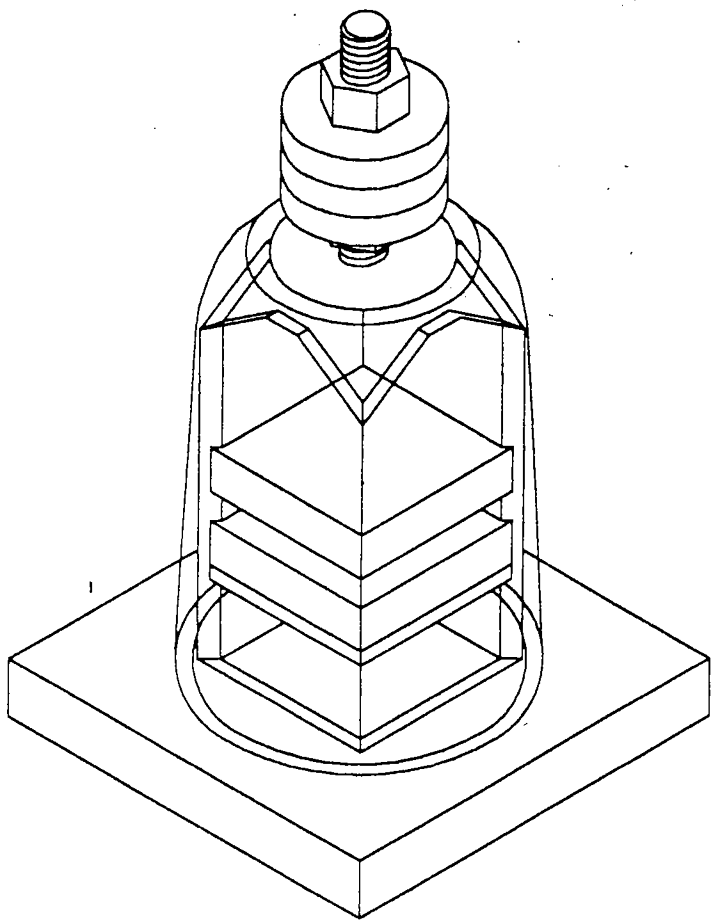
INSTRUCTIONS AND EXPERIMENTS
for the Educational Innovations

DIAMAGNETIC LEVITATION APPARATUS



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Transparent Devices

Introduction

Magicians for years have created the *illusion* of levitation as one of their greatest accomplishments. The levitation in this device is *not* an illusion. It is understandable, repeatable, and based on well known scientific principles. On the other hand, it would not be a reality without the great technological advances in materials science that have brought us rare earth magnets and materials of extreme purity such as the graphite plates used in this device. These advances bring to mind a quote attributed to Arthur C. Clarke: "Technology sufficiently advanced is indistinguishable from magic." We hope this device will bring some magic, as well as some real science, to your students and colleagues.

Within this apparatus are two black graphite plates, with a space between them. In the space is a cube shaped magnet, plated in 24K gold. While it is likely that the cube is levitating straight out of the box, vibrations during shipping may make a simple adjustment necessary:

Loosen the upper hex nut slightly. A wrench should not be necessary. Do not use tools to tighten the nuts.

If the cube is resting on the bottom graphite plate, turn the lower hex nut clockwise (as seen from above). Maintain a small downward force on the ceramic ring magnets so they follow the nut downward. Watch the cube as you do this, and stop when the cube levitates. Then tighten the top hex nut, "finger tight".

If the cube is against the top graphite plate, turn the lower hex nut counterclockwise (as seen from above). Watch the cube as you do this, and stop when the cube levitates. Then tighten the top hex nut, "finger tight".

Thanks to Charles Sawicki of North Dakota State University for bringing the principles and practice of diamagnetically stabilized levitation to the attention of the science teaching community in his article in The Physics Teacher. (December, 2001, pages 556 - 558) This is highly recommended reading.

Included in this apparatus:

A sealed unit, ready for use and display, including high purity diamagnetic graphite plates, a gold-plated rare earth levitating magnet, and adjustable field magnets.

Also included are two clear plastic plates for experiments investigating the function of the graphite, and a hex key to permit unsealing the apparatus for detailed experimentation.

Care and use:
Some simple precautions will help ensure that this apparatus provides years of use.

