# The relationship between magnetic field on a magnet and its levitation distance

Simple experiment connected to Maglev Trains
Theory well developed

## ***Introduction***

### *Personal Engagement*

Since I was little, I was always fascinated about trains, and one of the things that fascinated me the most were their mechanisms and how the trains worked. My interest piqued when I saw that there are magnetic high-speed trains that aren't touching the tracks. I later saw that this had to do with the fact that no friction would lead to less resistance and more speed due to magnetism, and then I wondered how this was working. What was the main magnetic mechanism needed for this to occur? I looked back at this curiosity when I was thinking about the topic for my IA, and my passion for physics in general.

### *Research Question*

How does the magnetic field strength placed on a magnet affect its levitation distance, while figuring out the n-value in the magnetic field equation?

This is expanded upon later

## ***Background***

### *Magnetism*

Magnetism is the force that is created around magnets. It works like this - every magnet, as weak or strong it is, has a north and a south pole. There is a very simple principle used with magnets - like poles repel, unlike poles attract. When one magnet is close to the other, they will attract, if unlike poles are facing each other, and if like poles face each other, then they will repel. The magnetic force is not created around only magnets, though. (Bowen-Jones)

Relevant background

The basic magnetic properties - like poles repel, unlike poles attract - can be further understood when one sees a magnetic field diagram. The field lines will be shown as attracting (connecting) and repelling (seeming as there is an asymptote between them) in their respective situations and diagrams. (Bowen-Jones)

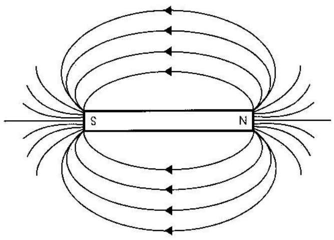



*Figure 1. The magnetic field lines of a magnet.*

This magnetic field represents the magnetic field of a magnet. The field lines always point from north to south. The figure below shows magnetic field lines for like poles facing each other and unlike poles facing each other:

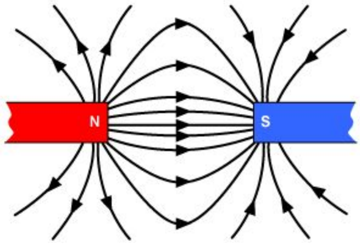



*Figure 2. The magnetic field lines when two unlike poles are facing each other.*

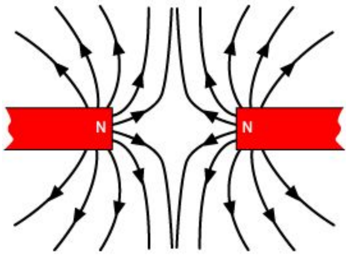



*Figure 3. The magnetic field lines when two like poles are facing each other.*

PE - going beyond the syllabus to find this law

***The Inverse Square Law***

The Inverse Square Law says that the magnetic force acting upon an object would be inversely proportional to the distance squared between two magnetic field sources. This law can be extended to more situations of magnets if we divide the field by the distance squared, cubed, etc. In the case of a monopole, or when a magnet has only one pole (a point source), then the theorem is modified so that the field is divided by the distance squared. In the case of a dipole, or when a magnet has two poles, then the theorem is modified so that the force is inversely proportional to the distance between the magnets cubed. The constant by which the field is multiplied by is the magnetic field that is applied. If put in an equation, where $F_B$ is the magnetic force, A is the area, B is the magnetic field, r is the distance between the magnets, and n is a constant, the equation would look like this:
(WW, How does magnetic)

