Science Physics Matter & Energy magnetism, phenomenon associated with magnetic fields, which arise from the motion of electric charges. This motion can take many forms. It can be an electric current in a conductor or charged particles moving through space, or it can be the motion of an electron in an atomic orbital. Magnetism is also associated with elementary particles, such as the electron, that have a property called spin. Basic to magnetism are magnetic fields and their effects on matter, as, for instance, the deflection of moving charges and torques on other magnetic objects. Evidence for the presence of a magnetic field is the magnetic force on charges moving in that field; the force is at right angles to both the field and the velocity of the charge. This force deflects the particles without changing their speed. The deflection can be observed in the torque on a compass needle that acts to align the needle with the magnetic field of Earth. The needle is a thin piece of iron that has been magnetizedi.e., a small bar magnet. One end of the magnet is called a north pole and the other end a south pole. The force between a north and a south pole is attractive, whereas the force between like poles is repulsive. The magnetic field is sometimes referred to as magnetic induction or magnetic flux density; it is always symbolized by B. Magnetic fields are measured in units of tesla (T). (Another unit of measure commonly used for B is the gauss, though it is no longer considered a standard unit. One gauss equals 104 tesla.) A fundamental property of a magnetic field is that its flux through any closed surface vanishes. (A closed surface is one that completely surrounds a volume.) This is expressed mathematically by div B = 0 and can be understood physically in terms of the field lines representing B. These lines always close on themselves, so that if they enter a certain volume at some point, they must also leave that volume. In this respect, a magnetic field is quite different from an electric field. Electric field lines can begin and end on a charge, but no equivalent magnetic charge has been found in spite of many searches for so-called magnetic monopoles. The most common source of magnetic fields is the electric current loop. It may be an electric current in a circular conductor or the motion of an orbiting electron in an atom. Associated with both these types of current loops is a magnetic dipole moment, the value of which is iA, the product of the current i and the area of the loop A. In addition, electrons, protons, and neutrons in atoms have a magnetic dipole moment associated with their intrinsic spin; such magnetic dipole moments represent another important source of magnetic fields. A particle with a magnetic dipole moment is often referred to as a magnetic dipole. (A magnetic dipole may be thought of as a tiny bar magnet. It has the same magnetic field as such a magnet and behaves the same way in external magnetic fields.) When placed in an external magnetic field, a magnetic dipole can be subjected to a torque that tends to align it with the field; if the external field is not uniform, the dipole also can be subjected to a force. All matter exhibits magnetic properties to some degree. When placed in an inhomogeneous field, matter is either attracted or repelled in the direction of the gradient of the field. This property is described by the magnetic susceptibility of the matter and depends on the degree of magnetization of the matter in the field. Magnetization depends on the size of the dipole moments of the atoms in a substance and the degree to which the dipole moments are aligned with respect to each other. Certain materials, such as iron, exhibit very strong magnetic properties because of the alignment of the magnetic moments of their atoms within certain small regions called domains. Under normal conditions, the various domains have fields that cancel, but they can be aligned with each other to produce extremely large magnetic fields. Various alloys, like NdFeB (an alloy of neodymium, iron, and boron), keep their domains aligned and are used to make permanent magnets. The strong magnetic field produced by a typical three-millimetre-thick magnet of this material is comparable to an electromagnet made of a copper loop carrying a current of several thousand amperes. In comparison, the current in a typical light bulb is 0.5 ampere. Since aligning the domains of a material produces a magnet, disorganizing the orderly alignment destroys the magnetic properties of the material. Thermal agitation that results from heating a magnet to a high temperature destroys its magnetic properties. Magnetic fields vary widely in strength. Some representative values are given in the Table.Typical magnetic fields inside atomic nuclei 1011 T in superconducting solenoids 20 T in a superconducting coil cyclotron 5 T near a small ceramic magnet 0.1 T Earth's field at the Equator 4(105) T in interstellar space 2(1010) T Magnetic resonance imaging (MRI) is an imaging technique used in radiology that uses strong magnetic fields, magnetic field gradients and radio waves to generate images of the organs in the body. Shutterstock/Gorodenkoff Every time you use a computer, you're using magnets. If your home has a doorbell, it probably uses an electromagnet to drive a noisemaker. Magnets are also vital components in CRT televisions, speakers, microphones, generators, transformers, electric motors, burglar alarms, cassette tapes, compasses and car speedometers. In addition to their practical uses, magnets have numerous amazing properties. They can induce current in wire and supply torque for electric motors. Maglev trains use magnetic propulsion to travel at high speeds, and magnetic fluids help fill rocket engines with fuel. Earth's magnetic field, known as the magnetosphere, protects it from the solar wind. According to Wired magazine, some people even implant tiny neodymium magnets in their fingers, allowing them to detect electromagnetic fields. Magnetic resonance imaging (MRI) machines use magnetic fields to allow doctors to examine patients' internal organs. Doctors also use pulsed electromagnetic fields to treat broken bones that have not healed correctly. This method, approved by the United States Food and Drug Administration in the 1980s, can mend bones that have not responded to other treatment. Similar pulses of electromagnetic energy may help prevent bone and muscle loss in astronauts who are in microgravity environments for extended periods. Magnets can also protect the health of animals. Cows are susceptible to a condition called traumatic reticulopericarditis, or hardware disease, which comes from swallowing metal objects. Swallowed objects can puncture a cow's stomach and damage its diaphragm or heart. Magnets are instrumental to preventing this condition. One practice involves passing a magnet over the cows' food to remove metal objects. Another is to feed magnets to the cows. Long, narrow alnico magnets, known as cow magnets, can attract pieces of metal and help prevent them from injuring the cow's stomach. People, on the other hand, should never eat magnets, since they can stick together through a person's intestinal walls, blocking blood flow and killing tissue. In humans, swallowed magnets often require surgery to remove. Some people advocate the use of magnet therapy to treat a wide variety of diseases and conditions. According to practitioners, magnetic insoles, bracelets, necklaces, mattress pads and pillows can cure or alleviate everything from arthritis to cancer. Some advocates also suggest that consuming magnetized drinking water can treat or prevent various ailments. Proponents offer several explanations for how this works. One is that the magnet attracts the iron found in hemoglobin in the blood, improving circulation to a specific area. Another is that the magnetic field somehow changes the structure of nearby cells. However, scientific studies have not confirmed that the use of static magnets has any effect on pain or illness. Clinical trials suggest that the positive benefits attributed to magnets may actually come from the passage of time, additional cushioning in magnetic insoles or the placebo effect. In addition, drinking water does not typically contain elements that can be magnetized, making the idea of magnetic drinking water questionable. Magnetism is a force of nature produced by moving