--If needed, clean only, with a damp rag with mild dish soap. Do not use abrasive cleaners, organic solvents, or harsh chemicals.
--Use only finger pressure to tighten the hex nuts.
--The ceramic ring magnets are brittle, and may break if removed and dropped
--Keep all magnets away from electronic equipment (including medical equipment such as pacemakers), delicate instruments such as watches, and magnetic media such as video and audio tapes, credit card magnetic stripes, etc.
--If the apparatus is opened, be aware that the graphite plates are brittle, and are easily broken or scratched. They are also messy. (Pencil "lead" is largely graphite.)
--The cube shaped magnet is also brittle, and may break merely by flying to the ceramic magnets.

Safety
Please teach and expect safe behavior in your classroom and lab. Safety considerations call for supervision of students at all times, safety eyewear, no horseplay, and immediate reporting to the instructor of accidents or breakage, among others.

Instructors should assess the appropriateness of this and all apparatus for the maturity level of their students.

Disassembly/ Reassembly

The apparatus is supplied as a sealed unit suitable for display. It may be opened to permit experimentation. To do so follow these steps:

1. Locate the hex key (a piece of hexagonal steel rod with a 90 degree bend.)

2. Insert the long arm of the hex key into one of the four holes in the sides of the base of the apparatus. A socket head set screw is deep within the hole. Use the hex key to unscrew the set screw three full turns. Turn counterclockwise.

3. Loosen all four set screws as described above.

4. Place one hand on the base, and using your other hand gently lift the bell housing.

5. Four plastic panels retain two graphite plates, a clear plastic shim, and a gold-plated neodymium-iron-boron magnet. Three of these panels are bonded together and to the base. The fourth panel is loose. Remove it by pulling the top of the panel slightly away from the other panels and the graphite plates. Then lift and remove the panel.

6. The removed panel may be stored away, and experiments done without it. The graphite plates may be removed and replaced with plates of different materials. The shim may be removed or replaced with other shims made of cardstock. Then the bell housing may be replaced.

Reassembly

7. Place the bottom of the loose panel in the groove in the base and press the panel downward. Adjust the height of the panel so the grooves in it line up with the graphite plates. Then press it inward. Do not use excessive force. If force is required, the panel is not aligned accurately.

8. Place the bell housing over the base assembly, making sure the bottom rim of the bell is seated all the way to the bottom of the circular groove.

9. Carefully tighten the four set screws, using the hex screw key. By looking into the groove where the bell housing enters the base, it is possible to see the tip of the set screw make contact with the bell. Watch for this, and notice the resistance in the hex key to avoid over-tightening. Excessive force will damage the bell housing.

Theory

The action of this levitation apparatus may be understood in terms of either forces, or potential energy. While forces provide the simpler explanation, consideration of potential energy and types of equilibrium offer deeper understanding, together with the possibility of predicting the results of changing materials, dimensions, etc.

Forces

First, the force of earth's gravity pulls downward on the cube magnet. Within this small apparatus the force of gravity is essentially constant.

The ceramic ring magnets exert an upward force on the cube magnet. The force exerted is greater the closer the cube magnet is to the ceramic magnets.

Two graphite plates, one above and one below, limit the cube magnet to approximately the correct distance from the ceramic magnets above.

The ceramic magnets are carefully lowered, using the nut and threaded rod. The upward force increases until it equals the force of gravity on the cube. It would seem that the cube should be able to "float" in this position.

However, if the cube rises even the tiniest amount, the force of the ceramic magnets will become greater, and the cube will accelerate upward. If the cube falls even the slightest amount, the force will become less, and the cube will accelerate downward. It is unstable.

The property of graphite called diamagnetism makes the cube stable. Diamagnetic substances repel either pole of magnets. If the cube begins to rise slightly, it comes closer to the upper graphite plate, and the graphite repels it downward. The force is tiny, but it is enough to stabilize the cube. The lower graphite performs a similar function if the cube begins to move downward.

