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 can be held in stable equilibrium by any combination of static magnetic or gravitational forces. 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 fixed 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 fields with mild repulsion (such as ferrofluid or oxygen, which makes them effectively diamagnetic). Paramagnetic objects can also be levitated if there is sufficient magnetic interaction with the cylinder. The presence of a diamagnetic cylinder results in the last term in equation (1) and, for the geometry of Fig. 1, we find that where \( B_0 \) 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 \( U = -MB(r) + mgz + U_{\text{dia}} \) has a minimum \( (\Delta U > 0) \), where \( U_{\text{dia}} \) is the energy of diamagnetic interaction with the cylinder. Closed to the equilibrium position at the field axis, where \( K(z) = -MB'(z)/2 \) and \( K_s(z) = -[MB'(z)/2]^2 - 28B(z)B'(z)/BB(z) \).

where \( \rho \) is the density of the magnet's material and \( A = 1.92 \). 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 \( \chi \) 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 \( \chi = 10^{-5} \)). To illustrate this point, we show another example of a levitating magnet in Fig. 2 in which human fingers are used as diamagnetic stabilizers. Here we use an alternative geometry 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 \( (K_v > 0) \), but not vertically \( (K_h < 0) \) (Fig. 1). Vertical stability is achieved by means of two horizontal diamagnetic plates (or by the fingertips).

In this geometry, the positive constant \( C = 6\mu_0d_1d_2/M^2 \pi d^4 \) counters \( K_v \) and the levitation condition is similar to equation (2), except that now \( D \) denotes the separation between the plates, \( A = 1.02 \) and \( L=4B^2/B' \) 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, \( B'(z) = mgz \). 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
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. In agreement with biophysical models proposing that the geomagnetic field interacts with photoreceptors, 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 extracocular photoreceptors, probably located in the pineal complex or deeper in the brain (perhaps the hypothalamus).

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. We recently trained newts under natural skylight to aim for the shore. Under long-wavelength light (~90° from the shoreward direction), newts orientated themselves parallel to the shoreward axis. 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). Under long-wavelength light, these newts oriented 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,d).

As well as ocular photoreceptors, newts have extracocular photoreceptors in the pineal complex and possibly the hypothalamus. To determine which photoreceptors are involved in the magnetic compass response, we manipulated the wavelength of light reaching the extracocular 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-