



Licentiate Thesis

Examining Hausdorff dimension and Scaling behaviour with Worm algorithm

Simon Rydell

Theoretical Particle Physics, Department of Theoretical Physics,
School of Engineering Sciences
Royal Institute of Technology, SE-106 91 Stockholm, Sweden

Stockholm, Sweden 2018

Typeset in L^AT_EX

Akademisk avhandling för avläggande av teknologie licentiatexamen (TeknL) inom ämnesområdet teoretisk fysik.

Scientific thesis for the degree of Licentiate of Engineering (Lic Eng) in the subject area of Theoretical physics.

TRITA-FYS-2010:05

© Simon Rydell, May 2018

Printed in Sweden by Universitetservice US AB, Stockholm May 2018

Abstract

Preface

Contents

Abstract	iii
Preface	v
Contents	vii
I Introduction and background material	1
1 Introduction	3
2 Background	5
2.1 Ising model	5
2.1.1 Loop expansion	5
2.1.2 Energy calculation	6
2.1.3 Heat capacity	7
2.2 n -vector model	8
2.3 XY model	8
2.3.1 Loop expansion	8
2.3.2 Winding number	9
3 Method	13
4 Graph Division and Hausdorff Dimension	15
4.1 Worm Algorithm	15
4.2 Graph Labeling	15
4.2.1 Hoshen Kopelman	15
4.3 Fractals	16
4.4 Box dimension	16
4.5 Graph Dividing Algorithm	16
5 Connection between Hausdorff Dimension and Scaling Behaviour	19

6	Results	21
6.1	Error Estimation	21
6.1.1	Monte Carlo error estimation	21
6.1.2	Bootstrap	22
7	Summary and conclusions	25
8	Appendix	27
8.1	Pseudo Code for Box Division Algorithm	27
	Bibliography	27

Part I

Introduction and background material

Chapter 1

Introduction

Chapter 2

Background

2.1 Ising model

2.1.1 Loop expansion

The Ising model energy

$$E = -J \sum_{\langle ij \rangle} S_i S_j \quad (2.1)$$

Let $K = \beta J$ where $\beta = 1/k_B T$.

$$\beta E = -K \sum_{\langle ij \rangle} S_i S_j \quad (2.2)$$

The partition function Z .

$$Z = \sum_{\text{all states}} e^{-\beta E} = \sum_{\text{all states}} e^{K \sum_{\langle ij \rangle} S_i S_j} = \sum_{\text{all states}} \prod_{\langle ij \rangle} e^{K S_i S_j} \quad (2.3)$$

Since $S_i S_j = \pm 1$ in the Ising model, Euler identities can be used to expand the exponential in equation (2.3).

$$\begin{aligned} e^{K S_i S_j} &= \frac{e^K + e^{-K}}{2} + S_i S_j \frac{e^K - e^{-K}}{2} \\ &= \cosh(K) + S_i S_j \sinh(K) \\ &= \{T = \tanh(K)\} \\ &= (1 + T S_i S_j) \cosh(K) \end{aligned}$$

For N spins there are $2N$ bonds, therefore the partition function is

$$\begin{aligned}
Z &= \sum_{\text{all states}} \Pi_{\langle ij \rangle} (1 + TS_i S_j) \cosh(K) \\
&= \cosh^{2N}(K) \cdot 2^N \left(2^{-N} \sum_{\text{all states}} \Pi_{\langle ij \rangle} (1 + TS_i S_j) \right) \\
&= \cosh^{2N}(K) \cdot 2^N Z'
\end{aligned}$$

And

$$\begin{aligned}
Z' &= 2^{-N} \sum_{\text{all states}} \Pi_{\langle ij \rangle} (1 + TS_i S_j) \\
&= 2^{-N} \sum_{S_1=\pm 1} \sum_{S_2=\pm 1} \dots \sum_{S_N=\pm 1} \left(1 + T \sum_{l=1} S_l S_{l+1} + T^2 \sum_{l=2} (S_l S_{l+1})(S_{l+2} S_{l+3}) + \dots \right)
\end{aligned}$$

Where the sums $\sum_{l=L}$ should be interpreted as the sum over all sets where the link length is L . Link length is the coupling between S -terms as

$$\begin{aligned}
(S_1 S_2) &- \text{Open with length 1} \\
(S_1 S_2)(S_2 S_3) &- \text{Open with length 2} \\
(S_1 S_2)(S_2 S_3)(S_3 S_4)(S_4 S_1) &- \text{Closed with length 4}
\end{aligned}$$

Since $\sum_{S_i=\pm 1} S_i = 0$, only terms with an even number of S_i are contributing to Z' . Call these terms closed, indicating that they represent a closed loop. The sum over all contributing terms gives a factor of 2^N , canceling the 2^{-N} .