electric charges. Sometimes these motions are microscopic and inside of a material known as magnets. Magnets, or the magnetic fields created by moving electric charges, can attract or repel other magnets, and change the motion of other charged particles.A magnetic field exerts a force on particles known as the Lorentz force, according to Georgia State University's HyperPhysics website. The force acting on an electrically charged particle in a magnetic field depends on the magnitude of the charge, the velocity of the particle, and the strength of the magnetic field. The Lorentz force has the peculiar property that it causes particles to move in right angles to their original motion.Some materials, such as iron, are known as permanent magnets, which means that they can sustain a permanent magnetic field. These are the most common forms of magnets encountered in everyday life. Other materials, such as iron, cobalt and nickel, can be given a temporary magnetic field by placing them inside of a larger, powerful field, but eventually those materials will lose their magnetism.You may like How magnetism worksMagnetic field of Earth. (Image credit: alxpin via Getty Images)Magnetic fields are generated by the motion of electric charges, according to HyperPhysics. Electrons all have a fundamental quantum mechanical property of angular momentum, known as "spin." Inside atoms, most electrons tend to form pairs in which one of them is "spin up" and the other is "spin down," or in other words their angular momenta point in opposite directions. In this case, the magnetic fields created by those spins point in opposite directions, so they cancel each other. However, some atoms contain one or more unpaired electrons, and these unpaired electrons create a tiny magnetic field. The direction of their spin determines the direction of the magnetic field, according to the Non-Destructive Testing (NDT) Resource Center. When a significant majority of unpaired electrons are aligned with their spins in the same direction, they combine to produce a magnetic field that is strong enough to be observed on a macroscopic scale.Magnetic field sources are dipolar, meaning that they have a north and south pole. Opposite poles (N and S) attract, and like poles (N and N, or S and S) repel, according to Joseph Becker of San Jose State University. This creates a toroidal, or doughnut-shaped field, as the direction of the field propagates outward from the north pole and enters through the south pole.Earth itself is a giant magnet. The planet gets its magnetic field from circulating electric current within the molten metallic core, according to NASA. A compass points north because the small magnetic needle in it is suspended so that it can spin freely inside its casing to align itself with Earth's magnetic field. Paradoxically, what we call the Magnetic North Pole is actually a south magnetic pole because it attracts the north magnetic poles of compass needles.History of magnetismMagnetite (also known as lodestone) is the most magnetic of all the naturally-occurring minerals on Earth. (Image credit: Aleksandr Pobedimskiy via Shutterstock)If the alignment of unpaired electrons persists without the application of an external magnetic field or electric current, it produces a permanent magnet. Permanent magnets are the result of ferromagnetism. The prefix "ferro" refers to iron because permanent magnetism was first observed in a form of natural iron ore called magnetite, Fe3O4. Pieces of magnetite can be found scattered on or near the surface of the Earth, and occasionally, one will be magnetized. These naturally occurring magnets are called lodestones. While scientists don't know exactly how lodestones form, "most scientists believe that lodestone is magnetite that has been hit by lightning," according to the University of Arizona.People soon learned that they could magnetize an iron needle by stroking it with a lodestone, causing a majority of the unpaired electrons in the needle to line up in one direction. According to NASA, around A.D. 1000, the Chinese discovered that a magnet floating in a bowl of water always lined up in the north-south direction. Thereafter, the magnetic compass became a tremendous aid to navigation, particularly during the day and on nights when the stars were hidden by clouds.Other metals besides iron can have ferromagnetic properties. These include nickel, cobalt, and some rare earth metals such as samarium or neodymium, which are used to make super-strong permanent magnets.Other forms of magnetismMagnetism takes many other forms, but except for ferromagnetism, they are usually too weak to be observed except by sensitive laboratory instruments or at very low temperatures. Anton Brugnams first discovered diamagnetism in 1778 while using permanent magnets in his search for materials containing iron. According to Gerald Kstler, a widely published independent German researcher and inventor, in his paper, "Diamagnetic Levitation Historical Milestones," published in the Romanian Journal of Technical Sciences, Brugnams observed, "Only the dark and almost violet-colored bismuth displayed a particular phenomenon in the study; for when I laid a piece of it upon a round sheet of paper floating atop water, it was repelled by both poles of the magnet."Diamagnetism is caused by the orbital motion of electrons within atoms creating tiny current loops, which produce weak magnetic fields, according to HyperPhysics. When an external magnetic field is applied to a material, these current loops tend to align in such a way as to oppose the applied field. This causes all materials to be repelled by a permanent magnet; however, the resulting force is usually too weak to be noticeable. There are, however, some notable exceptions.Pyrolytic carbon, a substance similar to graphite, shows even stronger diamagnetism than bismuth, albeit only along one axis, and can actually be levitated above a super-strong rare earth magnet. Certain superconducting materials show even stronger diamagnetism below their critical temperature (the temperature at which they become superconducting) and so rare-earth magnets can be levitated above them. (In theory, because of their mutual repulsion, one can be levitated above the other.)Paramagnetism occurs when a material becomes magnetic temporarily when placed in a magnetic field and reverts to its nonmagnetic state as soon as the external field is removed. When a magnetic field is applied, some of the unpaired electron spins align themselves with the field and overwhelm the opposite force produced by diamagnetism. However, the effect is only noticeable at very low temperatures, said Daniel Marsh, a professor of physics at Missouri Southern State University.Other, more complex, forms include antiferromagnetism, in which the magnetic fields of atoms or molecules align next to each other; and spin glass behavior, which involve both ferromagnetic and antiferromagnetic interactions. Additionally, ferrimagnetism can be thought of as a combination of ferromagnetism and antiferromagnetism due to many similarities shared among them, but it still has its own uniqueness, according to the University of California, Davis.Electricity and magnetismInfographic showing how Fleming's right-hand rule works. (Image credit: fridas via Shutterstock)When a conducting wire is moved in a magnetic field, the field induces a current in the wire. Conversely, a magnetic field is produced by an electric charge in motion, such as when a wire is carrying a current. So all the electric wires in your household produce tiny magnetic fields. This relationship between electricity and magnetism is described by Faraday's Law of Induction, which is the basis for electromagnets, electric motors and generators. A charge moving in a straight line, as through a straight wire, generates a magnetic field that spirals around the wire. When that wire is formed into a loop, the field becomes a doughnut shape, or a torus.Direct current can also produce a constant field in one direction that can be switched on and off with the current. This field can then deflect a movable iron lever causing an audible click. This is the basis for the telegraph, invented in the 1830s by Samuel F. B. Morse, which allowed for long-distance communication over wires using a binary code based on long- and short-duration pulses, according to the Library of Congress. Skilled operators sent the