Order and **disorder: frustrated magnetism** sets the example

Magnetic materials provide a particularly good illustration of 'frustration', where the elements of a complex system are unable to follow their individual tendencies to minimise their energies of interaction. These materials offer examples of frustrated systems *without disorder*, and also, with spin glasses, frustrated systems *with disorder.* Both afford physicists theoretical and experimental tools that help to gain a better understanding of the world around us.

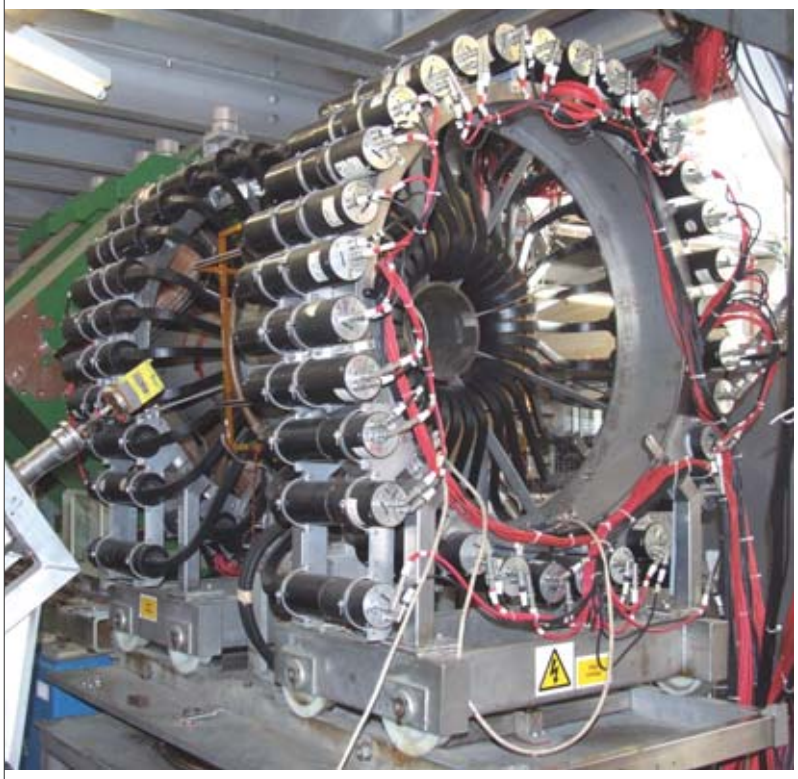


Photo courtesy of the ISIS Pulsed Neutron and Muon Source

Experimental set-up for muon spectroscopy at the ISIS Facility, Rutherford Appleton Laboratory (United Kingdom). This method was used to study the ground states of mixed oxides of magnetic and non-magnetic materials. Photo courtesy of the ISIS Pulsed Neutron and Muon Source.

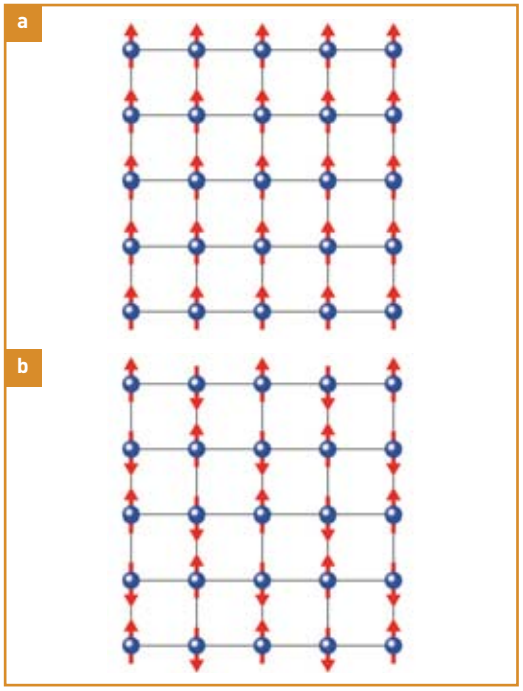


Figure 1.
Orders of magnetic moments in a square lattice.
(a) Ferromagnetic. (b) Antiferromagnetic.

It is the **magnetisation** of a compass that makes it align with the **Earth's magnetic field** (**Focus D**, *The Earth's magnetic field, weak but vital*, p. 99). On a macroscopic scale this magnetisation results from the total effect (vectorial sum) of the microscopic **magnetic moments** of the **atoms** in the material of the instrument. It is due to **quantum** interactions among these magnetic moments. These interactions, which involve **electrons**, belong essentially to two categories: **ferromagnetic** and **antiferromagnetic**. Ferromagnetic interactions tend to align magnetic moments or **spins** of neighbouring atoms the same way, i.e. parallel. This is what happens in a material used to make **permanent magnets** or store information in our computer hard disks. Antiferromagnetic interactions, on the other hand, favour opposite alignment of these moments, *i.e.* they tend to align neighbouring magnetic moments head to tail, or antiparallel, to give an 'antiferromagnetic' structure in which the total magnetisation is null. Figure 1 illustrates these two possibilities for atoms located in a square lattice. The magnetic orders that are formed, whether ferromagnetic or antiferromagnetic, are seen only below a certain temperature. Above a *critical temperature* specific to the material, spins fluctuate rapidly and are disordered: they are said to be in a **paramagnetic** state. The transition occurs when the **thermal agitation** energy of the spins overrides the magnetic interaction energy. This transition temperature is called the **Curie temperature** for ferromagnetic systems and the **Néel temperature** for antiferromagnetic systems. In the vast majority of cases it is below ambient temperature. The materials used for compasses or data storage devices are of course exceptions to the rule.

Geometrical magnetic frustration

Geometrical frustration is a property of matter with implications extending far beyond magnetism.

In the two examples of ferro- and antiferromagnetism, the magnetic moments (most often equated, for simplicity, with the 'spin' of the electrons, which is at the basis of magnetism) have an ordered structure, the magnetic equivalent of the **crystalline** order of the positions of atoms in an ordered solid. If the temperature is high enough, a solid melts to form a liquid in which the positions of the atoms move about randomly. Likewise, a magnetically ordered material 'melts' to form a phase (called a paramagnetic phase) in which the orientations of the magnetic moments fluctuate randomly.

Let us now consider the case of a crystalline structure in which the magnetic moments are at the vertices of triangles and interact antiferromagnetically (Figure 2a). Clearly, the first two spins can be aligned to satisfy this condition, but there is no way the third spin can be aligned antiparallel to the first two. Here the interactions between pairs of magnetic moments cannot all be satisfied simultaneously. This situation is termed **magnetic frustration**. It is called *geometrical* because it results solely from the geometry of the system. The system cannot minimise all the interaction energies simultaneously and so it finds a compromise to minimise the overall energy.

