On the origin of temperature: Testing the Eigenstate Thermalisation Hypothesis in nanoscopic model systems.

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ABSTRACT

Quantum mechanics has time evolution by unitarity. However, this implies that no entropy is produced in quantum systems. Even so, it is empirical fact that a system put in a far-from equilibrium initial state does eventually relax to an entropic thermal state. This conflict might be resolved by the Eigenstate Thermalisation Hypothesis (ETH), which we propose to investigate aiming at finite size effects in nanoscopic systems. New theoretical methods have become available to address non-equilibrium quantum many-body physics. I will aim at exploring what these have to say regarding the ETH in nanoscopic laboratory systems, looking for critical experimental tests of the ETH. A central focus will be on quantum critical states which are of particular interest because of their very dense many body entanglement.

1

BASIC DETAILS

1.1 DETAILS OF APPLICANT

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1.2 DETAILS OF INTENDED SUPERVISOR

- Name: Prof. Dr. Jan Zaanen
- Address: Instituut-Lorentz, Universiteit Leiden, 2300 RA Leiden, The Netherlands
- Telephone: +31 71 527 55 06
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1.3 HOST INSTITUTION

The Lorentz Institute for theoretical physics, part of the Leiden Institute of Physics (LION) in the Netherlands.

2

RESEARCH PROPOSAL

2.1 RESEARCH FIELD

The research field is non-equilibrium quantum condensed matter physics, with a particular focus on relaxation dynamics of nanoscopic model systems.

2.2 TITLE OF RESEARCH PROPOSAL

On the origin of temperature: Testing the Eigenstate Thermalisation Hypothesis in nanoscopic model systems

2.3 INTRODUCTION

The question of interest for this proposal is how an isolated quantum system, initially in some non-equilibrium excited state, reaches thermal equilibrium. It is usually assumed that it does[10], based on largely classical notions.

However, the temporal evolution encoded in the Schrödinger equation tells a different story. Any quantum system with Hamiltonian H and energy eigenvalues and states described by $H|\alpha\rangle = E_\alpha |\alpha\rangle$ has a time-evolution operator $U(t) = \exp\left\{-\imath H \frac{t}{\hbar}\right\}$ that is clearly unitary. To use the language of quantum information theory, the von Neumann Entropy $S = -\mathrm{Tr}\left\{\rho \ln \rho\right\}$ is invariant under a unitary transformation of ρ. The time-evolution of ρ is described by:

$$\begin{aligned}\rho(t) &\equiv \sum |\alpha(t)\rangle \langle \alpha(t)| \\ &= U|\alpha(0)\rangle \langle \alpha(0)| U^\dagger \\ &= U\rho(0)U^\dagger \end{aligned} \tag{1}$$

As a result, the 'time-evolved' entropy in any quantum system is unchanged, $S\big(\rho(t)\big) = S\big(U\rho(0)U^\dagger\big) = S\big(\rho(0)\big)$. A quantum system does not produce entropy, which is counter intuitive; the second law of thermodynamics prescribes $\delta S \geq 0$ and the equilibrium ground state entropy of an arbitrary highly excited initial state is by definition different than that of a canonical ensemble. This leaves no room for vague descriptions that invoke in one way or another the understanding of the thermalisation in classical systems that rest on dynamical chaos leading to ergodicity.

It seems imperative to replace these vague descriptions with a proper notion of how quantum physics prescribes classical and thermal behaviour. A quite modern notion to explain this is the Eigenstate Thermalisation Hypothesis (ETH) [14].

If we consider an arbitrary laboratory quantum system, it has a humongous Hilbert space associated with it. If we consider the system as N qubits, then N must be of the order of Avogadro's number,

$N \approx 10^{23}$. The Hilbert space thus has a dimension of $2^N \approx 2^{10^{23}}$, a number larger than the amount of protons in the observable universe. The associated states are in a coherent superposition, leading to a ridiculous complexity.

