How does Temperature affect Magnetism?

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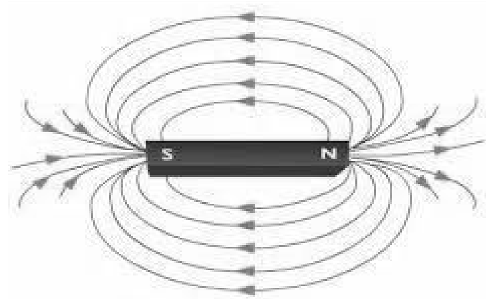
Research Question:

Does the relationship defined by Curie's law between the temperature of a paramagnetic material and its magnetism also apply to ferromagnetic materials?

Background:

Magnets, from electromagnets to bar magnets, are objects and/or devices that emit a magnetic field. In the case of this experiment, I used a bar magnet, and a bar magnet is a magnetized piece of iron, and its magnetic field functions like this:



[1]

Graphic 1: A visual of the direction of field lines around a bar magnet

Where the magnetic poles create a circular field that circulates around the magnet. The strength of the magnetic field is somewhat dependent on the alignment of the iron atoms within the magnet. If all the atoms are aligned with magnetic fields in the same direction, the piece of metal becomes magnetized. With that in mind, temperature is the kinetic energy of the atoms and molecules, and at higher temperatures atoms and molecules move more with an increase in kinetic energy. It can be inferred that if magnetic strength is based on the alignment of atoms within the magnet, and kinetic energy makes atoms move more, an increase in temperature

[1] "Magnetic field lines around a bar." *How Things Work*, www.how-things-work-science-projects.com/how-to-make-a-magnet/

would result in a decrease in magnetic field strength because the iron atoms move out of alignment more and allow for there to be less magnetic alignment.[2]

While working on magnetism in the late 1800's, Pierre Curie discovered a similar relationship in paramagnetic materials, which gave birth to Curie's Law. Curie's law states that the magnetization of a paramagnetic object is proportional to its magnetic field divided by its temperature[3], or, in mathematical terms:

$$M = C * \frac{B}{T}$$

<u>Where:</u>

- M = The resulting magnetization.
- C = The Curie constant for the material.
- B = The magnetic field density.
- T = The Temperature of the magnet.

In Pierre Curie's equation, temperature is the denominator, meaning that if everything but that stays constant, the resulting magnetization would decrease as temperature increases. However, Curie's law describes the relationship between the temperature and magnetism of paramagnetic materials, and doesn't directly apply to the physics of bar magnets. Paramagnetic materials are made magnetic through the application of a magnetic force onto them. "When exposed to an external magnetic field, internal induced magnetic fields form in the material that are ordered in the same direction as the applied field. Once the applied field is removed, the material loses its magnetism as thermal motion randomizes the electron spin orientations." [4] When paramagnetic materials are exposed to the external magnetic field, they align to the field in a way similar to the orientation of atoms in ferromagnetic materials.[5] However, ferromagnetic materials have the ability to retain their magnetic strength, and therefore have differing properties in comparison to the paramagnetic materials from Curie's equation. Ferromagnetic materials also do not have a magnetic field acting on them, and therefore I won't have a measurable B field for the equation, though it would be interesting to see how the relationship still applies.

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[2] Arana, Whitney. "How Does Heat Affect Magnets?" *Sciencing.com*, 24 Apr. 2017, sciencing.com/heat-affect-magnets-4926450.html.

[3] "Curie's Law." *BYJU' classes*, byjus.com/physics/curies-law/.

[4] Helmenstine, Anne Marie. "Paramagnetism and How It Works." Thoughtco., Dotdash, 28 June 2018, www.thoughtco.com/definition-of-paramagnetism-605894.

[5] "Ferromagnetic, Paramagnetic and Diamagnetic Substances." Redefining Knowledge, 4 Dec. 2018, hemantmore.org.in/foundation/science/physics/types-magnetism/2992/.

