# Diamagnetic Levitation

*Known since the 1930s, a simple technique for suspending objects magnetically is just now finding practical application*

Ronald E. Pelrine

The ability of magnets to exert forces on one another without touching intrigues most children—and more than a few adults. It is a short step from pondering this curious phenomenon to wondering whether the force from one magnet could be used to levitate another, seemingly in defiance of gravity. Unfortunately, as any frustrated would-be levitator has discovered, the answer is no: A magnetic field can be arranged so that at some position it just balances the gravitational force on a small magnet, but any disturbance to the levitated magnet, no matter how tiny, causes it to crash. This inherent lack of stability is summed up in a statement of physical law known as Earnshaw's Theorem, first elucidated in 1842. It is a direct consequence of Maxwell's fundamental equations describing electricity and magnetism.

Mastery of Maxwell's equations isn't needed to understand Earnshaw's Theorem. One needs merely to know that the behavior of a magnet can be described in terms of something called the magnetic potential, which is analogous to more familiar forms of potential energy (stored energy). Consider a marble placed on an undulating surface. The marble will roll in the direction that decreases its potential energy most rapidly, becoming free of any force only where the potential attains a local minimum—the flat bottom of a depression. Similarly, a levitated magnet would be stable only if it could be situated at a local minimum of the magnetic potential. But Maxwell's equations dictate that the magnetic potential at a point in space must be the average of the potential at surrounding positions. The magnetic potential thus cannot attain a local minimum anywhere in free space: Some nearby points will always have lower magnetic energy, while others will have higher energy.

Faced with the obvious implications of Earnshaw's Theorem, investigators have looked for other ways to levitate. The most common tactic is to use time-varying magnetic fields, to which Earnshaw's Theorem doesn't apply. Active-feedback levitation, for example, uses sensors to measure the position of a levitated object, adjusting the applied field in just the right way to keep things suspended. This approach has been used for decades in active magnetic bearings and experimental "maglev" trains. Although workable, such systems have considerable drawbacks: They consume power and are relatively complex, which means that they are expensive and can be prone to failure. But it turns out that there is a way to levitate a magnet without such complications. To understand how this feat can be carried out more simply, one needs at least a rudimentary understanding of the different types of magnetic materials.

## The Right Stuff

Magnetic materials come in three flavors: ferromagnetic, paramagnetic and diamagnetic. Ferromagnetic materials, such as iron, can often be permanently magnetized, allowing objects made of them, for example, to stick to refrigerator doors indefinitely. Paramagnetic substances, such as the mineral biotite, become magnetized only while they are exposed to an external magnetic field. They are attracted to permanent magnets and thus do not help in the quest for stable, passive levitation. Diamagnetic substances act differently. They repel permanent magnets, and in this way make such levitations rather easy.

A very simple model of the atom helps explain why diamagnetic materials act in this way. Consider an electron in orbit around the nucleus of an atom of diamagnetic material. Being a charge in motion, this electron generates a magnetic field that is just like that of a tiny current-carrying loop of wire. In the absence of an external magnetic field, this orbiting electron and its many neighbors generate randomly aligned fields, which cancel one another, so the material does not generate an overall field of its own. But when subjected to an external field (say, one from an approaching permanent magnet), these electrons speed up or slow down so as to oppose the change in the field inside their orbits. (This is just the atomic-scale version of a rule of electricity and magnetism called Lenz's Law.) The net effect is an induced magnetization that opposes the applied field, causing a repulsive force.

One can exploit this force to levitate permanent magnets above fixed diamagnetic materials. Or one can reverse things and levitate diamagnetic materials above one or more stationary magnets. The German physicist Werner Braunbeck demonstrated such diamagnetic levitation for the first time in 1939 when he floated some strongly diamagnetic materials (bismuth and graphite) using a fixed electromagnet.

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**Figure 1. Floating between thumb and forefinger, this small magnet demonstrates the surprising phenomenon of diamagnetic levitation. In this experiment, a powerful superconducting magnet located on the floor above provides the lifting force necessary to counter gravity. Having one magnet lift another in that way is, however, inherently unstable, as anyone who has played with a pair of refrigerator magnets can attest. In this case the weak diamagnetism of the investigator's fingers provides a modest repulsive force when the small magnet approaches, stabilizing the levitation. The author and his engineering colleagues have used this same principle to design devices intended for commercial application. (Courtesy of Andre Geim, University of Manchester.)**

The stable levitation of small permanent magnets above superconductors, a familiar sight in recent years, is just another form of diamagnetic levitation: Superconductors are not only perfectly conductive, they are highly diamagnetic.