pulses by quickly turning the current on and off using a spring-loaded momentary-contact switch, or key. Another operator on the receiving end would then translate the audible clicks back into letters and words.A coil around a magnet can also be made to move in a pattern of varying frequency and amplitude to induce a current in a coil. This is the basis for a number of devices, most notably, the microphone. Sound causes a diaphragm to move in and out with the varying pressure waves. If the diaphragm is connected to a movable magnetic coil around a magnetic core, it will produce a varying current that is analogous to the incident sound waves. This electrical signal can then be amplified, recorded or transmitted as desired. Tiny super-strong rare-earth magnets are used to make miniaturized microphones for cell phones, Marsh told Live Science.When this modulated electrical signal is applied to a coil, it produces an oscillating magnetic field, which causes the coil to move in and out over a magnetic core in that same pattern. The coil is then attached to a movable speaker cone so it can reproduce audible sound waves in the air. The first practical application for the microphone and speaker was the telephone, patented by Alexander Graham Bell in 1876, according to the Smithsonian Institution. Although this technology has been improved and refined, it is still the basis for recording and reproducing sound.The applications of electromagnets are nearly countless. Faraday's Law of Induction forms the basis for many aspects of our modern society including not only electric motors and generators, but electromagnets of all sizes. The same principle used by a giant crane to lift junk cars at a scrap yard is also used to align microscopic magnetic particles on a computer hard disk drive to store binary data, and new applications are being developed every day.Staff Writer Tanya Lewis contributed to this report.Additional resourcesBibliographyNASA, "Earth's Magnetosphere", Magnetism." DISCovering Science. Gale Research, 1996. Reproduced in Discovering Collection. Farmington Hills, Mich.: Gale Group. December, 2000. David J. (1998). Introduction to Electrodynamics (3rd ed.). Prentice Hall. ISBN 978-0-13-805326-0. OCLC 40251748.Wow! Thats some impressive magic. Hang on, it looks like someone had a magnet in their wand.Title: MagnetismMagnetism is a force we cant see. Something is magnetic if it can pull another magnetic object towards it. Just like these fridge magnets.A magnet attracts or repels things made from certain metals even before they actually touch.When a magnet attracts, it pulls another object towards it. When a magnet repels, it pushes another magnet away.A magnet has opposite ends called a north pole and a south pole. Between the poles is a magnetic force that we cant see. This is a non-contact force. The area around the magnet that is affected by this force is called a magnetic field.These tiny bits of iron make the invisible visible. The metal pieces follow the shape of the magnetic field.If you could see a magnetic field, this is what it would look like.Opposite magnetic poles are attracted to each other. This means the north pole of the magnet pulls towards the south pole of another magnet. Two of the same poles will repel.We use magnets everyday on many things, from the toys you play with, to the things you might find at home, to really big magnets in this scrap metal yard.Not every metal is attracted to a magnet.If you have a magnet, try seeing what objects it will attract or repel.Class of physical phenomena"Magnetic" and "Magnetized" redirect here. For other uses, see Magnetic (disambiguation), Magnetism (disambiguation), and Magnetized (disambiguation).The shape of a bar magnet's magnetic field is revealed by the orientation of iron filings sprinkled on the table around it. ElectromagnetismElectricityMagnetismOpticsHistoryComputationalTextbooksPhenomenaElectrostaticsCharge densityConductorCoulomb lawElectretElectric chargeElectric dipoleElectric fieldElectric fluxElectric potentialElectrostatic dischargeElectrostatic inductionGauss's lawInsulatorPermittivityPolarizationPotential energyStatic electricityTriboelectricityMagnetostaticsAmpre's lawBiotSavart lawGauss's law for magnetismMagnetic dipoleMagnetic fieldMagnetic fluxMagnetic scalar potentialMagnetic vector potentialMagnetizationPermeabilityRight-hand ruleElectrodynamicsBremsstrahlungCyclotron radiationDisplacement currentEddy currentElectromagnetic fieldElectromagnetic inductionElectromagnetic pulseElectromagnetic radiationFaraday's lawJefimenko equationsLarmor formulaLenz's lawLinardWiechert potentialLondon equationsLorentz forceMaxwell's equationsMaxwell tensorPoynting vectorSynchrotron radiationElectrical networkAlternating currentCapacitanceCurrent densityDirect currentElectric currentElectric powerElectrolysisElectromotive forceImpedanceInductanceJoule heatingKirchhoff's lawsNetwork analysisOhm's lawParallel circuitResistanceResonant cavitiesSeries circuitVoltageWattWaveguidesMagnetic circuitAC motorDC motorElectric machineElectric motorGyratorcapacitorInduction motorLinear motorMagnetomotive forcePermeanceReluctance (complex)Reluctance (real)RotorStatorTransformerCovariant formulationElectromagnetic tensorElectromagnetism and special relativityFour-currentFour-potentialMathematical descriptionsMaxwell equations in curved spacetimeRelativistic electromagnetismStressenergy tensorScientistsAmpreBiotCoulombDavyEinsteinFaradayFizeauGaussHeavisideHelmholtzHenryHertzHopkinsonJefimenkoJouleKelvinKirchhoffLarmorLenzLinardLorentzMaxwellNeumannOhmrstedPoissonPoyntingRitchieSavartSingerSteinmetzTeslaThomsonVoltaWeberWiechertvteMagnetism is the class of physical attributes that occur through a magnetic field, which allows objects to attract or repel each other. Because both electric currents and magnetic moments of elementary particles give rise to a magnetic field, magnetism is one of two aspects of electromagnetism.The most familiar effects occur in ferromagnetic materials, which are strongly attracted by magnetic fields and can be magnetized to become permanent magnets, producing magnetic fields themselves. Demagnetizing a magnet is also possible. Only a few substances are ferromagnetic; the most common ones are iron, cobalt, nickel, and their alloys.All substances exhibit some type of magnetism. Magnetic materials are classified according to their bulk susceptibility.[1] Ferromagnetism is responsible for most of the effects of magnetism encountered in everyday life, but there are actually several types of magnetism. Paramagnetic substances, such as aluminium and oxygen, are weakly attracted to an applied magnetic field; diamagnetic substances, such as copper and carbon, are weakly repelled; while antiferromagnetic materials, such as chromium, have a more complex relationship with a magnetic field.[vague] The force of a magnet on paramagnetic, diamagnetic, and antiferromagnetic materials is usually too weak to be felt and can be detected only by laboratory instruments, so in everyday life, these substances are often described as non-magnetic.The strength of a magnetic field always decreases with distance from the magnetic source,[2] though the exact mathematical relationship between strength and distance varies. Many factors can influence the magnetic field of an object including the magnetic moment of the material, the physical shape of the object, both the magnitude and direction of any electric current present within the object, and the temperature of the object.Main article: History of electromagnetic theoryThis section needs additional citations for verification. Please help improve this article by adding citations to reliable sources in this section. Unsourced material may be challenged and removed. (October 2024) (Learn how and when to remove this message)Lodestone, a natural magnet, attracting iron nails. Ancient humans discovered the property of magnetism from lodestone.An illustration from Gilbert's 1600 De Magnete showing one of the earliest methods of making a magnet. A blacksmith holds a piece of red-hot iron in a northsouth direction and hammers it as it cools. The magnetic field of the Earth aligns the domains, leaving the iron a weak magnet.Drawing of a medical treatment using magnetic brushes. Charles Jacque 1843, France.Magnetism was first discovered in the ancient world when people noticed that lodestones, naturally magnetized pieces of the mineral magnetite, could attract iron.