Darshana Jolts

Magnetism

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When one rubs a pointed (iron) needle upon a lodestone, it acquires the property of pointing to the south.... – Pen Tshao Yen I (A 12th century Chinese Text)

Introduction

In the third century BCE, geomancy flourished in China: the goal of this enterprise was to acquire occult knowledge about a region and the spirits that dwelled in it. This knowledge would enable the geomancer to predict the fortunes and calamities awaiting the people inhabiting the place. Some historians of Chinese science tell us that it is from these efforts to know about the land that the directive property of magnetic materials came to be discovered[1]. For a long time these were mere curiosities, chunks of metallic stones that kept turning in the same direction no matter how they were suspended. In later centuries the Chinese made what became the mariner's (magnetic) compass which was a direction-finder for sailors at sea. Since it led travelers, they came to be called *leading stones* in English, an epithet that turned into *lodestones*. Aristotle reported that Thales of Miletus, often regarded as the instigator of science and philosophy in the Western tradition, knew about the attractive 'soul-like property' of loadstones. In Turkey there is still a region called Manisa, which in ancient times used to be called Magnesia by the Greeks who probably first noticed loadstones there. They described it as the stone from Magnesia. This eventually led to the word *magnet* of current usage.

Science is an ancient human endeavor. It flourished in many cultures in a variety of modes, and led to advancement in human knowledge. The year 1600 ushered in a century of new knowledge and investigating methods, new insights and instruments in the scientific quest[2]. That year, William Gilbert published a book entitled *De Magnete, Magneticisque corporibus, et de magno magnete tellure; physiologia nova, plurimus & argumentis, & experimentis demonstrata*[3]. This book brought together the then current knowledge of magnetism and electricity. It also

[1] Joseph Needham, *Science and Civilisation in China*, Volume 4, Physics and Physical Technology, Part 1, *Physics,* XXIV, p.434, Cambridge University Press, 1962.

[2] Though we know when and where many major discoveries and inventions occurred (like the concept of zero in India, gunpowder in China, wheels everywhere, etc.), the reasons why they occurred in particular places are far more difficult to understand.

[3] An English translation of Gilbert's *De Magnete* by O Fleury Mottelay is available from Dover Publications, 1958.

presented details of Gilbert's own findings which were based on careful observations. Gilbert described the propensity of attraction as '*coition*'. He recognized that the earth is endowed with an inherent magnetic property, and said that it endowed this to some other materials also. Gilbert rejected the ancient view of four elements (earth, water, fire, air), and imagined that everything (on earth) was made up of only one element: earth. He not only wrote on magnetism and electricity, but expounded the new experimental philosophy in understanding Nature. The book reveals his contempt for the magic-mongers and pseudo-scientists of his time. His was one of the earliest no-nonsense books in physics.

Magnets, Poles and Fields: ***Magnets have some resemblance to electric charges.***

Magnets are now commonplace. Children play with flat and bulky bars of iron marked N and S to which little paper clips cling. This is the magic of Nature: nails being pulled to a magnet without thread or stick or glue or finger: intriguing and impressive and entertaining. If we are not struck by this wonder, we are missing something important in life's experience.

Physicists construct huge magnets under whose imposing influences tiny protons and electrons are made to swing and smash, vanishing and creating new entities. That is what transpires within the scientific sanctuaries today known as high energy accelerators.

The most striking property of magnets is that they have two poles which are referred to *north* and *south*. In earlier times they used to be called (more precisely) north-seeking and south-seeking poles, for that is what these poles do when suspended freely. The north pole invariably points in the northern direction, and the south pole in the southern.

Magnetism is the overt property of only some materials, and under certain conditions. Iron and steel, cobalt and nickel are the most common examples. These materials can be magnetized, i.e., endowed with the magnetic property. Like electric charges, magnets generate magnetic fields: regions where magnetic materials experience pushes and pulls. We picture the strength of fields through arrowed lines drawn from a north pole and merging into a south. More lines represent a stronger field. As we move farther away from a magnetic pole, the field strength diminishes. At long distances from a magnetic pole, field lines are only few and far between.

