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# HISTORY OF MAGNETISM

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## **Abstract.**

Magnetism is a science with more than two millennia of recorded history. The attraction of ferrous objects to a permanent magnet across a distance has been a source of curiosity since the iron age. Investigations of magnetic phenomena led to the invention of steel magnets — needles and horseshoes — and the compass that enabled the exploration of the planet. A host of discoveries following Oersted's 1821 demonstration of the relation between electric current and magnetic field led to the electromagnetic revolution that by the end of the 19<sup>th</sup> century had resulting in global communications and electrification. The discovery of the electron, together with the emergence of quantum theory and relativity in the early 20<sup>th</sup> century established the modern theoretical understanding of magnetism. A panoply of hard and soft magnetic materials has been developed to underpin the modern magnetics industry and a marriage of magnetism and electronics in thin film devices has eased the birth of the information revolution. Aside from the revolutionary technological advances, magnetism played a key role in clarifying basic concepts in condensed matter physics throughout the 20<sup>th</sup> century.

## **Keywords.**

Ferromagnetism; Ferrimagnetism; Compass; Electromagnetic revolution; Permanent magnets; Soft magnets; Angular momentum of electrons; Spin; Exchange interaction; Coercivity; Magnetic recording; Micromagnetism; Thin films; Spintronics; Magnetic units



## Key points.

- Magnetic attraction was first investigated more than 2000 years ago with pieces of naturally-magnetized rocks rich in magnetite,  $\text{Fe}_3\text{O}_4$ .
- Compasses using floating or pivoted steel magnets appeared in the 12<sup>th</sup> century. They led to the great voyages of discovery and mapping of the planet.
- Gilbert identified the Earth as the source of the directional magnetic attraction in 1600, and pioneered the modern experimental method of scientific investigation
- Oersted's 1820 discovery that electric currents create magnetic fields triggered a series of advances that culminated in Maxwell's theory of electricity, magnetism and light, and practical electromagnetic energy conversion that revolutionized energy distribution and communication by the end of the 19<sup>th</sup> century.
- Then, with the discovery of the electron, and the demonstration that magnetism is associated with angular momentum, it became possible in 1928 to use relativity and quantum mechanics to explain magnetism as a consequence of the orbital and intrinsic spin angular momenta of electrons.
- The key practical achievement of the 20<sup>th</sup> century was the mastery of hysteresis, and the achievement of a wide variety of metallic or insulating hard and soft magnetic materials. Important outcomes were analog and digital magnetic recording and high-frequency electromagnetic devices.
- Development of technology to produce uniform magnetic films just a few nanometers thick in the 1960s opened the prospect of using the spin of the electron to be used as well as its change in electronic devices. Semiconductor electronics and magnetic memory are parents of the information revolution.
- Modern theory of condensed matter in areas such as phase transitions and topology has benefitted from magnetic model systems.

## EARLY HISTORY

Feeble permanent magnets are widespread in Nature in the form of lodestones, pieces of rock that are mainly composed of the iron oxide mineral magnetite ( $\text{Fe}_3\text{O}_4$ ). Outcrops can be magnetized by the huge currents in lightning strikes and such natural magnets were known and studied in ancient Greece, Egypt, China and Mesoamerica. Aristotle attributed early thoughts on the nature of magnetic attraction to Thales, who was born in Milet in Asia Minor in 624 BC. He was an animist who credited the magnet with a soul on account of its ability to create movement. This strange idea was to persist in Europe until the 17<sup>th</sup> century. The magnet itself is thought to be named after Magnesia, a city in Asia Minor that was a source of lodestone. In the 5<sup>th</sup> century BC, when Empedokles postulated the existence of four elements, Earth, Water, Air and Fire; magnetism was related to Air with special effluvia somehow passing through pores in magnetic material, a theory echoed much later by Descartes. The Roman poet Lucretius writing in the first century BC mentions the ability of a magnet to induce magnetism in iron and the ability of two magnets to either attract or repel; repulsion had been missed earlier. However, the Greek approach of developing a philosophy into which natural observations were supposed to fit was not conducive to open-minded exploration of the natural world.

A more productive approach was followed in China (Needham 1962), where magnetism was linked to geomancy. The art of adapting the residences of the living and the tombs of the dead to harmonize with local currents of the cosmic breath demanded a knowledge of its direction. A South-pointer consisting of a carved lodestone spoon free to rotate upon a polished baseplate (Fig.1) was in use in the first century BC, and may have been known hundreds of years earlier. An important discovery, attributed to Zheng Gongliang in 1064, was that iron could acquire a thermoremanent magnetization when rapidly cooled from red heat in the ambient magnetic field. A short step led to the suspended magnetic needle, which was described by Shen Kua around 1088 and seen to deviate, like the South-pointer, from a strictly North-South axis.

The compass made its appearance in Europe about a hundred years later, being referred to by Alexander Neckham in 1190. Floating compasses were also developed around this time. The compass (Fig.2) was the enabling technology for the great voyages

of discovery of the 15<sup>th</sup> century, leading the Ming admiral Cheng Ho to the coasts of Africa in 1433, and Christopher Columbus, who rediscovered declination, to America in 1492. Columbus's landfall was on the continent of the Olmecs, who seem to have had a knowledge of magnetism in their massive stone carvings of human figures and sea turtles dating from the second millennium BC. Not long after these heroic voyages, the land masses and oceans of our planet were mapped and explored. According to Francis Bacon, writing in *Novum Organum* in 1620, the magnetic compass was one of the three things, along with printing and gunpowder, that had "changed the whole face and state of things throughout the world". All were Chinese inventions. It was the first occasion when magnetism changed the world. Two more were to follow.

The first authentic magnetic experimentalist in Europe was the French crusader monk Petrus Peregrinus. His paper *Epistola de Magnete* recounts experiments with floating pieces of lodestone and carved lodestone sphere that he called 'terellae,' performed during the 1269 siege of Lucera, a Muslim settlement in Southern Italy. He discovered the poles of a magnet, related magnetic attraction to the celestial sphere, and included a proposal for a magnetic perpetual motion device – which became an obsession of charlatans up to the present day. However, credit for the inauguration of the experimental method in a recognizably modern form belongs to William Gilbert. Physician to the English queen Elizabeth I, Gilbert himself conducted a series of experiments on terellae and concluded that the Earth itself was a great magnet. Magnets aligned themselves not with the celestial sphere, but with the Earth's poles. He induced magnetism by cooling iron in the Earth's field and destroyed it by heating or hammering. Gilbert was at pains to dispel the accretion of superstition that clung to the magnet, preferring to rely on his own experimental evidence. His investigations are described in his masterwork *De Magnete* published in 1600 (Gilbert 1958), which is arguably the first modern scientific text.

## **FROM NAVIGATION TO INDUSTRY**

Gilbert's theories held sway in the 17<sup>th</sup> century until the appearance of Edmond Halley's 1692 shell model for the Earth's magnetic structure, which greatly influenced compass technology and navigation. Magnetic research at the time was driven principally by naval

interests. An early observation of a connection between electricity and magnetism was made in 1681, when a ship bound for Boston was struck by lightning. It was evident from the stars that “the compasses were changed; the North point was turn’d clear South”; with the compass so reversed, the ship sailed on to its destination.

The 18<sup>th</sup> century was marked by professionalization of the scientist or ‘natural philosopher’ as they were then called (Fara 1996). Developments in magnetism were associated with improvements in navigation and the prestige of the great voyages of discovery. Accordingly, the natural philosopher with his mantle of theory was afforded social status, access to public funding and credibility beyond that extended to artisans on the one hand, and quacks such as the colourful Anton Mesmer with his theories of ‘animal magnetism’ or James Graham with his ‘royal Patagonian magnetic bed’ for nightly rent in a fashionable London townhouse on the other. Halley conducted magnetic surveys, producing charts of inclination and declination for seafarers (Fig.3). The English entrepreneur Gowin Knight, representative of this new breed of natural philosopher, later improved the quality of magnetic materials and compasses for sale to the Navy, coupling scientific endeavour with commercial acumen.

A major technical breakthrough of the 18<sup>th</sup> century was the 1755 discovery by Johann Dietrich that the horseshoe was an ideal magnet shape. His invention, an ingenious practical solution to the problem of self-demagnetization in steel bar magnets, was enthusiastically promoted by his patron Daniel Bernouilli.

This period also saw rapid developments in the harnessing of electricity, from the 1660 invention of the Leyden jar, culminating in Volta’s 1800 invention of the Voltaic cell. There were compelling analogies between electrostatics and magnetism and some cogent speculation relating magnetism and rotational motion such as that of Richard Kirwan (1797), but a formal link between electricity and magnetism was not established experimentally until 1820. During a public demonstration by the Danish scientist Hans Christian Oersted, a suspended compass needle was found to be deflected when an electric current was switched on in a copper wire. His report launched an experimental frenzy. François Arago (who briefly became President of France in 1848) immediately performed an experiment in Paris establishing that a current-carrying conductor behaved like a magnet. A week after Arago’s report, André-Marie Ampère presented a paper to

the French Academy suggesting that ferromagnetism in a body was caused by internal currents flowing perpendicular to the magnetic axis and, by analogy, that steel needles magnetized in a solenoid would show stronger magnetization. Together with Arago, he successfully demonstrated this theory in November 1820. Ten days later, the British scientist Humphrey Davy reported similar results. A practical horseshoe electromagnet was constructed by William Sturgeon in 1825, and five years later Joseph Henry in the USA built a powerful electromagnet with layers of closely-spaced copper windings; he discovered self-induction and made an electric relay and an electric bell.

In the ensuing ferment in Europe and North America, it is often difficult to attribute credit for any advance, distinguishing between who had the idea, who devised a convincing experimental demonstration, and who created the first practical, working machine. Scientists and engineers belonged to different communities, with different approaches.