[3] The word magnet comes from the Greek term magntis lithos,[4] "the Magnesian stone, lodestone".[5] In ancient Greece, Aristotle attributed the first of what could be called a scientific discussion of magnetism to the philosopher Thales of Miletus, who lived from about 625BCE to about 545BCE.[6] The ancient Indian medical text Sushruta Samhita describes using magnetite to remove arrows embedded in a person's body.[7]In ancient China, the earliest literary reference to magnetism lies in a 4th-century BCE book named after its author, Guiguzi.[8]The 2nd-century BCE annals, Lshi Chunqiu, also notes:"The lodestone makes iron approach; some (force) is attracting it."[9] The earliest mention of the attraction of a needle is in a 1st-century work Lunheng (Balanced Inquiries): "A lodestone attracts a needle."[10] The 11th-century Chinese scientist Shen Kuo was the first person to writein the Dream Pool Essaysof the magnetic needle compass and that it improved the accuracy of navigation by employing the astronomical concept of true north.By the 12th century, the Chinese were known to use the lodestone compass for navigation. They sculpted a directional spoon from lodestone in such a way that the handle of the spoon always pointed south.Alexander Neckam, by 1187, was the first in Europe to describe the compass and its use for navigation. In 1269, Peter Peregrinus de Maricourt wrote the Epistola de magnete, the first extant treatise describing the properties of magnets. In 1282, the properties of magnets and the dry compasses were discussed by Al-Ashraf Umar II, a Yemeni physicist, astronomer, and geographer.[11]Leonardo Garzoni's only extant work, the Due trattati sopra la natura, e le qualit della calamita (Two treatises on the nature and qualities of the magnet), is the first known example of a modern treatment of magnetic phenomena. Written in years near 1580 and never published, the treatise had a wide diffusion. In particular, Garzoni is referred to as an expert in magnetism by Niccol Cabeo, whose Philosophia Magnetica (1629) is just a re-adjustment of Garzoni's work. Garzoni's treatise was known also to Giovanni Battista Della Porta.In 1600, William Gilbert published his De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure (On the Magnet and Magnetic Bodies, and on the Great Magnet the Earth). In this work he describes many of his experiments with his model earth called the terrella. From his experiments, he concluded that the Earth was itself magnetic and that this was the reason compasses pointed north whereas, previously, some believed that it was the pole star Polaris or a large magnetic island on the north pole that attracted the compass.An understanding of the relationship between electricity and magnetism began in 1819 with work by Hans Christian rsted, a professor at the University of Copenhagen, who discovered, by the accidental twitching of a compass needle near a wire, that an electric current could create a magnetic field. This landmark experiment is known as rsted's Experiment. Jean-Baptiste Biot and Flix Savart, both of whom in 1820 came up with the BiotSavart law giving an equation for the magnetic field from a current-carrying wire. Around the same time, Andr-Marie Ampre carried out numerous systematic experiments and discovered that the magnetic force between two DC current loops of any shape is equal to the sum of the individual forces that each current element of one circuit exerts on each other current element of the other circuit.In 1831, Michael Faraday discovered that a time-varying magnetic flux induces a voltage through a wire loop. In 1835, Carl Friedrich Gauss hypothesized, based on Ampre's force law in its original form, that all forms of magnetism arise as a result of elementary point charges moving relative to each other.[12] Wilhelm Eduard Weber advanced Gauss's theory to Weber electrodynamics. From around 1861, James Clerk Maxwell synthesized and expanded many of these insights into Maxwell's equations, unifying electricity, magnetism, and optics into the field of electromagnetism. However, Gauss's interpretation of magnetism is not fully compatible with Maxwell's electrodynamics. In 1905, Albert Einstein used Maxwell's equations in motivating his theory of special relativity,[13] requiring that the laws held true in all inertial reference frames. Gauss's approach of interpreting the magnetic force as a mere effect of relative velocities thus found its way back into electrodynamics to some extent.Electromagnetism has continued to develop into the 21st century, being incorporated into the more fundamental theories of gauge theory, quantum electrodynamics, electroweak theory, and finally the standard model.See also: Magnetic momentMagnetism, at its root, arises from three sources:Electric currentSpin magnetic moments of elementary particlesChanging electric fieldsThe magnetic properties of materials are mainly due to the magnetic moments of their atoms' orbiting electrons. The magnetic moments of the nuclei of atoms are typically thousands of times smaller than the electrons' magnetic moments, so they are negligible in the context of the magnetization of materials. Nuclear magnetic moments are nevertheless very important in other contexts, particularly in nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI).Ordinarily, the enormous number of electrons in a material are arranged such that their magnetic moments (both orbital and intrinsic) cancel out. This is due, to some extent, to electrons combining into pairs with opposite intrinsic magnetic moments as a result of the Pauli exclusion principle (see electron configuration), and combining into filled subshells with zero net orbital motion. In both cases, the electrons preferentially adopt arrangements in which the magnetic moment of each electron is canceled by the opposite moment of another electron. Moreover, even when the electron configuration is such that there are unpaired electrons and/or non-filled subshells, it is often the case that the various electrons in the solid will contribute magnetic moments that point in different, random directions so that the material will not be magnetic.Sometimeseither spontaneously, or owing to an applied external magnetic fieldeach of the electron magnetic moments will be, on average, lined up. A suitable material can then produce a strong net magnetic field.The magnetic behavior of a material depends on its structure, particularly its electron configuration, for the reasons mentioned above, and also on the temperature. At high temperatures, random thermal motion makes it more difficult for the electrons to maintain alignment.Hierarchy of types of magnetism.[14]Main article: DiamagnetismDiamagnetism appears in all materials and is the tendency of a material to oppose an applied magnetic field, and therefore, to be repelled by a magnetic field. However, in a material with paramagnetic properties (that is, with a tendency to enhance an external magnetic field), the paramagnetic behavior dominates.[15] Thus, despite its universal occurrence, diamagnetic behavior is observed only in a purely diamagnetic material. In a diamagnetic material, there are no unpaired electrons, so the intrinsic electron magnetic moments cannot produce any bulk effect. In these cases, the magnetization arises from the electrons' orbital motions, which can be understood classically as follows:When a material is put in a magnetic field, the electrons circling the nucleus will experience, in addition to their Coulomb attraction to the nucleus, a Lorentz force from the magnetic field. Depending on which direction the electron is orbiting, this force may increase the centripetal force on the electrons, pulling them in towards the nucleus, or it may decrease the force, pulling them away from the nucleus. This effect systematically increases the orbital magnetic moments that were aligned opposite the field and decreases the ones aligned parallel to the field (in accordance with Lenz's law). This results in a small bulk magnetic moment, with an opposite direction to the applied field.This description is meant only as a heuristic; the BohrVan Leeuwen theorem shows that diamagnetism is impossible according to classical physics, and that a proper understanding requires a quantum-mechanical description.All materials undergo this orbital response. However, in paramagnetic