Measuring Densities of Solids and Liquids Using Magnetic Levitation: Fundamentals

SUPPORTING INFORMATION

Katherine A. Mirica, Sergey S. Shevkoplyas, Scott T. Phillips, Malancha Gupta,

and George M. Whitesides*

Department of Chemistry & Chemical Biology, Harvard University, Cambridge, MA 02138

* Corresponding author E-mail: gwhitesides@gmwgroup.harvard.edu

General Methods

The NdFeB magnets (5 cm × 5 cm × 2.5 cm) were purchased from K&J Magnetics (www.kjmagnetics.com) and aligned on top of one another 4.5 cm apart within aluminum blocks. Similar magnets can also be obtained from Applied Magnets, www.magnet4less.com at a lower price. The strength of the magnetic field within the device was measured using a hand-held DC magnetometer (AlphaLab Inc, www.trifield.com). Calibrated density standards (± 0.0002 g/cm^3 at 23°C) were purchased from American Density Materials (Stauton, VA; www.densitymaterials.com). Spherical polymer samples were purchased from McMaster-Carr (www.mcmaster.com). Polystyrene microspheres with precisely defined radii were supplied by Duke Scientific Corporation (www.dukescientific.com), Polysciences, Inc. (www.polysciences.com), and Spherotech (www.spherotech.com). All other samples and reagents were purchased from Sigma Aldrich (Atlanta, GA) and used without further purification. "Levitation height" of samples was measured using a ruler with millimeter-scaled marking. Helium pycnometery measurements were performed by Quantachrome Instruments for a fee on an Ultrapyc 1200e instrument.

Figure S0. A plot generated using numerical simulation using COMSOL Multiphysics showing the dependence of the *z*-component of the magnetic field B_z on the separation between magnets (*h*) for *h* = 25, 35, 45, 55, 65, 75 mm along the centerline between the two magnets.

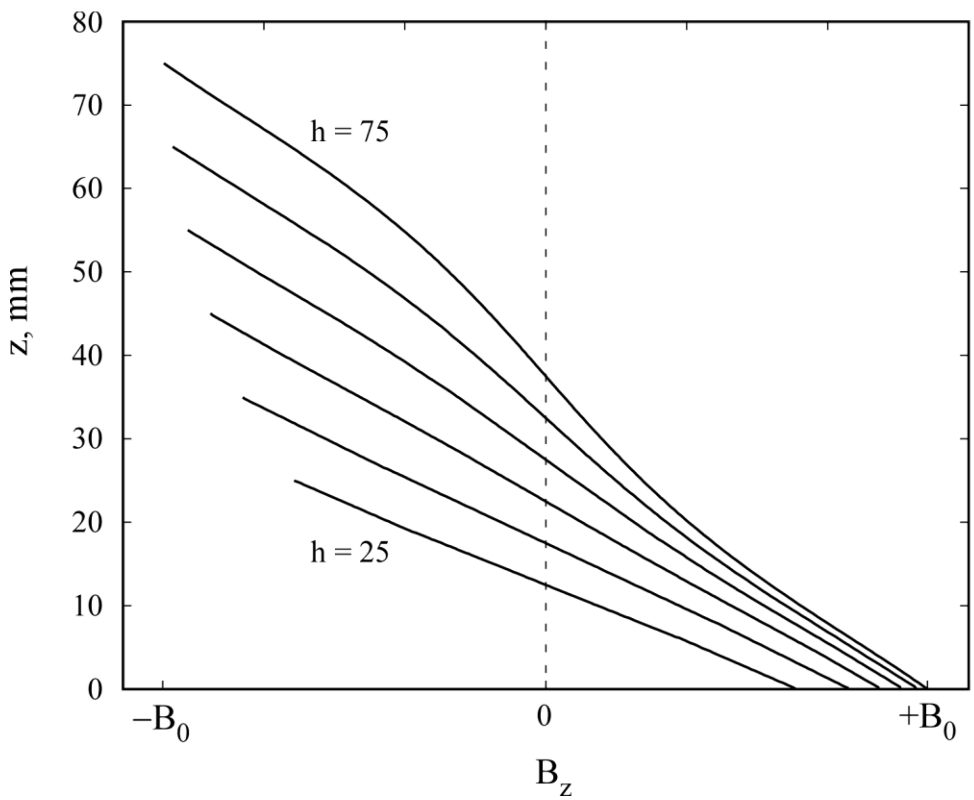


Figure S1. Photographs demonstrating levitation of a glass bead (density = 1.1500 ± 0.0002 g/cm^3) in different aqueous paramagnetic solutions (1M $MnCl_2$, 1M $MnBr_2$, 1M $CuSO_4$, 1M $GdCl_3$, 1M $FeCl_2$).