19<sup>th</sup> century electromagnetic science was driven, however, by Michael Faraday. Working entirely by observation and experimentation, with no dependence on formal theory, he developed the concept of ‘magnetic field’. Faraday classified materials as ferromagnetic (substances such as iron which were easily magnetized and drawn towards stronger magnetic fields), paramagnetic (substances which are attracted by the field but much more weakly than iron) or diamagnetic (materials which were pushed away by the field). Working with an electromagnet, he discovered the phenomenon of ‘electromagnetic induction’ — that a flow of electricity can be induced by a changing magnetic field. He demonstrated electrical ↔ mechanical energy conversion in a model motor and a dynamo with steel permanent magnets, which were used in most of the early demonstrations, but electromagnets proved indispensable for later, practical electromagnetic machines. His conviction that a magnetic field should have an influence on light led to his 1845 discovery of the magneto-optic Faraday effect — the rotation of the plane of polarization of light passing through a magnetic medium in a direction parallel to its magnetization. Figure 4 illustrates a collection of magnets from the 18<sup>th</sup>, 19<sup>th</sup> and late 20<sup>th</sup> centuries, when permanent magnets finally became indispensable for many practical applications.



A classical theory emerged to account simultaneously for magnetism and its relationship with electricity. Around 1824 Siméon Denis Poisson developed a mathematical theory of magnetostatics. Letters from Ampère to Fresnel and Faraday found after his death show that by 1822 he had considered the possibility that the currents causing ferromagnetism were ‘molecular’ rather than macroscopic in form. Wilhelm Weber formally presented the idea that ‘molecules’ of iron were capable of movement around their centres, suggesting that they lay in different directions in unmagnetized material, but aligned in a common direction in the presence of an applied magnetic field. This was the beginning of an explanation of hysteresis, the central phenomenon of technical magnetism, demonstrated experimentally by James Ewing using a board of small, pivoting magnets. He then built an ingenious instrument based on the bending of a ferromagnetic current-carrying wire in the gap of an electromagnet to measure  $B$  and  $H$  under AC and DC excitation, with which he discovered and measured hysteresis loops in 1889 (Fig. 5). Ewing’s activities as a young professor at the University of Tokyo in the 1890s established the strong Japanese tradition of research on magnetic materials that continues to thrive today.

James Clerk Maxwell, the Scottish theoretician, “resolved to read no mathematics on the subject till he had first read through Faraday’s *‘Experimental Researches in Electricity’*”. Maxwell’s unprecedented equations formally defined the relationship between electricity and magnetism and bridged the gap, between oscillating electric charge and magnetic field. His theory considered electromagnetic waves traveling through an all-pervading aether at speeds close to that of light, measured with 5% accuracy by Hyppolite Fizeau in 1849. - In 1888 Heinrich Hertz showed that Maxwell’s electromagnetic waves were, in fact, identical with radio waves and light.

The subsequent technological developments of all these discoveries would have been impossible without a stable and powerful source of electric energy that batteries were unable to provide. Starting from Faraday’s rotation, Arago’s rotary magnetism and his own understanding of electrodynamics, Ampère and the young instrument maker Hypolyte Pixii demonstrated the principle of a DC generator in 1832. The first DC motor with a commutator came two years later (credit has been claimed for Moritz von Jacobi in Russia, Anyos Jedlic in Hungary and Thomas and Emily Davenport in Vermont), but

the first industrial machine issued from Siemens brothers' workshop only in 1854. However, these energy converters needed very big steel magnets to work effectively. The English engineer Henry Wilde dared in 1864 to replace permanent magnets with a series of multi-turn electromagnets in a dynamo thereby reduced the mass while greatly improving the performance. A similar machine was built independently by Werner von Siemens shortly afterwards. A new design of DC generator came in 1859 from Antonio Pacinotti in Italy. His innovation, published only in 1865, was in the design of the rotor (Pacinotti's ring) that improved the efficiency. With further improvements, the design was launched commercially in 1870 by Zénobe Gramme in France. In addition to Pacinotti's ring, Gramme fed the electromagnet directly from the rotor (Fig. 6). Then with further modifications reduce the mass and increase the efficiency, notably by Siemens, the design was stabilized. Surprisingly, the reversibility of the DC generator was observed by Hyppolite Fontaine only in 1873; he found that by applying a DC current to Gramme's machine he could make it spin.

The first electric streetlights were bright high-voltage DC arc discharge lamps with short-lived elements that replaced the gas lights of Paris in 1879, but they were too dangerous for domestic use. In 1882, Thomas Edison built the first system of electric distribution for 59 customers in New York and developed a working light bulb operating at 110V DC. However, the expansion of the electric power grid was only made possible by Nikola Tesla's AC system, which enabled efficient long-range distribution at high voltages with minimal electrical losses together with a safe local voltage by means of step-down transformers. Based on Elihu Thomson's AC generator (1879), the transformer of Lucien Gaulard and John Gibbs (1881) and Tesla's induction motor (1886), this system was taken on by the Westinghouse company, and it has remained almost unchanged up to the present day.

Siemens exhibited a miniature electric locomotive pulling a little train around a 300 m track to amuse visitors at a Berlin exhibition in 1879. His company installed the first electric trams in Berlin two years later and by 1900 they had an electric train capable of 200 kmh<sup>-1</sup>. Horses and their droppings soon vanished from the city streets.

One of the main problems besetting the development of efficient magnetic material in the 19<sup>th</sup> century was the difficulty to measure magnetization and field

precisely. Coulomb adapted the principle of the electrostatic torsion balance in 1784 to measure electric charge, but it could only work approximately with the inseparable ‘poles’ of permanent magnets; the magnetic moment couldn’t be fitted in to the existing system of units. By 1880, it was possible to estimate the permeability by AC voltage and current measurement, especially John Hopkinson observed the enhancement of permeability just before reaching the temperature at which ferromagnetism disappears in 1885. After the invention of the first ballistic galvanometer or fluxmeter (actually an electromechanical voltage integrator) by Arsène d’Arsonval around 1881, it became possible to measure time- or space-varying fields. It was using this instrument, Pierre Curie could measure a magnetic field and its gradient. With the very sensitive torsion balance illustrated in Fig. 7 that could operate in large fields and at high temperature, he determined his law of paramagnetism, showing that ferromagnets behave like paramagnets above their magnetic transition temperature — known as the Curie point.

The astonishing transformation of science and society that began in 1820 is known as the electromagnetic revolution. By the end of the century it was heralding the electrification of the planet and changing forever human communications, transportation and conditions of life and leisure. This was the second time that magnetic technology changed the world.

Finally, the century closed with the all-important discovery of the electron, the elusive carrier of electricity. A new age was born.

There are one-volume histories of magnetism (Kloss 1994), and of electricity and magnetism (Meyer 1972, Mottelay 1975), and a short accounts of in magnetism textbooks (Matthis 1965, Coey 2010)

## **UNITS**

By the middle of the 19<sup>th</sup> century, it was becoming urgent to devise a standard set of units for electrical and magnetic quantities. The burgeoning telegraph industry, for example, needed a standard of electrical resistance to control the quality of electrical cables. Separate electrostatic and electromagnetic cgs unit systems based on the gram, centimetre and second had come into existence. Maxwell and Jenkin proposed combining them in a coherent set of units in 1863. Their Gaussian cgs system was internationally

adopted in 1881. Written according to this system, Maxwell's equations relating electric and magnetic fields contain factors of  $c$ , the velocity of light. Maxwell also introduced the idea of dimensional analysis, based on three basic quantities of mass, length and time. The magnetic field  $\mathbf{H}$  and the induction  $\mathbf{B}$  were measured in units of Oersted and Gauss, respectively in the cgs system, but there is no numerical distinction between them in free space.

Another basic unit, that of electric current, was adopted in the *Système International d'Unités* (SI) in 1948. The number of basic units and dimensions in any system is an arbitrary choice; SI uses four, the metre, kilogram, second and ampere. It has been adopted worldwide for the teaching of science and engineering, employing the familiar electrical units of volt, ampere and ohm. Maxwell's equations written in terms of two electric and two magnetic fields contain no factors of  $c$  or  $4\pi$  in the SI system. The magnetic field  $\mathbf{H}$ , like the magnetization  $\mathbf{M}$ , has units of  $\text{Am}^{-1}$ . The induction  $\mathbf{B}$  is measured in tesla ( $1 \text{ T} \equiv 1 \text{ kgs}^2\text{A}^{-2}$ ). Magnetic moments are measured in units of  $\text{Am}^2$ , clearly indicating the origin of magnetism in electric currents, and the consequent absence of magnetic 'poles' as real physical entities. The velocity of light is defined as exactly  $299,792,458 \text{ ms}^{-1}$ . Two constants  $\mu_0$  and  $\epsilon_0$ , the permeability and permittivity of free space respectively, are related by  $\mu_0\epsilon_0 = c^2$ .  $\mu_0$  was defined to be  $4\pi \cdot 10^{-7} \text{ kgs}^2\text{A}^{-2}$  until 20 May 2019, but with the new definition of the ampere and the retirement of the Pt-Ir standard kilogram, it is now defined as  $1.25663706212(19) \times 10^{-6} \text{ kgs}^2\text{A}^{-1}$ . Gaussian cgs units remain in widespread use in magnetism in some parts of the world, despite the manifest practical advantages of SI.

## FUNDAMENTAL UNDERSTANDING

The discovery of the electron in the closing years of the 19<sup>th</sup> century was a giant step towards a fundamental understanding of magnetism. The elementary charged particle with mass  $m_e = 9.109 \times 10^{-31} \text{ kg}$  and charge  $e = -1.602 \times 10^{-19} \text{ C}$  had been named by the Irish scientist George Johnstone Stoney in 1891, several years before Jean Perrin identified negatively charged particles in a cathode ray tube and Joseph John Thompson measured their charge to mass ratio  $e/m_e$  by deflecting them in a magnetic field. George Francis Fitzgerald suggested in 1900 that magnetism might be due to rotation of these

electrons. Electrons turned out to be the essential magnetic constituent of atoms and solids, as well as the carriers of electric current.

Based on measurements of the low-temperature saturation magnetization of iron and nickel, and the paramagnetic properties of transition metals salts, Weiss proposed in 1911 an experimental unit of atomic magnetism  $\mu_w = 1.853 \times 10^{-24} \text{ JT}^{-1}$ . Known as the Weiss magneton, it remained in use for about 30 years, notably by Blas Cabrera in Spain who used it to interpret very precise measurements of susceptibility above the Curie point. It was abandoned in favour of the Bohr magneton  $\mu_B = e\hbar/2m_e = 9.274 \times 10^{-24} \text{ JT}^{-1}$ , which involves the quantum of angular momentum  $\hbar$  (Quédec 1988). The Einstein-de Haas experiment established a relation between magnetization and angular momentum experimentally, in 1915. The intrinsic spin angular momentum of the electron was unknown at that time (Tomonaga 1974).