and ferromagnetic substances, the diamagnetic effect is overwhelmed by the much stronger effects caused by the unpaired electrons.Main article: ParamagnetismIn a paramagnetic material there are unpaired electrons; i.e., atomic or molecular orbitals with exactly one electron in them. While paired electrons are required by the Pauli exclusion principle to have their intrinsic ('spin') magnetic moments pointing in opposite directions, causing their magnetic fields to cancel out, an unpaired electron is free to align its magnetic moment in any direction. When an external magnetic field is applied, these magnetic moments will tend to align themselves in the same direction as the applied field, thus reinforcing it.Main article: FerromagnetismA ferromagnet, like a paramagnetic substance, has unpaired electrons. However, in addition to the electrons' intrinsic magnetic moment's tendency to be parallel to an applied field, there is also in these materials a tendency for these magnetic moments to orient parallel to each other to maintain a lowered-energy state. Thus, even in the absence of an applied field, the magnetic moments of the electrons in the material spontaneously line up parallel to one another.Every ferromagnetic substance has its own individual temperature, called the Curie temperature, or Curie point, above which it loses its ferromagnetic properties. This is because the thermal tendency to disorder overwhelms the energy-lowering due to ferromagnetic order.Ferromagnetism only occurs in a few substances; common ones are iron, nickel, cobalt, their alloys, and some alloys of rare-earth metals.Main article: Magnetic domainsMagnetic domains boundaries (white lines) in ferromagnetic material (black rectangle)Effect of a magnet on the domainsThe magnetic moments of atoms in a ferromagnetic material cause them to behave something like tiny permanent magnets. They stick together and align themselves into small regions of more or less uniform alignment called magnetic domains or Weiss domains. Magnetic domains can be observed with a magnetic force microscope to reveal magnetic domain boundaries that resemble white lines in the sketch. There are many scientific experiments that can physically show magnetic fields.When a domain contains too many molecules, it becomes unstable and divides into two domains aligned in opposite directions so that they stick together more stably.When exposed to a magnetic field, the domain boundaries move, so that the domains aligned with the magnetic field grow and dominate the structure (dotted yellow area), as shown at the left. When the magnetizing field is removed, the domains may not return to an unmagnetized state. This results in the ferromagnetic material's being magnetized, forming a permanent magnet.When magnetized strongly enough that the prevailing domain overruns all others to result in only one single domain, the material is magnetically saturated. When a magnetized ferromagnetic material is heated to the Curie point temperature, the molecules are agitated to the point that the magnetic domains lose the organization, and the magnetic properties they cause cease. When the material is cooled, this domain alignment structure spontaneously returns, in a manner roughly analogous to how a liquid can freeze into a crystalline solid.Antiferromagnetic orderingMain article: AntiferromagnetismIn an antiferromagnet, unlike a ferromagnet, there is a tendency for the intrinsic magnetic moments of neighboring valence electrons to point in opposite directions. When all atoms are arranged in a substance so that each neighbor is anti-parallel, the substance is antiferromagnetic. Antiferromagnets have a zero net magnetic moment because adjacent opposite moment cancels out, meaning that no field is produced by them. Antiferromagnets are less common compared to the other types of behaviors and are mostly observed at low temperatures. In varying temperatures, antiferromagnets can be seen to exhibit diamagnetic and ferromagnetic properties.In some materials, neighboring electrons prefer to point in opposite directions, but there is no geometrical arrangement in which each pair of neighbors is anti-aligned. This is called a canted antiferromagnet or spin ice and is an example of geometrical frustration.Ferrimagnetic orderingMain article: FerrimagnetismLike ferromagnetism, ferrimagnets retain their magnetization in the absence of a field. However, like antiferromagnets, neighboring pairs of electron spins tend to point in opposite directions. These two properties are not contradictory, because in the optimal geometrical arrangement, there is more magnetic moment from the sublattice of electrons that point in one direction, than from the sublattice that points in the opposite direction.Most ferrites are ferrimagnetic. The first discovered magnetic substance, magnetite, is a ferrite and was originally believed to be a ferromagnet; Louis Nel disproved this, however, after discovering ferrimagnetism.Magnetic orders: comparison between ferro, antiferro and ferrimagnetismMain article: SuperparamagnetismWhen a ferromagnet or ferrimagnet is sufficiently small, it acts like a single magnetic spin that is subject to Brownian motion. Its response to a magnetic field is qualitatively similar to the response of a paramagnet, but much larger.Japanese physicist Yosuke Nagaoka conceived of a type of magnetism in a square, two-dimensional lattice where every lattice node had one electron. If one electron was removed under specific conditions, the lattice's energy would be minimal only when all electrons' spins were parallel.A variation on this was achieved experimentally by arranging the atoms in a triangular moir lattice of molybdenum diselenide and tungsten disulfide monolayers. Applying a weak magnetic field and a voltage led to ferromagnetic behavior when 100150% more electrons than lattice nodes were present. The extra electrons delocalized and paired with lattice electrons to form doublons. Delocalization was prevented unless the lattice electrons had aligned spins. The doublons thus created localized ferromagnetic regions. The phenomenon took place at 140 millikelvins.[16]MetamagnetismMolecule-based magnetsSingle-molecule magnetAmorphous magnetAn electromagnet attracts paper clips when current is applied, creating a magnetic field. The electromagnet loses them when current and magnetic field are removed.An electromagnet is a type of magnet in which the magnetic field is produced by an electric current.[17] The magnetic field disappears when the current is turned off. Electromagnets usually consist of a large number of closely spaced turns of wire that create the magnetic field. The wire turns are often wound around a magnetic core made from a ferromagnetic or ferrimagnetic material such as iron; the magnetic core concentrates the magnetic flux and makes a more powerful magnet.The main advantage of an electromagnet over a permanent magnet is that the magnetic field can be quickly changed by controlling the amount of electric current in the winding. However, unlike a permanent magnet that needs no power, an electromagnet requires a continuous supply of current to maintain the magnetic field.Electromagnets are widely used as components of other electrical devices, such as motors, generators, relays, solenoids, loudspeakers, hard disks, MRI machines, scientific instruments, and magnetic separation equipment. Electromagnets are also employed in industry for picking up and moving heavy iron objects such as scrap iron and steel.[18] Electromagnetism was discovered in 1820.[19]Main article: Classical electromagnetism and special relativityAs a consequence of Einstein's theory of special relativity, electricity and magnetism are fundamentally interlinked. Both magnetism lacking electricity, and electricity without magnetism, are inconsistent with special relativity, due to such effects as length contraction, time dilation, and the fact that the magnetic force is velocity-dependent. However, when both electricity and magnetism are taken into account, the resulting theory (electromagnetism) is fully consistent with special relativity.