For the triangle considered here, the three spins will, for example, position themselves at an angle of 120° to each other.

A massively degenerate ground state

One of the lattices in which the effects of geometrical frustration are important is the kagome lattice, named after a figure of traditional Japanese basketwork. This lattice (Figure 2b) is made up of triangles connected to each other by their vertices. As each vertex belongs to only two triangles, the lattice is said to have low *connectivity*. The result is that the configuration adopted by a given triangle will have little influence on that of its neighbours. Thus, at the macroscopic scale, which corresponds typically to 10^{20} triangles, the system can adopt an extremely large number of configurations because all of them have the same energy. The ground state of the system is then said to be *massively degenerate*. This is one of the features that distinguish geometrically frustrated systems from ordinary systems in which there is only one, well-defined, ground state, i.e. state of lowest energy, undisturbed by thermal agitation.

Spin liquids

Geometrical frustration thus causes the system to remain paramagnetic down to very low temperatures, tending to absolute zero. In addition, owing to the degeneracy described above, the system will be able to switch among different configurations in the ground state and so remain dynamic. This state, characterised by short-range dynamic magnetic correlations, is called a *spin liquid*, by analogy with other liquids, which present similar structural correlations. Spin liquids are attracting a lot of attention from condensed matter physicists. Quantum effects are expected from such states that remain dynamic right down to absolute zero, for example collective magnetic excitation involving fractional quantum numbers.

Until now, only the 'exchange' interactions between two neighbouring spins have been considered, as these are dominant. In real materials, however, other interactions come into play. These include exchange interactions between more remote neighbours or dipole interactions. Dipole interactions are much weaker than exchanges between near neighbours and so influence the behaviour of traditional magnetic materials only moderately. By contrast, in frustrated systems, because of the type of equilibrium imposed by their geometry, these interactions, which are usually neglected, will often be determining. Other important variables to be taken into account are magneto-crystalline **anisotropy**, which causes magnetic moments to line up according to the particular directions of the crystal lattice, and magneto-elastic coupling, which can occur between spins and the crystal structure.

The relative intensities of all these interactions lead to a broad range of ground states, some of which are specific to geometrically frustrated systems. In the last ten years, several hitherto unknown states have been identified by various teams in different parts of the world. Thus, even states that may seem banal at first sight, such as magnetic order, can have unusual specific features that challenge scientists' ordinary intuition. Two such states studied in the CEA's SPSMS laboratory (1) are presented here.

A frustration model

The materials in which these new properties have been observed are mixed metal oxides of general chemical formula $R_2T_2O_7$. One metal (R) is magnetic and the other (T) not. The R atoms are those of **elements** belonging to the **lanthanides** or **rare earths** in Mendeleev's periodic table, which are also constituents of the materials used for permanent magnets. These mixed oxides crystallise in a structure called pyrochlore, named after a mine-

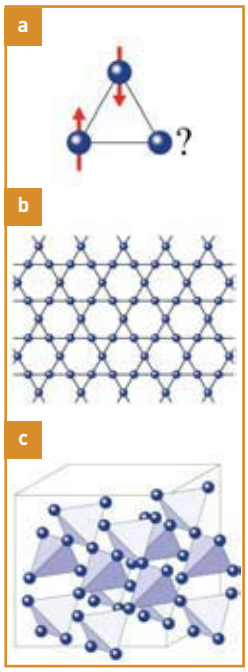
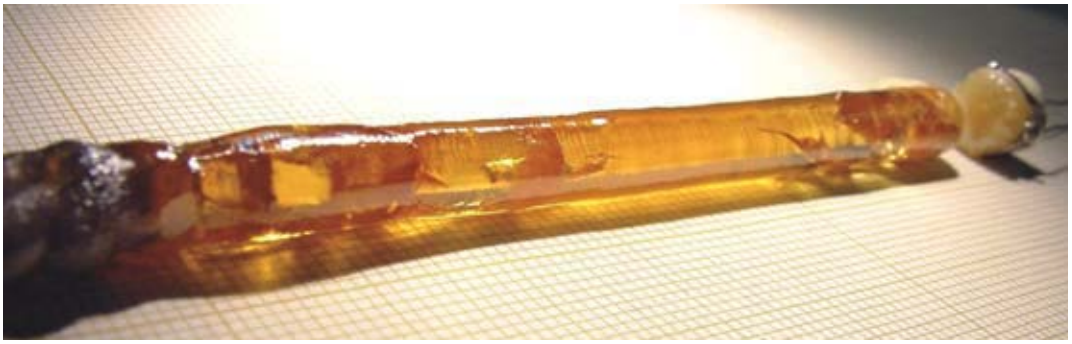


Figure 2.
(a) Three spins in an antiferromagnetic interaction on a triangle.
(b) Kagome lattice.
(c) Pyrochlore lattice.

(1) SPSMS: Department of Statistical Physics, Magnetism and Superconductivity of the Institute for Nanoscience and Cryogenics (Inac, ex-DRFMC). The results were obtained jointly by researchers at CEA Grenoble and CEA Saclay (SPEC, Laboratory of Condensed Matter Physics) together with the **Rutherford Appleton** Laboratory, United Kingdom, and the **Paul Scherrer Institute**, Switzerland.



C. Marin/DRFMC/DSM/CEA

Crystal of an oxide with a pyrochlore structure (different from those of Figure 3) synthesised in the SPSMS laboratory (Department of Statistical Physics, Magnetism and Superconductivity). The graph paper gives the scale.

ral they are related to. In the oxides studied by the SPSMS in Grenoble, the lattice formed by the magnetic elements is composed of regular tetrahedra linked together by their vertices (Figure 2c). This makes them three-dimensional analogues of the kagome lattice described above. The high symmetry of this structure – all the triangles that compose it are equilateral – and its low connectivity – each atom belongs to only two tetrahedra – make it a good model for the study of the effects of frustration. In addition, the compounds presented here have no notable structural defects (lacunae or site exchanges).

A novel transition in magnetism

The first new ground state demonstrated by the researchers at CEA Grenoble was obtained after a thermodynamic transition. In general, the ordering of a magnetic system is associated with thermal effects seen in a marked increase in the specific heat of the system near the phase transition. This is the case for the compound $Yb_2Ti_2O_7$, whose **specific heat** shows a very intense peak at about 0.25 **kelvin**, although it presents no long-distance magnetic order. In fact, only short-range dynamic magnetic correlations are present in the ground state, and the thermodynamic transition is associated with a very sudden, spectacular slowing down of magnetic fluctuations (Figure 3a). This transition is novel in magnetism. It strongly calls to mind the liquid-vapour phase transition of matter, which is also accompanied by the appearance of short-range dynamic structural correlations and a very marked slow-down in the dynamics. It was possible to determine the properties of the ground state of $Yb_2Ti_2O_7$ through studies using combinations of different experimental techniques. Some of these were macroscopic, such as the measurement of specific heat. Others used microscopic nuclear probes such as **neutron scattering**, **Mössbauer spectroscopy** or **muon spectroscopy**.

