Magnet levitation at your fingertips

The stable levitation of magnets is forbidden by Earnshaw's theorem, which states that no stationary object made of magnets in a fixed configuration can be held in stable equilibrium by any combination of static magnetic or gravitational forces[1–3]. Earnshaw's theorem can be viewed as a consequence of the Maxwell equations, which do not allow the magnitude of a magnetic field in a free space to possess a maximum, as required for stable equilibrium. Diamagnets (which respond to magnetic fields with mild repulsion) are known to flout the theorem, as their negative susceptibility results in the requirement of a minimum rather than a maximum in the field's magnitude[2–4]. Nevertheless, levitation of a magnet without using superconductors is widely thought to be impossible. We find that the stable levitation of a magnet can be achieved using the feeble diamagnetism of materials that are normally perceived as being non-magnetic, so that even human fingers can keep a magnet hovering in mid-air without touching it.

Stable levitation has been demonstrated for diamagnetic objects such as superconducting pellets and live creatures[2,5–7]. Strong diamagnetism of superconductors allows the situation to be reversed, so that a magnet can be levitated above a superconductor[8]. Paramagnetic objects can also be levitated if placed in a stronger paramagnetic medium, such as ferrofluid or oxygen, which makes them effectively diamagnetic[9].

We set out to lift a magnet by applying a magnetic field and then stabilizing the intrinsically unstable equilibrium with repulsive forces from a nearby diamagnetic material. We found that, surprisingly, the forces created by almost non-magnetic materials (susceptibility χ of about 10^{-5}) are sufficient to stabilize levitation over distances as large as several millimetres under Earth gravity conditions, even though they decay rapidly with distance as $1/x^5$ (Fig. 1).

For stable levitation, an equilibrium requires that the magnetic force $MB'(z)$ compensates the gravitational force mg, where M is the magnetic moment and $B(z)$ and $B'(z)$ are the magnetic field on the axis and its derivative, respectively. For the equilibrium to be stable, it must be in a region where the total energy of the magnet $U=-MB(r)+mgz+U_{dia}$ has a minimum ($\Delta U>0$), where U_{dia} is the energy of diamagnetic interaction with the cylinder. Close to the equilibrium position at the field axis[3,10],

$$U \approx U_0+[mg-MB'(z)]z+K_v z^2+K_h r^2+Cr^2+\ldots \qquad (1)$$

where $K_v(z)\equiv -MB''(z)/2$ and $K_h(z)\equiv -M[B'(z)^2-2B(z)B''(z)]/8B(z)$.

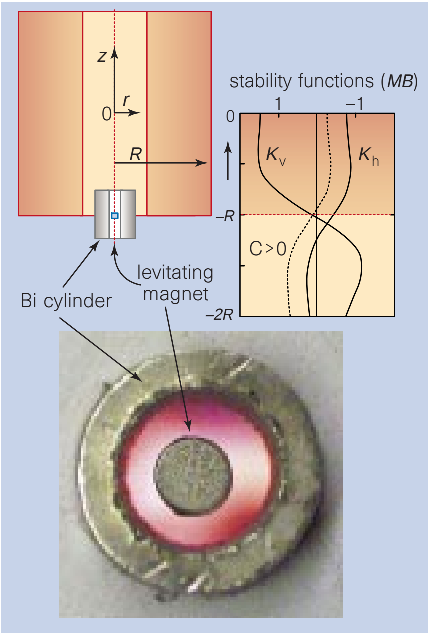

Figure 1 A NdFeB magnet (an alloy of neodymium, iron and boron; 4 mm high and 4 mm in diameter) levitating at the axis of a vertical solenoid of radius $R\approx10$ cm and length $\approx 2R$ in a magnetic field of 100 gauss. The levitation is stabilized by a bismuth cylinder ($\chi=-1.5\times10^{-4}$) with inner diameter $D\approx8$ mm. The photograph shows the top view of the levitating magnet. The right-hand plot shows the stability functions K_v and K_h calculated for a solenoid with a height of twice its radius (solid curves). Diamagnetic interaction C shifts the horizontal stability function K_h to the left (dashed curve) and a small region of positive ΔU emerges above the point where $K_v=0$.

The presence of a diamagnetic cylinder results in the last term in equation (1) and, for the geometry of Fig. 1, we find that $C=45\mu_0|\chi|M^2/16D^5$, where μ_0 is the permeability of free space. If there is no diamagnet ($C=0$), the stability can never be reached (at no point are K_v and K_h both positive; Fig. 1). The diamagnetic interaction allows the energy U to have a minimum ($K_v>0$ and $K_h+C>0$) which emerges for $C>MB'(z)^2/8B(z)$ just above the point of a maximum field gradient ($B''(z)=0$). It is counterintuitive that levitation is easiest in the most inhomogeneous field region, rather than in the centre of a solenoid where the field is almost uniform.