Rewrite Z' in terms of loop lengths.

$$Z' = \sum_L g(L) T^L \quad (2.4)$$

Where $g(L)$ is the number of loops with length L . Finally write the expression for the partition function.

$$Z = 2^N \cosh^{2N}(K) \sum_L g(L) T^L \quad (2.5)$$

2.1.2 Energy calculation

$$E = -\frac{1}{Z} \frac{\partial Z}{\partial \beta} = -\frac{J}{Z} \frac{\partial Z}{\partial K} \quad (2.6)$$

Therefore

$$\begin{aligned}
\frac{\partial Z}{\partial K} &= 2^N 2N \cosh^{2N-1}(K) \cdot \frac{\partial \cosh(K)}{\partial K} Z' + 2^N \cosh^{2N}(K) \cdot \frac{\partial Z'}{\partial K} \\
&= 2^N \cosh^{2N}(K) \left(2N \tanh(K) Z' + \frac{\partial Z'}{\partial K} \right) \\
&= 2^N \cosh^{2N}(K) \tanh(K) \left(2N Z' + \frac{1}{\tanh(K)} \frac{\partial Z'}{\partial K} \right)
\end{aligned}$$

Examine $\tanh^{-1}(K) \frac{\partial Z'}{\partial K}$.

$$\begin{aligned}
\tanh^{-1}(K) \frac{\partial Z'}{\partial K} &= \tanh^{-1}(K) \frac{\tanh(K)}{\partial K} \sum_L g(L) L \tanh^{L-1}(K) \\
&= \frac{1}{\tanh^2(K) \cosh^2(K)} \sum_L g(L) L \tanh^L(K) \\
&= \frac{Z'}{\sinh^2(K)} \frac{\sum_L g(L) L \tanh^L(K)}{\sum_L g(L) \tanh^L(K)} \\
&= \frac{Z'}{\sinh^2(K)} \langle L \rangle
\end{aligned}$$

And finally

$$E = -J \tanh(K) \left(2N + \frac{\langle L \rangle}{\sinh^2(K)} \right) \quad (2.7)$$

where

$$\langle L \rangle = \frac{\sum_L g(L) L \tanh^L(K)}{\sum_L g(L) \tanh^L(K)} \quad (2.8)$$

2.1.3 Heat capacity

$$C = \frac{\partial E}{\partial T} = -\beta^2 \frac{\partial E}{\partial \beta} = -K \beta \frac{\partial E}{\partial K} \quad (2.9)$$

Let $A = 2N + \frac{1}{\sinh^2(K)} \langle L \rangle$. Then

$$\frac{E}{J} = -\tanh(K) A \quad (2.10)$$

and

$$\frac{1}{J} \frac{\partial E}{\partial K} = -\frac{\partial \tanh(K)}{\partial K} A - \tanh(K) \frac{\partial A}{\partial K} \quad (2.11)$$

where

$$\begin{aligned}\frac{\partial A}{\partial K} &= \langle L \rangle \frac{\partial \sinh^{-2}}{\partial K} + \tanh^{-1}(K) \sinh^{-2}(K) (\langle L^2 \rangle - \langle L \rangle^2) \frac{\partial \tanh(K)}{\partial K} \\ &= \frac{1}{\sinh^2(K) \tanh(K)} \left(-2\langle L \rangle + \frac{\langle L^2 \rangle - \langle L \rangle^2}{\cosh^2(K)} \right)\end{aligned}$$

and finally

$$C = \frac{K^2}{\sinh^2(K)} \left(\frac{\langle L^2 \rangle - \langle L \rangle^2}{\cosh^2(K)} - E \tanh(K) - 2\langle L \rangle \right) \quad (2.12)$$

2.2 n -vector model

The n -vector model describes a classical system of n -dimensional classical spins s_i of unit length interacting on a lattice. It is a generalization of the Ising model where each spin can have a continuous set of values. The Hamiltonian is then

$$H = -J \sum_{\langle ij \rangle} s_i \cdot s_j \quad (2.13)$$

where J is the bond strength and $\langle ij \rangle$ refers to a nearest neighbour interaction.