Let us consider the (isolated) quantum system from before, with a large but finite number of degrees of freedom $N \gg 1$ [12, 13]. Assume that:

$$\bar{E} = \langle H \rangle \propto N \tag{2}$$

$$\mathrm{Var}\{E\} = \sqrt{\langle H^2 \rangle - \langle H \rangle^2} \ll \bar{E} \tag{3}$$

Define the thermal value of an arbitrary observable $\mathscr{O}$ as:

$$\mathscr{O}_{\text{th}} \equiv \mathrm{Tr}\left\{\mathscr{O} e^{-\beta H}\right\} \tag{4}$$

Additionally, we define that thermal equilibrium means the following criterion holds:

$$|\langle \mathscr{O} \rangle - \mathscr{O}_{\text{th}}| < \epsilon, \tag{5}$$

where ϵ is some arbitrary small tolerance.

The ETH states that thermal equilibrium will be reached for all states $|\Psi\rangle$ that meet these conditions, for operators A; $A_{\alpha\beta} = \langle \alpha | A | \beta \rangle$ that satisfy:

$$|A_{\alpha\alpha} - A_{\text{th}}(E_\alpha)| < \epsilon \tag{6}$$

$$\left|A_{\alpha\beta}\right| < \epsilon \quad \alpha \neq \beta \tag{7}$$

How to explain that the ETH is satisfied? Why have we observed entropy production in the second law of thermodynamics for centuries?

Consider a system that can be considered as two subsystems, such that $H = H_A \otimes H_B$. Not all eigenstates are separable as $|\alpha\beta\rangle = |\alpha\rangle \otimes |\beta\rangle$; this is a familiar notion from any introduction to quantum mechanics: singlet/triplet states.

The subadditivity property of the entropy in quantum information theory tells us that subsystems can have nonzero entropy while the total system does not. This provides us with the explanation inherit to ETH:

> *The ETH explains that thermalisation occurs because observations made by the human species are inherently limited to 'local' operators that measure only a vanishingly small part of the Hilbert space. The highly entangled nature of excited quantum many-body states then appears as a 'quantum information overload' in the form of thermalisation at long times. Temperature and probability are explained as ramifications of this extreme overload of indecipherable quantum information according to the ETH.*

Until recently, no general mathematical methods were available to address quantum non-equilibrium systems their temporal evolution, which are typically highly entangled in vast many-body Hilbert spaces beyond the reach of classical computations. This means that this is a typical first application of quantum computers.

However, such a method is now available; it originates in the unexpected corner of String Theory. The Anti-de Sitter/Conformal Field Theory (AdS/CFT) correspondence allows for a direct computation. In principle, this a weak/strong correspondence that allows us to take a strongly coupled QFT and calculate its dual system, a weakly coupled AdS space-time [17]. In this way, we have a method for directly calculating condensed-matter systems. When it comes to time-evolution, then a quantum critical problem has as a dual a non-stationary problem in General Relativity, such as the formation of a black hole.

One of the most important restrictions imposed by the AdS/CFT correspondence is that the quantum condensed matter system must be quantum critical, i.e. invariant under scale transformations. Quantum critical systems are extremely entangled by default. It is this limit of extreme quantum many-body entanglement that enables us to perform a direct computation in a gravity system (AdS).

AdS/CFT calculations have made several suggestions as to what effects should be found in quantum condensed matter systems.

The first important wisdom is that quantum critical systems are subject to the principle of Planckian Dissipation when one considers the linear response of these systems.

Second, AdS/CFT calculations suggest an extremely rapid thermalisation that occurs when one departs from highly excited non-equilibrium initial states.

Third, dealing with finite size quantum condensed matter systems leads to a prediction of quantum revivals.

It is these suggestions that we want to consider. Ultimately we regard the ETH in finite systems, aiming at predictions for nanoscopic devices. It is possible with classical computers to exactly diagonalise model systems at scales sufficiently large to find ETH, but also behaviour that departs from thermalisation that provides critical (laboratory) tests for ETH.

There are two model systems we want to consider. The first is the transversal field Ising model, which is a 'fruit-fly' of quantum condensed matter systems that has a parameter region in which it is critical [11]. The second model system is the Sachdev-Ye-Kitaev model which features extreme quantum entanglement [7]. The Hilbert-space of a N-qubit system is trivially of dimension 2^N. Thus, with a Hilbert space of order $2^N \approx 2^{10}$ to 2^{15} we can still exactly diagonalise and thus precisely study the non-equilibrium time evolution. For example, Hosur and Qi [6] exactly diagonalised and mapped to the Fock space of operators, a case in point for the exact diagonalisation of finite systems.

