same end of the iron bar, that end of the bar become a north pole, the other end a south pole. If the permanent **magnet** is removed, the soft iron returns to its original unmagnetized state.

Magnetic Fields

A **magnet** can attract or repel another **magnet** or a piece of soft iron without touching it. Magnetic forces are exerted even when empty space, air, or any nonmagnetic material such as cardboard separates the two. Furthermore, two magnets can exert a force on each other even when they are placed at an angle to each other. Scientists describe the space around a **magnet** as occupied by a magnetic field. They can 'map' the field by observing the direction of the magnetic force at many points around the **magnet**.

For example, a small compass may be placed in different positions near a long bar **magnet**. Since the compass is free to swing around, it will point in the direction of the magnetic field at each position. By observing the way the compass points, the direction of the magnetic field at any position can be determined.

The compass is moved in short steps, always in the direction in which it points. After each move, the position of the compass is marked. If the marks are connected by lines, they are seen to start at one pole and move around to the other pole. These lines are called lines of force, or lines of flux, of the magnetic field. By convention, the magnitude of the magnetic field is described as positive when it goes from north to south, negative when it goes from south to north. The lines of force exist inside the **magnet** as well: they go from one pole to the other. One may also sprinkle tiny iron filings on a piece of stiff paper covering a flat bar **magnet**. If the paper is gently tapped while the iron filings are sprinkled, the filings jump around and arrange themselves along the lines of the magnetic field. Where the lines are close to one another, the field is strong; where the lines are far apart, the field is weak. The lines and the filings are densest at the poles of the **magnet**, where the magnetic field is strongest.



A basic law of magnetism is that unlike poles a...

A basic law of magnetism is that unlike poles attract each other. Two bar magnets can illustrate this. One is hung so that it swings freely. A pole of the second is brought, in turn, near each of the two ends of the hanging magnet. One end of the hanging magnet is attracted.

The shape of a magnetic field can be changed by changing the shape of a **magnet**. If a long bar **magnet** is bent into a horseshoe shape, the magnetic poles are brought closer together. Most of the magnetic field lines lie between the two tips of the horseshoe. Since the field is strongest where the lines are densest, this shape produces a highly concentrated field between the two tips of the horseshoe. Magnets can be made in other shapes to produce other magnetic field patterns.

Magnetism and Electricity

Like electricity and gravity, **magnetism** is a fundamental force. **Magnetism** and electricity are closely related and are regarded as two expressions of a single force, the electromagnetic force.

The first evidence for this relationship was observed in 1820 by the Danish physicist Hans Oersted. A wire that could carry an electric current was pointed in a north-south direction. A compass lay near the wire. Before the current was switched on, the compass pointed in a north-south direction parallel to the wire. When the current started flowing through the wire, the compass needle swung around and pointed in a different direction which was at a right angle to the wire. When the direction of current flow was reversed, the compass needle swung around to point in the opposite direction, still at a right angle to the direction of current flow.

This effect of current flow on a nearby **magnet** occurs because the moving electric charges that make up the current set up a magnetic field that curls around the wire. The direction of the magnetic field is expressed by the right-hand rule. If the thumb of the right hand points in the direction of current flow from the positive to the negative terminal, then the four fingers of the right hand curl in the direction of the magnetic field.

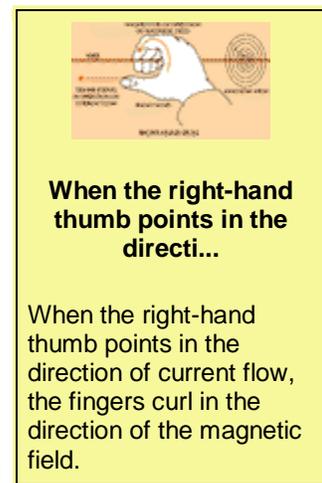
Oersted's discovery led to speculation that if an outside magnetic field were applied to a conducting wire, the outside field might interact with the magnetic field created by the current flow, and this interaction could cause the wire to move. Michael Faraday succeeded in demonstrating that an external magnetic field could cause a conducting wire to rotate and also that if the wire were held in place the external **magnet** itself would rotate.

More evidence for the interrelationship of **magnetism** and electricity was provided in 1831, when Faraday created an electric current by moving a **magnet** near an electric conductor. This showed that a **magnet** could induce an electric current if the **magnet** was moving relative to the electric conductor.

