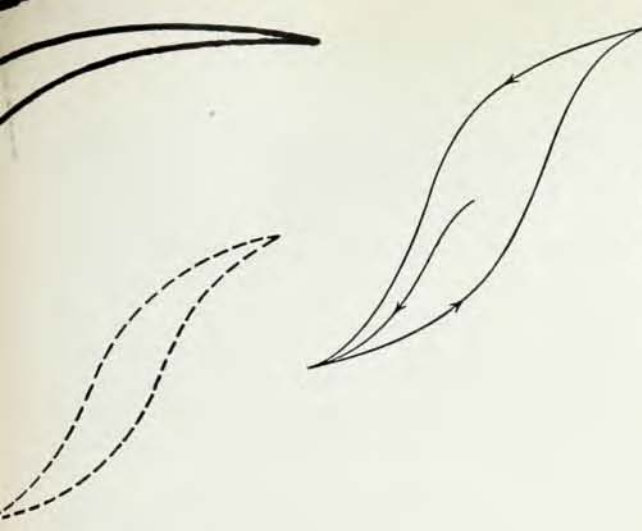






An intangible force that keeps us in touch with points as remote as the sun, or the other end of town, or the atomic nucleus, magnetism is little understood though widely used.



MAGNETISM

by Francis Bitter

The same force that drives the great majority of the rotating shafts of industry (and makes possible the communication which prevents our industrial civilization from breaking down under its own complexity) is used as a probe for investigating the minutiae of atoms and nuclei. So fundamental to existence itself is magnetism that the extent to which we can use this force has far outdistanced our understanding of its nature; in taking the measure of magnetism, scientists must range over many worlds.

Francis Bitter, professor of physics at MIT, has done much research in magnetism. He took part in the development of transformer steel with oriented grains and made the first powder pictures of magnetic patterns in single crystals. During the war, in the Navy, he worked in degaussing, mine warfare, and operational analysis and since then, he writes, he has been "catching up with physics and starting investigation of nuclear magnetism and . . . working on an elementary text." This work has been supported in part by the Signal Corps, the Air Materiel Command, and the ONR.

Magnetic forces are likely to remain outstanding in the realm of the transmission of energy or information, not only in machines and circuits, but also in atoms and nuclei. The existence of magnetism seems to be a consequence of the existence of particles which spin. The interactions of electrically charged spinning particles—gyroscopes—are precisely the interactions which we feel and call magnetic when we hold two bar magnets close together. This gyroscopic aspect of magnetism, however, is a subtlety which cannot be detected without delicate instruments, and men were consequently unaware of it prior to the flowering of modern science during the past hundred years.

To most people the distinctive aspects of magnetic forces are their magnitude and range, and it is precisely this felt force, plus the fact that magnetization can be electrically controlled by currents in wires and therefore conveniently controlled from a distance, that has resulted in the outstanding application of magnetism to the production of the mechanical forces making our industrial civilization possible. If to this we add the role of ferromagnetic materials in coupling electrical circuits to each other, as in the transmission of information or of power, and its use as a probe in atomic research, we have covered just about all the current applications of magnetism. Moreover, with the possible exception of the production of extremely low temperatures by magnetic means, a phenomenon which will be discussed further on, there does not appear to be any great prospect that the situation will change.

Materials

To begin with, however, let us consider magnetic materials for electric machines and circuits. The properties desired are easily described. First, mag-

nets should be strong. Second, the ease with which they may be magnetized should be subject to control. For some applications the intensity of magnetization should be delicately controllable by small currents in the external coils, while for others the magnetization should be firmly frozen in, and difficult to change. And finally, the magnetic material should be electrically insulating for applications to high frequency circuits. Any given combination of properties should also be available at a reasonable price.

