Magnets By Fire:

How Temperature Affects Magnetism

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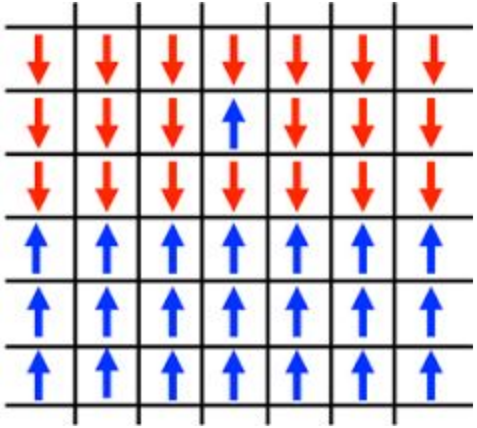
This project is an exploration of how ferromagnetic materials magnetic properties are influenced by high temperatures. There are three scientific topics that an understanding is required to understand the mechanisms and behaviors observed in this project.

Inspiration

Scientific Topics:

magnetic moments;
the Ising model;
properties of ferromagnetic materials;


μ
i
A



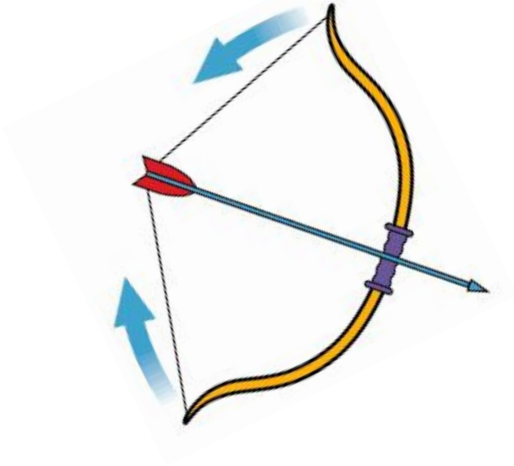
Magnetic Moments

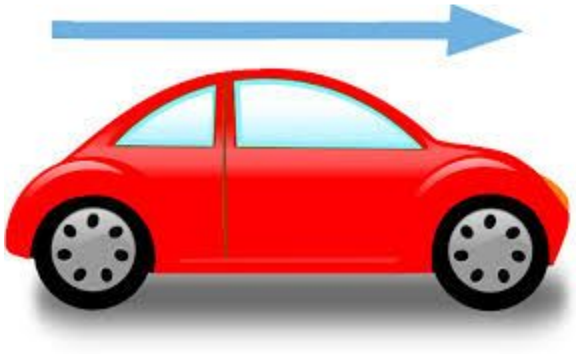
μ is a
vector quantity
that represents the measure of an object's tendency to interact with an external magnetic field

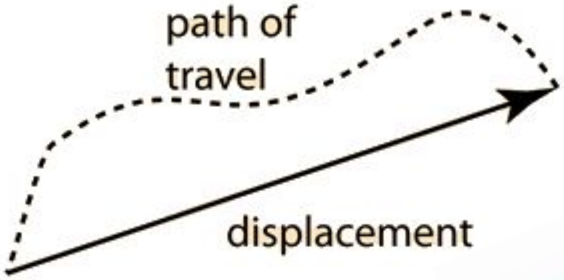
$\vec{\mu}$ or $\boldsymbol{\mu}$

Examples of vector quantities:

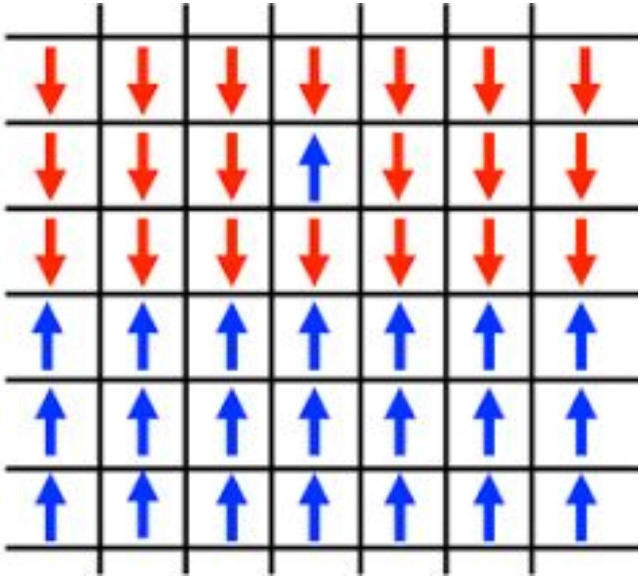
- ➢ Displacement
- ➢ Velocity
- ➢ Acceleration
- ➢ Force
- ➢ Momentum







Ising Model



The Ising model can represent many physical systems:
magnets, alloys, and gases are three examples of possible physical systems.