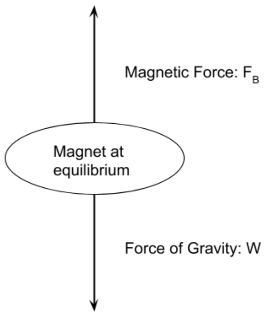
$$F_B = \frac{AB}{r^n}$$

***Levitation***

Explaining the experiment

An application of magnetism is magnetic levitation, in which magnetism makes magnets not touch the ground. A “levitation” effect happens when there are two magnets, one on top of the other, and like poles facing each other. This is the way it works: First, if one looks at the field lines, one will see that there is no line that is pointing directly from and to the center of the magnets. There is one other factor that is important - the gravitational force. Since the magnets are almost never going to be able to fall one on top of the other, the magnet will be a little bit to the side. The weight of the magnet, which is the force of gravity, can push down on the magnetic field lines on that side, so the field lines could be bent. With no outer interference, there can’t be a perfect levitation scenario. Because of this, the magnet falling may flip, and the magnets will end up attracting like normal. The effect of not being able to levitate a magnet with no interference can also be explained using Earnshaw's theorem, which states that a collection of magnets cannot be maintained in an equilibrium configuration strictly by the magnetic field. A way to fix this is by using diamagnetic materials and rotating magnetic fields.

Since gravity is also a force, there will be a point of translational equilibrium. This point of translational equilibrium is when the magnet ends up not falling anymore, but not touching the other magnet; in other words, levitation. When more magnets are being placed on top of each other, with like poles facing each other, magnetic field strength rises. Because of this, the magnetic field strength ends up being greater than the force of gravity, so the magnet gets levitated more and more from the center of the cluster of the magnets. This can be demonstrated in the diagram below.




Freebody diagram made by student that connects to the experiment

*Figure 4. A free body diagram of a magnetic disk in translational equilibrium. (Self-made)*

Using summation of forces:

$$F_B - W = 0$$

Where W is the force of gravity acting on the magnet. Substituting for $F_B$ and rearranging gives:

$$\frac{B}{r^n} = W$$
$$\frac{B}{W} = r^n$$
$$log(\frac{B}{W}) = log(r^n)$$
$$n \times log(r) = log(B) - log(W)$$
$$log(r) = \frac{1}{n}(log(B)) - \frac{1}{n}(log(W))$$

Use of logs to find the exponent and to connect to a straight line graph - beyond Physics syllabus

This can be seen as a linear equation, where x = log(B), the gradient is 1/n, y = log(r), and the y-intercept is -(1/n)log(W). Because of this, the hypothesis will be that B increases as r increases, and that B is proportional to r to a power which will be determined in this investigation.

***Final Hypothesis***

The magnetic field strength on a magnet will affect its levitation distance in a way that the magnetic field strength will be proportional to levitation distance cubed.

***<u>Experiment</u>***

***Methodology***

| **Variables** | **Measurement of Variables** | **Range of Measurements** |
|---|---|---|
| **Independent:**<br><br>Magnetic Field Strength (milliTeslas (mT))<br><br>The magnetic field strength will be changed with magnets<br><br>Typical error on magnetic field strength:<br>+/- 0.0001mT or +/- $10^{-8}$ Teslas | The Magnetic Field Strength will be measured with a Vernier Lab Pro Magnetic Field Sensor. This will be measured by placing the sensor 2 centimeters away from the cluster of magnets. 2 centimeters can be considered the lowest levitation distance for these magnets.<br><br>Uncertainty on scale = +/- 0.0001 mT<br><br>Unit for magnetic field strength: Tesla<br><br>There is a background magnetic field strength of 0.1368 mT. Because of this, the uncertainty for the measured magnetic field strength is +/- 0.0002mT<br><br>The fields to the right had to be measured because only using the number of magnets will not result in a linear increase. | Magnets clustered together, one on top of the other, unlike poles facing each other, and these are the total magnetic field strengths:<br><br>5 magnets: 3.4 mT<br><br>4 magnets: 2.8 mT<br><br>3 magnets: 2.6 mT<br><br>2 magnets: 2.2 mT<br><br>1 magnet: 1.1 mT<br><br>The aforementioned field strengths do not include background field.<br><br>These magnetic field strengths are the range for the independent variable. |
| **Dependent:**<br><br>Levitation distance | The levitation distance will be measured using a 30cm ruler.<br><br>Uncertainty on ruler = +/- 0.1 cm<br><br>I will be measuring the levitation distance from the center of the clustered magnets to the middle of the magnet being levitated. | Equipment used to measure the distance:<br><br>30cm ruler<br><br>Easy DV to measure |