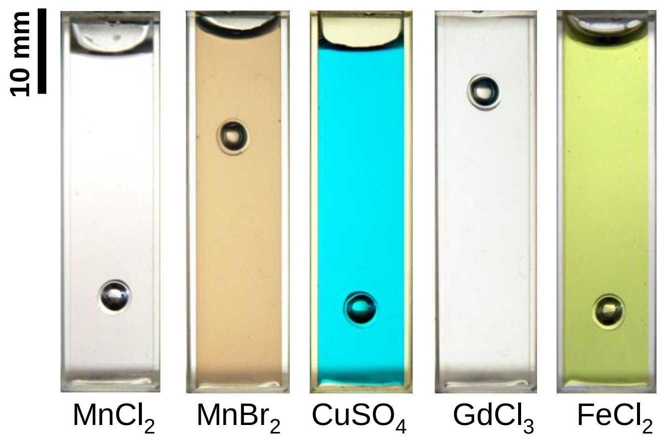


Figure S2. Net Volumetric Magnetic Susceptibilities of Common Diamagnetic Substances[1-7]

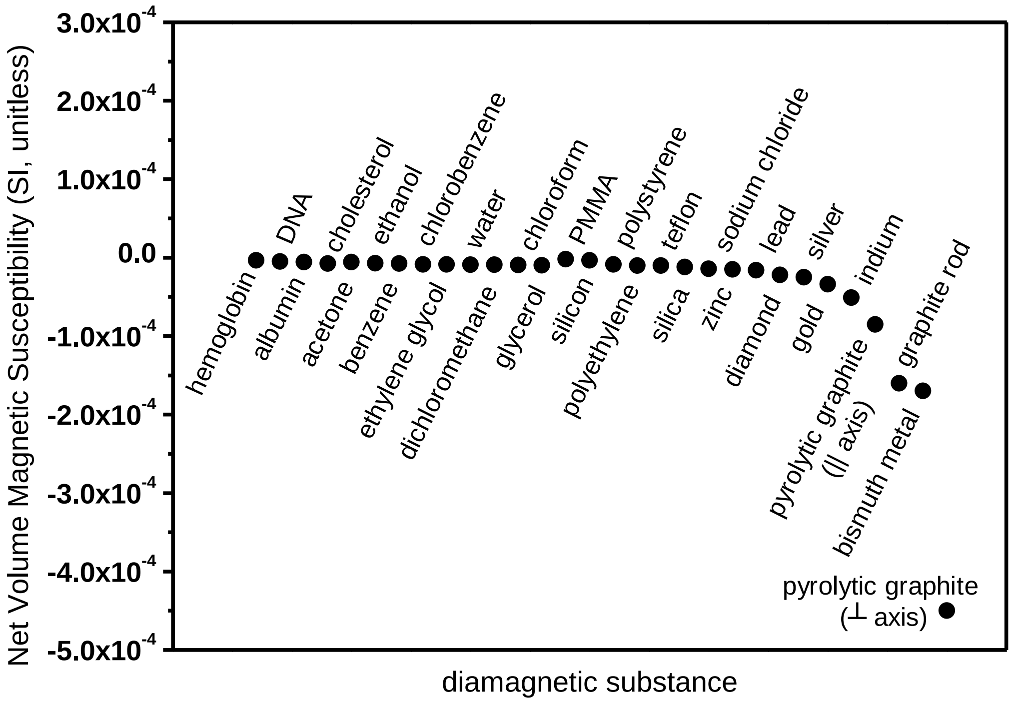


Figure S3. Deliberate misalignment of the container with the centerline between the magnets (red dotted line). Beads of different densities (from top to bottom: 1.0500, 1.0800, 1.1000, 1.1200, 1.1500 g/cm^3) levitating in 1M $MnCl_2$ align with the centerline between the magnets regardless of the position of the container, as long as the centerline is accessible within the container (A and B). Inability of the beads to align with the centerline (C and D) does not result in significant change in the levitation height of the beads. Scale bar represents 10 mm.

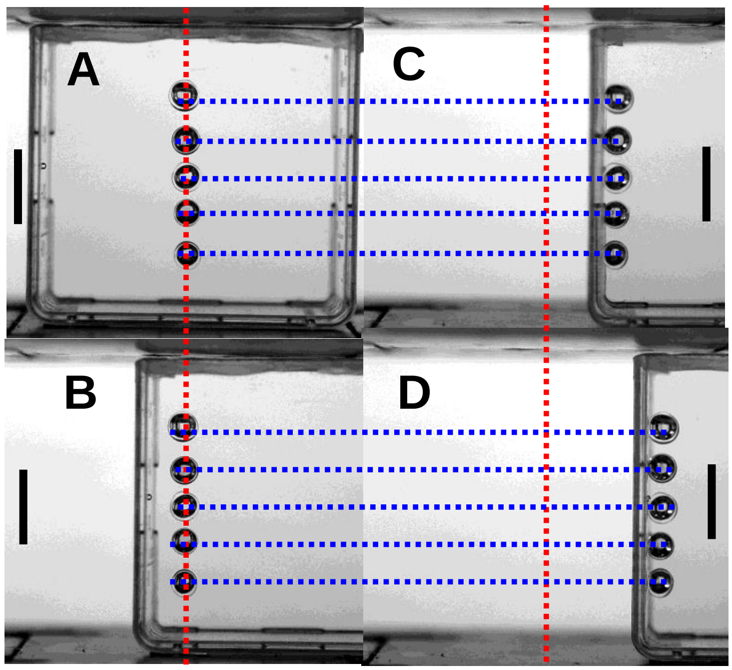


Figure S4. Effect of tilting the experimental set-up on height at which the objects levitate. A) Photographs of beads of different density (from top to bottom: 1.0500, 1.0800, 1.1000, 1.1200, 1.1500 g/cm^3) levitating in 1 M $MnCl_2$ at different values of tilt angle θ. The dimensions of the container in which the beads levitate are 50 mm × 30 mm × 45 mm. The container spans the entire width and height of the magnets and is centered lengthwise between the magnets. B) Images in shown in panel A rotated by angle θ to emphasize the effect of tilting on the levitation height of the beads.