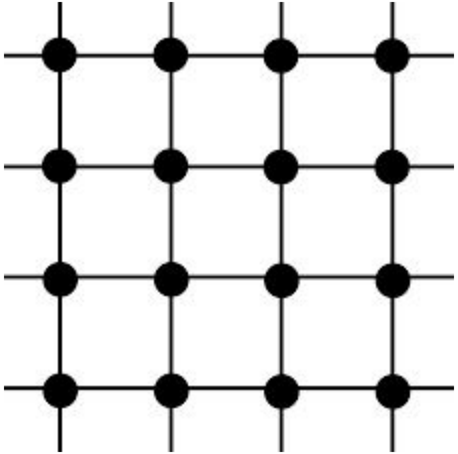
For this project, the Ising model will be used as a theoretical model of a magnet.

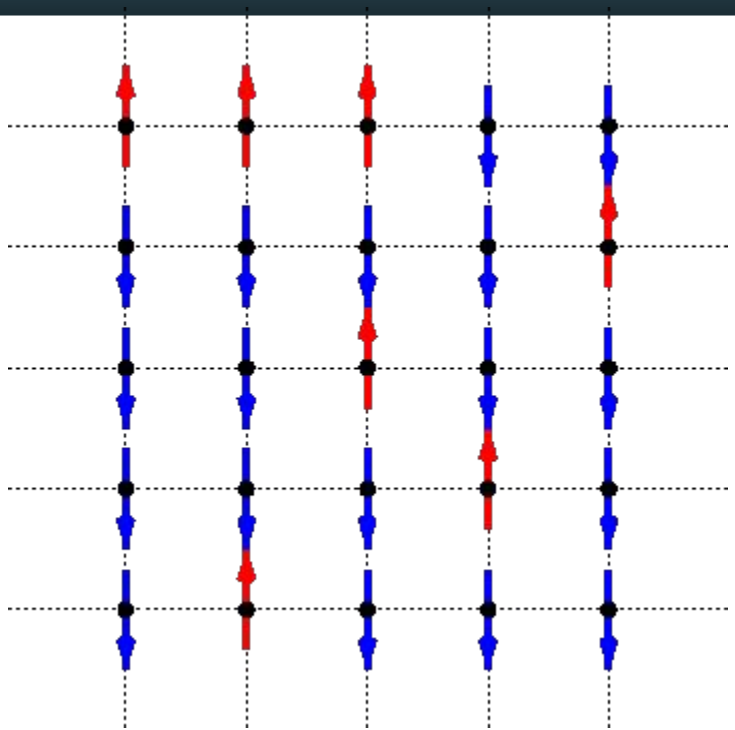
Ising Model

The Ising model is made up of variables which represent magnetics moments that are in one of two states: spin up or spin down (+1 or -1).

The model is constructed by putting these variables in a graph (a lattice is usually used) allowing each spin to interact with its neighbors.

Lattice: a regular repeated n-dimensional arrangement of atoms, ions, or molecules in a metal or other crystalline solid



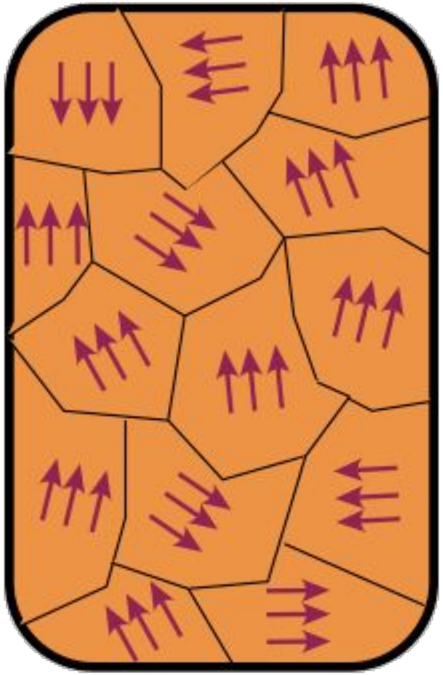


The magnetization of a magnetic material is made up of the combination of many small magnetic moments spread throughout the material. The orientation of these magnetic moments with respect to one another determines the magnetization of the material.