Persistent fluctuations

The second exotic ground state identified concerns magnetically ordered compounds. Most generally, spontaneous magnetic excitations are observed in the ordered phases of magnetic materials, and correspond to narrow deviations in magnetic moments relative to their nominal orientation. These excitations are propagated like waves, which are called spin waves. These waves are very numerous near the magnetic transition, but diminish rapidly as the temperature is lowered. The system then becomes magnetically frozen. It therefore came as a great surprise to observe persistent magnetic moment dynamics in several geometrically frustrated systems with orders, continuing down to the lowest temperatures attainable with conventional laboratory techniques. The persistence of such fluctuations is inherent to frustrated systems whose ground states are of the spin liquid type, but is unexpected in an ordered system.

In the case illustrated in Figure 3b, these dynamics are observed at a temperature 50 times lower than the transition temperature. In such conditions, a normal magnetic system is totally frozen. The presence of these fluctuations is associated with the degeneracy of the ground state in frustrated systems, but their underlying mechanism is still not understood and requires further study. An interpretation of the near temperature-independence of the relaxation rate in the magnetic phase gives a density of states for magnetic excitation characterised by a weight pile-up above a small gap.

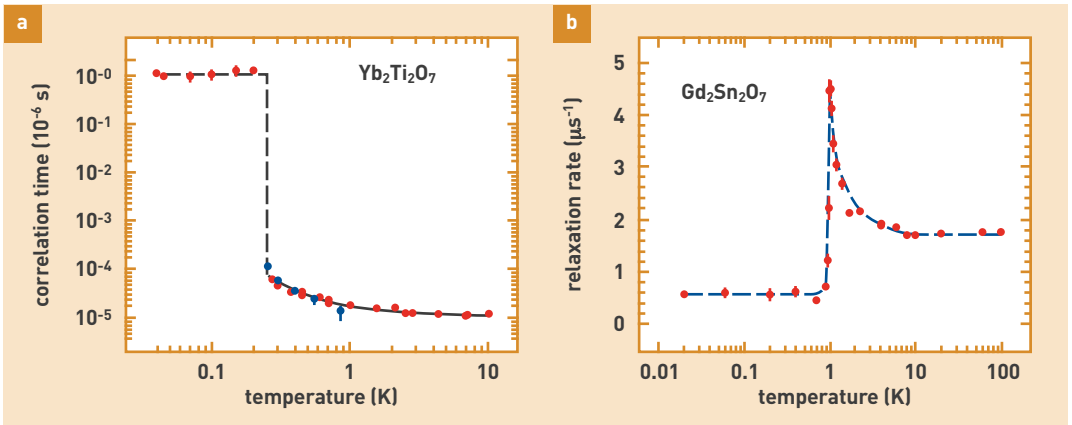


Figure 3.
(a) Thermal variation of the correlation time of magnetic moments of ytterbium in $Yb_2Ti_2O_7$. The red points are data from muon spectroscopy measurements and the blue points are from Mössbauer spectroscopy obtained by Pierre Bonville and James A. Hodges at the SPEC (CEA Saclay).
(b) Spin-lattice relaxation rate measured by muon spectroscopy in $Gd_2Sn_2O_7$. This compound becomes magnetically ordered at 1 K (temperature corresponding to the peak in relaxation rate). The persistence of magnetic fluctuations down to 20 mK is attested by the non-nil values of this rate.

Discovering new states of matter

Investigating geometrically frustrated magnetic systems thus offers remarkable scope for discovering new states of matter, as research in recent years has shown. This is a field in which researchers have had to question what had previously seemed uncontroversial. In the examples cited, only the investigation of magnetic properties by different techniques and the comparison of results (see note [1], p. 89) have finally made it possible to determine ground states. Conventional interpretations based on behaviour observed in classical systems give an inconsistent picture.

More generally, geometrical frustration is a common physical property of matter with implications that go far beyond magnetism. It is at work in the properties of crystalline ice, **proteins** folding and the conformation of **polymers**. In addressing these phenomena through magnetism, the physicist can use a large number of theoretical and experimental tools to help gain deeper insight into the mechanisms underpinning the natural world.

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The spin glass, a model complex system

Spin glasses are frustrated but disordered systems whose study offers insight into other disordered systems such as glasses and polymers.

In a disordered solid such as a glass, the positions of **atoms** are mostly random like in a liquid. A glass looks like a solid, but structurally it is a liquid, albeit an exceptionally stiff one that flows at an astronomically low rate. However, owing to thermal agitation, the atoms gradually move to more favourable positions, in a process called 'ageing'. Likewise, in the **polymers** that compose plastics, long **molecular** chains are tangled in a totally disordered manner, yet the 'plastic' is still a solid. During the ageing process, the **macromolecular** chains will, however, shift to positions of lower energy, gradually reducing the free volume. This results in a hardening of the material.

Glasses and spin glasses

These disordered solids have their magnetic equivalents: '**spin glasses**'. These materials are obtained, for example, by randomly diluting a few percent of manganese or iron (magnetic elements) in a non-magnetic metal such as copper or gold. The magnetic atoms are located at fixed positions that are random distances apart. The signs of the magnetic interactions in a metal oscillate according to distance, and so the interactions between the magnetic atoms of this alloy are randomly **ferro-** or **antiferromagnetic**. The magnetic moments (or **spins**) are subjected to conflicting influences from their different neighbours, which they cannot satisfy simultaneously. This situation is termed 'frustration' (see *Geometrical magnetic frustration* p. 89). The equilibrium state of such a system presents no obvious symmetry and is very difficult to picture. In mathematical **modelling**, as the number of spins increases, the task of finding the ground state of a spin glass rapidly becomes unrealisable for even the most powerful computers. For a spin glass, equilibrium seems to be impossible to find whatever patient the observer is. A spin glass seems to be trapped in a multitude of **metastable states**, which are slowly explored as spins are flipped by thermal agitation. 'Slowly', here, means that energy barriers of all sizes separate these metastable states, and produce response times at all scales from the microscopic flipping time of a single spin ($\sim 10^{-12}$ s), with no upper limit ever having been observed.
Likewise, a glass or a polymer remains 'out of equilibrium'. However, spin glasses offer the advantage of being conceptually simpler, as they can be modelled as a set of objects in random interaction, which mathematically reduces to a simple sequence of numbers ('frozen disorder'). In glasses and poly-

S. Nakamae/Spec/Iramis/CEA

Tens of micron-sized Hall probes (Drecam/LSI and Itron collaboration) are used to explore the magnetic noise and the spatial correlations of the magnetisation in a 'superspin' glass formed by interacting magnetic nanoparticles.
The pre-amplifiers have to be protected with shielding (metal box) to process these very weak signals.

mers, the frustration evolves as the atoms or molecules shift (the disorder is not 'frozen'), making theoretical microscopic modelling much more difficult.

