



Universiteit
Leiden

The Netherlands

Numerical exploration of statistical physics

Bukva, A.

Citation

Bukva, A. (2023, October 10). *Numerical exploration of statistical physics*. *Casimir PhD Series*. Retrieved from <https://hdl.handle.net/1887/3643232>

Version: Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/3643232>

Note: To cite this publication please use the final published version (if applicable).

Numerical Exploration of Statistical Physics

Proefschrift

ter verkrijging van
de graad van doctor aan de Universiteit Leiden,
op gezag van rector magnificus prof.dr.ir. H. Bijl,
volgens besluit van het college voor promoties
te verdedigen op dinsdag 10 oktober 2023
klokke 13:45 uur

door

Aleksandar Bukva
Geboren te Kikinda, Servië
in 1994

Promotores:

Prof. dr. J. Zaanen

Prof. dr. K.E. Schalm

Promotiecommissie:

Prof.dr. C.W.J. Beenakker

Dr. J. Tura Brugués

Dr. J. van Wezel

Prof.dr. A. Achúcarro

Prof.dr. J.S. Caux

Casimir PhD series, Delft-Leiden 2023-23

ISBN 978-90-8593-571-1

An electronic version of this Thesis can be found at

<https://openaccess.leidenuniv.nl>

The cover was created by me, representing the synergy of the whole thesis in a single image.

To myself and my family.

Contents

1	Introduction	1
1.1	Statistical physics	3
1.2	Monte Carlo techniques	10
1.3	Machine learning	25
1.3.1	Neural networks for ML	31
1.3.2	Neural quantum states	34
1.4	This thesis	38
1.4.1	Chapter 1 - Thermalization in quantum systems	38
1.4.2	Chapter 2 - Symmetry restoration through “registry”	38
1.4.3	Chapter 3 - Entanglement entropy of lattice gauge theories	39
1.4.4	Chapter 4 - Phase space and efficient learning of deep neural networks	40
2	Operator Thermalization vs Eigenstate Thermalization	41
2.1	Introduction	42
2.2	Model details	44
2.3	Operators: thermalizing and non-thermalizing	45
2.4	OTH vs ETH	47
2.4.1	Thermalizing operator, E dependence	49
2.4.2	Non-thermalizing operator, E dependence	50
2.4.3	Statistics	50
2.4.4	Dependence on energy difference ω	53
2.5	Discussion and outlook	54

3	Replicating Higgs Fields in Ising Gauge Theory: the Registry Order	57
3.1	Introduction	58
3.2	A short review of Z_2 gauge theory with matter.	62
3.3	Replicating the Z_2 matter fields: two copies.	66
3.4	The case of many Z_2 matter fields.	72
3.5	Replicating $O(2)$ matter.	73
3.6	Discussion and conclusions	78
3.7	Appendix	79
3.7.1	Monte Carlo Simulations	79
3.7.2	Determining order of phase transition	80
4	Dense Entanglement in Critical States	83
4.1	Introduction	83
4.2	Neural Quantum State approximation to groundstates of $Z_2 \times Z_2 \times \dots \times Z_2$ / Z_2 transverse field "Ising" lattice gauge theory	85
4.2.1	NQS from RBM Set-Up: application to Z_2 gauge theory	85
4.3	Entanglement entropy	88
4.4	Dense entanglement at criticality or not?	89
4.5	Discussion	92
4.6	Appendix	93
4.6.1	NQS States and Entanglement for 1D transverse field Ising Model	93
5	Criticality versus Uniformity in Deep Neural Networks	95
5.1	Introduction	96
5.2	The line of uniformity	99
5.3	The edge of chaos	101
5.4	The impact of uniformity along the edge of chaos	103
5.5	Uniformity away from the EOC	105
5.6	Appendix	109
5.6.1	Independence of σ_*^2 on σ_1^2	109

5.6.2	Analytic Details of the Fixed Point Computation	109
5.6.3	Implementation Details	112
5.6.4	SWISH activation function	112
 References		 114
 Samenvatting		 123
 Summary		 125
 List of Publications		 127
 Curriculum Vitae		 129
 Acknowledgements		 131