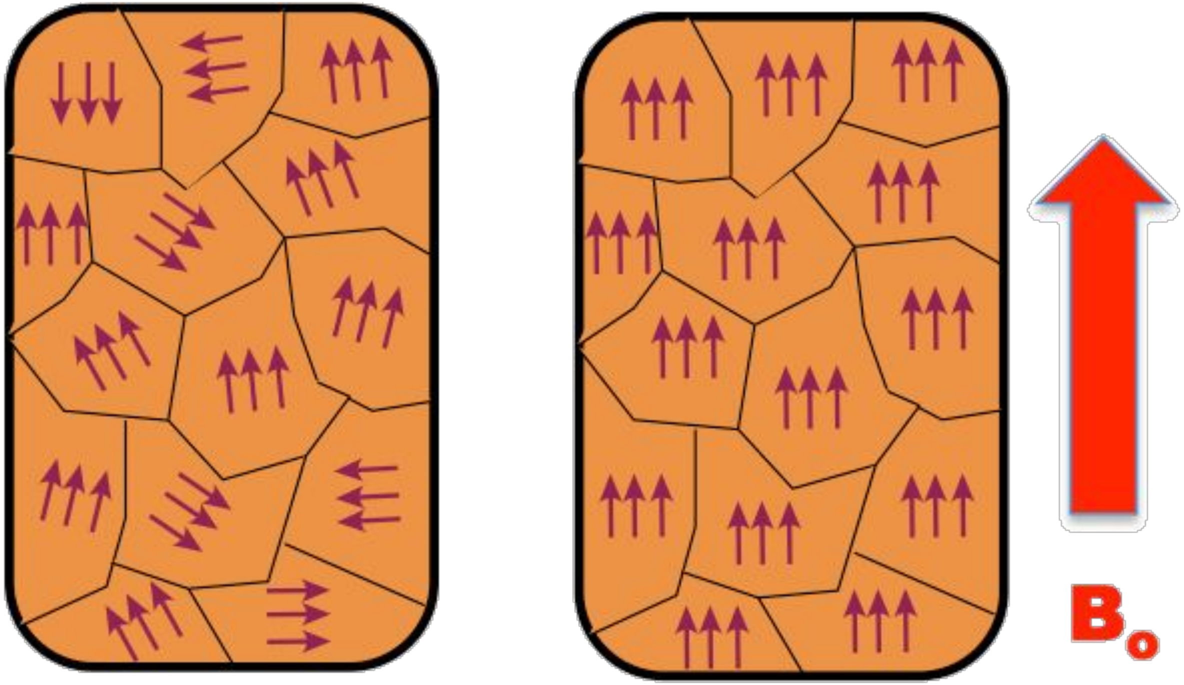
Ferromagnetism

For a material to be ferromagnetic, the material is defined to have…

"a high susceptibility to magnetization, the strength of which depends on that of the applied magnetizing field, and which may persist after removal of the applied field."



At the atomic level of iron, or any ferromagnetic material, there are multiple regions in the material which have differing alignments. Each one of these regions is comprised of atoms, but the atoms' magnetic moments only display ferromagnetic order within their respective regions. These regions are called domains.



Imagine an external magnetic field imposed on our sample.
The resulting sample has a net **μ** from each domain pointing in the same direction.

Using the Ising model to represent a sample of ferromagnetic material, we can explore how changing the amount of thermal energy in the system (the ferromagnetic material sample) affects the order of the system.

Models

Model 1: The Ising Model

$$H(\sigma) = -J \sum_{\langle i\ j \rangle} \sigma_i \sigma_j . \qquad \textbf{Eq.1}$$

- ➢ J is a positive interaction constant
- ➢ σ is a spin configuration
- ➢ i is a site in σ
- ➢ j is a neighboring site in σ
- ➢ H(σ) is the function that gives the energy of the spin configuration σ

$$M = \frac{1}{N}\sum_{i=1}^{N}\sigma_i . \qquad \textbf{Eq.2}$$

- M is the magnetization of σ
- σ is a spin configuration
- i is a site in σ
- N is the number of spins in σ

Model 2: $M = |\boldsymbol{\mu}|\tanh(JM/\mathrm{k_B}{*}T)$

In the mean-field theory of ferromagnetism, the strength of magnetization of a ferromagnetic material depends on temperature as given by the formula:

$$M = |\boldsymbol{\mu}| \tanh(JM/k_B {}^* T) \qquad \textbf{Eq.3}$$

- M is the strength of magnetization of the ferromagnetic material
- $|\boldsymbol{\mu}|$ is the magnitude of the magnetic moment
- J is a coupling constant
- k_B is Boltzmann's constant
- T is the temperature of the material

Creating new equations from variables in equation 3:

$$m = M / |\boldsymbol{\mu}| \qquad \textbf{Eq.4}$$

$$C = |\boldsymbol{\mu}| * J / k_B \qquad \textbf{Eq.5}$$

Plugging equations 4 and 5 into equation 3, we get:

$$m = \tanh(C*m / T) \qquad \textbf{Eq.6}$$

Numerical Methods

Model 1

Numerical method for this model is the Monte Carlo simulation. A Monte Carlo simulation is the name given to any computer simulation that uses random numbers to simulate a random physical process in order to estimate something about the outcome of that process. The simulation conditions are that there are only two possible states for a site in the simulation to have: +1 or -1.

Model 2

The numerical method for this model will be the relaxation method to solve equation 6 for different solutions (where a solution for the equation is always at m=0).