There seems to be only air in the space around us. There is the gravitational field of the earth. There are the electric fields created by electrical charges. We have magnetic fields caused by magnets. We are bathed in this sea of fields. However, only the gravitational field has tangible effects on us. It keeps us to the ground, and holds the earth in orbit around the sun.

Physicists measure magnetic fields in units of *tesla* or *gauss*. A tesla is pretty strong, and a gauss is a ten thousandth part of a tesla.

Earth's Magnetic Field: ***Our earth is a gigantic magnet.***

The poet Samuel Taylor Coleridge wrote (*Dejection*: *An Ode*):

Ah! *from the soul itself must issue forth*
A light, a glory, a fair luminous cloud
Enveloping the Earth –

There is more light and glory enveloping the earth than what poets sometimes speak of, for there are invisible and imperceptible fields, gravitational and magnetic, all around it. The fall of the apple makes the earth's gravitational field obvious. The jerk of the magnetic compass reminds us of the earth's magnetic field.

Gilbert, in 1600, wrote in his book that "magnetic bodies are governed and regulated by the earth..." He was one of the first to suspect that the earth is a large magnet of sorts. A hundred years later, when Edmund Halley of comet fame captained a small ship which spanned a considerable distance from north to south, he measured the variations of the earth's magnetic field. He wanted to use the data as an indicator of longitudes for sailors: in other words, this would serve as a magnetic map. Another century rolled by before Alexander von Humboldt (1769–1859) made extensive measurements of the earth's magnetic field. During a trip to South America in the first decade of the nineteenth century Humboldt measured the variation of the intensity of the earth's magnetic field from the polar to the equatorial regions.

The earth's magnetic field arises from the circulation of liquid iron and charged particles deep in the earth's interior where it is enormously hot. This magnetic field near the surface is of the order of half a gauss. It extends quite far into space, way beyond our atmosphere, where it is strong enough to deflect the energetic electrons that are flung at us from outbursts in the sun.

Rocks from the ocean floor and lava from volcanoes have been analyzed by geophysicists for their magnetic properties. Those studies suggest that a couple of million years ago, the earth's magnetic poles were not quite where they are now. There have been frequent (in geological terms: fifty thousand to twenty million years) polarity reversals of the earth's magnetic field. Some have suggested that in the process the field may disappear for some time[4]. This could have ominous effects on earthlings: after all, the magnetic field is what detracts cosmic rays away from the main body of the earth. What a dreadful thought: the slow swing of terrestrial magnetism can silently extinguish some species!

[4] For details, see Ronald T Merrill, McElhinny, W Michael, Phillip L McFadden, *The magnetic field of the earth: paleomagnetism, the core, and the deep mantle*, Academic Press, New York, 1996.

The sun is also magnetically endowed. Though immensely more massive than the earth, its average magnetic field is only two to four times as strong as the earth's. But there are regions on the sun's surface where the fields become horrendously large: 250 to 5000 gauss strong! These occur in places where, for some reason, temperatures are much lower. The so-called sunspots are related to these powerful magnetic fields.

Human ingenuity has produced far stronger magnetic fields. Using the phenomenon of superconductivity, we have been able to generate fields of the strength of 200,000 gauss. These are used to run the so-called MagLev trains[5].

Source of Magnetic Field: ***Moving charges give rise to magnetic fields.***

Masses create gravitational fields which are significant for massive bodies like the sun, planets and planetary satellites. Tiny electric charges are responsible for electric fields. It turns out that all that is needed to create a magnetic field is a moving electric charge. Any electric charge in motion splashes out a magnetic field. A whole new range of phenomena arise from restless charges. We came to know about this only in the nineteenth century. We may recall in passing that while European governments and trading companies were exploring and exploiting the rest of the world economically and politically, during this same time scientists and mathematicians in Europe were unraveling countless aspects of the universe, never before known to humankind. That knowledge was to become valuable to one and all in due course[6].

What about bar magnets and horse-shoe magnets? At the deepest microcosmic level there are electrons whizzing around atomic nuclei. Thus every atom is a source of magnetic fields. In most instances, the configurations of atoms mutually cancel out the resultant magnetic fields. As a result, the moving electrons in most atoms do not create a net magnetic field on our scale.