How is it that this form of levitation does not violate Earnshaw's Theorem? The answer is that the theorem applies only to a static magnetic field, and in such diamagnetic levitations the motion of the suspended magnet itself causes the levitating field to change. If, for example, a floating magnet is pushed downward, it induces a stronger repulsive field in the diamagnetic material below, lifting the magnet back up. Likewise, if some disturbance causes the suspended magnet to rise a bit, the supportive magnetic field diminishes, easing the payload back down. In a sense, the diamagnetic material automatically accomplishes what the sensors and electronic controls do in an active-feedback levitation system.

Surely such remarkable diamagnetic materials must have exotic compositions or be hard to fabricate, right? Not at all. Diamagnetic substances are everywhere. Indeed, in a basic sense, all materials are diamagnetic, but in ferromagnetic and paramagnetic objects this universal property is masked by stronger magnetic effects. Water, most plastics and glasses, and many ceramics and metals are diamagnetic. Bismuth is strongly diamagnetic, and a form of carbon known as pyrolytic graphite shows

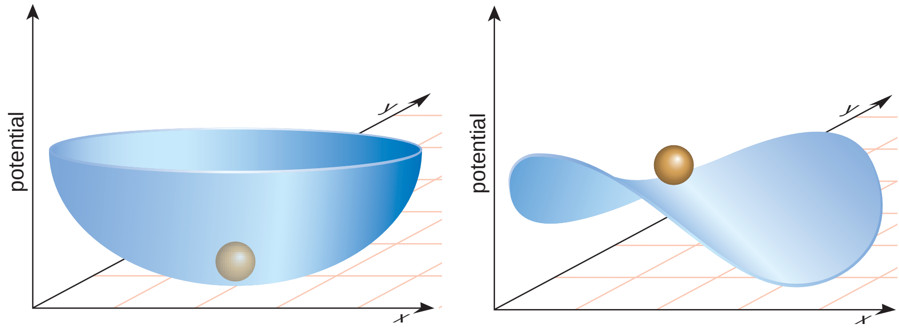


**Figure 2. Magnetic levitation is stable when the potential energy of the system is at a local minimum, just as it is for a marble sitting at the bottom of a bowl *(left)*. But Earnshaw's Theorem, a 19th-century result based on Maxwell's equations, indicates that it is not possible to configure a fixed magnetic field that minimizes the magnetic potential at a point in free space; the best one can do is achieve a saddle-shaped potential *(right)*. Hence, it has long been clear that a static magnetic field is not capable of stable levitation. But, as many physicists and engineers have lately come to realize, the phenomenon of diamagnetism provides a simple mechanism for altering the supporting magnetic field dynamically, thus providing a way around the constraints of Earnshaw's Theorem.**

the highest diamagnetism of all at room temperature. It has this property because some of its electrons effectively travel in larger-than-normal orbits, so the magnetic field they produce from diamagnetism is much stronger than that generated in other materials.

Although such strongly diamagnetic substances are the easiest to suspend, all diamagnetic materials can be levitated with a sufficiently intense magnetic field. Andre Geim, a physicist at the University of Manchester, and his collaborators have exploited this fact in recent years to produce some spectacular levitations—including one of a live frog—using a powerful superconducting magnet.

## Balancing Act

The fact that diamagnetic levitation can be stable does not mean it always will be stable. Proper design is needed. The basic idea in levitating diamagnetic materials is to set up a geometry that can support the object against gravity and at the same time ensure stability.

One straightforward approach is to arrange two like magnetic poles so that they face each other but are separated by a gap. The fields of the two magnetic poles thus cancel completely halfway between them. Poised at that one spot, a small piece of diamagnetic material has zero magnetic energy. Any deflection only increases its magnetic energy, which makes this midpoint a stable energy minimum. Although this configuration is conceptually simple to understand, it proves somewhat difficult to implement in practice.

Other geometries provide for the levitation of an anisotropic diamagnetic material (one in which the degree of diamagnetism depends on the direction of the applied field), such as pyrolytic graphite, which is typically formed using the decomposition of a high-temperature gas to deposit carbon atoms in a carefully controlled manner on a solid substrate. A horizontal slab of pyrolitic graphite is strongly repelled by vertical fields but is little affected by in-plane fields. So, for example, a flat graphic ring (one shaped like an ordinary washer) can readily be made to levitate above the junction between two concentric magnetic rings, where the field is horizontal. Interestingly, such a graphite ring is free to rotate as it floats.