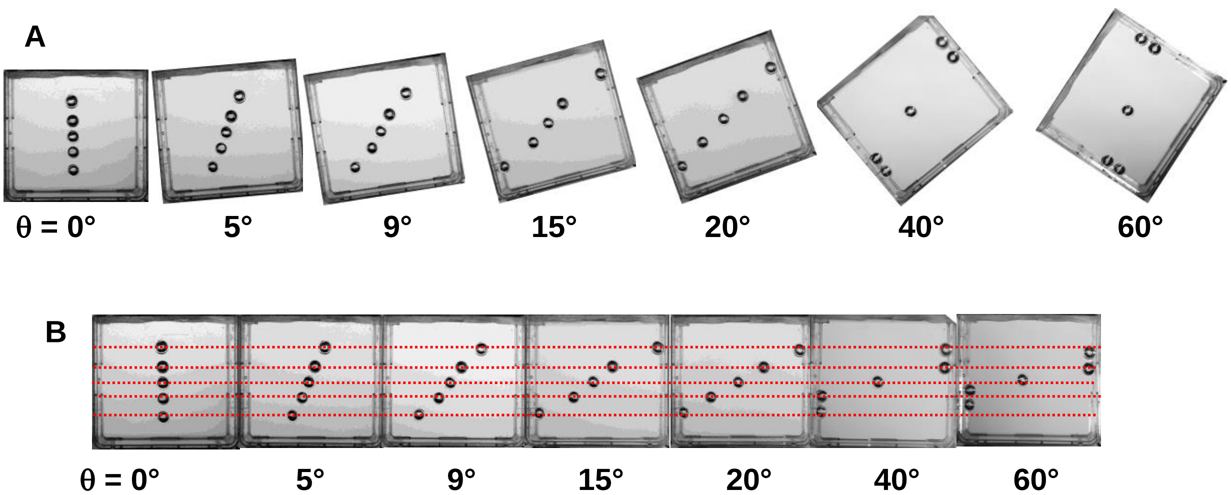
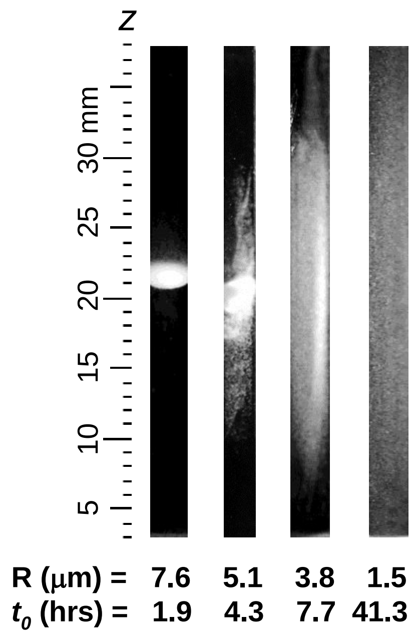


Figure S5. Photographs of polystyrene spheres of different radii levitating at t_0 in aqueous 500 mM $MnCl_2$. Spheres of R > ~ 7 μm form well defined clusters at z_0, spheres of ~ 2 μm < R < ~ 7 μm form diffuse clouds centered around z_0, while spheres of R < ~ 2 μm remain essentially uniformly dispersed throughout the solution.



Sources and Magnitude of Errors for Calculating Densities of Objects Using Eqn (8)

Experimental parameters and constants: B_0, h, g, c, and T

We measured the magnitude of the magnetic field at the center on the surface of the bottom magnet with a magnetometer and found that in the configuration shown in **Fig. 1a** B_0 was (0.375 ± 0.003) Tesla.

The distance between the two magnets, h, remained constant in our experiments and was equal to (45 ± 0.5) mm.

The acceleration due to gravity, g, at the surface of the Earth ranges from 9.78 – 9.82 m/s^2, where the exact value depends on the latitude and other factors; we used the average value of 9.80 m/s^2 in our calculations and neglected this variation in our error analysis. The typical variation in g does not constitute a significant source of uncertainty in calculation of density using eqn 8.

We measured T using a thermometer with an accuracy of ± 1 °C.

We did not measure c directly—instead, we calculated it (eqn. S0A) based on the mass of the salt m (g) measured using an analytical balance with accuracy of $\delta m = 0.1 \times 10^{-3}$ g (as specified by the manufacturer of the analytical balance), the total volume of solution V (L) measured using a volumetric flask with accuracy of $\delta V = 0.08 \times 10^{-3}$ L (as specified by the manufacturer of the volumetric glassware), and the molecular weight of the salt M (g/mol) as provided by the vendor. We estimated the error associated with our calculation of concentration, δc, using eqn (S0B),[8] and found it to be less than ± 0.002 M for the range of concentrations we used in this study.

$$c = \frac{m}{MV} \tag{S0A}$$

$$\delta c = \sqrt{\left(\frac{1}{MV}\delta m\right)^2 + \left(-\frac{m}{MV^2}\delta V\right)^2} \qquad \text{(S0B)}$$