An electric current is simply a river of charges: charges drifting along a wire. So we may expect magnetic fields to result from them. Wherever there is a current, there is also a magnetic field. Given that all our homes and gadgets conceal in their core wires through which currents flow, every time we turn on a switch, we are also switching on a magnetic field. Fortunately, magnetic fields are fairly harmless generally. Or so it seems to be as of now. For more than a century now we have been cozy with appliances through which currents have been flowing. No dramatic

[5] Today Magnetic Levitation trains have been realized in many countries, including India. But the key idea for it was already patented in the first decade of the twentieth century, i.e., more than a hundred years ago.

[6] It is important to recall this in our own times when, as a result of the political and economic harm that the West did to India, there is a growing anti-Western-civilization literature in India (in books, articles, and internet exchanges) which, with all its justifiable condemnation, is totally blind to or ignorant of the contribution of Western civilization to human knowledge through modern science, medicine, and technology.

ailment or complication has been traced thus far to magnetic fields. At least at moderate strengths magnetic fields seem thus far to be harmless.

Current in a Magnetic Field: ***A wire carrying current will be affected if it is in a magnetic field.***

The mother gives birth to the child, and the child affects the mother too. In like manner, a moving charge gives birth to a magnetic field, and the magnetic field affects the moving charge also. More exactly, if a moving charge enters a magnetic field it will experience a force. What this means is that if a current-carrying wire is in a magnetic field, it will experience a push[7]. This simple law of nature has enormous implications. Pushes imply forces, forces imply work and energy: This means that by placing wires carrying currents in a magnetic field we can have some work done, we can extract energy.

All around us are a hundred gadgets that work on this principle: be it an electric shaver, a hair dryer, or the common fan that keeps us cool. If we probe into the mechanism of such contrivances we discover that they have rotatable coils compactly balanced between the poles of little magnets: i.e., placed in magnetic fields. Switch on the current and the coils begin to turn.

Many measuring devices (meters) are constructed by utilizing the effect of magnetic fields on currents. For example, the pointers on the dials in cars work on this principle. The amount by which they turn indicates the intensity of the current causing them to turn, which in turn is a measure of something else. Apparatuses measure the charge and mass of electrons and protons by noting how the particles are deflected when they enter a known magnetic field. These are among the countless ingenious applications to which we have put the law to use.

All kinds of effects arise from this in grand Nature also. Let us consider but two: Up there in interstellar space there are magnetic fields of varying intensities, and there are very fast moving electrons too. Not infrequently, some of these wandering electrons trespass into a magnetic field and the jolt they receive produces electromagnetic radiations that astronomers can recognize as such. We call them *synchrotron radiation*, after a machine that was constructed here on earth[8].

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[7] The interaction between magnetic and electric fields was an accidental observational discovery made by Hans Christian Oersted (Ørsted) (1771–1851)). For details, see Bern Dibner, *Oersted and the discovery of electromagnetism*, New York, Blaisdell, 1962. It was further explored quantitatively by André Marie Ampère (1775–1836). Magnetism has also been explained in terms of relativistic effects of motion between moving charges. Modern theories, initiated by John van Vleck and Louis Néel, use the framework of quantum mechanics to trace the origin of magnetism. H J Van Vleck, *The Theory of Electric and Magnetic Susceptibilities*, Clarendon Press, Oxford, 1932.

[8] The first electron synchrotron was put into operation in 1945 in Berkeley, California. We have synchrotrons in India at the Raja Ramanna Centre for Advanced Technology in Indore.

These are powerful radiations which reveal to us grand supernovas, exploding galaxies, and the gigantic quasars too.

There are countless electrically charged particles from the sun and distant stars that shower the earth: the so-called cosmic rays. They can cause much damage to terrestrial life if they fall right to the ground and impinge on us. This does not happen because the earth, being a gigantic magnet, serves as a protective field by deflecting the charged cosmic-ray bullets towards the polar regions. These torrents of charged particles produce the spectacular glows we call auroras.

Flux of Fields: *Fields flow across surfaces and through loops.*

A flow often reminds us of a stream or a river, of water more generally. But one may also speak of the flow of heat through a protective slab, of light across a window, and one can imagine the flow of a field, electric or magnetic. We do not see with our physical eyes, nor ever will, electric and magnetic fields flowing through a surface or a loop, but we can picture this through the mind's eye, through images and formulas.

