# Prosjekt 4

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## Abstract

Si meg, hva betyr adjø?
Er det bare trist?
Noe som sårer deg?
Tro meg, vi skal ta adjø
Ikke sånn som sist
Da jeg gikk fra deg

## Introduction

In this project we will study the Ising model in two dimensions. This is a model which is used to simulate phase transitions. The model exhibits a phase transition from a magnetic phase to a phase with zero magnetization. We study electrons in a lattice which is a binary system because each electron only can take two values, spin up or spin down.

The energy we get from the Ising model without an externally applied magnetic field is given by:

$$E = -J \sum_{<kl>}^{N} S_k S_l$$

where $s_k, s_l = \pm 1$ and represents classical spin values. N is the total number of spins and J is a coupling constant expressing the strenght of the interactions between neighboring spins. $< kl >$ indicates that we sum over the spins of the nearest neighbors. We apply periodic boundry conditions as well as the Metropolis algorithm. We also assume that we have a ferromagnetic ordering, so $J > 0$.

## Method

When calculating the degenerate energies for the case of 2x2, we start with the equation $E_i = -J \sum_{\langle kl \rangle}^{2} s_k s_l$

The case for all spin up looks like this $\begin{matrix} \uparrow & \uparrow \\ \uparrow & \uparrow \end{matrix}$

And the equation will be.

$$\begin{aligned}
E_i &= -J\sum_{< kl >}^{2} s_k s_l \\
&= -J((s_1s_2+s_1s_3)+(s_2s_1+s_2s_4)+(s_3s_1+s_3s_4)+(s_4s_3+s_4s_2)) \\
&= -J((1+1)+(1+1)+(1+1)+(1+1)) \\
E_i &= -8J
\end{aligned}$$

The reason why the same interaction is included several times is because of the unit cell repeating itself to inflinity in both x and y derection. Therefore the $s_1$ will interact with $s_2$ and $s_3$ inside the unit cell, and $s_2$ and $s_3$ "outside" the unit cell.

When this is known for all the degenerate energies we can calculate the walue of the partian function.

$$z = \sum_{i=1}^{2^n} e^{-\beta E_i}$$

In out case we have $n = 4$ since we have a 2x2 lattice.

$$\begin{aligned}
z &= \sum_{i=1}^{2^4} e^{-\beta E_i} \\
z &= e^{-\beta E_1} + e^{-\beta E_2} + \ldots + e^{-\beta E_1 6} \\
z &= e^{8\beta J} + 4e^{-\beta\cdot 0} + 2e^{-8\beta J} + 4e^{-\beta\cdot 0} + 4e^{-\beta\cdot 0} + 4e^{-\beta\cdot 0} + e^{8\beta J} \\
z &= 2e^{8\beta J} + 2e^{-8\beta J} + 16
\end{aligned}$$

This gives us the ability to calculate the expectationvalue of the energy $\langle E\rangle$

$$\langle E\rangle = \sum_{i}^{2^n} \frac{E_i e^{-\beta E_i}}{z}$$

We know we have several energyvalues which is zero. If we do not write these we get

$$\begin{aligned}
&= \frac{-8Je^{8\beta J} + 2\left(8Je^{-8\beta J}\right) + (-8J)\, e^{8\beta J}}{2e^{8\beta J} + 2e^{-8\beta J} + 16} \\
&= \frac{16J\left(e^{-8\beta J} - e^{8\beta J}\right)}{2(e^{8\beta J} + e^{-8\beta J} + 8)} \\
&= 8J\frac{e^{-8\beta J} - e^{8\beta J}}{e^{8\beta J} + e^{-8\beta J} + 8}
\end{aligned}$$

Thus

$$\langle E\rangle^2 = \left(8J\frac{e^{-8\beta J} - e^{8\beta J}}{e^{8\beta J} + e^{-8\beta J} + 8}\right)^2$$

At the same time we calculate $\left\langle E^2 \right\rangle$

$$\begin{aligned}\left\langle E^2 \right\rangle &= \sum_{i}^{2^n} \frac{E_i^2 e^{-\beta E_i}}{z} \\ &= \frac{64Je^{8\beta J} + 16Je^{4\beta J} + 16e^{-4\beta J} + 64e^{-8\beta J}}{2e^{8\beta J} + 2e^{-8\beta J} + 16}\end{aligned}$$

When this is known we can also calculate the heat capasitace.