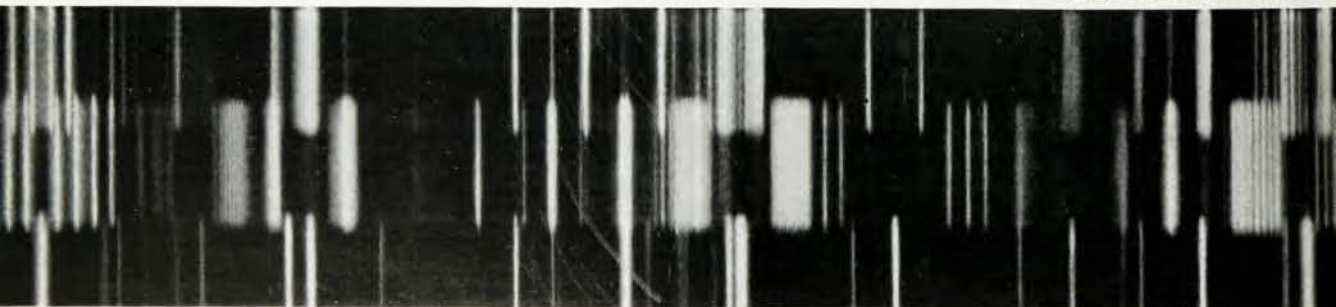
Nature has provided us with an abundant element, iron, which, in the hands of the metallurgist and in combination with a few other substances, seems to satisfy most of our industrial needs. This development has been almost entirely an empirical one. The metallurgist, like many another "practical" pioneer out ahead of the scientist, simply tried this, that, and the other thing until he finally developed a feel, an accumulation of more or less unorganized experience that functioned like a sixth sense to guide him through the intricacies of his subject. Even now, technical and engineering publications may be full of plausible explanations based on the electron theory of metals, but none of this represents the kind of solid ground on which an industry may be built, such as physics has provided, for instance, for the electrical engineer.

The man in a mill who can really specify how to make a sheet of transformer iron, or a permanent magnet for a galvanometer movement, is not too much interested in physics. But physicists are interested in him. The products of a mill have many properties that the scientist has difficulty in accounting for quantitatively. The existence and range of these properties, however, have been most valuable in giving us an insight into the subtleties of the solid state.

Zeeman patterns for columbium at 95,000 oersteds

Top, parallel components; middle, perpendicular components; bottom, spectrum without magnetic field

National Bureau of Standards



Here, in brief, is the currently accepted picture of the inside of a magnet, and how it came to be. Atomic theory told us how many atoms there were in any given piece of matter. From the known strength of macroscopic magnets it was therefore possible to estimate the strength of atomic magnets. The orientation of these atomic magnets in a magnetic field is determined by the violence of the thermal agitation of the atoms, and can be calculated in much the same way that one calculates the density of a gas in a gravitational field as a function of height. As one might expect, the answer comes out that magnetically weak atoms are more easily disoriented than magnetically strong atoms.

The quantitative part of the calculation was dramatic and noteworthy because it revealed that atomic magnets of the size which actually exist should be so completely disoriented by thermal agitation at normal temperatures that available magnetic fields should be incapable of producing any appreciable magnetization. How then would a magnet remain a magnet outside of a very effective refrigerator? Obviously some other force existed that kept the atomic magnets in iron lined up in spite of the large disruptive forces resulting from their thermal motion. This turned out to be a quantum mechanical force that was able to account for many features of atomic spectra in addition to requiring a high temperature to destroy the magnetization of iron.

The quantum theory also made it clear why none of the many alloys turned out by the metallurgist was much more magnetic than iron. More powerful magnets than are now available would be extremely useful to both the engineer and the scientist. The fact that every electron in an atom is a permanent magnet itself might seem to indicate that the strongest magnet we could make would contain some substance like lead that has many electrons per atom. There is, however, ample theoretical and experimental justification for predicting that all these electronic magnets can never be made use of. The quantum theory of atomic structure tells us that the normal tendency is for these electronic magnets to cancel each other in pairs. In isolated atoms one never finds more than a few of the electronic magnets aligned, and of these only a few retain their magnetization when they are combined into solids.

An interesting area that has not as yet been extensively explored (with the view in mind of fab-



H. J. Williams, R. M. Bozorth, W. Shockley

*Magnetic domains outlined by powder
suspended in liquid
and photographed through a microscope*

ricating magnetic materials) is the region of the periodic table occupied by the rare earths, particularly in the range of moderately low temperatures, such as can be produced by liquid air. But if we are willing to include consideration of very low temperatures, in the sense of a degree or less on the absolute scale, then many substances that we generally call nonmagnetic would compete with, and in some respects surpass, iron. Liquid helium, which is a prerequisite for working at these low temperatures, is only beginning to become readily available for experimental work. We have as yet only the results of a few preliminary measurements. In magnetism as well as in other respects surprises are doubtless in store for the observant and adventuresome explorer of this antarctica.