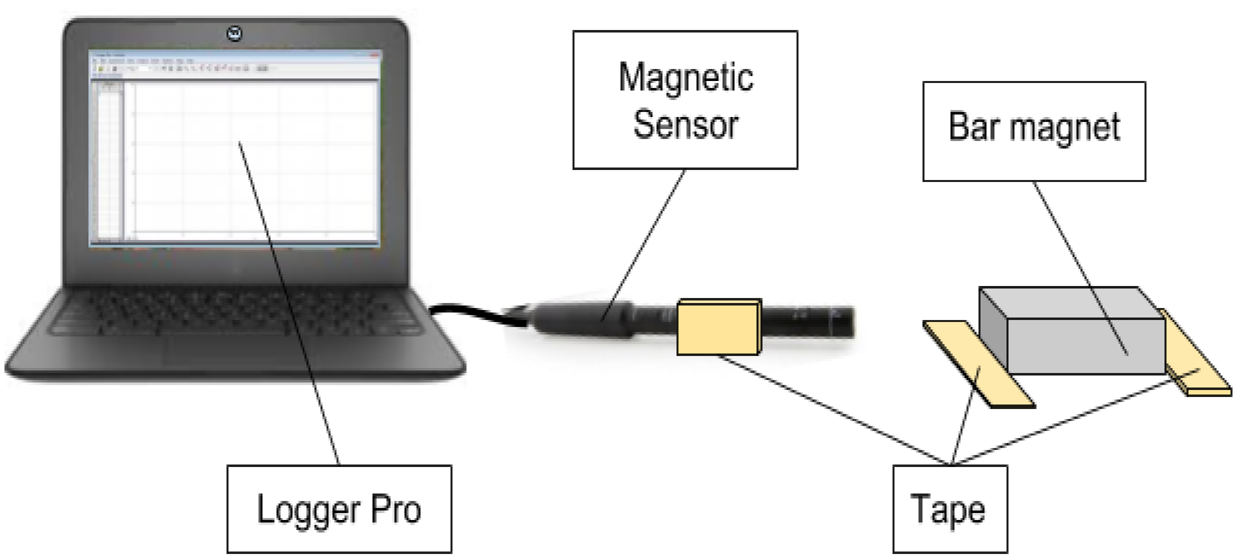
Variables:

Table 1: The Variables in my Experiment	
Type	**Variable**
Independent	Temperature of the bar magnet
Dependent	Magnetic field strength of the bar magnet
Controlled	Distance from the sensor to the bar magnet

How the control variable is controlled:

The strength the sensor feels from the bar magnet will change based on its distance to that magnet. To minimize the effect from that variable, I will use tape to create markers where the magnet should go every time I test its field strength. Keeping a constant distance should make the effect from distance negligible.

Setup and Procedure:



Graphic 2: The setup I used to carry out my experiment. Note, not all the materials I used are in this diagram.

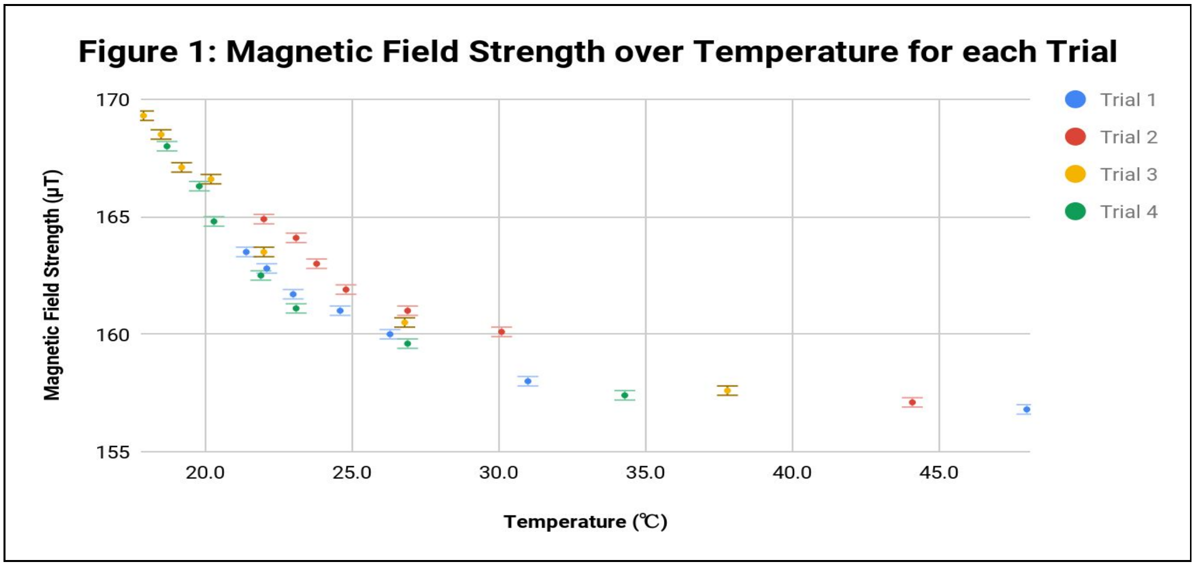
I was able to obtain a wide range of temperatures for my magnet by heating the bar magnet in a toaster oven for around 5 minutes before cooling it for a couple minutes between trials inside a refrigerator. To measure the magnetic field strength of the bar magnet, I hooked up a field sensor to a Chromebook and marked out with tape a specific placement for the magnet. The field sensor was suspended to the table with more tape to keep it in a fixed position relative to where the magnet should be. For the first couple trials, during which the magnet was too hot to handle with my bare hands, I used two metal tongs to pick up, move, and place the bar magnet. While the LoggerPro software measured the magnetic field strength of the bar magnet, I used an infrared sensor to measure the temperature of the bar magnet.