Thirty years were to elapse before contradictions at the heart of early 20<sup>th</sup> century magnetism could be resolved. In these tumultuous years, classical physics and the lingering wisps of aether were blown away, and new principles of quantum mechanics and relativity were established. If, following Ampère, we believe that all magnetism is traceable to circulating electric currents, why does iron not melt? Its magnetization  $M$  is equivalent to a surface current of  $1.76 \times 10^6 \text{ Am}^{-1}$ , how could such a current be sustained indefinitely? Weiss had postulated in 1907 the existence of an internal ‘molecular field’ proportional to the magnetization,  $\mathbf{H}_i = n_w \mathbf{M}$ , to account for the abrupt disappearance of ferromagnetism at the Curie point  $T_C$  and paramagnetism at higher temperatures. He was at a loss, however, to explain why no trace of his enormous field – a thousand teslas ( $n_w \approx 1000$ ) – was detectable in the vicinity of a piece of fully-magnetized ferromagnetic material, as predicted by the continuity of  $\mathbf{B}$  in Maxwell’s equation. He concluded that the origin of this field must be electrostatic (Weiss and Foëx 1926). In the unmagnetized state Weiss had accepted the existence of domains magnetized in different directions to give no resultant moment, but there are no domains in the saturated state. The ‘anomalous’ Zeeman splitting of spectral lines in a magnetic field was a mystery. Niels Bohr in 1911 and Hendrika van Leeuwen in 1919 had proved that at any finite temperature and in any magnetic or electric field, the net magnetization of any collection

of classical electrons vanishes identically. Classical electron physics was incompatible with any kind of magnetism whatsoever!

By 1930, quantum mechanics and relativity had come to the rescue, and a new understanding of magnetism emerged in terms of the physics of Einstein, Bohr, Pauli, Dirac, Schrödinger and Heisenberg. The source of magnetism in condensed matter was identified with the *angular momentum* of elementary particles such as the electron. The perpetual currents in atoms were quantized in stationary states that did not decay, with angular momentum that was a multiple of Planck's constant  $\hbar = 1.055 \times 10^{-34}$  Js. Weiss's 'molecular field' was not a magnetic field at all, but a manifestation of electrostatic Coulomb interactions constrained by Pauli's exclusion principle, which forbade the occupancy of a quantum state by two electrons with the same spin. The intrinsic spin angular momentum of an electron was found by Samuel Goudsmit and George Uhlenbeck in 1925 to have the value  $\frac{1}{2}\hbar$ . The corresponding electronic magnetic moment, however, was one Bohr magneton, twice as large as anticipated for orbital angular momentum. The problem of the electron's magnetism was finally resolved by Paul Dirac in 1928 when he succeeded in writing Schrödinger's equation in a relativistically invariant form, obtaining the electron spin in terms of the 2 x 2 spinor matrices previously proposed by Wolfgang Pauli. Together with Werner Heisenberg, Dirac formulated the Hamiltonian  $-2J\mathbf{S}_i \cdot \mathbf{S}_j$  to describe the coupling between the vector spins  $\mathbf{S}_i$  and  $\mathbf{S}_j$  of two many-electron atoms  $i$  and  $j$ . The value of the exchange integral  $J$  was directly proportional to Weiss's molecular field coefficient  $n_w$ .

The theory was almost complete after the description of spin waves by Felix Bloch in 1930 to be the elementary excitations of an array of atoms coupled by Heisenberg exchange interactions, and the band theory of ferromagnetic metals developed by Edmund Stoner and John Slater in the 1930s, which accounted for the non-integral spin moments found in Fe, Co and Ni, and their alloys.

The sixth Solvay conference, held in Brussels in October 1930, (Fig. 8) was devoted to magnetism (Marage and Wallenborn 1995). It followed four years of brilliant discovery in theoretical physics, which set out the modern electronic theory of matter. Yet the immediate effect on the practical development of magnetism was surprisingly slight. Dirac there made the perceptive remark "The underlying physical laws necessary

for the mathematical theory of a large part of physics and the whole of chemistry are completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble”.

## **MAGNETIC PHENOMENOLOGY and MATERIALS**

A less fundamental theoretical approach was needed. Louis Néel, a student of Weiss, pursued a phenomenological approach to magnetism, oblivious to the triumphs of quantum mechanics. His extension of Weiss theory to two oppositely-aligned sublattices led to the idea of antiferromagnetism in 1932. This hidden magnetic order awaited the development of neutron scattering in the 1950s before it could be revealed directly. Néel later explained the ferrimagnetism of oxides such as magnetite ( $\text{Fe}_3\text{O}_4$ ) – the main constituent of lodestone – in terms of two unequal, antiferromagnetically-coupled sublattices. The spinel structure of magnetite has an ‘A’ sublattice of iron sites in tetrahedral oxygen coordination, and twice as many sites in octahedral coordination forming a ‘B’ sublattice. The ‘B’ sites are occupied by a mixture of  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$ , and the ‘A’ sites by oppositely-aligned  $\text{Fe}^{3+}$ . This yields a net spin moment of  $4\mu_B$  per formula – a quantitative explanation of the magnetism of the archetypical magnet in terms of lattice geometry and atomic moments associated with electron spin.

An important family of spinel ferrites derived from magnetite was developed by Jacobus Snoek at the Philips Research Laboratory, beginning in the 30’s and more intensively following Néel’s theory of ferrimagnetism. The expansion of radio communications has been possible, thanks to Ni-Zn ferrites and power electronics for phone or car chargers; choppers and inverters for DC and AC motors and rectifiers could not have advanced without Mn-Zn ferrites. Mg ferrite was used for television tubes and the countless thousands of 2 mm ferrite rings threaded on a lattice of copper wires that served as non-volatile computer memories in the 1970’s. Another family of ferrimagnetic iron oxides, the rare-earth iron garnets, included  $\text{Y}_3\text{Fe}_5\text{O}_{12}$ , the ideal material for low-loss microwave components. For some time, Co ferrite was used for hard magnets, but a decisive breakthrough was the discovery at Philips in 1953 of a family of hexagonal ferrite permanent magnets based on  $\text{BaFe}_{12}\text{O}_{19}$ , which were the first magnets to break the shape barrier. They were endowed with sufficient coercivity to be

fabricated into any desired shape without self-demagnetization. Electromagnetic machine design was freed at last from the shackles of the horseshoe. As a result, a million tonnes of hard ferrite is being produced every year to make billions of small DC motors and actuators.

For many practical purposes, it is possible to ignore the atomic and electronic basis of magnetism, and simply regard the magnetization of a solid as a continuous vector. The hysteresis loop  $M(H)$  (Fig.9) is a record of the resultant of a metastable structure of domains and domain walls arising from the thermal and magnetic history of a particular sample. Evidence for discontinuous jumps in the Weiss domains as the magnetization was saturated was picked up with headphones by Heinrich Barkhausen in 1919, and in 1931 the domains were visualized in a microscope by Francis Bitter using a colloidal suspension of magnetite particles.

Bloch introduced the idea of a domain wall in 1932 as a region where the magnetization rotates continuously from one direction to another. The exchange energy cost, written in the continuum approximation as  $A(\nabla M)^2$  where  $A \propto J$ , is balanced by the gain in magnetostatic energy  $\frac{1}{2}\mu_0 H^2 dV$  associated with the magnetic field created by the ferromagnet throughout its own and the surrounding space, where  $V$  is volume. Another term, the anisotropy energy, is needed to restrict the wall width, which can arise from the sample shape, or intrinsically from spin-orbit coupling, a relativistic effect. The sum of these free energy terms, together with the Zeeman energy in an external field, is minimized to yield the domain structure. Based on these concepts, Lev Landau in 1935 explained the formation of domains such as closure domains in iron single-crystals. The complete theory of ‘micromagnetism’ was formulated by William Fuller Brown in 1940. However, describing the macroscopic magnetic properties from microscopic equations remains an unsurmountable challenge. So far, hysteresis has been modelled using the approach proposed by the Hungarian engineer Ferenc Preisach, a student of Barkhausen, in 1935 (Vajda and della Torre 1995).

Domain walls in solids tend to be pinned by local crystal imperfections or microstructures, leading to the metastable states represented on a hysteresis loop. The control of hysteresis was the main challenge for magnetic materials design in the 20<sup>th</sup> century, and the challenge was met more by metallurgical art than by recourse to



fundamental physical theory. Back the 19<sup>th</sup> century, practical ferromagnetic magnetic materials were limited to soft low-carbon and hard high-carbon steels with additives such as Co, Cr or W. Progress with soft magnets was rapid after Robert Hadfield, working in Sheffield in 1900, discovered the improved magnetic behaviour and higher resistivity of silicon steel. Mass production of Fe-Si sheets began in Germany the same year. A lower magnetization was offset by much lower AC losses, and improved efficiency of generators, motors and especially transformers after the development of textured grain-oriented silicon steels by Norman Goss in 1937.

A significant improvement of hard magnets beginning in 1932 was due to the Japanese metallurgist Tokushichi Mishima, who found that adding Al to Ni-Fe alloys improved their magnetic properties. Addition of Co with traces of other elements, and development of a series of complex heat treatments gave us the family of ‘Alnico’ alloys over the following 50 years. All have elongated nanoparticles of soft ferromagnetic Fe-Co in a paramagnetic Ni-Al matrix. The magnetic hardness and coercivity is due to the shape anisotropy of the separated nanoparticles.

The mastery of coercivity gained over the course of the 20<sup>th</sup> century (Fig.10) was spectacular. Burgeoning applications of magnetism were the direct consequence. Microscopic quantum theory only began to contribute to this process in the 1970s after the advent of rare earth permanent magnets such as SmCo<sub>5</sub> and Nd<sub>2</sub>Fe<sub>14</sub>B in particular, where an understanding of the quantum mechanics of intrinsic, magnetocrystalline anisotropy helped in the design of new permanent magnet materials.