[13][20] In particular, a phenomenon that appears purely electric or purely magnetic to one observer may be a mix of both to another, or more generally the relative contributions of electricity and magnetism are dependent on the frame of reference. Thus, special relativity "mixes" electricity and magnetism into a single, inseparable phenomenon called electromagnetism, analogous to how general relativity "mixes" space and time into spacetime.All observations on electromagnetism apply to what might be considered to be primarily magnetism, e.g. perturbations in the magnetic field are necessarily accompanied by a nonzero electric field, and propagate at the speed of light.[21]See also: Magnetic field H and B inside and outside of magnetic materialsIn vacuum, B = 0 H , {\displaystyle \mathbf {B} \ =\ \mu _{0}\mathbf {H} ,} where 0 is the vacuum permeability.In a material, B = 0 (H + M) . {\displaystyle \mathbf {B} \ =\ \mu _{0}(\mathbf {H} +\mathbf {M}).\ } The quantity 0M is called magnetic polarization.If the field H is small, the response of the magnetization M in a diamagnet or paramagnet is approximately linear: M = H , {\displaystyle \mathbf {M} =\chi \mathbf {H} ,} the constant of proportionality being called the magnetic susceptibility. If so, 0 (H + M) = 0 (1 +) H = r 0 H = H . {\displaystyle \mu _{0}(\mathbf {H} +\mathbf {M})\ =\ \mu _{0}(1+\chi)\mathbf {H} \ =\ \mu _{r}\mu _{0}\mathbf {H} \ =\ \mu \mathbf {H} .} In a hard magnet such as a ferromagnet, M is not proportional to the field and is generally nonzero even when H is zero (see Remanence).Magnetic lines of force of a bar magnet shown by iron filings on paperDetecting magnetic field with compass and with iron filingsMain article: Magnetic fieldThe phenomenon of magnetism is "mediated" by the magnetic field. An electric current or magnetic dipole creates a magnetic field, and that field, in turn, imparts magnetic forces on other particles that are in the fields.Maxwell's equations, which simplify to the BiotSavart law in the case of steady currents, describe the origin and behavior of the fields that govern these forces. Therefore, magnetism is seen whenever electrically charged particles are in motionfor example, from movement of electrons in an electric current, or in certain cases from the orbital motion of electrons around an atom's nucleus. They also arise from "intrinsic" magnetic dipoles arising from quantum-mechanical spin.The same situations that create magnetic fieldscharge moving in a current or in an atom, and intrinsic magnetic dipolesare also the situations in which a magnetic field has an effect, creating a force. Following is the formula for moving charge; for the forces on an intrinsic dipole, see magnetic dipole.When a charged particle moves through a magnetic field B, it feels a Lorentz force F given by the cross product:[22] q F = q (v B) , {\displaystyle q\mathbf {F} =q(\mathbf {v} \times \mathbf {B}),} where q {\displaystyle q} is the electric charge of the particle, and v {\displaystyle v} is the velocity vector of the particle.Because this is a cross product, the force is perpendicular to both the motion of the particle and the magnetic field. The magnitude of the force is q F = q v B sin , {\displaystyle qF=qvB\sin \theta \ ,} where {\displaystyle \theta } is the angle between v and B.One tool for determining the direction of the velocity vector of a moving charge, the magnetic field, and the force exerted is labeling the index finger "V"[dubious discuss], the middle finger "B", and the thumb "F" with your right hand. When making a gun-like configuration, with the middle finger crossing under the index finger, the fingers represent the velocity vector, magnetic field vector, and force vector, respectively. See also right-hand rule.Main article: Magnetic dipoleA very common source of magnetic field found in nature is a dipole, with a "South pole" and a "North pole", terms dating back to the use of magnets as compasses, interacting with the Earth's magnetic field to indicate North and South on the globe. Since opposite ends of magnets are attracted, the north pole of a magnet is attracted to the south pole of another magnet. The Earth's North Magnetic Pole (currently in the Arctic Ocean, north of Canada) is physically a south pole, as it attracts the north pole of a compass.A magnetic field contains energy, and physical systems move toward configurations with lower energy. When diamagnetic material is placed in a magnetic field, a magnetic dipole tends to align itself in opposed polarity to that field, thereby lowering the net field strength. When ferromagnetic material is placed within a magnetic field, the magnetic dipoles align to the applied field, thus expanding the domain walls of the magnetic domains.Main article: Magnetic monopoleSince a bar magnet gets its ferromagnetism from electrons distributed evenly throughout the bar, when a bar magnet is cut in half, each of the resulting pieces is a smaller bar magnet. Even though a magnet is said to have a north pole and a south pole, these two poles cannot be separated from each other. A monopoleif such a thing existswould be a new and fundamentally different kind of magnetic object. It would act as an isolated north pole, not attached to a south pole, or vice versa. Monopoles would carry "magnetic charge" analogous to electric charge. Despite systematic searches since 1931, as of 2010[update], they have never been observed, and could very well not exist.[23]Nevertheless, some theoretical physics models predict the existence of these magnetic monopoles. Paul Dirac observed in 1931 that, because electricity and magnetism show a certain symmetry, just as quantum theory predicts that individual positive or negative electric charges can be observed without the opposing charge, isolated South or North magnetic poles should be observable. Using quantum theory Dirac showed that if magnetic monopoles exist, then one could explain the quantization of electric chargethat is, why the observed elementary particles carry charges that are multiples of the charge of the electron.Certain grand unified theories predict the existence of monopoles which, unlike elementary particles, are solitons (localized energy packets). The initial results of using these models to estimate the number of monopoles created in the Big Bang contradicted cosmological observationsthe monopoles would have been so plentiful and massive that they would have long since halted the expansion of the universe. However, the idea of inflation (for which this problem served as a partial motivation) was successful in solving this problem, creating models in which monopoles existed but were rare enough to be consistent with current observations.[24]SI electromagnetism unitsvteSymbol[25]Name of quantityUnit nameSymbolBase unitsEenergyjouleJ = CV = Wskgm2s2Qelectric chargecoulombCAsIelectric currentampereA = C/s = W/VAJelectric current densityampere per square metreA/m2Am2U, V; ; E, potential difference; voltage; electromotive forcevoltV = J/Ckgm2s3A1R; Z; Xelectric resistance; impedance; reactanceohm = V/Akgm2s3A2resistivityohm metremkgm3s3A2Pelectric powerwattW = VAkgm2s3CcapacitancefaradF = C/Vkg1m2A2s4Eelectric fluxvolt metreVmkgm3s3A1Eelectric field strengthvolt per metreV/m = N/CkgmA1s3Delectric displacement fieldcoulomb per square metreC/m2Asm2permittivityfarad per metreF/mkg1m3A2s4eelectric susceptibility(dimensionless)11pelectric dipole momentcoulomb metreCmAsmG; Y; Bconductance; admittance; susceptancesiemensS = 1kg1m2s3A2, , conductivitysiemens per metreS/mkg1m3s3A2Bmagnetic flux density, magnetic inductionteslaT = Wb/m2 = NA1m1kgs2A1, M, Bmagnetic flux weberWb = Vskgm2s2A1Hmagnetic field strengthampere per metreA/mAm1Fmagnetomotive forceampereA = Wb/HARmagnetic reluctanceinverse henryH1 = A/Wbkg1m2s2A2Pmagnetic permeancehenryH = Wb/Akgm2s2A2L, MinductancehenryH = Wb/A = Vs/Akgm2s2A2permeabilityhenry per metreH/mkgms2A2magnetic susceptibility(dimensionless)11mmagnetic dipole momentampere square meterAm2 = JT1Am2mass magnetizationampere square meter per kilogramAm2/kgAm2kg1gauss the centimeter-gram-second (CGS) unit of magnetic field (denoted B).oersted the CGS unit of magnetizing field (denoted H)maxwell the CGS unit for magnetic fluxgamma a unit of magnetic flux density that was commonly used before the tesla came into use (1.0 gamma = 1.0 nanotesla)0 common symbol for the permeability of free space (4 107 newton/(ampere-turn)2)A live frog levitates inside a 32 mm diameter vertical bore of a Bitter solenoid in a very strong magnetic fieldabout 16 teslasSome organisms can detect magnetic fields, a phenomenon known as magnetoception. Some materials in living things are ferromagnetic, though it is unclear if the magnetic properties serve a special function or are merely a byproduct of containing iron. For instance, chitons, a type of marine mollusk, produce magnetite to harden their teeth, and even humans produce magnetite in bodily tissue.