Ageing, rejuvenation and memory

The ageing of a spin glass, which obeys the same scaling laws as the ageing of glasses and polymers, thus consists of local rearrangements of spins that allow it to slowly approach equilibrium, but without ever actually reaching it. CEA researchers at the Department of Condensed Matter Physics (SPEC)(1) have been studying more specifically how these effects can be influenced by temperature changes. They discovered the astonishing effects of 'rejuvenation and memory' that appear spectacularly in experiments such as that depicted in Figure 4. Here **magnetic susceptibility** χ is being measured, *i.e.* the weak magnetisation that develops in response to the application of a weak alternating field. More precisely, it is the 'delayed' (or 'out of phase') component χ'' of χ that is presented here. It is zero in the paramagnetic phase (as all the spins respond in phase to the alternating field) but it is non-zero in the spin glass phase, which appears at low temperature and so is characterised by a delayed response. In this experiment, conducted jointly with the **University of Uppsala**, the spin glass is cooled in successive steps. The ageing is seen in a relaxation of χ'' during the time-course at each step, the susceptibility decreasing slowly towards its equilibrium value.

The first surprise comes after a first step during which χ'' decreases appreciably (ageing). The spin glass is cooled a further 1-2 **K** to start the next step. Even though the thermal agitation is slightly lower, χ'' is observed to suddenly rise back and begin a fresh relaxation, as if the ageing observed during the preceding step had been of no effect. This 'rejuvenation' effect is observed at each further cooling step. Time at a given step allows equilibrium to be approached at a given temperature (decrease in χ'', *ageing*), but a further cooling increment seems to cancel the preceding effect (*rejuvenation*).

The second surprise comes when, after this slow stepwise cooling, the spin glass is gradually reheated. Close to each temperature at which an ageing step has been carried out, the susceptibility χ'' shows a marked dip. The spin glass remembers it has aged at each of these temperatures, by a 'memory' effect. In Figure 4 the spin glass has stored at least four *memories* of ageing at different temperatures during cooling, despite its apparent *rejuvenations*. As heating is continued, these memories are erased until they disappear completely when the paramagnetic phase is reached.

The 'rejuvenation and memory' effects discovered in spin glasses were then sought, and often found, in other glassy systems. Sergio Ciliberto's group at **ENS Lyon** has shown that the dielectric constant of the polymer MPMA (methyl polymethacrylate) retains a record of ageing steps carried out at different temperatures. However, in glasses and polymers these effects are only clearly visible near the glass transition temperature, whereas in spin glasses they are very marked over a broad range of temperatures (Figure 4).

Another interesting example was described by A. Parker and V. Normand at the Swiss company **Firmenich** in measurements of the elastic modulus of gelatin, a substance widely used in the food industry. Here we seem to be a long way from magnetism, and yet the slow relaxation of this modulus (corresponding to hardening) is an ageing process similar to that observed in the magnetic susceptibility of spin glasses. In an experiment with two-step cooling (Figure 5), the memory of the two temperatures at which the gelatin has been left to age appeared very distinctly during reheating. Of course, gelatin is not a glass or an ordinary polymer. It has a complex structure made up of triple helices of collagen, reversibly degradable by heat. It thus possesses additional degrees of freedom, which might not, however, be considered as essential to this effect. We note that the glass transition and the effects of ageing in structural glasses are very similar to those observed in polymers even though the building blocks of glasses (atoms or small molecules) look much simpler than those of polymers (long macromolecular chains).

(1) Saclay Institute of Matter and Radiation (Iramis, ex-Drecam).

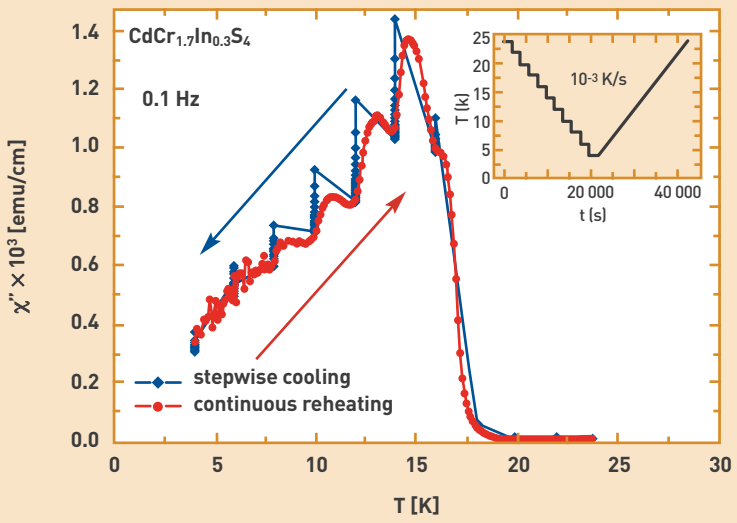

Figure 4.
'Out-of-phase' (or delayed) component χ'' of the magnetic susceptibility of a spin glass, which is nil in the paramagnetic phase above 17 K. The sample was cooled in steps in the spin glass phase (procedure in box). During cooling (blue rhombi), χ''diminishes slowly in each step (ageing), but at each new cooling step χ'' increases suddenly before beginning a new relaxation (rejuvenation). During reheating (red circles), the memory of each ageing step is shown by a dip in χ'' [J.-P. Bouchaud, V. Dupuis, J. Hammann, and E. Vincent, *Phys. Rev.* B 65, 024439 (2001)].

What do the spins do?