Boundary conditions: $0 < m < max$

Results

Initial Lattice

+1 -1 -1 +1
+1 -1 -1 +1
+1 -1 +1 +1
-1 +1 +1 -1

M = 1

Monte-Carlo Step $\longrightarrow$

Subsequent Lattice

-1 -1 -1 +1
+1 -1 -1 +1
+1 -1 +1 +1
-1 +1 +1 -1

M = 0

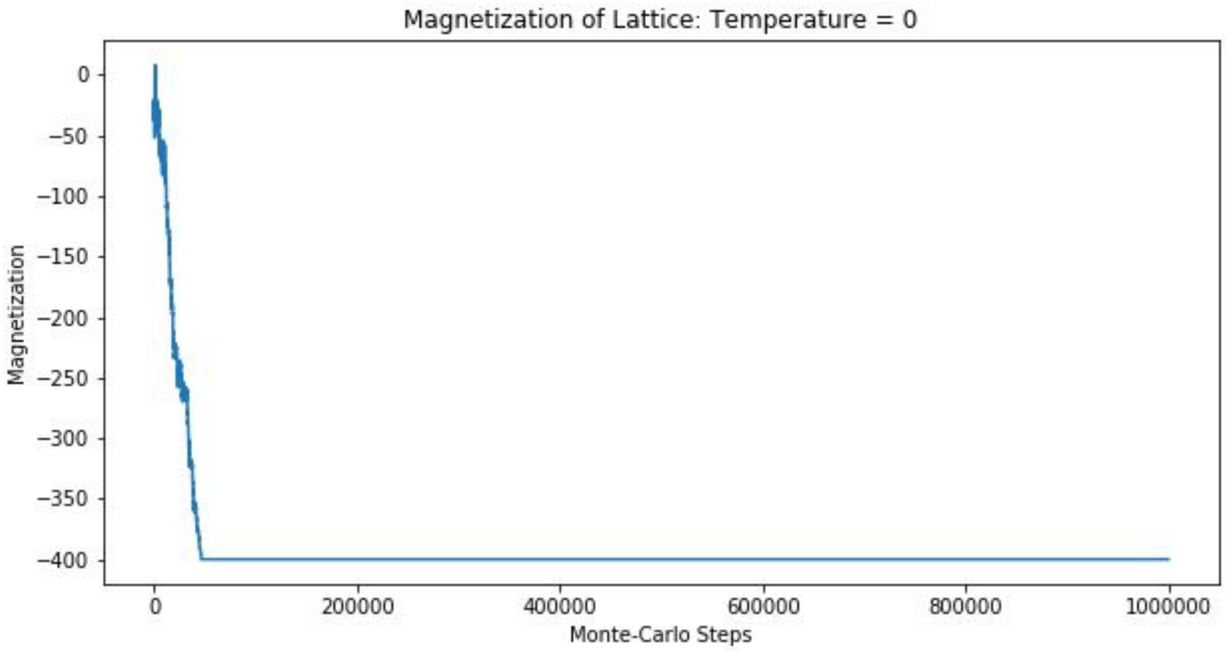


Fig. 1: Plot of the magnetization of a 20x20 lattice, generated with an Ising model, for one million Monte-Carlo steps, when the temperature T of the system is T = 0. The magnetization M of the lattice starts at approximately M = 0. As the number of steps increase we can see that the magnetization steadily decreases and sets on a value of -400.