[26] Magnetobiology studies the effects of magnetic fields on living organisms; fields naturally produced by an organism are known as biomagnetism. Many biological organisms are mostly made of water, and because water is diamagnetic, extremely strong magnetic fields can repel these living things.In the years after 1820, Andr-Marie Ampre carried out numerous experiments in which he measured the forces between direct currents. In particular, he also studied the magnetic forces between non-parallel wires.[27] The final result of his work was a force law that is now named after him. In 1835, Carl Friedrich Gauss realized [12] that Ampere's force law in its original form can be explained by a generalization of Coulomb's law. Gauss's force law states that the electromagnetic force F 1 {\textstyle \mathbf {F} _{1}} experienced by a point charge, q 1 {\displaystyle q_{1}} with trajectory r 1 (t) {\displaystyle \mathbf {r} _{1}(t)} , in the vicinity of another point charge, q 2 {\displaystyle q_{2}} with trajectory r 2 (t) {\displaystyle \mathbf {r} _{2}(t)} , in a vacuum is equal to the central force F 1 = q 1 q 2 4 0 r | r | 3 (1 + | v | 2 c 2 3 2 (r | r | v c) 2) {\displaystyle \mathbf {F} _{1}={\frac {q_{1}\,q_{2}}{4\,\pi \,\epsilon _{0}}}\,{\frac {\mathbf {r} }{|\mathbf {r} |^{3}}}\,\left(1+{\frac {|\mathbf {v} |^{2}}{c^{2}}}-{\frac {3}{2}}\,\left({\frac {\mathbf {r} }{|\mathbf {r} |}}\cdot {\frac {\mathbf {v} }{c}}\right)^{2}\right)} ,where r = r 1 (t) r 2 (t) {\textstyle \mathbf {r} =\mathbf {r} _{1}(t)-\mathbf {r} _{2}(t)} is the distance between the charges and v = r 1 (t) r 2 (t) {\textstyle \mathbf {v} ={\dot {\mathbf {r} }}_{1}(t)-{\dot {\mathbf {r} }}_{2}(t)} is the relative velocity. Wilhelm Eduard Weber confirmed Gauss's hypothesis in numerous experiments.[28][29][30] By means of Weber electrodynamics it is possible to explain the static and quasi-static effects in the non-relativistic regime of classical electrodynamics without magnetic field and Lorentz force.Since 1870, Maxwell electrodynamics has been developed, which postulates that electric and magnetic fields exist. In Maxwell's electrodynamics, the actual electromagnetic force can be calculated using the Lorentz force, which, like the Weber force, is speed-dependent. However, Maxwell's electrodynamics is not fully compatible with the work of Ampre, Gauss and Weber in the quasi-static regime. In particular, Ampre's original force law and the Biot-Savart law are only equivalent if the field-generating conductor loop is closed.[31] Maxwell's electrodynamics therefore represents a break with the interpretation of magnetism by Gauss and Weber, since in Maxwell's electrodynamics it is no longer possible to deduce the magnetic force from a central force.While heuristic explanations based on classical physics can be formulated, diamagnetism, paramagnetism and ferromagnetism can be fully explained only using quantum theory.[32][33]A successful model was developed already in 1927, by Walter Heitler and Fritz London, who derived, quantum-mechanically, how hydrogen molecules are formed from hydrogen atoms, i.e. from the atomic hydrogen orbitals u A {\displaystyle u_{A}} and u B {\displaystyle u_{B}} centered at the nuclei A and B, see below. That this leads to magnetism is not at all obvious, but will be explained in the following.According to the HeitlerLondon theory, so-called two-body molecular {\displaystyle \sigma } -orbitals are formed, namely the resulting orbital is: (r 1 , r 2) = 1 2 (u A (r 1) u B (r 2) + u B (r 1) u A (r 2)) {\displaystyle \psi (\mathbf {r} _{1},\,\,\mathbf {r} _{2})={\frac {1}{\sqrt {2}}}\,\,\left(u_{A}(\mathbf {r} _{1})u_{B}(\mathbf {r} _{2})+u_{B}(\mathbf {r} _{1})u_{A}(\mathbf {r} _{2})\right)} Here the last product means that a first electron, r1, is in an atomic hydrogen-orbital centered at the second nucleus, whereas the second electron runs around the first nucleus. This "exchange" phenomenon is an expression for the quantum-mechanical property that particles with identical properties cannot be distinguished. It is specific not only for the formation of chemical bonds, but also for magnetism. That is, in this connection the term exchange interaction arises, a term which is essential for the origin of magnetism, and which is stronger, roughly by factors 100 and even by 1000, than the energies arising from the electrodynamic dipole-dipole interaction.As for the spin function (s 1 , s 2) {\displaystyle \chi (s_{1},s_{2})} , which is responsible for the magnetism, we have the already mentioned Pauli's principle, namely that a symmetric orbital (i.e. with the + sign as above) must be multiplied with an antisymmetric spin function (i.e. with a sign), and vice versa. Thus: (s 1 , s 2) = 1 2 ((s 1) (s 2) (s 1) (s 2)) {\displaystyle \chi (s_{1},\,\,s_{2})={\frac {1}{\sqrt {2}}}\,\,\left(\alpha (s_{1})\beta (s_{2})-\beta (s_{1})\alpha (s_{2})\right)} ,I.e., not only u A {\displaystyle u_{A}} and u B {\displaystyle u_{B}} must be substituted by and , respectively (the first entity means "spin up", the second one "spin down"), but also the sign + by the sign, and finally ri by the discrete values si (=12); thereby we have (+ 1 / 2) = (1 / 2) = 1 {\displaystyle \alpha (+1/2)=\beta (-1/2)=1} and (1 / 2) = (+ 1 / 2) = 0 {\displaystyle \alpha (-1/2)=\beta (+1/2)=0} . The "singlet state", i.e. the sign, means: the spins are antiparallel, i.e. for the solid we have antiferromagnetism, and for two-atomic molecules one has diamagnetism. The tendency to form a (homoeopolar) chemical bond (this means: the formation of a symmetric molecular orbital, i.e. with the + sign) results through the Pauli principle automatically in an antisymmetric spin state (i.e. with the sign). In contrast, the Coulomb repulsion of the electrons, i.e. the tendency that they try to avoid each other by this repulsion, would lead to an antisymmetric orbital function (i.e. with the sign) of these two particles, and complementary to a symmetric spin function (i.e. with the + sign, one of the so-called "triplet functions"). Thus, now the spins would be parallel (ferromagnetism in a solid, paramagnetism in two-atomic gases).The last-mentioned tendency dominates in the metals iron, cobalt and nickel, and in some rare earths, which are ferromagnetic. Most of the other metals, where the first-mentioned tendency dominates, are nonmagnetic (e.g. sodium, aluminium, and magnesium) or antiferromagnetic (e.g. manganese). Diatomic gases are also almost exclusively diamagnetic, and not paramagnetic. However, the oxygen molecule, because of the involvement of -orbitals, is an exception important for the life-sciences.The Heitler-London considerations can be generalized to the Heisenberg model of magnetism (Heisenberg 1928).The explanation of the phenomena is thus essentially based on all subtleties of quantum mechanics, whereas the electrodynamics covers mainly the phenomenology.CoercivityGravitomagnetismMagnetic hysteresisMagnetarMagnetic bearingMagnetic circuitMagnetic coolingMagnetic field viewing filmMagnetic stirrerSwitched-mode power supplyMagnetic structureMicromagnetismNeodymium magnetPlastic magnetRare-earth magnetSpin waveSpontaneous magnetizationVibrating-sample magnetometerTextbooks in electromagnetism^ Jiles, David (2 September 2015). Introduction to magnetism and magnetic materials (Thirded.). Boca Raton. ISBN978-1-4822-3887-7. 