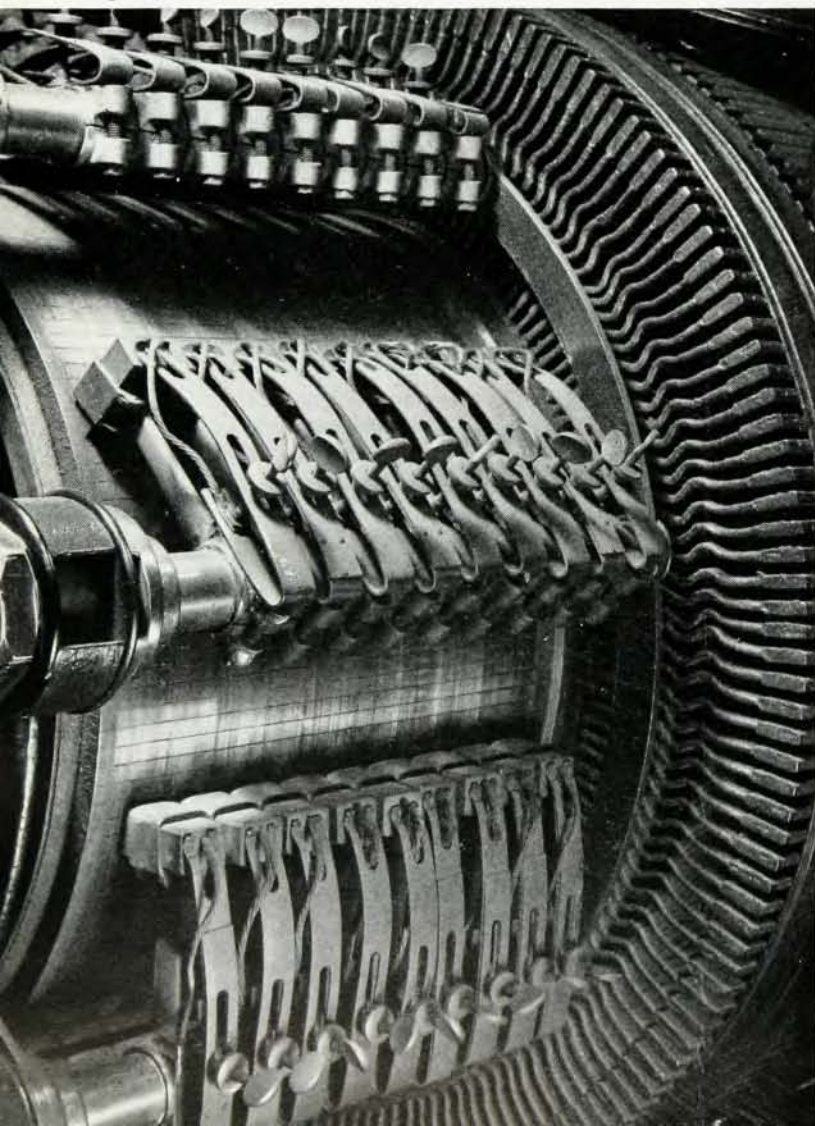
Magnetization

Magnetic materials should, first of all, have a sufficient "saturation" value—that is, they should be composed of a sufficient number of atomic magnets, each of which is sufficiently strong so that (when aligned) a satisfactory over-all magnetization is achieved.

The second important aspect of magnetic materials is the ease or difficulty with which the magnetic state may be changed. We have seen that in ferromagnetic materials a force exists that tends to align the magnetic moments of neighboring atoms. This will produce spontaneously magnetized regions in a ferromagnetic crystal, but these regions will not necessarily cover an entire piece of magnetic material, any more than a piece of metal is likely to consist of a single crystal grain. The existence of these magnetic domains can be demonstrated experimentally,

and in some cases their shapes and sizes can be accounted for. But in general the reorientation of the magnetization of these domains, and their expansion and contraction in response to varying applied magnetic fields, cannot be predicted. Both the detailed structure of metals and the detail of the atomic interactions involved in a magnetizing process are so complicated that we must for the present be satisfied with a very general and qualitative description of ferromagnetic phenomena.

The third aspect of magnetic materials of importance to the engineer is the electrical conductivity, which is responsible for the waste in energy resulting from induced eddy currents in alternating current applications. The conventional remedies for this are to reduce conductivity by using an alloying element, such as silicon in transformer sheet, or to use thin tape or wire, as in various high frequency applications of high permeability materials. These are,



*Electric generator
Curtis Reider—Black Star*

however, only partial remedies. As long as magnetic materials are metallic, eddy current losses at high frequencies will be objectionable.

It has been known for many years that certain oxides and other nonconducting or semiconducting compounds are feebly ferromagnetic. Until recently, however, such materials had not been considered seriously for practical applications in magnetic circuits because their properties were so very far from those which could be obtained in metals. During the war, extensive work on these substances was undertaken in Holland, and the knowledge of how to prepare a whole new category of magnetic material was acquired. As in the case of metals, particular properties can be brought out in only certain special materials prepared according to relatively complicated recipes. And here again, our understanding of the material is qualitative and general rather than detailed and complete. The substances in question tend to have large and complicated unit cells in their crystallographic structure; features that are difficult to observe, such as the location of ions in different states of valency, seem to be important.