Science consists not simply in gathering brute facts about the world, but in organizing, processing, conceiving and coordinating those facts. Much of the power of science arises from the ability to construct concepts in terms of which we can describe and interpret the phenomenal world. It is in this sense, more than in any other, that science is human-centered. Being a human is a necessary, but not a sufficient condition for scientific understanding.

Thus we get the idea of the flow of fields. We give it a technical name, and call it *flux*; more exactly, flux across a surface. We may grasp this idea with some analogies. We have walked in the rain with an umbrella. Imagine that the border of the umbrella is intact while the protective material is water-transparent. There is rain all over, and a certain amount of it is flowing through the material of the umbrella. This is the (water) *flux* through it. By tilting the umbrella this way and that, we can change the flux. Or again, consider a window pane in the house. When there is light outside the house or inside, there is also some flux of light across it. Depending on the orientation of the window with respect to the source of light, this light flux will change. If we hold a plane piece of glass in the line of a beam of light, the light flux through it would be nil. Or imagine a crowd running every which way. If there are doorways of different dimensions we may speak of the flux of the crowd through the various outlets.

Wherever there is an electric or a magnetic field, we may imagine a surface or a loop, and talk about and measure the amount of the field going through the surface or the loop. By changing or turning the surfaces, we can increase or decrease the flux.

This is not slipping into a world of fantasy or poetry, for fantasy has no basis in reality. The flux idea is an extension of reality into the conceptual domain. The notion of the magnetic flux is at the basis of electro-technological civilization. To live in the modern world without recognizing this is like being a citizen of a country without knowing a word about its constitution.

It may be noted in passing that the magnetic flux through a superconducting ring is quantized; the unit of quantized magnetic flux is about 2×10^{-7} gauss cm^2.

Electromagnetic Induction: ***Change in flux through a loop causes current to flow.***

Imagine a coil of wire placed in front of a bar magnet. There is a magnetic flux through the coil due to the field from the magnet. Move the magnet towards or away from the coil. The flux will change. When such a change occurs, a current will flow through the coil. In technical jargon, there will be an *induced current*. The relationship cannot be simpler: a change in flux through a coil causes a current in the coil.

It was the non-mathematical scientific genius Michael Faraday (1791–1857) who discovered this law of *electromagnetic induction* in the 1830s. Faraday was a keen observer, an ingenious experimenter, and an insightful concept-builder. His momentous discovery was that if we have a coil, a magnet, and motion of one relative to the other, then we will have an electric current.

The little gadget attached to the bicycle wheel that lights the lamp at the handle is a modest device in which a tiny coil rotates in the field of a magnet as the wheels of the bike turn. Then there are the huge and complex systems under natural falls and artificial dams where powerful surges of perpetual water flow cause motions in magnetic fields to generate electricity in quantities that light up homes and cities. These also work on the Faraday principle. Or, we may use the power of puffing steam (produced by burning oil or coal, or through nuclear reactions) to cause the turnings of contrived coils to create currents, as they do in thermal stations and nuclear power plants. No matter how, it all comes down to an ingenious use of Faraday's law of electromagnetic induction.

All kinds of discoveries have been made, and continue to be made, in the world of scientific investigation. These are interesting, but some have dramatic effects: to the point of changing the face of human civilization. The simple relationship between magnetic flux and electric currents is one such.

Magnetism and Life: ***Magnetism can be perceived by some forms of life.***

In the course of the eighteenth century, when mathematics and astronomy, electricity and mechanics, were all climbing steadily towards the peaks they would reach in the next century, medicine too was undergoing all kinds of changes. In this context there appeared a Viennese physician named Franz Anton Mesmer (1734–1815) who put the ancient wine of planetary influences on human life into a new bottle. He proclaimed effectively that there was a powerful magnetism in human bodies, by manipulating which ailments could be cured and health restored[9]. He acquired a large credulous clientele in Vienna and Paris. Men and women would throng to his dimly-lit apartment where, clad in the costume of a magician, he touched and stroked the excitable patients, stirring them to shrieks, transferring (as they all believed) his magnetic fluid into them. All these antics earned him much money and the wrath of the scientific establishment, but like his successors in other pseudo-sciences in our own times, he simply did not care. He went about his practice to the satisfaction of those who came to him for magnetic massages, and gave the English language the word: *mesmerism*. Thanks to him we still talk of the magnetic personality of leaders, and to this day, in some parts of the world, traditional doctors suggest the hanging of magnets over cups of water in a patient's room for rapid recovery[10].