Raw Data Collection:

The raw data I used for my analysis is displayed below. Uncertainties are given for each variable, though my rationale for each uncertainty value can be found later in my report.

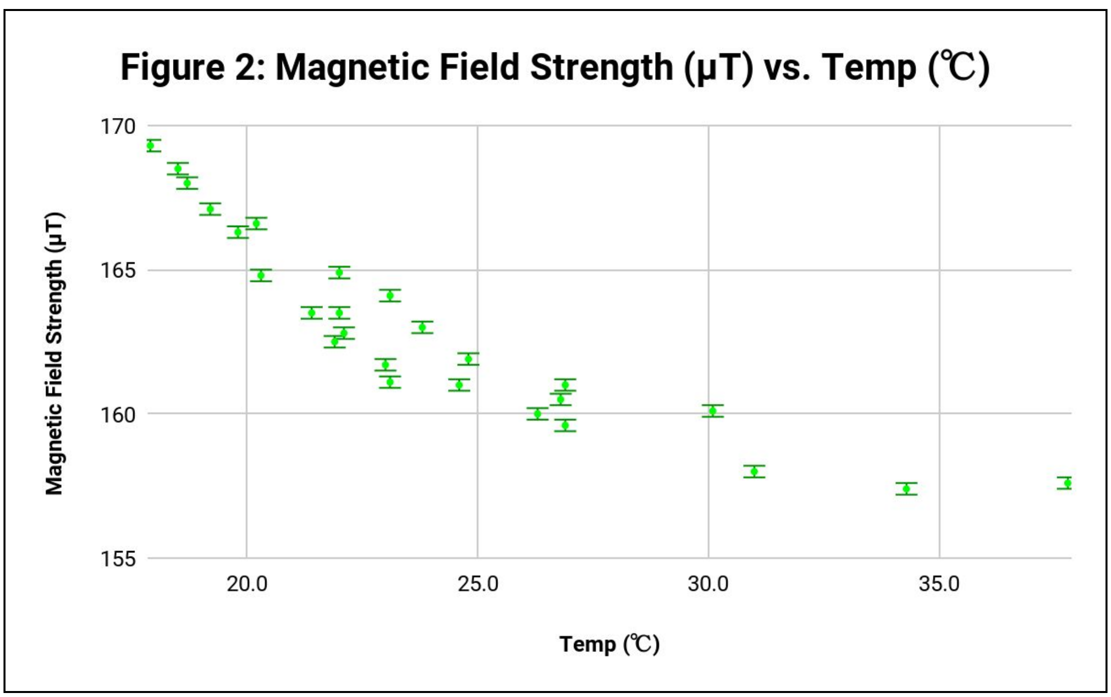
Table 2: Raw Data from the Temperature and Magnetic Field Sensors

Test #	Trial 1		Trial 2		Trial 3		Trial 4	
	Temperature (±1.1℃)	**Magnetic Field Strength** (±0.2μT)	**Temperature** (±1.1℃)	**Magnetic Field Strength** (±0.2μT)	**Temperature** (±1.1℃)	**Magnetic Field Strength** (±0.2μT)	**Temperature** (±1.1℃)	**Magnetic Field Strength** (±0.2μT)
1	48.0	156.8	44.1	157.1	37.8	157.6	34.3	157.4
2	31.0	158.0	30.1	160.1	26.8	160.5	26.9	159.6
3	26.3	160.0	26.9	161.0	22.0	163.5	23.1	161.1
4	24.6	161.0	24.8	161.9	20.2	166.6	21.9	162.5
5	23.0	161.7	23.8	163.0	29.2	167.1	20.3	164.8
6	22.1	162.8	23.1	164.1	28.5	168.5	19.8	166.3
7	21.4	163.5	22.0	164.9	17.9	169.3	18.7	168.0