Indeed, using a few permanent magnets to levitate graphite is easy, because it is comparatively light. But it proves surprisingly difficult to flip things around and levitate permanent magnets by themselves, because they are much more dense. I was the first to do so, in 1992, using an array of small magnets to increase the magnetic field intensity per unit mass.

Another way to levitate a magnet is to use a second, fixed magnet to provide the needed lift. Of course, the lifting magnet (or, as it is often called, the bias magnet) tends to make the levitated one unstable, according to Earnshaw's Theorem. But since at least the 1950s it has been known that strongly diamagnetic materials, such as bismuth or graphite, placed close to the floating magnet readily stabilize the levitation. With proper balancing, one can also use weakly diamagnetic materials, such as plastics

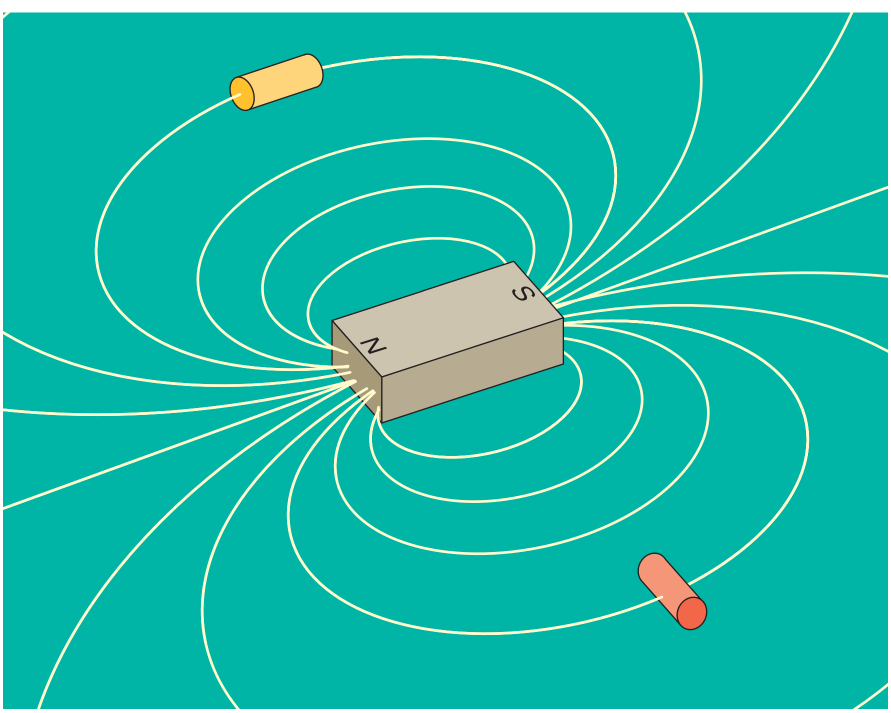


**Figure 3. Diamagnetism and paramagnetism derive their names from the behavior of various substances under the influence of a magnetic field. If free to rotate, an elongate piece of paramagnetic material *(yellow)* will align itself in parallel with the ambient field, whereas a similarly shaped piece of diamagnetic material *(red)* will align itself across the direction of the field.**

and silicon. Indeed, Geim and his colleagues have recently performed some remarkable levitations using a powerful superconducting magnet for lift and nothing more than a pair of human fingers, which are diamagnetic because of their water content, for stabilization.

Schemes for diamagnetic levitation range from such simple arrangements to sophisticated designs in which computer modeling is applied to calculate the resistance against outside disturbances such as vibration and shock. Engineers like myself pay special attention to such things, recognizing that unwanted oscillations at the resonant frequency of the system would increase in magnitude over time, causing the levitation ultimately to fail.

Because the suspended object is not in direct contact with the rest of the device, common damping techniques, such as affixing a shock absorber to the relevant components, are not suitable. Fortunately, the strong magnetic fields involved provide the ideal solution to this problem: eddy-current damping, which occurs, for example, when a permanent magnet is moved near a fixed electrical conductor. In that case, the changing magnetic field induces electrical currents in the conductor, which cause it to heat up. This process thus damps unwanted movements by dissipating their energy as heat.

Unless they are intentionally quashed in this way, motions in the suspended object will persist for long periods of time—which in some instances may be a very desirable property, say for a flywheel. A good demonstration of what can be done dates back to 1966, when Robert D. Waldron (then working for The Garrett Corporation in Phoenix) levitated a 4-centimeter graphite ring and arranged for it to spin at 100 rotations per minute for hours in a vacuum. He was able to determine that the drag on it dissipated a mere 4 nanowatts.