By way of a summary of the present state of the art of developing magnetic materials, the situation seems to be that a gradual improvement such as has been going on for many years is likely to continue, but that dramatic jumps seem unlikely, except in the realm of low temperatures and in the development of pure rare earths, neither of which are likely to be industrially important. In so far as our understanding of magnetic properties is concerned, an important obstacle seems to be our lack of information regarding important features in the structure of solids. Between those aspects of structure revealed by x-rays and those aspects revealed by microscopes there seem to be important features about which we are pretty well in the dark.

Magnetic Moments

And now we come to that other aspect of magnetism, namely its role in revealing to us the nature, not of some especially prepared sample of matter, but rather the nature of existence itself—the nature of the elementary particles of which the universe is composed, and the kinds of interactions of which these particles are capable. Here we return to the gyroscopic aspect of magnetism mentioned earlier.

Every reader of this article is probably familiar

with these facts: a spinning top does not fall over even when it is leaning to one side, it precesses or wobbles around a vertical axis; and an electric charge whirling around in some sort of a circular path gives rise to a magnetic field, as does the current in a circular coil, and is in every way equivalent to a magnet.

Because of the association of charge with mass, as in an electron, one would expect a magnet composed of rotating charges to have associated with it a certain angular momentum. That this is so may be easily verified experimentally. A piece of iron wire suspended axially from a fiber experiences a twist when it is magnetized. This twist is just that required to insure the constancy of the system's total angular momentum when the part associated with the atomic electrons is changed by magnetization.

The above makes plausible a statement that can be shown to follow from the basic laws of physics. A magnetic field cannot reorient an isolated magnet. It can merely make it precess around the field direction. The component of the magnetic moment in the field direction remains unchanged. In other words a magnetic field could never magnetize a piece of iron if the atoms did not interact with each other. The details of the mechanism by which a state of magnetization is changed is only beginning to be understood. It is nevertheless clear that the role of the magnetic field is to produce the possibility of magnetization. The actual change is produced by the thermal agitation of the substance being magnetized.

The situation is quite analogous to the expansion of a gas. By raising the piston in a cylinder we do not expand a gas, we merely make it possible for a gas to expand. The thermal motions actually produce the expansion. This analogy may be carried further: since we can cool a gas by expansion, we can cool a solid by changing its magnetic state. This is so, but is of importance only at very low temperatures, in the vicinity of one degree absolute, where all gases are condensed and therefore useless for refrigeration. Temperatures far below one degree absolute have already been produced by this process, called adiabatic demagnetization.

Resonance

There are two typical ways of making measurements on a magnet. One is to measure the mechani-

cal force exerted on it when it is brought near another magnet. It is difficult to draw any accurate conclusion, from such a measurement, regarding the nature of the elementary magnets composing a solid or liquid, because the interpretation necessarily involves a complicated statistical theory that is likely to be full of inadequacies. Accurate measurements of the mechanical force acting on individual atoms is technically extremely difficult.

The second way is to measure the precessional frequency—the number of wobbles per second as it spins on its axis—of an atomic magnet in a magnetic field. The interpretation of such a measurement is perfectly straightforward, and great experimental accuracy is possible. The development of atomic theory was intimately concerned with the results of such measurements in the Zeemann effect in which spectral lines are split when the substance whose light is being analyzed is put in a strong magnetic field. The precessional frequencies show up as difference frequencies between the various Zeemann components.

A new era in magnetic measurements is now upon us following the development of techniques for measuring the precessional frequencies directly, rather than as a difference between two very much higher frequencies. This means that instead of having to be satisfied with knowing magnetic quantities to a few parts in a hundred or a thousand, we can look forward to discovering detail that can be revealed only by measurements good to one part in a million or better. This, for the student of particles, may turn out to be a gift comparable to the microscope for the student of germs. Techniques are still being developed, but even with the first versions of the experiment, outstanding results have been achieved.

The idea underlying the experiment is the production of resonance. Resonance is to be expected whenever a system having a natural frequency of its own is stimulated by an outside force having this same frequency, and can be recognized either by a particularly lively response of the system being resonated, or by a strong reaction on the source of the external force. The precessional frequencies of atoms depend very much on whether their angular momentum originates in the system of external electrons or in the atomic nucleus, since the ratio of charge to mass differs by several orders of magnitude in the two cases. Even including this wide range of

experimental material, however, precessional frequencies in conveniently obtainable magnetic fields ranging from a few to several thousand gauss turn out to lie between one-megacycle radio waves and one-centimeter microwaves, a range that is for the most part readily accessible to the experimenter.