Potential energy

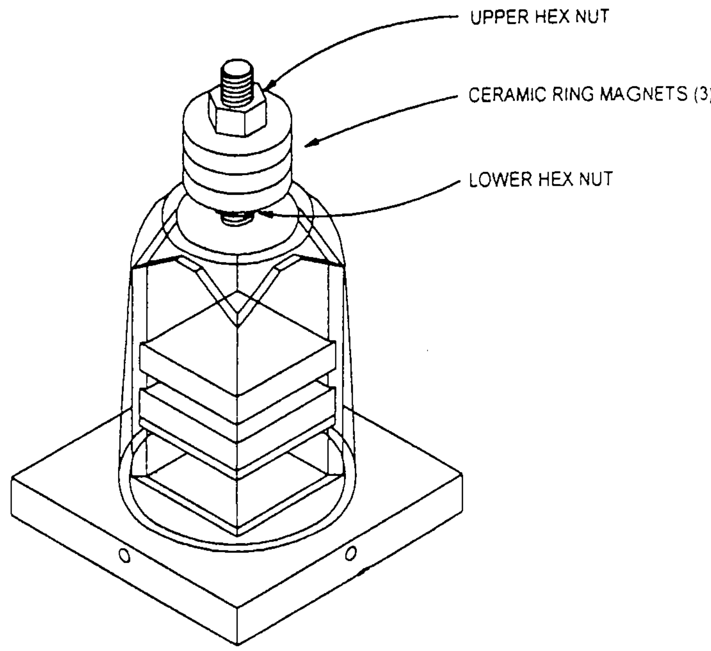
The theory involving potential energy is described and explored in Experiment 1 that follows.

Experiment 1

The purpose of this experiment is to discover how consideration of potential energy can be used to predict stability and levitation of objects.

Materials required:

Levitation Apparatus with
--2 thick plastic plates (clear)
--1 thin plastic plate
--2 graphite plates (black)
--1 NeFeB magnet (cube, gold plated)



Warning: Pick this apparatus up with one hand on the base, and one hand on the bell housing. The bell housing is loose and could fall off while being carried

Safety considerations:
Obey ordinary safety rules established by your instructor, such as use of safety eyewear, no horseplay, etc.

Care for the apparatus:
Treat this equipment with care due a delicate scientific instrument. In particular, be aware that:

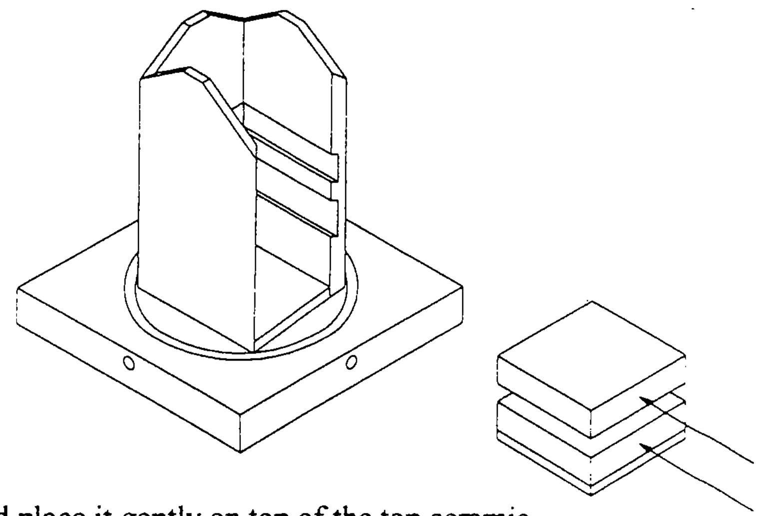
The graphite plates are brittle and may easily be broken if dropped. They are also easy to scratch. Finally, they can rub off and leave marks on skin clothing, etc. You may wish to handle them with tissue.

The magnets are brittle, and may break if dropped or allowed to attract and strike each other. Also they may damage nearby watches, electronic equipment (including medical equipment such as pacemakers!), and magnetic media such as video and audio tapes, and magnetic information stripes on credit cards, etc.

Instructions:

With one hand on the base, lift the bell housing. (If the bell housing does not easily lift free from the base, consult your instructor.)

If graphite plates are installed in the slots of the apparatus, remove them. If they seem stuck, wiggle them slightly while pulling them out. Do not use excessive force.



Install a clear plastic plate in the upper slot. In the lower slot, install the thin plastic plate, and then slide the thick plastic plate over it in the same slot.

Hold the small cube-shaped magnet, and place it gently on top of the top ceramic magnet at the top of the apparatus. When you release it, it will rotate if needed so that it is attracted by the ceramic magnet. DON'T let it fly toward the ceramic magnet. It is both expensive and brittle.

Now lift the cube magnet away from the ceramic magnet, and WITHOUT ROTATING IT, place it between the two plastic plates.

Lower the bell housing into the circular groove.
Gravity is pulling the cube magnet downward. The ceramic ring magnets are attracting the cube upward. If the cube magnet is resting on the bottom plate, the magnetic force is too weak, because the ceramic magnets are too far away. If the cube is against the upper plate, the magnetic force is too great, because the ceramic magnets are too close.