Those losses, small as they were, could probably have been avoided. They were most likely the result of parasitic eddy currents swirling around in the ring of graphite, which is an electrical conductor. This source of drag could thus be drastically reduced by using a ring constructed of insulated graphite particles or one made of a diamagnetic material that is an intrinsic insulator. A rotating ring optimized in this way might spin for months or even years in a vacuum. Indeed, it is not clear at this point what the main source of drag would be in such a system.

### The Magic of Levitation

Diamagnetic levitation is a striking physical phenomenon, one that has been studied for many decades now. Yet surprisingly few people, even scientists and engineers, are familiar with it. One reason is that, with the exception of some kits being sold as scientif-

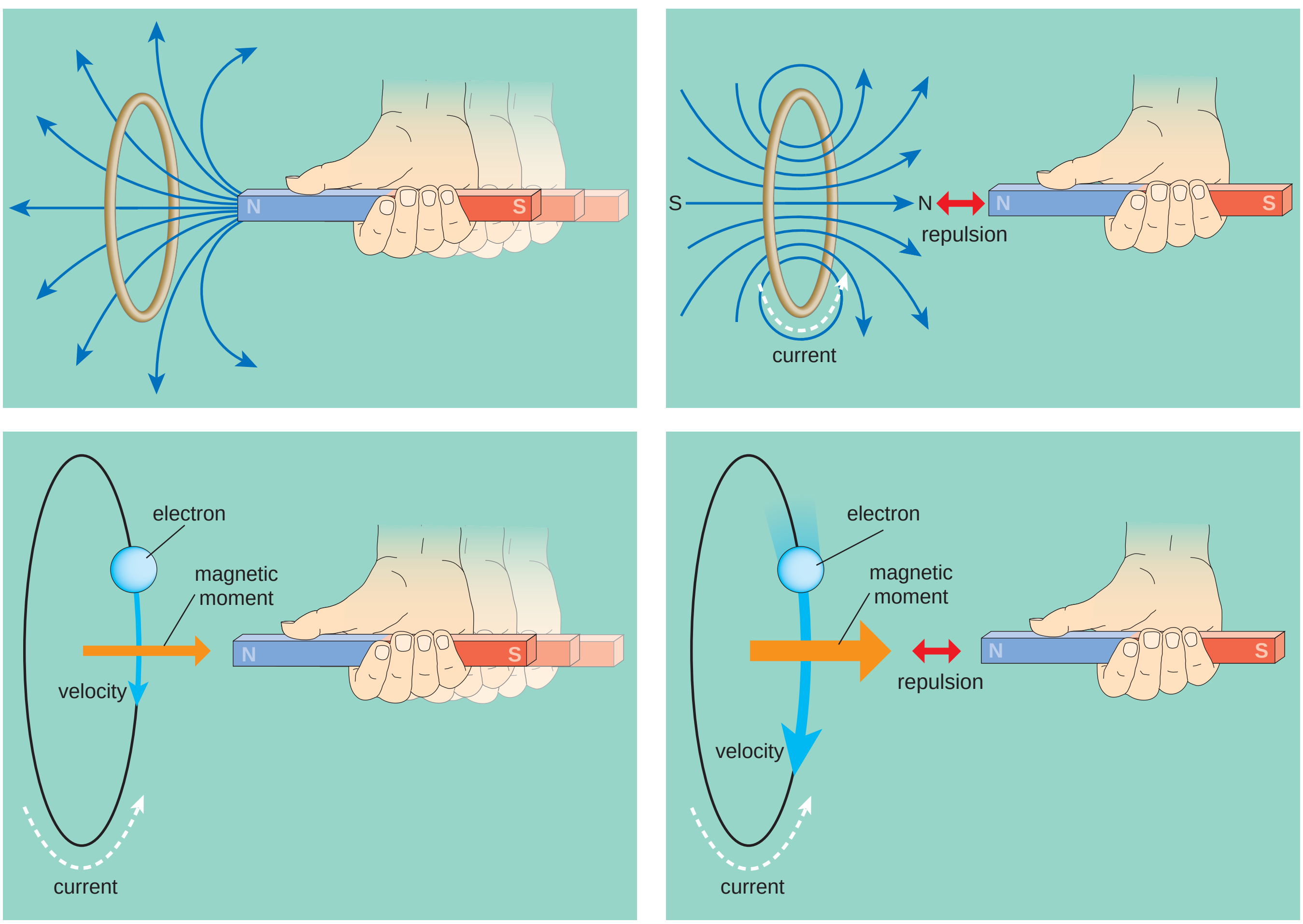


**Figure 4. Diamagnetism arises from an atomic-scale version of Lenz's law, which dictates that altering the magnetic flux through a conductive loop of wire *(upper left)* will induce electric currents that in turn give rise to a magnetic field opposing the change *(upper right)*. In a diamagnetic material, an electron in orbit around an atom acts, in a sense, like a conductive loop of wire, speeding up or slowing down so as to oppose any change in the magnetic field it experiences *(bottom)*. The magnetization induced in a diamagnetic object thus always manifests itself as a repulsive force.**