Data Analysis

For my data, simply by examining the graph and the table, I determined that my values for the highest temperature in each of my trials were outliers. Even at differences of a couple of degrees Celsius, they all seemed to have a similar strength and I determined that somewhere I made an error in placing the magnet (either in orientation or position) and decided to treat those values as outliers. With the remaining set of values, graphing them yielded a fairly linear plot:



Conclusion

The data I collected, while in the realm of microteslas, showed that there was an inverse relationship between temperature and magnetic field strength. The magnet exhibited higher magnetic field strength values at lower temperatures. The relationship presented by my data is consistent with the relationship presented by Curie's law. Even though I am dealing with a ferromagnetic material, the influence that temperature has on its magnetic strength is similar to that of the influence it has on paramagnetic materials. As stated before, when magnetized by an external magnetic force, act similar to paramagnets where their atoms align in the direction of the field. Increasing the temperature of any substance makes its atoms move in and out of alignment faster, decreasing the amount of time each atom is in the right place to contribute to the field strength. If in both cases, the magnetism is based on the alignment of these atoms, it makes sense that temperature would affect both similarly and that the relationship put forward by Curie's law would be able to apply to each case.

In designing my experiment, I was able to minimize the number of variables, and the uncertainties associated with that, to three. My numerical uncertainty for my data and each of these variables is mostly based on manufacturer's specifications, whose values are given in Table 2. However, I think that my experiment was prone to a couple of different errors that could have hindered my ability to collect sufficient and accurate data, or could have affected the values of the data I have. The sources and effects of some of these errors are given in the following table.

Table 3: Ideas for Improvement			
Area of Improvement	**Effect**	**Significant?**	**Potential Improvements**
The Magnet's Distance, there was some human error as to the distance the magnet was to the sensor.	It would change the reported magnetic field strength value, skewing my data.	**Yes**, I found that slight differences in distance resulted in differences of field strength equal to half of the range of my entire data. Even small differences are bad, and since I myself was the only deterrent for that error, the error would have been relatively large.	Find a way to heat and cool the magnet without moving it from its position. An example of this is using a blow dryer or heat gun to heat it and then a fan or ice in contact with the magnet to cool it.

Magnetic strength, the bar magnet's field was weak and maybe even unreliable.	This would have made it difficult to get values that were far enough apart to observe a change.	**Sort of**, having a weak magnet made it hard to get changes in field strength that were significant. I was still able to get very usable data however without the magnet being very strong.	For this, I would just need to find a stronger bar magnet or use another type of magnet (like an electromagnet) that I could test.
Manipulating the Magnet at higher temperatures, it was hard to be precise with placement when the bar magnet was very hot.	If my magnet was misaligned due to an inability to place it exactly (because I couldn't use my fingers), the field value would change (probably becoming a lower value)	**No**, it wasn't especially difficult to move the magnet into the right place, even without touching it with my fingers. I doubt it would have made much error. Even with the knowledge that my higher temperatures points were outliers, I believe that was more of an effect of the first error on this list.	Don't use high temperatures (only cool the magnet for the experiment) or find a way to manipulate the magnet with my fingers without touching it directly (like a glove).
Temperature change, slight changes in temperature made it hard to see a pattern.	If the difference between my points were low, it would be harder to see a significant relationship.	**No**, while the values I'm working with are very small, it still was able to show a relationship and therefore didn't have much of an effect on determining that.	Heat and cool it more. Instead of 3 minutes, let it cool for 5 to 10 minutes and encounter a much larger temperature change.
Temperature consistency, temperature was not constant across the magnet, meaning that the temperature I recorded may have been different from reality.	The infrared sensor I was using only reported the temperature at a thing point on the magnet. If temperature was inconsistent, I would have reported wrong for different magnetic field values.	**Sort of**, if inconsistent temperature led to inconsistent field strength, my data could have been skewed away from reality.	Find a way to heat evenly or use a smaller magnet that doesn't have a lot of area to lose heat over. I could also use multiple temperature readings from across the magnet and use them to find an average temperature value.

Bibliography

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"Ferromagnetic, Paramagnetic and Diamagnetic Substances." Redefining Knowledge, hemantmore.org.in/foundation/science/physics/types-magnetism/2992/.