The first magnetic resonance experiments were conducted on atoms or molecules in a beam emerging from an oven, and passing through a slit system into a high vacuum. The resonance condition was recognized by its effect on the trajectory of the particles in the beam. More recently experiments have been performed on solid, liquid, and even gaseous samples, resonance being recognized by its effect on the electrical circuit producing the high frequency oscillations.

Probing the Nucleus

These magnetic resonance experiments constitute one of the most recently added links in our communication system with the "under" world—the submicroscopic world of elementary particles which is the skeleton below the surfaces we see and feel. Here are some examples of bits of information that have recently come to light.

The Dirac theory of the electron predicts that the magnetic moment of the electron itself should be exactly equal to that of a hydrogen atom in its ground state as calculated on the basis of the old Bohr model of the atom. Experiments showed a discrepancy of about one part in a thousand in this relationship. The magnitude of the discrepancy itself was established to within a few percent, and has been accounted for quantitatively by a new development of the theory of the interaction of the electron with radiation. New experimental evidence has thus been furnished regarding the properties of the "ether"—that something between particles which still remains to a large extent unexplored and unknown.

As in the case of Newton's laws of motion, the quantum theory provides us with a generally applicable procedure for computing the properties of an arbitrary assemblage of bodies, but a procedure impossible to apply rigorously to more than two. In other words our real test of the laws of motion of an electron must be sought in the properties of the hydrogen atom. In this one case a detailed comparison of experiment and theory may be expected to reveal more than the validity of the mathematical

*Generators
in the
power house
of Pickwick
Landing Dam,
T.V.A.
Ewing
Galloway*



approximations used in applying the theory. New details are being found, and accounted for by the theorists, one might almost say, within a few minutes! An example is the hyperfine structure of the ground state of hydrogen. This splitting of the ground state results from the interaction of the electron with the magnetic moment of the nucleus, and can be rigorously calculated for hydrogen if

the magnitude of the nuclear moment is known. The magnetic moments of two different hydrogen nuclei, namely the proton and the deuteron, are now known to one part in a hundred thousand. The hyperfine splitting of the levels is far too small to be observable as a detail of the visible spectrum, but it has been measured directly by the absorption of microwaves in an atomic beam. Again a discrepancy

was found, this time amounting to only a few parts in a hundred thousand. And again the discrepancy was explained, this time in terms of the structure of the deuteron. The electron in its journeyings around its nucleus apparently spends sufficient time inside the deuteron so that its motion, or more correctly its energy, is observably influenced by the inner structure of this particle.

The future of such investigations may be very interesting. Considerable improvement in accuracy is still obtainable. No one has yet tried to go the limit. Further, only a very small area of the complete chart of levels of the hydrogen atom and their perturbations by external fields has been carefully explored. While most experimenters might hesitate to undertake large scale new researches in this field, on the ground that nothing new is to be expected, some skeptic will presently go and see. Perhaps the most fantastic conceivable result of such a venture on an extended scale would be the report that everything is exactly as predicted.

Beyond this high precision type of experimentation there is the general survey of the properties of atomic systems. In so far as the electronic structure of atoms is concerned, this is in the main finished work. The periodicities revealed by the periodic table of the elements were reflected in their magnetic properties. The investigation of the states of atoms

in solids, liquids, and gases was greatly helped by magnetic investigations. New results are being obtained, but these are more apt to be elucidations of detail than of principle. In the field of nuclear physics, however, we are not yet at this advanced stage. Magnetic resonance experiments, supplemented by the older spectroscopic investigations in the early thirties, are bringing some broad features of the situation into focus. For example, nuclei containing an even number of protons and an even number of neutrons appear to be nonmagnetic. This will probably not turn out to be a generally applicable rule, but it is true in a sufficient number of cases so that the exceptions should be of particular interest. As in the case of atoms, a periodicity in nuclear structure seems to be coming to light. Structures containing 2, 8, 10, 20, 50, or 82 neutrons or protons are found to be outstanding, as though they had closed shell structures like the rare gases. One can then try to assign quantum numbers of configurations having one excess proton or neutron, as in the alkali metals, or one too few, as in the halogens.

Playing such games is likely to become increasingly rewarding as more data is accumulated and data is rapidly being accumulated. For the present, at any rate, physicists seem to have the means, the time, and the inclination to pursue these matters.

