

# Worksheet 6: Finite-Size Scaling and the Ising Model

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## 1 General Remarks

- Deadline for the report is **Monday, February 1, 2016**
- On this worksheet, you can achieve a maximum of 20 points.
- The report should be written as though it would be read by a fellow student who attends to the lecture, but does not do the tutorials.
- To hand in your report, send it to your tutor via email
  - Michael ([mkuron@icp.uni-stuttgart.de](mailto:mkuron@icp.uni-stuttgart.de)) (Thursday 11:30-13:00)
  - Johannes ([zeman@icp.uni-stuttgart.de](mailto:zeman@icp.uni-stuttgart.de)) (Friday 14:00-15:30)
- Please attach the report to the email. For the report itself, please use the PDF format (we will *not* accept MS Word doc/docx files!). Include graphs and images into the report.

- If the task is to write a program, please attach the source code of the program, so that we can test it ourselves.
- The report should be 5–10 pages long. We recommend using L<sup>A</sup>T<sub>E</sub>X. A good template for a report is available online.
- The worksheets are to be solved in groups of two or three people.

On this worksheet, you will combine all the methods and skills that you have obtained during the term and use them to compute the critical temperature  $T_c$  and the critical exponents  $\beta_m$  and  $\nu$  of the two-dimensional Ising model.

All files required for this tutorial can be found in the archive `templates.tar.gz` which can be downloaded from the lecture's homepage.

As on the previous worksheet, we will perform simulations of the two-dimensional Ising model on a  $(L \times L)$  square lattice.  $\sigma_{i,j}$  denotes the spin at lattice position  $(i, j)$ .

The (total) energy of the system is defined by

$$E = \frac{1}{2} \sum_{i=0}^{L-1} \sum_{j=0}^{L-1} E_{i,j} \quad (1)$$

where

$$E_{i,j} = -\sigma_{i,j}(\sigma_{i-1,j} + \sigma_{i+1,j} + \sigma_{i,j-1} + \sigma_{i,j+1}) \quad (2)$$

The system uses periodic boundary conditions, *i.e.*

$$\begin{aligned} \sigma_{-1,j} &= \sigma_{L-1,j} & \sigma_{L,j} &= \sigma_{0,j} \\ \sigma_{i,-1} &= \sigma_{i,L-1} & \sigma_{i,L} &= \sigma_{i,0} \end{aligned}$$

As an observable, we are interested in the (mean) *energy per site*  $e$ , which is defined by

$$e = \left\langle \frac{E}{L^2} \right\rangle$$

and the (mean) *magnetization per site*  $m$

$$m = \langle |\mu| \rangle \quad (3)$$

where

$$\mu = \frac{1}{L^2} \sum_{i=0}^{L-1} \sum_{j=0}^{L-1} \sigma_{i,j} \quad (4)$$

Magnetization in the Ising model on an infinite lattice is unity at  $T = 0$ , decreases with increasing temperature and vanishes in a first-order phase transition at critical

temperature  $T_c$ . At this temperature, the correlation length  $\xi$  diverges. This means that fluctuations on all length scales exist close to the critical point and thermodynamic observables diverge following a power-law dependence, for example of the type

$$\xi \sim t^{-\nu}, \quad m \sim t^{-\beta_m}, \quad t \equiv |1 - T/T_c|. \quad (5)$$

For  $2D$ , the values of  $T_c$  and the critical exponents  $\beta_m$  and  $\nu$  are known analytically as well as the critical temperature:

$$\beta_c = \frac{J}{k_B T_c} = \frac{\ln(1 + \sqrt{2})}{2}, \quad (6)$$

Note that for historical reasons the symbol  $\beta$  is used both for the inverse temperature and the critical exponent for magnetization. To clearly distinguish between them, in this worksheet, we will use  $\beta_m$  for the critical exponent for magnetization.

Simulations can only be performed on finite lattices, usually with periodic boundary conditions. By construction, these cannot handle infinite-ranged correlations close to the critical point. Therefore, the results obtained from finite-lattice simulations will systematically differ from the infinite limit.

## 2 Speeding up the Simulation

The Ising Monte-Carlo simulation from the last worksheet is written in pure Python. Unfortunately, when the size of the lattice  $L$  grows, the performance of the simulation is too low.