2.3 XY model

A special case of the n -vector model is the XY model when $n = 2$. Here the spins are two dimensional rotors as $s_i = (\cos \theta_i, \sin \theta_i)$. This yields the Hamiltonian

$$H = -J \sum_{\langle ij \rangle} \cos(\theta_i - \theta_j) \quad (2.14)$$

The partition function is therefore

$$Z = \prod_i \int \frac{d\theta_i}{2\pi} e^{-\beta H} = \prod_i \int \frac{d\theta_i}{2\pi} e^{K \sum_{\langle ij \rangle} \cos(\theta_i - \theta_j)} \quad (2.15)$$

where $K = J\beta$.

2.3.1 Loop expansion

Since equation (2.15) is invariant under the transformation $\theta_i - \theta_j \rightarrow \theta_i - \theta_j + 2\pi n$, $n \in \mathbb{Z}$, it can be expanded using the identity

$$e^{\alpha \cos \beta} = \sum_{\gamma=-\infty}^{\infty} I_{\gamma}(\alpha) e^{i\gamma\beta} \quad (2.16)$$

where $I_{\gamma}(\alpha)$ is the modified Bessel function. Using that $e^{\sum_i x_i} = \prod_i e^{x_i}$

$$Z = \prod_i \int \frac{d\theta_i}{2\pi} \sum_{J_{\langle ij \rangle}=-\infty}^{\infty} \prod_{b=\langle ij \rangle} I_{J_{\langle ij \rangle}}(K) e^{iJ_{\langle ij \rangle}(\theta_i - \theta_j)} \quad (2.17)$$

$$= \prod_i \sum_{J_b} \left(\int \frac{d\theta_i}{2\pi} e^{iN_i(\theta_i - \theta_j)} \right) \left(\prod_b I_{J_b} \right) \quad (2.18)$$

Where in the last step, $\prod_{\langle ij \rangle} e^{iJ_{\langle ij \rangle}(\theta_i - \theta_j)} = e^{iN_i(\theta_i - \theta_j)}$. N_i is therefore the sum of J for the nearest neighbours of site i . Noting that

$$\int \frac{d\theta_i}{2\pi} e^{iN_i(\theta_i - \theta_j)} = C \delta_{N_i, 0} \quad (2.19)$$

leads to the conclusion that the sum of incoming and outgoing flux J into a site i must be zero, in other words, the configurations are divergence free. This in turn means that a configuration of the system must contain closed loops of flux J .

2.3.2 Winding number

In the ground state all the spins are aligned, while at higher energy states, the spins are pointed in random directions as can be seen in figure (??).

Therefore, making a constant phase shift $\Phi_{\mu} = \frac{A}{L}$ of $\theta_i - \theta_j$ in the μ direction would change the energy drastically for the ground state while, on a statistical average, not change the higher states energy at all (see figure (??)).

The free energy change ΔF for such a shift is

$$\Delta F = L^d \cdot \frac{1}{2} \rho_s \left(\frac{A}{L} \right)^2 \Rightarrow \rho_s = \lim_{A \rightarrow 0} L^{2-d} \frac{\partial^2 \Delta F}{\partial A^2} \quad (2.20)$$

where d is the dimension and ρ_s is the superfluid density which is zero for a high energy state. The free energy is

$$F = -T \ln(Z) \Rightarrow F'' = T \left(\left(\frac{Z'}{Z} \right) - \left(\frac{Z''}{Z} \right)^2 \right) \quad (2.21)$$

where $F' = \partial F / \partial A$. Examining Z from (2.18) with the added shift

$$Z = \prod_i \int \frac{d\theta_i}{2\pi} \sum_{J_{\langle ij \rangle} = -\infty}^{\infty} \prod_{b=\langle ij \rangle} I_{J_{\langle ij \rangle}}(K) e^{iJ_{\langle ij \rangle}(\theta_i - \theta_j + \Phi_\mu)} \quad (2.22)$$

$$= \prod_i \sum_{J_b} \left(\int \frac{d\theta_i}{2\pi} e^{iN_i(\theta_i - \theta_j)} \right) \left(\prod_b I_{J_b} \right) \cdot e^{iA \frac{1}{L} \sum_i J_{i,i+\mu}} \quad (2.23)$$

$$(2.24)$$

where in the last step

$$\prod_i \left(\prod_{\langle ij \rangle} e^{iJ_{\langle ij \rangle} \Phi_\mu} \right) = \quad (2.25)$$