That there are currents in the human body, very weak of course, cannot be denied. Inevitably, these must create magnetic fields in however small a measure. How effectively these can be transferred to another individual by touch or stroke is another question. One may still reflect on the fact that though there is all this magnetic field around the earth, but we have not even an inkling of them. We see light and we hear sound, but whoever experiences magnetic fields?

But some other creatures can sense magnetism without using instruments and making calculations. They have a gut feeling about magnetism, as it were, and they put it to good use too. Scientists have come to suspect that some birds and bees, some fish and turtles are magnetically endowed: they have magnetic materials in their tissues which sense the geomagnetic lines of force as they swim or crawl or fly. There is even a class of micro-organisms, the so-called magneto-static bacteria, which respond to magnetic fields[11].

Electromagnetic Waves: ***Moving charges generate electromagnetic waves of many wavelengths and frequencies.***

When electrons oscillate, the electric and magnetic fields they produce get inextricably

9 In this context see the interesting and informative book: Alan Crabtree, *From Mesmer to Freud, Magnetic Sleep and the Roots of Psychological Healing*, Yale University Press, 1993.

10 About this and magnetic therapy, see Robert L Park, *Voodoo Science*: *The Road from Foolishness to Fraud*, Oxford University Press, New York, 2000.

11 David B Dusenbery, *Living at Micro Scale*, pp.164–167, Harvard University Press, Cambridge, Massachusetts, 2009.

intertwined into electromagnetic fields which surge forth in space with the incredibly large speed of three hundred million meters a second. These are the so-called electromagnetic waves, the subtle substratum of the physical universe, which link every nook and corner of the universe. And they carry energy. As noted in an earlier article in this series, the theoretical discovery of electromagnetic (EM) waves by James Clerk Maxwell in the nineteenth century was one of the greatest intellectual achievements in history.

The world is filled with electromagnetic waves of different wavelengths. Wood may appear as minute slivers or small twigs or as gigantic trunks of trees. Likewise, these waves appear in all wavelengths and frequencies. We refer to the totality of their range as the electromagnetic spectrum. Electromagnetic waves of different wavelengths are described as light, heat radiation, ultraviolet and infra-red radiations, X-rays, gamma rays, etc., often differentiated by the impacts they have on the human body: they have different properties, and different effects on biological systems[12]. The part of the EM spectrum with which we are most familiar in our everyday activities is light.

Consider, for example, the so-called ultraviolet (UV) radiation: electromagnetic waves whose wavelengths are between a hundred millionth and a millionth of a meter. Already by the close of the 18th century it was suspected that there were such radiations. However, it was only in 1801 that strong observational evidence came for their existence. J W Ritter (177–1810) discovered that blue and violet light was far more effective in breaking up silver chloride than red or orange[13]. He also found that such effects could be found in radiations beyond the violet. Hence the name *ultra violet* which simply means *beyond* violet.

Our sun is the source of much UV radiation. Most of the UV radiation from the sun that falls on the earth's atmosphere is filtered out by the ozone in the upper layers of the atmosphere. Nevertheless, the solar energy which reaches the ground still contains some UV. This is responsible for unpleasant sunburn and the suntan. Sunbathing produces vitamin-D. But too much sunbathing exposes one to too much exposure to UV, which may lead to skin cancer.

At the other end of the visible spectrum are the infra-red (IR) radiations: electromagnetic waves of wavelengths longer than red and a little over a ten thousandth of a meter in length. This was first observed in solar radiation by the astronomer William Herschel (1738–1822) as early as in 1800. However, it was only some three decades later that they were studied systematically by

[12] See in this context, Lawrence Fagg, *Electromagnetism: Nature's Force That Shapes Our Lives*, University Press, Nottingham, UK, 2011.