Try to make the cube magnet levitate between the two plates. To do this, you will need to raise or lower the ceramic magnets. First loosen the upper hex nut above the ceramic magnets. Now rotate the lower hex nut to move the magnets. Rotating the hex nut clockwise (looking down from above) will make it move down. The reverse, of course, will raise the magnets. When lowering the hex nut it may be necessary to push down on the magnets to make them follow the nut.

If you succeeded in making the cube levitate between the plastic plates, tell what you did in your lab notes and show your instructor.

If you were unable to make the cube levitate, try to suggest in your lab notes what the difficulty may be, and then tell your instructor.

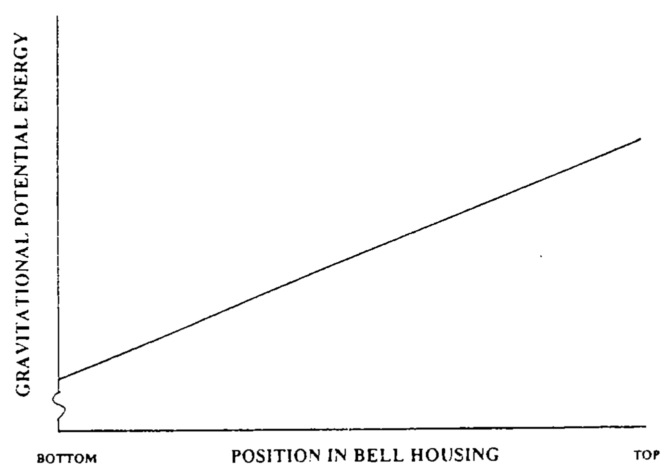
Can you adjust the magnets so that the cube rests on the bottom plate but moves to the top plate if you jiggle the apparatus slightly, and then moves back if you jiggle it again?

Read the following discussion of the theory involved before continuing with the experiment.

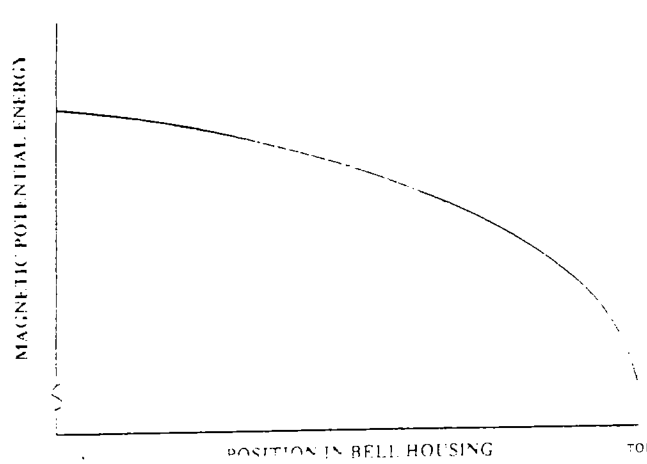
Some theory...
It is difficult to make the cube magnet levitate, because the opposite forces due to the earth's downward gravitational attraction and the ceramic magnets' upward magnetic attraction must be equal in magnitude. If so, they would cancel, or add to zero, and we would say that the cube was in equilibrium. For the cube to levitate, it must be in equilibrium.

Thinking about potential energy is a useful way to better understand equilibrium.

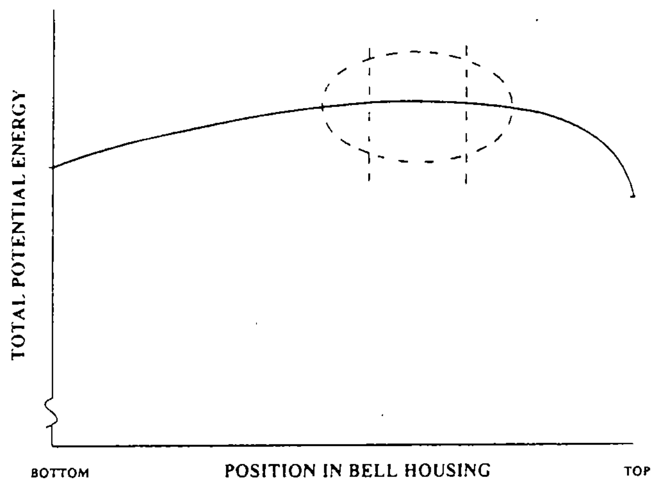
The graph below shows the gravitational potential energy of the cube if it were located at different heights within the apparatus. (Assume that the ceramic ring magnets have been removed.) An object has more gravitational potential energy (GPE) when it is at a greater height. It could do work falling from that position. Conversely, we would have do work, and expend energy, to raise it to that height.