These three phenomena can be summarized as follows: (1) moving electric charges produce magnetic fields; (2) magnetic fields exert forces on moving electric charges; and (3) changing magnetic fields in the presence of electric charges cause a current to flow. Any theory of electricity and **magnetism** had to account for these interactions.

Faraday also developed a visual model of the magnetic field. His theory implied that moving a **magnet** or an electric charge disturbs the lines of force surrounding the **magnet** or charge. The disturbance travels through space at a definite speed.

In 1864 James Clerk Maxwell published a mathematical theory describing how the disturbance caused by moving electric charges or moving magnetic lines of force would travel. Maxwell said the disturbance could be treated as a wave motion with a speed of 3108 meters per second—the experimentally determined speed of light.



He concluded that light was an electromagnetic wave (see [Light; Radiation; Energy](#)). According to one concept of the wave structure of electromagnetic radiations, including light, such waves consist of the growth and collapse of electric and magnetic fields at right angles to each other.

Oersted's original discovery was that an electric current flowing through a wire would set up a magnetic field around the wire and that increasing the current would strengthen the magnetic field. The field may also be strengthened by forming the wire into a loop. The lines of force are circles around each bit of wire; where these circles overlap a stronger magnetic field is produced. If the wire is wound to form a hollow cylinder in which a continuous series of loops are next to one another-this may be done by winding wire around a pencil-the magnetic field inside the cylinder is equal to the sum of the magnetic fields associated with all the loops. A **magnet** in this form is called a solenoid.

Solenoid magnets have several advantages over permanent magnets. They can be turned on and off. The strength of the magnetic field can be varied by increasing or decreasing the current in the coil. In fact, the field in the center of the solenoid is directly proportional to the size of the current.

This magnetic field may be strengthened by placing a bar of magnetically soft iron inside the solenoid. The magnetic field of the solenoid induces **magnetism** in the bar, and the total field outside the solenoid is the sum of the solenoid's field plus the field induced in the soft iron. The magnetic field of the magnetized iron bar can be much stronger than that of the solenoid alone. This combination of a solenoid and a magnetic bar is called an electromagnet.

Increasing the current in the solenoid increases the magnetic field induced in the bar **magnet**-but only up to a certain point. This is called the saturation value. The strength of an electromagnet depends on the saturation value of the bar **magnet**.

Although only the few materials that are visibly attracted to a magnetic field are called magnetic, all matter-including 'nonmagnetic' substances-has magnetic properties. This is because all matter is made up of moving charged particles-electrons and protons-whose motion sets up magnetic fields.

Most kinds of nonmagnetic matter are diamagnetic, or very weakly repelled by a magnetic field. Other kinds of nonmagnetic matter are weakly attracted by a magnetic field. This reaction is called paramagnetism. Paramagnetism is usually somewhat stronger than diamagnetism. When iron, cobalt, or nickel is placed in a magnetic field, it is strongly and visibly attracted. This attraction is called ferromagnetism.

To understand why different substances react differently to the application of a magnetic field, it is necessary to understand the atoms and molecules that make up each substance. According to modern atomic theory, atoms consist of a massive, dense, positively charged center called the nucleus around which light, negatively charged electrons circulate. Each electron generates a magnetic field.

Usually the electrons of an atom are paired in such a way that the magnetic field of one electron in a pair is canceled by the magnetic field of the other. Similar structures occur in molecules. Atoms join chemically to form molecules by sharing electrons. The electrons in the bond are usually paired so their magnetic fields cancel. Substances composed of atoms and molecules having only paired electrons are diamagnetic. The electrons in diamagnetic substances resist the imposition of an outside magnetic field by setting up weak opposing fields within the individual atoms or molecules. In one sense, however, all substances-including magnetic substances-are diamagnetic. When an outside magnetic field is applied to any substance, at least part of the response of its electrons is to oppose the outside field.

Some substances are made up of atoms or molecules that have uneven numbers of electrons. This means that each molecule contains at least one unpaired electron. Such materials are usually paramagnetic.

Paramagnetism is usually too small to be observed in everyday life, but it is strong enough to more than compensate for the diamagnetism that exists in paramagnetic materials. Both phenomena depend on the presence of an outside magnetic field. If this is removed, the magnetic fields associated with the electrons swing around and cancel one another.

An atom can be paramagnetic in one compound and diamagnetic in another. This occurs because electrons have different motions in different kinds of molecules. For example, the oxygen-containing gases oxygen (O₂) and nitrous oxide (NO) are paramagnetic because in these molecules some oxygen electrons are unpaired. But in water (H₂O) all the oxygen electrons are paired within the oxygen atom. Water is therefore diamagnetic.

