Everyone's Magnetism

Though it seems counterintuitive, today's research magnets can easily levitate seemingly nonmagnetic objects, thereby opening an Earthbound door to microgravity conditions.

Andrey Geim

If you were to tell a child playing with a horseshoe magnet and pieces of iron that his uncle has a much bigger magnet that can lift everything and everybody, the child would probably believe you and might even ask for a ride on the magnet. If a physicist were present at such a conversation, he or she—armed with knowledge and experience—would probably smile condescendingly. The physicist would know well that only a very few materials—such as iron or nickel—are strongly magnetic, while the rest of the world's materials are not; to be precise, the rest of the world is a billion (10^9) times less magnetic. This number seems obviously too large to allow common substances (water, for example) to be lifted even by the most powerful magnets; a billionfold increase in magnetic fields can be found only on neutron stars. In this case, however, knowledge and experience would mislead the physicist: In fact, all materials can be lifted by using magnetic fields that are rather standard these days. In principle, even a child can be levitated by a magnet, as we shall see below.

Our twice-cheated intuition

The photographs that accompany this article show a hazelnut (see inset in figure 1, which shows the experimental setup), a frog (figure 2), and a globule of water (figure 3) all hovering—levitating—in a magnetic field of about 10 T. This field strength is only several times more than that of existing permanent magnets (about 1.5 T) and only 100 times or so stronger than that of a typical refrigerator magnet. One need just open a textbook on magnetism to realize that such fields can lift "nonmagnetic" materials. Indeed, the magnetic force acting on a material of volume V with susceptibility χ in a magnetic field $\mathbf{B}$ is $\mathbf{F} = (\mathbf{M}\cdot\nabla)\mathbf{B}$ where the magnetic moment $\mathbf{M} = (\chi/\mu_0)V\mathbf{B}$. This force should compensate the gravitational force $m\mathbf{g} = \rho V\mathbf{g}$ (ρ is the material density and $\mathbf{g}$ is the gravitational acceleration) and, hence, the vertical field gradient ∇B^2 required for lifting has to be greater than $2\mu_0\mathbf{g}(\rho/\chi)$ (here we use "lifting" to distinguish it from "levitation," which means stable floating).

Owing to the readjustment of electron orbits in a magnetic field, all objects, even "nonmagnetic" ones, exhibit diamagnetism, which determines the lowest possible limit of their magnetic response. Standard handbooks show that, for the great majority of materials, the ratio χ/ρ is close to 10^{-5} per gram per cubic centimeter. Lifting such materials thus requires a vertical field gradient on the order of 30 T^2/cm. Assuming $l = 10$ cm as the typical size of a high-field solenoid and approximating $\nabla B^2 = B^2/l$, one finds that fields of about 10 T are sufficient to lift practically any substance around us. Our intuition is twice cheated: First, we tend to neglect the square increase of the lifting power with magnetic field; second, the magnetic field actually required to lift a piece of iron is just a few gauss, much less than the field in the bulk of a horseshoe magnet.

Diamagnetism was discovered by Michael Faraday in 1846, but no one at the time thought that it could lead to any appreciable effects. William Thomson (Lord Kelvin), referring to levitation as the problem of "Mohamet's coffin," had this to say: "It will probably be impossible *ever* to observe this phenomenon, on account of the difficulty of getting a magnet strong enough, and a diamagnetic substance sufficiently light, as the [magnetic] forces are excessively feeble."[1]