$$\{\Phi_\mu \neq 0 \text{ only for neighbours in the } \mu \text{ direction}\} = \quad (2.26)$$

$$\prod_i (e^{iJ_{i,i+\mu} \Phi_\mu}) = \quad (2.27)$$

$$e^{iA \frac{1}{L} \sum_i J_{i,i+\mu}} \quad (2.28)$$

Introduce the winding number in the μ direction as

$$W_\mu = \frac{1}{L} \sum_i J_{i,i+\mu} \quad (2.29)$$

Intuitively, this describes the net flux in the μ -direction. Given a loop within the bounds of the lattice, the winding number is always zero. This is since an equal amount of flux in $+\mu$ as in $-\mu$ is needed to form a loop. However, this is not the case for a percolating cluster going, for example, from $-\mu$ to $+\mu$ connecting with periodic boundary conditions. For such a ‘winding’ cluster, the winding number will be $+1$. An example can be seen in figure (??).

Using the definition (2.29) for the winding number in the partition function in equation (2.24) yields

$$Z = \sum_{J_b} \left(\prod_b I_{J_b} \right) \prod_i \left(\int \frac{d\theta_i}{2\pi} e^{iN_i(\theta_i - \theta_j)} \right) \cdot e^{iAW_\mu} \quad (2.30)$$

$$= \sum_{J_b, N_i=0} Z_0 \cdot e^{iAW_\mu} \quad (2.31)$$

$$= \sum_{W_\mu} Z_0 \cdot e^{iAW_\mu} \quad (2.32)$$

Using this result in equation (2.21)

$$\frac{\partial^2 F}{\partial A^2} = T \left(\left(\frac{\sum_{W_\mu} (iW_\mu) Z_0 e^{iAW_\mu}}{\sum_{W_\mu} Z_0 e^{iAW_\mu}} \right)^2 - \frac{\sum_{W_\mu} (-W_\mu^2) Z_0 e^{iAW_\mu}}{\sum_{W_\mu} Z_0 e^{iAW_\mu}} \right) \quad (2.33)$$

$$= T \left(-\langle W_\mu \rangle^2 + \langle W_\mu^2 \rangle \right) \quad (2.34)$$

$$= T \langle W_\mu^2 \rangle \quad (2.35)$$

Where $\langle W_\mu \rangle = 0$ since there is an equal chance of percolating from $-\mu$ to μ as the other way around.

The superfluid density can finally be determined as

$$\rho_s = L^{2-d} T \langle W_\mu^2 \rangle \quad (2.36)$$

Chapter 3

Method

Chapter 4

Graph Division and Hausdorff Dimension

4.1 Worm Algorithm

4.2 Graph Labeling

4.2.1 Hoshen Kopelman

To find the clusters a modified version of the Hoshen Kopelman algorithm was used. A raster scan is used to label disjoint sets into groups with some canonical label[1]. It is a variant on the union-find algorithm and is most easily described through the associated functions. Intuitively, applying the find function on a site i returns the canonical, often implemented as the smallest, label in the cluster that i belongs to. Union uses find to ensure that two sites i and j are connected by setting the canonical label of i to that of j (or vice versa).

An example implementation would be to have a 2D graph without periodic boundary conditions of zeros and ones, where a site is occupied if it has a one associated with it, and unoccupied otherwise. A disjoint set here is a number of occupied sites neighbouring each other with unoccupied sites surrounding them. For simplicity the scan can start in the lower left corner, moving right and up, while search for neighbours left and down, ensuring that if a neighbouring site is occupied, it has been labeled before.

Start by setting each site to a unique label, putting all sites in individual clusters. Go through the lattice until an occupied site i is found. Search the neighbours below and to the left. If none of these neighbours are occupied, label i have a unique label and move to the next site. If i has one occupied neighbour it must have been labeled before, so i inherits the neighbours label. Finally if both neighbours are occupied, site i must be connecting a cluster and a union is performed on the neighbours to

join their labels. A final pass through the lattice using the find function ensures that all sites have their canonical label.

In this paper an occupied site corresponds to a site with connections to the neighbouring sites (in the 2D example above, each site could have four such connections). In the original paper by Hoshen and Kopelman the labels for the sites who did not originally carry the canonical label, were set to a negative integer, symbolizing that they were aliases. A positive value was used at the canonical label, showing the number of sites in that cluster. This was not used in this project since the number of links in a cluster is not necessarily equal to the number of sites.