When an ideal ferromagnetic material (with no disorder or impurities) is suddenly quenched from its paramagnetic phase, the setting up of the ferromagnetic order (alignment of spins) occurs gradually by the well-known process of **domain** growth, in which the size increases in proportion to the square root of the time. This growth is very diffe-

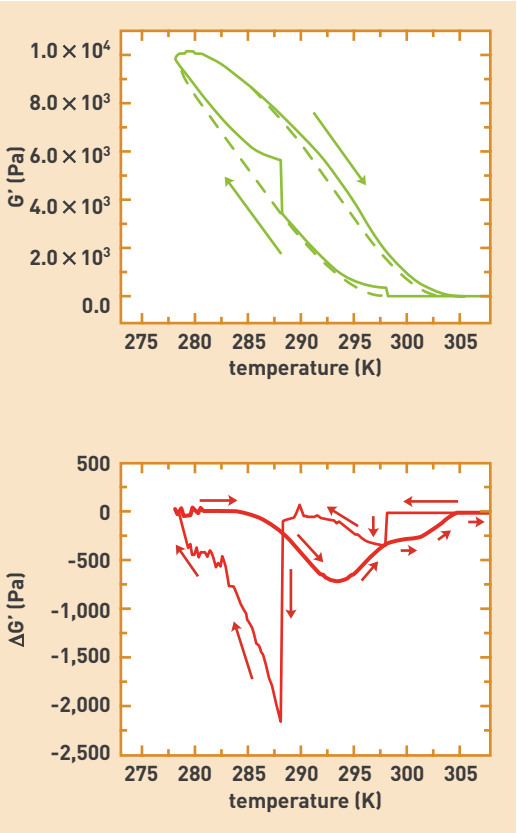

Figure 5.
Memory effect observed in the elastic modulus G' of gelatin. The sample was cooled with two delay steps at 298 K and 288 K (25°C and 15°C). The top figure shows G' (continuous line: with steps, dotted line: direct cooling). During the steps, G' increases slowly (ageing, the gelatin hardens). During reheating, an excess G' value indicates a memory of the ageing during the stepwise cooling. The memory effect is more clearly visible in the lower figure, which shows the difference ΔG' between the results of the direct procedure and the stepwise procedure. Two quite distinct dips show the two memories [Alan Parker and Valéry Normand, Corporate R&D Division, Firmenich SA; http://fr.arxiv.org/abs/cond-mat/0306056].

rent in nature from the ageing of disordered systems. It occurs much faster, and (in first approximation) is not temperature-dependent. The case of a *non-ideal* ferromagnetic material (with disorder) is very different: experiments conducted at the SPEC[2] have demonstrated spin glass-like effects, thought to be linked to the complexity of the domain **wall** pinning dynamics. The walls themselves seem to behave like a *spin glass*. However, for simple domain growth dynamics (the case of ideal ferromagnetism), corresponding to a one-way evolution, it is difficult to see how this could be accompanied by temperature-dependent rejuvenation and memory effects.

To understand how the spins in a disordered magnetic system can become organised and produce effects such as rejuvenation and memory, we have to look in greater detail at what happens during ageing after rapid cooling. Starting with a random configuration, the spins can flip under the influence of thermal agitation, and gradually succeed in adopting configurations that minimise their interaction energies over ever-greater distances, which define a *dynamic correlation length* (dynamic in the sense that groups of spins of this size flip collectively). We thus arrive at a picture of a growth of a characteristic length, but this length is not the size of a domain in the ferromagnetic sense. Its definition is purely dynamic, and above all an essential difference from the ferromagnetic case is that this 'spin glass order', which develops gradually, possesses no visible symmetry. Only in **numerical simulations** involving complex mathematical treatments can the growth of such 'glassy ordered domains' be visualised (Figure 6).

How can the temperature-dependence of these dynamic structures produce rejuvenation and memory effects? If the *memory* of the ageing is associated at a given temperature with the *freezing of a dynamic structure* of a certain size (dynamic correlation length described above, defined over times of the order of a few minutes to a few hours, *i.e.* about 10^{15} times the microscopic times), we can reasonably assume that this characteristic size will be smaller at lower temperatures. It will thus be possible to *conserve the memory* of the ageing carried out at different temperatures *provided these lengths are sufficiently different*. This is the 'temperature microscope' effect proposed by Jean-Philippe Bouchaud (SPEC). At each successively lower temperature, the 'glassy order' is set up over shorter and shorter characteristic lengths (which we see through our susceptibility measurement 'microscope'). These lengths are sufficiently different to allow multiple memories.

Domains that behave like sponges

However, why should a structure set up at a particular temperature be rearranged at a smaller scale when a lower temperature is attained (rejuvenation)? Without going into the question of a possible *temperature chaos*, which is widely discussed in the literature, we can propose an explanation drawn from the example of another system that is easier to model than a spin glass. This is an elastic surface or line (*e.g.* a ferromagnetic domain wall) in the presence of a disordered potential (such as impurities in a ferromagnetic material, which tend to pin domain walls). The dynamics of this system are shown schematically in Figure 7. The elastic line tends to minimise is curvature, but pinning by the disordered potential tends instead to distort it. This is a frustrated system, with many metastable states.

At a given temperature T, the line gradually succeeds in optimising its configuration up to a length L_T, which increases as a function of time (*ageing*). At small scales ($L \ll L_T$), many configurations are roughly equivalent at this temperature, and the line fluctuates rapidly among the details at the small scale L. However, when we now cool the system to $T - \Delta T < T$, some of these configurations are no longer equivalent simply because of the thermal variation of their statistical weight. At a scale $L_{T-\Delta T} < L_T$, the line must once again find its most favourable configuration. It does this by a fresh process of ageing, which constitutes the *rejuvena-*

Figure 6.
Development of 'spin glass order' starting from a random configuration (corresponding to a **quench**) can be visualised in numerical simulations. Here, the evolution of the same spin glass is studied in two independent Monte-Carlo simulations, and the result is presented after times t = 2, 27 and 57,800 Monte-Carlo steps (top to bottom). The grey scale indicates the angle made by the same spin at the same time t in the two simulations. The uniform grey regions, which visibly increase with time, are therefore regions in which the relative angles of the different spins are the same in the two independent simulations (although the overall orientation of these regions can be different from one simulation to another). They thus describe types of 'glassy order domains' with visibly complex geometries, reproducible from one simulation to another [L. Berthier and A.P. Young, *Phys. Rev.* B 69, 184423 (2004)].

(2) Doctoral Thesis, Vincent Dupuis.