A fertile approach to the problem of hysteresis was to focus on magnetization reversal in the simplest case of single-domain particles. Edmund Stoner and Peter Wolhfarth proposed an influential model for this in 1948. Néel had envisaged magnets made from elongated iron particles in 1942 and published some results in one the short notes he wrote for *Comptes Rendus* in 1947. Seeking to understand the remanent magnetism of baked clay, Néel proposed a model of thermally-driven ‘superparamagnetic’ fluctuations of the magnetization of micron-sized ferrimagnetic particles the following year. The fluctuation time depended exponentially on the ratio of the energy barrier to magnetization reversal to the thermal energy. As a result, a component of magnetization became blocked on cooling in the Earth’s magnetic field.

Application of this idea of thermoremanent magnetization to cooling igneous rocks delivered a direct and convincing argument for continental drift, as rocks cooling at different times experienced fields of different polarity (Fig.11). This all led to the subfield of palaeomagnetism, and establishment of the theory of global plate tectonics, which had far-reaching consequences for Earth science (McElhinney 1973).

The Earth's magnetism had been a perennial topic of interest since the seminal work of Gilbert. Alexander von Humboldt, who became interested in 'magnetic storms' in the course of his travels in South America where he made numerous measurements of the Earth's field, organized a group of laboratories in Paris, Freiburg, Berlin and Kazan to make synchronous measurements of the field in the course of a single day in March 1829.

Remarkably, all of them revealed the same pattern of short-term fluctuations. Humboldt's embryonic *Magnetische Verein* was soon entrusted to Wilhelm Weber and Carl Friedrich Gauss in Göttingen, who expanded the collaboration to include dozens of magnetic observatories across Europe, Asia and North America, spanning the globe from Dublin in the West to Alaska in the East. They collated the worldwide measurements made on a daily schedule of Göttingen time in an unprecedented international scientific collaboration aimed at understanding the behaviour of the Earth's magnetic field. It lasted until 1841 and continued in another guise for a further decade. Gauss developed spherical harmonic analysis to reduce the data and concluded that the greater part of the field was of internal origin. The external component was associated with an 11-year cycle of sunspot activity by Edward Sabine, but no amount of data, however scrupulously acquired, was capable of predicting the variations of an essentially chaotic system.

## **MODERN DEVELOPMENTS**

Magnetism since 1945 has been an area of rich and productive discovery, not least because of the enormous increase in numbers of scientists and engineers working in the field. Magnet ownership for citizens of the developed world has skyrocketed from one or two magnets in 1945 to a few hundred seventy-five years later, or something of order a trillion if we count the individual magnetic bits on a hard disc in a personal computer! Magnetic recording dates from the final years of the 19<sup>th</sup> century, when the Danish engineer Valdemar Poulsen recorded his voice on steel wire (Daniel, Mee and Clark

1998), It developed into analogue recording on tape covered with ferrimagnetic microparticles in Germany in the 1930s but in the modern era, digital recording has come to overshadow all else. Hard discs, introduced by IBM in 1957 offer large amounts of nonvolatile computer memory. Initially using inductive read-write heads and particulate media, they developed to provide the bulk of the mass storage in data centres, where all the readily-accessible information of the internet is stored. Much non-volatile personal data is now recorded in semiconductor flash memory, but archival back-up storage of mountains of digital data generated daily uses magnetic tape. Magnets and semiconductors were the mainstays of the first decades of the information revolution — semiconductors to process the data and magnets to store it. The success of magnetic recording lay in its ability to keep pace with the relentless exponential doubling of the areal density of transistors on silicon chips every one or two years. This is due to the scale-invariance of the dipole field of a pattern of permanent magnetism, and the ability of spin electronics to develop magnetic field sensors based on thin film stacks that can operate on ever-smaller length scales. Magnetic recording is a foundation of the information society.

Modern achievements can be classified as those contributing to a basic understanding of condensed matter, those associated with new experimental probes, and those leading to new materials, preparation methods and industrial technologies.

## **Theory**

From a fundamental viewpoint, magnetism has been a fertile field for cultivating condensed-matter theory. After Weiss's original mean-field theory, magnetism has inspired more sophisticated theories of phase transitions, and provided the data to support them. A milestone was Onsager's 1944 solution of the two-dimensional Ising model, where spins are regarded as scalars which take values  $\pm 1$ . The behaviour of more complex and realistic systems such as the three-dimensional Heisenberg model were solved numerically using the renormalization group technique in the 1970s. The ability to tailor magnetic model systems having an effective spatial dimension of 1 or 2 with structures of isolated chains or planes of magnetic ions and an effective spin dimension

similarly limited by anisotropy to 1, 2 or 3 in the Ising, xy or Heisenberg models, laid the foundation of the modern theory of phase transitions.

Coulomb correlations among the electrons in a metal, and their coupling to the crystal lattice, generate a wealth of ground states and unexpected phenomena in solids. Experimental studies of dilute magnetic alloys such as **AuFe** or **CuMn** raised two questions that preoccupied theorists in the last decades of the 20<sup>th</sup> century. One was whether a single atomic impurity in a nonmagnetic metal can retain its magnetic moment. The question focused attention on the relation between magnetism and electronic transport in metals, a nexus that has been immensely productive. The other concerned the nature of the transition to the ‘spin glass’ state when the magnetic moments of the impurities freeze in random directions at sufficiently low temperatures. The single impurity problem was related to a shallow resistivity minimum at low temperature where the atom appears to lose its magnetic moment. The effect was explained by Jun Kondo using perturbation theory for spin-flip scattering, where the impurity enters a singlet state due to Coulomb interaction with the conduction electrons. The Kondo problem was eventually solved exactly in 1983 by Natan Andrei. In spin glasses, multiple dilute impurities interact with each other via indirect ‘RKKY’ exchange through spin polarization of the conduction electrons, which produces a symmetric Gaussian distribution of positive and negative exchange interactions  $J$ . Spin glasses show a frequency-dependent peak of the magnetic susceptibility at the spin freezing temperature  $T_f$ , which it is thought would be a thermodynamic phase transition for Heisenberg spins in four spatial dimensions. The wider problem of spin freezing in amorphous solids resulting from topologically-frustrated antiferromagnetic interactions in odd-membered rings or random single-ion anisotropy, especially for rare-earth atoms, was investigated in the context of amorphous magnetism in the 1970s, as discussed further in the following section on Materials.

Theoretical studies of the ground states of chains, ladders, triangular lattices and the two-dimensional electron gas catalysed a wider understanding of the role of topology in condensed matter, where magnetism has provided model systems that help to clarify the concepts. Topological properties of matter are invariant under small changes of external

variables — pressure, temperature, or magnetic field — unlike the usual linear response. An early example of topological quantum matter was the one dimensional,  $S = 1$  antiferromagnetic chain that Duncan Haldane discovered in 1981 exhibited a spin gap and behaved as a quantum spin liquid. At about the same time, Klaus von Klitzig at the Grenoble High Magnetic Field Laboratory discovered that the Hall effect in the two-dimensional electron gas of a silicon MOSFET exhibited a series of steps in applied field, where the Hall conductance was a precise integral multiple of  $e^2/h$ , to within one part in a billion. This provided a new standard of resistance  $h/e^2 = 25.81280745 \text{ k}\Omega$ . A corresponding quantum anomalous Hall effect was observed in magnetic materials in the absence of an applied field. The anomalous Hall effect, itself a puzzle for over a hundred years after its discovery by Edwin Hall in 1879, was interpreted as an intrinsic feature of a ferromagnetic metal related to the topology of the band structure, characterized by its Berry curvature.

### **Numerical simulations**

With the arrival of cheap, powerful computers in the 1990s, numerical simulations of the electronic structure and properties of ideal crystals based on spin-dependent density-functional theory became widespread. They opened the prospect of discovering potentially-interesting new magnetic materials without the bother of entering a laboratory. Simulations were successfully applied to calculate the magnetic ground state properties of correlated electrons in metallic systems, and obtain magnetization, anisotropy and Curie temperature. Phase stability may depend on stoichiometry, disorder or a variety of crystallographic defects, and a single phase may be unstable with respect to disproportionation into a lower-energy combination of two or more phases. While no new magnetic materials have yet been discovered that are worthy to join the handful that can be profitably commercialized, the method provides insight into trends in the electronic structure and properties of large numbers of ideal compounds. Numerical simulations began to accompany experimental reports on properties of magnetic materials. Machine learning from large databases of known phases can improve the accuracy of predicted magnetic properties such as Curie temperature.

On a different scale, simulations based on the Landau-Lifschitz-Gilbert equation are appropriate for simulating the short-term dynamics and micromagnetism of microscopic systems. The mesoscopic scale is computationally the most demanding.

## **Experimental methods**

Force magnetometers remained in use for most of the 20<sup>th</sup> century for static measurements of magnetization. DC magnetometers based on the ballistic galvanometer were replaced by electronic integrators based on John Ragazzini's valve-based operational amplifiers (1947) and their solid-state successors (1968), and then usually by digital integration. The vibrating sample magnetometer (VSM), a laboratory workhorse, was invented by Simon Foner in 1959 to measure the voltage induced in a quadrupole pickup coil by the oscillatory movement of a magnetized sample using a phase-sensitive lock-in detector, thereby converting a one-shot measurement to the continuous detection of a steady voltage. The principle is similar to that of the electric guitar microphone invented by Adolf Rickenbacker in 1931. Due to its versatility and sensitivity of order  $10^{-8}$  Am<sup>2</sup> or  $10^{15}$   $\mu_B$ , the VSM became the standard laboratory method for measuring magnetic moment, either equipped with an electromagnet or a superconducting coil. A trend in laboratory experiments has been to generate and process ever-growing quantities of data, thanks due to the ability of computers to accumulate and store digital information on ever-shorter timescales. The precision and detail of the measurement is thereby enhanced.

