

# *PHYSICS HL*

# *EXTENDED ESSAY*

The Effect of Number of Magnets Falling Inside a Copper Tube on the Back Emf Created

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## Personal Engagement:

I find it enlightening to try to explain the phenomena that happen around me with the laws of physics. A friend of mine had come up with a projectile shooter that uses magnetism to speed up an iron projectile. Then the idea of using a magnet as the projectile came into my mind. Since the device used magnetism as a force source, I thought the projectile would shoot out even faster than the iron one. It was a surprise to see the magnet just fall almost straight to the ground. That is when I made a thought experiment to find the reason behind my observation. It was apparent that the magnet was causing a force opposite of the direction of movement. However, how this force was created was not that obvious. After some research, I found out that the phenomena I observed was related to the Faraday's Law and Lenz's Law. Faraday's Law states a change in magnetic field(flux) induces a current on a conductive material. Lenz's Law states that the induced current produces magnetic fields which opposes the change in magnetic flux that induces such currents. These two laws are in effect when a magnet moves beside a metallic plate, which in return slows down the magnet. The back emf effect in result applies a force directly opposite of the direction of movement.

### Background Information:

According to Faraday's Law of Induction, any change in the magnetic environment of a coil will induce an emf (electromotive force) in the coil. The voltage or emf generated by the change in magnetic environment is given by the formula <sup>(1)</sup>:

$$V = -N \frac{d(BA)}{dt}$$

Where;

V=Voltage

B=Magnetic field strength

A=The area magnetic field passes through

t=time

Lenz's Law states that the induced current produces magnetic fields of its own which opposes the change in magnetic flux that induces such currents. Lenz's law is given by the formula <sup>(2)</sup>:

$$EMF = - \frac{d\Phi}{dt}$$

where;

$\phi$ =magnetic flux

EMF (Electromotive force) =induced voltage

t=time

minus sign (-) represents the opposite direction of voltage generated

There were two experimental setups that came to my mind. One included a copper plate with a gradient for the magnet to roll on while the other included a copper tube for the magnet to fall through. With the first setup, although taking measurements would have been easier since the movement of magnet is a lot slower,

friction would need to be introduced and the effect of temporary polarization would be more significant rather than just the induced current's magnetic field. Using the setup with the copper tube and letting the magnet fall freely reduces the contact of magnet with copper tube to a minimum.

The material of the tube is chosen to be copper because it is diamagnetic and conductive. A ferromagnetic material would cause the magnet to get pulled to the tube or if not get stuck to it. The conductivity allows the induced current to have observable properties. Also copper is moderately cheap and soft which in return makes it easier to obtain and shape.

Considering the use of copper tube rather than a plate with gradient, a more precise measuring method was required. One way to increase precision was to use a camera and calculate the time for every trial but this would take too much time and the frame rate would be limiting the measuring process. To overcome these problems, I decided to go with an electrical chronometer that uses two infrared sensors that detect the magnet just when it enters and exits the copper tube.

Arduino Leonardo board has an easy to use interface and is one of the universal boards people can have access to. This makes the repetition of the experiment by different people around the world less challenging. The production company's products are also more reliable than the cheaper alternatives, reducing the experimental error. The Arduino board also has an inner time counter allowing it to keep track of time.

## **Exploration**

Research Question: How does the number of magnets freefalling inside a non-magnetic conductive metal tube affect the back emf created by induction?

Hypothesis: As the number of magnets increases the back emf it creates increases directly proportional to it.