Use of technology to find B

Background B is subtracted off

| **Control Variables:** | **Why it needs to be controlled:** | **How to control:** |
|---|---|---|
| 1. Background Magnetic Field<br>2. Magnet Tilting | 1. This variable needs to be controlled because if it's not controlled, there could be outer interference acting on the magnet, and the magnet can change position based on the outer interference, and this will alter results.<br>2. This variable needs to be controlled because if it is not controlled, the magnet will be attracted to the other magnets, and the experiment will not be conducted well because humans can't capture the magnet the exact moment it is not tilted. | 1. The Magnetic Field Strength will be controlled by keeping the experiment away from other metals and electronics. Background magnetic field strength will be measured before the experiment and it will be subtracted from all the magnetic field strengths.<br>2. There will be a pole that will go through the disks, and this pole will prevent flipping. If there is still a degree of tiltedness, then I will measure the distance to the center of the magnet in the center of the pole. |

Simple experiment with few variables to control

*Materials Needed*

- 1 30cm ruler (to measure the levitation distance) (error: +/- 0.1 cm)
- 1 experiment magnetic field mechanism
  - Vernier Lab Pro Software
  - Vernier Lab Pro Magnetic Field Sensor (to measure magnetic field strength (error: +/- 0.0001 mT)
- 6 magnets, with the same brand and size (to use them for the experiment)
- 1 pencil or stick (to keep tilting constant and to a low angle in order to get exact measurements)

*Final method used for experiment*

1. Set up the Vernier Lab Pro software and Magnetic Field Sensor
2. Check background magnetic field by collecting data for ten seconds and finding the average using steps 3 through
3. Measure the magnetic field strength for one magnet by measuring 2 cm from one magnet and measuring the magnetic field strength using the magnetic field strength sensor from there.
4. Repeat step 3 for two, three, four, and five magnets, facing each other, clustered together. Keep the same 2cm distance for each number of magnets.

5. Set up the experiment by dropping one magnet down the pole, and drop another magnet, like poles facing each other, down the pole. There should be a levitation effect.
6. Measure from the center of the magnet(s) below to the center of the magnet above. This is the levitation distance.
7. Drop the same magnet the was being levitated down the pole four more times, and measure the same distance.
8. After measuring, drop two, then three, then four, then five magnets, unlike poles facing each other, down the pole, and repeat steps 6 and 8. Magnet being levitated should be the same for all trials.
9. Average all measurements, for each number of magnets, and begin analysis of data.

**Safety:** Small magnets are used, so no significant safety constraints.

Suitable method and safety considered

***Analysis***

Table #1

These are the experimental distances of the levitation between the top magnet and the magnets below, with their respective number of magnets and magnetic field strengths.

| Number of magnets | Total Magnetic Field Strength at 2cm (in mT) | Levitation Distance 1 | Levitation Distance 2 | Levitation Distance 3 | Levitation Distance 4 | Levitation Distance 5 |
|---|---|---|---|---|---|---|
| | +/-0.0001 mT | +/- 0.1 cm | +/- 0.1 cm | +/- 0.1 cm | +/- 0.1 cm | +/- 0.1 cm |
| 1 | 0.9632 | 2.2 | 2.1 | 2.0 | 2.0 | 2.0 |
| 2 | 2.0632 | 2.5 | 2.6 | 3.0 | 2.8 | 2.8 |
| 3 | 2.4632 | 3.1 | 3.4 | 3.6 | 3.4 | 3.3 |
| 4 | 2.6632 | 3.7 | 3.6 | 3.7 | 3.5 | 3.7 |
| 5 | 3.2632 | 4.0 | 4.1 | 3.8 | 4.0 | 4.0 |

Sufficient raw data

Table #2

Here are the magnetic field strengths with their average levitation distances and the experimental error on their respective levitation distances.

Correct +- 0.0002 in error as two values subtracted

| Total Magnetic Field Strength (mT) (+/-0.0002) | Average Levitation Distance (cm) (+/- 0.1) | Error on average Levitation Distance (cm) |
|---|---|---|
| 0.9632 | 2.1 | 0.1 |
| 2.0632 | 2.8 | 0.3 |
| 2.4632 | 3.3 | 0.3 |
| 2.6632 | 3.6 | 0.1 |
| 3.2632 | 4.0 | 0.2 |

*Sample Calculations*

Average Levitation Distance for each Magnetic Field Strength comes from:

$$\frac{\text{Distance 1 + Distance 2 + Distance 3 + Distance 4 + Distance 5}}{5}$$