**Figure 5. Pieces of pyrolitic graphite, cut into various shapes, hover intriguingly. In this demonstration, about 120 objects in all floated above a base of permanent magnets. A powered device that could lift an equally large number and variety of objects using active feedback would be a significant engineering challenge to design and build, whereas this simple system of passive, diamagnetic levitation is straightforward to assemble. (Courtesy of the author.)**

ic novelties, diamagnetic levitation has not yet been exploited commercially—although various possibilities, including useful sensors and frictionless transport systems, have been fashioned in academic and industrial labs.

Why did so many decades pass between the first demonstration of diamagnetic levitation in 1939 and the development of useful devices based on this principle? The chief reason is that powerful neodymium-iron magnets, which make diamagnetic levitation quite easy today, were discovered only in the 1980s and didn't become widely available until the 1990s. In that sense, diamagnetic levitation was invented long before its time.

I first became familiar with this phenomenon in the mid-1980s during my Ph.D. studies, while trying to figure out how to design tiny robotic manipulators. The notion was that if these could be controlled to high precision at small scales, one could put together a compact system with all the mechanical complexity and precision of a modern manufacturing facility. Such a "microfactory" might be used, say, to mass-produce small-scale components at very low cost, to analyze compounds or for drug screening.

The engineering challenges to fashioning such a system are, of course, formidable. The biggest problem is that a centimeter-scale robot is extremely difficult to make autonomous, because it would need to carry on-board power, controls, navigation systems and so forth. The best way to overcome this obstacle, I realized, was to put the power and controls elsewhere and to exert magnetic or electrostatic forces on the robotic manipulators from external fixtures. Still, I needed to figure out what sort of bearings would allow the microrobots to move around. Conventional techniques just wouldn't do: Sliding surfaces have problems with friction and wear, and tiny wheels would be difficult to make and assemble.

Levitation seemed the natural solution. But imagine the difficulty of actively levitating, say, 1,000 microrobots, particularly if they needed to interact. The failure of even one sensor or control circuit could cause havoc. I thus began to investigate diamagnetic levitation, which, being automatic and virtually 100 percent reliable, might make the envisioned system of interacting microrobots feasible.

## A New Spin

Although I never built such a microfactory, thinking about the diminutive robots that would be needed for one led me to consider the more basic problem of how to provide bearings for micromachines. Rotary micromotors, for ex-

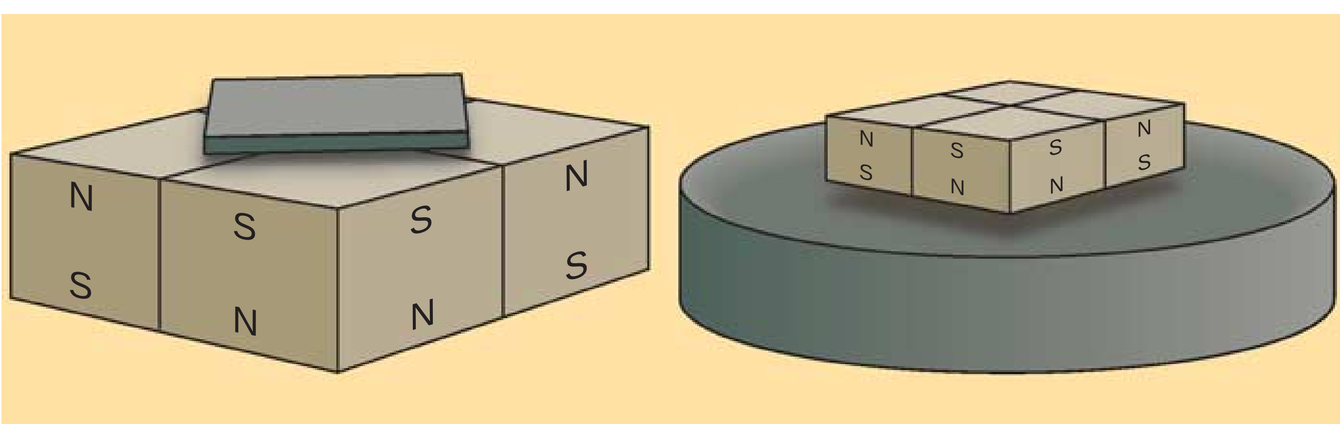


**Figure 6. Levitation of pyrolitic graphite *(gray)* typically involves a suitably configured array of neodymium-iron magnets *(brown)*, which were developed in the 1980s and have been readily available since the 1990s *(left)*. Inverting the sense of levitation is difficult, however, because the neodymium-iron alloy is much more dense than graphite. The author discovered a way to do so in 1992, using an array of four neodymium-iron magnets and a shallowly dished graphite base, which held the levitated magnets in a centered position *(right)*.**