Independent Variable: Number of magnets

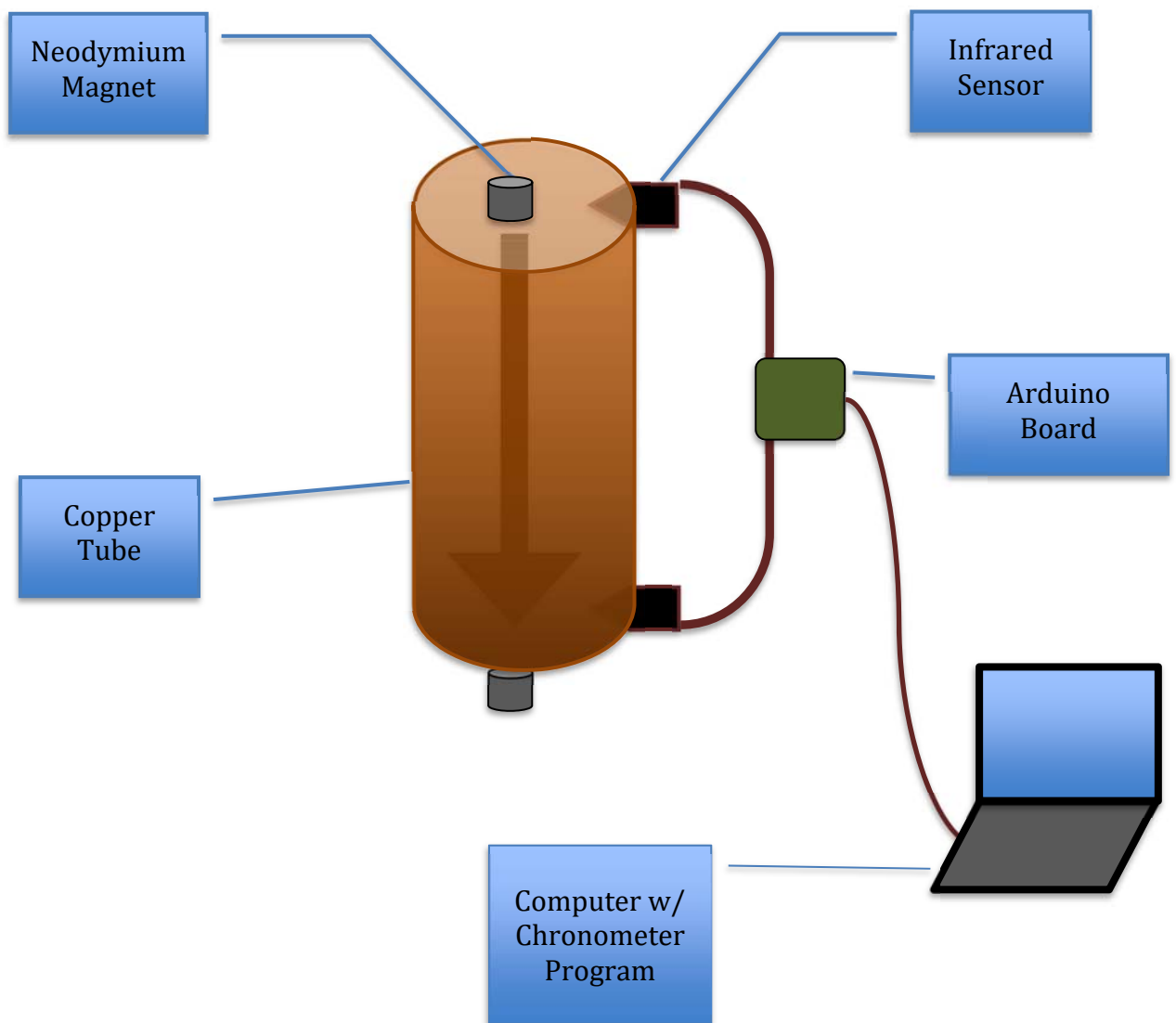
Dependent Variable: Strength of back emf

Control Variables: Type of metal (The same tube is used in every trial), material and shape of magnet (All magnets are identical), air current (the experiment is done in an enclosed environment), external magnetic forces (the copper tube creates a natural faraday cage while the tube only contacts plastic), alignment of copper tube (the tube is mounted on a fixed wall)

### Materials:

- Copper Tube (1mm thickness, 1.5cm outer radius, 100cm length)
- 6 Identical Neodymium Cylindrical Rod Magnets (1cm radius, 2cm height)
- 2 Infrared Sensors
- Arduino Leonardo board
- Blue-tack
- 2 Telephone Cables (150cm long)
- Ruler
- Solder and Soldering Machine
- Computer
- 2 Wires (75cm length)

**Experimental Setup:**



Method:

1. Arduino Leonardo board is connected to the computer and the free open software interface for operating the device is opened.
2. The code for the chronometer is written:

```
int IR1;

int IR2;

//two integer variables are set by the names IR1 and IR2.

unsigned long StartTime;

unsigned long CurrentTime;

float ElapsedTime;

void setup () {

Serial.begin(9600);

StartTime = 0;

CurrentTime = 0;

ElapsedTime = 0;

}

//three variables StartTime, CurrentTime and ElapsedTime are set to zero

void loop () {

int IR1 = analogRead(A1);

if (IR1 > 0) {

    StartTime = millis();

}

int IR2 = analogRead(A2);

if (IR2 > 0) {
```



```

CurrentTime = millis();

}

//The inner counter's value is set for the first infrared value when it passes by it
//The inner counter's value is set for the second infrared sensor value when it reaches
//the end of the tube and passes by the second infrared

ElapsedTime = ((float)CurrentTime - (float)StartTime) / 1000.0;

//Elapsed time is calculated by the difference between the values of IR1 and IR2
//It is then divided by 1000 to turn the milliseconds to seconds

Serial.print("Elapsed Time = ");

Serial.println(ElapsedTime);

delay (1);

}

//The ElapsedTime is then calculated and shown on the screen every millisecond.

```

3. The infrared sensors are connected to the Arduino board with wires to their corresponding ports analog one (A1) and analog two (A2).
4. The serial port screen is opened and program is run to test if sensors are connected properly.
5. The copper tube is mounted on a wall with blue-tack. Its made sure that the copper tube is perpendicular to the ground, using the ruler.
6. The infrared sensor heads are fixed on two ends of the copper tube with blue-tack. The centers of infrared sensors are put just on level with the opening to measure exactly the time it takes for an object to go through the tube; not a bigger distance.

7. A magnet is dropped inside the tube to check is it gets stuck to any of the infrared sensors or if it slides on only one side of the tube rather than falling. The tube is realigned and the sensors are moved according to the test drop.
8. The serial port screen is opened again and the program is run.
9. A magnet is dropped inside the tube making sure to not add any extra force to it when releasing.
10. The time measured is taken from the serial port screen and noted down.
11. Steps 9 and 10 are repeated 8 times.
12. Steps 9 through 11 are repeated with 2, 3, 4, 5 and 6 cylindrical rod magnets that are connected to each other head to head.

### Data Analysis

Number of Magnets Dropped (N)	Trials	Length of Copper Tube ( $\pm 0.5\text{cm}$ )	Time It takes for the Magnet(s) to Reach the End of Tube ( $t/\pm 0.01\text{s}$ )
1	1	100.0	6.89
	2		6.93
	3		7.03
	4		6.94
	5		7.03
	6		6.94
	7		6.89

	8		6.71
2	1	100.0	5.85
	2		5.83
	3		5.80
	4		5.90
	5		5.88
	6		5.88
	7		5.80
	8		5.85
3	1	100.0	4.11
	2		4.07
	3		4.06
	4		4.05
	5		4.05
	6		4.07
	7		4.07
	8		4.06
4	1	100.0	3.12
	2		3.06
	3		3.11
	4		3.05
	5		3.05
	6		3.08