Example (MFS 5):

$$\frac{4 + 4.1 + 3.8 + 4 + 4}{5}$$

4.0 cm

Error on average time for each Magnetic Field Strength comes from:

$$\frac{\text{max distance for each MFS - min distance for each MFS}}{2}$$

Example (MFS 5):

$$\frac{4.1 - 3.8}{2}$$

Sample calculations showing appropriate data processing

0.2 cm

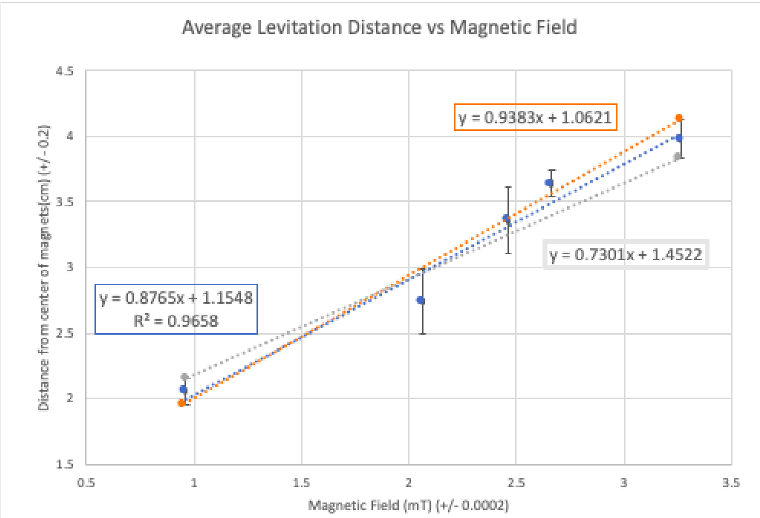
Despite the error on the ruler being 0.1 cm, a better estimate of the experimental errors would be averaging the uncertainties. If we do this, we will get

$$\frac{0.1 + 0.25 + 0.25 + 0.1 + 0.15}{5}$$

0.2 cm = fixed experimental error

Graph #1

The graph of the average levitation distance against the Magnetic field strength. In this graph, the trendline is the blue line, the orange line is the high line, and the gray line is the low line. The magnitudes of the vertical error bars depended on what error did every average levitation distance have respectively, and the horizontal error bars are dependent on magnetic field measuring errors. The horizontal error bars could not be seen because the error was too small at +/- 0.0002mT.




Graph showing that linear relationship is a possible fit but only due to large errorbars

Table #3

Here are the logarithms of the levitation distances and magnetic field strengths with their respective experimental errors. Logarithms are unitless quantities, so no units shown.

| Number of Magnets | $Log_{10}$ of Levitation Distance | Error on $log_{10}$ of Levitation Distance | $Log_{10}$ of Magnetic Field Strength | Error on $log_{10}$ of Magnetic FIeld Strength |
|---|---|---|---|---|
| 1 | 0.31 | 0.02 | -0.0163 | $9.0177x10^{-5}$ |
| 2 | 0.44 | 0.02 | 0.3145 | $4.2099x10^{-5}$ |
| 3 | 0.53 | 0.01 | 0.3915 | $3.5263x10^{-5}$ |
| 4 | 0.56 | 0.01 | 0.4254 | $3.2614x10^{-5}$ |
| 5 | 0.60 | 0.01 | 0.5136 | $2.6618x10^{-5}$ |

