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Magnetism in future

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Abstract

As a backdrop to help focus on the shape of magnetism in future, seven ages in the history of magnetism from ancient times to the 20th century are discussed. Drivers and beneficiaries are identified in each age. Some current trends in the areas of hard magnets, soft magnets and magnetic recording are described and extrapolated. Key developments are the ability to structure materials and devices on characteristic magnetic length scales in the nanometer range, and the emergence of the new science of spin electronics. Some speculative suggestions about areas where breakthroughs could be expected in future are included. © 2001 Elsevier Science B.V. All rights reserved.

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1. Past

It is easier to describe the past than to predict the future. Although past record is no guide to future performance, an appreciation of what has gone before provides a perspective on the present situation, and allows current trends to be extrapolated a little way ahead. It also prepares us for breakthroughs and paradigm shifts, with unforseeable consequences. Who would have foreseen in 1820 that Oersted's accidental discovery of the relationship between electricity and magnetism could have led within 80 years to electrification of the planet, and girding of the globe with intercontinental telegraph cables and wireless systems offering communication at the speed of light? Who could have predicted that the discovery of the spin of the proton would have led to techniques for imaging the human brain?

In broad terms, the three-thousand year history of magnetism can be divided into seven 'ages', outlined in Table 1. The ages are of different duration and character, and overlap to some extent. A specific technology such as magnetic recording may have its origins in the Electromagnetic Age (1820–1900), but its mass implementation belongs to the Age of Applications (1960–1995), and its future lies in the new Age of Spin Electronics. The first age lasted two millennia, while three ages were packed into the 20th century. The great achievements are mentioned for each age, with names of some key individuals, representative materials and an indication of the main drivers and beneficiaries of the research. The golden Age of Understanding (1900–1935), which marks the intellectual summit in the history of magnetism, has been followed by ages where the benefits of magnetic technology have been placed in the hands of many, perhaps even most, of the people on Earth through the operation of the global market economy.

The growth of magnetic research in the 20th century was remarkable. Thirty-five people attended the 1930 Solvay Conference on Magnetism, whereas there have been about 1000 at recent ICM meetings.

Besides the lesson of unsustainable growth, another lesson from the past is that theoretical understanding is no prerequisite for practical advance. The Age of Understanding situated solid state magnetism in the realm of relativistic quantum mechanics of the electron, but this knowledge had no practical influence on the development in the 1930s of Alnico or new applications such as

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Table 1
The seven ages of magnetism

Age	Time	Key names	Driver	Achievements	Materials	Applications/devices
Ancient	− 1000–1500	Shen Kua Petrus Peregrinus	State	Force field, induced magnetism, thermoremanence	Iron, Lodestone	South-pointer, compass
Early	1500–1820	Gilbert Descartes D. Bernoulli	Navy	Earth's field	Iron, Lodestone	Dip circle, Horseshoe magnet
Electromagnetic	1820–1900	Oersted, Ampère, Faraday, Maxwell, Hertz	Industry (infrastructure)	Electromagnetic induction, Maxwell's equations	Electrical steels	Motors, generators, telegraph, wireless, magnetic recording
Understanding	1900–1935	Weiss, Bohr, Heisenberg, Pauli, Dirac, Landau	Academy	Spin, Exchange interactions	Alnico	
High frequency	1935–1960	Bloch, Pound, Purcell	Military	Microwaves, EPR, FMR, NMR	Ferrites	Radar, television, MRI
Applications	1960–1995	—	Industry (consumers)	New materials miniaturisation of magnetic circuits	Nd–Fe–B, Sm–Co	Consumer electronics
Spin Electronics	1995– ⋯	—	Industry (consumers)	Thin film devices	Multilayers	High density magnetic recording, MRAM …

tape recording. Incremental technology has a logic and momentum of its own, independent of basic theory. It is not necessary to have a fundamental understanding of something in order to improve it. Conversely, new theoretical possibilities such as spin-polarized electron tunneling may wait for a generation or more until technology has developed to the point where they can be effectively exploited. The desire for discovery and understanding and the desire for optimization of practical products have been the twin drivers of magnetic research for two millenia. This is expected to continue in future, but the symbiotic relationship between theory and practice is rarely a straightforward matter of cause and effect.