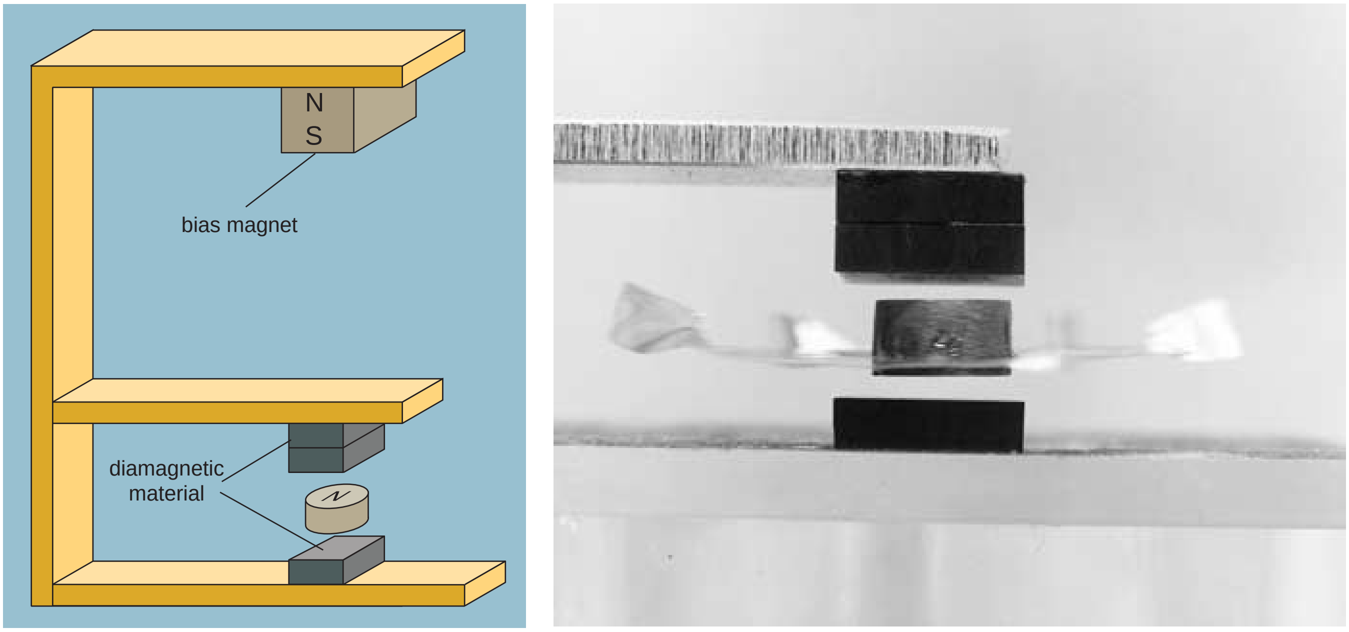


**Figure 7. Heavier objects can be lifted through the use of a bias magnet (which provides the force necessary to counter gravity) so long as diamagnetic materials are used to stabilize the levitation *(left)*. The author and his colleagues used this simple arrangement to fashion a prototype flowmeter by attaching vanes to the levitated magnet *(right)*. Using a magnetic bearing for the spinning vanes overcomes the static friction inherent in conventional bearings, allowing such a device to measure extremely low rates of gas flow. The lack of friction also helps under conditions of high flow and rapid spin, which otherwise can generate enough friction to compromise the accuracy of a meter. (Photograph courtesy of the author.)**

ample, typically spin on a shaft with sliding friction, causing wear and making their control difficult. Some engineers have attempted to construct such devices using active levitation, with varying degrees of success. To explore the effectiveness of diamagnetic bearings in this regard, I built a 1-millimeter-wide micromotor a few years back using a self-levitated array of magnets driven electromagnetically. I was able to get it to do 21,000 rotations per minute in air.