We want to explore the ETH in these models, mostly tuned to their quantum critical phases so that we can also study predictions made by AdS/CFT calculations. The focus is on systems that are experimentally viable, so that we can propose laboratory tests for the ETH.

2.4 APPROACH

The quantum critical phase is a very special phase featuring extremely entangled ground states, and even higher entanglement in excited states, with finite size-scaling showing logarithmic divergence [15]. This allows us to explore finite-size effects of the ETH.

A proper 'fruit-fly' of quantum systems is the extensively studied transversal field Ising model [11]:

$$\mathscr{H}_{\text{Transversal Ising}} = -J \sum_{\langle ij \rangle} \sigma_i^z \sigma_j^z - K \sum_i \sigma_i^x, \tag{8}$$

where σ_i^μ denotes a Pauli-matrix in the direction of μ at site i. The model parameters are J and K.

The phase diagram is shown in figure 1. The considerations are not specific to this model [11]. The tuning parameter $g = \frac{K}{J}$ expresses the strength of the classical Ising interaction versus that of the transversal field. If there is no transversal field, we have a classical Ising model. If the field dominates, $g \gg 1$, then the zero-temperature ground state is $\prod_i |\rightarrow_i\rangle$ and thus the ground state is a paramagnetic state. Likewise, for $g \ll 1$, the Ising interaction dominates and we find a ferromagnetic, doubly-degenerate ground state ($\mathbb{Z}_2$ symmetry). The quantum critical point is of course found at $g = g_c$.

At finite temperatures, thermal fluctuations destroy some of the required order, effectively moving the tuning parameter g towards g_c. Thus, the quantum critical phase can be found at higher temperatures than zero. When the temperature $k_B T$ is smaller than the characteristic energy scale Δ (e.g. energy difference between ground-state(s) and first excited state), $\Delta > k_B T$, we find good agreement with the $T = 0$ analysis, simply because we are in the low-temperature regime. The relaxation time always satisfies:

$$\tau \gg \frac{\hbar}{k_B T}$$

When $k_B T > \Delta$, thermal fluctuations dominate. Here, the relevant energy scale is $k_B T$ and we find the smaller relaxation time of a quantum critical system:

$$\tau \propto \frac{\hbar}{k_B T}$$

However, such a simple model is likely to be increasingly inaccurate when raising the temperature. Even so, this should make it clear that quantum critical phases are experimentally accessible, see e.g. Caviglia et al. [2]. Note that restricting the theoretical studies to a fruit-fly model does not necessarily exclude us from hypothesising about the ETH in generic quantum critical systems.

A chain of length L has a Hilbert space of dimension 2^L, so that chains of length 10 to 15 are still exactly diagonalisable within computational limits. For larger systems we can of course turn to the large amount of numerical methods for finding the eigenvalues and eigenvectors of a (large) matrix, e.g. the Lanczos algorithm or a divide-and-conquer algorithm.

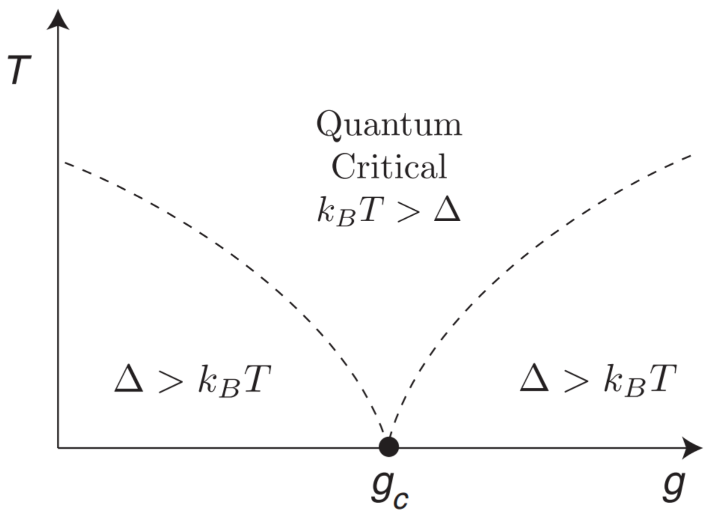

Figure 1: Separation of the phase diagram into distinct regimes determined by the energy scale Δ that characterises the ground state and the temperature $k_B T$. The dashed lines are smooth crossovers, not phase transitions. Image adopted from Sachdev [11]