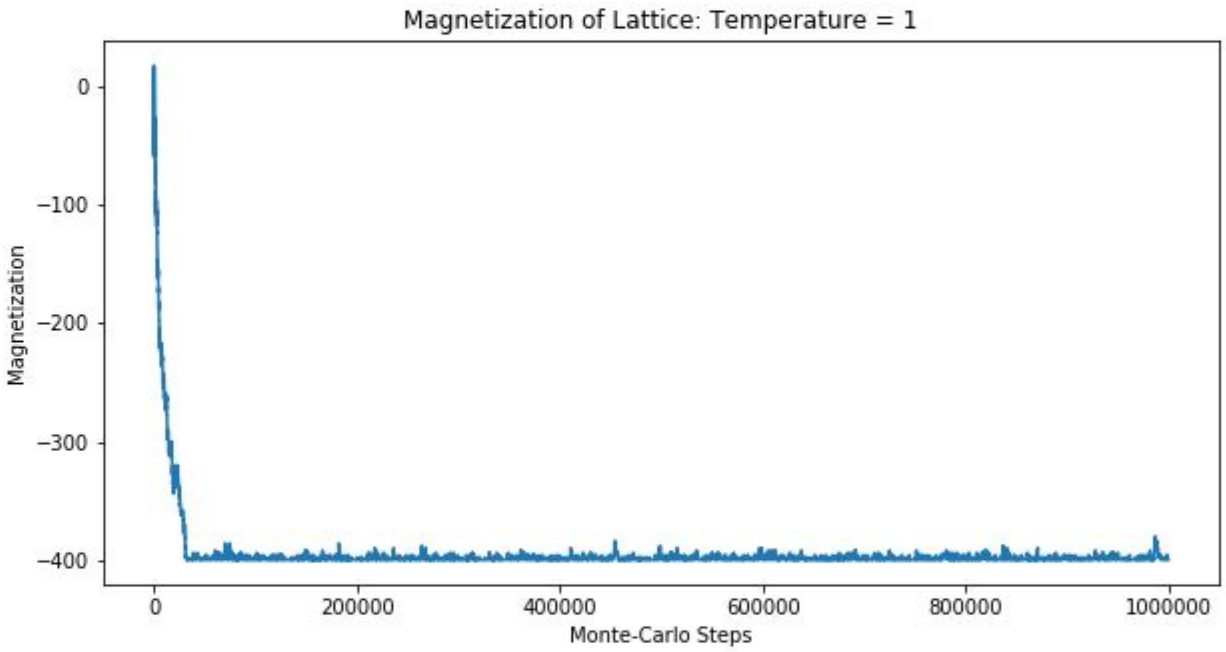


Fig. 2: Plot of the magnetization of a 20x20 lattice, generated with an Ising model, for one million Monte-Carlo steps, when the temperature T of the system is T = 1. The magnetization M of the lattice starts at approximately M = 0. As the number of steps increase we can see that the magnetization steadily decreases and towards a value of -400. The systems M reaches this value after approximately 50,000 Monte-Carlo steps and continues to fluctuate around this value of M for the remainder of the simulation

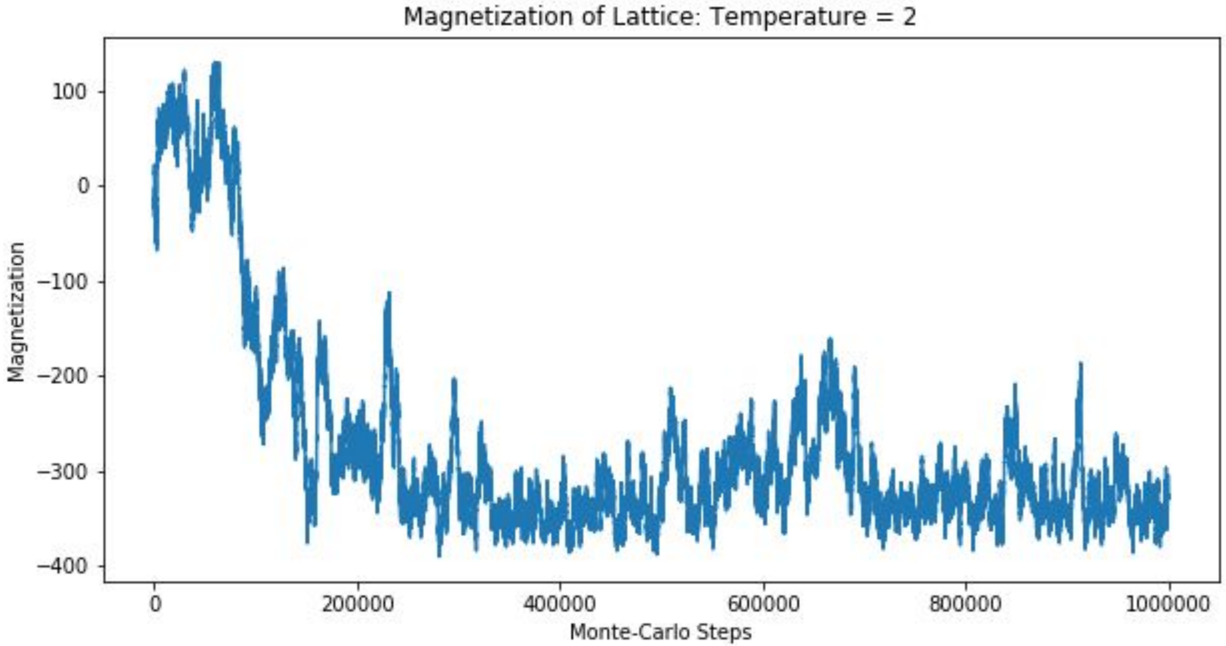


Fig. 3: Plot of the magnetization of a 20x20 lattice, generated with an Ising model, for one million Monte-Carlo steps, when the temperature T of the system is T = 2. The magnetization M of the lattice starts at approximately M = 0. As the number of steps increase we can see that the magnetization fluctuates between a negative and positive M, with M ≈ ±100 for the first 100,000 steps before the system maintains a negative M value for the remainder of the simulation. From the graph we can see that while M of the system remains negative, the magnetization never settles or fluctuates around a single value.