This success and similar advances by other investigators suggest that diamagnetic levitation can solve many of the problems that afflict micromachine bearings, particularly those used to support the "proof masses" used in sensors. These applications abound. For example, mechanical gyroscopes measure rotation using a bearing to support a spinning or vibrating mass. Similarly, accelerometers typically use a proof mass supported by a spring or flexible arm (both of which are "bearings" in the engineering sense). Likewise, gravimeters generally use a proof mass held on a spring to measure gravity, and tiltmeters and turbine flowmeters employ a mass supported on a bearing that allows rotation. In each case, the nature of the bearing is critical to the sensitivity, accuracy, frequency range, robustness and cost of the device.

Diamagnetic levitation has already proved its worth for several high-precision scientific sensors. Ivan Simon and colleagues at the Cambridge consulting firm Arthur D. Little, for example, used a levitated graphite rod to make a tiltmeter that has a sensitivity well below a microradian (less than six hundred thousandths of a degree). He also patented the design for a high-precision accelerometer based on diamagnetic levitation. And V. M. Ponizovskii of Perm State University in Russia built manometers capable of measuring gas pressures as low as $10^{-10}$ torr (that found in ultrahigh vacuum systems) using rotating vanes that are suspended with diamagnetic levitation. My SRI colleagues and I have experimented with flowmeters of related design in an effort to get around the problems with conventional turbine-type devices, where the static friction of the bearing makes it hard to measure low rates of gas flow. Friction in the bearing also induces considerable drag at high speeds, compromising the ability of conventional instruments to measure high rates of flow. Diamagnetic bearings avoid both problems, allowing a flowmeter to work accurately over an enormous range.

Although they measure widely different quantities, these instruments all utilize the ability of levitation to make bearings with very low stiffness in one direction (or around one axis), which allows them to function with high precision. Low stiffness allows measurable displacements of the proof mass with very minute forces and torques. Conventional sensors employ *flexures* (mechanical bending elements) to make the

| material | $\chi$ |
|---|---|
| bismuth | –280 |
| tin | –37 |
| table salt | –30 |
| gold | –28 |
| lead | –23 |
| silver | –20 |
| water | –13 |
| germanium | –12 |
| diamond | –6 |
| zinc | –9 |
| copper | –5 |
| silicon | –3 |

**Figure 8. Many substances, such as those listed above, are diamagnetic, as reflected in their negative values of magnetic susceptibility ($\chi$, given here in units of $10^{-6}$ cubic centimeters per mole). Pyrolitic graphite exhibits diamagnetism that (in one direction) can be even greater than that of bismuth.**

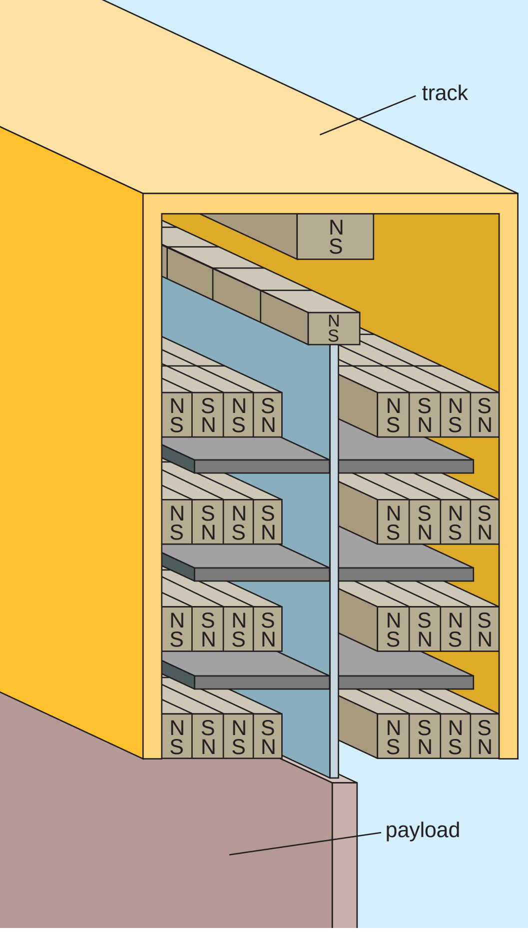


**Figure 9. Current record-holder for the amount of mass levitated using room-temperature diamagnetism is a prototype system built by the author and his colleagues. This device was intended to function in a clean-room environment, where conventional bearings and the particles they generate would pose a threat of contamination. As can be seen in this schematic representation, three horizontal diamagnetic plates *(gray)* are arranged between four banks of fixed magnets *(brown)*, providing stabilization. At the top of the vertical support for the carrier sits a line of magnets used to provide lift by virtue of their attraction to a similar line of bias magnets attached to the track.**

bearings for their proof masses. These devices are often constructed using techniques more commonly employed to mass produce microchips. Such microflexures are effective at frequencies above 100 hertz, but lower frequencies demand lower stiffness, making the bending elements difficult to fabricate. And even if they can be made, they tend to be weak and prone to breakage. (Full-size flexures and springs for high-precision sensors are often susceptible to such damage too.) By contrast, even very small diamagnetic bearings with low stiffness are extraordinarily shock tolerant, because there are no delicate parts to break. Thus, it's reasonable to expect that diamagnetic levitation might soon find commercial application in a new class of high-precision, rugged microsensors.