As regards development of the ferromagnetic materials on which practical progress in magnetism largely depends [1], the most significant advance in the 20th century was the mastery of coercivity (Fig. 1) resulting from combined control of magnetocrystalline anisotropy and microstructure. From a set of poorly differentiated hard and soft steels in 1900, we have progressed to the point where the anisotropy constant K_1 spans five orders of magnitude. This means that we can now have whatever shape hysteresis loop an application demands. As a result, the prospects of permanent magnets have been transformed, and the path cleared for efficient electrical machines and high-density magnetic recording.

There has been great progress in improving the secondary properties of ferromagnets. Magnetostriction can be varied more or less independently of anisotropy in the range of $0 < \lambda_s < 10^{-3}$. Large intrinsic and extrinsic (microstructure-related) magnetoresistance effects have been discovered. Materials and multilayers have been devised which show substantial magneto-optic Kerr and Faraday rotation. But, despite decades of intense materials research, there has been no advance whatever on the records for the primary intrinsic properties of Curie temperature (Co; $T_C = 1390$ K) and spontaneous polarization at room temperature (bulk $Fe_{65}Co_{35}$; $J_s = 2.45$ T). Of course, materials such as new rare-earth alloys for permanent magnets have been found which offer combinations of properties including high T_C and high J_s, but the records of Co and $Fe_{65}Co_{35}$ still stand after about 100 years.[1]

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[1] A possible exception is α"$Fe_{16}N_2$ where there is a disputed claim of a room-temperature polarization of 2.7 T at room temperature in thin films [2].

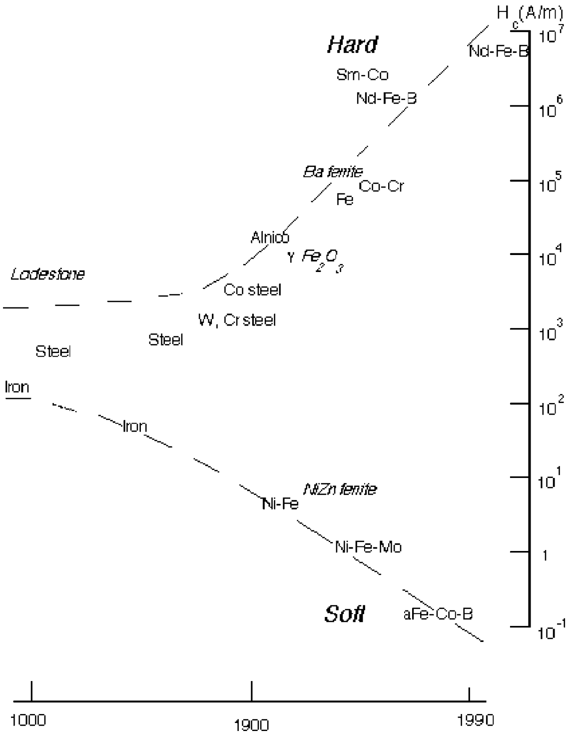

Fig. 1. Development of coercivity in the 20th century.

2. Present

One overview of the present state of magnetism is provided by the market for magnetic materials in the three broad areas of hard magnets, soft magnets and magnetic recording. The market, worth about 30B$/year, is broken down as shown in Fig. 2. The figures come to life when they are converted to the average amounts produced for everyone on earth, including 80 g of hard ferrite, 1 m^2 of magnetic tape, < 10% of a hard disc and 0.25 m^2 of electrical sheet. Growth overall is about 10%/year. Almost all of this market is accounted for by just a dozen materials, listed in Table 2. Hard and soft materials are commodities, finished in simple forms like arc segments and thin sheet for laminations. In magnetic recording, semihard material in particulate or thin film form is processed into tape or disk media, and soft materials in thin film stacks are processed into read and write heads. The value there resides in the structure, not in the material itself.

If Fig. 2 summarizes the economic impetus for research in magnetism at present, the intellectual drivers are less easy to quantify. In recent times, magnetic systems have been central for the understanding of phase transitions, including those in low dimensions and in the presence of disorder, as well as the rich many-body physics of highly correlated electrons, and issues of metastability and irreversibility. The high-T_C problem has a strong magnetic dimension. More important in future may be the problem of quantum information storage. But the most fertile ground in the coming decade is likely to be the exploration of nanoscale magnetism, as it becomes increasingly possible to structure materials on the magnetic length scales summarized in Table 3 for a typical hard magnet and a typical soft magnet. These are defined in terms of the magnetic hardness parameter $\kappa = \sqrt{(\mu_0 K_1/J_s^2)}$. Values of κ for Fe and $Nd_2Fe_{14}B$ are 0.12 and 1.54, respectively. Other nanoscopic length scales which are central in the emerging science of spin electronics are the mean free path for ↓ and ↑ electrons (typically 1 and 5 nm in 3d ferromagnets), and the much longer spin diffusion length for spin-flip scattering. The Fermi wavelength (≈ 0.5 nm) can also play a role.