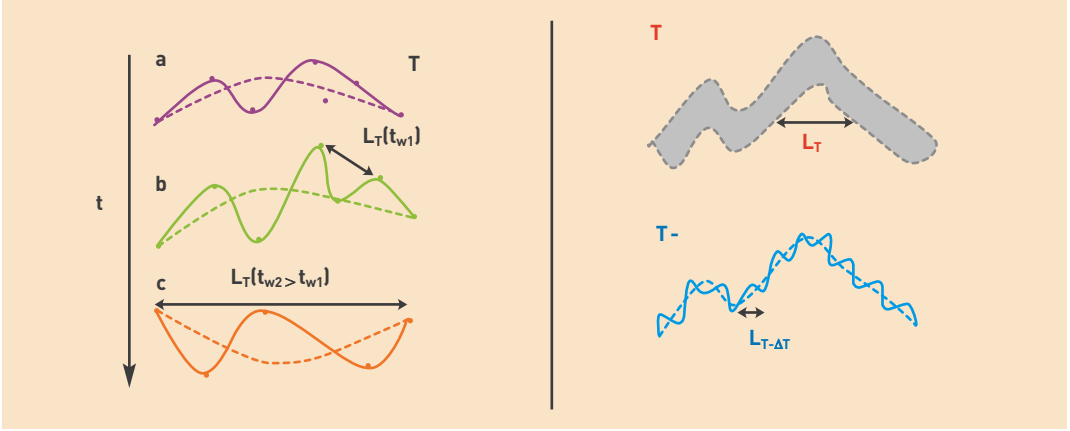

Figure 7. Schematic diagram illustrating the difficulty met by an elastic line to reach equilibrium on a disordered potential, a possible model for the effects of ageing in a spin glass (see text). The elastic line, subjected to the conflicting influences of elastic energy (which tend to straighten the curvature) and the disordered potential (tending to keep it on the pinning sites), becomes gradually organised over a length L_T that increases over time (ageing). The section on the right illustrates how rejuvenation at T - ΔT (scale $L_{T-\Delta T}$) can be achieved while keeping the memory of ageing at T (shape of the line at scale LT). [J.-P. Bouchaud (SPEC), Soft and Fragile Matter, published by M.E. Cates and M.R. Evans, Institute of Physics Publishing, Bristol (2000); http://fr.arxiv.org/abs/cond-mat/9910387

tion observed in the experiments. During this rejuvenation at T - ΔT, which concerns small details at scale $L_{T-\Delta T}$, the structure established at T over a greater length L_T is conserved (*memory*), because to rearrange this at this lower temperature would require an exponentially longer time.

This problem has been explored analytically, and the results obtained confirm the intuitive picture briefly presented here. But how can this elastic line model help us to get a more precise picture of the 'glassy ordered domains' acting in disordered systems? This question does not yet have an answer. These 'domains' are certainly much more subtle than ferromagnetic domains. They are very probably non-compact, possibly more like imbricated sponges. Strangely, they may be more like *walls* than *domains*, as the behaviour of walls in a disordered ferromagnetic material may well model what happens in spin glasses.

A 'glassy order' in disordered systems in general?

There is a body of quantitative information, generated through both numerical simulations and experiments on real spin glasses, that nevertheless proves fairly consistent. These results have made it possible to address the time- and temperature-dependence of the *dynamic correlation length*. The result is that on a laboratory time scale (seconds to hours), the spins successfully organise themselves over distances of a few tens of interatomic distances. This dynamic 'glassy order' thus develops very slowly, and this slowness seems to be an essential characteristic of frustrated systems.

What about glasses? The concept of dynamic correlation length that has emerged from experiments on spin glasses is very close to that of 'dynamic heterogeneity', which has appeared in recent years in research on glasses. Experiments show that a glass responds to external excitation by local collective movements of molecules that are dynamically correlated over finite distances describing dynamic heterogeneities. These distances are currently estimated to measure a few intermolecular distances, somewhat smaller than in spin glasses. These distances are relatively small yet they are associated with extremely long response times. This is why glass does not flow even though it has a liquid structure. It is currently thought that the size of the dynamic heterogeneities increases near the glass transition point, but without diverging like the correlation length in a transition to an ordered state.

Recently two new methods have been proposed by Jean-Philippe Bouchaud (SPEC) and Giulio Biroli (Institute for Theoretical Physics, CEA) to extract this temperature evolution from dielectric **spectroscopy** experiments, which are now in progress[3]. Thus there is a fruitful two-way flow of results between glasses and spin glasses, and between magnetism and the dielectric or mechanical properties of materials. This is made possible by the universal scope of the methods of statistical physics, which in recent years have undergone important theoretical developments, and now provide us with common conceptual tools to address what are collectively known as 'complex systems'.

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(3) Research group Denis L'Hôte, François Ladieu and Sawako Nakamae (SPEC).

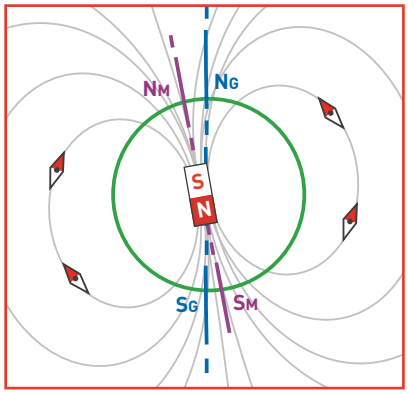
FOR MORE INFORMATION

E. Vincent, *Ageing, rejuvenation and memory: the example of spin glasses*, course at the University of Luxembourg Summer School, September 2005, Springer *Lect. Notes Phys.*, 716, 7–60, (2007); http://fr.arxiv.org/abs/cond-mat/0603583

FOCUS D

The Earth's magnetic field, weak but vital

The Earth has its own **magnetic field**, which acts like a giant **magnet**. **Geomagnetism** is the name given to the study of this field, which can be roughly described as a centred **dipole** whose axis is offset from the Earth's axis of rotation by an angle of about 11.5°. This angle varies over time in response to movements in the Earth's core (Figure). The angle between the direction of the *magnetic* and *geographic* north poles, called the



magnetic declination, varies at different points on the Earth's surface. The angle that the magnetic field vector makes with the horizontal plane at any point on the Earth's surface is called the **magnetic inclination**.

This centred dipole exhibits magnetic **field lines** that run between the north and south poles. These field lines convergent and lie vertical to the Earth's surface at two points known as the **magnetic poles**, which are currently located in Canada and Adélie Land. Compass needles align themselves with the magnetic north pole (which corresponds to the south pole of the 'magnet' at the Earth's core).

The Earth's magnetic field is a result of the **dynamo effect** generated by movements in the planet's core, and is fairly weak at around 0.5 **gauss**, i.e. 5 10^{-5} **tesla** (this is the value in Paris, for example). The magnetic north pole actually 'wanders' over the surface of the Earth, changing its location by up to a hundred kilometres every year. Despite its weakness, the Earth's dipolar field nevertheless screen the Earth from charged particles and protect all life on the planet from the harmful effects of cosmic radiation. In common with other planets in our solar system, (Mercury, Jupiter, Saturn, Uranus and Neptune), the Earth is surrounded by a **magnetosphere** that shields its surface from solar wind, although this solar wind does manage to distort the Earth's magnetic field lines.

The Earth's magnetic field is far from uniform. It is affected by **magnetic anomalies** which show up as variations in the magnetic field in relation to the global magnetic field. These anomalies can be quite large, affecting areas on a regional scale. One example is the *South Atlantic anomaly*, which affects the amount of cosmic radiation reaching the passengers and crew of any plane and spacecraft led to cross it.