The Sachdev-Ye-Kitaev (SYK) model features conformal symmetry at low energies [9], and is given by the Hamiltonian:

$$\mathscr{H}_{\text{Sachdev-Ye-Kitaev}} = \frac{1}{4!} \sum_{i,j,k,l=1}^{N} J_{ijkl} \chi_i \chi_j \chi_k \chi_l, \tag{9}$$

where χ_i are Majoranas $\{\chi_i, \chi_j\} = \delta_{ij}$ and the model has quenched disorder with the couplings J_{ijkl} drawn from a distribution.

Both of these models are quantum critical models that are solvable. At finite system size, comparable to the nanoscopic systems in a laboratory setting, they are still exactly diagonalisable. Therefore we can precisely study their non-equilibrium time evolution.

Holography, also known as AdS/CFT or gauge/gravity duality, is a result from string theory. Two particular theories correspond with one another in string theory, and their limits of AdS and CFT have been demonstrated to also be dual to one another. Relevant for this proposal is that a Conformal Field Theory corresponds to an Anti-de Sitter space-time problem. As a result, we can address the extremes of strongly coupled quantum condensed matter systems and non-equilibrium quantum physics in a controlled way[17]. Results from AdS/CFT calculations are used as inspiration for questions to explore in our toy-models which are strictly the quantum condensed matter systems.

For the first project, we want to investigate the relaxation of our model systems for linear responses, that is relaxation from initial states that are close-to equilibrium. In this linear-response set up, we also expect to see evidence of Planckian Dissipation [16] and shed some light on Wick rotations.

Furthermore, exact diagonalisation and small departures from equilibrium should allow us to investigate finite-size effects for the ETH, thus leading to possible laboratory tests of these effects.

The second project determines the rates of thermalisation for various highly-excited initial states and possible finite-sized effects. AdS/CFT predicts extremely-rapid, even near-instantaneous thermalisation that we should be able to find when exploring the thermalisation from such highly-excited far-from equilibrium states in our model systems.

The third project focuses on the suggestions of quantum revivals in finite-sized systems. The AdS system under consideration is an infalling shell in a hard-wall model, where numerical studies find oscillating solutions in some regimes [4], which means thermalisation in the dual field theory does not occur. This has been interpreted as quantum revivals [5], i.e. a return to the initial wave-state of the system.

Such revivals should be available in our toy models [1], where we should be able to tune to these oscillating regimes of the dual AdS system and thus test for these revivals in our systems.

Crucially these revivals should be very visible in measurement. The fact that revivals are suggested for finite systems, which are both computationally accessible and accessible in nanoscopic experiments makes this our focus for laboratory tests.

2.5 PLAN OF WORK AND COLLABORATIONS

Here I present the plan of work that accomplishes the completion of these research goals in the next four years. Additionally, I describe the planned collaborations for each goal. The plan is visually represented in table 1.

My main collaborator is of course Prof. Dr. Jan Zaanen, one of the most accomplished theoretical physicists of the Netherlands as evident by his NWO Spinoza Prize. The very modern notion of the

ETH intrigues him. Furthermore, he is also looking at the AdS/CFT correspondence to see what it can mean for condensed matter physics [17].

While the Master programme at Delft University of Technology has well prepared me to serve as an intermediary between Theory and Experiment, it did not contain a number of the cornerstones of modern physics, e.g. quantum Field Theory or Group Theory. This shortcoming needs to be rectified. Furthermore, laying down the groundwork of the computer code is an important step in preparation. Finally, studying the literature is also a trivial requirement. These three parts make up Goal 0.

For the first project, essentially the linear response thermalisation of our toy-models, we are planning to collaborate with the University of Amsterdam (UvA). The first project, including the writing of the resulting manuscripts, makes up Goal 1.