Progress in each of the three applications areas is constrained by cost and technical performance of the materials. The operating temperature for almost every practical application has to be room temperature or above. Trends have been summarized in Ref. [1]. The technical performance of hard magnets is determined by their maximum energy product $(BH)_{max}$, which doubled every 12 years during the 20th century, a progress that was almost entirely due to improvements in coercivity of the hard magnets rather than any improvements in their polarization [3]. For a perfect square loop, $(BH)_{max} \leqslant (1/4\mu_0)J_s^2$. Even if the polarization were to reach 2.45 T, the energy product would not exceed 1200 kJ m^{-3}. It seems unlikely that we will ever succeed in doubling the current energy-product record of Nd–Fe–B magnets (450 kJ m^{-3}) more than once again in conventional hard magnets. Prospects for superconducting permanent magnets with very high energy products [4,5] seem set to remain an option only at cryogenic temperatures.

Progress with soft magnetic materials has also been impressive. Low-frequency losses of electrical steel have diminished to the point where they are insignificant compared to copper losses. The static permeability has also been increased to huge values in materials with near-zero anisotropy and near-zero magnetostriction. Nanostructure engineering of bulk material has become a valuable new tool for reducing anisotropy in exchange-coupled soft nanocomposites [6] and also for increasing polarization in hard nanocomposites [7]. Saturation polarization remains the glass ceiling for further development of both hard and soft materials. Furthermore, losses in the megahertz range are a bottleneck for the development of switched-mode power supplies. Permeability at frequencies in the high megahertz range is an obstacle for further development of high-density recording.

The areal density of magnetic recording has been increasing over the past few years at 60%/annum due to concurrent optimization of successive generations of thin film read heads (induction/AMR/spin valve),

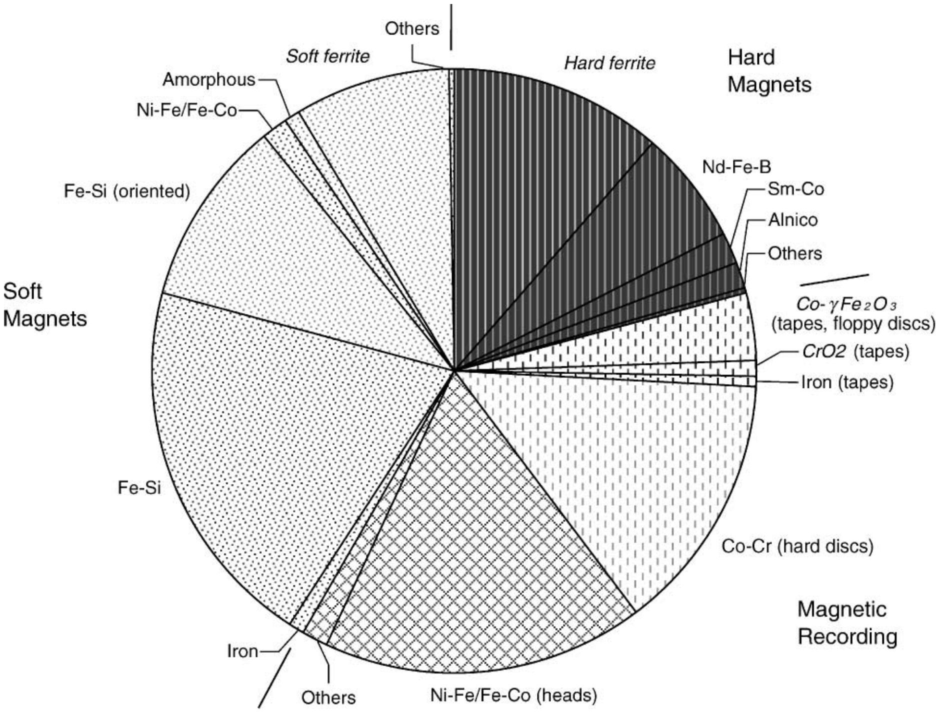

Fig. 2. Global market for magnetic materials. The total in 1999 was about 30 B$.