It is instructive to introduce a characteristic scale L on which the field changes: $B'=B/L$. At the optimum levitation point ($B''(z)=0$), L varies between R and $1.2R$ for long and short solenoids, respectively. If we approximate our levitating magnet by a sphere of diameter d with a remnant field B_r, then $M=(\pi/4\mu_0)B_r d^3$, and the requirement for levitation becomes

$$A(|\chi|LB_r^2d^3/\mu_0\rho g)^{1/5}>D>d \qquad (2)$$

Figure 2 Levitation at your fingertips. A strong NdFeB magnet (1.4 tesla) levitates 2.5 metres below a powerful superconducting magnet. The field at the levitation point is about 500 Gauss.

where ρ is the density of the magnet's material and $A\approx1.92$. Calculation shows that a magnet several millimetres in size with remnant magnetization of about 1 tesla (NdFeB) can be levitated with a clearance gap, $D-d$, of several millimetres using a 10-cm solenoid and strongly diamagnetic Bi or graphite, in agreement with our experiment.

Equation (2) depends on the product of χ and L, which means that by increasing L (scaling up the magnet's size) we can achieve the same D as above using ordinary materials (such as plastic or wood, with $\chi\approx-10^{-5}$). To illustrate this point, we show another example of a levitating magnet in Fig. 2 in which human fingers ($\chi\approx-10^{-5}$) are used as diamagnetic stabilizers. Here we use an alternative geometry[11] in which L is easier to scale up because it is determined not only by the magnet size, but also by its strength. The levitating magnet is placed below a solenoid in the region where the equilibrium is stable horizontally ($K_h>0$) but not vertically ($K_v<0$) (Fig. 1). Vertical stability is achieved by means of two horizontal diamagnetic plates (or by the fingertips).

In this geometry, the positive constant $C=6\mu_0|\chi|M^2/\pi D^5$ counters K_v and the levitation condition is similar to equation (2), except that now D denotes the separation between the plates, $A\approx1.02$ and $L\equiv4B'/B''$ is approximately the distance from the centre of a solenoid to a levitating magnet. The larger the distance, the easier it is to stabilize levitation by diamagnetic repulsion. L is limited by the requirement on the field gradient, $B'(z)=mg/M$. To reach such a large L, as in Fig. 2, we used an 11-tesla superconducting solenoid a metre in diameter. If stronger diamagnets are used (such as graphite or bismuth), this type of levitation can also be achieved with small permanent magnets, making miniature hand-held devices accessible to everyone (M. D. S., unpublished data). These could replace the existing servo levitation devices for some applications.

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Extraocular magnetic compass in newts

Geomagnetic orientation is widespread among organisms, but the mechanism(s) of magnetoreception has not been identified convincingly in any animal[1]. In agreement with biophysical models proposing that the geomagnetic field interacts with photoreceptors[2–4], changes in the wavelength of light have been shown to influence magnetic compass orientation in an amphibian, an insect and several species of birds (reviewed in ref. 5). We find that light-dependent magnetic orientation in the eastern red-spotted newt, *Notophthalmus viridescens*, is mediated by extraocular photoreceptors, probably located in the pineal complex or deeper in the brain (perhaps the hypothalamus).