The Earth's magnetic field has other, weaker, *non-dipolar* components whose effects are superimposed on the main dipole, but have far shorter time constants and so do not have any significant effect beyond the Earth's surface.

The Earth's magnetic field has fluctuated strongly over the course of geological time, suffering periods of major instability that occur with no observable regularity, and has experienced repeated reversals of its polarity. All this can be confirmed by studying the igneous or sedimentary sequences that accumulate on ocean floors. Both these rock types have the ability to acquire and lock in a magnetisation oriented parallel to the ambient geomagnetic field that existed at the time they cooled to their **Curie temperature** (**Curie point**), just below 500°C. These rocks can therefore be used to chart the polarity of the magnetic field that existed at the Earth's surface during this cooling period (or during their deposition as tiny magnetic sediment grains). This phenomenon, called **magnetic remanence**, was pivotal to the development of the field of **paleomagnetism**. The direction of the remanent field, which may be completely different from the present-day local field, provides a record of the polarity of the local field at the time the rock was formed. Volcanic rocks are first forced through the Earth's crust at a temperature higher than the Curie point of their constituent minerals. As they cool, they recross this Curie point and their constituent grains become magnetised in the direction of the ambient field. While sedimentary rocks are less sensitive to remanent magnetisation, any magnetic grains they contain will be magnetised in the direction of the Earth's magnetic field in existence at the time of their deposition.

Ocean floor sediments are particularly rich in magnetic minerals, the easiest of which to identify is the famous magnetite. This magnetisation is proportional to field strength and does not vary at standard temperatures. Other factors affecting remanent magnetisation include continuous action of the Earth's magnetic field, transient high-energy fields (due to lightning, for instance), and crystallisation processes, which can modify both the strength and direction of the magnetic field locked into the magnetic mineral grains.

Reversals and excursions in the Earth's magnetic field

The Earth's magnetic field records two types of instability, reversals and excursions. Reversals occur when the north and south magnetic poles switch polarity, an event that last took place some 790,000 years ago. This type of reversal was first suggested in France in 1906 by the geophysicist Bernard Bruhnes, but it was not until the 1960s that research started to pick up pace and confirm that these reversals were a global manifestation of the Earth's magnetic field. In particular, it was shown that these reversals were both erratic and unpredictable, alternating long periods of stable field polarity (lasting hundred thousand of years) with shorter periods of rapid field reversal (lasting just a few thousand years). It was also shown that the reversal rate had increased over the last hundred million years, from one reversal at the beginning of this period to four reversals per million years over the last five million years. This would seem to suggest that the current period of 'normal' polarity is 'abnormally' long. Geomagnetic excursions are simply shorter bursts of instability. While, like reversals, the polarity of the Earth's magnetic field flips over, it flips back to its initial polarity just as quickly. Research conducted by the Climate and Environmental Sciences Laboratory (LSCE, CEA-CNRS-Versailles-Saint-Quentin-en-Yvelines University) has demonstrated that excursion periods generally run for about 1,500 years, thus providing preliminary confirmation of the theory suggested by English geophysicist David Gubbins, according to which excursions only occur in the Earth's external *liquid* outer core and not in its inner *solid* core.

The different types of magnetism

The origins of magnetism lie in the properties of electrons as explained by the laws of quantum physics. Part of an electron's magnetic properties (*spin magnetism*) results from its quantum-mechanical spin state, while another part results from the orbital motion of electrons around an atom's nucleus (*orbital magnetism*) and from the magnetism of the nucleus itself (nuclear magnetism). This is put to use, in particular, for nuclear magnetic resonance imaging in the medical field. Magnetism is therefore produced by electric charges in motion. The force acting on these charges, called the Lorentz force, demonstrates the presence of a magnetic field.

Electrons have an intrinsic magnetic dipole moment (the magnetic quantum state being the Bohr *magneton*), which can be pictured as an electron's rotational motion of spin around itself in one direction or another, oriented either upwards or downwards. The *spin quantum number* (one of the four numbers that 'quantifies' the properties of an electron) equals 1/2 (+ 1/2 or - 1/2). A pair of electrons can only occupy the same *orbital* if they have opposite magnetic dipole moments.

Each atom acts like a tiny magnet carrying an intrinsic magnetic dipole moment. A nucleus (the neutron and proton individually have a half-integer spin) will have a half-integer spin if it has an odd atomic mass number; zero spin if the atomic mass number and charge are even, and an integer spin if the atomic mass number is even and the charge odd.

On a larger scale, several magnetic moments can together form magnetic domains in which all these moments are aligned in the same direction. These spatial regions are separated by domain walls. When grouped together, these domains can themselves form a macroscopic-scale magnet (Figure E1).

The type of magnetism that comes into play is determined by how these elementary constituents are ordered, and is generally associated with three main categories of material: *ferromagnetic*, *paramagnetic* and *diamagnetic*.

Any material that is not diamagnetic is by definition paramagnetic provided that its magnetic susceptibility is positive. However, ferromagnetic materials have particularly high magnetic susceptibility and therefore form a separate category.

1. Ferromagnetic materials are formed of tiny domains inside which atoms exhibiting parallel magnetisation tend to align themselves in the direction of an external magnetic field like elementary dipoles. In fact, the magnetic moments of each atom can align themselves spontaneously within these domains, even in the absence of an external magnetic field. Applying an external field triggers domain wall movement that tends to strengthen the applied field. If this field exceeds a certain value, the domain most closely oriented with the direction of the applied field will tend to grow at the expense of the other domains, eventually occupying the material's whole volume. If the field diminishes, the domain walls will move, but not symmetrically as the walls cannot fully reverse back to their original positions. This results in remanent magnetisation, which is an important feature of naturally occurring magnetite, or of magnets themselves.

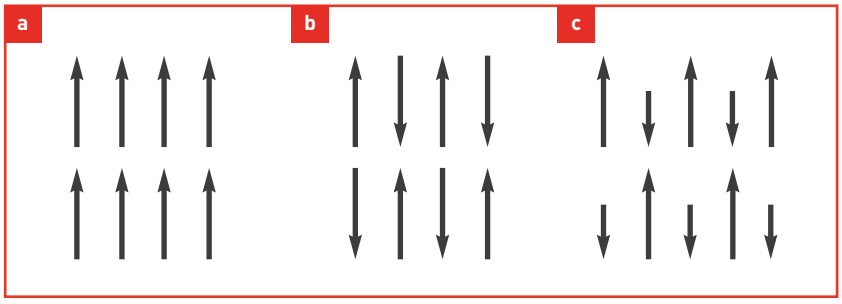


Figure E1.
Intrinsic magnetic dipole moments have parallel alignment in ferromagnetic materials (a), anti-parallel alignment but zero magnetisation in antiferromagnetic materials (b), and anti-parallel alignment with unequal moments in ferrimagnetic materials (c).