The second project, which regards the rates of thermalisation starting from extremely excited non-equilibrium initial states while looking at predictions from Holography, will include collaboration with Prof. Dr. Koenraad Schalm (Lorentz-Institute) and Prof. Dr. Ben Craps (Vrije Universiteit Brussel). Both collaborations with Prof. Dr. Jan Zaanen are well established. This project including collaborations with these holography experts constitute Goal 2.

Finally, for the third project, that investigates quantum revivals predicted by hard-wall holography, we plan to collaborate with Dr. Andrea Caviglia (Kavli Institute). Dr. Caviglia recently acquired a ERC 2015 Starting Grant on the proposal 'AlterMateria: Designer Quantum Materials Out of Equilibrium'. Complex oxide heterostructures have emerged as multifunctional materials of striking flexibility, with both electronic and phononic tuning inducing phase shifts. For example, a long-lived structural distortion of five-orders-of-magnitude increased electrical conductivity was found to propagate across the interface [3]. Another exotic example is light-induced non-equilibrium superconductivity [8]. The problem of temperature definition itself emerges naturally for these phenomena, especially as materials are tuned through their phase transitions including their quantum critical point. Dr. Caviglia's grant is to start a new lab with femtosecond pump-probe experiments to explore the non-equilibrium behaviour of complex oxides, particularly ABO_3 perovskite heterointerfaces.

In addition to the quantum revivals, other experimentally verifiable predictions from Goals 1 and 2 will also be taken into account here. Thus, the investigation of quantum revivals and the design of a pump-probe experiment that leads to empirical validation of the ETH is Goal 3.

Of course, the writing of the Ph. D. thesis and the handling of the final manuscripts are also planned. This makes up the 'Thesis' in the timescale of table 1.

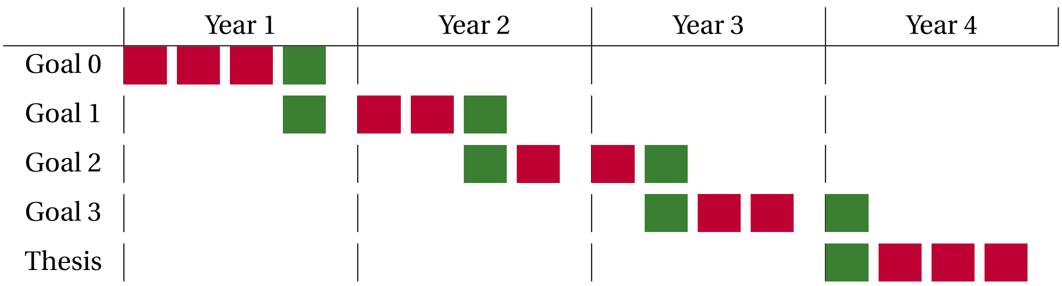

Table 1: Visualisation of the plan of work. Each red block represents 3 months. Green blocks overlap, and are dedicated to preparing manuscripts and new projects.

2.6 RESOURCES AND FACILITIES

The high-powered intellectual environment provided first by the Institute-Lorentz in Leiden and second by the Delta Institute for Theoretical Physics (Leiden University, Universiteit van Amsterdam, Utrecht University) is of the utmost importance, both because of the relevant theoretical expertise and because of the plethora of theoretical suggestions to consider for laboratory testing.

Of course, Prof. Dr. Jan Zaanen resides here, as does Prof. Dr. Koenraad Schalm. Prof. Dr. Jan Zaanen is one of the most accomplished theoretical physicists in the Netherlands, and has very recently developed an active interest in the notion of the ETH. He has a long and fruitful collaboration with Prof. Dr. Koenraad Schalm.

Leiden itself is a long established stronghold of applied holography, and we would like to take this to the laboratory. For this purpose we have the proposed collaborations with the UvA, the UU, Prof. Dr. Ben Craps at the Vrije Universiteit Brussel and Dr. Andrea Caviglia at the Kavli Institute for Nanoscience.

These are the required intellectual resources. Beyond that, we have access to the Maris Cluster of Leiden University for smaller calculations and the established partnership with CERN provides us with free access to the GRID, putting a prodigious amount of processing power at our disposal.