Magnetic Susceptibility of the Medium, χ_m

The magnetic susceptibility of the suspending medium, χ_m , depends on concentrations and magnetic properties of all the species present in solution. We calculated χ_m using eqn (S1), in which χ_p is the molar magnetic susceptibility of the paramagnetic salt (m^3/mol, units of SI), c is the concentration of the paramagnetic salt (mol/L), and -9×10^{-6} is the bulk magnetic susceptibility of water.[9, 10] The dependence of the molar magnetic susceptibilities of the paramagnetic salt χ_p on temperature follows the Curie-Weiss law given by eqn (S2), where T is the temperature of the medium (expressed in ºK), C_{CW} is the Curie constant (m^3 K / mol) and θ is the Weiss constant (ºK) of the paramagnetic salt.[10] The dependence of magnetic susceptibility of the medium on temperature is then given by eqn (S3), in which we assumed that the magnetic properties of water do not change significantly with temperature.[1, 2]

$$\chi_m = \chi_p c - 9\times10^{-6} \qquad \text{(S1)}$$

$$\chi_p = \frac{C_{CW}}{T-\theta} \qquad \text{(S2)}$$

$$\chi_m = \frac{C_{CW}}{T-\theta} c - 9\times10^{-6} \qquad \text{(S3)}$$

In eqns (S1, S3), we neglected the contribution of the magnetic properties of gasses dissolved in the suspending medium. For example, air-saturated water at room temperature contains up to 0.3 mM of dissolved O_2 gas ($\chi_{O_2}^{molar} = 3449\times10^{-6}$)[1, 11] — the contribution of O_2 to the magnetic susceptibility of the medium is $\chi_{O_2} = 1.3\times10^{-8}$, which is at least three orders of magnitude less than typical values of χ_m.

Density of the Paramagnetic Solution, ρ_m

The dependence of density of the medium ρ_m on the concentration of paramagnetic salt in solution and on temperature of the solution is given by eqn. (S4), where T is expressed in ºC, $\rho_W(T)$ is the density of pure water ($W_0 = 999.65$, $W_1 = 2.0438\times10^{-1}$, $W_2 = -6.1744\times10^{-2}$), and *A*–*F* are empirical, dimensional parameters specific to the paramagnetic salt (for $GdCl_3$: $A = 2.538\times10^2$, $B = -1.149\times10^{-1}$, $C = 1.386\times10^{-3}$, $D = -1.306\times10^{-1}$, $E = 0$, and $F = 0$; for $MnCl_2$: $A = 1.022\times10^2$, $B = 4.966\times10^{-1}$, $C = -1.307\times10^{-2}$, $D = -3.659\times10^{-0}$, $E = -1.631\times10^{-1}$, and $F = 4.774\times10^{-3}$)[12].

$$\begin{aligned}\rho_m(T,c) &= \rho_W(T) + Ac + BcT + CcT^2 + Dc^{3/2} + Ec^{3/2}T + Fc^{3/2}T^2 = \\ &= W_0 + W_1T + W_2T^{3/2} + Ac + BcT + CcT^2 + Dc^{3/2} + Ec^{3/2}T + Fc^{3/2}T^2\end{aligned} \tag{S4}$$

Magnetic Susceptibility of the Sample, χ_s

The typical values of χ_s for diamagnetic substances are temperature-independent, small (about $-1\times10^{-6}...-10\times10^{-6}$) and vary little from substance to substance (see **Fig. S2** for typical values of magnetic susceptibilities of common substances).[1, 2, 9] We neglected these differences in calculations of densities based on the empirical estimates of α and β (eqn 8) from the calibration curves. For the measurements of density via the direct application of eqn (8), we neglected the magnetic susceptibility of the sample with respect to the magnetic susceptibility of the medium (that is, we set $\chi_s = 0$) and estimated the accuracy of this assumption as $\delta\chi_s = 10^{-5}$ (unitless).

This type of oversimplification and the estimation of uncertainty may not be general for all cases, especially when strongly diamagnetic ($|\chi_s| >> 10^{-5}$) or slightly paramagnetic samples are levitated. In such cases, either an accurate value of χ_s should be used when calculating densities of eqn (8) or a larger margin of error assumed for this type of density measurement. [13]

Levitation Height, z_0

We measured the levitation heights of objects z_0 using a ruler—we estimate the precision of this measurement to be ±0.5 mm.

Error Analysis

To estimate the error of our measurements of density using the calibration curves, we assume that we know parameters α and β in eqn (8) exactly, and consider ρ_s to be a function of only one variable z_0; we use eqn. (S5) to propagate the uncertainty in z_0 for these types of measurements.[8] In eqn (S5), α is the calibration parameter from eqn (8) and δz_0 is ± 0.5 mm.

$$\delta\rho_s = \left|\frac{d\rho_s}{dz_0}\right|\delta z_0 = \alpha\delta z_0 \qquad \text{(S5)}$$

To estimate the error associated with the direct use of eqn (8) for measuring the density, we treat ρ_s as a function of several independent variables: B_0, h, χ_s, T, c, and z_0, each of which is a source of independent random error (eqn. S6).[8] (Notice that ρ_m and χ_m are not independent parameters – they are calculated from T and c using eqns (S4) and (S3), respectively.)