The discovery of magnetic resonance, the sharp absorption of microwave or radio-frequency radiation by Zeeman-split levels of an atom or nucleus in a magnetic field, was a landmark in modern magnetism. Significant mainly for the insight provided into solids and liquids at an atomic scale, electron paramagnetic resonance (EPR) and nuclear magnetic resonance (NMR) spectroscopies were later complemented by that provided by the Mössbauer effect in 1958. Hyperfine interactions of nuclei and electrons provided a point probe of electric and magnetic fields at the centre of the atom. In a magnetically-ordered state, precession of the magnetic sublattices in a field leads to ferromagnetic resonance (FMR) at the Larmor precession frequency of  $28 \text{ GHzT}^{-1}$ . The ability to

measure the response of materials short timescales when they are out of equilibrium has been enhanced by pump/probe methods involving short intense, sub-ns pulses of energy from lasers or particle beams. Some of the methods involve special large-scale facilities, to which many users have access to supplement the facilities in their home laboratories. Communications among academic researchers intensified in the modern period — electronic communications have replaced postal reprint requests, and the scientific literature has become increasingly accessible. Collaboration between laboratories to address a particular problem as effectively as possible is increasingly common.

Of the new experimental probes of magnetism, neutron scattering was initially the most influential and generally useful. A beam of thermal neutrons from a nuclear reactor was first exploited for neutron diffraction by Clifford Shull and Ernest Wohlan in 1951, who used the magnetic scattering to reveal the antiferromagnetic order in MnO. Countless magnetic structures have been measured since, using specially-constructed research reactors at Chalk River, Harwell, Brookhaven, Grenoble and elsewhere. Excitations could be characterized by inelastic scattering of thermal neutrons, with the help of the three-axis spectrometer developed by Bertram Brockhouse in Canada to measure the change of energy and momentum. Complete spin-wave dispersion relations were used to provide a wealth of information on anisotropy and exchange. Spallation sources at Oak Ridge and elsewhere, which provide intense pulses of neutrons by collision of highly energetic protons with a target of a heavy metal such as tungsten, are most useful for studying magnetization dynamics.

Other beams produced at large-scale facilities that proved useful for probing magnetism were muons and especially synchrotron radiation. The intense, tuneable ultraviolet and X-ray radiation from the circulating electrons in a synchrotron allows the measurement of magnetic dichroism from deep atomic levels, permitting the separate determination of spin and orbital contributions to the magnetic moment by X-ray circular dichroism. The intensity of the radiation from synchrotrons and free-electron lasers is greatly enhanced by arrays of permanent magnets around the beam known as undulators or wigglers, that generate intense coherent or incoherent radiation, respectively. Bending electromagnets are used to direct and focus the charged particle beams.

Direct imaging of domain structures at surfaces or in thin films with light, electron microscopy or scanning probe, magnetic-force microscopy have all contributed to an improved understanding of micromagnetics. Bulk domain structures can be accessed, with difficulty, by neutron tomography. X-ray photo-electron microscopy offers fast time-resolved imaging of domains in thin films.

Increasing availability of commercial superconducting magnets from the late 1960s has led to a boom in diagnostic imaging of tissue based on pulsed proton NMR in magnetic fields of 1 – 3 T. Tens of thousands of these scanners in hospitals across the world provide images of hearts, brains and every sort of tumour. Superconducting magnets can now provide fields of over 20 teslas for NMR and general laboratory use. Coupled with SQUID sensors, ultrasensitive magnetometers capable of measuring magnetic moments of  $10^{-11}$  Am<sup>2</sup> are widely available. Larger fields of up to 30 T require expensive special installations with water-cooled Bitter magnets consuming many megawatts of electrical power. Resistive/superconducting hybrids in Tallahassee, Grenoble and Tokyo can generate steady fields in excess of 40 T. Still higher fields above 50 T demand millisecond pulses; the higher the field, the shorter the pulse; 200 T can be reached in small volumes with a single turn sacrificial coil. Even greater transient fields can be attained by explosive flux compression.

### **Materials and technology**

For many physical studies, magnetic materials are needed in special forms, such as single crystals or thin films. Skilled crystal-growers are assiduously cultivated by neutron scatterers and other condensed matter physicists. With large crystals, tensor properties such as susceptibility, magnetostriction and magnetotransport can be measured in any direction.

A far-reaching advance after 1970 was the appearance of multi-target thin-film growth facilities (sputtering, pulsed-lased deposition, molecular-beam epitaxy) in magnetism research laboratories. Ultra-high vacuum facilitated the study of surface magnetism at an atomic level, but much of the motivation was to investigate magnetoresistance or magneto-optics or of thin, high-quality metal films, and especially



the thin film multilayer structures that have contributed massively to the development of spintronics and magnetic data storage. An example of a fairly complex stack that, after suitable heat treatment, exhibits perpendicular magnetic anisotropy and 200% tunnelling magnetoresistance (TMR) is illustrated in Fig. 12.

Conventional electronics ignored the spin of the electron because unlike electron charge, electron spin is not necessarily conserved in scattering events. A conduction electron in a metal may undergo 100 scattering events before a spin flip. If the mean free path is 2 nm it will only have travelled about 12 nm before losing its spin memory. Unpolarized electrons acquire a spin polarization on traversing a couple of nanometres of cobalt, but the spin-polarized current does not go far in an insulator or nonmagnetic metal before losing its spin memory. Hence the choice of materials in a stack and their thickness is critical. Layers of an antiferromagnet such as  $\text{IrMn}_e$  are used for exchange bias to pin the magnetization of an adjacent ferromagnetic layer in spin valves from the mid 1990s. The anisotropic magnetoresistance  $\approx 1\%$  (AMR) of single a layer of permalloy was used for the first sensors or memory elements in the 1980s. A sandwich spin-valve structure with a nonmagnetic metal spacer layer that exhibited giant magnetoresistance  $\approx 10\%$  (GMR) was more versatile, with fixed and pinned layers oriented parallel for a switchable memory element and perpendicular for a linear field sensor. The moments were oriented in-plane in the first devices and perpendicular to the plane in later ones. Greater sensitivity was achieved in spin valves with an insulating tunnel barrier of amorphous  $\text{AlO}_s$  or crystalline  $\text{MgO}$  where greater tunnel magnetoresistance  $\approx 200\%$  could be achieved. The timeline for the adoptions of these sensors in read heads for magnetic recording where they have to read the stray fields just above the disc surface is illustrated in Fig. 13. The writer has always been a miniature electromagnet. The sensors, originally designed for magnetic recording, found important applications in partnership with magnetic nanoparticles in bio-assay.

The development of non-volatile thin film memory underwent a similar evolution beginning with thin film permalloy memory with a lattice of current carrying wires to create local magnetic fields sufficient to switch the bits, analogous to ferrite cores, in the 1960s. Then, after the discovery of giant magnetoresistance by Albert Fert, Peter

Grunberg and others in 1988, spin valve memories based on half-select magnetic field toggle switching appeared in the 1990s. The field switching was not scaleable, so a new generation of spin-transfer torque magnetic random-access memory developed around 2010 used the angular momentum of a spin-polarized current passing perpendicular to the stack to switch the free layer. In suitable conditions, the switch becomes an oscillator.

The spin Hall effect, rediscovered in 1999 by Jaime Hirsch, is the creation of a transverse spin current flowing perpendicular to a charge current in a heavy metal, due to spin-orbit scattering. It is harnessed in heavy metal/ferromagnetic bilayers to inject angular momentum into the ferromagnet and switch its magnetization by ‘spin-orbit torque’, another potential scheme for magnetic memory. Magnetic recording and spin electronics became major research preoccupations in the magnetic research community after about 1990. A cognate growing discipline is magnonics, where spin waves rather than electrons are used to transmit and process data.

A quite different, earlier preoccupation arose from studies of phase transitions in model magnetic systems in the 1970s, namely effect of atomic disorder and the absence of a crystalline lattice on magnetic order. A seed was shown by Pol Duwez in 1960 who first produced small samples of amorphous metal by splat cooling, but applications became feasible only after the invention in 1976 of continuous melt spinning, where a jet of molten metal impinges on a copper wheel rotating with a surface velocity of about  $50 \text{ ms}^{-1}$  to give a quench rate of up to  $10^6 \text{ Ks}^{-1}$ , sufficient to freeze eutectic metallic melts into amorphous solids. Other melts such as Nd-Fe-B became nanocrystalline. The first soft magnetic amorphous materials  $\text{Fe}_{80}(\text{P,B,C})_{20}$  were spun in 1976 by Robert O’Handley and Ryusuke Hazegawa and a range of Fe- Co- and FeNi-based alloys were subsequently commercialised the 1980s by Allied Chemical as *Metglas*. The amorphous alloys found niche markets in network transformers, components for power electronics and many kinds of magnetic sensors due to their exceptional magnetic softness. A parallel discovery made at Hitachi Metals by Yoshihito Yoshisawa in 1988 while trying to lower high frequency losses by pinning domain walls with micro-size crystallites was *Finemet*, a Fe-Si-B-Nb alloy with 1% of copper. This material is a composite of nanocrystals of Fe-Si in an amorphous matrix. It combines polarization of 1.25 T, larger than permalloy, and is as soft as cobalt based amorphous alloys, all with no cobalt. The

astonishing softness of nanocrystalline materials was explained a year later by Giseler Herzer at Vacuumschmelze, where similar alloys were being developed.

Perhaps the most far-reaching advances in bulk magnetic materials for electromagnetic applications in the modern period was the development of rare earth permanent magnets. They are more expensive to make than hard ferrites, but they offer stored energy densities that are an order of magnitude greater. First were magnets based on the binary intermetallic phases  $\text{SmCo}_5$  or  $\text{Sm}_2\text{Co}_{17}$  that were pioneered by Karl Strnat in the 1960s. A global cobalt supply crisis brought about by war in Zaire in 1979, led to a renewed effort to find an Fe-based substitute, which bore fruit in 1983 in two different ways. First was the discovery by Masato Sagawa at Sumitomo Special Metals of  $\text{Nd}_2\text{Fe}_{14}\text{B}$ , a tetragonal iron-rich interstitial phase with boron, using the methods of classic powder metallurgy. Favourable phase relations included a low-melting nonmagnetic Nd-rich phase that surrounded the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  grains and facilitated the development of coercivity. The properties were continuously improved over the following years with additives of Co or heavy rare earths (Dy, Tb) and optimized crystallite orientation and milling to increase the volume fraction and reduce the size of the hard magnetic crystallites. Many grades became available with a trade-off between remanence and coercivity, which determines the maximum operating temperature.