[13] See in this context, Roberto de Andrade Martins, 'Ørsted, Ritter and magnetochemistry', in *Hans Christian Ørsted and the Romantic Legacy in Science: Ideas, Disciplines, Practices*, Eds. R M Brain, R S Cohen and O Knudsen, pp.339–385, Springer, New York, 2007.

Macedonio Melloni (1798–1854). Today we have sophisticated instruments like the spectrophotometer to record and measure it in all its variety.

IR rays constitute heat radiation. They play an important role in the regulation of the body temperature. They are also given out in abundance in nuclear explosions. When sunlight hits the ground, it is first absorbed and much of it is then radiated back. This re-radiated energy has a larger wavelength, principally in the IR region. The carbondioxide and the water vapor in the atmosphere absorb some of this. It is this energy that drives the weather systems of the planet.

Gold-lined IR bulbs mounted in a metal reflector used to be a popular device called radar ranges. In these systems, IR radiation did the cooking. Because heat energy is given by radiation (which travels very fast), rather than by conduction (as in the usual cooking devices), it took far less time to cook small quantities of food by this method. Hot bodies emit IR radiation. When rapid heating of surfaces is required, as on newly painted surfaces, the area is exposed for a very short time to very hot sources. This is another practical application of IR radiation.

Magnetic Monopole: *There are no unattached magnetic poles.*

As we have free electric charges, positive and negative, wouldn't it be nice to have single magnetic poles too: north and south? So physicists thought, ever since P A M Dirac pointed out that monopoles could explain why there are basic units of charge on electrons and protons[14]. Other fundamental theories of matter and energy (like grand unified theories) assured us that such entities must exist in the physical universe. They must have inevitably arisen when the cosmos burst forth in its celebrated Big Bang. There must be magnetic monopoles floating all around.

So when the possible existence of magnetic monopoles was heralded by some theorists, experimenters applied for grants to go on hunting expeditions of the monopole. Now and again, a lone group would report excitedly that one has been tracked down: this would be achievement enough for a Nobel medallion. But when it came to confirmation by fellow physicists, the reports have not panned out. Like reports of UFOs, spirits knocking doors at night, and ESP, magnetic monopoles turn out to be more in the believing than in the seeing realm, at least thus far. There seems to be no trace of any magnetic monopole that might have emerged at the dawn of creation[15].

There was only one way out: Modify our theories suitably to erase monopoles for good. This was accomplished by an ingenious cosmological theory, too technical in details to be cursorily

14 P A M Dirac, *Proc. Roy. Soc*., Vol.A133, 1931.

15 For a technical discussion of magnetic monopoles, see Yakov M Shnir, *Magnetic Monopoles*, Springer-Verlag, 2005.

presented. This is the so-called inflationary model[16], a take-off from the Big Bang. This model imagines the birth of the universe to be slightly different from the older version, but in which, among other things, the first traces of monopoles would be gobbled up for good. Not one of them would be left for physicists to lay their probing eyes on in eons to come.

Magnetic poles always occur in pairs. The poet Percy Beeshy Shelley was not thinking of magnetic monopoles when he wrote these lines, but they could be relevant here:

Nothing in the world is single,
All things, by a law divine,
In one another's being mingle....

So, as of now, there seems to be no hope of finding a magnetic monopole. We are left with a universe where magnetic poles appear only in pairs. This is a pity, not because there is no chance of anyone winning a Nobel Prize for the discovery of a monopole, but theoretically speaking, these entities could be used as a source of energy. In fact, if a monopole interacted with a proton, bingo, it would unleash an energy jackpot. On the other hand, it is perhaps good these beasties were gobbled up right at the outset because, left to themselves, they would switch off much of the magnetism in the universe, and wreak who knows what other havoc.

[16] This explanation is not universally accepted. Martin Rees expressed this lack of consensus rather pungently as follows: "Skeptics about exotic physics might not be hugely impressed by a theoretical argument to explain the absence of particles that are themselves only hypothetical. Preventive medicine can readily seem 100 percent effective against a disease that doesn't exist!" Martin Rees, *Before the Beginning*, Basic Books, New York, 1998.

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