Fields strong enough to lift diamagnetic materials became available during the mid-20th century. In 1939, W. Braunbeck levitated small beads of graphite in a vertical electromagnet.[2] Graphite has the largest ratio χ/ρ known for diamagnetics (8×10^{-5} cm^3/g); today, this experiment can be repeated using just a strong permanent magnet, such as one made of neodymium, iron and boron. Leaving aside superconductors (which are ideal diamagnetics), first levitated by Arkadiev in 1947, it took another fifty years to rediscover the possible levitation of conventional, room-temperature materials. In 1991, Eric Beaugnon and Robert Tournier magnetically lifted water and a number of organic substances.[3] They were soon followed by others, who levitated liquid hydrogen and helium[4] and frog eggs.[5] At the same time, Jan Kees Maan and I rediscovered diamagnetic levitation at the University of Nijmegen, in collaboration with Humberto Carmona and Peter Main of Nottingham University in England. In our experiments,[6] we levitated practically everything at hand, from pieces of cheese and pizza to living creatures including frogs and a mouse. Remarkably, the magnetic fields employed in these experiments had already been available for several decades and, at perhaps half a dozen laboratories in the world, it would have taken only an hour of work to implement room-temperature levitation. Nevertheless, even physicists who used strong magnetic fields every day in their research did not recognize the possibility. For example, when my colleagues and I first presented photographs of levitating frogs (figure 2) many of our colleagues took them for a hoax, an April fool's joke.

However counterintuitive the magnetic lifting of

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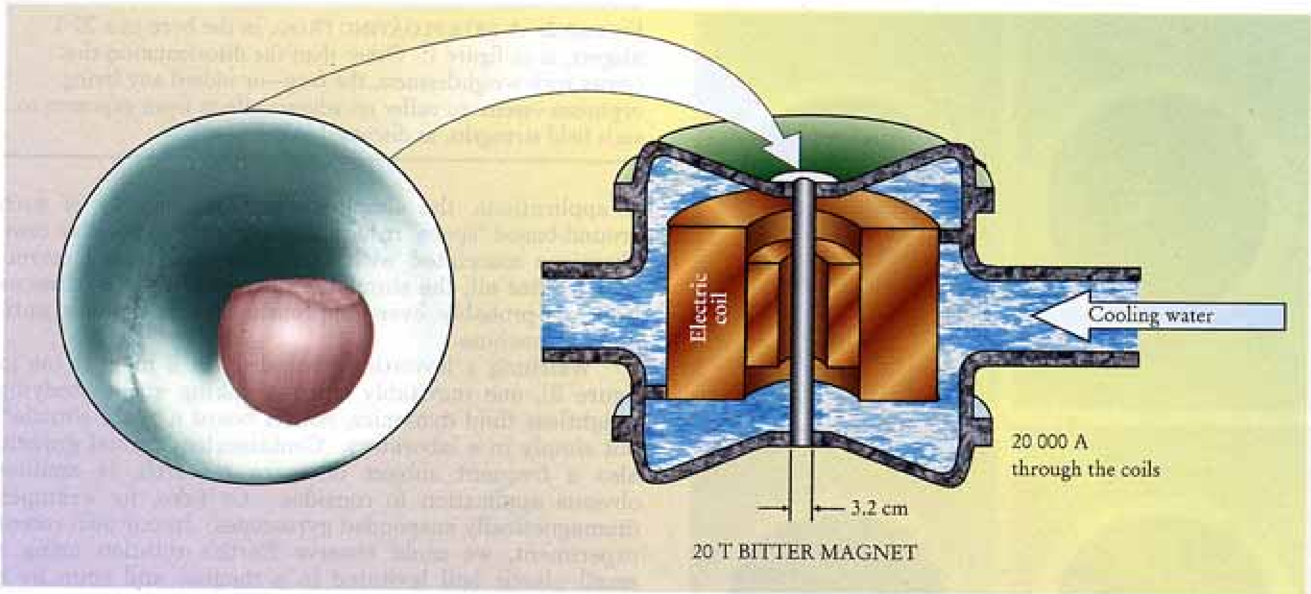

FIGURE 1: LEVITATING NUTS–EXPERIMENTAL SETUP. The object, in this case a hazelnut (inset), is placed in the 3.2 cm bore of a 20 T Bitter magnet. When the field in the center is about 16 T, the magnetic gradients at the levitation point (near the top of the inner coil) are just right to cancel the pull of gravity at the molecular level in this manifestly "nonmagnetic" object. There, the applied field is about 10 T and the nut becomes a weak magnet, having an induced field of about one gauss. This implies a surprisingly large current (about one amp) circulating in the nut's shell, but the current represents the summation of induced microscopic currents in atoms and is not dissipative. Thus, living creatures are not electrocuted when levitating.