Log measurements with errors suitablt considered

Errors on $log_{10}$ of distance came from

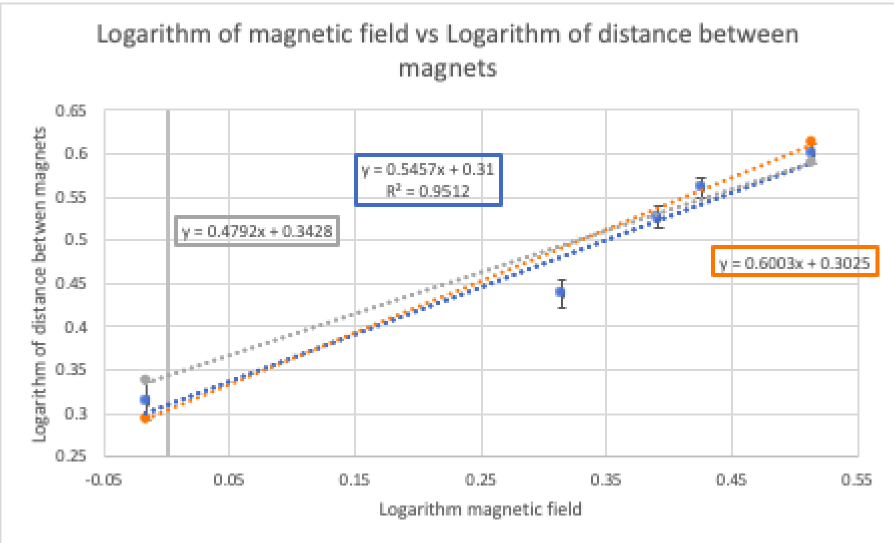
Errors on $\log_{10}$ of MFS came from $$\frac{log(r+\Delta r)-log(r-\Delta r)}{2}$$

This gives suitable errors for now - the theory of log errors gets very complicated but for IB this is sufficient

$$\frac{log(b+\Delta b)-log(b-\Delta b)}{2}$$

Graph #2

This is a graph of the average levitation distance against the Magnetic field strength. In this graph, the trendline is the blue line, the orange line is the high line, and the gray line is the low line. The magnitudes of the vertical error bars were the 5th column of Table #3 for each data point, and this is because of errors on rounding. This is a really small error, so the error bars cannot be seen on the graph. The horizontal errors are the 3rd column of Table #3. The errors are also due to rounding errors.




Still not a good fit but a linear slope is considered and analysed further.

Interpretation:

First of all, it is important to notice that the trendline doesn't pass through all the data, so this line might not be a good fit. However, a linear trend was expected, so I will continue with this trendline.

(High - low)/2 is the error on the slope. So (0.6003-0.4792)/2 = 0.0606, so the true slope is = 0.55 +/- 0.06 cm/mT (maintaining two significant figures), then 0.06/0.55=11%. Turns out 0.06 is almost 3 errors away from 0 so the slope is significant. To figure out how the intercept is affected by the errors, the error on the intercept is (high - low)/2. So (0.3428-0.3025)/2 = 0.0202, so the true intercept is = 0.31 +/- 0.02 mT (maintaining two significant figures), then 0.02/0.31 = 6.5%, so the intercept is very significant. The real trendline ends up being y = (0.55 +/- 0.06)x + (0.31 +/- 0.02) cm.

The results of the experiments make sense and were expected, due to the fact that the trends in the graphs show that 1 magnet, with a smaller MFS, had less average levitation distance than the other ones, and the experiment with 5 magnets had the most average levitation distance. Then, in this case, with more MFS, 1 magnet still has gravity as the main force. During my experiments, all the magnets had no change in direction, but less distance.

Since "n" in the magnetic force equation is 1/slope on the final graph, n would be equal to 1/0.5457 = 1.833, which is not equal to 2, but close to two by 8.35%, so the answer can be considered to be around 2.

Found a value fairly close to 2 but 3 was possibly expected

***Conclusion***

The research question was: How does the magnetic field strength placed on a magnet affect its levitation distance? According to the trends observed in graph #2, the results were that the distance from the center of the clustered magnets below to the levitated magnet was greater when the magnetic field was greater, partially supporting the hypothesis, since this was also a trend in which the magnetic field was rising while the distance to the nth power was rising. This does not mean that the trend was proportional, since there is a straight line, but the line does not pass through the origin, a requirement for proportionality. The equation for the trendline was 0.55x + 0.31 with an error on slope of +/- 0.06 and an error on the y-intercept of +/- 0.02. This slope led to a value of 1.8 +/- 0.1. The overall error is 8.35%. In my original hypothesis, I predicted that there would be a cubed relationship, or that n = 3 because dipoles should have a cubed relationship, but I got something closer to n = 2, meaning a squared relationship, closer to what was expected for monopoles.