The next graph considers only the potential energy of the cube as a result only of the nearness of the ceramic magnets. Imagine that the earth is nowhere near, and that gravity is not a significant force. In this case the cube would be as close to the ceramic magnets as possible, and we would have to do work (and expend our energy) to move the cube away from the ceramic magnets. At first the force would be great, and we would expend considerable energy removing the cube. The energy we expended would become potential energy of the cube. As the separation became greater, the force would lessen, and the gain in potential energy would be more gradual. You can see this as you look from *right* to *left* on the graph.



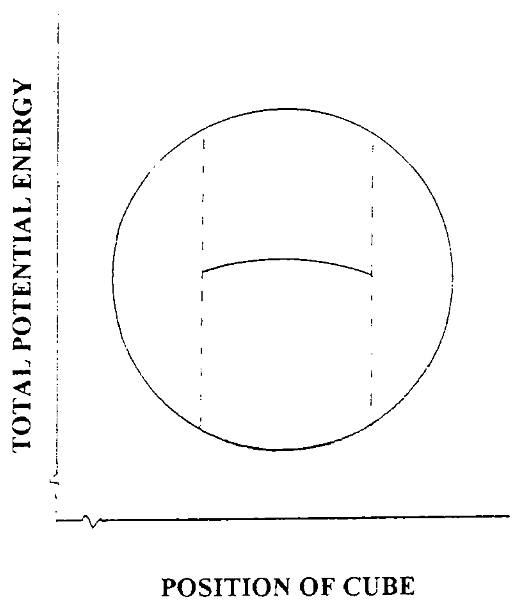
The next graph shows the total potential energy of the cube in various positions within the apparatus, when both gravity and the attraction of the ceramic magnets are considered. The two vertical lines show the positions of the plastic plates, if they were installed. The ellipse is an area of interest which is expanded in a later graph.



Everyday observation shows that things tend to move to a place of lower potential energy. Imagine that the plastic plates have been removed. Without the ceramic magnets, the cube would fall to the lowest place it could get. The first graph shows that this is the place with the lowest potential energy.

If there were no gravity, the cube would get as near to the ceramic magnets as possible. The second graph shows this as the place with lowest potential energy.

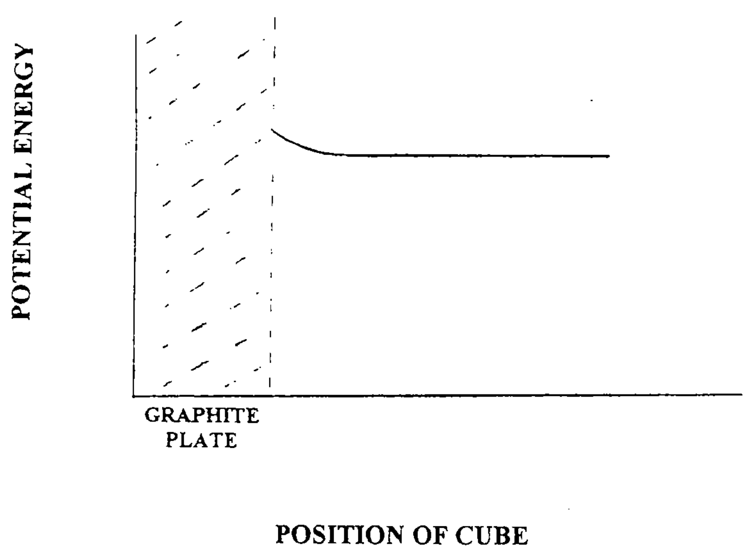
Now consider the third graph, with the plastic plates installed. The graph shows that the cube has greatest total potential at a point approximately half way between the plates. If we magnify the circled area of the graph, and magnify the vertical scale more than the horizontal scale, this becomes clearer:



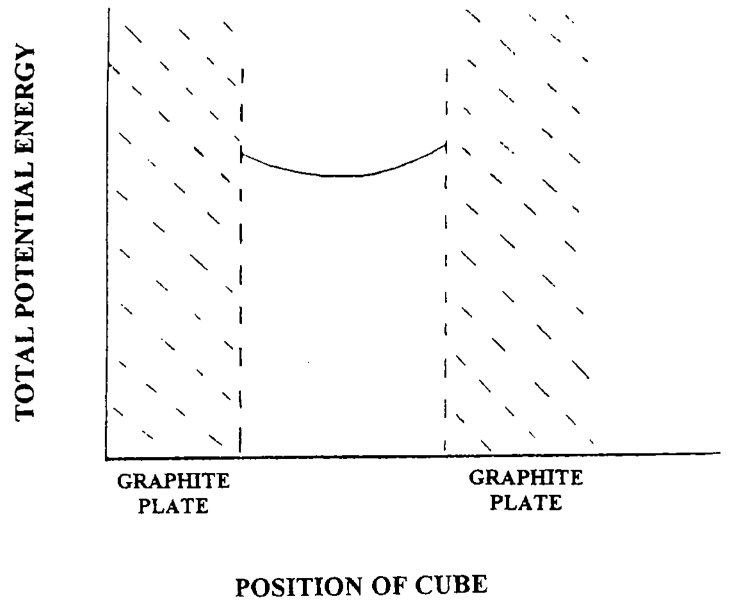
The previous graph shows that the cube has less potential energy when it is against either the lower plastic plate or the upper plate than it does halfway between them. The cube is in equilibrium halfway between the plates, but it is *unstable equilibrium*. The cube will rest against one of the plates or the other, but it will not stay in the middle. Jiggling the apparatus may give the cube enough energy to move to the other position.

Very highly pure graphite has the peculiar property of repelling magnets. It will repel either pole of a magnet. This property is called diamagnetism. Actually diamagnetism is not uncommon at all, but rather is so weak in most substances that it is impossible to detect without highly sensitive instruments. Even the force of repulsion using graphite, one of the most highly diamagnetic materials, is very tiny. However, it is enough to stabilize the cube in this apparatus and make it levitate.

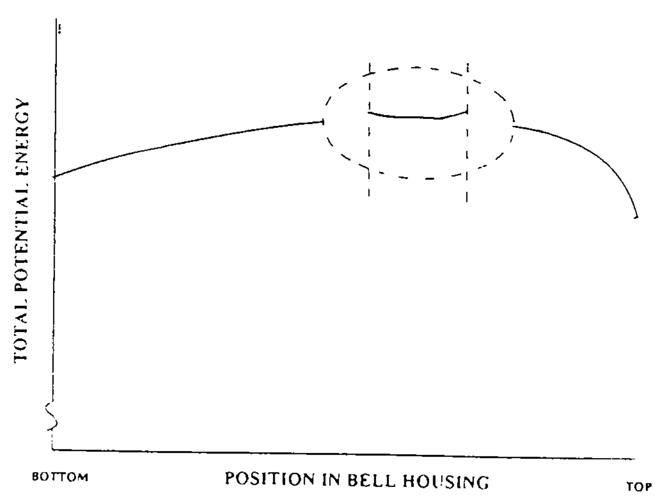
The cube magnet would have more potential energy near a block of graphite, than farther away. (We would have to expend energy to push it near the graphite, and this energy would become potential energy.) The graph shows how the potential energy might vary with distance from the graphite.



If the cube magnet were placed between two graphite blocks, the graph of potential energy as a function of position might be expected to look like this:



When the potential energy graph due to the diamagnetic force is added to the preceding graph, the total potential energy graph appears as follows:



Examining the graph in the region between the plates shows that the lowest point (a local minimum) is about midway between the plates. The cube magnet could be expected to levitate at that location! At that position, the cube is in *stable equilibrium.*

Experiment (continued)

Use the graphite plates, and make the cube levitate between them.

--Remove the bell housing.
--Gently remove the thick clear plastic plates
--Install the graphite plates. The thin plastic plate should be installed *under* the lower graphite plate.
--Replace the bell housing.
--Adjust the height of the ceramic ring magnets if needed.

If you are unable to make the cube levitate, get help from your instructor.

Now remove the thin plastic plate, so that the spacing between the graphite plates is greater. Make adjustments to the height of ceramic ring magnets, and jiggle the apparatus gently. In your lab notes, describe the changed behavior of the cube. Sketch a potential energy graph which explains this behavior.

Is it possible to make the cube levitate using only one graphite plate? (Replace the lower graphite plate with a thick plastic plate on top of a thin plastic plate.) Make careful adjustments to the height of the ceramic magnets. In your lab notes, tell the results of your efforts, and sketch a potential energy graph which explains your results.

Try placing a graphite plate in the bottom slot and a plastic plate in the upper slot. Try to levitate the cube. In your lab notes, tell the results of your efforts, and sketch a potential energy graph which explains your results.