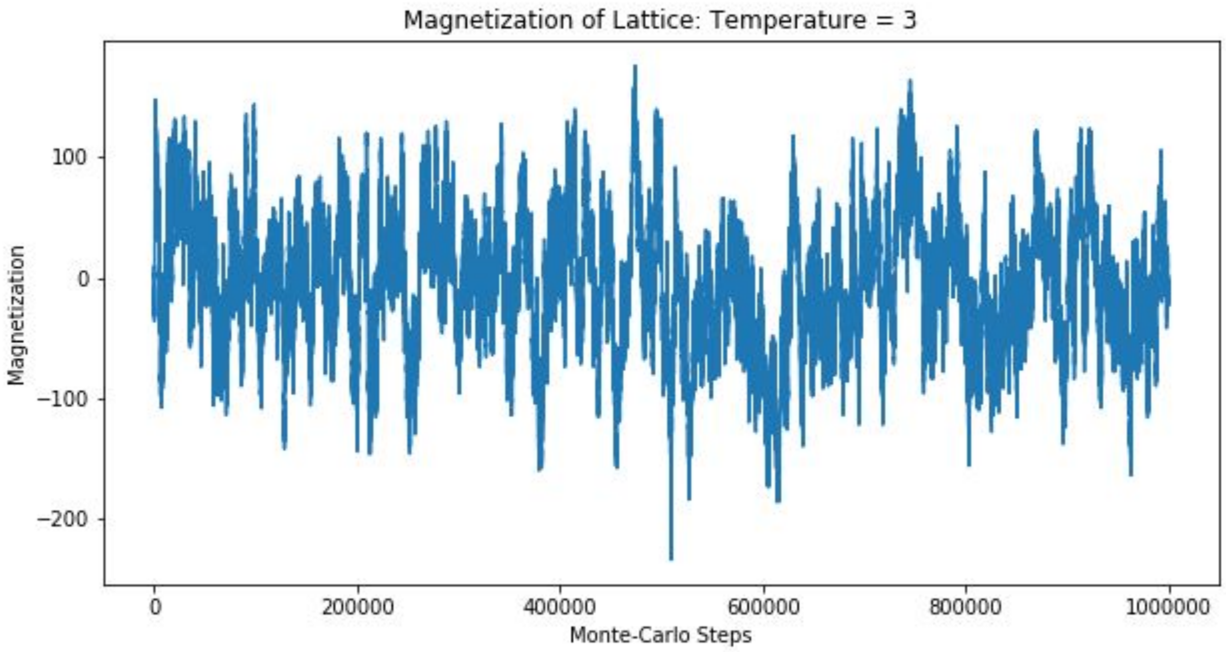


Fig. 4: Plot of the magnetization of a 20x20 lattice, generated with an Ising model, for one million Monte-Carlo steps, when the temperature T of the system is T = 4. The magnetization M of the lattice starts at approximately M = 0. As the number of steps increase we can see that the magnetization fluctuates over the entire simulation between negative and positive magnetizations, resulting in a disordered system.