$$\delta\rho_s = \sqrt{\left(\frac{\partial\rho_s}{\partial T}\delta T\right)^2 + \left(\frac{\partial\rho_s}{\partial c}\delta c\right)^2 + \left(\frac{\partial\rho_s}{\partial\chi_s}\delta\chi_s\right)^2 + \left(\frac{\partial\rho_s}{\partial z_0}\delta z_0\right)^2 + \left(\frac{\partial\rho_s}{\partial h}\delta h\right)^2 + \left(\frac{\partial\rho_s}{\partial B_0}\delta B_0\right)^2} \qquad \text{(S6)}$$

Eqn. (S7) summarizes eqn. (8) and eqns (S3) and (S4) in a form convenient for calculating the partial derivatives in eqn. (S6).

$$\begin{aligned}
&\rho_s = \left(\frac{4(\chi_s-\chi_m)B_0^2}{g\mu_o h^2}\right)z_0 + \left(\rho_m - \frac{2(\chi_s-\chi_m)B_0^2}{g\mu_o h}\right),\\
&where:\\
&\rho_m(T,c) = W_0 + W_1T + W_2T^{3/2} + Ac + BcT + CcT^2 + Dc^{3/2} + Ec^{3/2}T + Fc^{3/2}T^2\\
&\chi_m = \frac{C_{CW}}{T-\theta}c - 9\times10^{-6}
\end{aligned} \qquad \text{(S7)}$$

The partial derivates of ρ_m and χ_m with respect to T and c are needed for estimating eqn. (S6) and are given below (eqns S8A-B).

$$\frac{\partial \chi_m}{\partial T} = -C_{CW}c\left(T-\theta\right)^{-2}$$
$$\frac{\partial \rho_m}{\partial T} = W_1 + \frac{3}{2}W_2T^{1/2} + Bc + 2CcT + Ec^{3/2} + 2Fc^{3/2}T \tag{S8A}$$

$$\frac{\partial \chi_m}{\partial c} = \frac{C_{CW}}{T-\theta}$$
$$\frac{\partial \rho_m}{\partial c} = A + BT + CT^2 + \frac{3}{2}Dc^{1/2} + \frac{3}{2}ETc^{1/2} + \frac{3}{2}FT^2c^{1/2} \tag{S8B}$$

The partial derivatives of ρ_s with respect to B_0, h, χ_s, T, c, and z_0 are given by eqns (S9A-F) below.

$$\frac{\partial \rho_s}{\partial T} = -\frac{4B_0^2}{g\mu_o h^2}\left(z_0 - \frac{h}{2}\right)\frac{\partial \chi_m}{\partial T} + \frac{\partial \rho_m}{\partial T},$$
$$where:$$
$$\frac{\partial \chi_m}{\partial T} = -C_{CW}c\left(T-\theta\right)^{-2}$$
$$\frac{\partial \rho_m}{\partial T} = W_1 + \frac{3}{2}W_2T^{1/2} + Bc + 2CcT + Ec^{3/2} + 2Fc^{3/2}T \tag{S9A}$$

$$\frac{\partial \rho_s}{\partial c} = -\frac{4B_0^2}{g\mu_o h^2}\left(z_0 - \frac{h}{2}\right)\frac{\partial \chi_m}{\partial c} + \frac{\partial \rho_m}{\partial c},$$
$$where:$$
$$\frac{\partial \chi_m}{\partial c} = \frac{C_{CW}}{T-\theta}$$
$$\frac{\partial \rho_m}{\partial c} = A + BT + CT^2 + \frac{3}{2}Dc^{1/2} + \frac{3}{2}ETc^{1/2} + \frac{3}{2}FT^2c^{1/2} \tag{S9B}$$

$$\frac{\partial \rho_s}{\partial \chi_s} = \frac{4B_0^2}{g\mu_o h^2}\left(z_0 - \frac{h}{2}\right) \tag{S9C}$$

$$\frac{\partial \rho_s}{\partial z_0} = \frac{4(\chi_s - \chi_m)B_0^2}{g\mu_o h^2} \tag{S9D}$$

$$\frac{\partial \rho_s}{\partial h} = \frac{2(\chi_s - \chi_m)B_0^2}{g\mu_o}\left(h^{-2} - 4z_0h^{-3}\right) \tag{S9E}$$

$$\frac{\partial \rho_s}{\partial B_0} = \frac{8(\chi_s - \chi_m)}{g \mu_o h^2}\left(z_0 - \frac{h}{2} \right) B_0 \tag{S9F}$$

Finally, to estimate the error $\delta\rho_s$ in the measurement of density of the sample ρ_s one needs to substitute the expressions for the partial derivatives (eqns. S9A-F) into eqn. (S6) and evaluate the resulting expression using the values of parameters B_0, h, χ_s, T, c, and z_0, and the tolerances of these parameters δB_0 = ± 0.003 (T), δh = ± 0.5 × 10^{-3} (m), $\delta\chi_s$ = ± 10^{-5} (unitless), δT = 1 (°K), δc = ± 0.002 (M), and δz_0 = ± 0.5 × 10^{-3} (m), respectively. We provide two examples of successful application of this procedure below.

Dependence of $\delta\rho_s$ on δT.