Suitable conclusion

Scientific context somewhat considered

In general, the data quality was sufficient as the typical error divided by typical value would be better than 10% (0.2/2.1). The control variables were controlled well by keeping the experiment away from anything else, and when having a background magnetic field strength, it was taken into account and subtracted from the entire magnetic field in order to only use the magnetic field created by the magnets. The tilting could also be fixed by using the stick, but there was still some tilting. There were some anomalies that had to do with this tilting - the magnet sometimes flipped. Trials with flipping magnets had to be discounted. Of course, because of the pole, the magnet wouldn't totally flip, but the magnet sometimes had a tilt factor. This may have been because of the fact that the pole may have not been so stable, slanting to one side; this was another observation. There was also a very limited range of the distance due to a limited range of the magnetic field.

Checking data quality

| ***Strengths*** | How this made the investigation more reliable |
|---|---|
| 1. Control over Background Magnetic field<br>2. Same kinds of magnets<br>3. Same distance from levitating magnet | 1. If this wasn't controlled, not only would the magnetic field measurements be less accurate, but it could also affect the position of the magnet, affecting the experiment as a whole. The background magnetic field was controlled by making all magnetic field sources except the magnets being used in the experiment stayed in the same positions throughout the entire experiment.<br>2. This strength made the experiment more reliable |

Srengths

| | | |
|---|---|---|
| | since using the same kinds of magnets keep the magnetic field strength change linearized, so this makes it easier to do, and I also do not have to account for other factors like material since this is not part of the experiment.<br>3. This strength was useful for the experiment since having the same distance from the levitated magnet would eliminate some variations in the magnetic field strength measurements. These variations would arise if there are different distances because there is an inverse-square relationship between the distance from the magnet and the force. | |
| ***Weaknesses*** | How it affected data | How it will be improved |
| 1. Inaccuracy of Naked Human Eye<br>2. Destabilization of pencil/stick<br>3. There was a very limited range of magnetic fields, giving a limited range of distances | 1. Since the human eye is always imperfect, there could have been an inaccuracy with the ruler measurements. The ruler also isn't perfect, so these together makes the fact that this may have been what caused the uncertainties for measurement.<br>2. The stick sometimes wasn't stable, and sometimes it would slant to one side, even just a little bit. This slanting to one side might have been what caused the magnet to sometimes tilt to one side. Although the stick just slanted a little, the tilting is a lot for the magnet because then the magnet will start to attract, by flipping.<br>3. If there had been a wider range of magnetic fields, I could have more insight into the slope | 1. I can use a better, more precise, ruler. The ruler used would measure to millimeters. If there was a ruler that could measure more than that, it could be used. Also, a picture can be taken of the experiment and the ruler in action, so measurements could be verified later after taking the measurements during the experiment.<br>2. This can be fixed by using a wider stick, but not really wide or else the magnet can't move freely. A base can also be used in order to keep the stick in its place.<br>3. [redacted] |

Limitations and improvements

| | | |
|---|---|---|
| | of the line, giving a clearer value of n. | |
| ***Extensions*** | | |
| 1. Different kinds of magnets<br>2. Seeing how the temperature can affect overall performance<br>3. Using an EMC (Equivalent Magnetic Circuit)-based computation to analyze the performance | 1. To see which one can be the best, different magnets can be used for the same magnetic levitation experiment. This way one can see which is better. The slope on the Magnetic Field Strength vs distance graph can determine which is best, and diamagnetic materials, ferromagnetic materials, paramagnetic materials, and even electromagnets can be used. One can also experiment with other magnetic materials on top that are different from the ones on the bottom. The highest slope can result in the best combination.<br>2. In the Maglev-Cobra system, a system for magnetic levitation, there was a temperature factor in which when the temperature got to 77 Kelvin, the levitation force (therefore the distance) was at its lowest, so one can try to see how the temperature can affect different combinations of magnets. These different combinations of magnets are specified above in the extension before this one, and we can see which one is better according to the temperature.<br>3. The performance of a system isn't only evaluated using the slope of the magnetic field vs distance graph, but it can also be analyzed using an equivalent magnetic circuit. Not only is the levitation distance important, but also airgap flux density (the force of levitation in and of itself, and back-EMF (the current that opposes the change induced on it). | |

Extensions

Clear, concise, complete report

***<u>Works Cited:</u>***

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