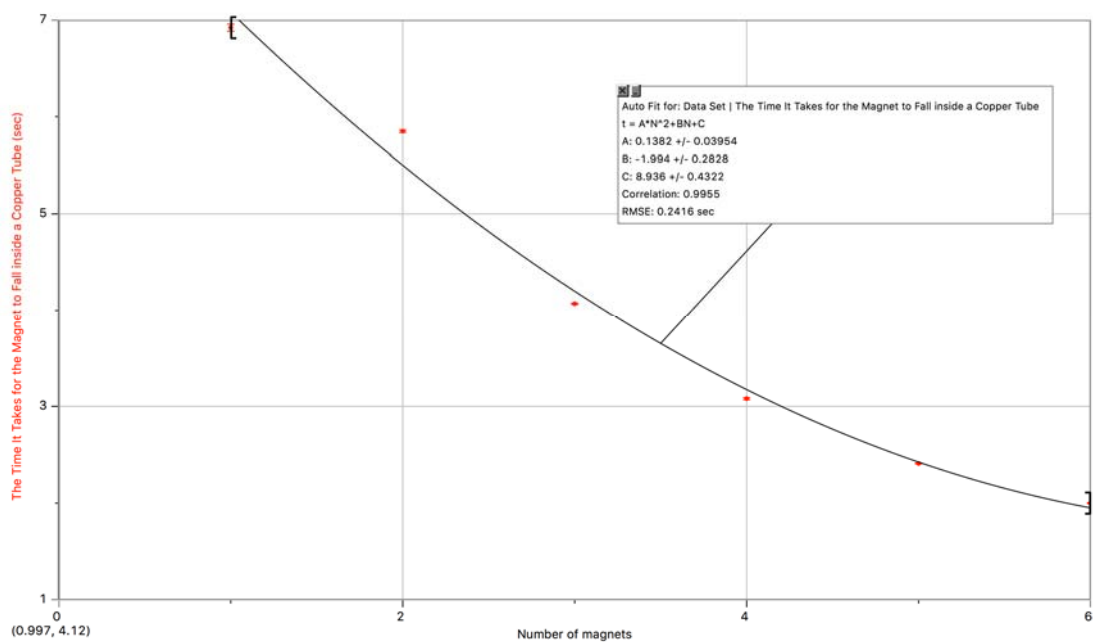
	7		3.07
	8		3.12
5	1	100.0	2.42
	2		2.41
	3		2.43
	4		2.42
	5		2.40
	6		2.40
	7		2.42
	8		2.39
6	1	100.0	1.99
	2		2.00
	3		1.98
	4		2.02
	5		2.02
	6		1.99
	7		2.00
	8		1.99

Table 1: The time it takes for different number of magnets to go through a copper tube for every trial

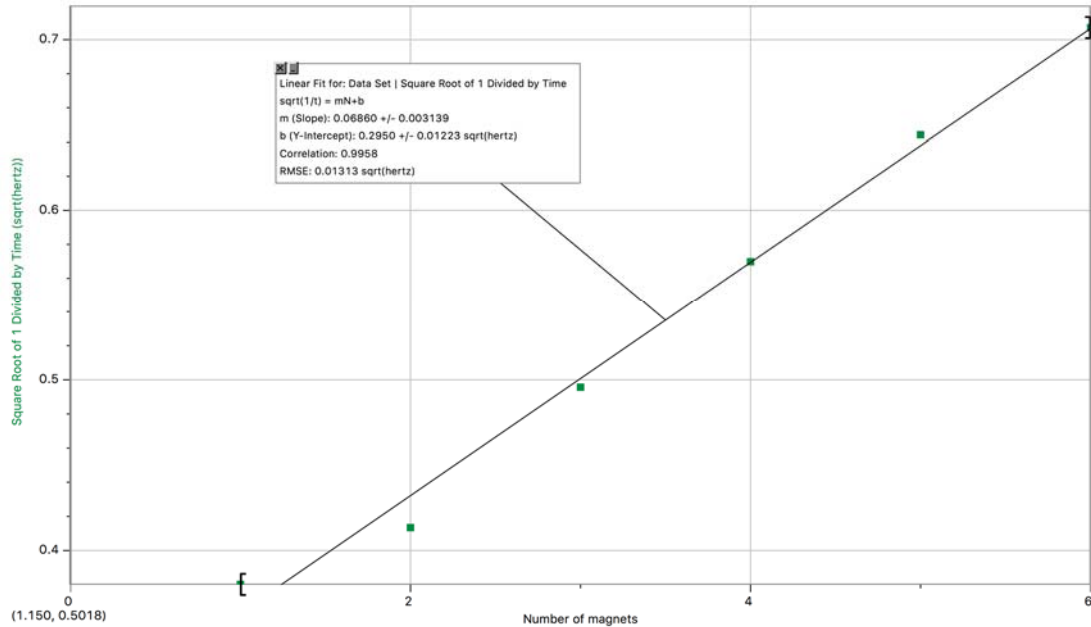
The means of every 8 trial is taken in order to better analyze the data collected. Standard error is also calculated to find the uncertainty in mean values.