4.3 Fractals

Everyone agrees that the dimension of a point is zero, and that of a smooth line is one, but what about a set of points? A definition could be to say that the dimension is the minimum number of coordinates needed to describe every point in the set. Effectively, a point would describe itself, and a curve could be parametrized to the distance of some point on the same curve.

The situation is more complex when examining fractals. Take for example the Koch curve, it starts out as a line segment of length L_0 , and successively adds a ‘bump’, making the total length $L_1 = 4/3 \cdot L_0$. Iterating n times gives a line length of $L_n = (4/3)^n \cdot L_0$, and so the final fractal length is infinite.

Any two point on the final curve has a distance of infinity between them, so parametrization is impossible. But the area is still finite, so the dimension should intuitively be somewhere between one and two.

A useful concept here is the similarity dimension, defined by the scaling of each iteration. If m is the number of similar elements after an iteration and r is the scaling factor, the dimension is defined by $m = r^d$, or equivalently

$$d = \frac{\ln m}{\ln r} \quad (4.1)$$

So for the Koch curve, each segment is divided into fourths with each having one third the length from the previous iteration, giving it a dimension of $\ln 4 / \ln 3 \approx 1.26$.

4.4 Box dimension

4.5 Graph Dividing Algorithm

In order to calculate the box dimension the lattice need to be divided into boxes of decreasing size. A step by step instruction of a graph dividing algorithm is provided below, and an implementation in pseudocode is available in the Appendix at Section 8.1.

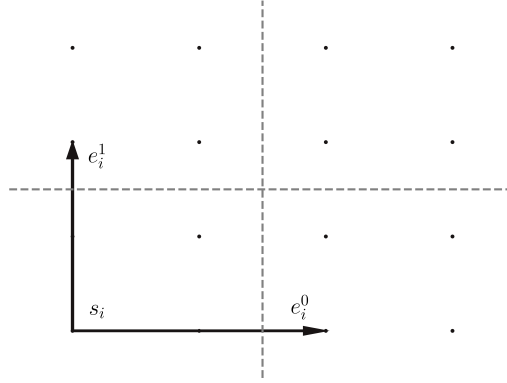


Figure 4.1: One step in the graph dividing algorithm where $l_i = 4$. e_i^0 and e_i^1 are drawn from site s_i and summed permutations of these will give the starts for the next boxes. The next iteration of boxes are shown via the dividing dotted lines.

For brevity some abbreviations are introduced.

d = dimension	l_i = side length of the current box
l_0 = side length of the smallest box allowed	e_i^j = vector of length $l_i/2$ in the j 'th direction
$\text{perm}(v)$ = All permutations of v	s_i = starting site of the current box

1. If $l_i \geq l_0$, go to 2, else stop.
2. Save all sites in the current box, starting for s_i going l_i in d directions.
3. Find all starting points for new boxes.

- (i) Form the matrix $E = (e_i^0, e_i^1, \dots, e_i^d)^T$
- (ii) For all vectors v_k in $\text{perm}(0, 0, \dots, 0), \text{perm}(1, 0, \dots, 0), \dots, \text{perm}(1, 1, \dots, 1)$, create the new start s_k as

$$s_k = v_k E$$

4. For each start s_k :
 - (i) $s_i = s_k, l_i = l_i/2$
 - (ii) Go to 1.

Chapter 5

Connection between Hausdorff Dimension and Scaling Behaviour

Chapter 6

Results

6.1 Error Estimation

In this thesis a number of error estimation techniques were used to know how much data was needed for each measurement. In this section the techniques will be described intuitively.

6.1.1 Monte Carlo error estimation

Given a Monte Carlo simulation where polling of some quantity A has been done N times an estimation of the expectation value of A is

$$\bar{A} = \frac{1}{N} \sum_{i=1}^N A_i \tag{6.1}$$

where each sampling was labeled A_i . To show that this is an unbiased estimator the expectation value of the difference between the estimation and the real value $\langle A \rangle$ is used.

$$\langle \bar{A} - \langle A \rangle \rangle = \langle \bar{A} \rangle - \langle A \rangle \quad (6.2)$$

$$= \left\langle \frac{1}{N} \sum_{i=1}^N A_i \right\rangle - \langle A \rangle \quad (6.3)$$

$$= \frac{1}{N} \sum_{i=1}^N \langle A_i \rangle - \langle A \rangle \quad (6.4)$$

$$= \frac{1}{N} \sum_{i=1}^N \langle A \rangle - \langle A \rangle \quad (6.5)$$

$$= \frac{1}{N} N \langle A \rangle - \langle A \rangle = 0 \quad (6.6)$$

where the fact that A_i is a random sampling from the distribution of A was used in (6.5).