seemingly nonmagnetic objects may be, there are more surprises in store for the physicist looking into diamagnetic levitation. Try, for example, to levitate a piece of iron: You will find you can lift it easily with a horseshoe magnet, but you will not be able to float it, whatever tricky configuration of magnets you design. To understand this state of affairs, it is useful to recall Earnshaw's theorem, which says (as recently reformulated by Michael Berry) that no stationary object made of charges, magnets and masses can be held in space by any fixed combination of electric, magnetic and gravitational forces.[6,7] The proof is simple: The stable equilibrium of a test magnet (or charge) in an external field would require its total energy (magnetic, electrostatic and gravitational) to have a minimum; but that is impossible because the energy must satisfy Laplace's equation, whose solutions have no isolated minima (or maxima), only saddles. Earnshaw's theorem appears to be so thoroughly forgotten that on many occasions I have been offered schemes that would supposedly allow stable levitation of permanent magnets or paramagnetic substances. The original theorem can be extended to the case of magnetized materials: Paramagnetic substances *cannot* levitate (unless placed in more strongly paramagnetic media, thereby making them effectively diamagnetic).

Only diamagnetic materials can flaunt the rule.[1,6] Surprisingly, Kelvin recognized this back in 1847—just eight years after Samuel Earnshaw put forth his theorem—and showed qualitatively that diamagnetic substances could be stably held in a magnetic field. The theorem fails because diamagnetism, a quantum phenomenon, cannot be approximated by any configuration of classical magnets, as considered in Earnshaw's theorem. Alternatively, one can say that diamagnetism involves electron motion around nuclei and, therefore, is not a fixed configuration as required by the theorem.

Just because an object *can* levitate does not mean that it *will* when placed in a strong enough magnetic field. The right conditions are surprisingly subtle; for instance, even an increase of only a few percent in magnetic field will normally destabilize levitation and cause the object to fall. A diamagnetic object can levitate only close to an inflection point of the vertical component of the magnetic field,[6] where $d^2B_z/dz^2 = 0$. Note that this is a purely geometrical condition, which does not depend on the field strength. The spatial extent of the region of stable levitation is typically a small fraction of the magnet's size—just 2 centimeters for our half-meter Bitter magnet, for example. Accordingly, the field strength must be carefully adjusted to compensate for gravity at that particular point. If the field is slightly weaker than required, the object falls; if stronger, the field is horizontally unstable and only the magnet walls stop the object from moving sideways and then falling.

A gentle touch or airflow can easily destroy the levitation. Those who have tried to levitate high-temperature superconductors would probably raise their eyebrows, since they encounter no problems. However, superconducting levitation takes advantage of magnetic flux lines being pinned inside a superconductor; this is what makes floating superconductors such a familiar sight. Eliminate pinning, and once again careful adjustments of both spatial position and field strength are required.

Unique features, exciting uses

The idea of diamagnetic levitation is so attractive that, when first learning about it, experimental physicists naturally start thinking—if only for a brief moment—about employing the effect in their own particular research. Indeed, superconducting magnets with a room-temperature bore are relatively cheap these days—a reasonable, basic setup costs about $100 000—making access to levitation affordable even for individual research groups.

With respect to possible applications, some features of diamagnetic levitation are really unique. First of all, such levitation provides a frictionless suspension whose parameters (such as rigidity) can be controlled at will by adjusting the field profile. This feature makes it possible