Number of Magnets (N)	Mean Time for Magnet to Fall Through Copper Tube (t/±SE)	Standard Error of Mean Time
1	6.92	0.35607
2	5.85	0.01315
3	4.07	0.00675
4	3.08	0.01065
5	2.41	0.00479
6	2	0.00515

Table 2: The mean time for magnet to fall through copper tube for different number of magnets



Graph 1: The change in time it takes for magnet to fall through copper tube in relation to the change in number of magnets connected together



Graph 2: The change in 1 over square root of time it takes for magnet to fall through copper tube in relation to change in number of magnets

In the graphs above, the relation between the number of magnets and the time they take to go through the copper magnet is shown. In graph 1 it can be seen that the time it takes for magnet to go through copper tube is inversely proportional to the number of magnets. The time decreases as the number of magnets attached increases. To achieve a linear graph, the square root of the inverse of time by multiplication is taken.

In graph 2, a graph with a linear equation is achieved in the form of

$$y = mx + b$$

where;

$$m=0.0686\pm 0.003139s^{-1/2}$$

$$b=0.295\pm 0.01223s^{-1/2}$$

As a result, my final equation is:

$$N = \sqrt{\frac{1}{t}} \times 14.577 - 0.295$$

#### Error Calculations:

The percentage error for my result can be calculated using the uncertainty of the graph in the linear form as shown:

$$\%Error = \frac{\text{uncertainty}}{\text{slope}} \times 100 = \frac{0.003139}{0.0686} \times 100$$

The percentage error is equal to 4.57%

#### **Conclusion**

Judging by the faraday's law of induction induced current and voltage should be directly proportional to the magnetic field strength. Combined magnetic field strength is found to be bigger than just one magnet's magnetic field strength since the the relation between the time it takes for different numbers of magnets does not decrease linearly with the magnet number. When adding magnets together if the mass increased directly proportional to the magnetic field strength, the number of magnets would not effect the time it takes to fall through the copper tube because the net force would be equal with every number of magnets. This is not the case since the graph showed a direct correlation between number of magnets and the time they take to fall through the copper tube.

The time it takes for magnet to fall through copper tube decreased as the number of magnets increased. This extends on my original hypothesis; As the number

of magnets increases the back emf it creates increases directly proportional to it. The induced emf and therefore the back emf increases due to the increased electromagnetic field strength by adding magnets head to head. However, the magnetic field strength is hindered by the increased distance between two poles of the bar magnet. This offsets the net force applied on magnets inside the copper tube since the force acting on magnet by gravity of earth increases more than the magnetic field strength of magnet and coincidentally the induced emf and the force by the back emf created by the current on copper tube.

Graph 2 should have shown a directly proportional relation between one over square root of time it takes for magnet to fall through the copper tube and the number of magnets. However, there was an offset of  $0.295 \pm 0.01223s^{-1/2}$  which is the y intercept of graph. This was probably caused by a systematic error in the measuring equipment such as the gap between the the copper tube and the infrared sensors. Also the length of the magnet combinations affects the time measuring system. For the sake of eliminating this error, a setup with identical shaped and sized magnets with different magnetic field strengths could be used and the infrared sensor could be molded at the end of the copper tube.

Another factor that could be better controlled is the temperature of copper tube. The current induced on copper tube can increase the temperature of the tube due to the resistance which would result in the expansion of the copper tube. The temperature of the tube could be set to a specific degree before each trial to prevent this error.

I believe that using a digital method of data collection rather than just observations increased my accuracy and precision significantly since the uncertainty of data regarding time measurements was decreased from 0.2 second, which is the



average reaction time of humans, to 0.01 seconds. Nonetheless, even more precise measuring equipment could be used.

### **Bibliography**

1. Gottlieb, Michael A, and Rudolf Phieffier. “The Feynman Lectures on Physics Vol. II Ch. 17: The Laws of Induction.” *The Feynman Lectures*, 1964, [www.feynmanlectures.caltech.edu/II\\_17.html](http://www.feynmanlectures.caltech.edu/II_17.html).
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