2.7 RELEVANCE FOR SCIENCE, TECHNOLOGY OR SOCIETY

The relevance of this proposal is scientific in nature. Resolving this mismatch between quantum mechanics and statistical physics, both cornerstones of modern theoretical physics, seems imperative. This project has the advantage that it focus lies solely on the ETH. In this way, we hope to develop tools for empirical verification of this hypothesis.

Perhaps it is relevant for technology. The ETH has a direct relation with quantum computations, and is likely among the first possible applications of a quantum computer. The world is non-equilibrium, and up to now quantum non-equilibrium problems are not within the reach of existing methods on classical computers. There might be very big surprises.

2.8 PERSONAL MOTIVATION

At the start of high school, I was diagnosed with what is called an Autism Spectrum Disorder under the DSM-V combined with a very high intelligence.

In high school, I was very isolated and above all very bored. I think that my setback in social development also emphasised the high intelligence, so that people thought me to be elitist and disinterested. Either way, I was socially isolated, educationally disinterested and still managed to pass all subjects.

I chose the B. Sc. in Applied Physics because I was promised a challenge. I wasn't ready for that challenge, of course; I first needed to learn discipline and other study habits. It took me some time to realise this; in fact, I was almost done with my B. Sc. before I finally crashed and went into therapy for autism once more.

Despite that blunt reawakening, I did learn those study habits and felt ready for the M. Sc. programme. Being able to choose what intrigues you makes a difference, but I still had to manage my autism.

I had learned that arbitrarily large groups in lectures left me depraved of retention and concentration for the rest of the day. Sadly, I found the regular group size of 20 students in M. Sc. lectures was still too much and I had to study at home.

Also, I found that a lot of lectures attempted to help students by presenting their information visually. While beneficial to most, I often struggle to understand visualisations.

I also had a handicap because I did not work in groups; some subjects accounted for the fact that most students work in groups in their grading scheme. I had to deviate time from subjects I enjoyed and did well at to subjects that just asked for more time.

I expected that I would find independent research more to my liking, but did not expect by how much. In Dr. Andrea Caviglia's group, I was allowed to immerse myself in the BCS theory of superconductivity with the aim of divising experiments of a fundamental nature.

With Prof. Dr. Jan Zaanen, I had to quickly learn the rudiments of several fields of theoretical physics in order to be able to collaborate with his group. I succeeded and was ultimately invited to co-author one of their papers (Liu et al. [19]). I was shown a world of fundamental theoretical physics undreamed of and found great joy, motivation and inspiration in my time there.

I went back to Delft for my M. Sc. Thesis, sure that I wanted to continue in Academia. During my thesis work I found that this was most definitely true. We had some very surprising results, some trouble explaining these and ultimately plan to write a paper explaining the new extension of the formalism and the implications for a model molecule.

I also found that fundamental questions and how to empirically test their answers are more interesting to me personally. Most definitely, I found that I enjoy and excel at research and that my determination to get a Ph. D. increased tenfold. And as you perhaps noticed, the diagnosis did no longer bother me during my research phase.

My motivation for working with Prof. Dr. Jan Zaanen has a lot to do with overlapping interests. He is not hesitant to elaborate on the most arcane subjects in physics, and I found that our interests often overlap. For instance, holography interests both of us. Dualities are the most astounding concepts in the history of physics, astounding to the point where a lot of people still get them wrong. Wave/Particle duality, for instance, does not mean it is either 'wave' or 'particle'; it is, of course, both at all times.

Can you imagine answering questions on the smallest scale by looking at the overwhelming dimensions of the night sky? Or that an astrophysicists walks into an experimental lab to work on a question involving celestial bodies? That is what holography promises to offer us.

As for this proposal itself, I think that it encompasses most skills I estimate I need to learn. Of course, I enjoy that we will use many tools to investigate *fundamental questions about nature*. Likewise, the broad literature focus intrigues me. Always thinking of empirical evidence and keeping in contact with experimental groups seems like a very valuable skill to learn. The focus on collaborations is beneficial, not only because we can sweep a broader expert community but simply because collaboration is a separate skill. Finally, the ability to present my research and interest others in it is very important.