Elements such as iron, cobalt, and nickel and many of their compounds are ferromagnetic. These elements contain many unpaired electrons. Such electrons within an atom spin in one direction; this means that their magnetic fields are pointed in the same direction. The total magnetic field of the atom is strong enough to influence surrounding atoms. In iron, for example, four electrons are unpaired. These four electrons line up to form a strong atomic **magnet**. Under the influence of this atomic **magnet** adjacent atomic magnets line up in the same direction, and the fields of all the aligned atoms combine to form an even stronger field. When all the spins of the unpaired electrons in an entire piece of iron are pointed in the same direction, the piece of iron is a **magnet**.

Why, then, are most pieces of iron not permanent magnets? The reason is that the spins of the unpaired electrons in a piece of iron are usually not all lined up in the same direction. Small regions, called domains, are magnetized in different directions. All the atoms within a domain contribute to the magnetic field of the domain. But nearby domains having magnetic fields that are pointed in other directions cancel one another out.

When an external magnetic field is applied to such a piece of iron, the domain that points in the direction of the external field grows in size. The atoms along the borders of the domain swing around until they become part of it. If all the atoms within the iron line up in one domain that points in the direction of the external field, the iron has become magnetized.

When the external magnetic field is removed, domains re-form, and the iron loses much of its **magnetism**. Because of this, iron is called a soft **magnet**.

In hard magnets, internal forces within the material prevent the domains from re-forming after the external magnetic field is removed. The spins in a permanent **magnet** remain in a single domain unless some outside force, such as heat or a hard blow, causes them to swing apart. Some iron alloys have internal structures that make them very strong permanent magnets.

These alloys include alnico, an alloy of iron, aluminum, cobalt, and nickel, which is used in magnetic door catches and other magnetic fasteners. Alloys of platinum and cobalt and of samarium and cobalt are even stronger permanent magnets.

Not all magnets are composed only of metals. For example, lightweight ceramics-ferrites-are used in computer memories because their **magnetism** can be reversed in less than one millionth of a second. A thin layer of ferrite accounts for the **magnetism** of the tape used in tape recorders.

Uses of Magnets

Common uses of magnets are based on simple magnetic attraction or repulsion, as in magnetic refrigerator latches. Large electromagnets are used to move loads of steel scrap and to process magnetic ores. Smaller electromagnets are used in relays, switches, and valves.

Magnetic fields induce electric currents in generators, motors, and transformers and can bend beams of charged particles. In television tubes, electrons are controlled partly by magnetic fields and

partly by electric fields so that they strike the television screen in patterns reproducing images sent from the station.

In atomic physics, **magnetism** associated with atoms is studied for clues about the internal structure of matter. Physicists working with magnets made of superconducting materials in the mid-1990s were able to produce a magnetic field 78,000 times stronger than the Earth's magnetic field.

Geologists study the magnetic orientation of rocks at the bottom of the sea. From their research they have learned that the Earth periodically reverses its **magnetism**.

Measuring the **magnetism** of astronomical bodies provides clues to the bodies' structure and history. Neutron stars have extremely powerful magnetic fields at their surfaces. The magnetic fields associated with galaxies, on the other hand, are very weak. Within the field of **magnetism** scientists are searching for evidence of a single magnetic pole. All the known magnets are dipoles. In electricity, however, positive and negative electric charges exist independently. Scientists have been trying to find single, isolated north or south poles called magnetic monopoles in cosmic rays, in magnetic ores, and with the use of particle accelerators. So far none has been confirmed to exist.

Magnetic resonance imaging (MRI), also called nuclear magnetic resonance (NMR), is a technique that involves subjecting certain atomic nuclei (such as those found in specific organs of the human body) to very strong stationary magnetic fields and then observing how they selectively absorb very high frequency radio waves. By the early 1980s, MRI had begun to be used in medicine because it presented a relatively hazard-free, noninvasive way to generate visual images of thin slices of the body by measuring the characteristic magnetic behavior of specific nuclei in the water and fats of the body. MRI images show great sensitivity in differentiating between normal tissues and diseased or damaged ones. (See also [Diagnosis](#).)

By the late 1980s, MRI had proved superior to most other imaging techniques in providing images of the brain, heart, liver, kidneys, spleen, pancreas, breast, and other organs. The images, in turn, can show tumors, blood-starved tissues, and other diseased or damaged states of the body. Though the technique presents no health hazards, it cannot be used on patients with cardiac pacemakers or certain other metal-containing devices implanted in their bodies.