Table 2
Practically useful magnetic materials

Material	Type	Form
Silicon–Iron	Soft	Sheet
(Ni, Zn) and (Mn, Zn) ferrite	Soft	Sintered
Metallic glasses	Soft	Melt spun ribbons
Ni–Fe, Fe–Co	Soft	Thin film
Co–Cr	Semihard	Thin film
Co : γFe_2O_3	Semihard	Powder
CrO_2	Semihard	Powder
Alnico	Hard	Cast, sintered
Sm–Co	Hard	Sintered
$Nd_2Fe_{14}B$	Hard	Sintered, bonded
$(Sr/Ba)Fe_{12}O_{19}$	Hard	Sintered, bonded

miniaturization of the planar write head and perfection of Co-based in-plane thin film media. Extrapolation of present trends to 2005 brings us to 100 Gbits/in^2, or 150 bits/μm^2. Classical moving-medium magnetic recording has proved amazingly resilient with immense capacity for self-improvement, but it must run out of track in the next decade. Perpendicular recording with patterned media may succeed in postponing the impact of the superparamagnetic limit [8] by recording on a single monodomain rather than a patch of a few hundreds of them, but thermal stability must eventually become the limiting factor.

A search for new materials with improved combinations of properties, not least of which is processabilty, is ongoing in many applications areas. The list of different ferromagnetic materials which have found large-scale industrial application is remarkably short (Table 2), in view of the thousands that are known to order ferromagnetically. The effort needed to add a new one should not be underestimated. We are moving beyond ternary to quarternary alloys. Emphasis is shifting from looking for completely new materials to making functional composites and bulk nanostructures, or else nanostructured thin film stacks to support the science of spin electronics in the new age.

3. Future

So what of the future? What new ages of magnetism lie ahead? What will the drivers be? Will magnetism survive?

As regards materials development, it would be naïve to extrapolate trends established in the 20th century very far into the 21st. Fundamental limitations on polarization, the superparamagnetic limit and ferromagnetic resonance constrain the future improvements likely for hard magnets, magnetic recording and losses in soft materials for high-frequency applications.

Table 3
Magnetic length scales in nm

Length	Symbol	Definition	Fe	$Nd_2Fe_{14}B$
Exchange length	l_{ex}	$\sqrt{(\mu_0 A/J_s^2)}$	1.5	1.9
Coherence radius	R_{coh}	$(\sqrt{24})l_{ex}$	7	9
Domain wall width	δ_w	$\pi l_{ex}/\kappa$	40	3.9
Single-domain size	R_{sd}	$36\kappa l_{ex}$	6	107
Superparamagnetic blocking radius at 300 K	R_b	$(6k_B T/K_1)^{1/3}$	8	1.7

Materials research, however, may be transformed in two ways by computer power. One will be the ability to predict the structure, stability and intrinsic magnetic properties of new phases in silicio before setting foot in the laboratory. Already magnetic moments of intermetallic compounds can be predicted to within a few percent using the local spin density approximation, and there is progress towards calculating the anisotropy correctly, an energy which is only $\approx 10^{-6}$ of the binding energy. A recent example of computational magnetism was the prediction, yet to be confirmed, of room-temperature ferromagnetism in semiconducting $(Zn_{0.95}Mn_{0.05})O$ and $(Ga_{0.95}Mn_{0.05})N$ [9]. A fully dopable room-temperature magnetic semiconductor is a prize that would transform the prospects of spin electronics. The other way in which computer power will come to bear is in simulating accurately the influence of microstructure or nanostructure on extrinsic properties such as coercivity or giant magnetoresistance. Future watchwords may be ‘computation before synthesis; simulation before sputtering’.

On the other hand, methods of systematic materials science which involve experimental exploration of huge numbers of compositions and testing for a specific physical property are being introduced [10] which permit the complexities of ternary and quarternary phase diagrams to be charted automatically.

The nanoscale world is set to become the focus of magnetism in the new age. As improved techniques of mesoscopic-scale patterning and self-assembly emerge, it will become possible to pattern devices on any of the characteristic length scales of Table 3. Already, optimized spin valve stacks include as many as 15 layers of seven different materials, including cobalt interface dusting layers that are barely a monolayer thick [11]. Magnetic random-access memory is likely to become a reality on some scale within the next few years.