A different approach was adopted by John Croat at General Motors, who used melt spinning to produce isotropic nanocrystalline material that was useful for making polymer bonded material by injection or compression moulding. These have lower energy products than sintered magnet, but great flexibility for manufacture.

Nd-Fe-B magnets have grown to dominate the permanent magnet market. They radically changed the design of motors for many applications. They were indispensable for the voice-coil motors in slim hard-disc drives and enhanced considerably the power density of small motors — a quadcopter could not take off without NdFeB magnets. They improve the efficiency of high-power electrical machines and applications are burgeoning in new areas of motors for electric vehicles and robotics, and in large direct-drive wind turbines.

In summary, the consequences of near-instantaneous access to virtually unlimited stores of magnetically recorded data in centres distributed across the world, and the ability to acquire and copy it electronically at practically no cost to the user is the basis of the ‘big data’ revolution that we are in the midst of. However, the quantities of data are so enormous that energy costs may become prohibitive. The implications for human life and society are unpredictable but are likely to be as profound as on the previous two occasions when magnetism changed the World.

## **OUTLOOK**

Past record is no guarantee of future performance, so one must be wary of extrapolating the history of any science or technology very far into the future. Magnetism, like much of physics itself, has often been dismissed as ‘finished’ in the past, only to confound the doomsayers with some new twist or unexpected development. The current focus on spin electronics and nanoscale magnetism in artificially-structured thin film devices will surely be sustained for some time to come.

The behaviour of magnetism on increasingly short timescales, the influence of topology in normal and reciprocal space, and information transfer and processing using magnons rather than spin directly are topics that are likely to attract continued research interest.

Industrial applications of magnetism are based on the properties of about a dozen commercially-produced magnetic materials. The discovery of just one more could animate the subject for a decade. It seems unlikely, though, that much advance will be achieved on the magnetic values on the hysteresis loop. There has been no advance in saturation magnetization in a century over that of  $\text{Fe}_{35}\text{Co}_{65}$ , and coercivity can already be controlled, albeit with much care and effort, to almost any desired value. No Curie temperature has ever exceeded that of cobalt, which has been known since 1912. The new material will probably commend itself by a useful combination of magnetic and nonmagnetic (electrical, optical, mechanical....) properties.

Magnetism has served the miniaturization of information technology and electromagnetic drives well and may continue to do so in future. New frontiers in cell

biology have to be explored. There have been half a dozen paradigm shifts – completely new ways of seeing the magnet and its field – during the three thousand years encounter of magnetism with human curiosity. Magnetism has practically transformed the world on three occasions; who can say there will not be another?

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## **KEYWORDS**

Ferromagnetism; Lodestone; Compass; Electromagnet; Permanent magnet; Electron; Spin; Quantum mechanics; Exchange interaction; Coercivity; Magnetic recording; Micromagnetism; Spintronics; Magnetic units

## **GLOSSARY**

$H$  – magnetic field strength ( $\text{Am}^{-1}$ )

$B$  – magnetic induction (T)

$M$  – magnetization ( $\text{Am}^{-1}$ )

$c$  – speed of light,  $2.99792458 \times 10^8 \text{ ms}^{-1}$

$\epsilon_0$  – electric permittivity of free space,  $8.854 \times 10^{-12} \text{ C}^2\text{N}^{-1}\text{m}^{-2}$

$\mu_0$  – magnetic permeability of free space,  $4\pi \times 10^{-7} \text{ TA}^{-1} \text{ m}$

$m_e$  – mass of an electron,  $9.109 \times 10^{-31} \text{ kg}$

$e$  – charge on an electron,  $1.602 \times 10^{-19} \text{ C}$

$n_w$  – Weiss molecular field coefficient

$T_c$  – Curie temperature (K)

$\hbar$  – Planck's constant,  $1.055 \times 10^{-34} \text{ Js}$

$\mu_B$  – Bohr magneton,  $9.274 \times 10^{-24} \text{ JT}^{-1}$

$S$  – spin vector

$J$  – exchange integral (J)

## **SUGGESTED CROSS-REFERENCES WITHIN MAGNETISM**

Ferromagnetism; Paramagnetism; Diamagnetism; Magnetic domains; Magnetic materials and applications; Magnetic memory and recording; Spintronics

## **PACS CODES**

History of science, 01.65.+g

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Magnetic properties and materials, 75

Geomagnetism and paleomagnetism, 91.25.–r

Magneto-optical effects, 78.20.Ls

Magnetic devices, 85.70.–w

Magneto-electronics, spintronics, 85.75.–d

FIGURE CAPTIONS

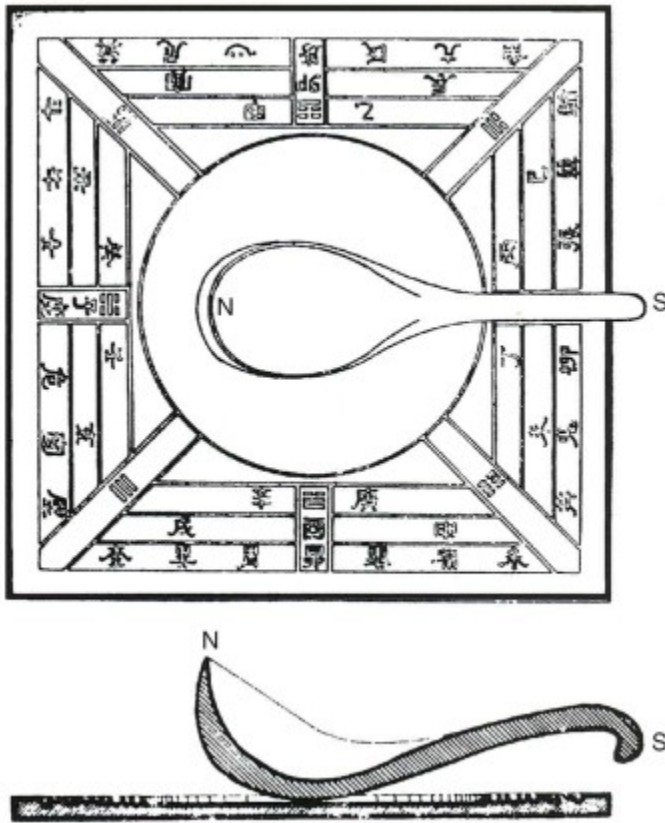


Figure 1 Baseplate and lodestone spoon of the South-pointer used in China from the first century B.C. (Needham 1962), courtesy of Cambridge University Press





Figure 2 15<sup>th</sup> century Portuguese mariner's compass (Boorstin 1992), courtesy of Editions Robert Laffont

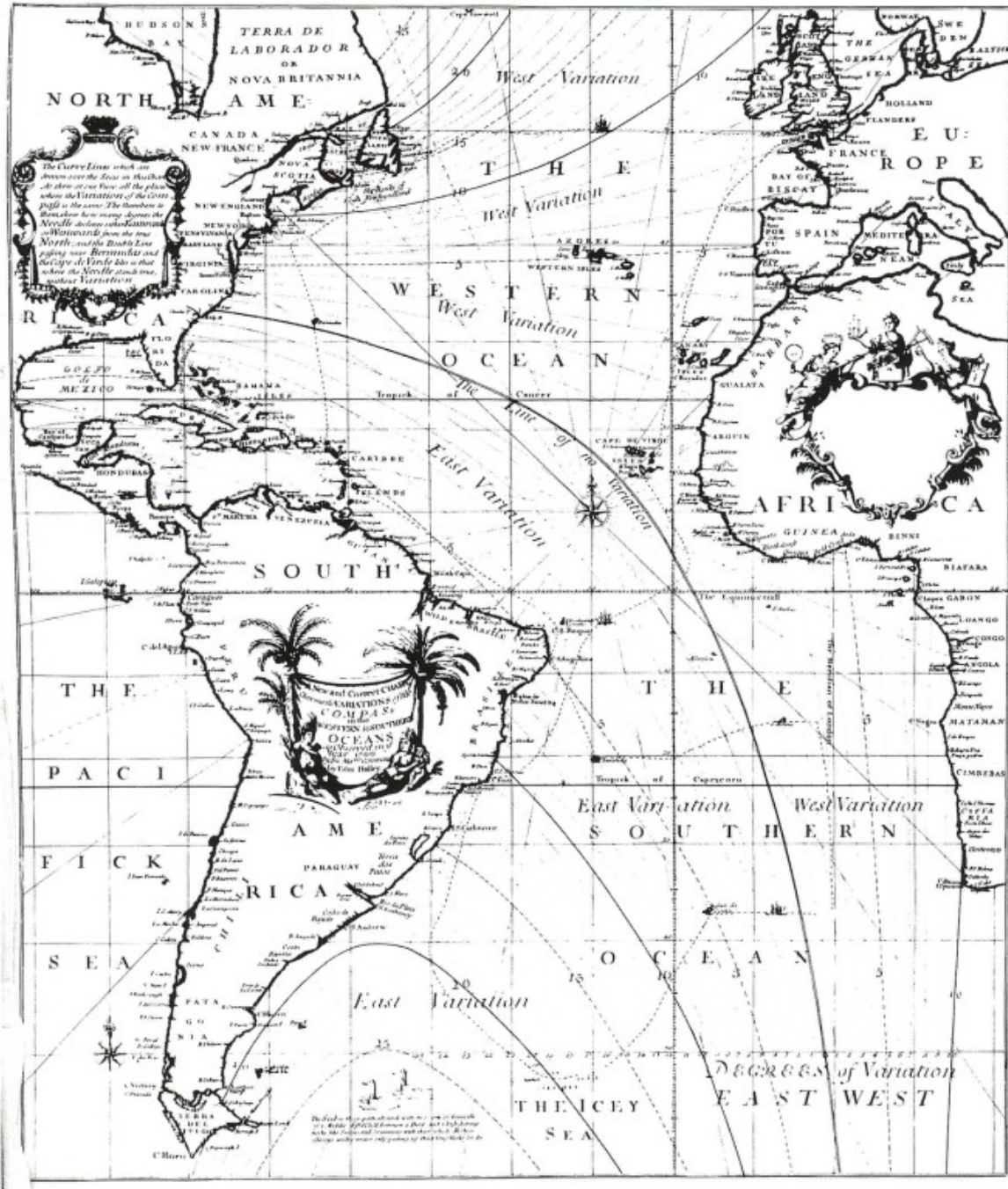


Figure 3 A section of Halley's world chart of magnetic variation published in 1700