Analysis

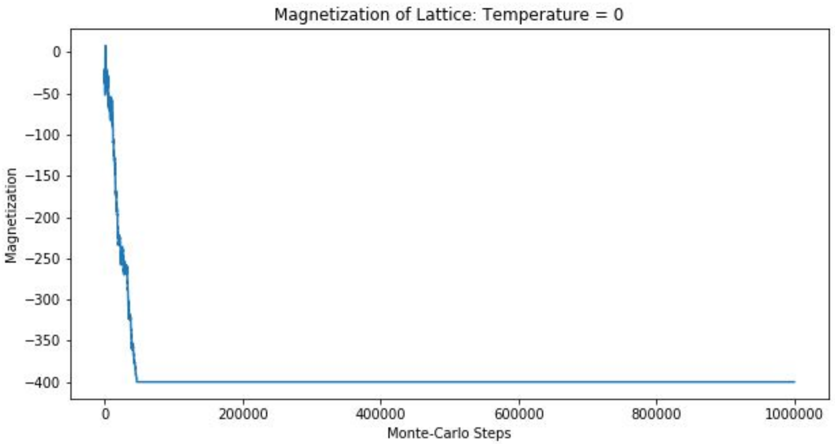


Fig. 1

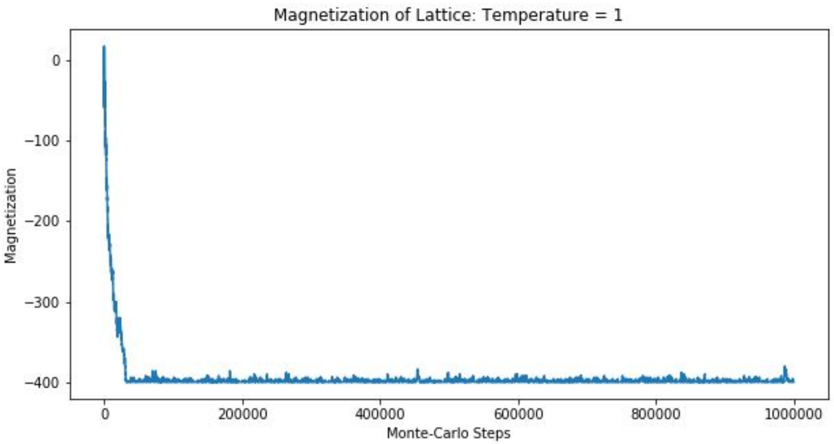


Fig. 2

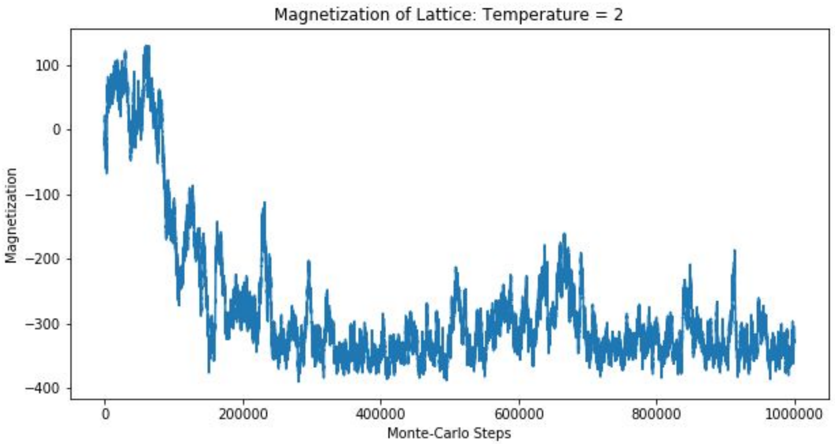


Fig. 3

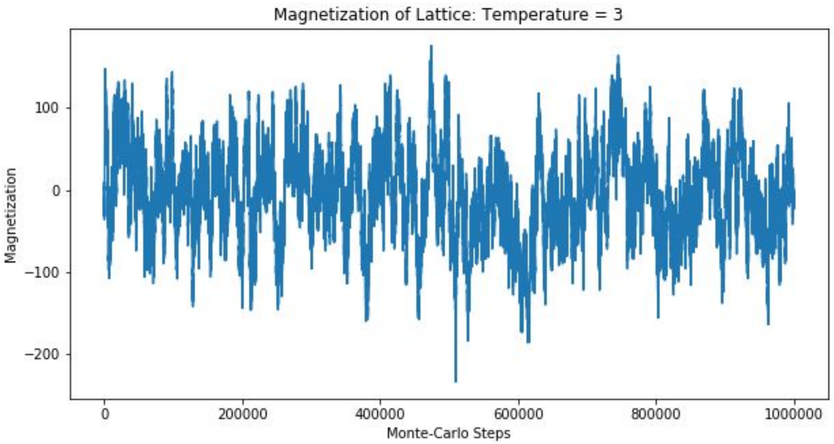


Fig. 4

Use Model 2 to check results from Model 1

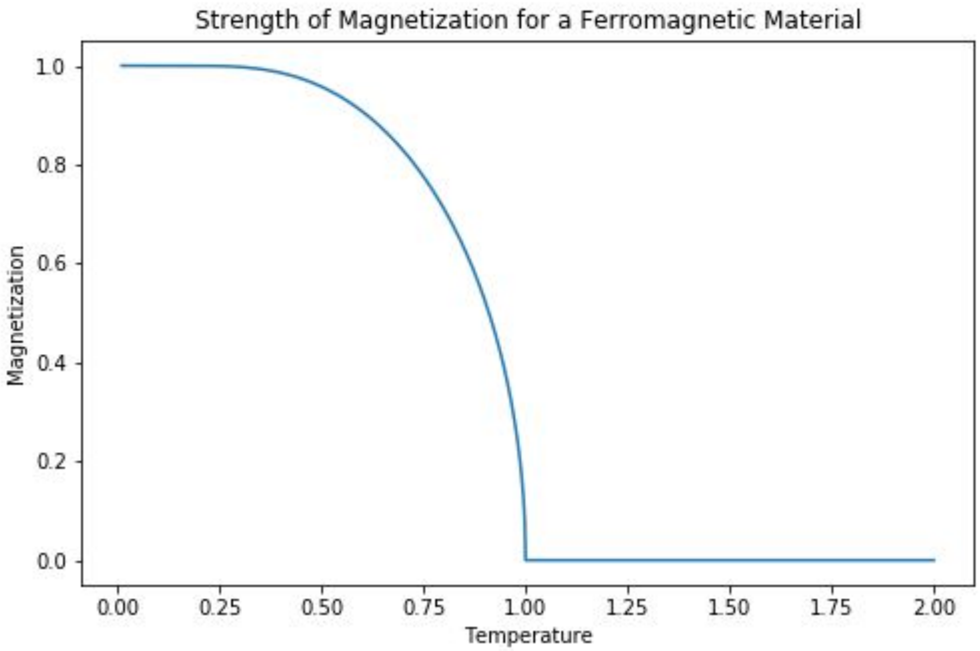
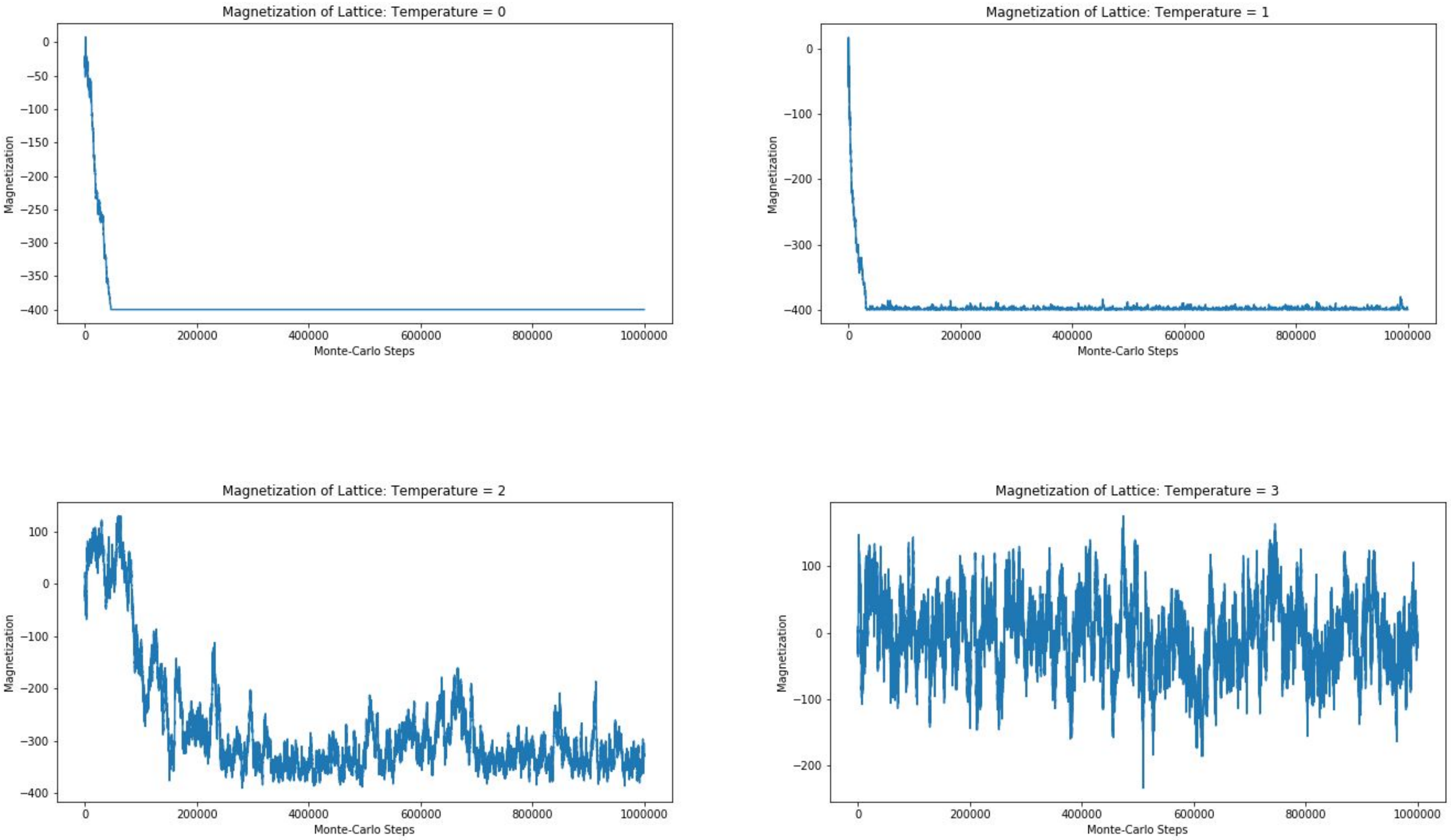


Fig. 5: Plot of the magnetization strength of a general ferromagnetic material using model 2, where C=1.. This graph shows the solutions to equation 6 found through using the relaxation method to solve for nonzero solutions. When the temperature T approaches T = 1, the magnetization of the ferromagnetic material goes to zero. When T ≥ 1, the only solutions are 0.


Magnetization of Lattice: Temperature = 0
Magnetization of Lattice: Temperature = 1
Magnetization of Lattice: Temperature = 2
Magnetization of Lattice: Temperature = 3
Magnetization
Monte-Carlo Steps
0
200000
400000
600000
800000
1000000
100
0
-50
-100
-150
-200
-250
-300
-350
-400

Summary

Personal

Magnetic Moments
Ising Model
Ferromagnetism

Increasing the thermal energy in a system (in our case a ferromagnetic material) decreases the magnetization of the system.

always

Always

ALWAYS

Use vector notation

$\vec{\mu}$ or $\boldsymbol{\mu}$