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ISBN978-1108717519.Magnetism at Wikipedia's sister projectsDefinitions from WiktionaryMedia from CommonsQuotations from WikiquoteTexts from WikisourceTextbooks from WikibooksResources from WikiversityData from WikidataThe Exploratorium Science Snacks Subject:Physics/Electricity & MagnetismA collection of magnetic structures MAGNDATARetrieved from " MIT physicists have demonstrated a new form of magnetism that could one day be harnessed to build faster, denser, and less power-hungry spintronic memory chips.The new magnetic state is a mash-up of two main forms of magnetism: the ferromagnetism of everyday fridge magnets and compass needles, and antiferromagnetism, in which materials have magnetic properties at the microscale yet are not macroscopically magnetized.Now, the MIT team has demonstrated a new form of magnetism, termed p-wave magnetism.Physicists have long observed that electrons of atoms in regular ferromagnets share the same orientation of spin, like so many tiny compasses pointing in the same direction. This spin alignment generates a magnetic field, which gives a ferromagnet its inherent magnetism. Electrons belonging to magnetic atoms in an antiferromagnet also have spin, although these spins alternate, with electrons orbiting neighboring atoms aligning their spins antiparallel to each other. Taken together, the equal and opposite spins cancel out, and the antiferromagnet does not exhibit macroscopic magnetization.The team discovered the new p-wave magnetism in nickel iodide (NiI2), a two-dimensional crystalline material that they synthesized in the lab. Like a ferromagnet, the electrons exhibit a preferred spin orientation, and,like an antiferromagnet, equal populations of opposite spins result in a net cancellation.However, thespins on thenickel atoms exhibit a unique pattern, forming spiral-like configurations within the material that are mirror-images of each other, much like the left hand is the right hands mirror image.Whats more, the researchers found this spiral spin configuration enabled them to carry out spin switching: Depending on the direction of spiralingspins in the material, they could apply a small electric field in a related direction to easily flip a left-handed spiral of spins into a right-handed spiral of spins, and vice-versa.The ability to switch electron spins is at the heart of spintronics, which is a proposed alternative to conventional electronics. With this approach, data can be written in the form of an electrons spin, rather than its electronic charge, potentially allowing orders of magnitude more data to be packed onto a device while using far less power to write and read that data. We showed that this new form of magnetism can be manipulated electrically, says Qian Song, a research scientist in MITs Materials Research Laboratory. This breakthrough paves the way for a new class of ultrafast, compact, energy-efficient, and nonvolatile magnetic memory devices.Song and his colleagues published their results May 28 in the journal Nature. MIT co-authors include Connor Occhialini, Batyr Ilyas, Emre Ergeen, Nuh Gedik, and Riccardo Comin, along with Rafael Fernandes at the University of Illinois Urbana-Champaign, and collaborators from multiple other institutions.Connecting the dotsThe discovery expands on work by Comins group in 2022. At that time, the team probed the magnetic properties of the same material, nickel iodide. At the microscopic level, nickel iodide resembles a triangular lattice of nickel and iodine atoms. Nickel is the materials main magnetic ingredient, as the electrons on the nickel atoms exhibit spin, while those on iodine atoms do not.In those experiments, the team observed that the spins of those nickel atoms were arranged in a spiral pattern throughout the materials lattice, and that this pattern could spiral in two different orientations.At the time, Comin had no idea that this unique pattern of atomic spins could enable precise switching of spins in surrounding electrons. This possibility was later raised by collaborator Rafael Fernandes, who along with other theorists was intrigued by a recently proposed idea for a new, unconventional, p-wave magnet, in which electrons moving along opposite directions in the material would have their spins aligned in opposite directions.Fernandes and his colleagues recognized that if the spins of atoms in a material form the geometric spiral arrangement that Comin observed in nickel iodide, that would be a realization of a p-wave magnet. Then, when an electric field is applied to switch the handedness of the spiral, it should also switch the spin alignment of the electrons traveling along the same direction.In other words, such a p-wave magnet could enable simple and controllable switching of electron spins, in a way that could be harnessed for spintronic applications.It was a completely new idea at the time, and we decided to test it experimentally because we realized nickel iodide was a good candidate to show this kind of p-wave magnet effect, Comin says.Spin currentFor their new study, the team synthesized single-crystal flakes of nickel iodide by first depositing powders of the respective elements on a crystalline substrate, which they placed in a high-temperature furnace. The process causes the elements to settle into layers, each arranged microscopically in a triangular lattice of nickel and iodine atoms.What comes out of the oven are samples that are several millimeters wide and thin, like cracker bread, Comin says. We then exfoliate the material, peeling off even smaller flakes, each several microns wide, and a few tens of nanometers thin.The researchers wanted to know if, indeed, the spiral geometry of the nickel atomss spins would force electrons traveling in opposite directions to have opposite spins, like what Fernandes expected a p-wave magnet should exhibit. To observe this, the group applied to each flake a beam of circularly polarized light light that produces an electric field that rotates in a particular direction, for instance, either clockwise or counterclockwise.They reasoned that if travelling electrons interacting with the spin spirals have a spin that is aligned in the same direction, then incoming light, polarized in that same direction, should resonate and produce a characteristic signal. Such a signal would confirm that the traveling electrons spins align because of the spiral configuration, and furthermore, that the material does in fact exhibit p-wave magnetism.And indeed, thats what the group found. In experiments with multiple nickel iodide flakes, the researchers directly observed that the direction of the electrons spin was correlated to the handedness of the light used to excite those electrons. Such is a telltale signature of p-wave magnetism, here observed for the first time.Going a step further, they looked to see whether they could switch the spins of the electrons by applying an electric field, or a small amount of voltage, along different directions through the material. They found that when the direction of the electric field was in line with the direction of the spin spiral, the effect switched electrons along the route to spin in the same direction, producing a current of like-spinning electrons.With such a current of spin, you can do interesting things at the device level, for instance, you could flip magnetic domains that can be used for control of a magnetic bit, Comin explains. These spintronic effects are more efficient than conventional electronics because youre just moving spins around, rather than moving charges. That means youre not subject to any dissipation effects that generate heat, which is essentially the reason computers heat up.We just need a small electric field to control this magnetic switching, Song adds. P-wave magnets could save five orders of magnitude of energy. Which is huge.We are excited to see these cutting-edge experiments confirm our prediction of p-wave spin polarized states, says Libor mejkal, head of the Max Planck Research Group in Dresden, Germany, who is one of the authors of the theoretical work that proposed the concept of p-wave magnetism but was not involved in the new paper. The demonstration of electrically switchable p-wave spin polarization also highlights the promising applications of unconventional magnetic states.The team observed p-wave magnetism in nickel iodide flakes, only at ultracold temperatures of about 60 kelvins.Thats below liquid nitrogen, which is not necessarily practical for applications, Comin says. But now that weve realized this new state of magnetism, the next frontier is finding a material with these properties, at room temperature. Then we can apply this to a spintronic device.This research was supported, in part, by the National Science Foundation, the Department of Energy, and the Air Force Office of Scientific Research.

Magnetic field strength and current relationship. Magnetic field strength from current. Magnetic field strength formula current. Magnetic field strength equation. How to measure earth magnetic field strength. How to measure magnetic field strength. What is magnetic field strength. How to calculate magnetic field strength.