We use eqn. (S6) (and eqns. (S9A-F)) to compare the effect of the uncertainty in temperature (± 1 °C vs. ± 10 °C) on the accuracy of the measurement of density of polystyrene spheres levitating in 350 mM solution of $MnCl_2$. This type of estimate may be appropriate for a user in a remote location with no immediate access to a thermometer for measuring temperature. For simplicity, we assume that all temperature-independent parameters and the value of B_0 are known *exactly*. **Table S1** summarizes the parameters used for and the result of this estimation.

Dependence of $\delta\rho_s$ on δB_0.

Similarly, we use eqn. (S6) (and eqns. (S9A-F)) to compare the effect of δB_0 = ± 0.003 T (typical accuracy established by using a magnetometer) vs. δB_0 = 0.1 T (a safe assumption for variation between NdFeB magnets supplied by various manufacturers) on the accuracy of the density measurement of polystyrene spheres levitating in 350 mM $MnCl_2$. For simplicity, we assume that all parameters except δB_0 are known exactly. **Table S2** summarizes the parameters used for and the result of this estimation – while the uncertainty in the measurement of density increases significantly from ± 0.0002 to 0.008 g/cm^3, the measurement of density is still fairly accurate and may be useful in less demanding situations.

Table S1. Dependence of uncertainty in measurement of density $\delta\rho_s$ on uncertainty in δT .

Parameter *P*	Description	Magnitude of *P*	δP	δP
experimental parameters				
B_0	strength of magnetic field at the surface of the magnet	0.375 T	known exactly	known exactly
h	distance between magnets	45 mm	known exactly	known exactly
T	Temperature	23 °C	**± 1 °C**	**± 10 °C**
c	Concentration of $MnCl_2$	0.350 M	known exactly	known exactly
Unknowns				
χ_s	bulk magnetic susceptibility of the sample	0 (SI, unitless)	known exactly	known exactly
calculated parameters				
$\rho_m(c,T)$	density of paramagnetic medium	1.0339 g/cm^3	± 0.0003 g/cm^3	± 0.0026 g/cm^3
$\chi_m(c,T)$	bulk magnetic susceptibility of the medium	± 56 × 10^{-6}	>> 1 × 10^{-6}	>> 1 × 10^{-6}
constants				
g	acceleration due to gravity	9.80 m/s^2	n/a	n/a
μ_0	permeability of free space	4π × 10^{-6} N·A^{-2}	n/a	n/a
independent variable				
z_0	"levitation height" of the sample above the bottom magnet	11.0 mm	known exactly	known exactly
dependent variable				
ρ_s	density of sample	1.0484 g/cm^3	**± 0.0003 g/cm^3**	**± 0.003 g/cm^3**

Table S2. Dependence of uncertainty in measurement $\delta\rho_s$ on ucertainty in δB_0.

Parameter *P*	Description	Magnitude of *P*	δP	δP
experimental parameters				
B_0	strength of magnetic field at the surface of the magnet	0.375 T	**± 0.003 T**	**± 0.1 T**
h	distance between magnets	45 mm	known exactly	known exactly
T	Temperature	23 °C	known exactly	known exactly
c	concentration of $MnCl_2$	0.350 M	known exactly	known exactly
Unknowns				
χ_s	bulk magnetic susceptibility of the sample	0 (SI, unitless)	known exactly	known exactly
calculated parameters				
$\rho_m(c,T)$	density of paramagnetic medium	1.0339 g/cm^3	known exactly	known exactly
$\chi_m(c,T)$	bulk magnetic susceptibility of the medium	± 56 × 10^{-6}	known exactly	known exactly
constants				
g	acceleration due to gravity	9.80 m/s^2	n/a	n/a
μ_0	permeability of free space	4π × 10^{-6} N·A^{-2}	n/a	n/a
independent variable				
z_0	"levitation height" of the sample above the bottom magnet	11.0 mm	known exactly	known exactly
dependent variable				
ρ_s	density of sample	1.0484 g/cm^3	**± 0.0002 g/cm^3**	**± 0.008 g/cm^3**

Table S3. Details of experimental parameters used for obtaining densities of solids using calibration curves in $MnCl_2$. Table 2 compares the calculated densities from Tables S3-S5.

Sample	$[MnCl_2]$ (mol/L)	z_0 (mm)	calibration curve used	Calculated ρ_s (g/cm^3)
glass beads				
d = 1.0100	0.100	16.7 ± 0.5	$z_0 = -3664\rho_s + 3717$	1.0099 ± 0.0002
d = 1.1000	1.000	22.0 ± 0.5	$z_0 = -247\rho_s + 294$	1.101 ± 0.002
d = 1.1500	1.500	21.9 ± 0.5	$z_0 = -160\rho_s + 206$	1.152 ± 0.003
spherical polymers				
polystyrene	0.500	23.5 ± 0.5	$z_0 = -449\rho_s + 493$	1.047 ± 0.001
nylon 6/6	1.000	13.5 ± 0.5	$z_0 = -247\rho_s + 294$	1.137 ± 0.002
polymethylmethacrylate	2.000	23.3 ± 0.5	$z_0 = -117\rho_s + 162$	1.186 ± 0.004
irregularly-shaped polymers				
polystyrene	0.500	22.0 ± 0.5	$z_0 = -449\rho_s + 493$	1.049 ± 0.001
poly(styrene-*co*-acrylonitrile)	1.000	28.1 ± 0.5	$z_0 = -247\rho_s + 294$	1.076 ± 0.002
poly(styrene-*co*-methylmethacrylate)	1.000	14.0 ± 0.5	$z_0 = -247\rho_s + 294$	1.133 ± 0.002
organic droplets				
chlorobenzene	1.000	18.5 ± 0.5	$z_0 = -247\rho_s + 294$	1.115 ± 0.003
2-nitrotoluene	1.000	5.2 ± 0.5	$z_0 = -247\rho_s + 294$	1.169 ± 0.003
dichloromethane	3.000	19.5 ± 0.5	$z_0 = -80.8\rho_s + 126$	1.324 ± 0.006
3-bromotoluene	3.000	12.5 ± 0.5	$z_0 = -80.8\rho_s + 126$	1.405 ± 0.006
chloroform	3.000	6.5 ± 0.5	$z_0 = -80.8\rho_s + 126$	1.479 ± 0.007