Figure 4 Magnets of four centuries shown clockwise from the left; 18<sup>th</sup> century horseshoe magnet; 19<sup>th</sup> century electromagnet; 17<sup>th</sup> century lodestone; and 20<sup>th</sup> century  $\text{Nd}_2\text{Fe}_{14}\text{B}$

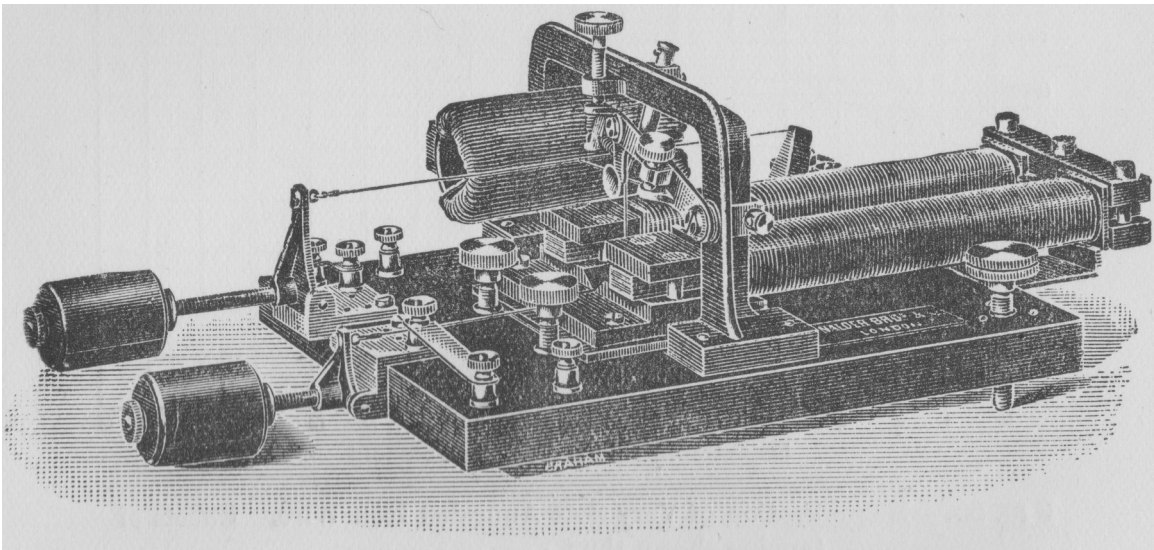


Figure 5 James Ewing's automatic hysteresis loop tracer. The sample is in the form of two long steel bars contained within the two horizontal solenoids (Ewing 1892)

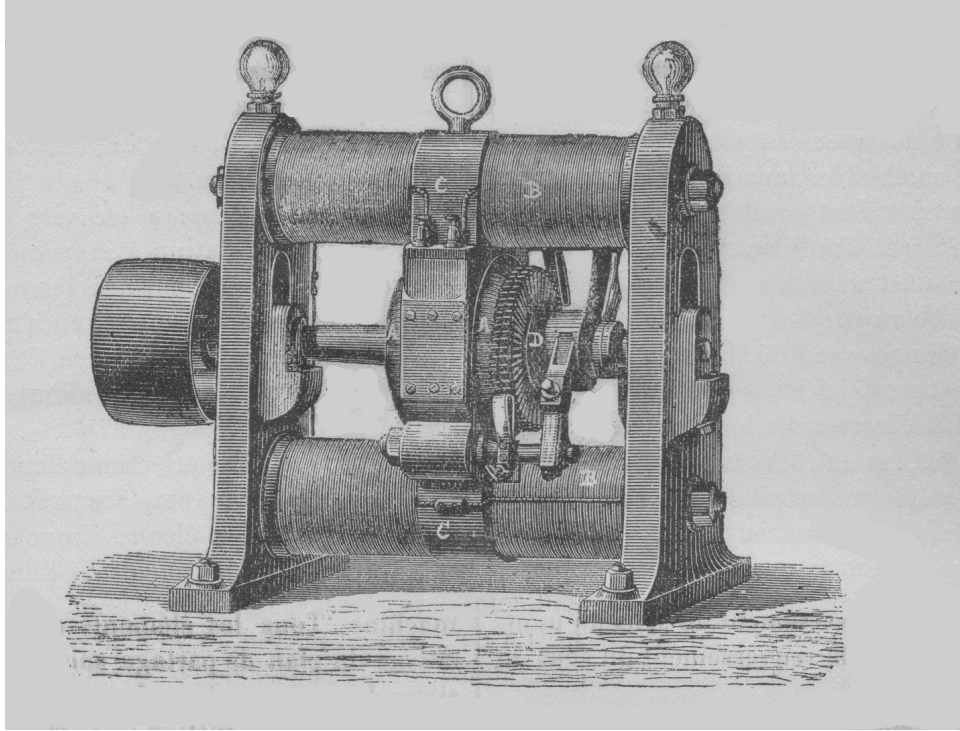


Figure 6 Zénobe Gramme's dynamo (1870)

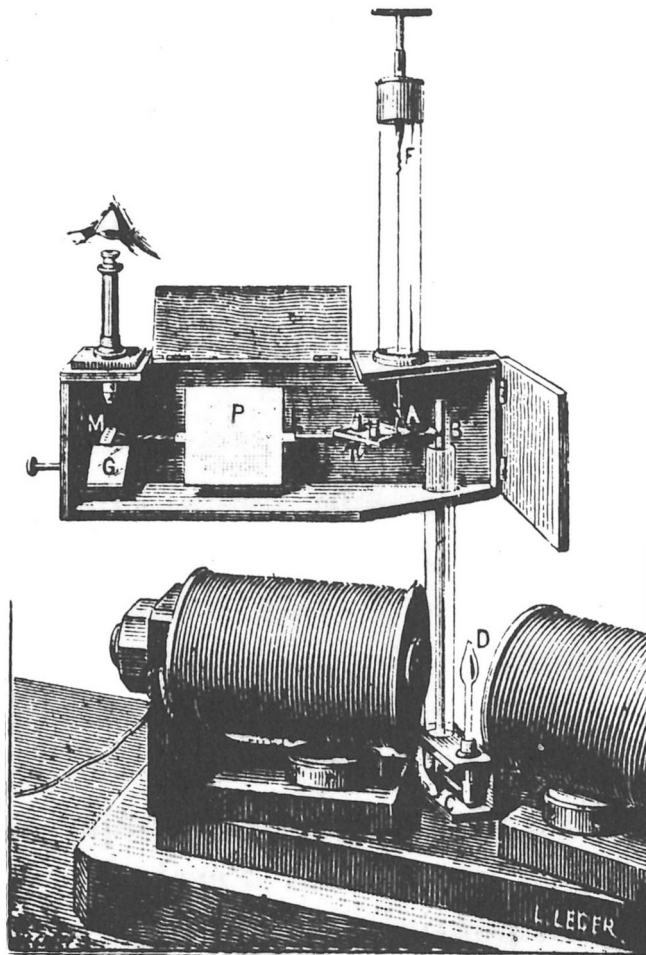


Figure 7 Pierre Curie's torsion balance used for quantitative measurements of magnetic susceptibility at high temperature in a horizontal magnetic field gradient (Curie 1895)



Figure 8 The 1930 Solvay Conference on Magnetism (Marage and Wallenborn 1995) courtesy of Université Libre de Bruxelles.

Back row: Herzen, Henriot, Verschaffelt, Manneback, Cotton, Errera, Stern, Piccard, Gerlach, Darwin, Dirac, Bauer, Kapitza, Brioullin, Kramers, Debye, Pauli, Dorfman, van Vleck, Fermi, Heisenberg.

Front Row: de Donder, Zeeman, Weiss, Sommerfeld, Curie, Langevin, Einstein, Richardson, Cabrera, Bohr, de Haas

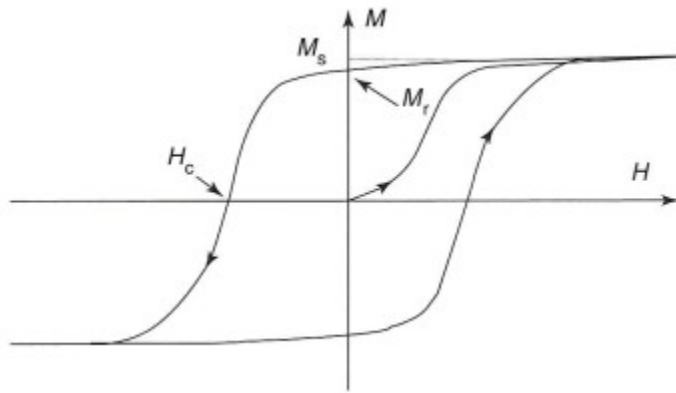


Figure 9 The hysteresis loop of  $M$  against  $H$  for a typical permanent magnet.  $M_s$  is the saturation magnetization,  $M_r$  the remanent magnetization at zero applied field, and  $H_c$  the coercive field required to reduce the magnetization to zero