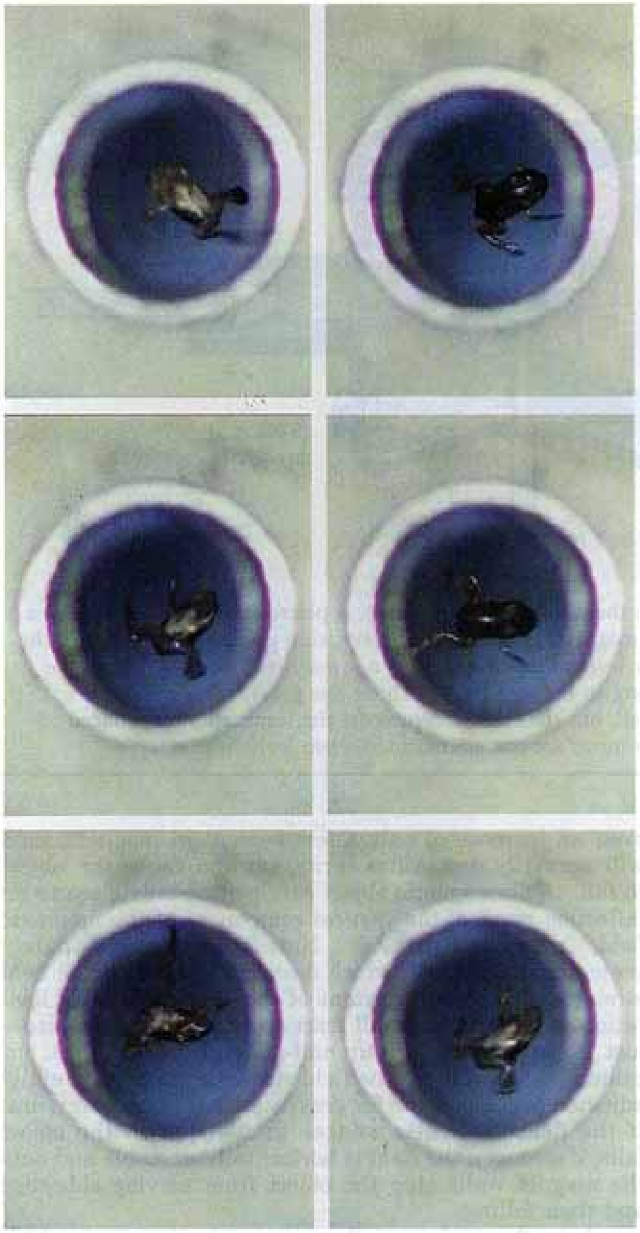

FIGURE 2: A FREE-FLOATING FROG, in the bore of a 20 T magnet, as in figure 1. Other than the disorientation that comes with weightlessness, the frog—or indeed any living organism—seems to suffer no adverse effects from exposure to such field strengths, as discussed in the text.

to design, for example, ultrasensitive gravimeters and other geophysical equipment where sensitivity to minor variations in the gravitational field is required. Along with the basic simplicity and flexibility of such instruments, the absence of flux jumps and the possibility of incorporating optical detection schemes make them an attractive alternative to devices based on superconducting levitation.[8] The most distinctive advantage of room-temperature diamagnetic levitation, however, is that—unlike any other known or feasible technique including superconducting levitation[9]—the suspension is distributed uniformly over the bulk. In fact, for a homogeneous material in a field with profile $B^2 \propto z$, gravity is canceled on the level of individual atoms and molecules, which makes it possible to closely simulate microgravity conditions right here on Earth. One should bear in mind that this is still not an ideal weightlessness: Deviations are present due to (1) an unavoidable field gradient in the horizontal direction (because $\nabla \cdot \mathbf{B} = 0$), (2) a distortion of the field by the presence of a magnetized object (on the order of μ, or 10^{-5}) and (3) a possible anisotropy of the diamagnetic susceptibility. Nevertheless, for a multitude of applications, the simplicity and accessibility of such ground-based "space" research outweighs the possible complications associated with these relatively small corrections. After all, the simulated microgravity is as close as we can—probably ever—approach science fiction's antigravity machine.

Watching a levitating waterdrop in a magnet (as in figure 3), one inevitably starts thinking about studying weightless fluid dynamics, not on board a space shuttle[10] but simply in a laboratory. Containerless crystal growth, also a frequent subject of space research, is another obvious application to consider. Or take, for example, diamagnetically suspended gyroscopes. In our own recent experiment, we could observe Earth's rotation using a small plastic ball levitated in a magnet and spun by a laser beam. Not a great achievement in itself, but already our first attempt has shown error drifts of just 0.1% of Earth's rotation, a record low for any type of gyroscope.