Increasing miniaturization of magnetic circuits will lead to integration of magnetic functionality with silicon micromechanics (MEMS). Another result may be the lifting of the constraint that all practical applications of magnetism should be at room temperature or above. The benefits of operating miniature devices at temperatures of order 10 K, where so much research has been done, could be immense. Limits on polarization and minimum superparamagnetic particle size would be raised. Superconductivity could be exploited. When reliable, miniature cryocoolers become a reality, the incremental improvements in magnetic technology will be impressive. Even if the technology proves impractical at the level of personal, hand-held products, we could have it in the home, and certainly use it in central facilities, like servers. Another attraction of the combination of low-temperature and nanoscale patterning is the possibility of overcoming the frequency limitations in magnetic devices by quantum tunneling. Single-electron spin electronics and magnetic quantum computing will probably demand cryogenic temperatures. More generally, magnetism will tend to become integrated with disparate subjects such as electronics, optics and biology in a series of new hybrid technologies.

On another scale, magnetic fields are likely to be exploited increasingly in materials processing, not only of magnetic materials and structures like permanent magnets and spin valves, as at present, but also of nonmagnetic materials such as silicon. The scale is that of the silicon wafer; 6”, 8”, 12”, etc. Magnetic fields are able to control the hydrodynamic flow and impurity concentration during crystal growth of large silicon boules [12]. Fields also influence electrodeposition [13] and turbulence. These areas are not completely understood. The use of permanent magnets in place of electromagnets to generate fixed and variable fields up to about 2 T is likely to increase in view of the energy saving, cost and size advantages.

When attempting to pick long-shot prospects or to anticipate future paradigm shifts, it may be useful to look at what is not understood—those mystery areas where the effects themselves are obscure, not just their explanation. It is worth recalling that a long time may elapse between the discovery of a phenomenon and a satisfactory physical explanation. Examples are superconductivity, the molecular field, and modern magnetism itself. A hundred years elapsed between Ampère’s observation that a magnet is equivalent to a current-carrying coil, and Bohr’s explanation of just how a perpetual surface current density of order 1 MA/m can exist in iron without melting it.

Two areas where there are interesting claims:

1. the influence of a magnetic field on nucleation and precipitation of nonmagnetic solids from a liquid—examples are the deposit of calcium carbonate from saturated solutions [14], crystal growth [15] and wax formation in oil wells [16];
2. the ability of a magnetic field to influence neurone activity [17,18] or the sensation of pain [19].

An imaginative investigation of any one of these phenomena might lead one to a new appreciation of magnetism and open the way to original applications that can sustain the research community in the future.

4. Conclusions

With the primacy of economics, the place of scientific research in the 'economy' is analyzed as never before. Magnetism is a science with strong fundamental and applied aspects, so it is interesting to try to identify the nature of the knowledge generated, the uses made of it and the social interactions involved (Fig. 3). The global effort of magnetic research and development can only be sustained at a level commensurate with public and private investment in our enterprise, which can change abruptly as exemplified by the decline of the Institutes of the Academies of Science of the former socialist states. The cost of our community is of order 1 B$/year.

Insofar as magnetic research is based in universities, it will flourish only if it continues to uncover new ideas and phenomena, which attract the attention of students. If the research is supposed to be justified in terms of practical applications, return should ultimately be commensurate with investment.

Improved, web-based information dissemination systems which have recently allowed us to keep abreast of the information explosion will reduce the scope for rediscovery and reworking what was already in the literature one or two decades previously. It is possible they will compensate for the fragility of expertise and knowledge built up over the years in areas which are no longer very active. Overall, the short-term future of magnetism looks exciting. In the longer term, the future of our science depends on what, if we knew now, would surprise us.

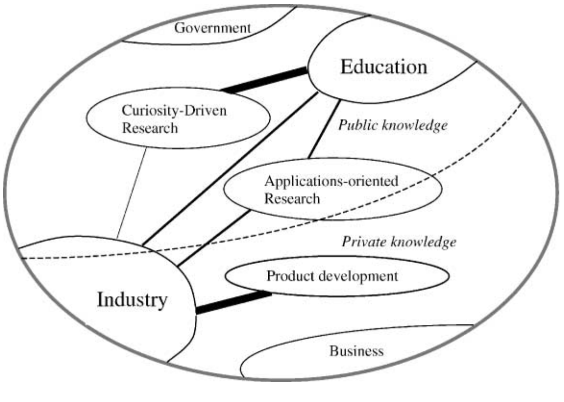

Fig. 3. Interactions in magnetic research.

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