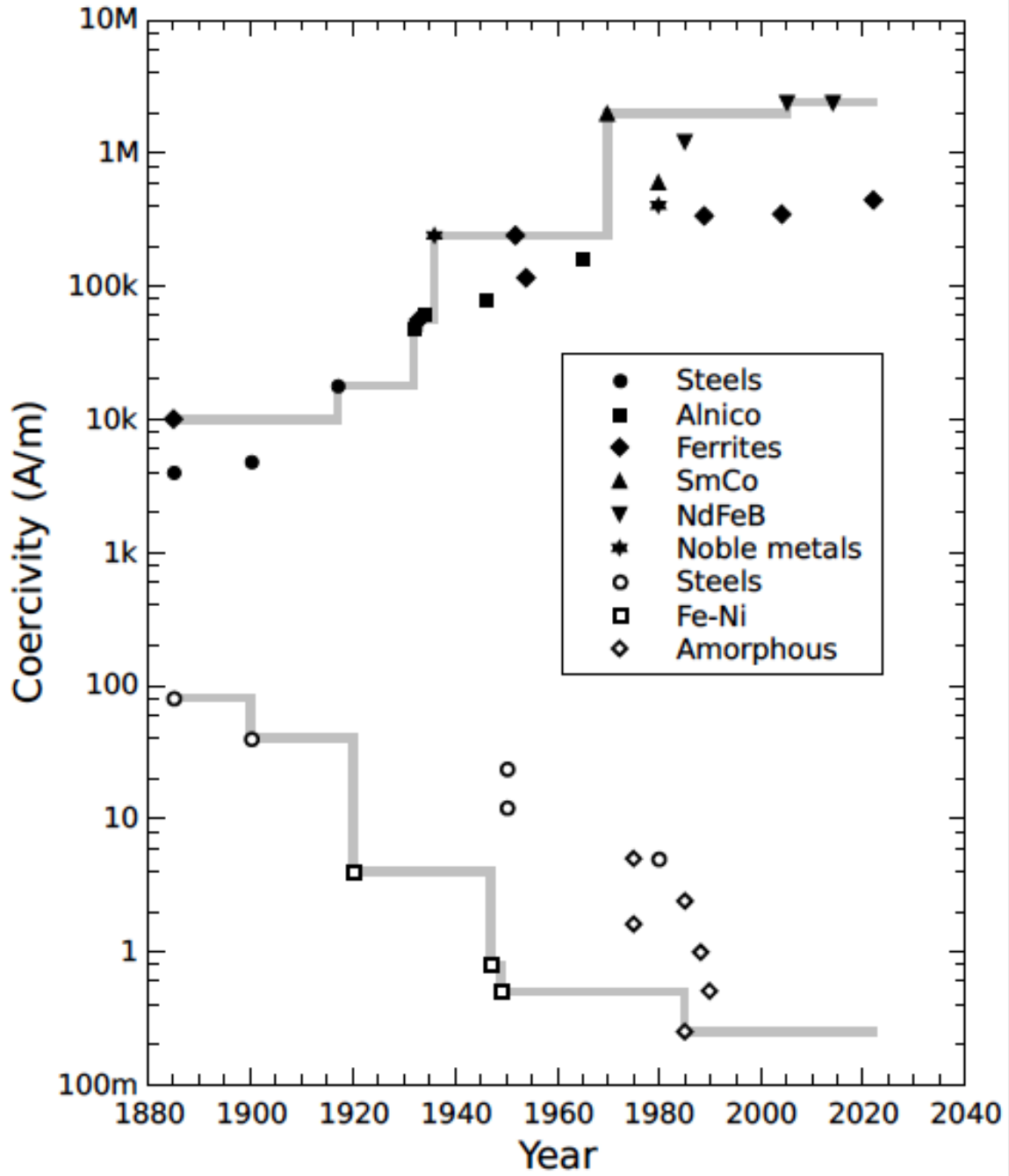


Figure 10 The development of coercivity in the 20<sup>th</sup> century



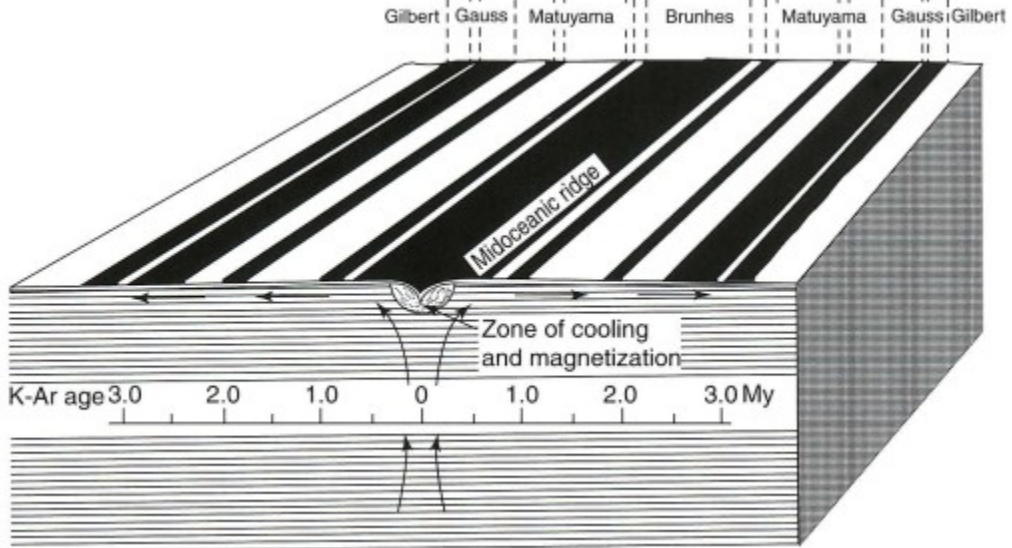


Figure 11 Sign of the thermoremanent magnetization measured across the floor of the Atlantic ocean. Random reversals of the Earth's field, which are dated from other igneous lava flows, follow a chronological pattern which determines the rate of continental drift (McElhinney1973), courtesy of Cambridge University Press)

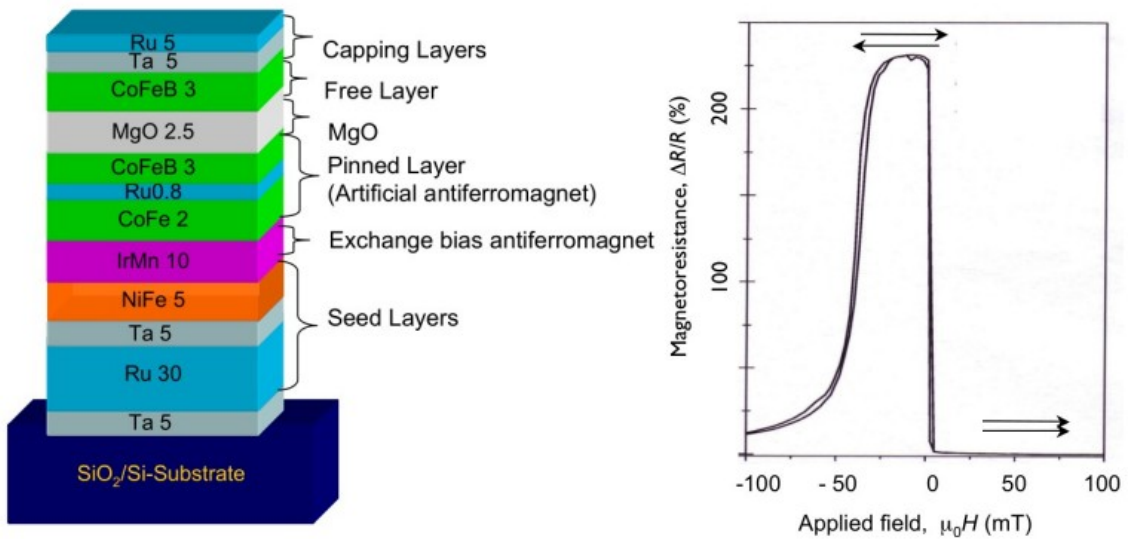


Figure 12 A thin film stack with a magnetic tunnel junction (left). The magnetic layer below the MgO tunnel barrier is pinned by coupling to the antiferromagnetic IrMn<sub>3</sub> layer to produce the magnetoresistance characteristic (right).

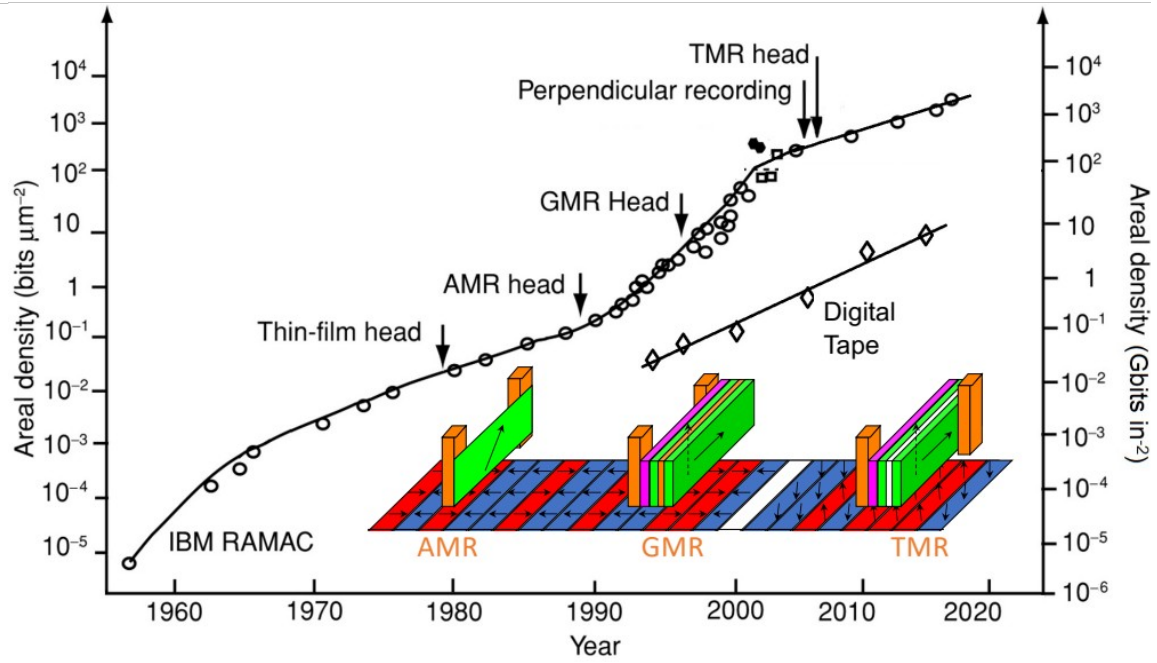


Figure 13 Exponential growth of magnetic recording density over 60 years, with an illustration of the read/write technology.