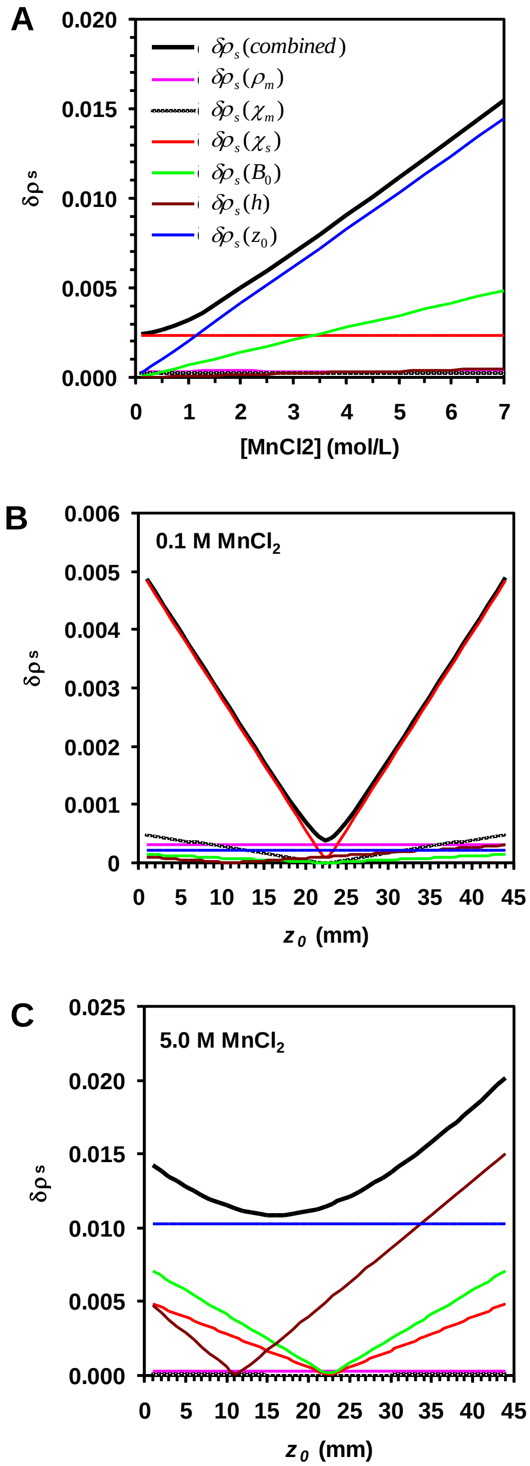
Table S4. Details of experimental parameters used for obtaining densities of solids using eqn (8) in $MnCl_2$. Table 2 compares the calculated densities from Tables S3-S5.

Sample	$[MnCl_2]$ (mol/L)	Density of $MnCl_2$ solution (g/cm^3)	χ_m (unitless)	z_0 (mm)	Calculated ρ_s (g/cm^3)
glass beads					
d = 1.0100	0.100	1.0081	18×10^{-6}	16.7 ± 0.5	1.0099 ± 0.0001
d = 1.1000	1.000	1.0994	183×10^{-6}	22.0 ± 0.5	1.101 ± 0.002
d = 1.1500	1.500	1.1486	275×10^{-6}	21.9 ± 0.5	1.152 ± 0.003
spherical polymers					
polystyrene	0.500	1.0492	92×10^{-6}	23.5 ± 0.5	1.047 ± 0.001
nylon 6/6	1.000	1.0994	183×10^{-6}	13.5 ± 0.5	1.137 ± 0.002
polymethylmethacrylate	2.000	1.1971	367×10^{-6}	23.3 ± 0.5	1.186 ± 0.004
irregularly-shaped polymers					
polystyrene	0.500	1.0492	92×10^{-6}	22.0 ± 0.5	1.049 ± 0.001
poly(styrene-*co*-acrylonitrile)	1.000	1.0994	183×10^{-6}	28.1 ± 0.5	1.076 ± 0.002
poly(styrene-*co*-methylmethacrylate)	1.000	1.0994	183×10^{-6}	14.0 ± 0.5	1.133 ± 0.002
organic droplets					
chlorobenzene	1.000	1.0994	183×10^{-6}	18.5 ± 0.5	1.115 ± 0.003
2-nitrotoluene	1.000	1.0994	183×10^{-6}	5.2 ± 0.5	1.170 ± 0.005
dichloromethane	3.000	1.2923	550×10^{-6}	19.5 ± 0.5	1.329 ± 0.007
3-bromotoluene	3.000	1.2923	550×10^{-6}	12.5 ± 0.5	1.416 ± 0.007
chloroform	3.000	1.2923	550×10^{-6}	6.5 ± 0.5	1.490 ± 0.008

Table S5. Details of experimental parameters used for obtaining densities of solids using eqn (8) in $GdCl_3$. Table 2 compares the calculated densities from Tables S3-S5.