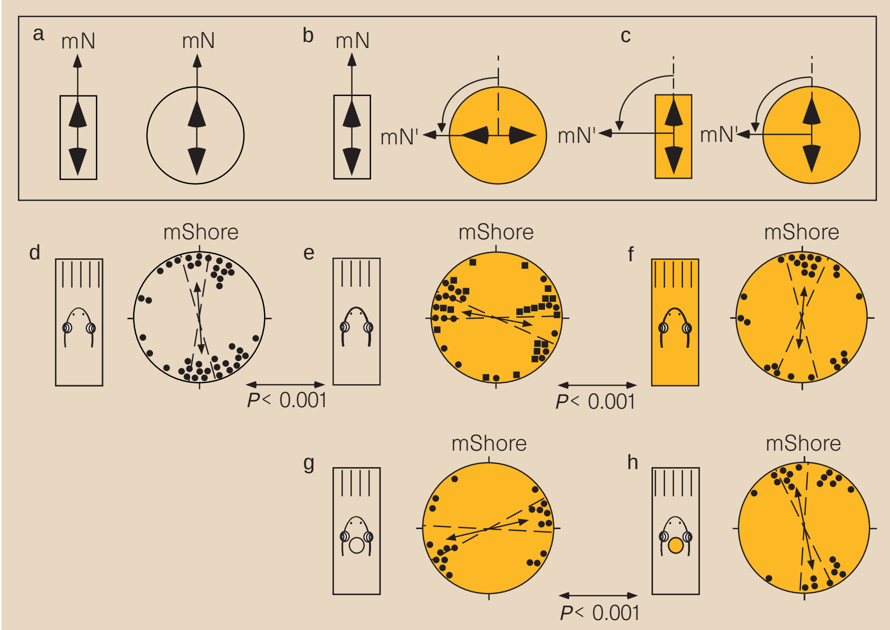

Figure 1 Effects of long-wavelength light and head caps on bimodal magnetic orientation in newts. **a–c**, Predicted orientation of newts (double-headed arrow) and their perception of the direction of the magnetic field (single-headed arrow)[5,6]. Training tanks have the shore towards magnetic north (mN); circular test arenas show the predicted response of the newts under either full-spectrum (beige) or long-wavelength light (yellow). **a**, Full-spectrum training and testing: newts should perceive the shore to be towards magnetic north and exhibit bimodal magnetic orientation along the shoreward axis. **b**, Full-spectrum training, long-wavelength testing: newts' perception of magnetic north in testing, and their orientation in the test arena, should be rotated 90° (mN′) from magnetic north during training. **c**, Long-wavelength training and testing: newts' perception of the magnetic field should be rotated 90° relative to the actual field during training and testing. Their perception of the magnetic field in the arena would be the same as in the outdoor tank. **d–h**, Results. Data points show the magnetic bearing of a newt tested in one of four symmetrical alignments of an Earth-strength magnetic field (magnetic north is geographic north (gN), east (gE), west (gW) or south (gS)). The magnetic field was altered by two orthogonally orientated, double-wrapped, Ruben's coils around the test arena[7]. Data are plotted with respect to the magnetic direction of shore (mShore) in the training tank (shore direction, 360°). Double-headed arrows indicate mean axis of orientation with the mean axis length, *r*, proportional to the strength of orientation (diameter of the circle corresponding to $r=1$). Dashed lines indicate 95% confidence intervals for the mean axis. Distributions are significant at $P<0.05$ or less by the Rayleigh test and *P*-values between circle plots indicate significant differences between distributions (Watson U^2 test). **d**, Newts trained under natural light and tested under full-spectrum light orientated along the shoreward axis[5]. **e**, Newts trained under natural light and tested under long-wavelength light orientated 90° from the shoreward direction (filled circles; tested under broadband long-wavelength (≥500 nm) light; filled squares, tested under a 550-nm light, 40 nm bandwidth, 12.5±0.1 log Quanta cm^{-2} s^{-1}; ref. 5). **f**, Newts trained and tested under long-wavelength light orientated along the shoreward axis[5]. **g**, After training under natural light, clear-capped newts tested under long-wavelength light orientated ~90° from the shoreward direction. **h**, After training under natural light, newts with long-wavelength-transmitting caps orientated along the shoreward axis under long-wavelength light.

Experiments investigating shoreward magnetic compass orientation have demonstrated that the newt's perception of the direction of the magnetic field is rotated 90° under long-wavelength (greater than 500 nm) light[5,6]. We recently trained newts under natural skylight to aim for the shore by placing them for 12–16 hours in water-filled tanks with an artificial shore at one end[5,7]. The magnetic orientation of individual newts was then tested in a circular, visually symmetrical indoor arena under depolarized light. Under full-spectrum light (from a xenon arc source), they exhibited bimodal magnetic orientation parallel to the shoreward axis in the training tank (Fig. 1a,d). In contrast, under long-wavelength light, they orientated themselves perpendicular to the shoreward direction (Fig. 1b,e).

To demonstrate that the 90° shift in orientation under long-wavelength light was due to a direct effect of light on the newts' perception of the magnetic field, we trained newts under long-wavelength light by covering the training tank with a long-wavelength-transmitting gel filter (two layers of Lee #101)[5]. Under long-wavelength light, these newts orientated themselves parallel to the shoreward axis, indicating that they had learned the direction of the shore with respect to the rotated magnetic information under long-wavelength light (Fig. 1c,f).

As well as ocular photoreceptors, newts have extraocular photoreceptors in the pineal complex[8] and possibly the hypothalamus[9]. To determine which photoreceptors are involved in the magnetic compass response, we manipulated the wavelength of light reaching the extraocular photoreceptors. Small round 'caps' (5 mm in diameter) were attached to the dorsal surface of the head of each newt using cyanoacrylate glue, and remained in place during both training and testing. Equal numbers of newts were capped with either a clear filter (Lee #130) or a filter that transmitted only long-wavelength light (equivalent to two layers of Lee #101). The caps were positioned to alter the spectral properties of light reaching the pineal and surrounding structures, whereas light reaching the eyes was unaffected. Clear-capped newts were tested to control for any nonspecific effects of the caps on the newts' orientation behaviour.

All newts were trained outdoors under natural skylight and tested for magnetic orientation in the testing arena under long-