The standard deviation of this estimate can be calculated through the variance.

$$\sigma_{\bar{A}}^2 = V(\bar{A} - \langle A \rangle) \quad (6.7)$$

$$= V(\bar{A}) - V(\langle A \rangle) \quad (6.8)$$

$$= \{\langle A \rangle \text{ is a constant} \Rightarrow V(\langle A \rangle) = 0\} \quad (6.9)$$

$$= V\left(\frac{1}{N} \sum_{i=1}^N A_i\right) \quad (6.10)$$

$$= \{\text{Monte Carlo simulations give independent samples}\} \quad (6.11)$$

$$= \frac{1}{N^2} \sum_{i=1}^N V(A_i) \quad (6.12)$$

$$= \{V(A_i) = \sigma_A^2\} \quad (6.13)$$

$$= \frac{1}{N^2} N \sigma_A^2 = \frac{\sigma_A^2}{N} \quad (6.14)$$

or

$$\sigma_{\bar{A}} = \frac{\sigma_A}{\sqrt{N}} \quad (6.15)$$

So the standard error in this estimation decreases as $N^{-1/2}$.

6.1.2 Bootstrap

Bootstrap is a resampling method to examine a probability distribution. In this thesis it was used to estimate the error propagation of parameters in curve fitting.

Given a set \mathbf{x} of N measurements from an unknown distribution $\hat{\phi}$, some statistical calculation of interest can be done as $\theta = s(\mathbf{x})$. A resampling \mathbf{x}_0 of \mathbf{x} comprised of N random measurements from \mathbf{x} (where one measurement can be included several times), can then be used to calculate $\theta_0^* = s(\mathbf{x}_0)$. Repeating this N_B times gives an estimate $\theta^* = (\theta_0^*, \theta_1^*, \dots, \theta_{N_B}^*)$ of the distribution $\hat{\theta}$. Assuming N_B is large then, by the central limit theorem, $\hat{\theta}$ is a normal distribution with some standard deviation σ_θ that can be used as an error estimation for θ .

Chapter 7

Summary and conclusions

Chapter 8

Appendix

8.1 Pseudo Code for Box Division Algorithm

Bibliography

- [1] J. Hoshen and R. Kopelman, *Percolation and cluster distribution. I. Cluster multiple labeling technique and critical concentration algorithm*, Physical Review B **14**, 3438 (1976).
- [2] S. H. Strogatz, *Nonlinear Dynamics and Chaos With Applications to Physics, Chemistry, and Engineering*, 2 ed. (Westview Press Inc, Boulder, Colorado, 2014).
- [3] Y. Holovatch, *Order, Disorder and Criticality* (WORLD SCIENTIFIC, 2004).
- [4] J. Hove, S. Mo and A. Sudbø, *Hausdorff Dimension of Critical Fluctuations in Abelian Gauge Theories*, Physical Review Letters **85**, 2368 (2000).
- [5] D. Schleicher, *Hausdorff Dimension, Its Properties, and Its Surprises*, The American Mathematical Monthly **114**, 509 (2007).
- [6] N. Prokofev and B. Svistunov, *Comment on Hausdorff Dimension of Critical Fluctuations in Abelian Gauge Theories*, Physical Review Letters **96** (2006).
- [7] O. Melchert, C. Norrenbrock and A. Hartmann, *Negative-weight Percolation: Review of Existing Literature and Scaling Behavior of the Path Weight in 2d*, Physics Procedia **57**, 58 (2014).
- [8] A. Raboutou *et al.*, *Fractal vortices in disordered superconductors*, Physica A: Statistical Mechanics and its Applications **207**, 271 (1994).
- [9] X. Dong *et al.*, *Phase transitions in 3D gravity and fractal dimension*, Journal of High Energy Physics **2018** (2018).
- [10] M. Wallin *et al.*, *Superconductor-insulator transition in two-dimensional dirty boson systems*, Physical Review B **49**, 12115 (1994).
- [11] N. Prokofev and B. Svistunov, *Worm Algorithms for Classical Statistical Models*, Physical Review Letters **87** (2001).
- [12] W. Janke and A. M. J. Schakel, *Fractal structure of spin clusters and domain walls in the two-dimensional Ising model*, Physical Review E **71** (2005).