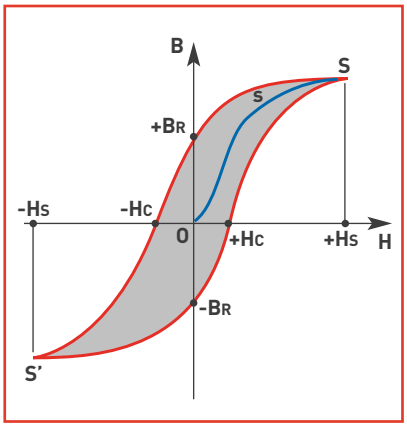


Figure E2.
The induction B of a magnetic material by a coil is not proportional to its magnetic excitation (*field H*). While the initial magnetisation forms an OsS-type curve, shown in blue in the figure, it reaches saturation at point s. Only a partial induction is retained if the field approaches zero; this remanent induction can only be cancelled out by reversing the magnetic field to a "coercive" field value. This hysteresis loop illustrates the losses due to "friction" between the magnetic domains shown on the area bounded by the magnetisation and demagnetisation curves.

The whole process forms a hysteresis loop, i.e. when the induced field is plotted against the applied field it traces out a *hysteresis curve* or *loop* where the surface area represents the amount of energy lost during the irreversible part of the process (Figure E2). In order to cancel out the induced field, a coercive field has to be applied: the materials used to make artificial permanent magnets have a high coercivity.

Ferromagnetic materials generally have a zero total magnetic moment as the domains are all oriented in different directions. This ferromagnetism disappears above a certain temperature, which is known as the Curie Temperature or Curie point.

The magnetic properties of a given material stem from the way the electrons in the metallic cores of a material or of a transition metal complex collectively couple their spins as this results in all their spin moments being aligned in the same direction.

Materials whose atoms are widely distributed throughout their crystal structure tend to better align these elementary magnets via a coupling effect. This category of materials, which is characterised by a very high positive magnetic

Stoiber Productions, München

A Transrapid train using magnetic levitation arriving at the Long Yang bus station in Shanghai (China). This German-built high-speed, monorail train was commissioned in 2004 to service the rail link to Pudong international airport.

susceptibility, includes iron, cobalt and nickel and their **alloys**, steels in particular, and some of their compounds, and, to a lesser extent, some **rare earth** metals and alloys with large crystal lattices, and certain combinations of elements that do not themselves belong to this category. In **ferrimagnetic** materials, the magnetic domains group into an anti-parallel alignment but retain a non-zero magnetic moment even in the absence of an external field. Examples include magnetite, ilmenite and iron oxides. Ferrimagnetism is a feature of materials containing two types of atoms that behave as tiny magnets with magnetic moments of unequal magnitude and anti-parallel alignment. **Antiferromagnetism** occurs when the sum of a material's parallel and anti-parallel moments is zero (e.g. chromium or haematite). In fact, when atoms are in a close configuration, the most stable magnetic arrangement is an anti-parallel alignment as each magnet balances out its neighbour so to speak (Figure E1).

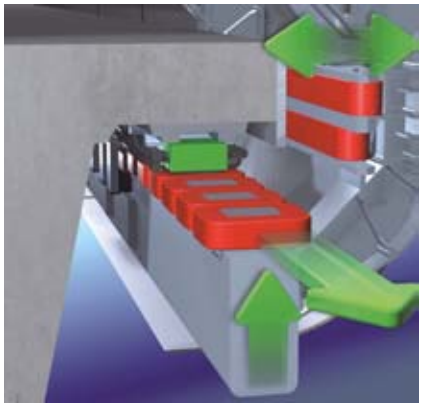
2. **Paramagnetic** materials behave in a similar way to ferromagnetic materials, although to a far lesser degree (they have a positive but very weak magnetic susceptibility of around 10^{-3}). Each atom in a paramagnetic material has a non-zero magnetic moment. In the presence of an external magnetic field, the magnetic moments align up, thus amplifying this field. However, this effect decreases as temperature rises since the thermal agitation disrupts the alignment of the elementary dipoles. Paramagnetic materials lose their magnetisation as soon as they are released from the magnetic field. Most metals, including alloys comprising ferromagnetic elements are paramagnetic, as are certain minerals such as pegmatite.

3. **Diamagnetic** materials exhibit a negative and an extremely weak magnetic susceptibility of around 10^{-5}. The magnetisation induced by a magnetic field acts in the opposite direction to this field and tends to head away from **field lines** towards areas of lower field strengths. A perfect diamagnetic material would offer maximum resistance to an external magnetic field and exhibit zero **permeability**. Metals such as silver, gold, copper, mercury or lead, plus quartz, graphite, the noble gases and the majority of organic compounds are all diamagnetic materials.

In fact, all materials exhibit diamagnetic properties to a greater or lesser extent, resulting from changes in the orbital motion of electrons around atoms in response to an external magnetic field, an effect that disappears once the external field is removed. As Michael Faraday showed all that time ago, all substances can be "magnetised" to a greater or lesser degree provided that they are placed within a sufficiently intense magnetic field.

Electromagnetism

It was the Danish physicist Hans Christian Ørsted, professor at the University of Copenhagen, who, in 1820, was first to discover the relationship between the hitherto separate fields of **electricity** and **magnetism**. Ørsted showed that a compass needle was deflected when an electric current passed through a wire, before Faraday had formulated the physical law that carries his name: the magnetic field produced is proportional to the intensity of the current. **Magnetostatics** is the study of static magnetic fields, i.e. fields which do not vary with time.



Close-up of the magnets used to guide and power the train.

Magnetic and **electric fields** together form the two components of **electromagnetism**. **Electromagnetic waves** can move freely through space, and also through most materials at pretty much every frequency band (radio waves, microwaves, infrared, visible light, ultraviolet light, X-rays and gamma rays). **Electromagnetic fields** therefore combine electric and magnetic **force fields** that may be natural (the Earth's magnetic field) or man-made (low frequencies such as electric power transmission lines and cables, or higher frequencies such as radio waves (including cell phones) or television.

Mathematically speaking, the basic laws of electromagnetism can be summarised in the four **Maxwell equations** (or **Maxwell-Lorentz equations**) which can be used to provide a coherent description of all electromagnetic phenomena from electrostatics and magnetostatics to electromagnetic wave propagation. James Clerk Maxwell set out these laws in 1873, thirty-two years before Albert Einstein incorporated the theory of electromagnetism in his *special theory of relativity*, which explained the incompatibilities with the laws of classical physics.