2.8.1 *References*

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3

CURRICULUM VITAE

3.1 PERSONAL DETAILS

- Bachelor of Science, Master of Science (will be)
- Initials, first name: J. S., Josko
- Surname: de Boer
- Date of Birth: 24-04-1991
- Place of Birth: Brummen, the Netherlands

3.2 EDUCATION

Disclaimer

We found it necessary to include the following. I have been diagnosed with an Autism Spectrum Disorder (DSM-V), which has led to severe delay during my B. Sc. and lower grades in both the B.Sc. the M. Sc. programmes. Therefore, grades are not expected to give a realistic estimate of quality, whereas the research phase of the M. Sc. should speak for itself.

3.2.1 *Master's degree*

First short rotation, Caviglia Lab

As a theorist working directly with an experimental group, I focused on the possibility of empirically finding the superconducting gap structure of $LaAlO_3/SrTiO_3$ hetero-interfaces. Conceptually this should be possible by using the phase-differences in Josephson junctions. For reasons of resolution I looked at a SQUID setup, where the junctions were formed of bottle-necks of suppressed superconductivity on a superconducting ring. However, I found that these structures were badly characterised theoretically and that we could not yet use a SQUID setup to determine the superconducting gap structure.

The final grade was 8.5/10.

Second short rotation, Zaanen Group

Having a very different theoretical physics background, I had to rapidly absorb the rudiments of several fields of theoretical physics. I then joined in improving the implementation of the novel Generalised Liquid Crystal model, a Metropolis Monte Carlo code that I was able to speed up. By improving the code I was able to look at several interesting parameter fields. In essence, we could tune the parameters to take the system of specific symmetry through the $O(3)$ discrete point group diagram, restoring and breaking symmetries as we pleased. The latter behaviour was of course verified by use of order parameters and their susceptibilities.

We have since submitted the paper [19]. The final grade was 9.5 / 10.

Master Thesis, Thijssen Group

When I visited Dr. Jos Thijssen for a master thesis project, he suggested we work on extending the transport formalism used in molecular electronics to include certain interactions analytically, thereby greatly improving the accuracy. Within weeks, we had the first results to explore and decided to do broad sweeps of the parameter fields for both a spinfull and spinless model, leading to various surprises that did seem to fit experimental findings. Of course, we were slightly pressed for time and have decided to write the manuscript after officially finishing my thesis, probably preprinted in late september [18]. The final grade was 8.5 / 10.

Grades

The coursework of the master resulted in an average grade of 7.3. The rotations and master thesis resulted in an average grade of 8.8.

3.2.2 *Bachelor's degree*

- Delft University of Technology
- Delft, the Netherlands
- 2009-2014
- September 2014
- Grade Average: 7.0
- Received governmental subsidies "Verlenging Prestatiebeurs", recognising significant delay due to a DSM-IV diagnosis.

3.2.3 *Secondary Education*

- Zuyderzee College
- Emmeloord, the Netherlands
- VWO - Gymnasium, old system, Nature and Technology
- Graduated 2009

3.2.4 *List of Publications*

[18] Josko S. de Boer, Jose A. Celis Gil, Jos Seldenthuis, and Jos M. Thijssen. Likely preprint late September.

[19] Ke Liu, Jaakko Nissinen, Josko de Boer, Robert-Jan Slager, and Jan Zaanen. Hierarchy of orientational phases and axial anisotropies in the gauge theoretical description of generalized nematics. *Phys. Rev. E. (submitted)*, June 2016. arXiv:1606.04507.

3.3 INTERNATIONAL ACTIVITIES AND OTHER ACADEMIC ACTIVITIES

Participated in the Casimir Summer School, "Frontiers of Condensed Matter physics" in Les Houches, France.

3.4 CURRENT WORK EXPERIENCE

- Manuscript writer, temporary (paid) collaboration with Dr. Jos Thijssen and Prof. Dr. Herre van der Zant, September 2016
- Volunteer, Vana Events, traffic controller, technical infrastructure, various other jobs, summers of 2010-present
- Student Assistant, TU Delft, Bachelor courses, Introduction to Thermodynamics, Mechanics and special relativity, February 2014 - April 2014
- Intern Technical Assistant, Penta College CSG Scala Rietvelden, September 2012 - February 2013
- Interface Designer and Software Developer, Webgamic, April 2006 - September 2008