Magnetic microgravity seems to work well even for complex biological systems. Several groups of biophysicists—such as those led by James Valles of Brown University, Karl Hasenstein of the University of Southwestern Louisiana and Markus Braun of the University of Bonn (Germany)—have already begun studies of plant and animal responses to such magnetically simulated microgravity. Biological systems are astonishingly homogeneous with respect to diamagnetic levitation: Seemingly diverse components such as water, tissues, bones and blood differ in their values of χ/ρ by only several percent,[11] which implies that gravity is compensated to better than 0.1 g throughout a complex living organism. Further, even if paramagnetic molecules and ions are present, as in blood, they contribute only to the average susceptibility; their strong response to the field is smeared out by temperature ($\mu_B B \ll kT$), Brownian motion and a much stronger coupling to the surrounding diamagnetic molecules.[11] Probably, the alignment of very long biomolecules along the field direction is the magnetic effect most likely to obscure true microgravity in complex systems.[12] Fortunately, one can always check for this and other nonmicrogravity effects by placing a system in an identical, but horizontal, field gradient or in a homogeneous field of the same intensity.

An interesting example of how the diamagnetic force can be exploited is an attempt to show that in space a magnetic field can replace gravity as a guide for plant growth: A germinating seed needs to know in which direction to grow so that it can successfully emerge from the soil before its limited resources are exhausted. Hasenstein's ground-based experiments[13] indicate that even a small permanent magnet can provide enough guidance for a growing plant on board a spaceship.

As for possible, and as yet unknown, adverse effects of strong constant magnetic fields on living systems (a subject of interest on its own), such effects are unlikely to be strong. In researching medical applications, volunteers have spent up to 40 hours inside a 4 T whole-body magnet without any ill effects[11] and further similar experiments currently under way at Ohio State University also indicate no danger at least up to 8 T, according to John Schenck from the General Electric Corporate Research and Development Center, in Schenectady, New York. So, when the researchers from Brown University

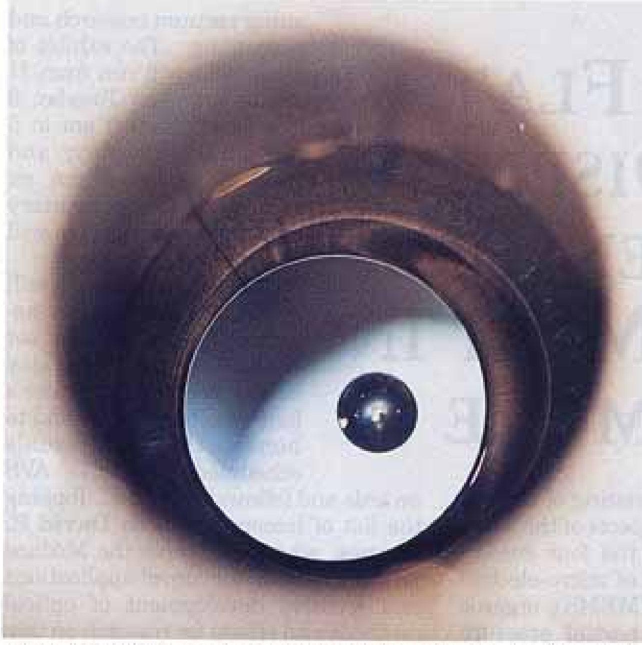

FIGURE 3: WEIGHTLESS FLUID DYNAMICS is one area in which research might exploit magnetic levitation, as exemplified by this hovering globule of water.

found an abnormal development of frog embryos in artificial microgravity, they probably rightly attributed it to the influence of weightlessness rather than to the magnetic field.

Finally, let us return to the child who wanted to levitate. However provocative, it is instructive to discuss this possibility: After all, the leader of a religious sect in England offered £1 million for a machine to levitate him in front of his congregation.[14] The magnetic field required to keep a uniform value of ∇B^2 increases with volume. The existing Bitter and superconducting magnets are capable of levitating objects a few centimeters in diameter. According to magnet designers from the National High Magnetic Field Laboratory in Tallahassee, Florida, existing technology can accommodate objects up to about 15 cm. However, levitating a human would require a special racetrack magnet of almost 40 T and about one GW of continuous power consumption. So, while the use of diamagnetic levitation is bound to become increasingly popular among scientists, the child and the priest will perhaps have to use less impressive but more conventional methods of levitation—like a helicopter.

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