<p><b>Task</b></p> <ul style="list-style-type: none"> <li>• Speed up the simulation program by implementing all or parts of it in C/Cython.</li> <li>• Give reasons why you rewrote what part of the program.</li> </ul>	(4 points)
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### Hints

- To generate random numbers in C, use the random number generator from the *GNU Scientific Library* (GSL), as the default random number generator (RNG) has a too short period for MC simulations. The file `cising-impl.c` contains functions that demonstrate the usage of the GSL RNG.
- The files `cising.pyx`, `cising-impl.c`, `setup.py` and `test_cising.py` contain a small sample Python/Cython/C-program that generates a list of random numbers. From the program, you should be able to pick all parts that you need to do the task.

### 3 Determining Equilibrium Values and Errors

In this task, your job is to perform simulations of the two-dimensional Ising model for different lattice sizes  $L$  and measure the equilibrium values of the magnetization and the energy and their errors.

<b>Task</b>	(4 points)
<ul style="list-style-type: none"><li>• Run simulations with <math>L \in \{16, 64\}</math> for <math>T \in \{1.0, 1.1, 1.2, \dots, 4.9, 5.0\}</math>.</li><li>• Determine equilibrium values and errors of <math>m</math> and <math>e</math> for all of these runs.</li><li>• Plot <math>m</math> and <math>e</math> (with errorbars) as a function of <math>T</math> for the different system sizes.</li><li>• Add the exact curve for <math>L = 4</math> from the last worksheet.</li><li>• How do the curves depend on <math>L</math>?</li></ul>	

#### Hints

- If you want to store simulation data to a file, remember the module `pickle`.
- To reduce the file size, you can use the module `gzip`. Open the file with `gzip.open`, then all following operations will work on a compressed file.

### 4 Finite Size Scaling

#### 4.1 Determining $T_c$

<b>Task</b>	(4 points)
<ul style="list-style-type: none"><li>• Implement the Binder parameter <math>U = 1 - \frac{1}{3} \frac{\langle \mu^4 \rangle}{\langle \mu^2 \rangle^2}</math>.</li><li>• Measure the Binder parameter for <math>L \in \{4, 16, 64\}</math> and <math>T \in \{2.0, 2.02, 2.04, \dots, 2.38, 2.4\}</math>.</li><li>• Plot <math>U</math> vs. <math>T</math> for the different values of <math>L</math>.</li><li>• Determine <math>T_c</math> to a precision of <math>\pm 0.02</math>.</li></ul>	

**Hints** Note that you need a pretty good accuracy of  $U$  to determine  $T_c$ .

## 4.2 Estimating $\beta_m$

### Task

(4 points)

- Perform simulations at  $T_c$  with different  $L \in \{8, 16, 32, 64, 128\}$
- Plot  $m$  against  $L$  in double logarithmic scale.
- From the theory, what is the scaling law of the magnetization, *i.e.* how does the magnetization depend on  $L$ ?
- Try to estimate  $\beta_m$  from the curve, given that  $\nu = -1$  for a two-dimensional Ising system.

## 4.3 The Master Curve

Note that the value of  $\beta_m$  determined in the previous task depends strongly on the value of  $T_c$ , so do not trust the value overmuch. In the following, you will learn about a method that is better suited to determine the value.

When plotting  $ML^{\beta_m/\nu}$  against  $tL^{-\nu}$ , for different values of  $L$  and  $t = |1 - T/T_c|$  (*reduced temperature*), all data should fall on a single *master curve*. To get a better estimate for  $\beta_m$ , one can use the following procedure: make plots of  $mL^a$  against  $tL^{-\nu}$  with different values of  $a$  and select one where all data points are on the same curve.

### Task

(4 points)

- Use all of your data from this worksheet and plot the master curve for the estimated value of  $\beta_m$  from the last task. Scale the x-axis to the range  $[-20, 20]$ .
- Try different values of  $\beta_m$  to plot the master curve. Provide the best-looking plot and your estimated value of  $\beta_m$ .

**Hints** The fit should be best in the core part of the curve, *i.e.* where  $ML^{\beta_m/\nu} \approx 1.0$  and  $tL^{-\nu} \approx 0.0$ .