Other types of sensors do not rely on low stiffness and low resonant frequencies for sensitivity. For example, some designs use a mass vibrating at a high resonant frequency. The response of the sensor to its stimulus (be it acceleration, gravity, rotation or something else) is a change in the resonant frequency. Such a device typically requires that the vibration takes place with very little damping to ensure that this frequency is sharply defined, allowing it to be measured with great precision. Diamagnetic levitation may thus offer advantages here too, in that it provides a way to avoid the damping losses in conventional bearings and solid flexures. Still other sensors rely on the isolation of a mass, such as thermal isolation for bolometers (radiation sensors) or the mechanical isolation of other sensing elements from unwanted vibrations. Diamagnetic levitation may be attractive for these types of sensors as well because of its ability to support objects without solid contact.

### Keeping Things Clean

Even before it makes its way into commercial sensors, diamagnetic levitation may well show up in industrial "clean rooms." The advantage in that setting is that levitated bearings, being free of wear and needing no lubricants, do not generate stray particles, which might contaminate a sensitive industrial process, say, the fabrication of electronic components or the preparation of pharmaceuticals. Active-feedback magnetic levitation and pressurized-gas bearings are currently being used in such environments, but these systems have drawbacks. For example, a power or sensor failure in an active-feedback levitation system may cause a movable platform to crash into the track on which it rides, spewing particles into the air and contaminating the apparatus. And gas bearings are obviously inapplicable to processes that require a vacuum. Diamagnetic levitation sidesteps these issues.

A few years ago, at the behest of a corporate client, my colleagues at SRI and I built a prototype system intended for clean-room operation in a vacuum. The levitated structure, which contains both permanent magnets for lift and diamagnetic material for stability, carries a pallet that holds multiple metal disks onto which a coating is deposited. The levitated mass is roughly a meter long and tall and 10 centimeters wide. Weighing in at 13 kilograms (more or less, depending on the number of disks loaded), it is the largest mass ever suspended using diamagnetic levitation, or, more correctly, using diamagnetic levitation that doesn't rely on superconductivity.

Diamagnetic levitation also offers promise for some other specialized applications. For instance, it can be used to explore the effects of weightlessness on both living organisms and engineered materials. These applications typically require the very intense fields generated by superconducting magnets. Although this equipment is expensive, the cost is negligible compared with that of an actual space mission.

It is possible that such experiments could be carried out without superconducting magnets, as long as the object to be suspended is small enough. According to my very rough calculations, modern permanent magnets should be able to levitate drops of water that are 160 micrometers or less in size. Such small-scale levitations would be technically challenging, but they are probably feasible and offer a low-cost way to achieve lasting weightlessness (or a very good facsimile of it) without venturing into orbit.

Were they ever to be applied in outer space, diamagnetic forces might prove quite useful there as well. The absence of gravity would allow large gaps between the levitated object and the rest of the apparatus. One can imagine such arrangements being used for vibration isolation or to support flywheels, which are commonly employed in spacecraft to store angular momentum. Diamagnetic forces might also provide a convenient way for astronauts to manipulate objects without making physical contact with them.

Indeed, applying diamagnetic levitation in space gets around its one major disadvantage here on Earth: The bearing pressure that can currently be obtained is too low for most mechanical applications. However, there is no fundamental reason why the diamagnetism of specially designed materials could not be 10 or even 100 times greater than what's available now. If such substances could be identified and developed, diamagnetic levitation would be instantly catapulted from a little-known curiosity to a major technology. Transportation engineers might, for example, consider building maglev trains in this way.

Barring such a breakthrough, diamagnetic levitation will still surely find practical use through incremental improvements in magnets, materials and designs. In any case, diamagnetic levitation is a fascinating physical phenomenon worthy of continued study. It incorporates a rich mix of electromagnetic theory, materials science and engineering design to achieve systems with unusual properties and a truly magical feel. I'm confident that future work in this area will yield some intriguing surprises.

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