Sample	[$GdCl_3$] (mol/L)	Density of $GdCl_3$ solution (g/cm^3)	χ_m (unitless)	z_0 (mm)	Calculated ρ_s (g/cm^3)
glass beads					
d = 1.0100	0.050	1.0100	18×10^{-6}	26.0 ± 0.5	1.009 ± 0.001
d = 1.1000	0.400	1.0950	140×10^{-6}	20.2 ± 0.5	1.101 ± 0.002
d = 1.1500	0.600	1.1426	210×10^{-6}	20.5 ± 0.5	1.151 ± 0.003
spherical polymers					
polystyrene	0.200	1.0468	70×10^{-6}	22.8 ± 0.5	1.046 ± 0.001
nylon 6/6	0.400	1.0950	140×10^{-6}	8.6 ± 0.5	1.133 ± 0.004
polymethylmethacrylate	0.750	1.1780	263×10^{-6}	21.3 ± 0.5	1.186 ± 0.003
irregularly-shaped polymers					
polystyrene	0.140	1.0321	49×10^{-6}	8.5 ± 0.5	1.050 ± 0.003
poly(styrene-*co*-acrylonitrile)	0.250	1.0589	88×10^{-6}	12.7 ± 0.5	1.081 ± 0.002
poly(styrene-*co*-methylmethacrylate)	0.530	1.1260	186×10^{-6}	20.9 ± 0.5	1.134 ± 0.003
organic droplets					
chlorobenzene	0.500	1.1189	175×10^{-6}	27.7 ± 0.5	1.096 ± 0.003
2-nitrotoluene	0.500	1.1189	175×10^{-6}	12.2 ± 0.5	1.165 ± 0.003
dichloromethane	1.500	1.3514	526×10^{-6}	26.2 ± 0.5	1.301 ± 0.007
3-bromotoluene	1.500	1.3514	526×10^{-6}	17.8 ± 0.5	1.415 ± 0.006
chloroform	1.500	1.3514	526×10^{-6}	11.8 ± 0.5	1.496 ± 0.007

Figure S6. Plots showing the dependence of error in ρ_s on various experimental parameters at constant temperature. A) Dependence of $\delta\rho_s$ on [$MnCl_2$] in water at 23 °C. Dependence of $\delta\rho_s$ on z_0 over the entire vertical distance between the magnets (45mm) at B) 0.1 M $MnCl_2$ and C) 5.0 M $MnCl_2$ at 23 °C.



References:

(1) Lide, D. R., Ed. *CRC Handbook of Chemistry and Physics*, 89th ed. [Online]; CRC Press: Boca Raton, FL, 2008.

(2) Du Tremolet de Lacheisserie, E., Gignoux, D., Schlenker, M., Eds. *Magnetism*; Kluwer Academic Publishers: Norwell, MA, 2002.

(3) Hirota, N.; Kurashige, M.; Iwasaka, M.; Ikehata, M.; Uetake, H.; Takayama, T.; Nakamura, H.; Ikezoe, Y.; Ueno, S.; Kitazawa, K. *Physica B* **2004**, *346*, 267-271.

(4) Ikezoe, Y.; Kaihatsu, T.; Sakae, S.; Uetake, H.; Hirota, N.; Kitazawa, K. *Energy Conv. Manag.* **2002**, *43*, 417-425.

(5) Kang, J. H.; Choi, S.; Lee, W.; Park, J. K. *J. Am. Chem. Soc.* **2008**, *130*, 396-397.

(6) Kuchel, P. W.; Chapman, B. E.; Bubb, W. A.; Hansen, P. E.; Durrant, C. J.; Hertzberg, M. P. *Concepts in Magn. Reson.* **2003**, *18A*, 56-71.

(7) Simon, M. D.; Geim, A. K. *J. Appl. Phys.* **2000**, *87*, 6200-6204.

(8) Taylor, J. R. *An Introduction to Error Analysis*; University Science Books: Sausalito, CA, 1997.

(9) Andres, U. *Magnetohydrodynamic & Magnetohydrostatic Methods of Mineral Separation*; John Wiley & Sons: New York, NY, 1976.

(10) Hatscher, S.; Schilder, H.; Lueken, H.; Urland, W. *Pure Appl. Chem.* **2005**, *77*, 497-511.

(11) Weiss, R. F. *Deep-Sea Research* **1970**, *17*, 721-735.

(12) Sohnel, O.; Novotny, P. *Densities of Aqueous Solutions of Inorganic Substances*; Elsevier: New York, NY, 1985.

(13) Paramagnetic samples will also levitate in this device provided that $\chi_m > \chi_s$.